12.3 Dating with Radioactivity

Reading Focus

Key Concepts

- What happens during radioactive decay?
- How are isotopes used in radiometric dating?
- How can radiometric dating be used to date organic material?
- How can radiometric dating be used to date sedimentary rocks?

Vocabulary

- radioactivity
- half-life
- radiometric dating
- radiocarbon dating

Reading Strategy

Monitoring Your Understanding Preview the key concepts, topics, headings, vocabulary, and figures in this section. Copy the chart below. List two things you expect to learn about each. After reading, state what you learned about each item you listed.

What I expect to learn	What I learned
1. a. ?	b. ?
2. c. ?	d. ?

Early geologists like William Smith could only determine the relative ages of rock layers. They could not find exact dates for events in Earth's past. Today, geologists can determine the *absolute age* of a rock. A rock's absolute age is the approximate number of years before the present that the rock formed. For example, we know that Earth is about 4.56 billion years old and that the dinosaurs became extinct about 65 million years ago. To understand the method geologists used to arrive at these dates, you need first to understand radioactivity.

What Is Radioactivity?

Radioactivity is a process that involves the nucleus of the atom. Recall from Chapter 2 that each atom has a nucleus made up of protons and neutrons. The forces that bind protons and neutrons together in the nucleus are usually strong. However, in some atoms, the forces binding the protons and neutrons together are not strong enough, and the atoms are unstable. **During radioactive decay, unstable atomic nuclei spontaneously break apart, or decay, releasing energy.** The term for the process by which atoms decay is **radioactivity.** Figure 14 shows how radioactive decay releases energy in the form of three types of particles.

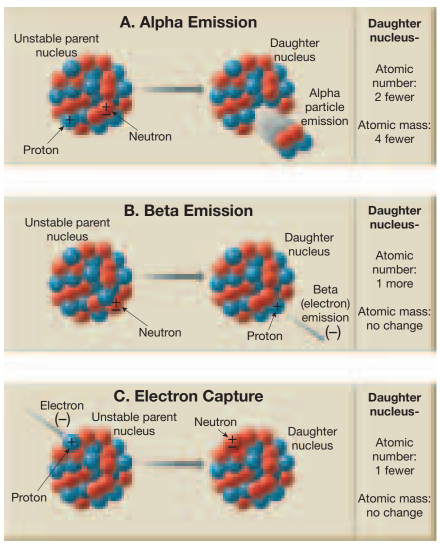

Figure 14 Radioactive Decay In each type of radioactive decay, the number of protons (atomic number) in the nucleus changes, thus producing a different element.

Section 12.3

1 FOCUS

Section Objectives

12.8 **Define** radioactivity and half-life.
12.9 **Explain** radiometric dating.
12.10 **Describe** how carbon-14 is used in radiometric dating.
12.11 **Explain** how radiometric dating of igneous rock layers can help date sedimentary rock layers indirectly.

Reading Focus

Build Vocabulary L2

Vocabulary Rating Chart Have students make a four-column chart with the headings "Term," "Can Define or Use It," "Heard or Seen It," and "Don't Know." Have them write *radioactivity*, *half-life*, *radiometric dating*, and *radiocarbon dating* in the first column. Students should then rate their knowledge of each term by putting a checkmark in one of the other columns. Ask them to revise their charts after they have read the section.

Reading Strategy L2

Sample answers include:
a. What is radioactivity? **b.** the breakdown of unstable nuclei; **c.** What is half-life? **d.** the time required for one half of the nuclei in a sample to decay to its stable isotope

2 INSTRUCT

What Is Radioactivity?

Build Science Skills L2

Using Models Have students draw models of atoms. Student models should show protons (positive charge) and neutrons (neutral charge) in the nucleus. Electrons (negative charge) should orbit outside the nucleus.
Kinesthetic, Logical

Use Visuals L1

Figure 14 Ask: **What happens to the number of protons in each case?** *(It either increases or decreases.)*
Visual

Facts and Figures

Quantum Mechanics and Statistics As a part of the theory of quantum mechanics, it is impossible to predict when a single unstable radioactive isotope will decay into its daughter products. However, this unpredictability does not call into question the ability of radiometric dating to determine the ages of old rock because of the statistics of large numbers. There are physical rules that control radioactive decay, and given a large sample of the radioactive isotopes, the rate of decay becomes very predictable. This is analogous to flipping a coin. If you flip a coin just once, it is impossible to predict if it will come up heads or tails. However, if you flip a coin two billion times, you can be sure that about a billion flips will come up heads and a billion will come up tails. Radioactive decay works in a similar way.

Use Visuals
L1

Figure 15 Have students predict how much of the radioactive parent will remain after six half-lives. *(1/64)* Ask: **At which point is the parent/daughter ratio 1:1?** *(after one half-life)*
Visual

Radiometric Dating
Build Science Skills
L2

Applying Concepts Have students review Figure 14 on p. 347. Tell them that the element thorium has an atomic number of 90 and a mass number of 232. Ask: **If a radioactive isotope of thorium emits six alpha particles and four beta particles during radioactive decay, what are the atomic number and mass number of the stable daughter product?** *(Each time beta decay occurs, the atomic number increases by one; mass number does not change. Each alpha decay decreases the atomic number by two and the mass number by four. Thus, for six alpha decays and four betas, the atomic number of the daughter would be 90 − (6 × 2) + 4 = 82. The mass number of the daughter would be 232 − (6 × 4) = 208).*
Logical

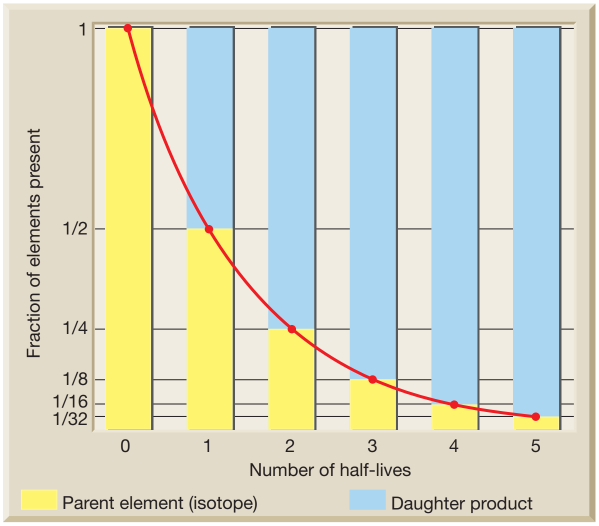

Figure 15 The Half-Life Decay Curve The radioactive decay curve shows change that is exponential. Half of the radioactive parent remains after one half-life. After a second half-life, one quarter of the parent remains, and so forth. **Interpreting Graphs** ***If $\frac{1}{32}$ of the parent material remains, how many half-lives have passed?***

Radioactive Isotopes Recall that the number of neutrons in the atoms of a given element can vary. These different forms of an element are called isotopes. An unstable, or radioactive, isotope of an element is called the parent. The isotopes that result from the decay of the parent are called the daughter products. What happens when unstable nuclei break apart? Radioactive decay continues until a stable or nonradioactive isotope is formed. For example, uranium-238 decays over time to form the stable isotope lead-206.

Half-Life A half-life is a common way of expressing the rate of radioactive decay. A **half-life** is the amount of time necessary for one half of the nuclei in a sample to decay to its stable isotope, as shown in Figure 15. If the half-life of a radioactive isotope is known and the parent/daughter ratio can be measured, the age of the sample can be calculated. For example, if the half-life of an unstable isotope is 1 million years, and $\frac{1}{16}$ of the parent isotope remains, this amount indicates that four half-lives have passed. The sample must be 4 million years old.

Radiometric Dating

Radiometric dating, also called radioactive decay dating, is a way of calculating the absolute ages of rocks and minerals that contain certain radioactive isotopes. **In radiometric dating, scientists measure the ratio between the radioactive parent isotope and the daughter products in a sample to be dated. The older the sample, the more daughter product it contains.**

How can a radioactive isotope serve as a reliable "clock"? The rates of decay for many isotopes have been precisely measured and do not vary under the physical conditions that exist in Earth's outer layers. Each radioactive isotope has been decaying at a constant rate since the formation of the rocks in which it occurs. The products of decay have also been accumulating at a constant rate. For example, when uranium is incorporated into a mineral that crystallizes from magma, lead isn't present from previous decay. The radiometric clock starts at this point. As the uranium decays, atoms of the daughter product (lead) are formed and begin to accumulate.

Of the many radioactive isotopes that exist in nature, five have proved particularly useful in providing radiometric ages for ancient rocks. The five radioactive isotopes are listed in Table 1.

Customize for English Language Learners

Give ELL students opportunities to interact verbally with non-ELL classmates. Place students in cooperative groups to discuss key concepts or chapter activities. Do not place all ELL students in one group—the goal is to help them improve their English skills in an informal setting. Encourage all students to be supportive during the discussions. For example, if a student easily grasps a difficult concept, he or she can attempt to simplify the concept for others in a relaxed manner.

Table 1 Radioactive Isotopes Frequently Used in Radiometric Dating

Radioactive Parent	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	713 million years
Thorium-232	Lead-208	14.1 billion years
Rubidium-87	Strontium-87	47.0 billion years
Potassium-40	Argon-40	1.3 billion years

For igneous rock, radiometric dating establishes when minerals in the rock crystallized. For metamorphic rock, radiometric dating determines when heat and pressure caused new minerals to form in the rock or when daughter isotopes escaped from the minerals.

One frequently used type of radiometric dating is the potassium-argon method. In this method, geologists measure the ratio of radioactive potassium-40 atoms to stable argon atoms in a sample. Given the long half-life of potassium-40, this method can be used to date rocks that are hundreds of millions of years old. For example, geologists used potassium-argon dating to date lava from the Hawaiian islands.

An accurate radiometric date can be obtained only if the mineral remained in a closed system during the entire period since its formation. If the addition or loss of either parent or daughter isotopes occurs, then it is not possible to calculate a correct date. For example, an important limitation of the potassium-argon method stems from the fact that argon is a gas. Argon may leak from minerals and throw off measurements. Cross-checking of samples, using two different radiometric methods, is done whenever possible to ensure accuracy.

Although the basic principle of radiometric dating is simple, the actual procedure is complex. The analysis that determines the quantities of parent and daughter must be very precise. In addition, some radioactive materials do not decay directly into the stable daughter product. Uranium-238, for example, produces thirteen intermediate unstable daughter products before the fourteenth and final daughter product, the stable isotope lead-206, is produced.

Reading Checkpoint *What is the potassium-argon method of radiometric dating?*

Q&A

Q *In radioactive decay, is there ever a time when all of the parent material is converted into the daughter product?*

A Theoretically, no. During a half-life, half of the parent material is converted into the daughter product. Then half of the remaining parent material is converted to the daughter product in another half life, and so on. By converting only half of the parent material with each half-life, there is never a time when all the parent material would be converted. However, after many half-lives, the parent material will be present in such small amounts that it is essentially undetectable.

Go Online SciLinks NSTA

For: Links on radioactive dating
Visit: www.SciLinks.org
Web Code: cjn-4124

Teacher Demo

Modeling Half-Lives L2

Purpose Students will recognize how a radioactive parent isotope decays into its daughter product.

Materials scissors, adding machine tape, metric ruler

Procedure Begin with a piece of adding machine tape approximately 1 m long. Cut the paper in half. Set the two equal pieces aside. Take another 1-m long piece of paper and fold it into four equal pieces. Cut off one-fourth of the paper and set the two pieces aside. Ask students which two pieces of paper represent the parent/daughter ratio after one half-life. Ask which two represent the ratio after two half-lives.

Expected Outcomes Students will recognize that the two equal pieces of paper represent one half-life. The unequal pieces of paper, cut to represent one-quarter of the remaining parent isotope, represent two half-lives.
Visual

Go Online NSTA SciLinks

Download a worksheet on radioactive dating for students to complete, and find additional teacher support from NSTA SciLinks.

Facts and Figures

In a sample of uranium-238, unstable nuclei decay and produce a variety of daughter products, including radon—a colorless, odorless, invisible gas. Radon itself decays, having a half-life of only about four days. Its decay products are mainly radioactive solids that stick to dust particles, many of which are inhaled by people. During prolonged exposure to a radon-contaminated environment, some decay will occur while the gas is in the lungs, thereby placing the radioactive radon in direct contact with delicate lung tissue. Growing evidence indicates that radon is a significant cause of lung cancer, second only to smoking.

Answer to . . .

Figure 15 *Five half-lives have passed.*

Reading Checkpoint *In potassium-argon dating, scientists measure the ratio of radioactive potassium-40 to argon (its decay product) in a sample.*

Dating with Carbon-14

Build Reading Literacy L1

Refer to **p. 246D** in **Chapter 9,** which provides the guidelines for relating cause and effect.

Relate Cause and Effect Remind students that a cause makes something happen; the effect is what happens because of the cause. After students have read about dating with carbon-14, ask: **Why do all organisms contain a small amount of carbon-14?** *(It circulates in the atmosphere and is absorbed by living matter.)* **Why is the ratio of carbon-14 to carbon-12 constant during an organism's lifetime?** *(Carbon-14 is continually replaced.)* **At what point does the amount of carbon-14 in an organism began to decrease?** *(when the organism dies and starts to decay)*
Verbal, Logical

Figure 16 Carbon-14 is used to date organic materials that formed up to about 75,000 years ago.

Dating with Carbon-14

To date organic materials, carbon-14 is used in a method called **radiocarbon dating.** Organic material is a substance that contains carbon and comes from a living thing. Carbon-14 is the radioactive isotope of carbon. Carbon-14 is continuously produced in the upper atmosphere. It quickly becomes incorporated into carbon dioxide, which circulates in the atmosphere and is absorbed by living matter. As a result, all organisms—including you—contain a small amount of carbon-14.

While an organism is alive, the decaying radiocarbon is continually replaced. Thus, the ratio of carbon-14 to carbon-12—the stable isotope of carbon—remains constant. **When an organism dies, the amount of carbon-14 gradually decreases as it decays. By comparing the ratio of carbon-14 to carbon-12 in a sample, radiocarbon dates can be determined.**

Because the half-life of carbon-14 is only 5730 years, it can be used to date recent geologic events up to about 75,000 years ago. The age of the object shown in Figure 16 was determined using radiocarbon dating. Carbon-14 has become a valuable tool for anthropologists, archaeologists, and historians, as well as for geologists who study recent Earth history.

Reading Checkpoint *What is compared when dating with carbon-14?*

Radiometric Dating of Sedimentary Rock

Radiometric dating can rarely be used to date sedimentary rocks directly. Sedimentary rocks may contain particles that can be dated. But these particles are not the same age as the rocks in which they occur. The sediment from which the rock formed probably weathered from older rocks. Radiometric dating would not be accurate since the sedimentary rock is made up of so many older rock particles.

Geologists have developed an indirect method of dating sedimentary rocks. **To determine the age of sedimentary rock, geologists must relate the sedimentary rock to datable masses of igneous rock.** Applying Steno's principles, geologists identify two igneous rock masses. One rock mass must be relatively older than the sedimentary rock. The other rock mass must be younger. Then they use radiometric methods to date the two igneous rock masses. The age of the sedimentary rock must lie between the ages of the igneous rocks.

Facts and Figures

Determining the Age of Granite The process of determining the age of a rock can be very hard work. In the case of granite, the rock contains tiny amounts of the crystal zircon, which is an excellent source for determining the rock's age because both uranium and lead stay trapped within the zircon crystal lattice. The hard part is getting the zircon out of the granite. A large block of granite, hundreds of kilograms in mass, is destroyed in order to extract a few microscopic zircon crystals. The granite is crushed, shaken, passed through a magnet, and then successively put in various fluids with densities slightly higher and lower than that of zircon. The final zircon crystals are then dissolved in hydrochloric acid and passed through a machine called a *mass spectrometer,* which counts the individual uranium and lead atoms. These numbers are then used to calculate the age of the granite.

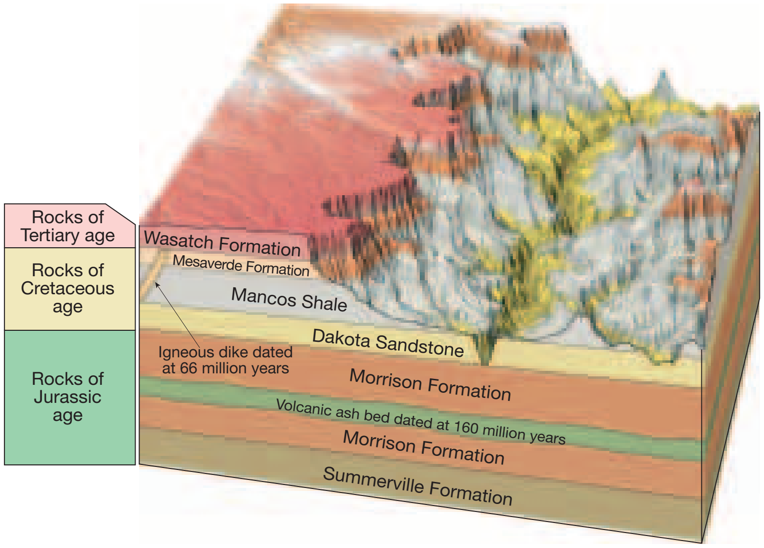

Figure 17 Sedimentary rock layers can be dated in relation to igneous rocks of known age—in this case, the volcanic ash bed and the igneous dike.
Inferring ***What can you infer about the age of the Dakota sandstone?***

Look at Figure 17. Using the principle of superposition, you can tell that all the layers above the volcanic ash are younger than the ash. Using the principle of cross-cutting relationships, you can see that the dike is younger than the layers it cuts across. Therefore, the age of the sedimentary layers in between must lie between the ages of the two igneous features.

Section 12.3 Assessment

Reviewing Concepts

1. What happens to atoms that are radioactive?
2. What is the role of isotopes in radiometric dating?
3. Describe radiocarbon dating.
4. How do geologists use radiometric dating to date sedimentary rock layers indirectly?

Critical Thinking

5. **Applying Concepts** A geologist wants to use potassium-argon dating to date a granite rock found on the surface. What is a possible source of inaccuracy in dating the rock?
6. **Classifying** Which of the following could *not* be dated using radiocarbon dating: charcoal, wooden beam, clay pot, food in the clay pot? Explain.
7. **Interpreting Diagrams** Look at Figure 17 above. What can you infer about the absolute age of the Wasatch Formation in relation to the igneous dike?

Writing in Science

Descriptive Paragraph Discuss the use of radiocarbon dating in determining the age of an ancient civilization.

Build Reading Literacy L1

Refer to **p. 186D** in **Chapter 7,** which provides the guidelines for relating text and visuals.

Relate Text and Visuals Have students reexamine Figure 17 and give specific examples of how Steno's principles can be used to interpret the relative ages of rocks. For example, ask: **How might you tell if the igneous dike is older than the Wasatch formation?** *(If you could determine that the Mesaverde/Wasatch boundary is an unconformity)*
Visual, Verbal

3 ASSESS

Evaluate Understanding L2

Have students choose a radioactive isotope from Table 1 on p. 349 and make a graph showing its decay curve through several half-lives.

Reteach L1

Use different-colored jelly beans to represent protons, neutrons, and electrons. Then model the common types of radioactive decay, using Figure 12 as a guide.

Writing in Science

Sample answer: Carbon-14 could be used to radiometrically date artifacts from an ancient human culture or civilization, assuming they are made of organic material and are younger than about 75,000 years.

Answers to . . .

Figure 17 *The Dakota sandstone is between 66 million and 160 million years old.*

Reading Checkpoint *The ratio of carbon-14 to carbon-12*

Section 12.3 Assessment

1. The nuclei decay or react by emitting alpha or beta particles.
2. A radioactive isotope decays into its stable daughter product at a constant rate. The time it takes for half of the isotope in a sample to decay is known as the *half-life* of the isotope. A radioactive isotope can thus serve as a "clock" that can be used to determine the age of a substance.
3. Scientists measure the ratio between the amount of radioactive isotope atoms and daughter product atoms in a substance. The ratio reflects how much time has passed since the substance formed.
4. Sedimentary rock layers that lie between two igneous rock units must have an age that lies somewhere between the absolute ages of the two igneous rock units. The latter can be dated using radiometric methods.
5. The rock may have been contaminated by other sources of potassium-40 on the surface. For radiometric dating to be accurate, a sample must remain in a closed system.
6. The clay pot, because clay is not an organic material
7. The Wasatch Formation must be less than 66 million years old because it cuts across the igneous dike.

understanding EARTH

Dating With Tree Rings

L2

Background

One of the most basic principles of geology is also used in the study of dendrochronology—the principle of uniformitarianism, which states that the same processes at work today were also active in the past. The doctrine helps dendrochronologists to make inferences about ancient environmental conditions. It also allows them to predict future patterns based on evidence of past conditions. Other doctrines used by dendrochronologists include the principle of limiting factors, which states that life processes, such as growth, are constrained by the most limiting environmental factor of a particular area, such as precipitation. The principle of ecological amplitude states that trees located at the extremes of their species' geographic range will be most vulnerable to changing environmental factors. Other dendrochronologic principles cover site selection, cross-dating, and sampling techniques.

Teaching Tips

- Obtain several thin cross-sections of tree trunks. Allow students to examine the rings. Have them count the rings and try to establish the age of the tree.
- Tell students that clues to ancient environments can also be determined by examining ice cores. The cores are obtained by drilling through thick layers of ice, which are found in places such as Greenland and Siberia. By analyzing gases and other materials trapped in the layers of ice, scientists can reconstruct past climatic conditions.

Visual

understanding EARTH

Dating With Tree Rings

The dating and study of annual rings in trees is called *dendrochronology.* Dendrochronology provides useful numerical dates for events in the historic and recent prehistoric past. Because tree rings are a storehouse of data, they are a valuable tool in the reconstruction of past environments.

If you look at the top of a tree stump or at the end of a log, you will see that it is made of a series of concentric rings, like those shown in Figure 18. Every year in temperate regions, trees add a layer of new wood under the bark. Each of these tree rings becomes larger in diameter outward from the center. During favorable environmental conditions, a wide ring is produced. During unfavorable environmental conditions, a narrow ring is produced. Trees growing at the same time in the same region show similar tree-ring patterns.

Because a single growth ring is usually added each year, you can determine the age of the tree by counting the rings. Cutting down a tree to count the rings is not necessary anymore. Scientists can use small, non-destructive core samples from living trees.

To make the most effective use of tree rings, extended patterns known as ring chronologies are established. They are produced by comparing the patterns of rings among trees in an area. If the same pattern can be identified in two samples, one of which has been dated, the second sample can be dated from the first by matching the ring pattern common to both. This technique, called cross dating, is illustrated in Figure 19. It allows the ages of tree remains that are no longer living to be dated. Tree-ring chronologies extending back for thousands of years have been established for some regions. To date a timber sample of unknown age, its ring pattern is matched against the reference chronology.

Tree-ring chronologies have important applications in such disciplines as climate, geology, ecology, and archaeology. For example, tree rings are used to reconstruct long-term climate variations within a certain region. Knowledge of such variations is of great value in studying and understanding the recent record of climate change.

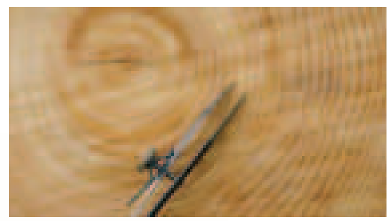

Figure 18 Each year's growth for a tree can be seen as a ring. Because the amount of growth (thickness of a ring) depends upon precipitation and temperature, tree rings are useful records of past climates.

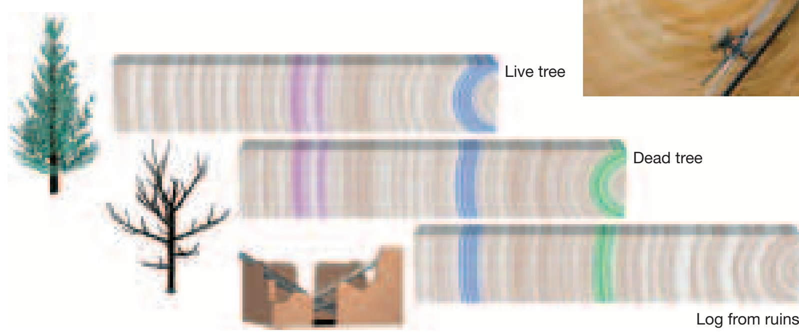

Figure 19 Using Tree Rings to Date Ancient Civilizations Cross dating is used to date an archaeological site by correlating tree-ring patterns using wood from trees of three different ages. First, a tree-ring chronology for the area is established using cores extracted from living trees. This chronology is extended further back in time by matching overlapping patterns from older, dead trees. Finally, cores taken from beams inside the ruin are dated using the chronology established from the other two sites.