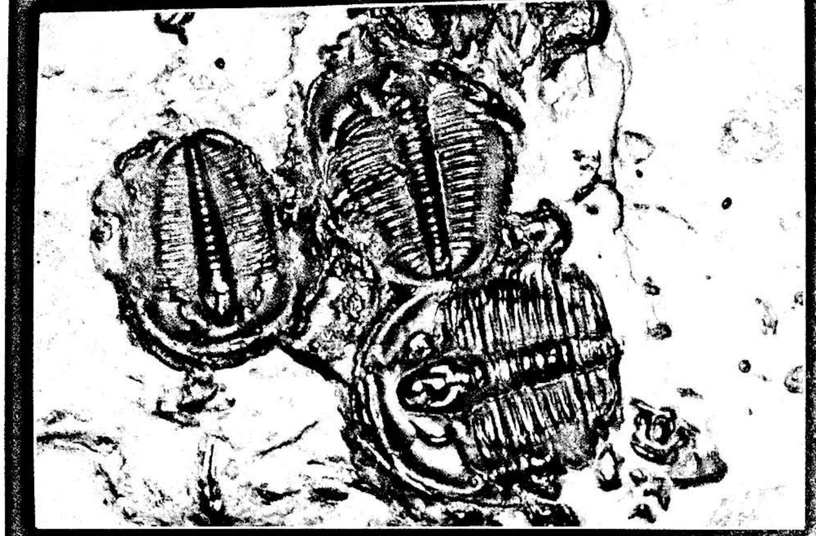
TOPIC XIII

INTERPRETING GEOLOGIC HISTORY



Knowing the time when this species of trilobites lived enables us to date the shale they are embedded in.

CHAPTER 22

Dating Geologic Events

You will know something about determining the relative and/or absolute age of a geological sample or event if you can:

1. Describe the types of evidence to be considered in determining the relative age of a rock or event.
2. Establish a correlation between rocks and/or events at different locations using rock and fossil evidence.
3. Describe how actual geologic ages can be measured using radioactive decay.

Unlocking the mysteries of past geologic events is like putting together a jigsaw puzzle. When you're doing a puzzle, you look for certain clues that can be of help—straight-edged pieces to make up the border, pieces of particular colors, or shapes, etc. Earth scientists also use certain types of "clues," which can help them to reconstruct the history of the earth. In this chapter we are going to see what clues present geologic features offer about past events.

RELATIVE DATING—THE ORDER OF GEOLOGIC EVENTS

As the geologist works to develop a model of the earth's history, he attempts to put events in chronological order—that is, in order of what happened first, what second, and so on. He attempts to find the *relative age* of a rock or event—its age compared with that of other rocks or events. He also attempts to find the *actual*, or *absolute, age*, which is the date that the event occurred or the rock was formed.

Before we get into our discussion of how earth scientists order past geologic events, there is a basic principle of earth science that should be mentioned—the principle of uniformitarianism.

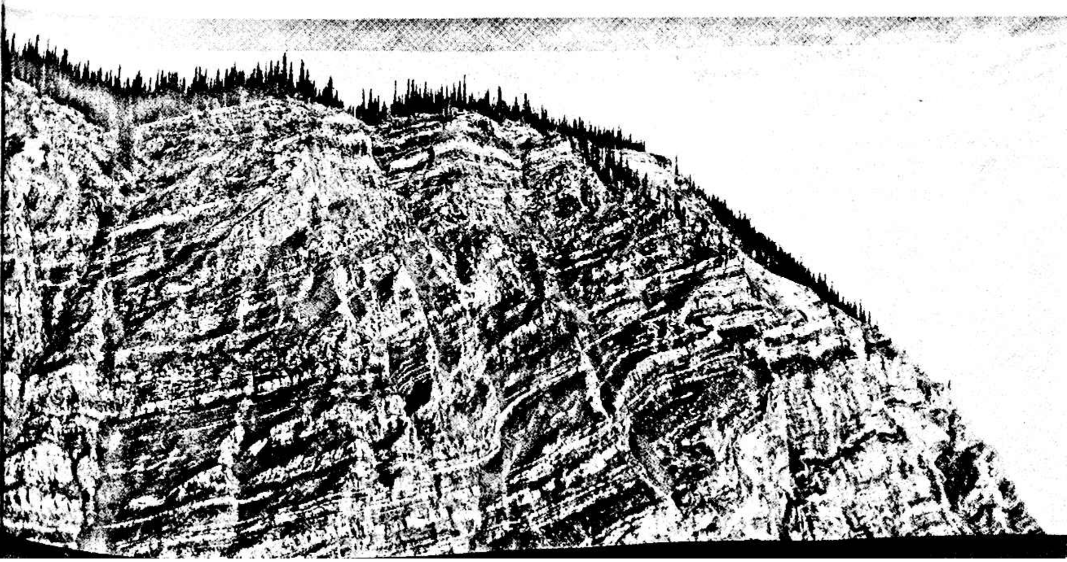
Uniformitarianism. In any discussion of geologic history we describe events that may have occurred in the past in terms of present-day processes. We assume that the forces at work on the earth have not changed with time—that rivers eroded their banks in the past in much the same way they do today, and that rocks weathered in the same way billions of years ago as they do now. This is the principle of *uniformitarianism*.

The principle of uniformitarianism was developed by a Scottish physician and farmer, James Hutton, in the late 1700's. Hutton stated that "the present is the key to the past." That is, by observing the geologic processes now at work on the earth, it is possible to unravel the mysteries of the earth's geologic history. Although Hutton's principle may seem quite obvious today, it represented a major step in geologic thinking at the time. Before Hutton, most 18th-century geologists tried to explain the earth's history in terms of one-of-a-kind, sudden, major changes, or *catastrophes*.

Keeping the principle of uniformitarianism in mind, we can now look at some of the evidence that earth scientists consider in dating events of the past.

Principle of Superposition. Figure 22-1 is an outcrop of rock, that is, ex-

Figure 22-1. An outcrop of rock showing layers.



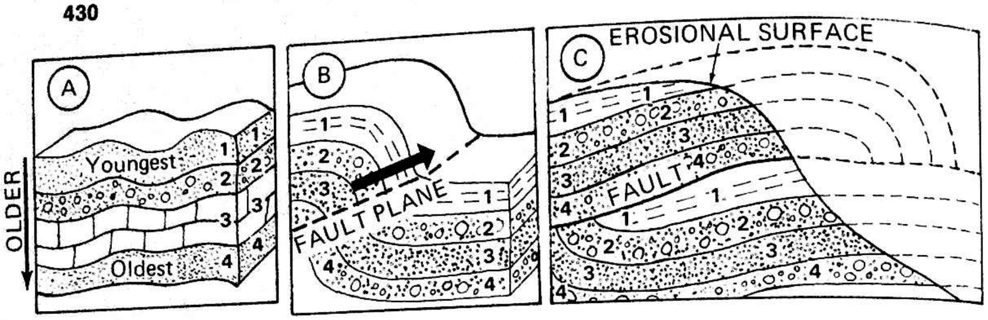


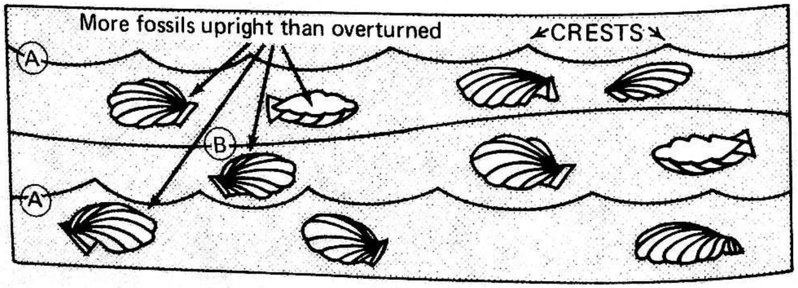
Figure 22-2. The principle of superposition and possible exceptions to it. (*A*) A rock layer is generally older than any layer above it. (*B*) and (*C*) The movement of layers along an overthrust fault can result in an exception to the principle of superposition.

posed bedrock without a covering of regolith. Examine it closely, and you will see that it consists of a number of layers. In Chapter 19 (page 368) we discussed the concept of *original horizontality*—that is, that sedimentary rocks generally form in horizontal layers, with new layers forming on top of existing layers. From this principle it is simple to infer that in sedimentary rock, the bottom layer is the oldest and the top layer the youngest. This idea is the *principle of superposition*, which is a basic concept in relative dating.

Is it always true that the bottom layer of sedimentary rock is the oldest? No. There can be complications. It is possible that in folded rocks, or where there has been movement along a fault, the layers have been overturned, so that older layers are on top of younger layers. Figure 22-2 shows how exceptions to the principle of superposition can occur.

How can you tell if the rock layers have been overturned? First you might look for general features. Are the rock layers in this outcrop more or less horizontal? Do other outcrops in the area show similar structures? If the answer to both questions is yes, then it is likely that the rock layers have not been overturned.

Figure 22-3. Use of ripple marks and fossils to determine whether rock layers have been overturned. (*A*) Ripple marks in the sand always form with their crests pointing upward. Such ripple marks can be seen in some sedimentary rock. If the crests of the ripple marks point upward, the rocks have probably not been overturned. (*B*) As shells fall to the bottom of the ocean, they usually land with the outside of the shell upward. If most of the fossil shells in a layer are upright, the layer has probably not been overturned.



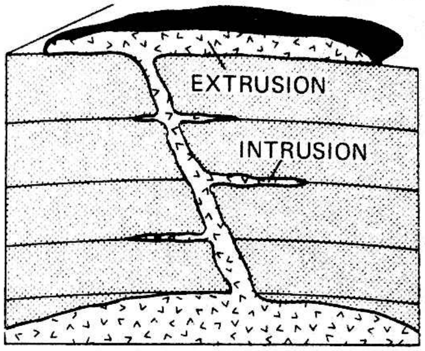


Figure 22-4. Igneous intrusion and extrusion. The intrusion is younger than the rock in which it is found. The extrusion is younger than the rock on which it rests.

There are also other points that can be checked. You should recall from Chapter 16 (page 314) that sediments deposited in water are generally deposited in a sequence, with coarse ones settling first and finest ones settling last. Thus, within a layer of sedimentary rock you might be able to detect a gradation in the size of particles from top to bottom in a layer. If the finer particles are on top and the coarser ones on the bottom, you can infer that the layer has not been overturned. Ripple marks and fossils may also be useful in answering this question. Figure 22-3 shows how ripple marks in sand and the position of fossils can be used in determining whether or not rock layers have been overturned.

Igneous Intrusions and Extrusions. In Chapter 18 (page 350) we learned that molten rock, or magma, can form intrusions in existing rock (see Figure 22-4). It should be clear that in any formation with an igneous intrusion, the intrusion must be younger than the rock it cuts through.

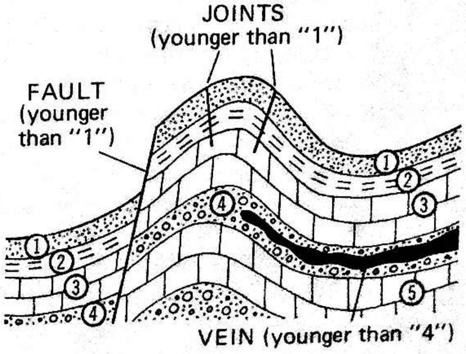
Figure 22-4 also shows an igneous extrusion—rock formed when magma flowed over the surface and solidified. Again, it should be obvious that the extrusion will be younger than the rock on which it rests. However, the extrusion will be older than any rocks that form on top of it.

Structural Features. Structural features of rocks, such as faults, joints, and folds, are evidence that forces have been acting on the rock and that crustal movement has occurred (see Chapter 19, page 369). (A *joint*, like a fault, is a crack in a rock, but unlike a fault, there has not been movement along the crack.) A rock is older than any fault, joint, or fold it may contain. Such features must have been produced *after* the rock was formed (see Figure 22-5).

Joints or cracks in rocks may become filled with mineral matter, as shown in Figure 22-5. The mineral deposit is younger than the event that produced the crack, and both the deposit and the crack are younger than the rock in which they occur. A mineral deposit of this type, which is formed from a solution filling a crack in a rock, is called a *vein*.

Internal Characteristics of Rocks. In many igneous intrusions there are fragments of rock, called *xenoliths*, that have not been melted (see Figure

Figure 22-5. Relative ages of structural features of rocks. Folds, faults, joints, and veins are younger than the rocks in which they occur.



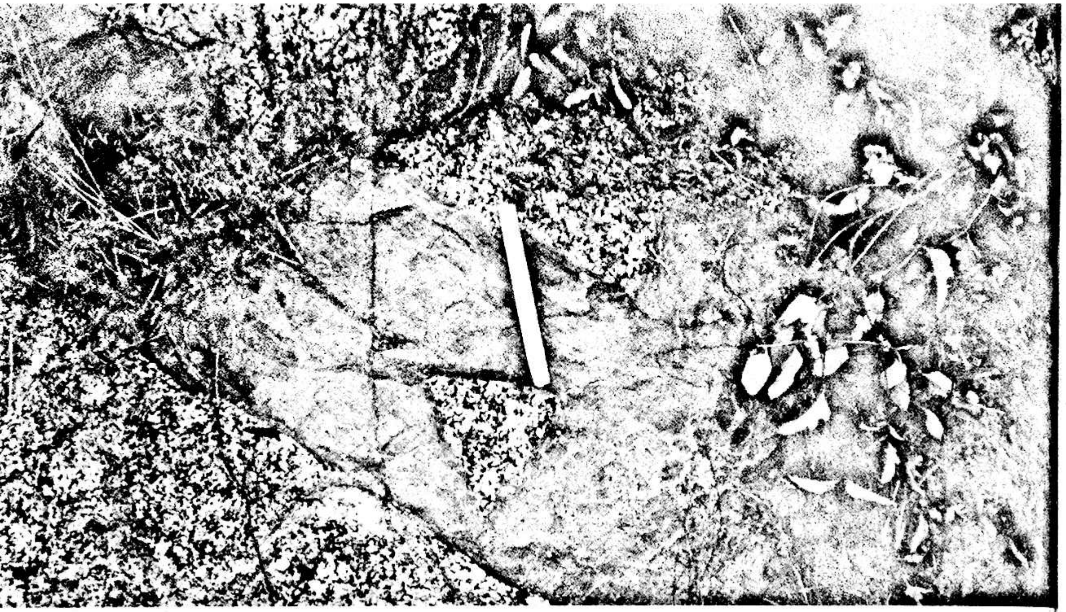


Figure 22-6. Xenolith in an igneous intrusion.

22-6). It appears that the fragments were broken off from surrounding rock and were carried along in the molten igneous material. Such fragments are older than the igneous material in which they are embedded.

In Chapter 18 we discussed, the formation of the various types of rocks. From that discussion you should recognize two facts about the relative age of sedimentary rocks. The sediments from which sedimentary rocks are formed are older than the rocks themselves. The sediments must also be older than the mineral cements found in them, because the cement forms after the sediments are deposited.

SUMMARY

1. Relative dating is an attempt to put geologic events or structures into proper chronological order.
2. The principle of uniformitarianism states that the geologic processes that occurred in the past are basically the same as those that are occurring now.
3. The bottom layer of a series of sedimentary layers is the oldest, unless the series has been overturned or has had older rock thrust over it.
4. Rock layers are older than igneous intrusions that cut through them or igneous extrusions that are above them.
5. Rocks are older than faults, joints, folds, or veins that appear in them.
6. Fragments of unmelted material occurring within a rock are older than the rock.
7. In sedimentary rocks, the sediments are older than the cements that bind them and the rock formation itself.

CORRELATION

Using the information given in the last section, geologists can determine the relative ages of the layers in a rock formation. But now another question arises. How can you determine whether the rocks or geologic events occurring at one location are of the same age as those at another location? The process of showing that rocks or geologic events occurring at different locations are of the same age is called *correlation*. Since certain minerals are found in rocks of a particular age, correlation can be an important tool in the search for mineral deposits.

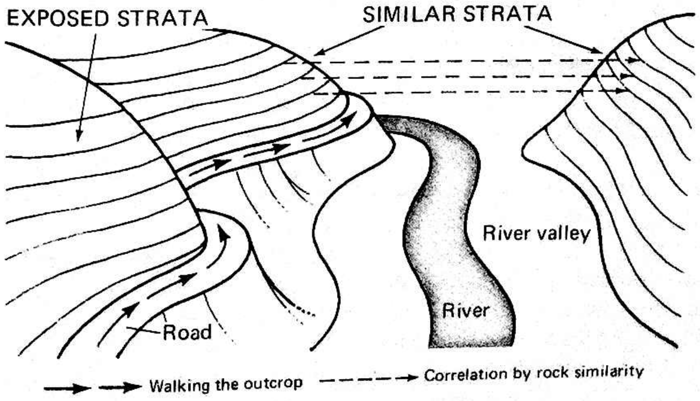
Following are some of the techniques used in correlation.

"Walking the Outcrop." The most direct method for observing a correlation between rocks or events at separate locations is by actually following a particular layer or formation from one location to the other. In this case you actually observe the physical continuity of the structure in question (see Figure 22-7). As you know, bedrock exposed at the earth's surface is called an outcrop. This method of correlation is called *walking the outcrop*, because you follow the outcrop from one location to another.

Similarity of Rock. Another method of correlation is the direct observation of similarities between layers of rock in different locations. Suppose you are examining an outcrop and notice three layers of rock with particular colors, composition, etc., and in a certain order. In a nearby location you observe three layers of similar color and composition and in the same order. From this evidence you could infer that the rock is the same at both locations. In other words, there is a correlation between the two rocks.

Index Fossils. Fossils are the remains or impressions of ancient plants and animals. They are usually found only in sedimentary rock. Geologists have developed a system for correlat-

Figure 22-7. Correlation by direction observation. A geologist can follow the layers in an exposed hillside by "walking the outcrop," for example, by walking along the road on the left side of this river valley. He may also be able to correlate layers on opposite sides of the valley by observing similarities in color, texture, and sequence of the rock layers.



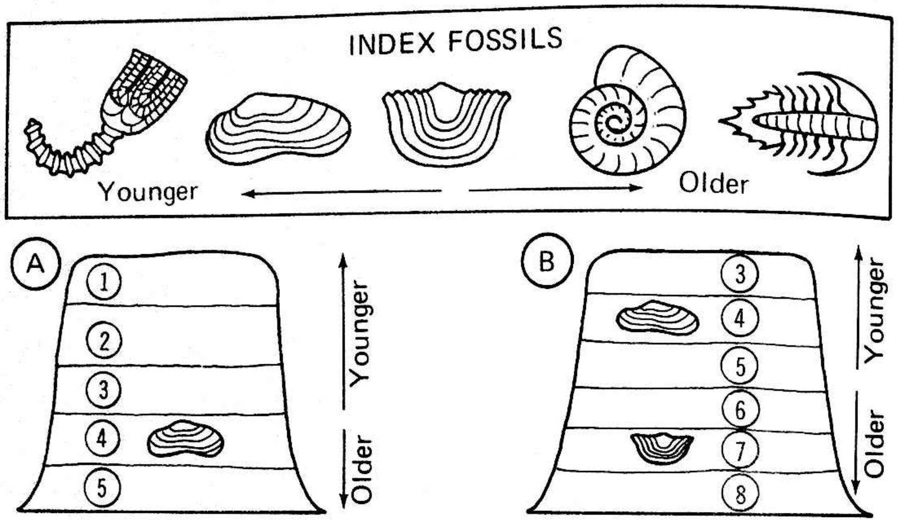


Figure 22-8. Correlation of rocks using index fossils. In (*A*) a fossil of an organism known to have lived *only* during Period *X* is found in rock layer 4. This layer was therefore deposited during Period *X*. The layers above it are younger, and those below it are older. In (*B*), a similar fossil is found in one of the layers. Therefore, this layer was also formed during Period *X*. An index fossil of Period *Y* is found in layer 7. This tells us that layers 5 and 6 are older than Period *X*, but younger than Period *Y*. Relative ages of the layers in both formations are indicated by the numbers in order of youngest to oldest.

ing sedimentary rock based on the presence of particular fossils, known as *index fossils*.

An index fossil is the remains or imprint of a particular type of plant or animal that existed for a relatively short period of time but which was found in many different parts of the world. If you think about it, you'll realize why these last two points are important. If the organism existed unchanged for many hundreds of millions of years, its presence would be of no use in dating a rock because it would be found in rock layers of many different ages. If the organism were found only in a few, specific locations, it would be of no use in correlating rock from widely separated regions. Figure 22-8 shows some index fossils and how they are used in relative dating.

Index fossils are one of the best means we have of correlating rocks. The idea of using fossils for such purposes originated about 1800, when William Smith, an English engineer and geologist, made a number of basic observations about fossils and rock formations. He noticed that in a given formation, different layers contained different fossils, but that the fossils in a particular layer of a rock formation were the same throughout the formation. On further investigation, Smith noticed that certain fossils were found in rock layers of the same age, even at widely separated locations. So, the presence of such fossils could be used to correlate the ages of rocks at different locations.

The presence of fossils also reveals something of the past environment. For example, the presence of fossils of marine organisms shows that during a certain period in the past the area was covered by an ocean. If the fossils are index fossils, you can say with some certainty just when, in the past, the ocean covered the area.

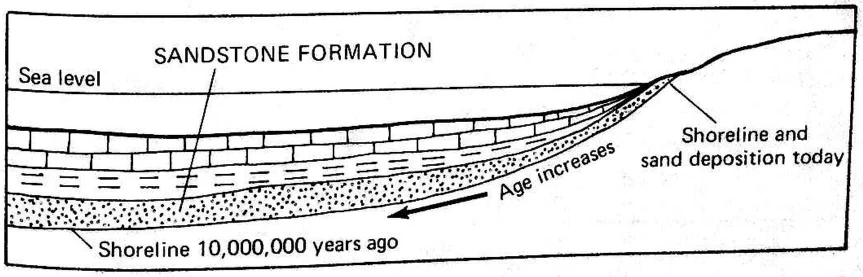
Volcanic Ash Deposits. When a volcano erupts, large quantities of volcanic ash are shot into the air. This ash, which consists of small pieces of igneous rock, may be carried for great distances before it falls to earth. So, ash from a single eruption may be deposited over large areas of the earth's surface in a very short period of time. Layers of ash settling in sediments may be incorporated into the rocks formed from the sediments. If these layers of volcanic ash can be identified in rock formations at different locations, they can be used for correlation. Deposits of volcanic ash are good "time markers," because they were deposited over such a short time period. Volcanic ash deposits can be especially useful in correlating rocks that contain no fossils.

Correlation Anomalies. An anomaly is something that does not fit the normal pattern. Anomalies in correlation are conditions or situations in which the results obtained by common correlation techniques are misleading or incorrect. Figure 22-9 shows one such situation. Here, in a single formation of sedimentary rock, the age of the rock varies by as much as 10 million years. Thus, you can see that even in a single formation, the rock may be much older in one place than in another. In this case the environment of deposition has moved very gradually over millions of years, thereby accounting for the different ages of the rock in the different parts of the formation.

Following is a description of another type of anomaly—one in which there is a clear correlation between certain parts of two separate formations, but apparently unexplainable differences between other parts. As you will see, establishing a correlation between rocks is not always a straightforward process.

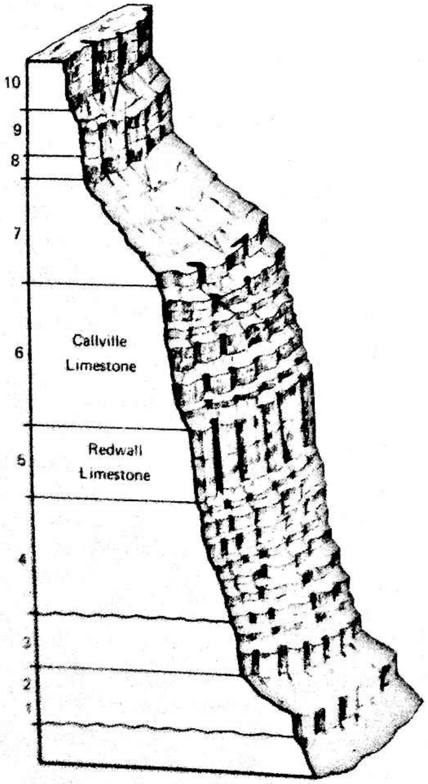
A geologist made the following observations at two locations in the Grand Canyon, about 160 km apart. In the first location, ten distinctive rock formations can be identified. These are shown in Figure 22-10. Figure 22-11 shows a section of the

Figure 22-9. Variations in the age of a formation. A sedimentary formation composed of the same type of sediment may be of different ages in different locations because of movement of the environment of deposition. In this diagram, the sandstone at the left is 10 million years older than the sandstone at the right, even though the formation is continuous and similar in composition.



canyon wall along the Bright Angel Trail, about 160 km away, which also contains ten distinctive formations. One easily identified rock formation in the Grand Canyon is the Redwall limestone. It is a tough limestone that is found as bold cliffs wherever it is exposed. The fossils found in the Redwall formation are also distinctive. Furthermore, this formation can be traced along the canyon walls continuously between the two locations. Thus, you can say that the Redwall formation is found at both locations.

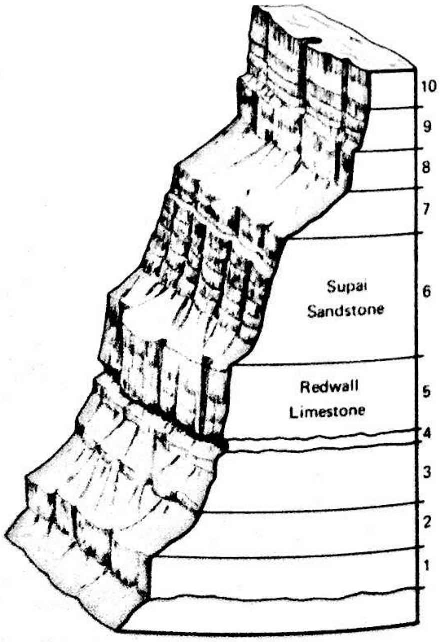
Figure 22-10. Section of the wall of the Grand Canyon near the mouth of the Colorado River.



The topmost layer of rock at both locations appears to contain the same fossils, is the same kind of rock (limestone), is about the same thickness, and it, too, can be traced continuously between the two locations. Thus, you can infer that there is a correlation between the topmost layer of limestone as well as between the Redwall formation at the two locations.

At the Bright Angel Trail location, there is a bright red sandstone just above the Redwall formation. This sandstone, called the Supai formation, contains fossil plants and footprints of land animals.

Figure 22-11. Section of the wall of the Grand Canyon along the Bright Angel Trail.



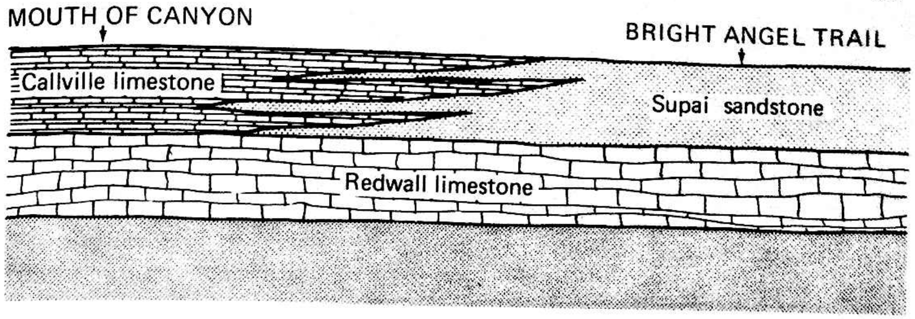


Figure 22-12. Alternating layers of sandstone and limestone, indicating a former shoreline.

At the second location, the rock lying just above the Redwall formation is a limestone, which is light gray in color and contains fossils of marine organisms. This limestone is known as the Callville formation.

So, while we have established a correlation between two rock layers at these two locations, we are left with the question of why there is no evidence of the Supai formation at one location and no evidence of the Callville formation at the other location. This is the type of correlation problem that geologists frequently face. Either part of the puzzle is missing, or parts that should fit, don't.

Fortunately, we know the answer to the puzzle in this case. If we follow the Callville limestone toward Bright Angel Trail, we find that the limestone beds become increasingly reddish in color and sandy in texture. Eventually, we reach an area that shows alternating layers of red sandstone and gray limestone, as shown in Figure 22-12. These alternating layers of marine and terrestrial rock indicate the location of a former shoreline. This shoreline moved first one way and then back, as the materials from both environments were deposited. So, we have the answer to our puzzle. The two formations—the Callville limestone of one location and the Supai sandstone of the other location—were deposited during the same period of time, but in different environments.

Unconformities. In their efforts to work out the geologic history of an area, geologists often find that part of the rock record is missing. Sometimes this is the result of a buried erosional surface, called an *unconformity*. Figures 22-13 and 22-14 show two types of unconformities and how they were formed.

The presence of an unconformity indicates that at some time in the distant past, the area was uplifted by crustal movement. Following uplift, the surface was weathered and eroded away, leaving a gap in the rock record. At a still later period, this area underwent subsidence and was covered by water. New layers of sediment were deposited on the erosional surface, resulting in the unconformity. In most cases, the new layers of sediment and the original rock, which has undergone uplifting, are not parallel to each other. But, as you can see in Figure 12-14, this is not always true.

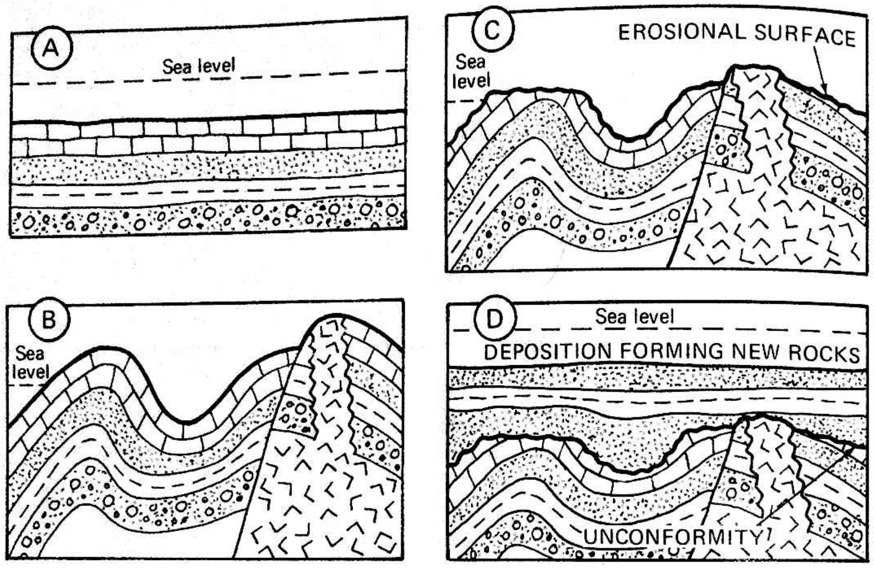


Figure 22-13. Events producing an unconformity with lack of parallelism. (*A*) Deposition forms sedimentary rock layers. (*B*) Crustal deformation and uplift occur. (*C*) Weathering and erosion remove part of the rock record. (*D*) Submergence and new deposition result in an unconformity along the erosional surface.

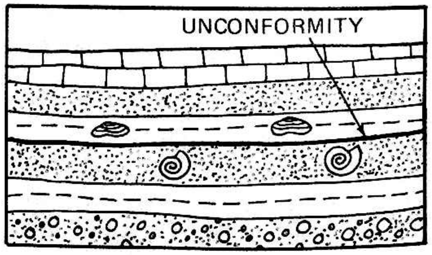


Figure 22-14. An unconformity in parallel strata. Uplift, erosion, and submergence have also occurred here, but without deformation. Evidence of a gap in the rock record may be given by widely different ages of the fossils in the layers above and below the unconformity.

SUMMARY

1. Correlation is the process of showing that rocks or geologic events occurring at different locations are of the same age.
2. In correlation, rock layers may be traced from one location to another directly by "walking the outcrop," thus showing the continuity of layers.
3. Rocks may be correlated on the basis of similarities in appearance, composition, and position in relation to other layers.
4. Fossils are the remains or impressions of ancient plants and animals. They are found almost exclusively in sedimentary rock.
5. Index fossils are the remains or imprints of organisms that existed for a relatively short period of time, but were widely distributed over the earth. The presence of an index fossil in a rock shows that the rock was formed over a definite, relatively short, period of time.

6. Fossils in rocks provide information about the environment in which the rock was formed.
7. Layers of volcanic ash in rock can be useful in correlation because they were deposited over a large area in a very short period of time.
8. Two similar rock formations may be of different ages, or a single formation may be older in some places than in others. These are anomalies to correlation.
9. An unconformity is a buried erosional surface. Where the surface has been eroded away, there is a gap in the rock record.

ABSOLUTE DATING AND RADIOACTIVE DECAY

We have seen some of the ways in which geologists establish the relative age of rocks or the order of events. But how can we find out how many years ago a particular rock was formed or a particular event occurred? Until Henri Becquerel's discovery of radioactivity in 1895, there was no way of finding the actual, or *absolute*, age of a rock or fossil. Only the relative age could be determined. However, within 10 years of the discovery of radioactivity, the English physicist Ernest Rutherford proposed that radioactivity could be used for dating rocks, and within a year he had succeeded in dating a uranium mineral.

Before you can understand what is involved in radioactive dating, you must know something about the structure of an atom and about the phenomenon of radioactivity, or radioactive decay.

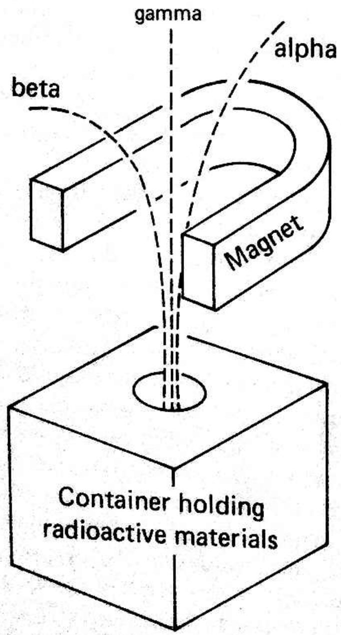
Elements and Isotopes. As you know, elements are substances that cannot be broken down into simpler substances by any chemical change. Elements are composed of atoms, which in turn are made up of three different kinds of particles — protons, neutrons, and electrons. Protons and neutrons are found in the dense *nucleus* of the atom, while electrons are found in the space around the nucleus. Protons are positively charged, while electrons are negatively charged, and neutrons show no electrical charge. One element differs from another in the number of protons in its nucleus.

In many cases, there are several different forms of an element, called *isotopes*. All atoms of a given element have the same number of protons in their nuclei. However, the number of neutrons may not be the same. Atoms with the same number of protons but different numbers of neutrons are different isotopes of the same element. For example, ordinary hydrogen has one proton and no neutrons in its nucleus. The two isotopes of hydrogen are deuterium, which has one proton and one neutron, and tritium, which has one proton and two neutrons.

Radioactive Decay. The nuclei of some isotopes are unstable and undergo radioactive decay. These are radioactive isotopes, or radioisotopes. During the decay process, they emit particles and electromagnetic energy, and in this way they are transformed into atoms of other, more stable elements.

In 1905, Pierre and Marie Curie discovered the element radium by painstakingly separating it from pitchblende, a uranium mineral. Radium is even more highly radioactive than uranium, and scientists began to study the radiation given off by this new element. They found that when a beam of radiation was passed through a magnetic field, it separated into three types of rays. One followed a slightly curving path; the second followed a strongly curving path; and the third followed a straight, unchanging path through the magnetic field (see Figure 22-15). The three types of radiation were given the names *alpha, beta,* and *gamma* radiation. (Alpha, beta, and gamma are the first three letters of the Greek alphabet.)

Figure 22-15. Effect of magnetic field on beam of radiation.



Further investigation showed that alpha radiation, which follows a slightly curving path in a magnetic field, is composed of positively charged particles—alpha particles. Beta radiation, which follows a strongly curving path in a magnetic field, is composed of negatively charged particles—beta particles. Gamma radiation, which is not affected by a magnetic field, does not appear to be composed of particles. Gamma rays are similar to X rays, but they are of shorter wavelengths and are more energetic.

Alpha particles, while positively charged, are heavier than ordinary protons. They have been found to consist of two protons and two neutrons. Thus, when an atom emits alpha particles during radioactive decay, it loses two protons and two neutrons.

Beta particles, which are negatively charged, are electrons. However, they come from within the nucleus. This fact presented a problem to researchers because the nucleus was thought to contain only protons and neutrons. It was eventually found that beta particles—electrons from the nucleus—are produced from the breakdown of neutrons (see Figure 22-16). In radioactive decay, a neutron may split to form a proton and an electron. The proton remains in the nucleus, while the electron is emitted as a beta particle. Thus, when an atom emits beta particles, it loses a neutron and gains a proton.

We know that the identity of an element is determined by the number of protons in the nuclei of its atoms. When alpha or beta particles are emitted from the nucleus of an atom during radioactive decay, the number of protons (and neutrons) in that atom is changed. When an alpha particle is given off, the atom loses two protons and two neutrons. When a beta particle is given off, the atom gains a proton. In this way, the original unstable atom is transformed into a stable isotope of another element.

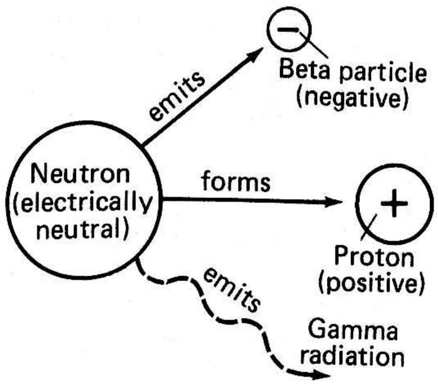


Figure 22-16. Breakdown of a neutron.

The transformation of an unstable isotope to a stable isotope of another element by radioactive decay may involve several intermediate stages in which other unstable isotopes are formed. These unstable isotopes also undergo decay, eventually reaching a stable form.

Half-Life of a Radioisotope. The breakdown, or disintegration, of a radioactive element is a random event. Just as you cannot predict which kernel of corn will pop next when you are cooking popcorn, you cannot predict which atom of a radioactive element will disintegrate. However, you can predict that within a given period of time a certain *number* of atoms will decay. How many depends on the particular element involved and the number of atoms present.

The amount of radiation given off by a sample can be measured with an instrument called a *Geiger counter.* With this instrument it is possible to measure the activity of a sample over a period of time. The activity decreases at a steady and predictable rate as the radioactive isotope disintegrates. The rate of radioactive decay is not affected by environmental factors, such as temperature and pressure. Chemical reactions also do not affect the decay rate. Thus, the decay of a radioactive isotope is an "atomic clock," which cannot be affected by external conditions.

Each radioisotope has a definite rate of decay. This means that over a given period of time, a certain characteristic fraction of the atoms in a sample will disintegrate. During the next equal time period, the *same fraction* of the remaining atoms will disintegrate. The length of time necessary for half of a sample of a radioactive element to disintegrate is called the *half-life* of that element.

Suppose, for example, you have a sample of iodine-131, a radioactive isotope of iodine. The half-life of this isotope is about 8 days. This means that after 8 days, half the atoms in your sample will have undergone radioactive decay. After 16 days, half of the remaining iodine-131 atoms will have decayed. Thus, three-fourths of the original sample will have undergone decay. After each 8-day interval, the activity of the original sample will be reduced by half. This is shown in graphic form in Figure 22-17.

The half-lives of radioactive isotopes vary from a fraction of a second to billions of years. To date rocks or fossils, isotopes with long half-lives are needed. Table 22-1 shows the isotopes most commonly used in dating, the stable isotopes produced by their decay, and their half-lives.

Radioactive Dating. When a radioactive isotope decays, an isotope of another element is formed and some form of radiation is given off. Thus, as decay continues, the amount of the original, or parent, isotope decreases, and the amount of the new, or daughter isotope, increases. Figure 22-18 illustrates the changing relationship between the amounts of the radioactive parent isotope and the stable daughter isotope present in a sample.

At the end of one half-life, half of the parent isotope will have decayed to the stable daughter isotope. There should now be equal amounts of the parent and daughter isotopes in the sample. At the end of two half-lives, three-fourths of the parent isotope will have decayed, so the ratio of parent to daughter isotope will be 1:3. The longer the decay process continues, the less parent isotope and the more daughter isotope there is in the sample. As you can see in Figure 22-18, the ratio of the amount of parent isotope to the amount of daughter isotope changes in a predictable manner. Where scientists can accurately measure the amounts of a radioisotope and its stable decay product in a sample, they can, knowing the half-life of the radioisotope, use the relative amounts of the two isotopes to calculate the age of the sample.

Figure 22-17. Decay of I-131.

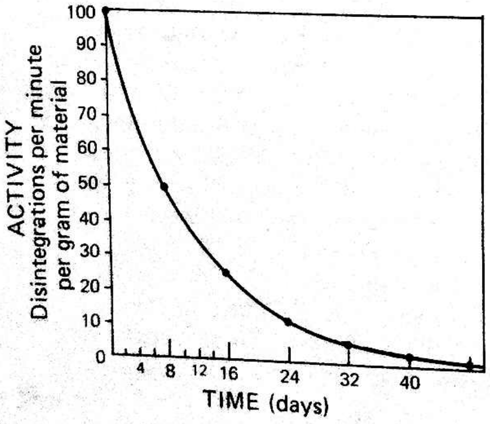
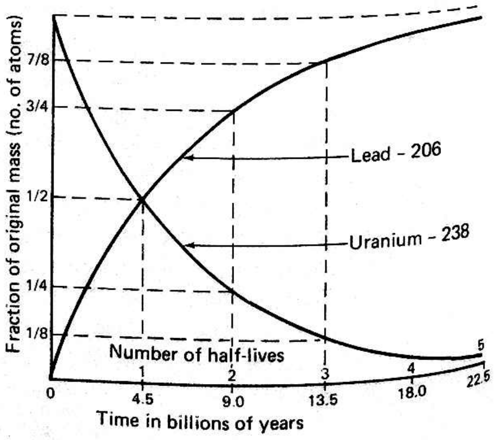


Figure 22-18. Curves showing radioactive decay of uranium-238 and formation of the stable decay product lead-206. After one half-life (4.5 billion years), half the original atoms of uranium have become atoms of lead.



As we have mentioned, the radioactive isotopes used to measure the ages of rocks or fossils must have long half-lives. In nature, these isotopes are generally found, in some small proportion, along with the stable isotopes of the same element. For example, potassium is found in many of the rock-forming minerals. Although most of this will be a stable isotope of potassium, some will be the radioactive isotope. As you can see in Table 22-1, the radioisotope potassium-40, with a half-life of 1.3 billion years, decays to the stable isotope argon-40. Scientists are able to measure even very small amounts of these isotopes in a rock sample. From this information they can calculate the age of the rock. Sometimes more than one radioactive element will be found in a rock sample. In such cases, it may be possible to cross-check results.

Radioactive Element	Stable Isotope Formed	Radiation Emitted	Half-Life
Uranium—U^{238}	Lead—Pb^{206}	8 alpha 6 beta	4.51 billion yrs.
Uranium—U^{235}	Lead—Pb^{207}	7 alpha 4 beta	0.71 billion yrs.
Thorium—Th^{232}	Lead—Pb^{208}	6 alpha 4 beta	13.9 billion yrs.
Rubidium—Rb^{87}	Strontium Sr^{87}	1 beta	50 billion yrs.
Potassium—K^{40}	Argon—A^{40}	1 electron capture	1.3 billion yrs.
Carbon—C^{14}	Nitrogen^{14}	1 beta	5,770 yrs.

Table 22-1. Radioisotopes used in dating.

For radioactive dating to be done, both the original radioisotope and its decay product must be present in the sample. When rocks undergo melting, both the radioisotope and its decay products are dispersed. For dating purposes, the "atomic clock" is reset at zero. When new rock forms, decay products again accumulate, and dating becomes possible.

Carbon-14 is a radioactive isotope with a half-life of 5,770 years. It is produced in the upper atmosphere by the bombardment of nitrogen-14 by cosmic rays. The carbon-14 produced is incorporated into carbon dioxide, which in turn is taken in by plants. The plants may be eaten by animals, so that their bodies, too, will contain some of this isotope. In living plants and animals the carbon-14 isotope will be present in approximately the same proportion as it is in the atmosphere. As long as the organism is alive, the proportion of carbon-14 in its tissues remains constant. However, when the plant or animal dies, no more carbon-14 is taken in. The carbon-14 present in the remains, decays, forming nitrogen-14. By measuring the proportion of carbon-14 present in plant and animal remains, scientists can say, with great accuracy, when the plant or animal lived. For example, in a tree that lived about 5,000 years ago the proportion of carbon-14 would be about half that in a tree living now.

Radiocarbon dating, as it is called, is used on the remains of plants and animals up to 50,000 years old. Because of the relatively short half-life of the carbon-14 isotope, it cannot be used to date objects more than 50,000 years old because, for practical purposes, there is no carbon-14 left in the sample after that timespan. It has all decayed. So, for older objects, the potassium-argon isotopes or uranium-lead isotopes are used.

The Age of the Earth. How old is the earth? This question has been asked and the answer sought throughout recorded history. Until recent times, a reliable method for determining the earth's age remained one of the missing pieces to the earth "puzzle." Early efforts by scientists to determine the earth's age included such methods as measuring the salt content of the oceans, the rates of erosion and deposition of sediments, the rate of cooling of the earth, and the luminosity of the sun. As you might expect, the results of such methods were quite inaccurate, and produced a variety of "ages" ranging from 5,000 to 40 million years.

With the discovery of radioactivity and the development of methods of radioactive dating, it has become possible to determine the ages of the rocks of the earth's crust quite accurately. The oldest crustal rocks found to date have been dated at about 4.1 *billion* years. Keep in mind, however, that since the time that the first crustal rocks were exposed to the earth's atmosphere, the processes of weathering and erosion have been at work wearing them down. Most of the rocks that are available for dating purposes—that is, rocks at or near the earth's surface—are *not* part of the original crust. They are considerably younger, and have been formed from the products of weathering and erosion of older rocks. Many of the rocks at the earth's surface have probably passed through the rock cycle more than once.

Fortunately, the earth's crust is not the only source of rock material. Meteorites and rocks from the moon are also available for radioactive dating. Since the moon has no atmosphere, rocks at the moon's surface are virtually unweathered. The oldest moon rocks have been found to be about 4.5 billion years old. Somewhat surprisingly, *all* of the meteorites that have fallen to earth, regardless of their composition, have been found to be of one age—4.5 billion years! Most scientists believe that the meteorites and the moon are parts of the solar system, and thus formed at the same time as the earth. If they are correct, the earth is approximately 4.5 billion years old.

SUMMARY

1. All atoms of a given element have the same number of protons in the nucleus. Different isotopes of a given element have the same number of protons but different numbers of neutrons in the nucleus.
2. The nuclei of some atoms undergo radioactive decay, during which particles and/or electromagnetic energy are given off, and a new element is formed.
3. The disintegration of an individual atom occurs as a random event.
4. The rate at which radioactive decay occurs is predictable, and is characteristic of the element involved.
5. The rate of decay is not affected by external factors, such as temperature, pressure, or chemical reaction.
6. The length of time necessary for half of a sample of a radioactive element to decay is the half-life of that element. Different radioactive isotopes have different half-lives.

7. Radioactive isotopes with relatively short half-lives, such as carbon-14, are used for dating recent organic remains. Isotopes with longer half-lives, such as uranium-238 and potassium-40, are used for dating older remains.
8. As decay continues in a sample, the amount of the original isotope present decreases, and the amount of the stable decay product increases.
9. By finding the relative amounts of the original radioisotope and the decay product in a sample, scientists, knowing the half-life of the isotope, can calculate the age of the sample.

REVIEW QUESTIONS

Group A

1. What is relative dating?
2. What is the principle of uniformitarianism?
3. In a series of sedimentary layers, which is usually the oldest?
4. How does the relative age of an igneous intrusion: (a) compare with that of the rock it cuts through, (b) compare with the age of rocks below and above it?
5. Are faults, joints, folds, and veins younger or older than the rocks in which they are found?
6. Are mineral cements and sediments younger or older than the rocks in which they are found?
7. What is correlation?
8. Describe several ways in which a correlation may be established between rock formations.
9. What are fossils? In what type of rock are they found?
10. What is an index fossil?
11. How can layers of volcanic ash be used in correlation?
12. What is an anomaly of correlation?
13. What is an unconformity?
14. All atoms of a given element have what in common?
15. How do the isotopes of an element differ from one another?
16. What happens to the nucleus of an atom undergoing decay?
17. Can you predict when a particular atom of a radioisotope is going to decay? If not, why not?
18. What can be said about the rate of decay of a given radioisotope?
19. What factors affect the rate of radioactive decay?
20. What is the half-life of an element?
21. Name some radioactive isotopes used in dating. Which are used to date (a) recent organic materials, and (b) older, inorganic materials?
22. In radioactive dating, how is the age of a sample calculated?

Group B

1. Relative dating of geologic events can be done by studying rock phenomena such as superposition, presence of intrusions and extrusions, structural features, and internal characteristics. Which of these phenomena would be most likely to be misinterpreted when used to date events? Explain.
2. List three forms of evidence that you could use to correlate rocks in one place with those in another place.
3. a. The process of radioactive decay is called a random event. What does this mean?
    b. How can the process of radioactive decay provide accurate information about the age of a rock?