Dating Rocks and Fossils Using Geologic Methods

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Using relative and radiometric dating methods, geologists are able to answer the question: how old is this fossil?

Despite seeming like a relatively stable place, the Earth's surface has changed dramatically over the past 4.6 billion years. Mountains have been built and eroded, continents and oceans have moved great distances, and the Earth has fluctuated from being extremely cold and almost completely covered with ice to being very warm and ice-free. These changes typically occur so slowly that they are barely detectable over the span of a human life, yet even at this instant, the Earth's surface is moving and changing. As these changes have occurred, organisms have evolved, and remnants of some have been preserved as fossils.

A fossil can be studied to determine what kind of organism it represents, how the organism lived, and how it was preserved. However, by itself a fossil has little meaning unless it is placed within some context. The age of the fossil must be determined so it can be compared to other fossil species from the same time period. Understanding the ages of related fossil species helps scientists piece together the evolutionary history of a group of organisms.

For example, based on the primate fossil record, scientists know that living primates evolved from fossil primates and that this evolutionary history took tens of millions of years. By comparing fossils of different primate species, scientists can examine how features changed and how primates evolved through time. However, the age of each fossil primate needs to be determined so that fossils of the same age found in different parts of the world and fossils of different ages can be compared.

There are three general approaches that allow scientists to date geological materials and answer the question: "How old is this fossil?" First, the relative age of a fossil can be determined. **Relative dating** puts geologic events in chronological order without requiring that a specific numerical age be assigned to each event. Second, it is possible to determine the numerical age for fossils or earth materials. Numerical ages estimate the date of a geological event and can sometimes reveal quite precisely when a fossil species existed in time.

Relative dating to determine the age of rocks and fossils

Geologists have established a set of principles that can be applied to sedimentary and volcanic rocks that are exposed at the Earth's surface to determine the relative ages of geological events preserved in the rock record. For example, in the rocks exposed in the walls of the Grand Canyon (Figure 1) there are many horizontal layers, which are called **strata**. The study of strata is called **stratigraphy**, and using a few basic principles, it is possible to work out the relative ages of rocks.

Figure 1: Individual rock layers, or strata, can be seen exposed in the wall of the Grand Canyon in Arizona, USA.

Just as when they were deposited, the strata are mostly horizontal (principle of original horizontality). The layers of rock at the base of the canyon were deposited first, and are thus older than the layers of rock exposed at the top (principle of superposition).

In the Grand Canyon, the layers of strata are nearly horizontal. Most sediment is either laid down horizontally in bodies of water like the oceans, or on land on the margins of streams and rivers. Each time a new layer of sediment is deposited it is laid down horizontally on top of an older layer. This is the **principle of original horizontality**: layers of strata are deposited horizontally or nearly horizontally (Figure 2). Thus, any deformations of strata (Figures 2 and 3) must have occurred after the rock was deposited.

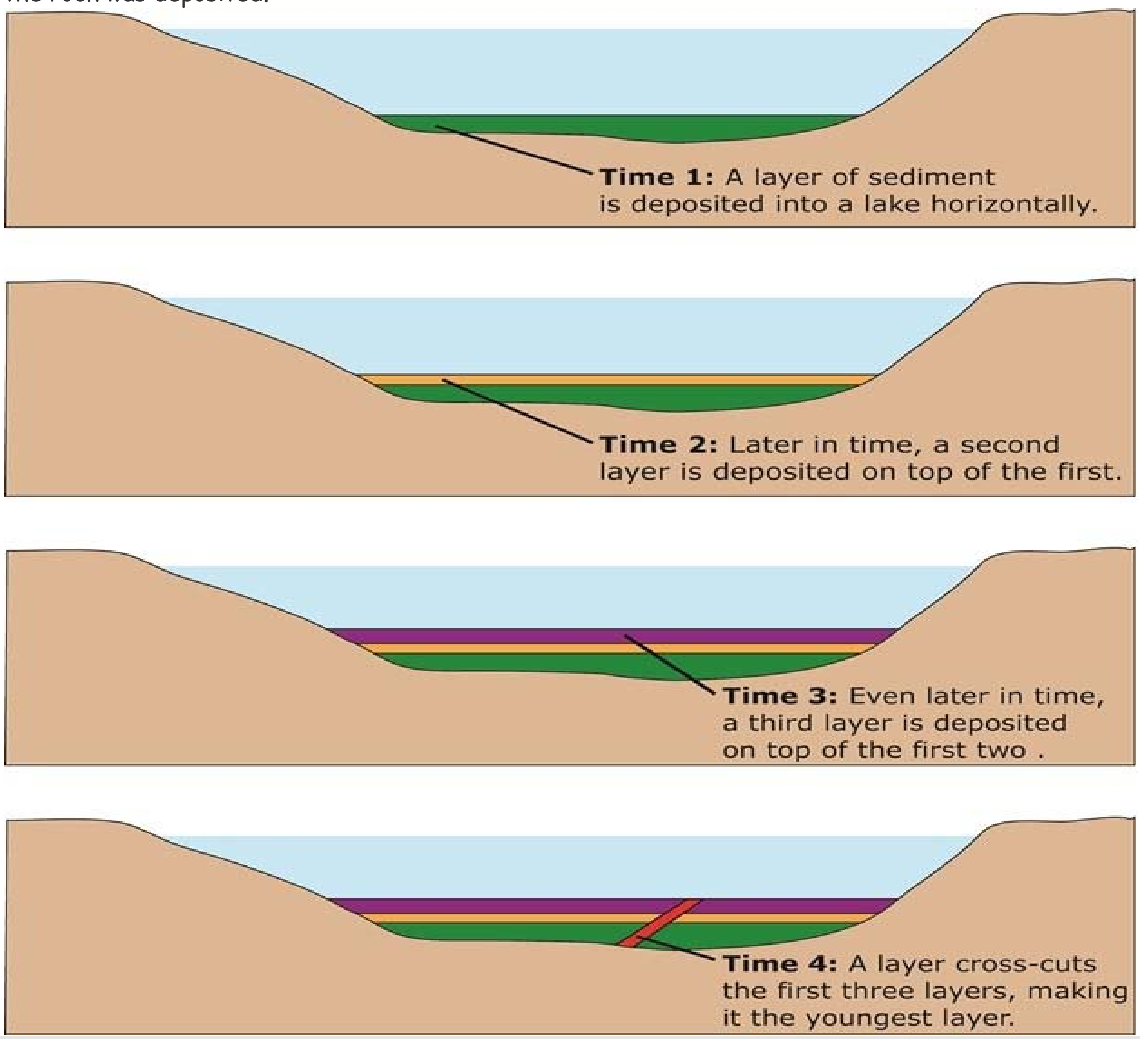

Figure 2: The principles of stratigraphy help us understand the relative age of rock layers.
Layers of rock are deposited horizontally at the bottom of a lake (principle of original horizontality). Younger layers are deposited on top of older layers (principle of superposition). Layers that cut across other layers are younger than the layers they cut through (principle of cross-cutting relationships).

The **principle of superposition** builds on the principle of original horizontality. The principle of superposition states that in an undeformed sequence of sedimentary rocks, each layer of rock is older than the one above it and younger than the one below it (Figures 1 and 2). Accordingly, the oldest rocks in a sequence are at the bottom and the youngest rocks are at the top.

Sometimes sedimentary rocks are disturbed by events, such as **fault** movements, that cut across layers after the rocks were deposited. This is **the principle of cross-cutting relationships**. The principle states that any geologic features that cut across strata must have formed after the rocks they cut through (Figures 2 and 3).

Figure 3: The sedimentary rock layers exposed in the cliffs at Zumaia, Spain, are now tilted close to vertical.
According to the principle of original horizontality, these strata must have been deposited horizontally and then titled vertically after they were deposited. In addition to being tilted horizontally, the layers have been faulted (dashed lines on figure). Applying the principle of cross-cutting relationships, this fault that offsets the layers of rock must have occurred after the strata were deposited.

The principles of original horizontality, superposition, and cross-cutting relationships allow events to be ordered at a single location. However, they do not reveal the relative ages of rocks preserved in two different areas. In this case, fossils can be useful tools for understanding the relative ages of rocks. Each fossil species reflects a unique period of time in Earth's history. The **principle of faunal succession** states that different fossil species always appear and disappear in the same order, and that once a fossil species goes extinct, it disappears and cannot reappear in younger rocks (Figure 4).

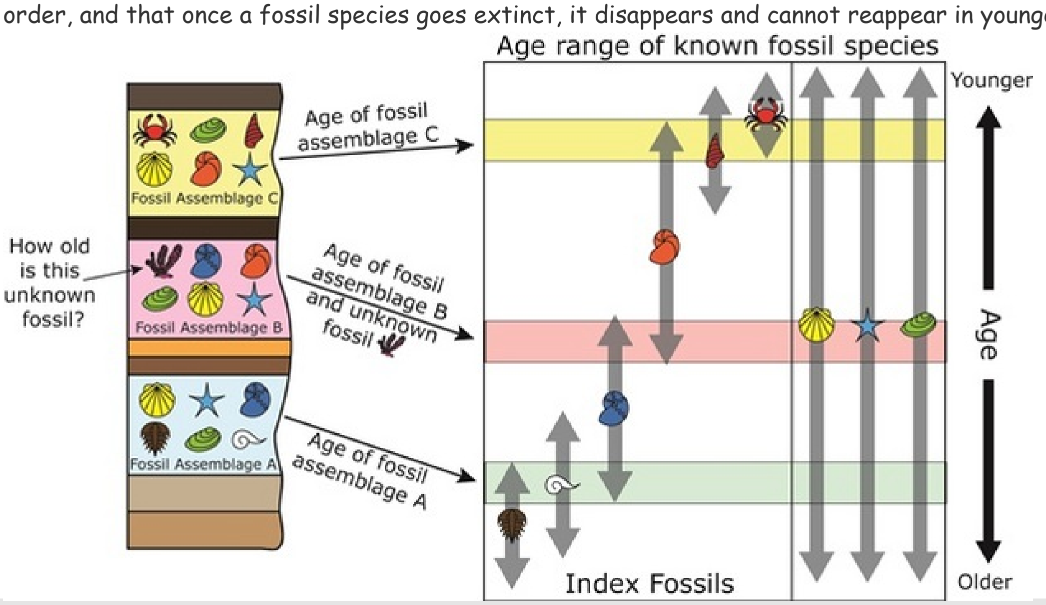

Figure 4: The principle of faunal succession allows scientists to use the fossils to understand the relative age of rocks and fossils. Fossils occur for a distinct, limited interval of time. In the figure, that distinct age range for each fossil species is indicated by the grey arrows underlying the picture of each fossil. The position of the lower arrowhead indicates the first occurrence of the fossil and the upper arrowhead indicates its last occurrence – when it went extinct. Using the overlapping age ranges of multiple fossils, it is possible to determine the relative age of the fossil species (i.e., the relative interval of time during which that fossil species occurred). For example, there is a specific interval of time, indicated by the red box, during which both the blue ammonite and orange ammonite co-existed. If both the blue and orange ammonites are found together, the rock must have been deposited during the time interval indicated by the red box, which represents the time during which both fossil species co-existed. In this figure, the unknown fossil, a red sponge, occurs with five other fossils in fossil assemblage B. Fossil assemblage B includes the index fossils the orange ammonite and the blue ammonite, meaning that assemblage B must have been deposited during the interval of time indicated by the red box. Because, the unknown fossil, the red sponge, was found with the fossils in fossil assemblage B it also must have existed during the interval of time indicated by the red box.

Fossil species that are used to distinguish one layer from another are called **index fossils**. Index fossils occur for a limited interval of time. Usually index fossils are fossil organisms that are common, easily identified, and found across a large area. Because they are often rare, primate fossils are not usually good index fossils. Organisms like pigs and rodents are more typically used because they are more common, widely distributed, and evolve relatively rapidly.

Using the principle of faunal succession, if an unidentified fossil is found in the same rock layer as an index fossil, the two species must have existed during the same period of time (Figure 4). If the same index fossil is found in different areas, the strata in each area were likely deposited at the same time. Thus, the principle of faunal succession makes it possible to determine the relative age of unknown fossils and correlate fossil sites across large discontinuous areas.

Determining the numerical age of rocks and fossils

Unlike relative dating methods, **absolute dating** methods provide chronological estimates of the age of certain geological materials associated with fossils, and even direct age measurements of the fossil material itself. To establish the age of a rock or a fossil, researchers use some type of clock to determine the date it was formed. Geologists commonly use **radiometric dating** methods, based on the natural **radioactive decay** of certain elements such as potassium and carbon, as reliable clocks to date ancient events. Geologists also use other methods - such as **electron spin resonance** and **thermoluminescence**, which assess the effects of **radioactivity** on the accumulation of electrons in imperfections, or "traps," in the crystal structure of a mineral - to determine the age of the rocks or fossils.

All elements contain **protons** and **neutrons**, located in the **atomic nucleus**, and **electrons** that orbit around the nucleus (Figure 5a). In each element, the number of protons is constant while the number of neutrons and electrons can vary. Atoms of the same element but with different number of neutrons are called **isotopes** of that element. Each isotope is identified by its **atomic mass**, which is the number of protons plus neutrons. For example, the element carbon has six protons, but can have six, seven, or eight neutrons. Thus, carbon has three isotopes: carbon 12 (^{12}C), carbon 13 (^{13}C), and carbon 14 (^{14}C) (Figure 5a).

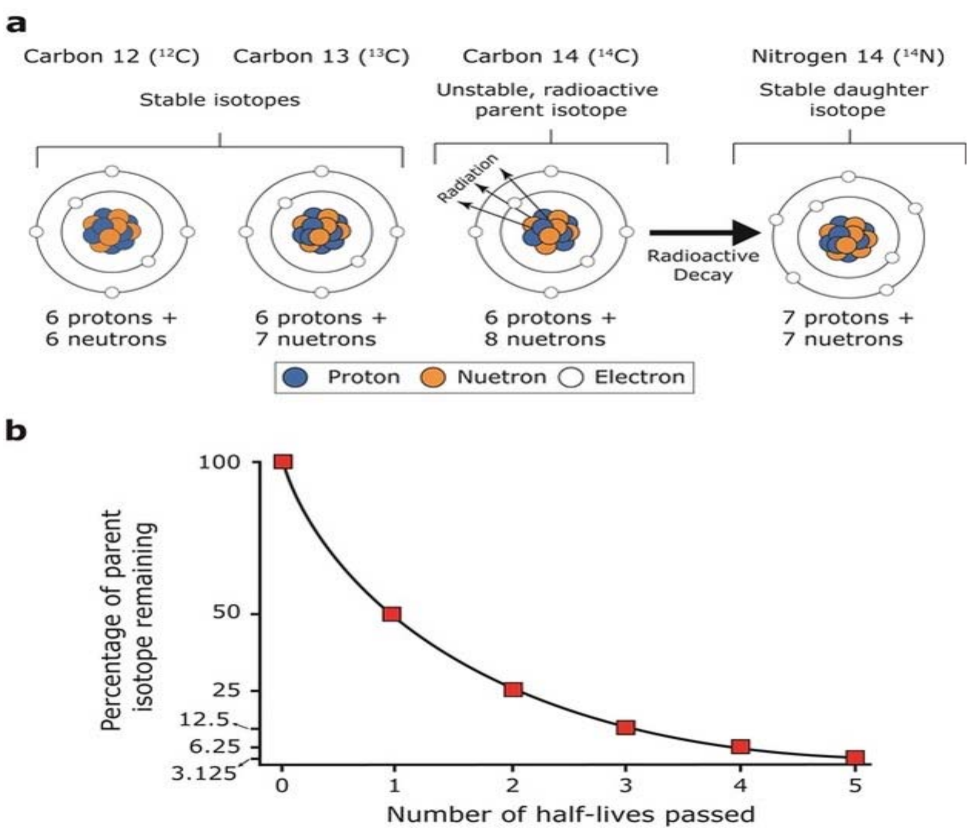

Figure 5: Radioactive isotopes and how they decay through time. (a) Carbon has three isotopes with different numbers of neutrons: carbon 12 (C^{12}, 6 protons + 6 neutrons), carbon 13 (C^{13}, 6 protons + 7 neutrons), and carbon 14 (C^{14}, 6 protons + 8 neutrons). C^{12} and C^{13} are stable. The atomic nucleus in C^{14} is unstable making the isotope radioactive. Because it is unstable, occasionally C^{14} undergoes radioactive decay to become stable nitrogen (N^{14}). (b) The radioactive atoms (parent isotopes) in any mineral decay over time into stable daughter isotopes. The amount of time it takes for half of the parent isotopes to decay into daughter isotopes is known as the half-life of the radioactive isotope.

Most isotopes found on Earth are generally stable and do not change. However some isotopes, like ^{14}C, have an unstable nucleus and are **radioactive**. This means that occasionally the unstable isotope will change its number of protons, neutrons, or both. This change is called radioactive decay. For example, unstable ^{14}C transforms to stable nitrogen (^{14}N). The atomic nucleus that decays is called the **parent isotope**. The product of the decay is called the **daughter isotope**. In the example, ^{14}C is the parent and ^{14}N is the daughter.

Some minerals in rocks and organic matter (e.g., wood, bones, and shells) can contain radioactive isotopes. The abundances of parent and daughter isotopes in a sample can be measured and used to determine their age. This method is known as radiometric dating. Some commonly used dating methods are summarized in Table 1.

The rate of decay for many radioactive isotopes has been measured and does not change over time. Thus, each radioactive isotope has been decaying at the same rate since it was formed, ticking along regularly like a clock. For example, when potassium is incorporated into a mineral that forms when lava cools, there is no argon from previous decay (argon, a gas, escapes into the atmosphere while the lava is still molten). When that mineral forms and the rock cools enough that argon can no longer escape, the "radiometric clock" starts. Over time, the radioactive isotope of potassium decays slowly into stable argon, which accumulates in the mineral.

The amount of time that it takes for half of the parent isotope to decay into daughter isotopes is called the **half-life** of an isotope (Figure 5b). When the quantities of the parent and daughter isotopes are equal, one half-life has occurred. If the half life of an isotope is known, the abundance of the parent and daughter isotopes can be measured and the amount of time that has elapsed since the "radiometric clock" started can be calculated.
For example, if the measured abundance of ^{14}C and ^{14}N in a bone are equal, one half-life has passed and the bone is 5,730 years old (an amount equal to the half-life of ^{14}C). If there is three times less ^{14}C than ^{14}N in the bone, two half lives have passed and the sample is 11,460 years old. However, if the bone is 70,000 years or older the amount of ^{14}C left in the bone will be too small to measure accurately. Thus, **radiocarbon dating** is only useful for measuring things that were formed in the relatively recent geologic past. Luckily, there are methods, such as the commonly used **potassium-argon (K-Ar) method**, that allows dating of materials that are beyond the limit of radiocarbon dating