# CHAPTER 8: GEOLOGIC EVENTS AND TIME

*This chapter focuses on determining the relative ages of rock units from field relationships and how we put together a geologic history or sequence of events. You will also learn how we determine the numerical ages of rock units.*

***(Note: Terms in red and italics appear as entries in the companion glossary.)***

Since the late 1700's, geologists have been determining the relative ages of rock formations based on their relationships with other rock formations and geologic features. *Relative ages* answer the simple question of whether one geologic feature (rock formation, fault, erosion surface, etc.) is older or younger than some other geologic feature. Another type of age is a *numerical age*, where the ages of geologic events are expressed as numbers of years before present. Numerical ages for relatively recent events can sometimes be associated with actual human observations, associations with known historic events with calendar ages such as a volcanic eruption, or the counting of annual layers in trees or sediment from the last ~12,000 years. In this case, numerical ages are often known with certainty and are referred to as *absolute ages*. However, this does not work for most pre-historic events. For less than a century, geologists have had numerical dating techniques based on chemical principles (decay of radioactive isotopes) at their disposal. These techniques provide numerical age estimates back many millions of years for rock formations such as those in the Fells.

## 8.1 RELATIVE DATING OF EVENTS

Past geologic processes can be complex, but they can usually be broken down into a sequence of events that brings some order to them. Using simple outcrop observations, we can usually determine the relative ages of different rock formations. We apply *fundamental principles* that were first established in the 1600's by Nicholas Steno and late 1700's by James Hutton, a Scottish geologist. This essentially marks the beginning of geology as a science, and it greatly changed our perception of the age of the Earth and the duration of geologic events. If you would like to know more about James Hutton and the beginnings of geology as a science, there is an excellent three-part series on the history of geology as a science and the development of fundamental principles that was made for the BBC. It is called "Men of Rock" (BBC, 2010) and it has three parts, each about an hour long, that give you the early history and more about the field of geology in Scotland. AND, they are entertaining!

Although Hutton used all the fundamental principles, they were not widely published or studied until John Playfair (1802), and later Charles Lyell, summarized Hutton's work in more available and easily read books. Lyell's publications, *Principles of Geology* (Lyell, 1830, 1832, 1833), are generally regarded as the first textbooks in geology. These widely circulated publications stated all the fundamental principles, which we still use today to determine the relative ages of geologic features and events. The fundamental principles may seem obvious today but in the late 18$^{th}$ century they were a breakthrough in geologic and scientific thought. They lifted constraints placed on science and geology by religious doctrines.

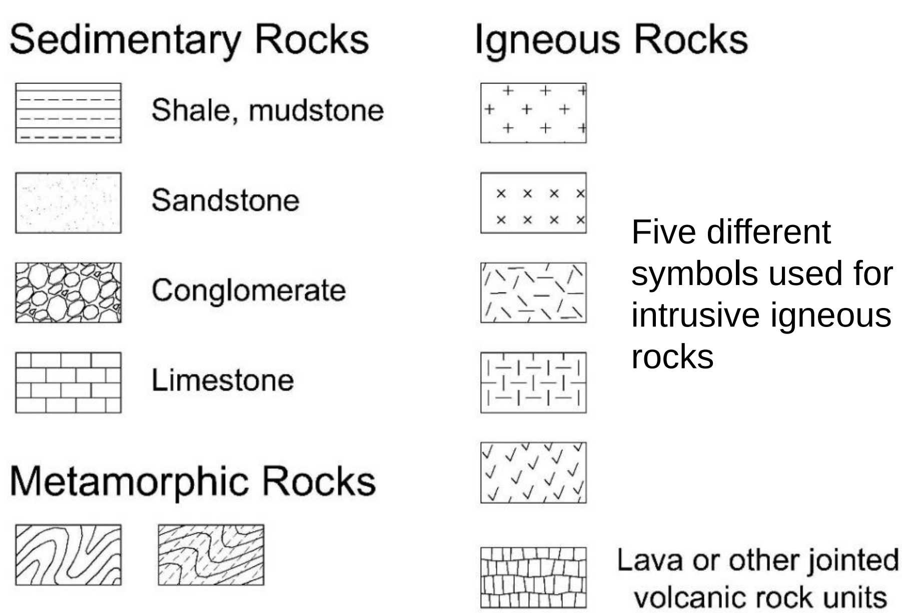
### 8.1.1 Geologic Events

The simplest geologic events are the formation of rock or other geologic units. The formation of an igneous rock unit refers to the time of magma solidification or crystallization to produce solid rock. In the case of sedimentary rocks, it is the time when sediment was deposited. This will also be the age of the fossils found in a sedimentary rock since they become a part of the rock when sediment accumulates and buries organisms or their parts to eventually preserve them as *fossils*. The age of metamorphic rocks can be trickier because geologists would not only like to know when metamorphism occurred that changed the rock but also the age of the *protolith*. These two times can be greatly different, and in the case of some metamorphic rocks that are metamorphosed multiple times we may be trying to determine the ages of several events (protolith formation, metamorphic event 1, metamorphic event 2, etc.).

Several types of events, such as metamorphism, operate on rock formations that have already been formed. Rocks can also be deformed by tilting of layers, folding, faulting, or fracturing, which all represent geologic events. Rock units can also be weathered and eroded, and these events represent times in which rock units were exposed at Earth's surface. Weathering and erosion can produce surfaces cut into rocks by removal of weathered material (*erosion surfaces*); thereby destroying a part of the geologic record. This boundary represents a time gap in the geologic record or a break in what is recorded by the rocks, known as an *unconformity*. Unconformities can also be the result of a period of non-deposition in a sedimentary rock sequence. Technically, an *unconformity* is: **a surface that represents a break in time and is overlain by a sedimentary unit, lava flow, or pyroclastic deposit**. Unconformities will be reviewed in more detail below.

To show the relationships between different rock formations and their relative ages, geologists often look at rock formations in *cross section*, or side view. This allows you to better see the relative positions of rock units and the character of their contact relationships. It also provides a better perspective for determining relative ages. Cross section views can sometimes be seen on photographs or on drawings that depict field relationships as might be drawn for notes in a field book. Camera images may be very useful, but many times they do not clearly show the observed rock types very well and a drawing can better record observations. Symbols for rock types and colors are used to tell various rock units apart. Figure 8.1 shows some standard symbols that are used in the Earth and Ocean Sciences Department at Tufts University to indicate various rock types in cross sections. Using this symbology, it is possible to draw cross section sketches (interpretive diagrams) that show the basic rock types and relationships seen in the field.

***Figure 8.1*** *– Standard rock symbols used to draw geologic cross sections in the Dept. of Earth and Ocean Sciences at Tufts University. These symbols are used by many others, and we have adopted the standard forms.*



### 8.1.2 The Fundamental Principles

In the late 1700's and early 1800's, natural scientists, who were the first geologists, formalized the set of rules, or *fundamental principles*, that could be applied to the formation of rock units and their relative ages. The development of the fundamental principles occurred at about the same time as the formalization of the laws of mathematics, chemistry, and physics that supplanted explanations based on divine intervention and *catastrophism* (large supernatural events) that relied on traditional stories in the Old Testament of the Bible related to Earth's creation and Noah's Flood. The fundamental principles were an outgrowth of advances in scientific reasoning that were applied to rocks, and they were consistent with observations made on modern processes that form rocks, especially sedimentary rocks and the rocks formed by volcanic eruptions. It took early geologists longer to understand intrusive igneous rocks because their formation was not something that they could observe at Earth's surface. None of the fundamental principles are rocket science, but the formulation of these principles back in the late 18$^{th}$ century triggered a revolution in how we perceived the formation of Earth and its history and age, and it established the science of geology. In addition to providing a rational explanation of geologic events and their sequence, *uniformitarianism* gave early geologists a sense of the vast amount of time in Earth's history.

The use of observations of modern processes to understand the character of ancient events is what is called the principle of *uniformitarianism*. Technically, *uniformitarianism* says that geologic events of the past were governed by the same laws of mathematics, chemistry, and physics that govern processes today. While conditions in the past may have been different, for example, there may have been less oxygen in the atmosphere, or temperatures may have been different, the laws of mathematics, chemistry, and physics that operate today are also applicable to ancient Earth systems. Uniformitarianism is often simplified to a cliché phrase: "the present is the key to the past". While there is some truth to this expression in terms of some similarities between modern and ancient rock-forming processes, the present is never an exact analog for the past because of differing conditions through geologic time.

In the early formulation of fundamental principles by Nicholas Steno in the 1600's, sedimentary rocks got much of the attention. Bedded sedimentary rock units were recognized to have been deposited as nearly horizontal layers, or beds, like modern sediments, with only a few exceptions. This is known as the principle *original horizontality* (Fig. 8.2). Sedimentary layers that we see tilted or folded today were not deposited in that configuration and therefore must have been tilted or folded at some later time after their deposition as horizontal layers. Exceptions to this rule are sedimentary structures called *crossbeds* (see Fig. 8.3), which are formed on the dipping faces of channel bars in rivers or sand dunes, and deposits left by mass movement such as landslides and mudflows. Mass movement deposits, which are not laid down layer upon layer, are frequently poorly sorted without well-defined bedding and can be chaotic with irregular surfaces.

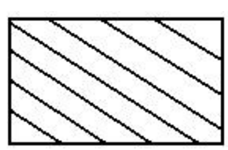


***Figure 8.2*** *– The principle of original horizontality says that sedimentary rock units were laid down as nearly horizontal layers with a few exceptions such as crossbeds and some mass movement deposits. Shown here are dipping beds of the Chinle Formation east of the Grand Canyon in Arizona that were tilted after being deposited horizontally.*

Sediments and sedimentary rock layers or beds are always deposited on some older surface. Another way of saying this is that younger sedimentary rock units are superposed on older units. This is the principle of *superposition* (Fig.8.3), which is Nicholas Steno's great contribution. Early naturalists also came to understand that sedimentary rock units, like modern sedimentary layers, did not form with abrupt ends where we see them exposed in cliff faces or other outcrops. Instead, they were once more continuous and today have been truncated by erosion at Earth's surface. This is the principle of *continuity* (Fig. 8.4). Sedimentary rock units are also made of particles that had to form at some time prior to the deposition of the sediment. They are pieces of other rock formations that must have been older. For example, if a conglomerate has pebbles made of granite, the pebbles of granite come from a granite rock formation that is older than the time at which the conglomerate was deposited. It indicates that there is granite older than the conglomerate. If the granite pebbles are somewhat unique, it can tell us specifically which granite is older than the conglomerate. This applies to the sand grains in sandstone, the silt particles in siltstone, and the clay particles in shale. They are all from eroded rock formations older than the sedimentary rock in which they are found. This is the principle of *derivation* – a sedimentary rock unit is younger than the rock units that are the sources of the particles that make up the sedimentary rock unit (Fig. 8.5)

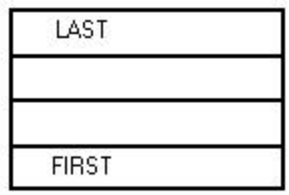
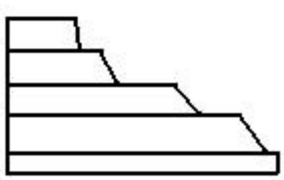



***Figure 8.3 (left)*** *– The principle of superposition says that sedimentary rock units are always laid down on older rock units or sediment. A sequence of sedimentary beds or layers, therefore, is always oldest at the bottom and youngest at the top. Shown here are horizontal beds of sandstone, each containing crossbeds, that rest one upon another with the oldest unit at the bottom and youngest unit at the top. The rock unit is the Navajo Sandstone in Zion National Park in Utah. Note the car for scale.*



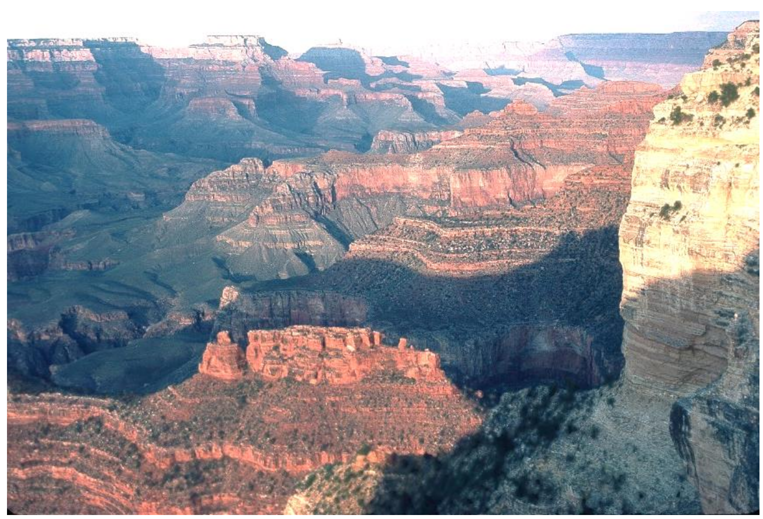


***Figure 8.4 (above right)*** *– The principle of continuity states that sedimentary layers found truncated at Earth's surface once extended in all directions until they thinned to nothing or reached the edges of their sedimentary basin. Shown here is the upper 2/3 of the Grand Canyon, which was once composed of horizontal layers that were more continuous prior to erosion. The same rock units are found on both sides of the canyon.*

***Figure 8.5*** *– The principle of derivation states that a sedimentary unit is made of particles that come from older rock units and it must therefore be younger than the rock units from which the particles (clasts) were eroded. Shown is the Pondville Conglomerate in Randolph, Massachusetts, which is largely made of boulders, cobbles, and pebbles (clasts) of an igneous rock unit exposed in the Blue Hills.*

Fundamental principles are also applied to igneous rocks. Intrusive igneous rock units, including plutons and dikes, are always younger than the rocks they intrude. They can't be older because the host rocks they intrude wouldn't exist yet and intrusions can't form in an open space without surrounding rocks to confine their shape. This is the principle of *intrusion* (Fig. 8.6). If there are two intrusive igneous rock formations in contact with each other, we will need additional information to figure out which is older or younger. In this case, a chill zone might occur in the younger of the two rock units along their contact, while there is no chill zone in the older of the two along the contact.

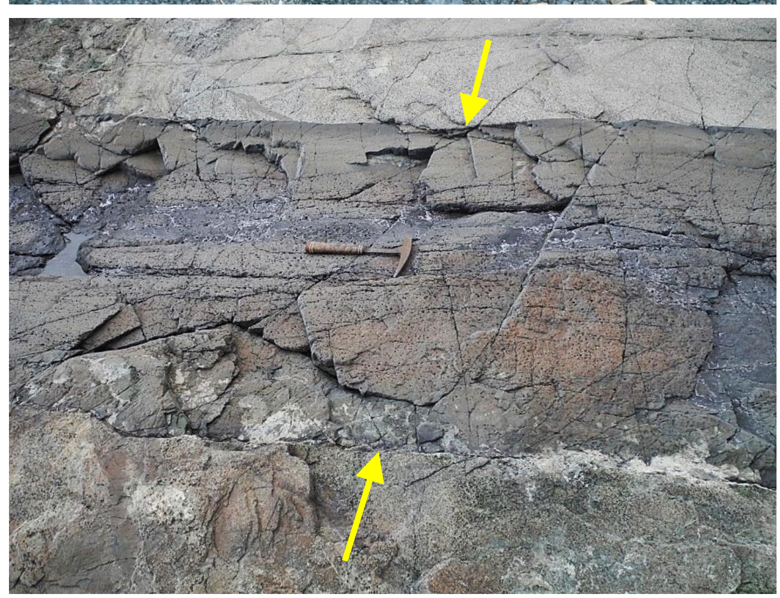
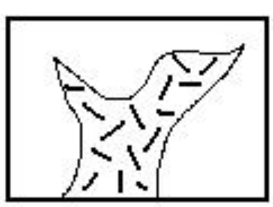


***Figure 8.6****– The principle of intrusion states that any intrusive igneous rock unit, including dikes, sills, and plutons, must be younger than the rock it intrudes.*

*(above) A basaltic dike cutting through horizontal beds of shale in the St. Lawrence Valley of Quebec. The edges of the dike weather to a lighter color where they are finer-grained in a "chill zone". Note the ragged sides of the dike.*

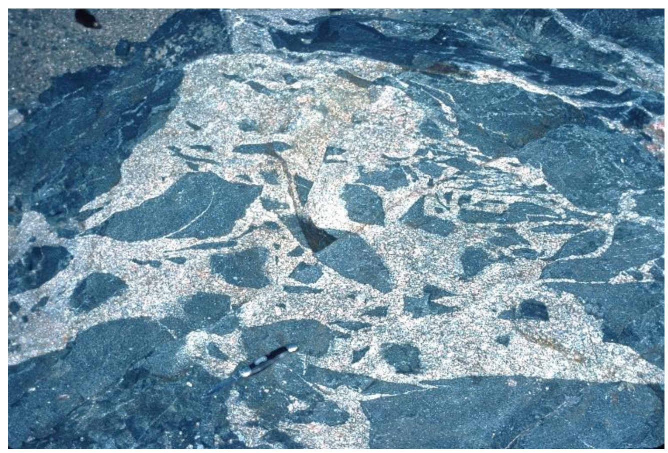
*(bottom) A basaltic dike cutting across the Nahant Gabbro at East Nahant, Massachusetts. The interior of the dike is vesicular while the edges (yellow arrows) have a fine-grained chill zone.*



An additional piece of evidence that geologists use to determine the relative ages of igneous rocks is to look for inclusions of older rock units in them. Inclusions are pieces of host rock formations that broke off into the magma (see Chapter 4). When the magma solidified, or crystallized, the inclusions were trapped in the surrounding igneous rock. Inclusions are always from older rock formations than the one in which they are trapped or included. This is the principle of *inclusion* (Fig. 8.7). Inclusions occur in both dikes and plutons, and the included fragments are often angular, forming a *plutonic breccia*. Lava flows and tuffs can also have fragments or inclusions of other rock formations, which are incorporated into magmas as they erupt to the surface. Some fragments are blown into the air as a result of the force of a volcanic eruption and become part of the ejecta (as lithic fragments) that makes up pyroclastic rocks.

One final fundamental principle that can be applied to a variety of rock types and situations is *crosscutting* (Fig. 8.8). Any feature or rock body that cuts across, or interrupts, another rock body or feature that was once continuous is said to crosscut the older rock or feature. All crosscutting features are younger than the things they crosscut. This principle applies to faults and fractures, which cut across older rocks, as well as intrusions. For example, dikes and faults can cut across older dikes, faults, fractures, sedimentary bedding, or the contacts between other rock units. Erosion surfaces and their associated unconformities (see below) also qualify as crosscutting features, and the erosion surface is younger than anything it cuts across.

***Figure 8.7 (right)*** *– The principle of inclusion states that inclusions found in an igneous rock unit must be derived from older rock units and the igneous rock unit is younger than the units from which the inclusions are derived. To the right are angular inclusions of gabbro in granite in northeastern Colorado. See also Chapter 4.*



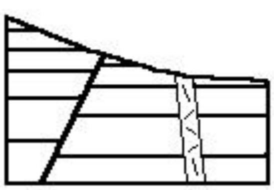


***Figure 8.8*** *– Crosscutting states that any feature that crosscuts or interrupts the continuity of other features or rock units is younger than the crosscut units or features. (left above) Two basalt dikes cutting across the Salem Gabbro at East Nahant, Massachusetts. The older of the two dikes (darker) has well developed chill zones, is crosscut by the lighter dike, and was offset as the sides of the younger dike separated. Rock hammer for scale. (right above) A normal fault (red arrow) crosscuts and offsets beds of the Brule Formation in Badlands National Park in South Dakota.*

### 8.1.3 More on Unconformities

There are three fundamental types of *unconformities* (Fig. 8.9), which are described below. An *angular unconformity* occurs when sedimentary layers are tilted and eroded, and new sedimentary units are put down horizontally over the eroded sequence (Figs 8.9A & 8.10A). The first sedimentary sequence was tilted and crosscut by erosion prior to deposition of the second sequence.

A *disconformity* (Fig. 8.9B) is where there is missing time, but the sedimentary units above the unconformity have the same bedding orientation as sedimentary units below. This can be due to erosion that is roughly parallel to the beds below, followed by burial of the erosion surface by more sediment with the same orientation. It can also be due to a period in which nothing was deposited, and when deposition resumed, the bedding orientation was the same as prior to the interval of non-deposition. There was no tilting event as with an angular unconformity.

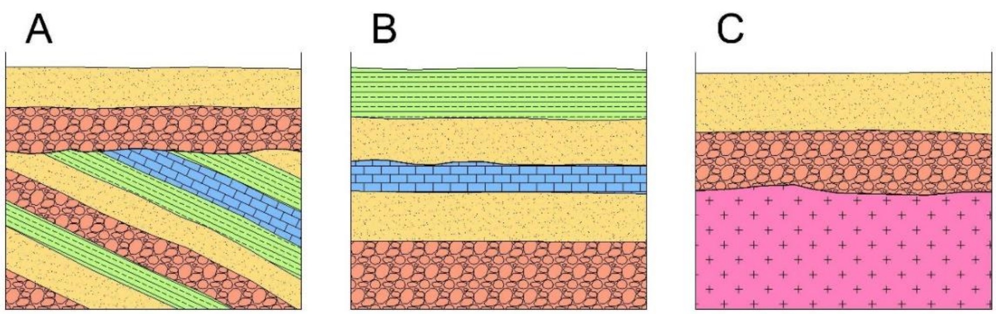



***Figure 8.9** – An **unconformity** is a boundary that represents a significant time gap in the geologic record between the rock units above and below it and is overlain by a sedimentary rock unit or extrusive igneous rock unit (lava flow or pyroclastic deposit). The diagrams use the standard symbols on Figure 8.1. There are three fundamental types of unconformities including: A) an **angular unconformity**, in which rocks below the unconformity were tilted and eroded prior to deposition of units above the unconformity; B) a **disconformity**, in which units above and below the unconformity have the same bedding orientation and there has been either erosion parallel to bedding or a period of non-deposition at the top of the limestone (blue unit); and C) a **nonconformity** that separates intrusive igneous or metamorphic rock units below from sedimentary rock units above. The rock units above the nonconformity could not be deposited until erosion exposed the intrusive igneous or metamorphic rock units at Earth's surface.*

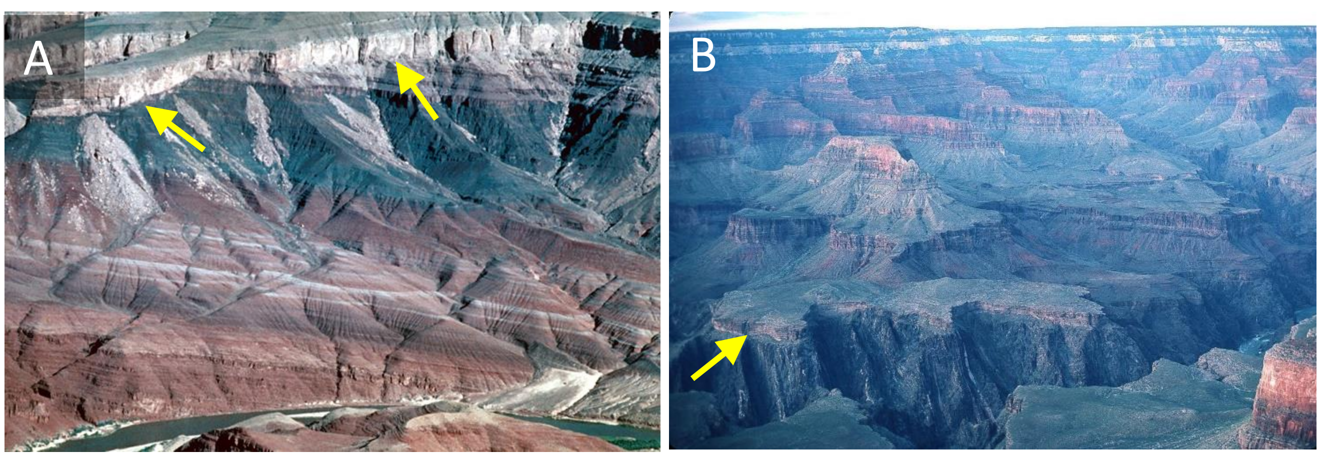



***Figure 8.10** – The great unconformity in the Grand Canyon that separates rocks of Precambrian age from the Cambrian Tapeats Sandstone. A) In the eastern Grand Canyon, the Tapeats Sandstone rests on tilted units of the Grand Canyon Series at an angular unconformity (arrows). (Image from USGS photo library, med 00280.) B) In the western Grand Canyon, the Tapeats Sandstone sits on much older igneous and metamorphic rocks (arrow) at a nonconformity. In both cases, the Tapeats Sandstone forms a resistant bench that is capping older units.*

A *nonconformity* (Fig. 8.9C) is when an igneous or metamorphic rock unit is eroded and exposed at Earth's surface, and then sedimentary layers or extrusive igneous rocks are put down on the eroded surface (Fig. 8.10B). In the case of coarse-grained igneous or metamorphic rock units, the nonconformity represents a great amount of erosion. The coarse igneous and metamorphic rocks had to have formed deep beneath Earth's surface, and everything above these units was removed by erosion before sedimentary or volcanic layers could be laid down upon them at Earth's surface.

### 8.1.4 Sequences of Events – Relative Time

Using the identification of rock types and the fundamental principles discussed above, it is possible to look at a whole section of rock formations and determine a sequence of relative ages based on field relationships. In Figure 8.11 are sketches of rock outcrops that use the standard symbols in Figure 8.1. The outcrops can be deciphered for the history of how the geologic units in the area were formed relative to each other, both spatially and temporally. These "sequences of events" bring order to what may initially seem like haphazard placement of rock units through time.

Sequences, like the ones in Figure 8.11 (A, B and C), are the fundamental basis for assembling more detailed studies that can later obtain numerical ages of the rock units. The relative age relationships of the rock units are based on the fundamental principles outlined above. However, finding evidence for relative ages along the contacts between geologic units in the field can sometimes be difficult. You often hear geologists say, "If only the contact was exposed!". The captions for Figure 8.11 give solutions to the sequences of events. Figure 8.12 is an example of a complicated geologic sequence that you can try to unravel by yourself. The solution for this diagram is given at the end of this chapter.

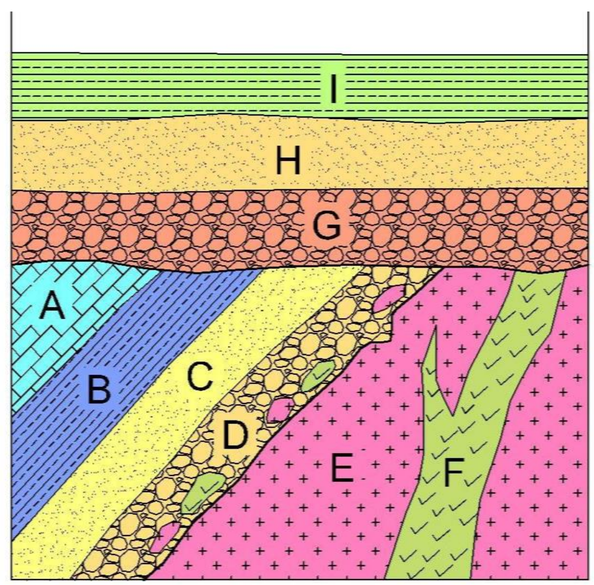



***Figure 8.11 – Cross section A**: This section contains two major unconformities, two sequences of sedimentary rock, and one group of igneous rocks.*

*E and F are the oldest rock units. We know they are older than sedimentary rocks (A-D) because pieces of both E and F occur in conglomerate D, the oldest sedimentary rock unit. (Note the different colored pebbles in the base of unit D.) D rests on a nonconformity eroded into E. G rests on an angular unconformity on its left side and a nonconformity on the right.*

*Here is the sequence (oldest at bottom):*

*deposit I*
*deposit H*
*deposit G*
*tilt A-F and erode –angular unconformity*
*deposit A*
*deposit B*
*deposit C*
*deposit D (particles from E and F)*
*erode E and F – nonconformity*
*intrude F into E*
*intrude E into rocks not visible here*

***Figure 8.11 – Cross section B:***

*This section has many crosscutting features.*

*A is the oldest rock unit (no symbol). It is intruded by dikes B through E and crosscut by the fault.*

*The fault is younger than dikes C and E. C crosscuts E. The fault is older than dikes D and B. B crosscuts D and may have intruded a fault because of the way dikes C and D are offset at B.*

*Here is the sequence (oldest at bottom):*

*land surface is eroded - unconformity*
*intrude B (along a fault?)*
*intrude D*
*fault crosscuts A, C and E*
*intrude C*
*intrude E*
*form rock unit A*

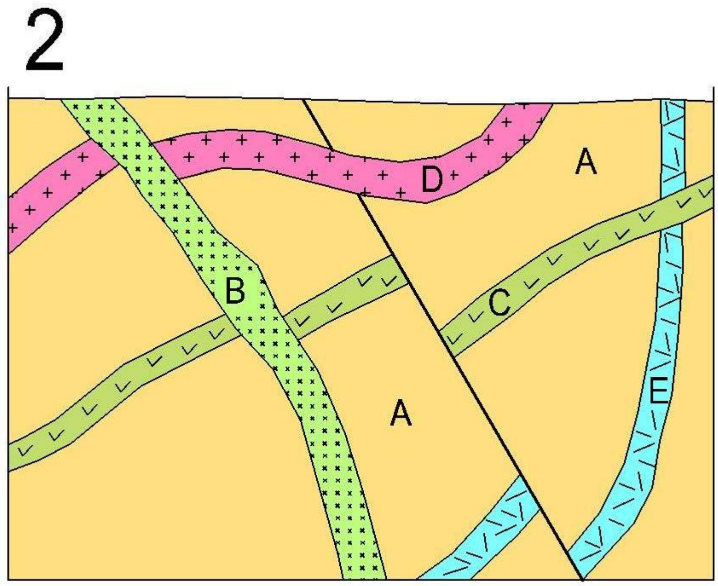
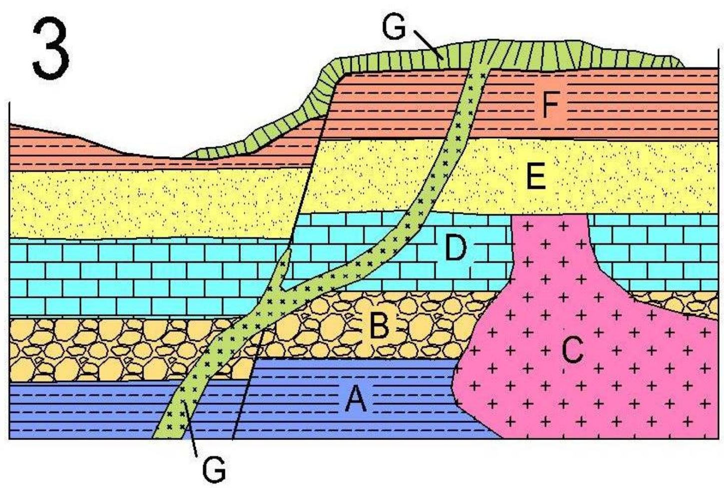



***Figure 8.11 – Cross section C:***

*This section contains an unconformity that is partly a disconformity and partly a nonconformity. It also has a fault and a crosscutting dike (G) that feeds a lava flow of the same age (G).*

*Here is the sequence (oldest at bottom):*

*intrude G that crosscuts the fault and reaches surface where it becomes lava flow that flows across a plateau and into the valley.*
*fault and erode valley into F (left side).*
*deposit F*
*deposit E*
*erode and form disconformity between E and D and nonconformity across C. C is crosscut.*
*intrude C*
*(deposit more units that are later eroded)*
*deposit D*
*deposit B*
*deposit A*



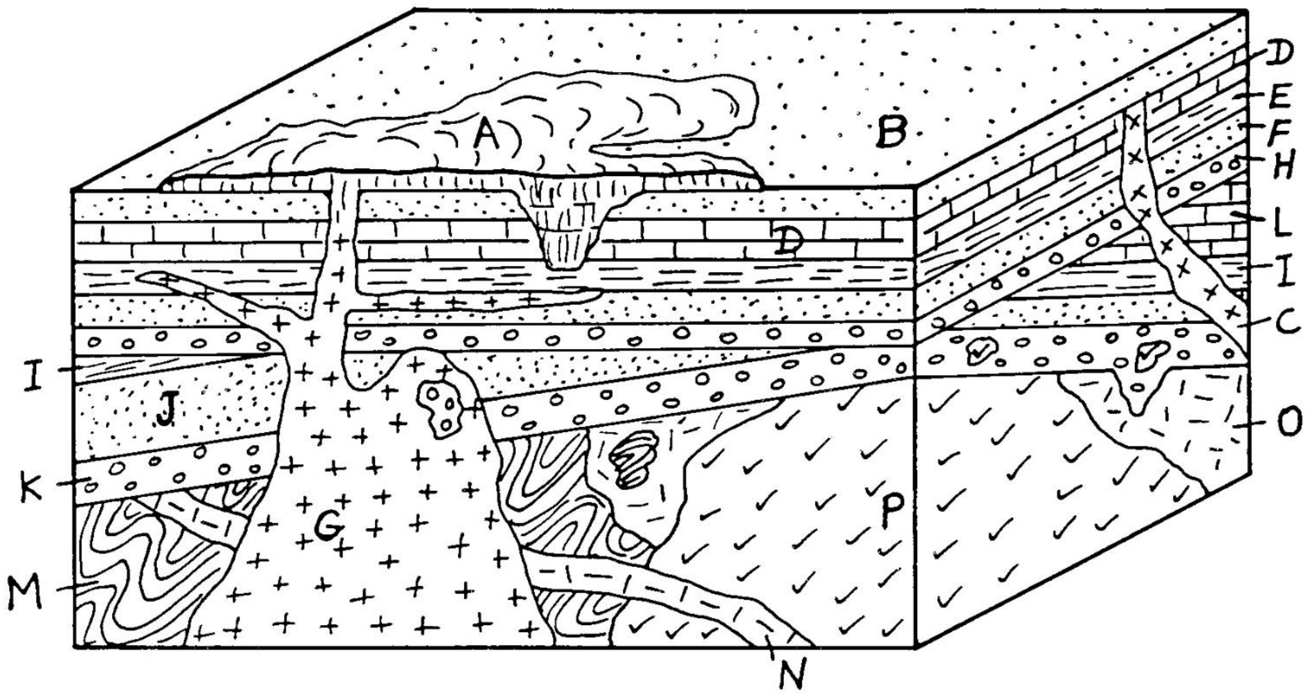



***Figure 8.12*** *– A complex sequence of events with many steps, 3 major erosional unconformities, and a metamorphic rock unit (M). The key to this sequence is at the end of this chapter.*

**8.2 FOSSILS AND GEOLOGIC TIME**

While the first geologists characterized sedimentary rock formations and deciphered rock sequences according to relative ages, they began to talk about the time periods in which the different rock formations were formed and gave the time periods names. So, for example, a rock unit called the Old Red Sandstone in England was deposited in what was defined as the Devonian Period. (We'll learn about time period names below. See Fig. 8.13.) Geologists also began to categorize the fossils that they found in sedimentary rock formations. They noticed that fossils in successive rock formations were different. However, no matter where the fossils were found, they always occurred in the same relative order. When geologists discovered that the same fossil sequences in the same relative order were found at different places around the world, they realized that they were looking at rock sequences with the same age and the same sequence of time periods. Fossils have since become very important for defining and recognizing geologic time periods in sedimentary rock formations and sequences.

Fossil types can change abruptly across the boundaries between rock formations, with some species disappearing from the rock record to never be seen again. These boundaries represent the *extinctions* of organisms and can be astounding events. For example, most people are familiar with the extinction event that killed off most of the dinosaurs at the end of the Cretaceous Period (Fig. 8.13) and was associated with an asteroid impact event. We now know that some dinosaurs had feathers, and that they survived the impact event and evolved into birds. In the most extreme extinction event (so far!), more than 80% of all genera went extinct at the end of the Permian Period! Trilobites (see Figs. 5.3B and 7.3) were fading in abundance and diversity by this time, but this event represents their complete demise.

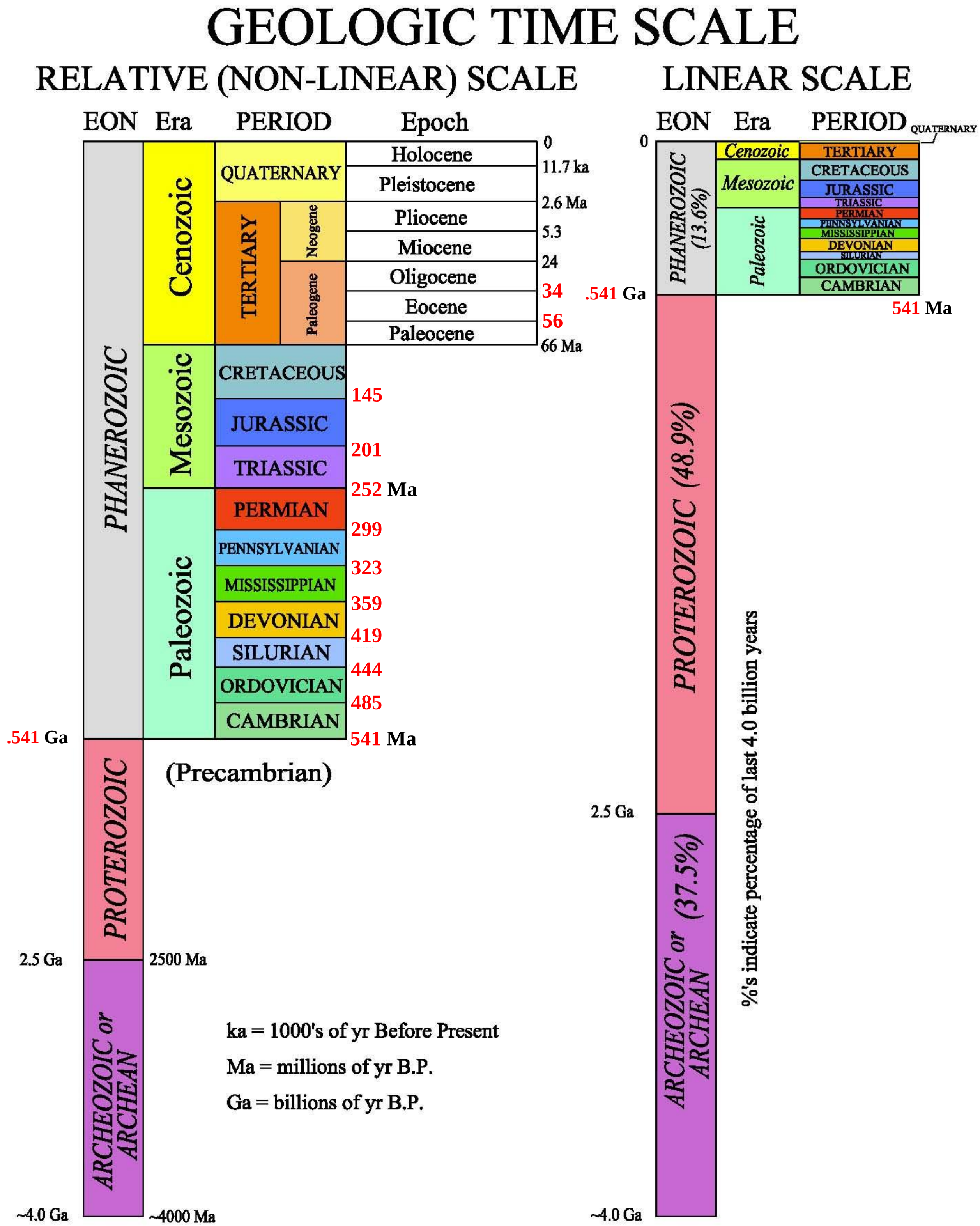



***Fig. 8.13** – The geologic time scale shows the subdivision of time represented by rocks we find today on Earth (~4.0 billion yr). Time units have a hierarchy of eons, subdivided into eras, subdivided into periods, subdivided into epochs. The time scale shown here is plotted in two ways. On the left is the relative order of time units without regard for their relative lengths (scale is not constant). On the right is a plot of geologic time on a constant linear scale, where the sizes of the time unit boxes indicate their relative lengths. Numbers have been applied to the boundaries of the time units based on radiometric dating techniques. Red numbers indicate revisions in the last 40 years. Based on [Walker and others (2018)](#).*

As more and more rock formations were studied, their relative ages determined, and their fossils cataloged, time periods were given names, all without knowing any numerical ages. This assemblage of time periods eventually covered the entire record of Earth's history represented by rocks. Today, we are still subdividing geologic time as we study it in more detail. The listing of names for time periods in the order of their occurrence is known as the *geologic time scale* (Fig. 8.13), which is under constant revision as new discoveries occur and lab techniques are improved. The geologic time scale has many different time units with their own hierarchy or subdivisions. *Eons* are divided into *eras*, which are divided into *periods*, which are divided into *epochs*, which are divided into *stages*. For the most recent version of a detailed time scale, see Walker and others (2018). In most cases, the geologic time scale is shown with the names of the time units appearing in boxes stacked according to their relative age. This can be misleading because it gives the impression that recent times have the same duration as ancient times, which is not the case. More recent time units are better represented by sedimentary rocks and fossils and can therefore be subdivided in more detail. Fossil preservation is often better in younger rock units, and younger rock units are less likely to have been eroded or metamorphosed. In other words, we know a lot more about the time periods of younger rock formations because the record is more complete, much like the way in which you probably know more about the lives of your parents than your great-great-grandparents or relatives back thousands of years ago.

It should be emphasized that the geologic time scale names and subdivisions were derived from observations of changes in rock sequences and fossil assemblages. The boundaries between time periods represent changes in rock sequences that can be visually recognized in the field. For example, the boundary between rocks of the Archaeozoic (or Archean) and Proterozoic Eons represents the appearance of red-colored sedimentary rocks, something that can be recognized in the field. This is when the atmosphere began to have free oxygen. Determining the relative ages of these events does not require numerical ages. All of the numerical ages you see posted on the geologic time scale were added after the subdivision of time was established and since the 1930's when numerical dating techniques that take advantage of radioactive isotopes first came into existence.

Unfortunately, there is no way to determine the time periods, or the relative ages of rock formations in the Fells, using fossils for three reasons. First, most of the rock units in the Fells are igneous rock formations and they do not contain fossils. There are situations where lava or volcanic ash might bury the remains of organisms, but this did not happen during formation of volcanic rocks in the Fells. These rare situations include charcoal fragments in modern pyroclastic deposits or forests buried by ash to produce petrified forests (search the internet for: Yellowstone petrified forest or Petrified Forest and Painted Desert). Second, we now know from radiometric dating that the sedimentary rock formations of the Fells are too old to have the fossilized hard parts of organisms or land plants. These sediments were formed prior to the evolution of exoskeletons, shells, bones, or land plants, which are much more easily fossilized than marine organisms that have just soft tissue. Finally, the third reason is that the sedimentary rock formations of the Fells have often been metamorphosed to the point where they could only have badly deformed or destroyed fossils. These rock formations are mostly quartz-rich metasandstones and argillite. As a result, in the Fells we rely on radiometric dating techniques.

### 8.3 RADIOMETRIC DATING AND NUMERICAL AGES

Since the 1930's, geologists have taken advantage of some of the natural laws of chemistry and physics to determine *numerical ages* for rocks, or what are sometimes incorrectly called absolute ages. *Absolute ages* are ages in years determined from actual observation or a tie to historic events of known age and therefore are known with certainty. *Numerical ages* are estimates of the ages of rock formations based on measurements of chemical and physical characteristics of rocks that have some laboratory uncertainty determined by the precision of laboratory measurements. Numerical ages are reported with plus or minus precision values, which have improved tremendously over the last century. Numerical ages are primarily the result of our understanding of the decay of radioactive elements. To understand radiometric dating techniques, we must understand some introductory physics and chemistry of elements and isotopes.

#### 8.3.1 Elements and Isotopes – Its Only Chemistry and Physics!

In order to understand the basics of radiometric dating techniques, it is necessary to understand the structure of atoms. Atoms are made of *sub-atomic particles*. In the center of an atom is its *nucleus*, made of *protons* and *neutrons*, while *electrons* orbit the nucleus. An *element* is a type of atom with a certain number of protons in its nucleus. For example, all atoms labeled as the element oxygen have 8 protons in their nuclei, all iron atoms have 26 protons in their nuclei, all uranium atoms have 92 protons in their nuclei, and so on. The number of protons in the nucleus is an element's *atomic number*. Atoms of the same element do not always have the same number of neutrons in their nuclei. This does not affect the type of element (which is dependent on only protons) but instead makes them different forms of the same element called *isotopes*. Isotopes are written as the abbreviation of the element's name with a superscript number preceding the abbreviation that gives the total number of protons plus neutrons in the nucleus. This is the isotope's *mass number*. For example, $^{238}U$ and $^{235}U$ are two different isotopes of uranium. They both have 92 protons, but one has 146 neutrons (for a total of 238 particles in the nucleus) and the other 143 neutrons (for a total of 235). All elements have several isotopes, but one is usually more abundant than the others. For example, the element carbon (6 protons in its nucleus) is about 98.9% $^{12}C$, 1.1% $^{13}C$, and an extremely tiny amount of $^{14}C$ (~$1.0 \times 10^{-10}$%). $^{14}C$, or what has been given the name radiocarbon, is unstable and decays to another element, which is $^{14}N$. This decay keeps its abundance very low. It would disappear entirely if it weren't for the continued production of $^{14}C$ by cosmic ray bombardment of Earth's upper atmosphere (Faure and Mensing, 2009).

#### 8.3.2 Radioactivity and Radiometric Dating

Isotopes of one element can be stable, or they can be unstable and undergo spontaneous *isotopic decay* to isotopes of other elements, releasing subatomic particles and energy. This spontaneous decay process is what we refer to as *radioactivity*. For example, the reason $^{14}C$ has such a low abundance is that it changes to nitrogen ($^{14}N$). Now, here is the important part. Through some complicated physics, and in some cases precise measurements, we can determine how fast radioactive elements decay or change to other isotopes. This allows us to set up atomic clocks for determining the ages of rocks. Here's how it works: when a rock forms from magma, it has a certain amount of a radioactive isotope in it. This should not alarm you because ALL things have radioactive material in them, but these amounts are usually very small. The starting isotope in a radioactive decay process is called the *parent isotope*. Over time, the parent isotope decays to another isotope that we call a *daughter isotope*. It takes a certain amount of time for half of the parent isotope that occurs in a rock to decay to the daughter isotope. This time is known as the *half-life* of the parent isotope. Sometime after the igneous rock was formed, some of the parent will have decayed. This creates daughter isotopes and a diminished abundance of the parent isotope. We can determine the age of the rock if we know the half-life of the parent isotope (i.e., its rate of decay) and can determine at least two of three things (we're lucky if we can determine all three!). These three things are: 1) the abundance of the parent isotope when the igneous rock formed, 2) the current abundance of the parent isotope, and 3) the abundance of daughter isotopes produced since the time the rock formed. Items 2 and 3 always add up to item 1, so if we know two, we can calculate the third one. If when the rock formed it already had some daughter isotopes, we will also have to know the starting abundance through other measurements.

An important consideration in all these techniques is that the parent and daughter isotope abundances in a rock, since the time it forms, must not later change by anything except radioactive decay. If parent or daughter isotopes are either gained or lost by processes other than radioactive decay within a mineral, we will not be able to use an analysis of the mineral to determine an accurate age without making additional measurements. As a result, geologists choose certain minerals that occur in igneous rocks for age analysis. These minerals do not allow their interior composition of isotopes to change over time except by radioactive decay, or perhaps by extreme heating and metamorphism.

An important set of reactions used to radiometrically date igneous rocks is the decay of $^{238}$U (Fig. 8.14) through a complex chain of events that results in lead ($^{206}$Pb). The half-life of $^{238}$U is about 4.5 billion years. For example, if a rock has the same amount of $^{238}$U and $^{206}$Pb, it would be one half-life old, or about 4.5 billion years, but any measurement of the ratio of $^{238}$U/$^{206}$Pb can be applied to a decay equation that will give the age of the rock. However, there is one problem. We would have to know that all the $^{206}$Pb in the igneous rock was only the result of $^{238}$U decay since the rock formed. Some $^{206}$Pb could have been in the rock at the time of the rock's formation. This would be $^{206}$Pb that did not form as a result of $^{238}$U decay in the igneous rock but was in the original

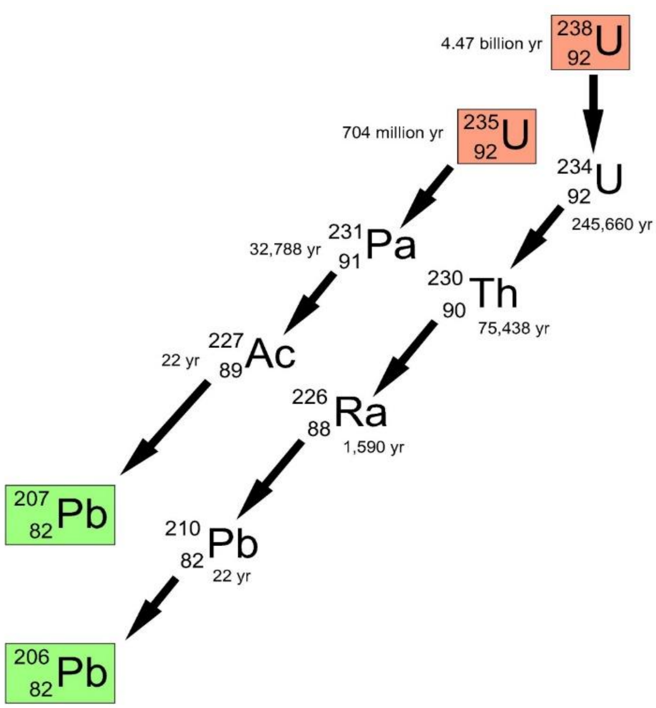



***Fig. 8.14** – The simplified decay of two radioactive isotopes of uranium, $^{235}$U and $^{238}$U. For each isotope, the superscript number is the mass number (neutrons plus protons in the nucleus), and the subscript number is the atomic number (protons in the nucleus). Shown are only those decay products with a half-life of more than 1 year. There are several very short-lived isotopes in both decay series that are not shown here. The lead (Pb) isotopes shown in green are stable. The decay of uranium in rocks is a key to many radiometric age determinations.*

magma. If we knew how much $^{238}U$ was in the rock when it formed, we could circumvent this problem, but we would never know this unless we already knew the age of the rock in advance. Our solution is that we also measure the abundance of parent and daughter isotopes in another uranium isotope decay series, $^{235}U$ decaying to $^{207}Pb$. The two decay sequences together, along with some complex calculations, provide the information needed to determine the ages of igneous rocks from about 4.5 billion to about 1 million years ago. This is just one example. There are about 40 radiometric dating techniques that can now be applied to determining numerical ages of geologic events from the early history of Earth (billions of years ago) to just a few years ago. Geologists apply different radiometric dating techniques to different parts of the geologic time scale and to different rock types being studied. A detailed treatment of these techniques as well as other applications of isotopes to solving geologic problems is found in Faure and Mensing (2009).

An important mineral for dating ancient rocks is zircon ($ZrSiO_4$; see Chapter 3), which has trace amounts of radioactive isotopes in it that can be used for dating (Fig. 8.15). Zircon occurs as tiny crystals in most non-mafic and some mafic igneous rocks. When a zircon crystal forms from magma to become a crystal in an igneous rock, either intrusive or extrusive, it traps trace amounts of impurities, most significantly isotopes of uranium and lead. Zircon is very chemically resistant and hard, so it does not weather significantly, or give up or obtain new isotopes from outside the original mineral grain, even during heating to high temperatures or during most metamorphism. To determine the age of a rock, we must crush it and extract the tiny zircon crystals for analysis. Abundances of uranium and lead isotopes in the zircon crystals can then be measured using a mass spectrometer. These abundances help us determine the age of the crystallization of the igneous rock.

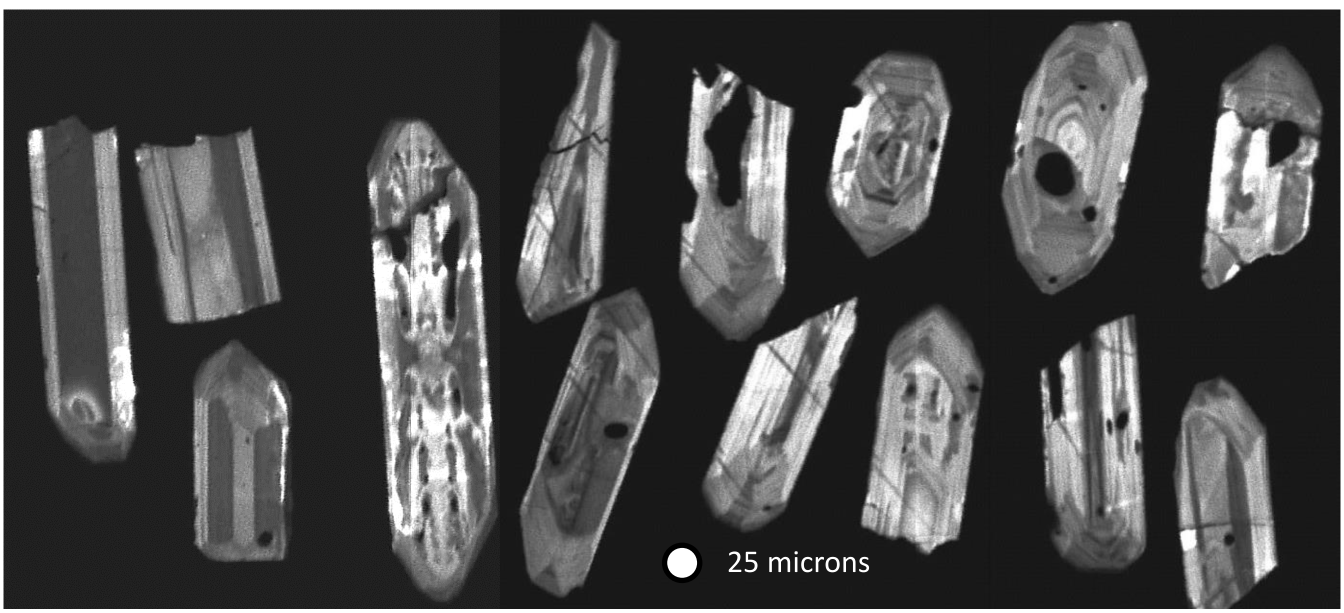



***Fig. 8.15*** *– Zircon crystals that are used to radiometrically date rocks in the Fells. The crystals were separated from crushed rock, and this is a scanning electron microscope image of polished zircon crystals showing their internal concentric layering, or zoning. The crystals are from the Rams Head Porphyry. Dating the cores of the crystals avoids alterations that may have occurred to the outside by later heating or metamorphic events.*

We can also apply zircon ages to putting limits on the ages of clastic sedimentary rocks. When igneous rocks weather, zircon crystals are released as tiny sand grains that are later deposited as grains in a sedimentary rock. If we crush a sedimentary rock and separate zircon grains, we can also date these crystals. However, they will give us the age of the original igneous rocks from which they came. Remember the principle of derivation! This will not give us the age of the sedimentary rock but the maximum possible age of the rock, which corresponds to the youngest zircon grain age, i.e., the youngest component we were able to measure from an original igneous rock source. This places a very important constraint on the age of the sedimentary rock. Since zircons will also survive substantial metamorphism, the maximum age of a metamorphic rock, for example a meta-sandstone, can also be determined by determining the youngest age of zircon crystals. This will give the maximum age of the protolith of the metamorphic rock. In the Fells, the maximum age of the oldest rock unit, a metasandstone (Westboro Formation), has been determined in this way.

### 8.3.3 The Power of Numbers

Radiometric numerical age estimates allow us to place numbers on the boundaries between time units on the *geologic time scale* (Fig. 8.13). This provides us with a sense of the antiquity of events in Earth's history and gives us an appreciation of the vast spread of time involved in our planet's history and that of the solar system. Numerical ages are also transferable to sequences of events, where they place limits on the ages of surrounding rock units and events. For example, if we know the age of a basaltic lava flow, we also know that no unit with a relative age younger than the lava can have a numerical age greater than the lava. The numerical age for the lava represents the maximum age for younger geologic features. We also know that inclusions in the lava or units upon which the lava rests are older than the lava flow. Therefore, the numerical age of the lava provides a minimum age for rock units older than the lava. Thus, we can place limits on the numerical age of a rock unit by knowing numerical ages for units from both before and after the rock's formation. In this way, we are "bracketing" the age of a rock unit.

To make communication simpler, geologists apply abbreviations to numerical ages (see Fig. 8.13). Billions of years before present is abbreviated as *Ga*, which stands for *giga-annum*. Millions of years before present is abbreviated as *Ma*, which stands for *mega-annum*. Thousands of years before present is abbreviated as *ka*, which stands for *kilo-annum*. For very young events, maybe from the last couple of centuries, ages may be given in *annum* (years), which is abbreviated as *a*. More frequently you will see younger events expressed in years or kilo-years (thousands of years) before present (yr BP or kyr BP).

### 8.3.4 Deep Time – Numbers that are Hard to Comprehend

Geologists love to throw around big numbers, especially for ages. We get so used to using big numbers that we often don't think about the huge amounts of time involved. What's a few million years here or there? Unfortunately, this makes it difficult to fully comprehend the length of geological time as compared to human historical time frames. It is very difficult to understand the massive length of time involved in Earth's history when we start talking about many thousands, millions, or billions of years because we have no frame of reference for things that are so long ago. So, what I am going to do is give you my favorite analogy for helping to understand the vast length of geologic time. You sometimes hear this vast time span referred to a "deep time".

Let's say that the last 4 billion years (the approximate age of the oldest rock on Earth) is represented by a book. This book has 500 pages, 25 lines on each page, and 75 characters per line. Below is how the history of the planet would read from 4 Ga to today. Hopefully, this puts the very long, deep history of the Earth in clearer focus as compared to human events. It began an extremely long time ago. Human history is less than a drop in the bucket!

**START**: p. 1, line 1, character 1 - 4 billion years ago (4.0 Ga).

p. 187 - Significant free oxygen appears in the atmosphere for the first time (2.5 Ga). In the 500 million years before this, photosynthesis started.

Not before p. 387 – Oldest rock unit in Fells (Westboro Formation, 909 Ma max) deposited as sandstone and shale.

p. 423-426 – Period of felsic magmatism in Fells, plutonic and volcanic units (Late Proterozoic).

p. 433 - The first organisms appear with hard parts, i.e., shells and exoskeletons (541 Ma). Note that this is already more than 87% of the way through Earth's history. It is called the Cambrian explosion.

p. 441 - Plants appear on land for the first time (~470 Ma).

p. 462 – Intrusion of Medford Dike, youngest rock unit in Fells. (304 Ma, Late Pennsylvanian).

p. 468, line 13 - Major extinction event. Trilobites go extinct (252 Ma, end of Permian).

p. 491, line 18 - Most dinosaurs go extinct (66 Ma). Some survive to become birds. This is about 98% of the way through Earth's history.

p. 500, last line, char. 28 - Our species evolves (~200 ka).

p. 500, last line, characters no. 68-74 – last time a glacial ice sheet covered the Fells (late Wisconsinan Glaciation, ~28-12 ka)

p. 500, last line, beginning of 2$^{nd}$ last character (no. 74) - End of the last ice age, mammoths and mastodons went extinct (~12.0 ka).

p. 500, last line, middle of char. 74 – Beginning of recorded human history and agriculture (~7 ka).

p. 500, last line, part way through the last character (char. 75) – beginning of ancient Greece (~3000 yr BP or 3 ka).

**Solution to geologic sequence on Figure 8.12**
**(oldest events at bottom)**

Intrude G to surface and form Lava A that fills valley
Erode valley into B, D, and E
Deposit B
Erosion of C and surface of D to form disconformity on D and nonconformity on C
Intrude C
Deposit H, F, E, and then D
Tilting and erosion forms angular unconformity across K, J, I, and L
Deposit K, J, I, and then L
Erosion - nonconformity cuts across O, P, metamorphic rocks, and N
Intrude O, and then P, and then dike N
Form protolith of M and then metamorphose M

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