Chapter 8 Measuring Geological Time

Learning Objectives

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Apply basic geological principles to the determination of the relative ages of rocks.
- Explain the difference between relative and absolute age-dating techniques.
- Summarize the history of the geological time scale and the relationships between eons, eras, periods, and epochs.
- Understand the importance and significance of unconformities.
- Estimate the age of a rock based on the fossils that it contains.
- Describe some applications and limitations of isotopic techniques for geological dating.
- Use isotopic data to estimate the age of a rock.
- Describe the techniques for dating geological materials using tree rings and magnetic data.
- Explain why an understanding of geological time is critical to both geologists and the public in general.

Time is the dimension that sets geology apart from most other sciences. Geological time is vast, and Earth has changed enough over that time that some of the rock types that formed in the past could not form today. Furthermore, as we've discussed, even though most geological processes are very, very slow, the vast amount of time that has passed has allowed for the formation of extraordinary geological features, as shown in Figure 8.0.1.

Figure 8.0.1 Arizona's Grand Canyon is an icon for geological time; 1,450 million years are represented by this photo. The light-coloured layered rocks at the top formed at around 250 Ma, and the dark rocks at the bottom (within the steep canyon) at around 1,700 Ma.

We have numerous ways of measuring geological time. We can tell the relative ages of rocks (for example, whether one rock is older than another) based on their spatial relationships; we can use fossils to date sedimentary rocks because we have a detailed record of the evolution of life on Earth; and we can use a range of isotopic techniques to determine the actual ages (in millions of years) of igneous and metamorphic rocks.

But just because we can measure geological time doesn't mean that we understand it. One of the biggest hurdles faced by geology students—and geologists as well—in mastering geology, is to really come to grips with the slow rates at which geological processes happen and the vast amount of time involved.

Media Attributions

8.1 The Geological Time Scale

William Smith worked as a surveyor in the coal-mining and canal-building industries in southwestern England in the late 1700s and early 1800s. While doing his work, he had many opportunities to look at the Paleozoic and Mesozoic sedimentary rocks of the region, and he did so in a way that few had done before. Smith noticed the textural similarities and differences between rocks in different locations, and more importantly, he discovered that fossils could be used to correlate rocks of the same age. Smith is credited with formulating the **principle of faunal succession** (the concept that specific types of organisms lived during different time intervals), and he used it to great effect in his monumental project to create a geological map of England and Wales, published in 1815. For more on William Smith, including a large-scale digital copy of the famous map, see the [William Smith Wikipedia page](https://en.wikipedia.org/wiki/William_Smith_(geologist)).

Inset into Smith's great geological map is a small diagram showing a schematic geological cross-section extending from the Thames estuary of eastern England all the way to the west coast of Wales. Smith shows the sequence of rocks, from the Paleozoic rocks of Wales and western England, through the Mesozoic rocks of central England, to the Cenozoic rocks of the area around London (Figure 8.1.1). Although Smith did not put any dates on these—because he didn't know them—he was aware of the **principle of superposition** (the idea, developed much earlier by the Danish theologian and scientist Nicholas Steno, that young sedimentary rocks form on top of older ones), and so he knew that this diagram represented a stratigraphic column. And because almost every period of the Phanerozoic is represented along that section through Wales and England, it is a primitive geological time scale.

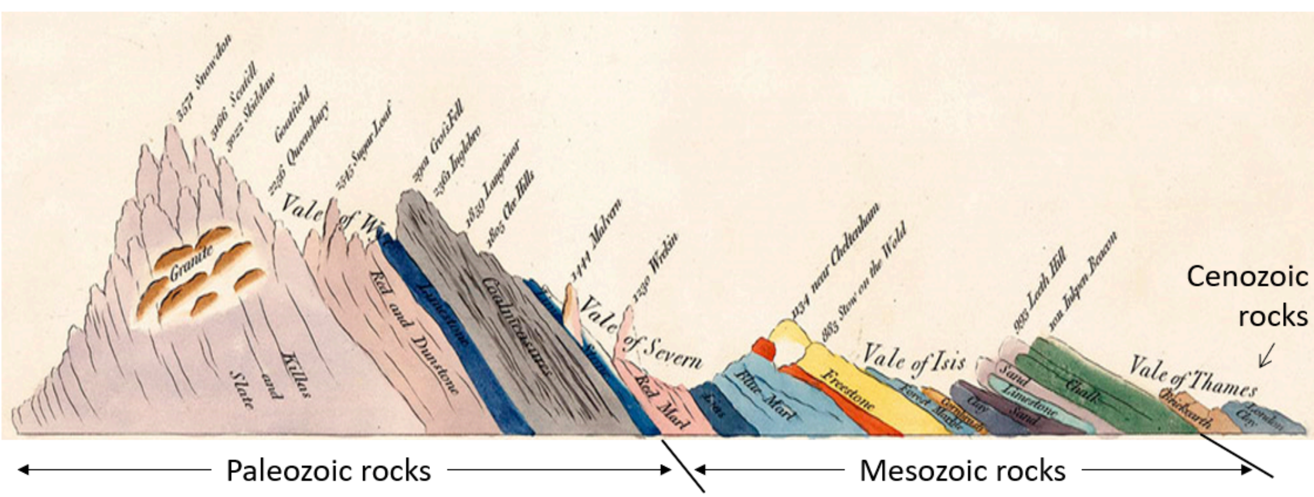

Figure 8.1.1 William Smith's "Sketch of the succession of strata and their relative altitudes," an inset on his geological map of England and Wales (with era names added).

Smith's work set the stage for the naming and ordering of the geological periods, which was initiated around 1820, first by British geologists, and later by other European geologists. Many of the periods are named for places where rocks of that age are found in Europe, such as Cambrian for Cambria (Wales), Devonian for Devon in England, Jurassic for the Jura Mountains in France and Switzerland, and Permian for the Perm region of Russia. Some are named for the type of rock that is common during that age, such as Carboniferous for the coal- and carbonate-bearing rocks of England, and Cretaceous for the chalks of England and France.

The early time scales were only relative because 19th century geologists did not know the ages of the rocks. That information was not available until the development of isotopic dating techniques early in the 20th century.

The geological time scale is currently maintained by the International Commission on Stratigraphy (ICS), which is part of the International Union of Geological Sciences. The time scale is continuously being updated as we learn more about the timing and nature of past geological events. You can view the ICS time scale online. It would be a good idea to print a copy (in colour) to put on your wall while you are studying geology.

Geological time has been divided into four eons: Hadean (4570 to 4850 Ma), Archean (3850 to 2500 Ma), Proterozoic (2500 to 540 Ma), and Phanerozoic (540 Ma to present). As shown in Figure 8.1.2, the first three of these represent almost 90% of Earth's history. The last one, the Phanerozoic (meaning "visible life"), is the time that we are most familiar with because Phanerozoic rocks are the most common on Earth, and they contain evidence of the life forms that we are familiar with to varying degrees.

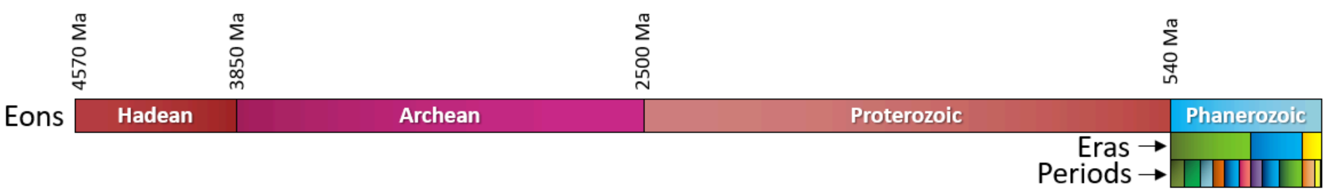

Figure 8.1.2 The four eons of Earth's history.

The Phanerozoic eon—the past 540 Ma of Earth's history—is divided into three eras: the Paleozoic ("early life"), the Mesozoic ("middle life"), and the Cenozoic ("new life"), and each of these is divided into a number of periods (Figure 8.1.3). Most of the organisms that we share Earth with evolved at various times during the Phanerozoic.

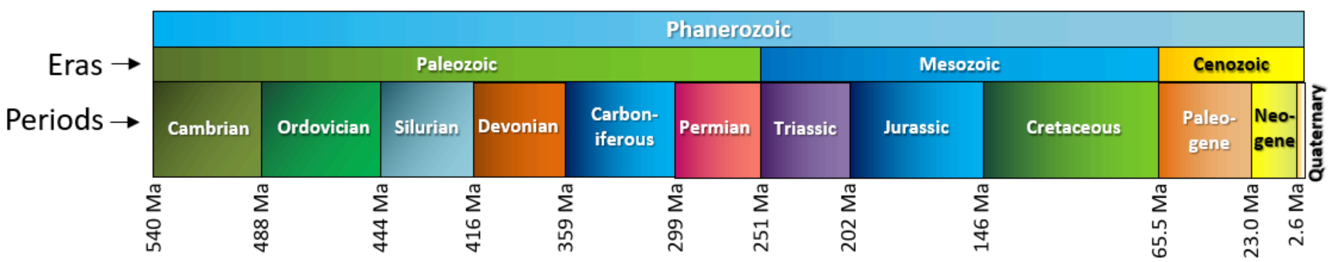

Figure 8.1.3 The eras (middle row) and periods (bottom row) of the Phanerozoic eon. [Image Description]

The Cenozoic era, which represents the past 65.5 Ma, is divided into three periods: Paleogene, Neogene, and Quaternary, and seven epochs (Figure 8.1.4). Dinosaurs became extinct at the start of the Cenozoic, after which birds and mammals radiated to fill the available habitats. Earth was very warm during the early Eocene and has steadily cooled ever since. Glaciers first appeared on Antarctica in the Oligocene and then on Greenland in the Miocene, and covered much of North America and Europe by the Pleistocene. The most recent of the Pleistocene glaciations ended around 11,700 years ago. The current epoch is known as the Holocene. Epochs are further divided into ages (a.k.a. stages), but we won't be going into that level of detail here.

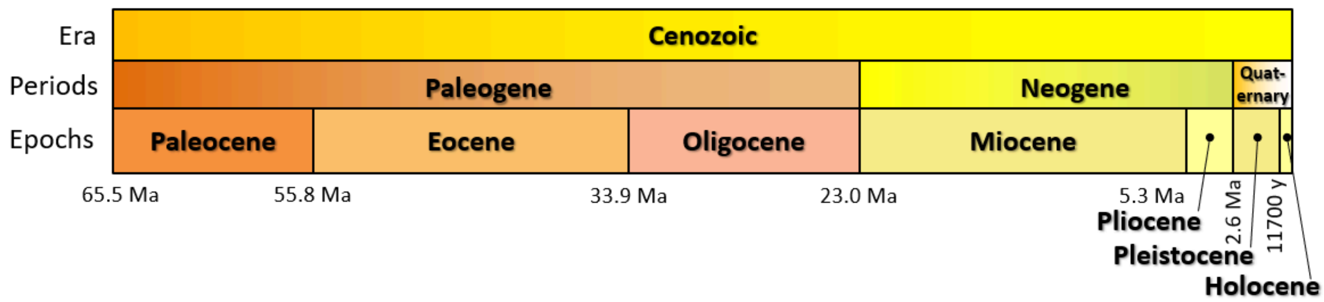

Figure 8.1.4 The periods (middle row) and epochs (bottom row) of the Cenozoic era. [Image Description]

Most of the boundaries between the periods and epochs of the geological time scale have been fixed on the basis of significant changes in the fossil record. For example, as already noted, the boundary between the Cretaceous and the Paleogene coincides exactly with a devastating mass extinction. That's not a coincidence. The dinosaurs and many other types of organisms went extinct at this time, and the boundary between the two periods marks the division between sedimentary rocks with Cretaceous organisms (including dinosaurs) below, and Paleogene organisms above.

Image Descriptions

Figure 8.1.3 image description: The eras and periods that make up the Phanerozoic Eon.

Era	Period	Time span
Paleozoic	Cambrian	488 to 540 Ma
Paleozoic	Ordovician	488 to 444 Ma
Paleozoic	Silurian	444 to 416 Ma
Paleozoic	Devonian	416 to 359 Ma
Paleozoic	Carboniferous	359 to 299 Ma
Paleozoic	Permian	299 to 251 Ma
Mesozoic	Triassic	251 to 202 Ma
Mesozoic	Jurassic	202 to 146 Ma
Mesozoic	Cretaceous	146 to 65.5 Ma
Cenozoic	Paleogene	65.5 to 23 Ma
Cenozoic	Neogene	23 to 2.6 Ma
Cenozoic	Quaternary	2.6 Ma to present

[Return to Figure 8.1.3]

Figure 8.1.4 image description: The periods and epochs that make up the Cenozoic era.

Period	Epoch	Time span
Paleogene	Paleocene	65.5 to 55.8 Ma
Paleogene	Eocene	55.8 to 33.9 Ma
Paleogene	Oligocene	33.9 to 23.0 Ma
Neogene	Miocene	23.0 to 5.3 Ma
Neogene	Pliocene	5.3 to 2.6 Ma
Quaternary	Pleistocene	2.6 Ma to 11,700 years ago
Quaternary	Holocene	11,700 years ago to the present

[Return to Figure 8.1.4]

Media Attributions

- Figure 8.1.1: "Sketch of the succession of strata and their relative altitudes" by William Smith. Adapted by Steven Earle. Public domain.
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8.2 Relative Dating Methods

The simplest and most intuitive way of dating geological features is to look at the relationships between them. There are a few simple rules for doing this, some of which we've already looked at in Chapter 6. For example, the principle of superposition states that sedimentary layers are deposited in sequence, and, unless the entire sequence has been turned over by tectonic processes or disrupted by faulting, the layers at the bottom are older than those at the top. The **principle of inclusions** states that any rock fragments that are included in rock must be older than the rock in which they are included. For example, a **xenolith** in an igneous rock or a clast in sedimentary rock must be older than the rock that includes it (Figure 8.2.1).

Figure 8.2.1a A xenolith of diorite incorporated into a basalt lava flow, Mauna Kea volcano, Hawaii. The lava flow took place some time after the diorite cooled, was uplifted, and then eroded. (geological rock hammer head for scale).

Figure 8.2.1b Rip-up clasts of shale embedded in Gabriola Formation sandstone, Gabriola Island, B.C. The pieces of shale were eroded as the sandstone was deposited, so the shale is older than the sandstone.

The **principle of cross-cutting relationships** states that any geological feature that cuts across, or disrupts another feature must be younger than the feature that is disrupted. An example of this is given in Figure 8.2.2, which shows three different sedimentary layers. The lower sandstone layer is disrupted by two **faults**, so we can conclude that the faults are younger than that layer. But the faults do not appear to continue into the coal seam, and they certainly do not continue into the upper sandstone. So we can infer that coal seam is younger than the faults (because it cuts them off), and of course the upper sandstone is youngest of all, because it lies on top of the coal seam.

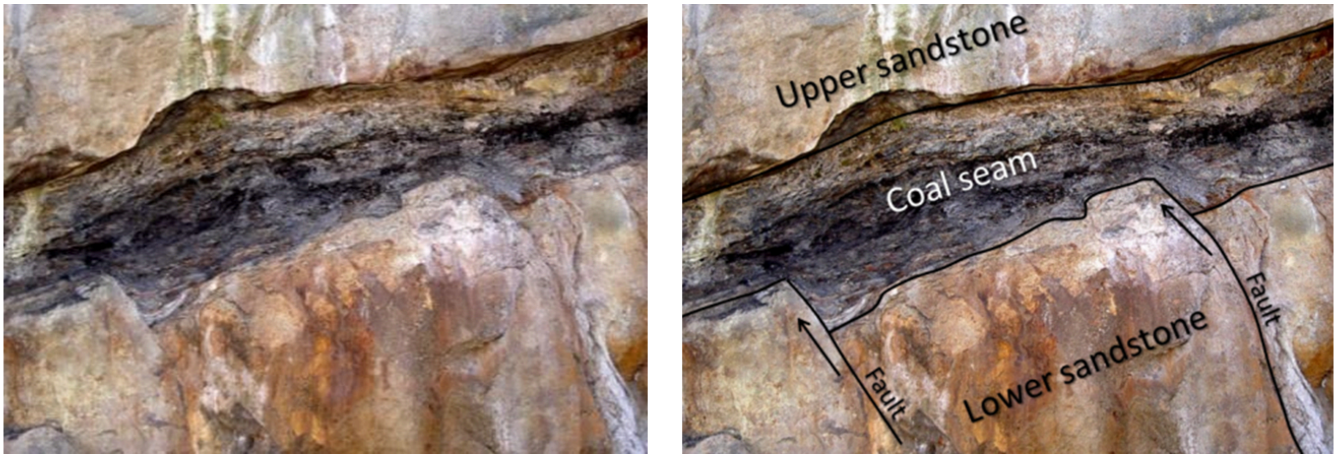

Figure 8.2.2 Superposition and cross-cutting relationships in Cretaceous Nanaimo Group rocks in Nanaimo, B.C. The coal seam is about 50 centimetres thick. The sequence of events is as follows: a) deposition of lower sandstone, b) faulting of lower sandstone, c) deposition of coal seam and d) deposition of upper sandstone.

Exercise 8.1 Cross-Cutting Relationships

Figure 8.2.3

The outcrop shown here (at Horseshoe Bay, B.C.) has three main rock types:

1. Buff/pink felsic intrusive igneous rock present as somewhat irregular masses trending from lower right to upper left
2. Dark grey metamorphosed basalt
3. A 50 centimetres wide light-grey felsic intrusive igneous dyke extending from the lower left to the middle right – offset in several places

Using the principle of cross-cutting relationships outlined above, determine the relative ages of these three rock types.

(The near-vertical stripes are blasting drill holes. The image is about 7 metres across.)

See Appendix 3 for Exercise 8.1 answers.

An **unconformity** represents an interruption in the process of deposition of sedimentary rocks. Recognizing unconformities is important for understanding time relationships in sedimentary sequences. An example of an unconformity is shown in Figure 8.2.4. The Proterozoic rocks of the Grand Canyon Group have been tilted and then eroded to a flat surface prior to deposition of the younger Paleozoic rocks. The difference in time between the youngest of the Proterozoic rocks and the oldest of the Paleozoic rocks is close to 300 million years. Tilting and erosion of the older rocks took place during this time, and if there was any deposition going on in this area, the evidence of it is now gone.

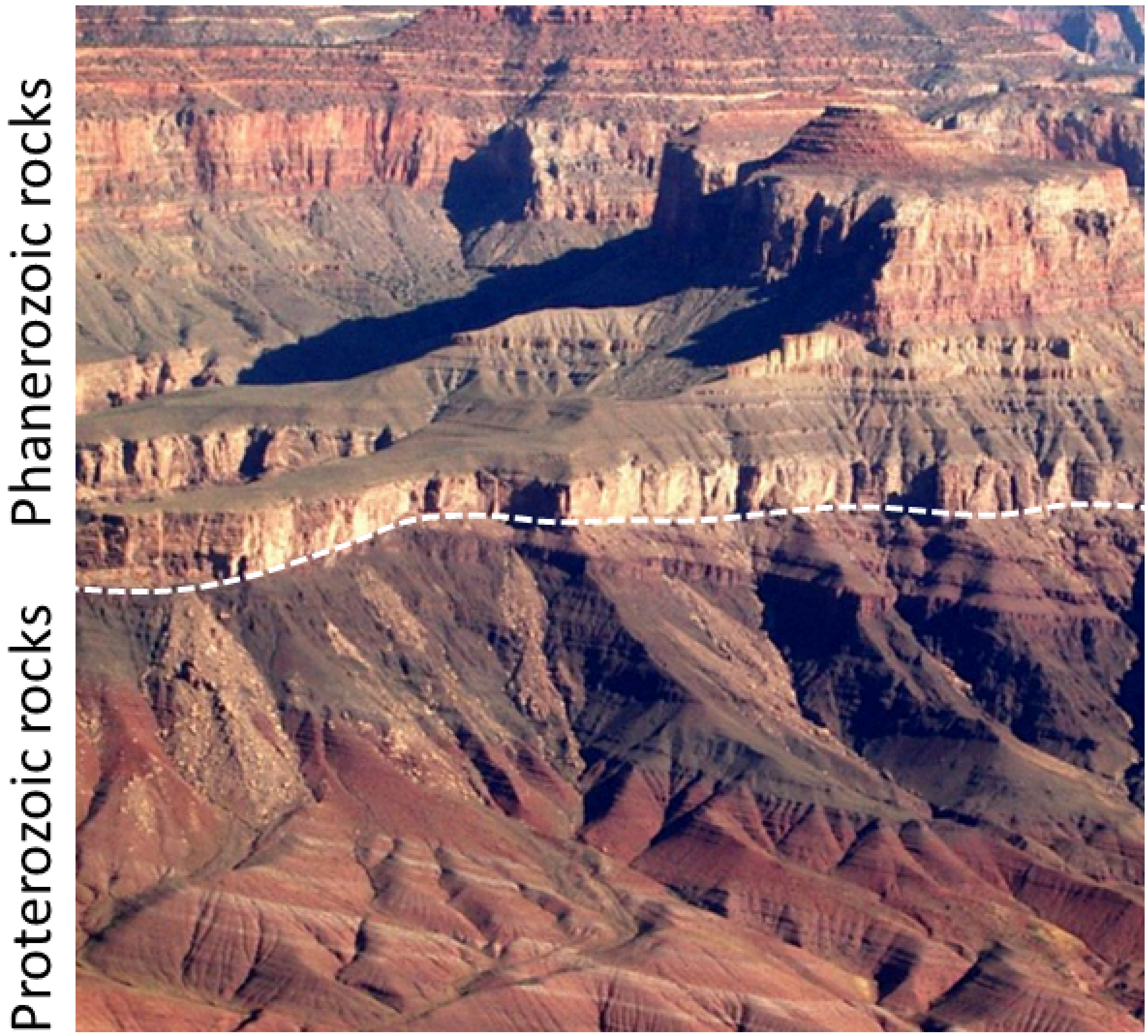

Figure 8.2.4 The great angular unconformity in the Grand Canyon, Arizona. The tilted rocks at the bottom are part of the Proterozoic Grand Canyon Group (aged 825 to 1,250 Ma). The flat-lying rocks at the top are Paleozoic (540 to 250 Ma). The boundary between the two represents a time gap of nearly 300 million years.

There are four types of unconformities, as summarized in Table 8.1, and illustrated in Figure 8.2.5.

Table 8.1 The characteristics of the four types of unconformities

Unconformity Type	Description
Nonconformity	A boundary between non-sedimentary rocks (below) and sedimentary rocks (above)
Angular unconformity	A boundary between two sequences of sedimentary rocks where the underlying ones have been tilted (or folded) and eroded prior to the deposition of the younger ones (as in Figure 8.2.4)
Disconformity	A boundary between two sequences of sedimentary rocks where the underlying ones have been eroded (but not tilted) prior to the deposition of the younger ones (as in Figure 8.2.2)
Paraconformity	A time gap in a sequence of sedimentary rocks that does not show up as an angular unconformity or a disconformity

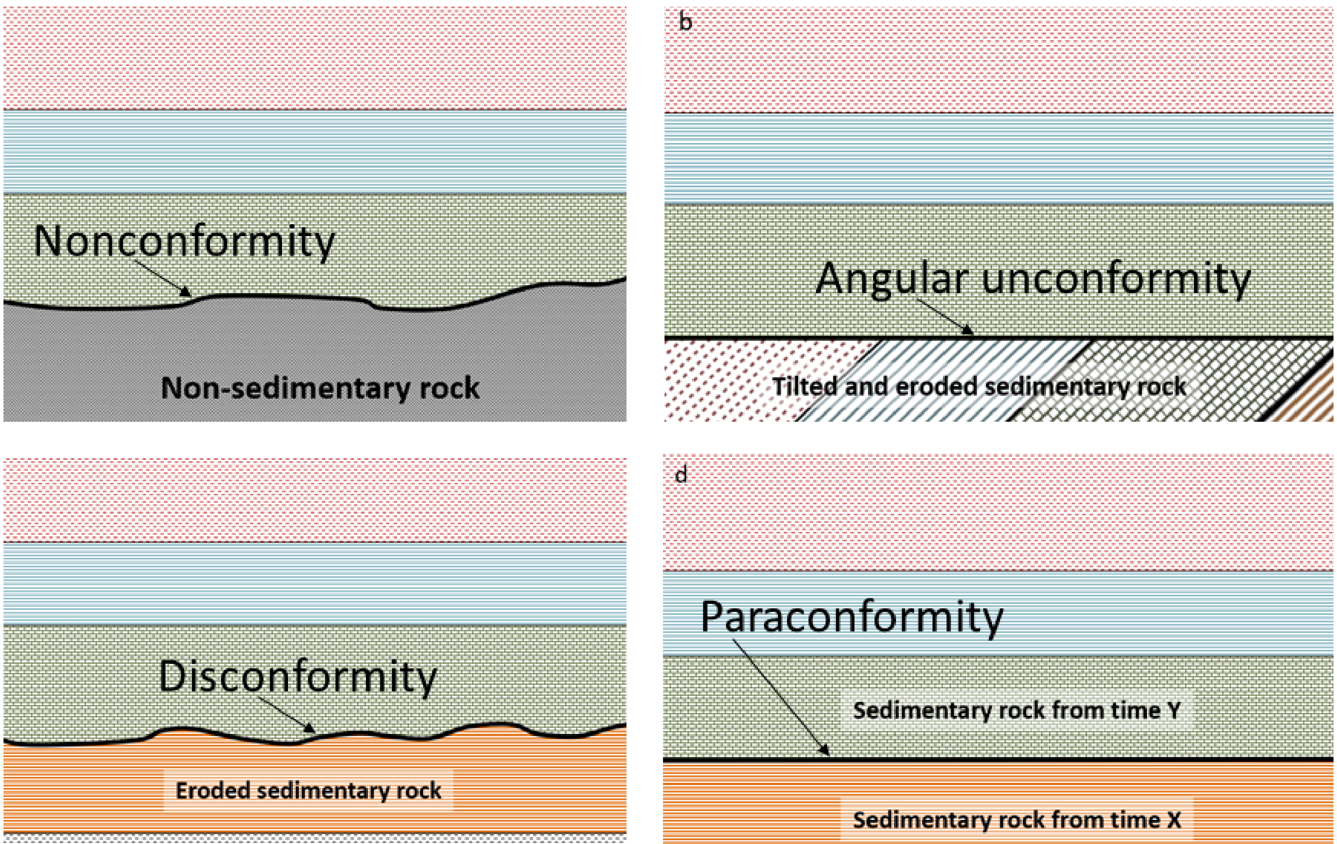

Figure 8.2.5 The four types of unconformities: (a) a nonconformity between older non-sedimentary rock and sedimentary rock, (b) an angular unconformity, (c) a disconformity between layers of sedimentary rock, where the older rock has been eroded but not tilted, and (d) a paraconformity where there is a long period (typically millions of years) of non-deposition between two parallel layers.

Media Attributions

- Figures 8.2.1ab, 8.2.2, 8.2.3, 8.2.4, 8.2.5:

8.3 Dating Rocks Using Fossils

Geologists get a wide range of information from fossils. They help us to understand evolution and life in general; they provide critical information for understanding depositional environments and changes in Earth's climate; and, of course, they can be used to date rocks.

Although the recognition of fossils goes back hundreds of years, the systematic cataloguing and assignment of relative ages to different organisms from the distant past—paleontology—only dates back to the earliest part of the 19th century. The oldest undisputed fossils are from rocks dated around 3.5 Ga, and although fossils this old are tiny, typically poorly preserved and are not useful for dating rocks, they can still provide important information about conditions at the time. The oldest well-understood fossils are from rocks dating back to around 600 Ma, and the sedimentary record from that time forward is rich in fossil remains that provide a detailed record of the history and evolution of life on Earth. However, as anyone who has gone hunting for fossils knows, that does not mean that all sedimentary rocks have visible fossils, or that they are easy to find. Fossils alone cannot provide us with numerical ages of rocks, but over the past century geologists have acquired enough isotopic dates from rocks associated with fossil-bearing rocks (such as igneous dykes cutting through sedimentary layers, or volcanic layers between sedimentary layers) to be able to put specific time limits on most fossils.

A very selective history of life on Earth over the past 600 million years is provided in Figure 8.3.1. The major groups of organisms that we are familiar with evolved between the late Proterozoic and the Cambrian (approximately 600 to 520 Ma). Plants, which evolved in the oceans as green algae, came onto land during the Ordovician (approximately 450 Ma). Insects, which evolved from marine arthropods, came onto land during the Devonian (400 Ma), and amphibians (i.e., vertebrates) came onto land about 50 million years later. By the late Carboniferous, trees had evolved from earlier plants, and reptiles had evolved from amphibians. By the mid-Triassic, dinosaurs and mammals had evolved from very different branches of the reptiles; birds evolved from dinosaurs during the Jurassic. Flowering plants evolved in the late Jurassic or early Cretaceous. The earliest primates evolved from other mammals in the early Paleogene, and the genus *Homo* evolved during the late Neogene (roughly 2.8 Ma).

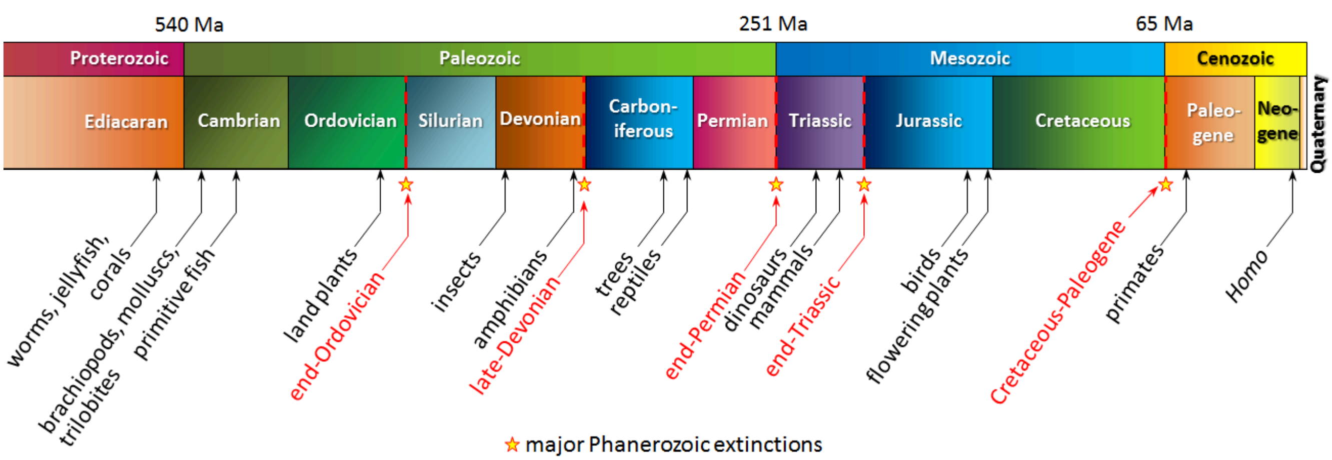

Figure 8.3.1 A summary of life on Earth during the late Proterozoic and the Phanerozoic. The top row shows geological eras, and the lower row shows the periods. [Image Description]

If we understand the sequence of evolution on Earth, we can apply knowledge to determining the relative ages of rocks. This is William Smith's principle of faunal succession, although of course it doesn't just apply to "fauna" (animals); it can also apply to fossils of plants and those of simple organisms.

The Phanerozoic has seen five major extinctions, as indicated in Figure 8.3.1. The most significant of these was at the end of the Permian, which saw the extinction of over 80% of all species and over 90% of all marine species. Most well-known types of organisms were decimated by this event, but only a few became completely extinct, including trilobites. The second most significant extinction was at the Cretaceous-Paleogene boundary (K-Pg, a.k.a. the K-T extinction). At that time, about 75% of marine species disappeared. Again, a few well-known types of organisms disappeared altogether, including the dinosaurs (but not birds) and the pterosaurs. Many other types were badly decimated by that event but survived, and then flourished in the Paleogene. The K-Pg extinction is thought to have been caused by the impact of a large extraterrestrial body (10 to 15 kilometres across), but it is generally agreed that the other four Phanerozoic extinctions had other causes, although their exact nature is not clearly understood.

As already stated, it is no coincidence that the major extinctions all coincide with boundaries of geological periods and even eras. Geologists have placed most of the divisions of the geological time scale at points in the fossil record where there are major changes in the type of organisms observed, and most of these correspond with minor or major extinctions.

If we can identify a fossil to the species level, or at least to the genus level, and we know the time period when the organism lived, we can assign a range of time to the rock. That range might be several million years because some organisms survived for a very long time. If the rock we are studying has several types of fossils in it, and we can assign time ranges to several of them, we might be able to narrow the time range for the age of the rock considerably. An example of this is given in Figure 8.3.2.

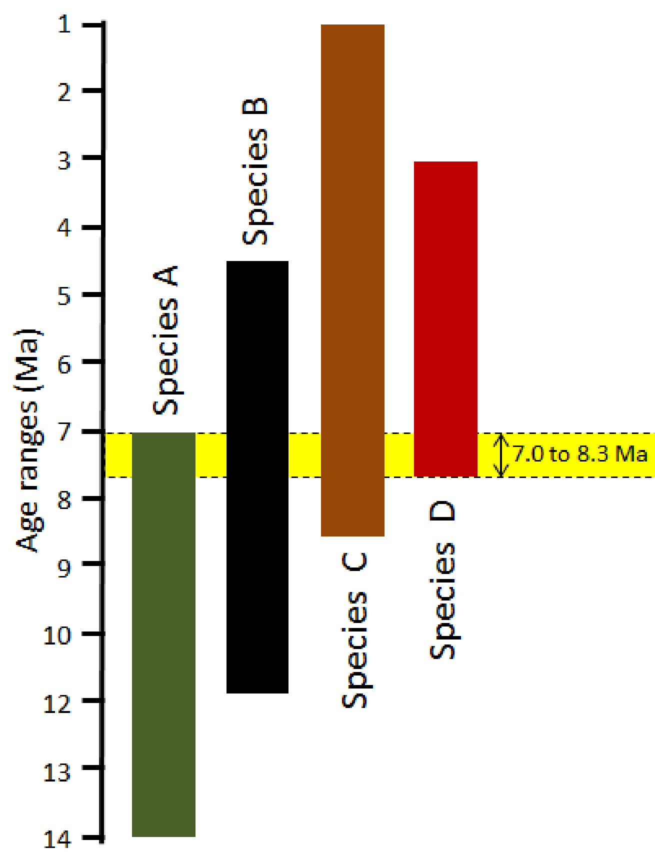

Figure 8.3.2 The application of bracketing to constrain the age of a rock based on several fossils. In this diagram, the coloured bars represent the time range during which each of the four species (A, B, C, D) existed on Earth. Although each species lived for several million years, we can narrow down the likely age of the rock to just 700,000 years during which all four species coexisted.

Some organisms survived for a very long time, and are not particularly useful for dating rocks. Sharks, for example, have been around for over 400 million years, and the great white shark has survived for 16 million years, so far. Organisms that lived for relatively short time periods are particularly useful for dating rocks, especially if they were distributed over a wide geographic area and so can be used to compare rocks from different regions. These are known as **index fossils**. There is no specific limit on how short the time span has to be to qualify as an index fossil. Some lived for millions of years, and others for much less than a million years.

Some well-studied groups of organisms qualify as **biozone** fossils because, although the genera and families lived over a long time, each species lived for a relatively short time and can be easily distinguished from others on the basis of specific features. For example, ammonites have a distinctive feature known as the **suture** line—where the internal shell layers that separate the individual chambers (**septae**) meet the outer shell wall, as shown in Figure 8.3.3. These suture lines are sufficiently variable to identify species that can be used to estimate the relative or absolute ages of the rocks in which they are found.

Figure 8.3.3 The septum of an ammonite (white part, left), and the suture lines where the septae meet the outer shell (right).

Foraminifera (small, carbonate-shelled marine organisms that originated during the Triassic and are still around today) are also useful biozone fossils. As shown in Figure 8.3.4, numerous different foraminifera lived during the Cretaceous. Some lasted for over 10 million years, but others for less than 1 million years. If the foraminifera in a rock can be identified to the species level, we can get a good idea of its age.

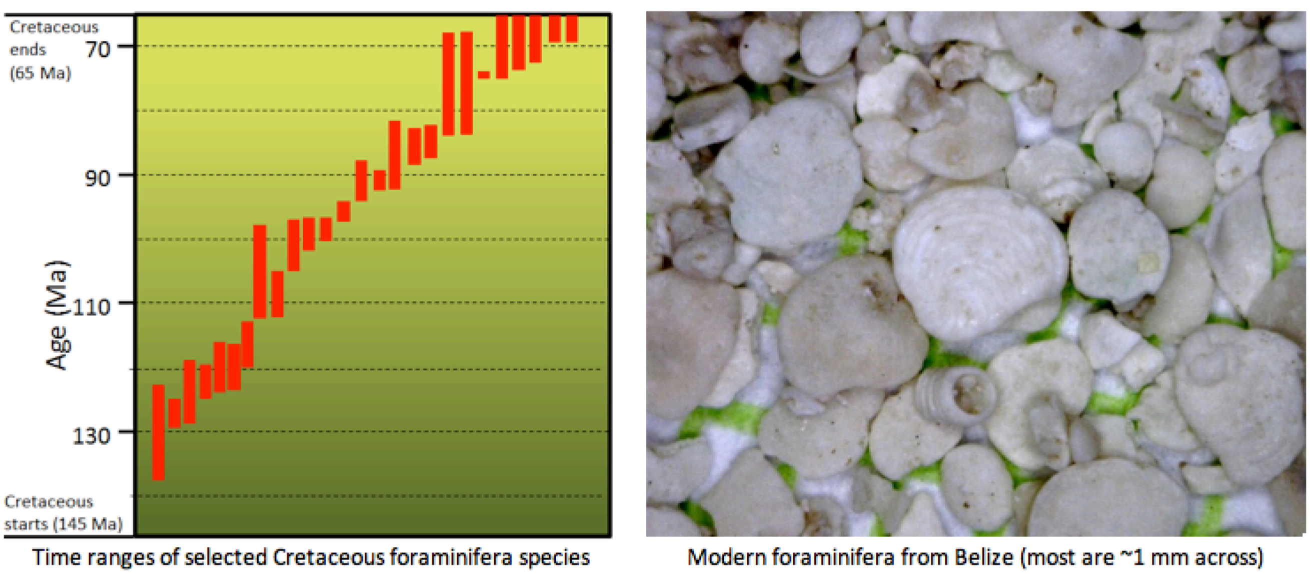

Figure 8.3.4 Time ranges for Cretaceous foraminifera (left). Modern foraminifera from the Ambergris area of Belize (right).

Exercise 8.2 Dating rocks using index fossils

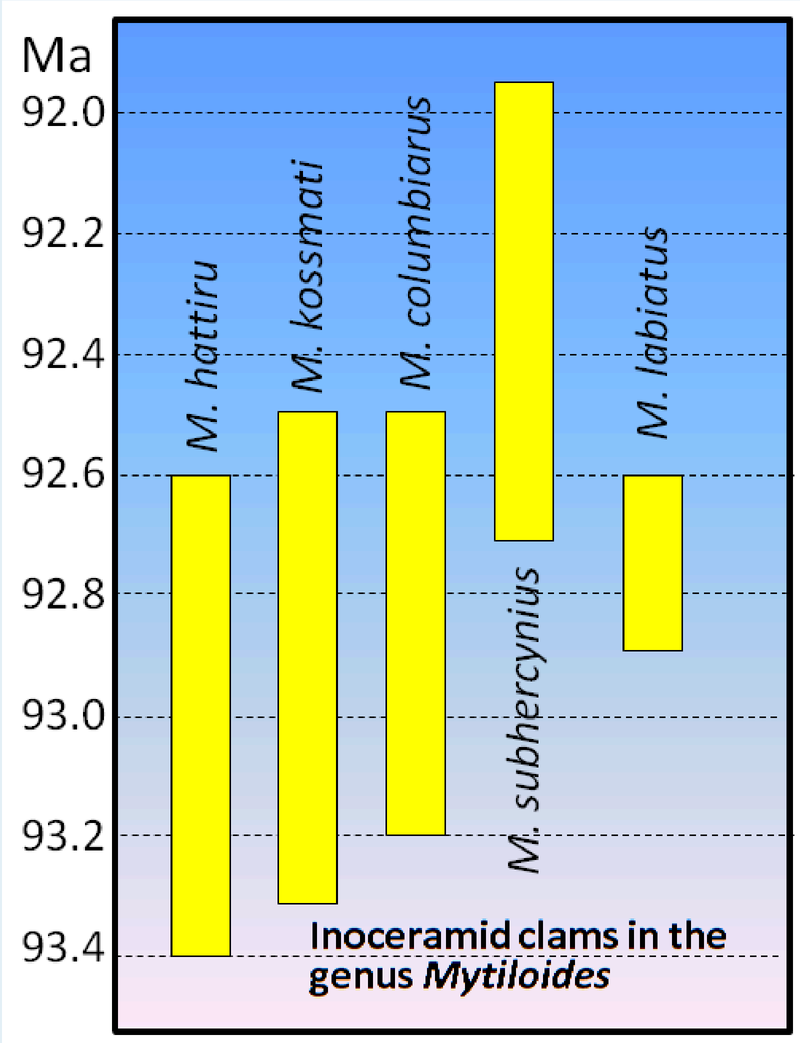

Figure 8.3.5 shows the age ranges for some late Cretaceous inoceramid clams in the genus Mytiloides:

Figure 8.3.5 shows the age ranges for some late Cretaceous inoceramid clams in the genus *Mytiloides:*

- *M. hattiru*, 93.4 to 92.6 Ma
- *M. kossmati*, 93.3 to 92.5 Ma
- *M. columbiarus*, 93.2 to 92.5 Ma
- *M. subhercynius*, 92.7 to 91.9 Ma
- *M. labiatus*, 92.9 to 92.6 Ma

Using the bracketing method described above, determine the possible age range of the rock that these five organisms were found in.

How would that change if *M. subhercynius* was not present in these rocks?

See Appendix 3 for Exercise 8.2 answers.

Image Descriptions

Figure 8.3.1 image description: Life on earth during the late Proterozoic and the Phanerozoic.

Eon	Ero	Period	Life on Earth
Proterozoic		Ediacaran	Worms, jellyfish, corals
Phanerozoic	Paleozoic (540 to 251 Ma)	Cambrian	Brachiopods, molluscs, trilobites, primitive fish
Phanerozoic	Paleozoic (540 to 251 Ma)	Ordovician	Land plants, the period ends with a major extinction
Phanerozoic	Paleozoic (540 to 251 Ma)	Silurian	
Phanerozoic	Paleozoic (540 to 251 Ma)	Devonian	Insects, amphibians, the period ends with a major extinction
Phanerozoic	Paleozoic (540 to 251 Ma)	Carboniferous	Trees, reptiles
Phanerozoic	Paleozoic (540 to 251 Ma)	Permian	The period ends with a major extinction
Phanerozoic	Mesozoic (251 to 65 Ma)	Triassic	Dinosaurs, mammals, the period ends with a major extinction
Phanerozoic	Mesozoic (251 to 65 Ma)	Jurrassic	Birds, flowering plants
Phanerozoic	Mesozoic (251 to 65 Ma)	Cretaceous	The period ends with a major extinction
Phanerozoic	Cenozoic, (65 Ma to present)	Paleogene	Primates
Phanerozoic	Cenozoic, (65 Ma to present)	Neogene	*Homo*
Phanerozoic	Cenozoic, (65 Ma to present)	Quaternary	

[Return to Figure 8.3.1]

Media Attributions

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- Figure 8.3.4 (left): © Steven Earle. CC BY. Based on data in R. Scott, 2014, "A Cretaceous chronostratigraphic database: construction and applications," *Carnets de Géologie,* Vol. 14.
- Figure 8.3.5: © Steven Earle. CC BY. Based on data at obtained from Lower Turonian Euramerican Inoceramidae: A morphologic, taxonomic, and biostratigraphic overview.

8.4 Isotopic Dating Methods

Originally fossils only provided us with relative ages because, although early paleontologists understood biological succession, they did not know the absolute ages of the different organisms. It was only in the early part of the 20th century, when isotopic dating methods were first applied, that it became possible to discover the absolute ages of the rocks containing fossils. In most cases, we cannot use isotopic techniques to directly date fossils or the sedimentary rocks they are found in, but we can constrain their ages by dating igneous rocks that cut across sedimentary rocks, or volcanic layers that lie within sedimentary layers.

Isotopic dating of rocks, or the minerals in them, is based on the fact that we know the decay rates of certain unstable **isotopes** of elements and that these rates have been constant over geological time. It is also based on the premise that when the atoms of an element decay within a mineral or a rock, they stay there and don't escape to the surrounding rock, water, or air. One of the isotope pairs widely used in geology is the decay of ^{40}K to ^{40}Ar (potassium-40 to argon-40). ^{40}K is a radioactive isotope of potassium that is present in very small amounts in all minerals that have potassium in them. It has a half-life of 1.3 billion years, meaning that over a period of 1.3 Ga one-half of the ^{40}K atoms in a mineral or rock will decay to ^{40}Ar, and over the next 1.3 Ga one-half of the remaining atoms will decay, and so on (Figure 8.4.1).

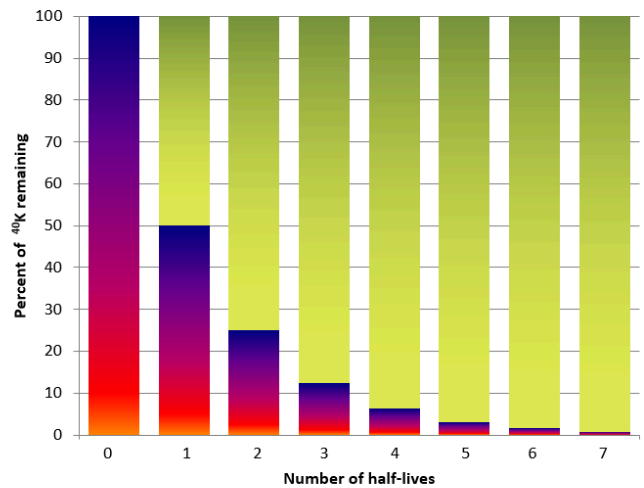

Figure 8.4.1 The decay of ^{40}K over time. Each half-life is 1.3 billion years, so after 3.9 billion years (three half-lives) 12.5% of the original ^{40}K will remain. The red-blue bars represent ^{40}K and the green-yellow bars represent ^{40}Ar. [Image Description]

In order to use the K-Ar dating technique, we need to have an igneous or metamorphic rock that includes a potassium-bearing mineral. One good example is granite, which normally has some potassium feldspar (Figure 8.4.2). Feldspar does not have any argon in it when it forms. Over time, the ^{40}K in the feldspar decays to ^{40}Ar. Argon is a gas and the atoms of ^{40}Ar remain embedded within the crystal, unless the rock is subjected to high temperatures after it forms. The sample must be analyzed using a very sensitive mass-spectrometer, which can detect the differences between the masses of atoms, and can therefore distinguish between ^{40}K and the much more abundant ^{39}K. Biotite and hornblende are also commonly used for K-Ar dating.

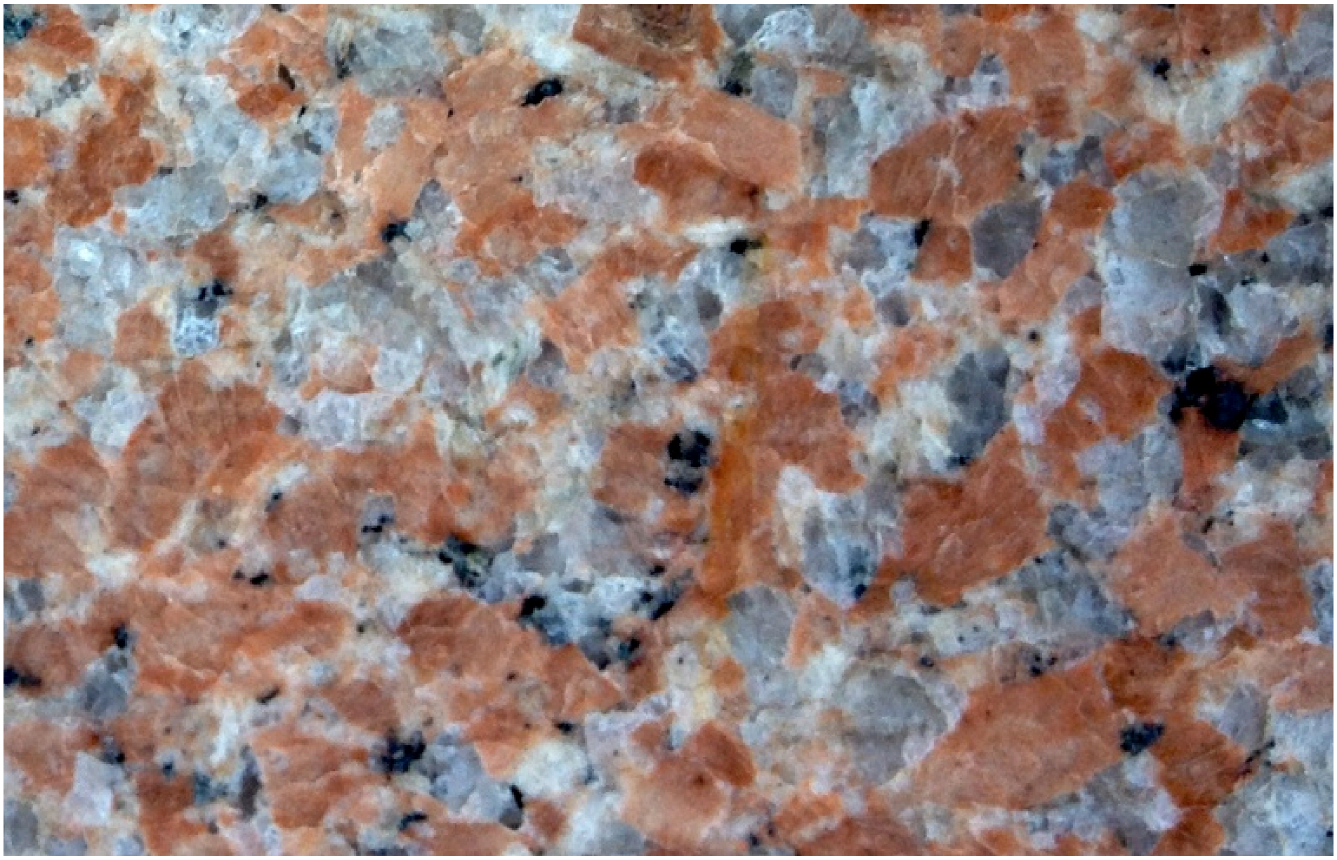

Figure 8.4.2 Crystals of potassium feldspar (pink) in a granitic rock are candidates for isotopic dating using the K-Ar method because they contained potassium and no argon when they formed.

Why can't we use isotopic dating techniques to accurately date sedimentary rocks?

Figure 8.4.3

An important assumption that we have to be able to make when using isotopic dating is that when the rock formed none of the daughter isotope was present (e.g., ^{40}Ar in the case of the K-Ar method). A clastic sedimentary rock is made up of older rock and mineral fragments, and when the rock forms it is almost certain that all of the fragments already have daughter isotopes in them. Furthermore, in almost all cases, the fragments have come from a range of source rocks that all formed at different times. If we dated a number of individual grains in the sedimentary rock, we would likely get a range of different dates, all older than the age of the rock. That could be useful information, but it would not provide an accurate date for the rock in question.

It might be possible to directly date some chemical sedimentary rocks isotopically, but there are no useful isotopes that can be used on old chemical sedimentary rocks. Radiocarbon dating can be used on sediments or sedimentary rocks that contain carbon, but it cannot be used on materials older than about 60 ka.

K-Ar is just one of many isotope-pairs that are useful for dating geological materials. Some of the other important pairs are listed in Table 8.2, along with the age ranges that they apply to and some comments on their applications. When radiometric techniques are applied to metamorphic rocks, the results normally tell us the date of metamorphism, not the date when the parent rock formed.

Table 8.2 A few of the isotope systems that are widely used for dating geological materials

[Skip Table]

Isotope System	**Half-Life**	**Useful Range**	**Comments**
Potassium-argon	1.3 Ga	10 Ka to 4.57 Ga	Widely applicable because most rocks have some potassium
Uranium-lead	4.5 Ga	1 Ma to 4.57 Ga	The rock must have uranium-bearing minerals, but most have enough.
Rubidium-strontium	47 Ga	10 Ma to 4.57 Ga	Less precision than other methods at old dates
Carbon-nitrogen (a.k.a. radiocarbon dating)	5,730 years	100 to 60,000 years	Sample must contain wood, bone, or carbonate minerals; can be applied to young sediments

Exercise 8.3 Isotopic dating

Assume that a feldspar crystal from the granite shown in Figure 8.4.2 was analyzed for ^{40}K and ^{40}Ar. The proportion of ^{40}K remaining is 0.91. Using the decay curve shown on the graph below, estimate the age of the rock.

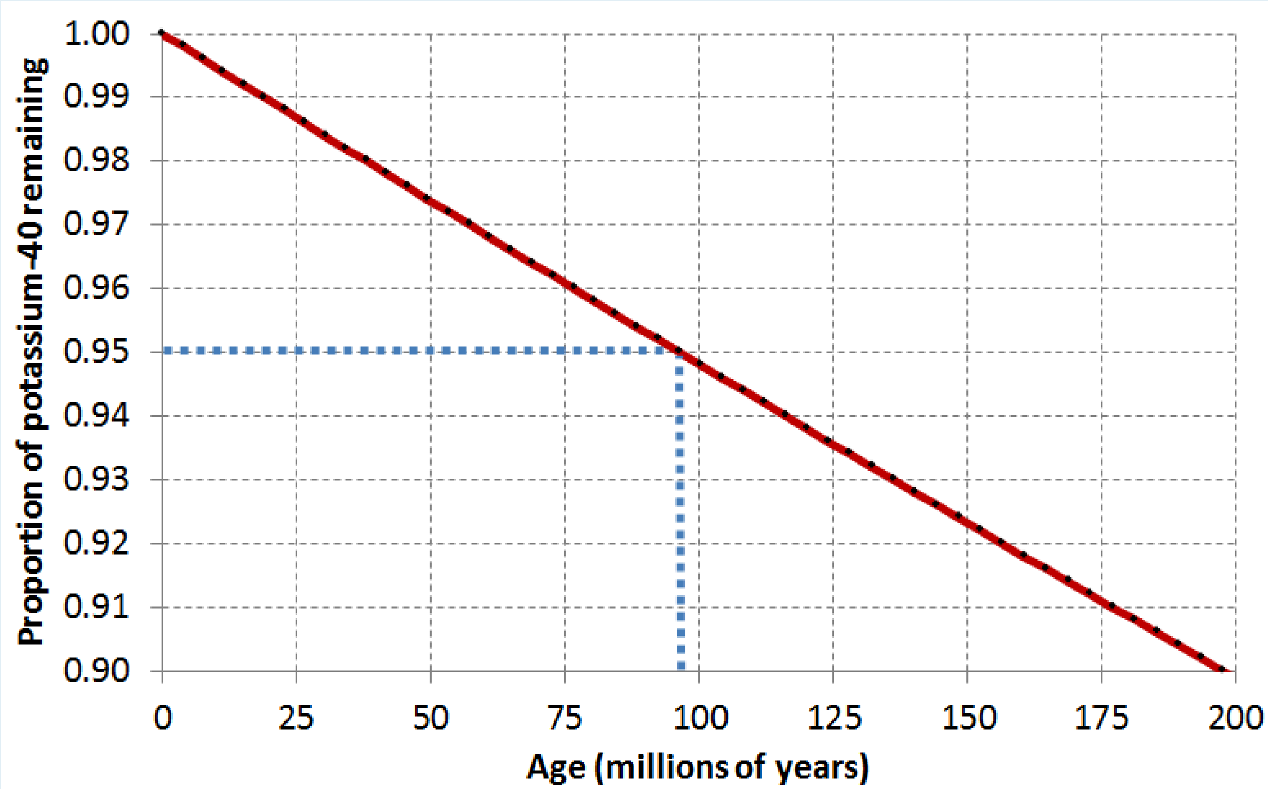

Figure 8.4.4 [Image Description]

An example is provided (in blue) for a ^{40}K proportion of 0.95, which is equivalent to an age of approximately 96 Ma. This is determined by drawing a horizontal line from 0.95 to the decay curve line, and then a vertical line from there to the time axis.

See Appendix 3 for Exercise 8.3 answers.

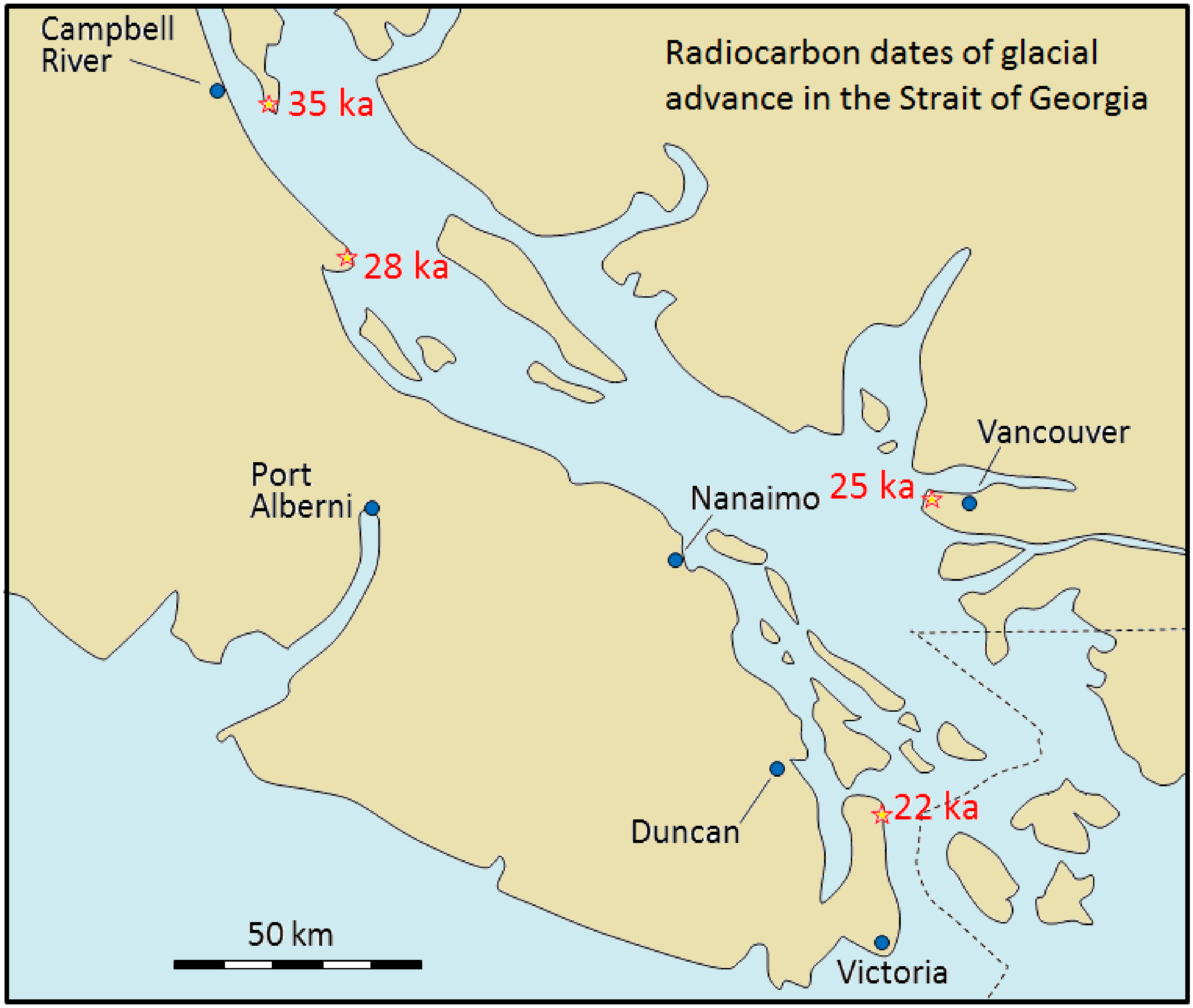

Figure 8.4.5 Radiocarbon dates on wood fragments in glacial sediments in the Strait of Georgia.

Radiocarbon dating (using ^{14}C) can be applied to many geological materials, including sediments and sedimentary rocks, but the materials in question must be younger than 60 ka. Fragments of wood incorporated into young sediments are good candidates for carbon dating, and this technique has been used widely in studies involving late Pleistocene glaciers and glacial sediments. An example is shown in Figure 8.4.5; radiocarbon dates from wood fragments in glacial sediments have been used to estimate the timing of the last glacial advance along the Strait of Georgia. It is evident that the ice-front of the major glacier that occupied the Strait of Georgia was near to Campbell River at around 35 ka, near to Nanaimo and Vancouver at about 25 ka, and had reached the Victoria area by around 22 ka.

Over the past decade there has been increasing use of U-Pb dating to study sedimentary rocks, not necessarily to find out the age of the rock, but to discover something about its history and origins. All clastic sedimentary rocks contain some tiny clasts of the silicate mineral zircon ($ZrSiO_4$), derived from the weathering of the sediment parent rocks. Zircon always has some uranium in it (but no lead) so it is a good candidate for U-Pb dating, and it isn't too difficult to separate the grains of zircon from the other grains in a sandstone. The procedure is to isolate a few hundred tiny zircons from a rock sample, and then carry out U-Pb dating on each one of them. An example of the types of results obtained are shown on Figure 8.5.6. All of the samples are from Nanaimo Gp. rocks on Vancouver Island and nearby Salt Spring Island.

The three samples from Vancouver Island have zircons aged around 90 Ma, 118 Ma and 150 Ma. The Salt Spring Island sample has some zircons aged around 150 Ma, but most are much older, at 200 Ma and 340 to 360 Ma. It is interpreted that the younger zircons (90 to 150 Ma) are mostly derived from granitic rocks in the Coast Range, while the older ones (>200 Ma) are from older rocks on Vancouver Island (Huang, 2018).

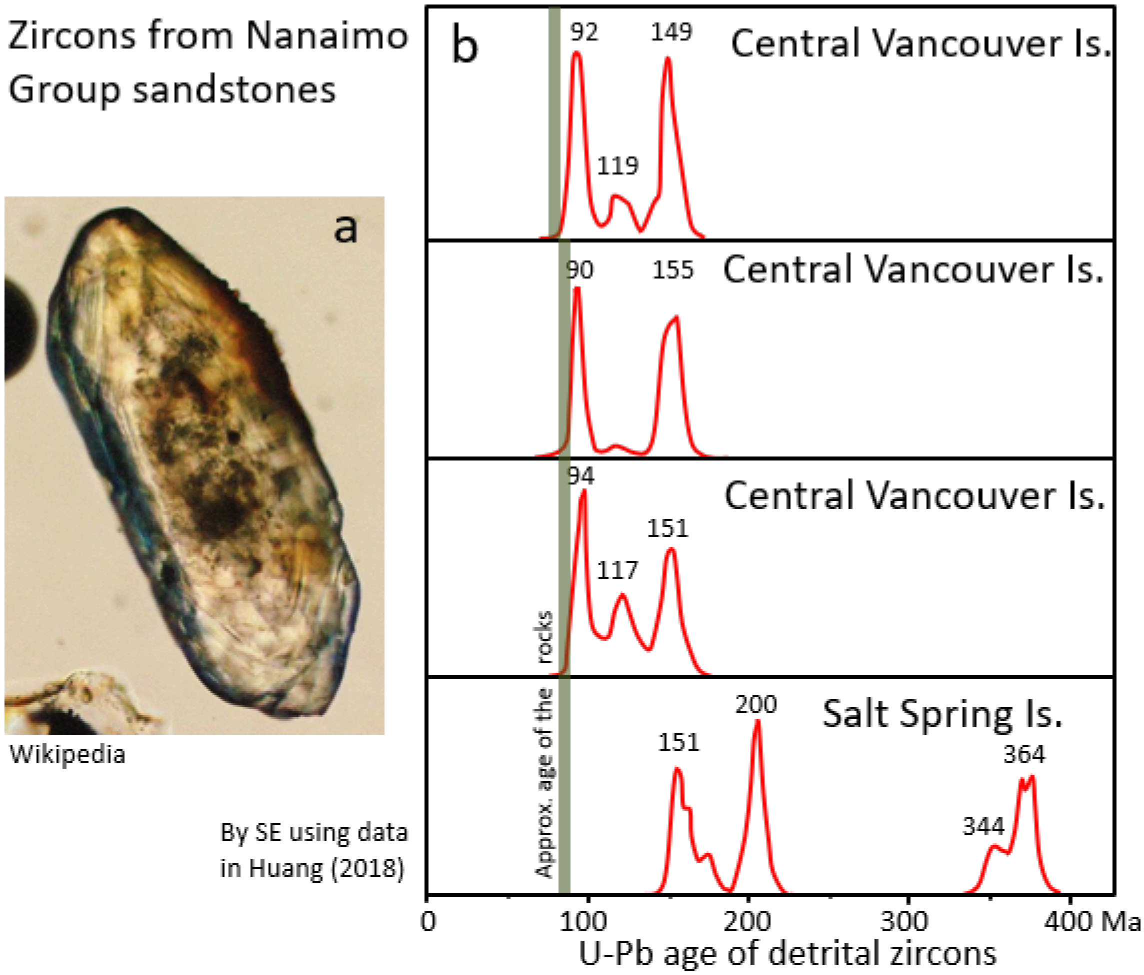

Figure 8.4.6 U-Pb dates for zircon samples from the Nanaimo Gp. (after Krause, 2018) a: a typical zircon clast (this one is about 1/4 mm long). b: plots of zircon ages for 4 sandstone samples.

Image Descriptions

Figure 8.4.1 image description: Decay of 40K over time.

Number of half-lives	Percent of 40K remaining	Percent of 40Ar
0	100	0
1	50	50
2	25	75
3	12.5	87.5
4	6.25	93.75
5	3.125	96.875
6	1.5625	98.4375
7	0.78125	99.21875

[Return to Figure 8.4.1]

Figure 8.4.4 image description: isotopic dating graph

Proportion of Potassium-40 remaining	Age (in millions of Years)
1.00	0
0.99	19
0.98	37
0.97	55
0.96	75
0.95	96
0.94	114
0.93	134
0.92	156
0.91	175
0.90	194

[Return to Figure 8.4.4]

Media Attributions

8.5 Other Dating Methods

There are numerous other techniques for dating geological materials, but we will examine just two of them here: tree-ring dating (i.e., dendrochronology) and dating based on the record of reversals of Earth's magnetic field.

Dendrochronology can be applied to dating very young geological materials based on reference records of tree-ring growth going back many millennia. The longest such records can take us back to 25 ka, to the height of the last glaciation. One of the advantages of dendrochronology is that, providing reliable reference records are available, the technique can be used to date events to the nearest year.

Dendrochronology has been used to date the last major subduction-zone earthquake on the coast of B.C., Washington, and Oregon. When large earthquakes strike in this setting, there is a tendency for some coastal areas to subside by one or two metres. Seawater then rushes in, flooding coastal flats and killing trees and other vegetation within a few months. There are at least four locations along the coast of Washington that have such dead trees (and probably many more in other areas). Wood samples from these trees have been studied and the ring patterns have been compared with patterns from old living trees in the region (Figure 8.5.1).

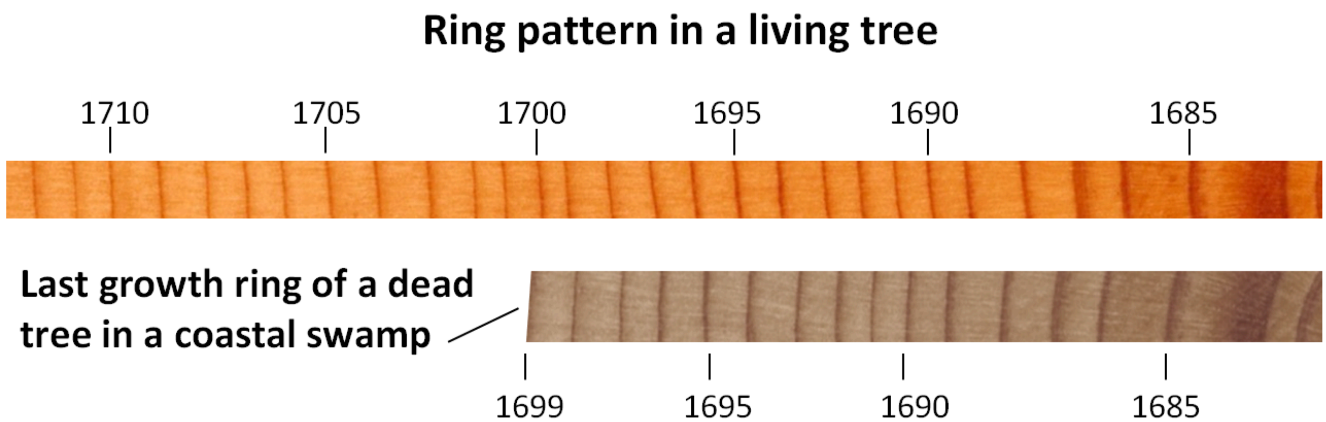

Figure 8.25.1 Example of tree-ring dating of dead trees.

At all of the locations studied, the trees were found to have died either in the year 1699, or very shortly thereafter (Figure 8.5.2). On the basis of these results, it was concluded that a major earthquake took place in this region sometime between the end of growing season in 1699 and the beginning of the growing season in 1700. Evidence from a major tsunami that struck Japan on January 27, 1700, narrowed the timing of the earthquake to sometime in the evening of January 26, 1700. For more information, see [The 1700 Juan de Fuca Earthquake](#).

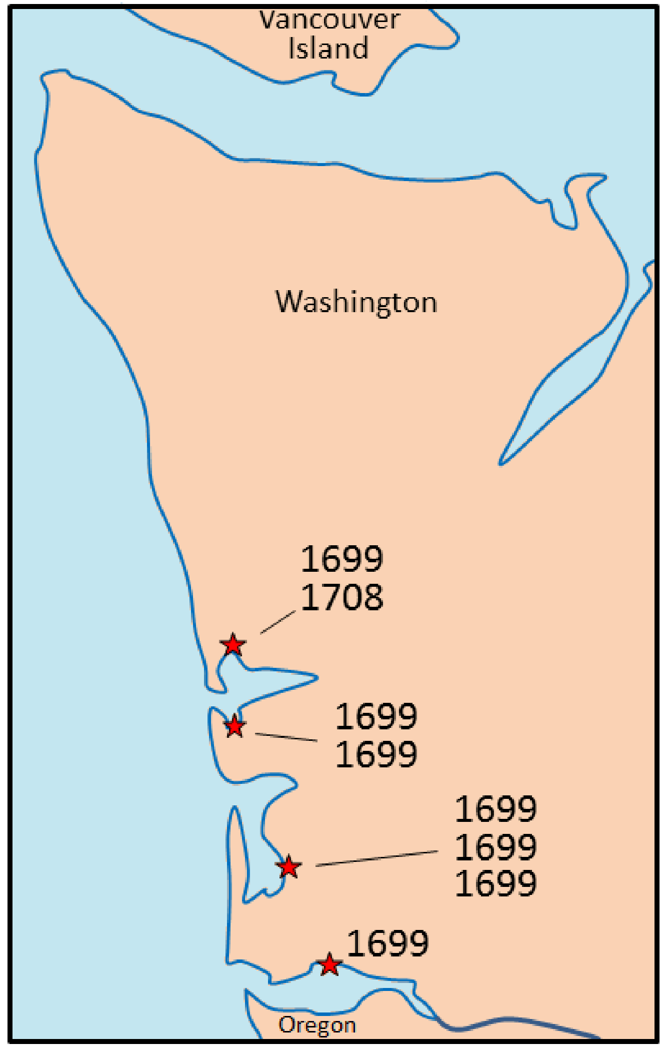

Figure 8.5.2 Sites in Washington where dead trees are present in coastal flats. The outermost wood of eight trees was dated using dendrochronology, and of these, seven died during the year 1699, suggesting that the land near to the coast was inundated by water at that time.

Changes in Earth's magnetic field can also be used to date events in geologic history. The magnetic field makes compasses point toward the North Pole, but, as we'll see in Chapter 10, this hasn't always been the case. At various times in the past, Earth's magnetic field has reversed itself completely, and during those times a compass would have pointed to the South Pole. By studying magnetism in volcanic rocks that have been dated isotopically, geologists have been able to delineate the chronology of magnetic field reversals going back to 250 Ma. About 5 million years of this record is shown in Figure 8.5.3, where the black bands represent periods of normal magnetism ("normal" meaning similar to the current magnetic field) and the white bands represent periods of reversed magnetism. These periods of consistent magnetic polarity are given names to make them easier to reference. The current normal magnetic field, known as Brunhes, has lasted for the past 780,000 years. Prior to that there was a short reversed period and then a short normal period known as Jaramillo.

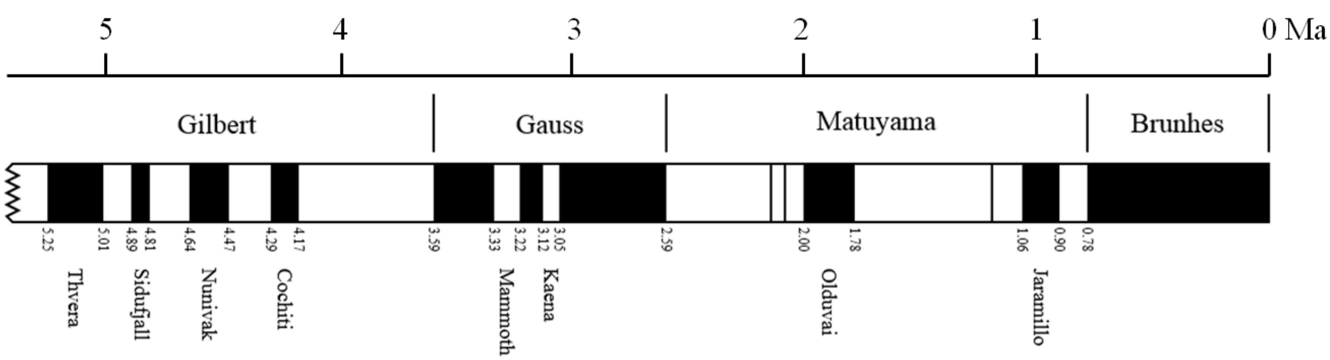

Figure 8.5.3 The last 5 Ma of magnetic field reversals.

Oceanic crust becomes magnetized by the magnetic field that exists as the crust forms from magma. As it cools, tiny crystals of magnetite that form within the magma become aligned with the existing magnetic field and then remain that way after all of the rock has hardened, as shown in Figure 8.5.4. Crust that is forming today is being magnetized in a "normal" sense, but crust that formed 780,000 to 900,000 years ago, in the interval between the Brunhes and Jaramillo normal periods, was magnetized in the "reversed" sense.

Chapter 9 has a discussion of Earth's magnetic field, including where and how it is generated and why its polarity changes periodically.

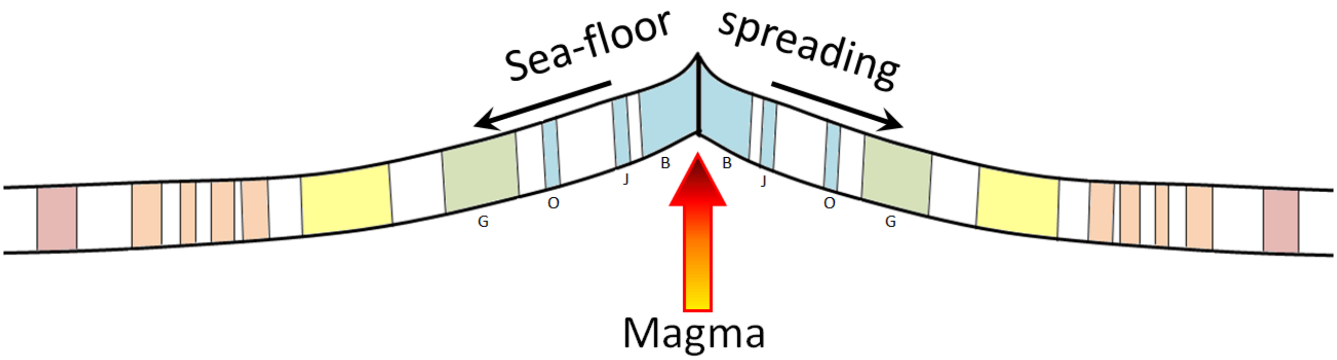

Figure 8.5.4 Depiction of the formation of magnetized oceanic crust at a spreading ridge. Coloured bars represent periods of normal magnetism, and the small capital letters denote the Brunhes, Jaramillio, Olduvai, and Gauss normal magnetic periods (see Figure 8.5.2).

Magnetic chronology can be used as a dating technique because we can measure the magnetic field of rocks using a magnetometer in a lab, or of entire regions by towing a magnetometer behind a ship or an airplane. For example, the Juan de Fuca Plate, which lies off of the west coast of B.C., Washington, and Oregon, is being and has been formed along the Juan de Fuca spreading ridge (Figure 8.5.5). The parts of the plate that are still close to the ridge have normal magnetism, while parts that are farther away (and formed much earlier) have either normal or reversed magnetism, depending on when the rock formed. By carefully matching the sea-floor magnetic stripes with the known magnetic chronology, we can determine the age at any point on the plate. We can see, for example, that the oldest part of the Juan de Fuca Plate that has not subducted (off the coast of Oregon) is just over 8 million years old, while the part that is subducting underneath Vancouver Island is between 0 and about 6 million years old.

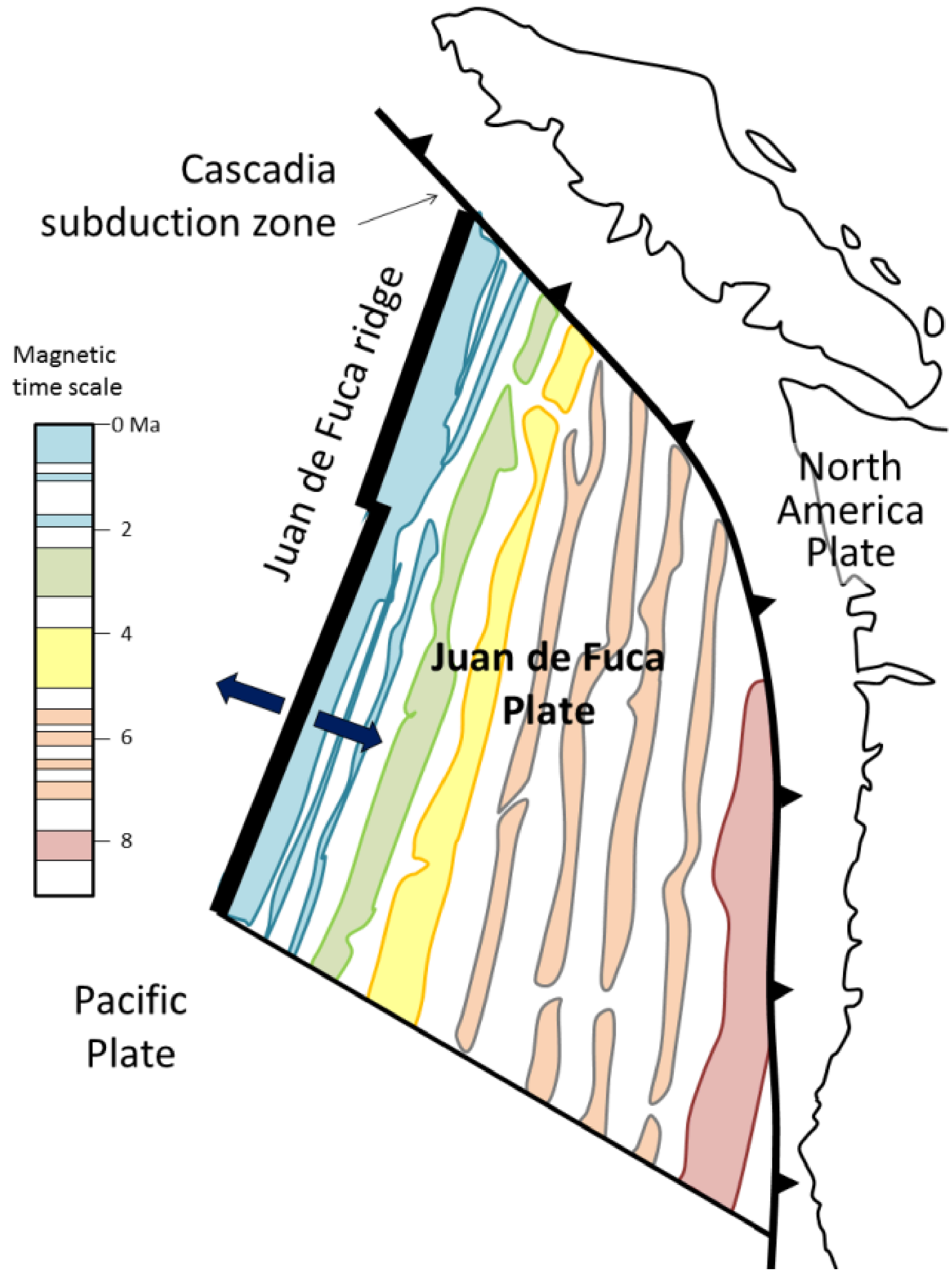

Figure 8.5.5 The pattern of magnetism within the area of the Juan de Fuca Plate, off the west coast of North America. The coloured shapes represent parts of the sea floor that have normal magnetism, and the magnetic time scale is shown using the same colours. The blue bands represent Brunhes, Jaramillo, and Olduvai; the green represents Gauss; and so on. (Note that in this diagram, sea-floor magnetism is only shown for the Juan de Fuca Plate, although similar patterns exist on the Pacific Plate.)

Exercise 8.4 Magnetic dating

The fact that magnetic intervals can only be either *normal* or *reversed* places significant limits on the applicability of magnetic dating. If we find a rock with normal magnetism, we can't know which normal magnetic interval it represents, unless we have some other information.

Using Figure 8.5.3 for reference, determine the age of a rock with normal magnetism that has been found to be between 1.5 and 2.0 Ma based on fossil evidence.

How about a rock that is limited to 2.6 to 3.2 Ma by fossils and has reversed magnetism?

See Appendix 3 for Exercise 8.4 answers.

Media Attributions

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- Figure 8.5.2: © Steven Earle. CC BY. From data in Yamaguchi, D.K., B.F. Atwater, D.E. Bunker, B.E. Benson, and M.S. Reid. 1997. Tree-ring dating the 1700 Cascadia earthquake. Nature, Vol. 389, pp. 922 – 923, 30 October 1997.
- Figure 8.5.3: "Geomagnetic polarity late Cenozoic" by the USGS. Adapted by Steven Earle. Public domain.

8.6 Understanding Geological Time

It’s one thing to know the facts about geological time—how long it is, how we measure it, how we divide it up, and what we call the various periods and epochs—but it is quite another to really understand geological time. The problem is that our lives are short and our memories are even shorter. Our experiences span only a few decades, so we really don’t have a way of knowing what 11,700 years means. What’s more, it’s hard for us to understand how 11,700 years differs from 65.5 million years, or even from 1.8 billion years. It’s not that we can’t comprehend what the numbers mean—we can all get that figured out with a bit of practice—but even if we do know the numerical meaning of 65.5 Ma, we can’t really appreciate how long ago it was.

You may be wondering why it’s so important to really “understand” geological time. There are some very good reasons. One is so that we can fully understand how geological processes that seem impossibly slow can produce anything of consequence. For example, we are familiar with the concept of driving from one major city to another: a journey of several hours at around 100 kilometres per hour. Continents move toward each other at rates of a fraction of a millimetre per day, or something in the order of 0.00000001 kilometres per hour, and yet, at this impossibly slow rate (try walking at that speed!), they can move thousands of kilometres. Sediments typically accumulate at even slower rates—less than a millimetre per year—but still they are thick enough to be thrust up into monumental mountains and carved into breathtaking canyons.

Another reason is that for our survival on this planet, we need to understand issues like extinction of endangered species and **anthropogenic** (human-caused) climate change. Some people, who don’t understand geological time, are quick to say that the climate has changed in the past, and that what is happening now is no different. And it certainly has changed in the past—many times. For example, from the Eocene (50 Ma) to the present day, Earth’s climate cooled by about 12°C. That’s a huge change that ranks up there with many of the important climate changes of the distant past, and yet the rate of change over that time was only 0.000024°C/century. Anthropogenic climate change has been 1.1°C over the past century,[1]; that is 45,800 times faster than the rate of natural climate change since the Eocene!

One way to wrap your mind around geological time is to put it into the perspective of single year, because we all know how long it is from one birthday to the next. At that rate, each hour of the year is equivalent to approximately 500,000 years, and each day is equivalent to 12.5 million years.

If all of geological time is compressed down to a single year, Earth formed on January 1, and the first life forms evolved in late March (roughly 3,500 Ma). The first large life forms appeared on November 13 (roughly 600 Ma), plants appeared on land around November 24, and amphibians on December 3. Reptiles evolved from amphibians during the first week of December and dinosaurs and early mammals evolved from reptiles by December 13, but the dinosaurs, which survived for 160 million years, were gone by Boxing Day (December 26). The Pleistocene Glaciation got started at around 6:30 p.m. on New Year’s Eve, and the last glacial ice left southern Canada by 11:59 p.m.

It’s worth repeating: on this time scale, the earliest ancestors of the animals and plants with which we are familiar did not appear on Earth until mid-November, the dinosaurs disappeared after Christmas, and most of Canada was periodically locked in ice from 6:30 to 11:59 p.m. on New Year’s Eve. As for people, the first to inhabit B.C. got here about one minute before midnight, and the first Europeans arrived about two seconds before midnight.

1. Climate change data from NASA Goddard Institute for Space Studies: http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts.txt

It is common for the popular press to refer to distant past events as being “prehistoric.” For example, dinosaurs are reported as being “prehistoric creatures,” even by the esteemed National Geographic Society.[2] The written records of our history date back to about 6,000 years ago, so anything prior to that can be considered “prehistoric.” But to call the dinosaurs prehistoric is equivalent to—and about as useful as—saying that Singapore is beyond the city limits of Kamloops! If we are going to become literate about geological time, we have to do better than calling dinosaurs, or early horses (54 Ma), or even early humans (2.8 Ma), “prehistoric.”

Exercise 8.5 What happened on your birthday?

Using the “all of geological time compressed to one year” concept, determine the geological date that is equivalent to your birthday. First go to Day Number of the Year Calculator to find out which day of the year your birth date is. Then divide that number by 365, and multiply that number by 4,570 to determine the time (in millions since the *beginning* of geological time). Finally subtract that number from 4,570 to determine the date back from the present.

For example, April Fool’s Day (April 1) is day 91 of the year: 91/365 = 0.2493. 0.2493 x 4,570 = 1,139 million years from the start of time, and 4,570 – 1,193 = 3,377 Ma is the geological date.

Finally, go to the Foundation for Global Community’s “Walk through Time” website to find out what was happening on your day. The nearest date to 3,377 Ma is 3,400 Ma. Bacteria ruled the world at 3,400 Ma, and there’s a discussion about their lifestyles.

See Appendix 3 for Exercise 8.5 answers.

2. http://science.nationalgeographic.com/science/prehistoric-world/

Summary

The topics covered in this chapter can be summarized as follows:

Section	Summary
8.1 The Geological Time Scale	The work of William Smith was critical to the establishment of the first geological time scale early in the 19th century, but it wasn't until the 20th century that geologists were able to assign reliable dates to the various time periods. Geological time is divided into eons, eras, periods, and epochs and the geological time scale is maintained and updated by the International Commission on Stratigraphy.
8.2 Relative Dating Methods	We can determine the relative ages of different rocks by observing and interpreting relationships among them, such as superposition, cross-cutting, and inclusions. Gaps in the geological record are represented by various types of unconformities.
8.3 Dating Rocks Using Fossils	Fossils are useful for dating rocks date back to about 600 Ma. If we know the age range of a fossil, we can date the rock, but some organisms lived for many millions of years. Index fossils represent shorter geological times, and if a rock has several different fossils with known age ranges, we can normally narrow the time during which the rock formed.
8.4 Isotopic Dating Methods	Radioactive isotopes decay at predictable and known rates, and can be used to date igneous and metamorphic rocks. Some of the more useful isotope systems are potassium-argon, rubidium-strontium, uranium-lead, and carbon-nitrogen. Radiocarbon dating can be applied to sediments and sedimentary rocks, but only if they are younger than 60 ka.
8.5 Other Dating Methods	There are many other methods for dating geological materials. Two that are widely used are dendrochronology and magnetic chronology. Dendrochronology, based on studies of tree rings, is widely applied to dating glacial events. Magnetic chronology is based on the known record of Earth's magnetic field reversals.
8.6 Understanding Geological Time	While knowing about geological time is relatively easy, actually comprehending the significance of the vast amounts of geological time is a great challenge. To be able to solve important geological problems and critical societal challenges, like climate change, we need to really understand geological time.

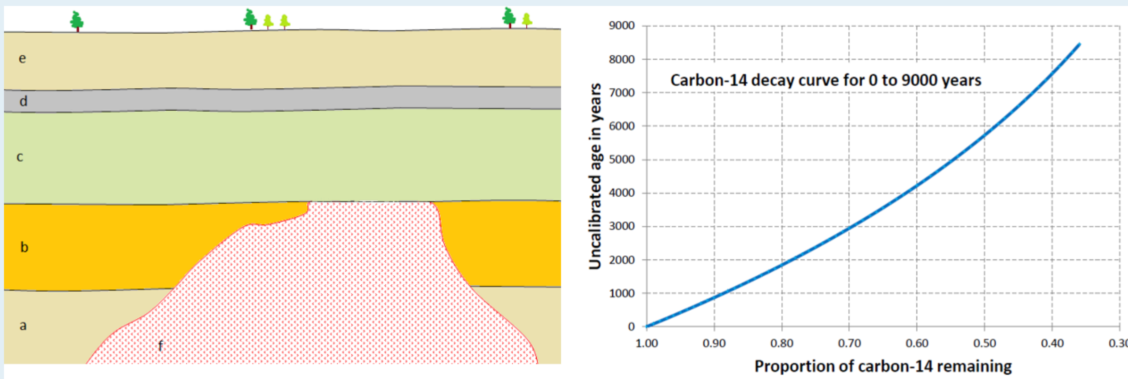
Questions for Review

Answers to Review Questions can be found in Appendix 2.

1. A granitic rock contains inclusions (xenoliths) of basalt. What can you say about the relative ages of the granite and the basalt?
2. Explain the differences between:

   1. a disconformity and a paraconformity
   2. a nonconformity and an angular unconformity

3. What are the features of a useful index fossil?
4. The bellow shows a geological cross-section. The granitic rock "f" at the bottom is the one that you estimated the age of in Exercise 8.3. A piece of wood from layer "d" has been sent for radiocarbon dating and the result was 0.55 ^{14}C remaining. How old is layer "d"? (You can use the carbon-14 decay curve of Figure 8.27 to answer this question.)



Left: Cross section through the crust for questions 4 to 7. Right: ^{14}C *decay curve for question 4.*

5. Based on your answer to question 4, what can you say about the age of layer "c" in Figure 8.27.?
6. What type of unconformity exists between layer "c" and rock "f"?
7. What about between layer "c" and layer "b"?
8. We can't use magnetic chronology to date anything younger than 780,000 years. Why not?
9. How did William Smith apply the principle of faunal succession to determine the relative ages of the sedimentary rocks of England and Wales?
10. Access a copy of the geological time scale (International Commission on Stratigraphy). What are the names of the last age (or stage) of the Cretaceous and the first age of the Paleogene? Print out the time scale and stick it on the wall above your desk!

Media Attributions

- Question 4 Figure: © Steven Earle. CC BY.