CHAPTER 6

Geologic Time and Stratigraphy

Major Concepts and Questions Addressed in This Chapter

- **A** What is the science of stratigraphy?
- **B** What are relative and absolute ages, and how are they established?
- **C** How is radiometric dating established?
- **D** How are relative and absolute ages integrated to date rocks?
- **E** How did the geologic time scale develop?
- **F** What is correlation, how is it accomplished, and what are its pitfalls?
- **G** Why can't rocks be equated with time?
- **H** How are fossils used in correlation?
- **I** How does the geographic distribution of organisms affect correlation?
- **J** How complete is the geologic record?
- **K** Why is sea-level change important?

Chapter Outline

The Grand Canyon. There is currently a great deal of debate about when the Grand Canyon formed in response to downcutting by the Colorado River as the Colorado Plateau was being uplifted. One recent estimate places the age at 70 million years ago, but this estimate has been criticized for methodological reasons. Other estimates are much younger: between about 6 and 17 million years ago. The rocks exposed along the sides of the canyon range in age from Precambrian to Permian.

6.1 Introduction

A James Hutton is said to have first grasped the enormity of geologic time at Siccar Point, Scotland, in the late 1700s (see Chapter 1). Here, it is said that Hutton realized the juxtaposition of horizontal and vertical rocks could only mean one thing: processes were acting on the planet that were not directly observable to humans because they acted so slowly as to be imperceptible and therefore Earth was incomprehensibly old (recall that Hutton lived well before Charles Darwin, whose theory of evolution also implied that Earth was quite old; see Chapter 5).

The concept of *geologic* durations of time—encompassing hundreds of millions to billions of years—is thought by some to be geology's greatest contribution to human thought. Another important implication of the great durations of passing time is that there has been plenty of time for Earth's systems to evolve. Given enough time the behavior and evolution of Earth's systems are not necessarily due only to the processes we can observe and measure on human time scales. But to unravel Earth's systems and their history, we must know not just *what* happened but *when* it happened. Knowing when events occurred, we can begin to understand cause and effect. If one event follows another in the geologic record, it is highly unlikely that the second event caused the first, but it is possible that the first event might have caused the second event, or at least set the stage for the second through contingency (see Chapter 1).

Age relationships in geology are typically established by the discipline of stratigraphy. **Stratigraphy** is the study of stratified (layered) rocks, or strata, and their age relationships. Stratigraphy studies sedimentary rocks because sedimentary rocks are typically stratified. It is by stratigraphy that we determine when things happened and decipher the history of a region from its geologic record. By establishing the history of events, we might also be able to infer the processes involved. Much of this chapter is concerned with how the ages and relationships of stratified rocks are established.

6.2 Relative Ages

B The easiest way to establish the age of something is to establish its age *relative* to something else. Such ages are called **relative ages**, meaning rocks and the fossils in them are older or younger than something else. Establishing relative ages involves recognizing *sequences* of events and therefore history.

In the case of Siccar Point, we can establish a sequence of events using relative ages. The **Principle of Superposition** states that younger sedimentary rocks lie on top of older rocks. The related **Principle of Original Horizontality** states that sedimentary strata are deposited initially as horizontal layers. Based on superposition and original horizontality, at Siccar Point there was first horizontal deposition of sedimentary layers or strata, followed by deformation and tilting of the strata. Then erosion of the tilted strata occurred, followed by more deposition of horizontal strata (see Chapter 1).

6.3 Absolute Ages

C Superposition yields relative ages. Although the general sequence of events in the history of a region could still be reconstructed without absolute ages, it is uncertain by exactly how much one layer is older than another.

By contrast, **radiometric dates** ("metric" for measure) provide **absolute ages** of rocks, or the age of rocks in years. Radiometric dates not only provide the ages of rocks and fossils, they also allow scientists to calculate the approximate *rates* of processes such as deposition, erosion, and uplift because they know how much time has elapsed during such processes.

Radiometric dates are derived from the decay of radioactive isotopes (**Figure 6.1**). These are the same types of isotopes that generate Earth's internal heat. A radiometric date is calculated based on the concept of the half-life. A **half-life** is the amount of time it takes for one-half of *any* amount of a radioactive isotope (called the **parent isotope**) to decay to its **daughter** product. For example, it takes 704 million years for one-half of any quantity of the radioactive isotope ^{235}U to decay to the nonradioactive element ^{207}Pb (lead-207; see Chapter 2 for notation of isotopes). The age of a rock can be estimated from the ratio of the parent to daughter (Figure 6.1). After the end of one half-life, half of the radioactive parent should be present. Thus, the ratio of daughter to parent is 0.5:0.5 or 1:1. After two half-lives have passed, one-fourth of the radioactive parent remains, and the daughter-to-parent ratio is 3:1, and so on.

Radioactive isotopes vary substantially in the durations of their half-lives. Some, such as uranium-lead and thorium-lead, have half-lives of billions of years. These isotopes have been present since the solar system formed and are commonly used to date igneous intrusive rocks. The same isotopes have also been used to date moon rocks and meteorites. The potassium-argon method is used to date volcanic (extrusive) igneous rocks such as ash layers from which individual crystals cannot be extracted.

One of the most famous radiometric dating methods is that of carbon-14 (^{14}C). Carbon-14 is produced naturally in Earth's atmosphere by cosmic ray bombardment (**Figure 6.2**). Carbon-14 is initially incorporated into the carbon cycle by photosynthesis and is then passed to animals when the plants are eaten. As long as an organism is alive, plant or animal, the ^{14}C that decays is replaced and is absorbed by organisms, along with ^{12}C, in a nearly constant ratio; after the organism has died the ratio begins to change as ^{14}C decays back to ^{14}N. Carbon-14 has a half-life of 5,730 years, which means it can be used back to about 70,000 years. Because the latter portion of this time interval includes the spread of human civilization, the carbon-14 technique has been widely used in archaeology to date charcoal, bones, and shells of organisms such as clams eaten by humans.

Sometimes the ^{14}C technique can be coupled with other means of dating that yield absolute ages. One widely used method is tree rings, which are studied by the science of **dendrochronology** ("dendro" for tree, "chronology"

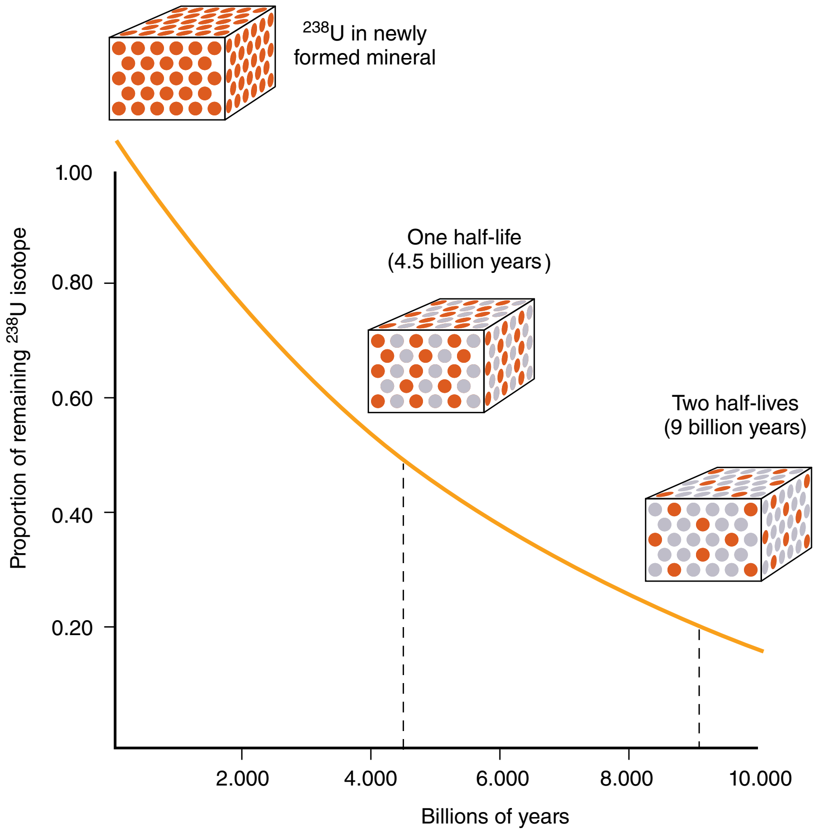


FIGURE 6.1 A general curve for the radioactive decay of an element. After one half-life has passed, one-half of the original radioactive parent is present. After two half-lives, one-fourth of the parent is still present, and so on. By finding the ratio of the daughter product to radioactive parent, one can determine the number of half-lives that have passed and thus the age of the rock.

for time; Figure 6.2). In dendrochronology, tree rings are counted to yield precise dates (in years). However, if the tree is dead the rings do not tell us *when* the tree died but its time of death can be determined by carbon-14 dating. We also can use tree rings to infer climatic conditions. Thick tree rings indicate relatively wet conditions, whereas thin rings indicate dry conditions or even drought. Coupled with carbon-14 dates, dendrochronologic studies can therefore be used to precisely infer the timing of past climatic conditions. Such studies can then be related to archaeological ones to determine the effect of past climatic conditions on humans.

We must keep in mind several factors when using radiometric dates, however. First, the radiometric "clock" only starts from the time when the mineral reached its blocking temperature. The **blocking temperature** of a mineral is typically hundreds of degrees cooler than the melting temperature of the mineral. The blocking temperature is therefore sufficiently cool to prevent the parent and daughter isotopes from breaking chemical bonds with the rest of the mineral and moving into and out of it, which can alter the age. Different minerals have different blocking temperatures; hornblende's is much higher than that of biotite's, for example.

Second, the mineral must have remained a closed system after the blocking temperature was reached. **Closure** means the loss or addition of either parent or daughter matter, which can alter the age. For example, the potassium-argon method measures the ratio of potassium-40 to argon-40. However, argon is a gas and can leak from the mineral crystal, lowering its apparent age. Leakage can occur in response to heat and pressure associated with metamorphism. If the daughter isotope is completely removed by metamorphism, we are actually dating the time since metamorphism.

Third, weathering and leaching can also affect ratios of different radioactive isotopes. Thus, only fresh, unweathered samples must be used for dating.

One means of determining the accuracy of dates is the method of cross-checks. If dates obtained using two different isotopic pairs agree, or are **concordant**, it is likely that this is the correct age of the rock. If the dates disagree, or are **discordant**, it is possible that one or both methods are incorrect, and we must use other techniques to determine which date, if either, is correct.

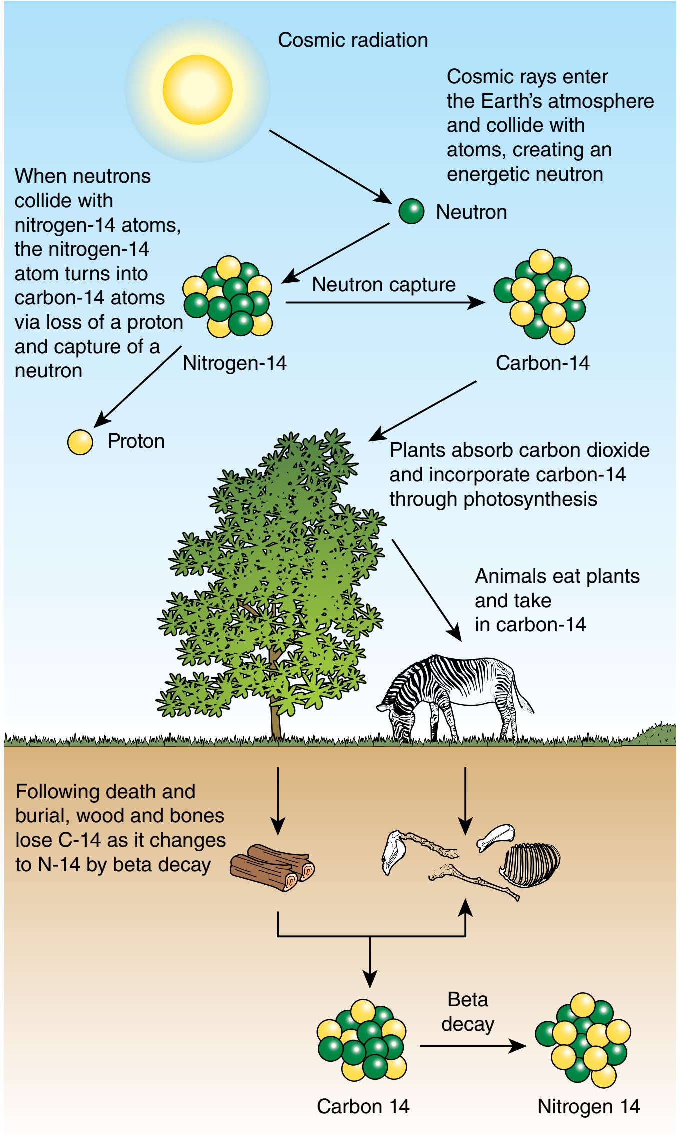
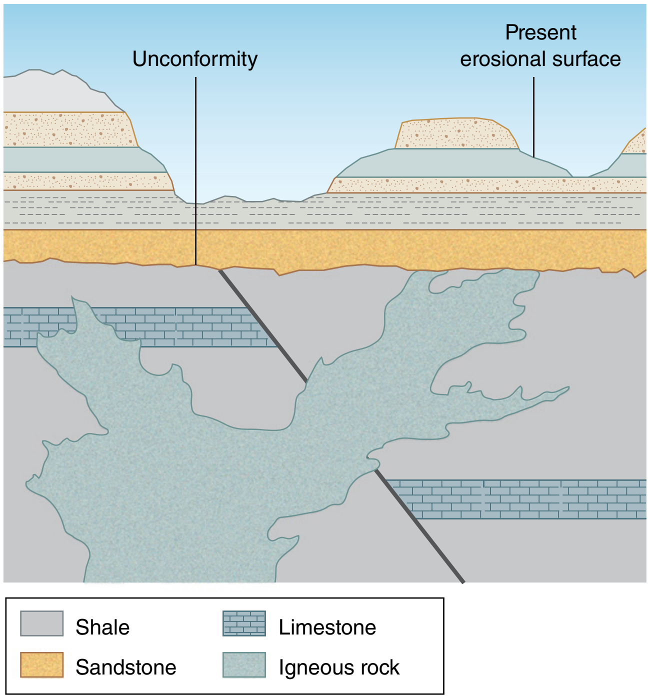


FIGURE 6.2 The carbon-14 dating technique. We can use this technique to date archaeological objects, bones, and tree rings, which yield paleoclimate information as shown. In temperate and higher latitudes, trees add annual layers (rings) that, when coupled with carbon-14 dates, we can use to precisely assess when past changes in precipitation occurred and their possible impact on human settlements.

D Despite the advantage of radiometric dates, absolute ages are not exact. Radiometric dates usually come from igneous rocks. Thus, if one is dealing primarily with a sequence of sedimentary rocks, the radiometric dates come from igneous plutons, dikes, or sills intruded into the sedimentary sequence (**Figure 6.3**). Based on the **Principle of Cross Cutting Relationships**, which states that rock bodies that cut across others must have come after them, the dikes and sills must have been injected after the deposition of the sedimentary rocks into which they were intruded. Still, we don't know exactly when the dikes or sills were intruded after the surrounding strata were deposited. Also, a



Data from: Levin, H. 2006. *The Earth Through Time.* 8th ed. Hoboken, NJ: John Wiley. Figure 2.11 (p. 20).

FIGURE 6.3 Radioactive isotopes provide absolute ages of rocks using the principle of cross-cutting relationships. Although the general sequence of events in the history of a region can be reconstructed without absolute ages, radiometric dates give scientists greater certainty to their conclusions and allows scientists to calculate rates of processes such as deposition, erosion, and uplift. However, even absolute dates give only approximate ages, as shown in this example. For example, in the figure, the sedimentary rocks penetrated by the igneous dike must have existed before the dike was intruded, but we cannot tell how long the sedimentary rocks existed before the intrusions without other evidence. Similar considerations apply to the fault cut by the dike and the unconformity at the top.

radiometric date is subject to error, sometimes up to millions of years, so that when an age is reported it must be remembered that the age really could be anywhere within the margin of error.

This means we must seek other data to establish finer subdivisions of time to produce a reliable geologic time scale. These finer subdivisions are based on the appearance and extinction of different fossil species through time.

CONCEPT AND REASONING CHECKS

1. What are the principles on which relative ages are based?
2. Do radiometric ages by themselves give the precise age of a particular stratum?
3. How many human life spans—or generations—do you believe an individual stratum might normally represent? A few? A lot? How much time might this represent in terms of absolute time?

6.4 Evolution of the Geologic Time Scale

E The earliest time scales were based on the Principle of Superposition. Similar sequences of rocks were observed by workers in Europe and Russia about the same time and led them to erroneous conclusions. Because the same kinds of rocks were geographically widespread, these workers concluded they must have all formed at once; therefore, each basic rock type represented a distinct phase in Earth's history. In fact, the doctrine of **Neptunism**, which was a form of catastrophism (see Chapter 1), stated that rocks were successively deposited from a global ocean. Catastrophism arose partly as an attempt to "fit" the slowness of geologic processes to the short time scales derived from biblical scripture (**Box 6.1**).

These early time scales had several major subdivisions based on lithology, or rock type (igneous rocks, shales, sandstones, limestones, and so on). The founders of the earliest time scales equated rock with time because the significance of fossils was unknown at that time, as was the theory of evolution. The earliest rocks at the base of the scale were called "primary" and consisted of crystalline rocks with metal ores (Ganggebirge for "ore mountain"; **Table 6.1**). "Secondary" rocks formed on top of primary rocks, were stratified, and contained fossils (Flötzgebirge or "layered mountain"). On top of secondary rocks came "tertiary" (or "third") rocks, which also contained fossils. These rocks were capped by the poorly consolidated alluvium such as the sands and gravels of stream and river channels. Alluvium was also referred to by wonderful tongue-twisters such as "Angeschwemmtgebirge," "Aufgeschwemmtgebirge," and "Neues Flötzgebirge" (Table 6.1). Although most of these terms have long since been dropped, some of the older terms such as "Tertiary" are still used, at least informally.

During the 18th and early 19th centuries, earth scientists such as Cuvier began to accept the existence of fossils as evidence for prehistoric life. However, it was not until 1815 that William Smith proposed the **Principle of**

BOX 6.1 Age of the Earth

In 1654, the Anglican Archbishop James Ussher of Ireland, a respected biblical scholar, calculated that Earth began on Sunday, October 23, 4004 B.C. According to Ussher, Earth was only 6,000 years old. He based his determination on Middle Eastern and Mediterranean history and biblical accounts of genealogies (family histories of ancestor–descendant relationships). Ussher also calculated that Adam and Eve were expelled from paradise 18 days after creation. Other scholars had earlier arrived at similar ages for Earth. These estimates severely constrained the thinking of many scientists who studied the history of Earth.

Much later the physicist Sir William Thompson (1824–1907), later known as Lord Kelvin, became a major antagonist in debates about the age of Earth and therefore the amount of time available for Darwinian evolution. By the last half of the 19th century, most investigators had accepted the idea that Earth was originally molten, based on phenomena like volcanism and that Earth was therefore losing heat. Kelvin pointed out that Lyell's concept of an equilibrium view of Earth (see Chapter 1) therefore had to be incorrect because Earth was losing heat. Kelvin reasoned that if Earth is hot now, it must have been hotter, and more likely molten, much earlier in its history.

After the initial publication of Darwin's *On the Origin of Species* in 1859, Kelvin published the paper "The 'Doctrine of Uniformity' in Geology Briefly Refuted." He calculated the rate of Earth's heat loss by assuming that (1) heat is lost from Earth at a constant rate, (2) Earth's composition is fairly uniform, and (3) there are no renewable sources of heat in Earth. Kelvin then extrapolated backward in time to Earth's molten state and calculated an age for Earth of about 100 million years. Although this is of course a long time, it was far less than Darwin's estimate of hundreds of millions of years based on the fossil record or Hutton's concept of nearly beginning-less time. In subsequent years, Kelvin continued to revise his age estimates downward, eventually settling on about 20 million years.

Kelvin's calculations for the age of Earth put Darwin in a bind from which he never escaped. To the end of his life Darwin believed Kelvin's calculations were wrong, although he could not explain why. Many scientists accepted Kelvin's calculations, mainly because they were based on physics and mathematical calculations rather than the science of the "higgle-de-piggledy" (as the famous 19th astronomer Sir John Herschel once referred to evolution). Also, Kelvin's stature in the scientific community was such that most other scientists

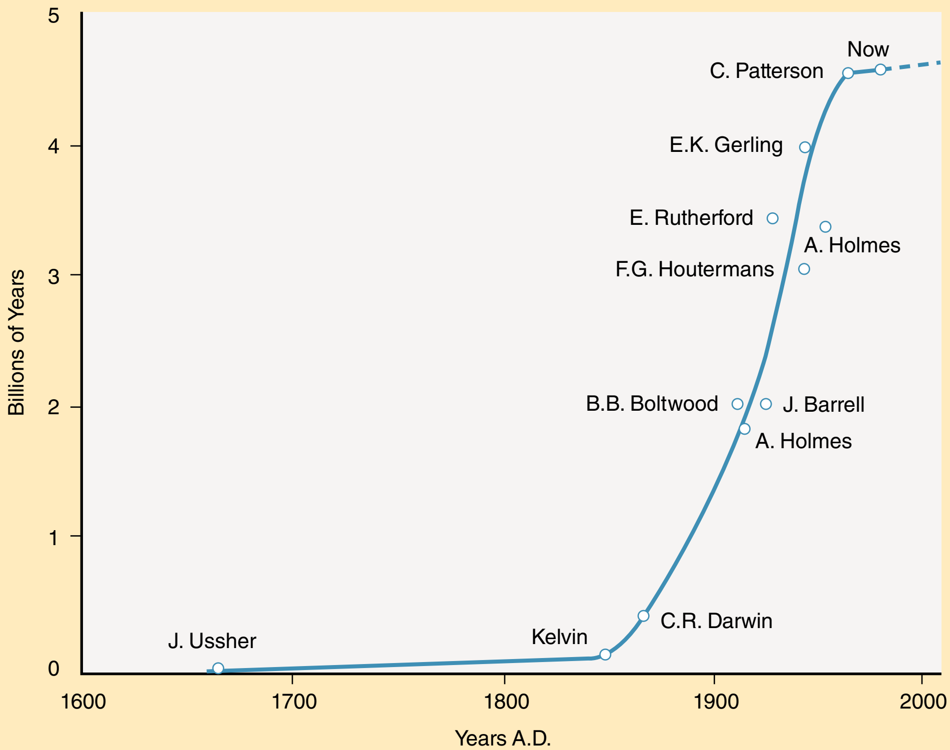
BOX 6.1 Age of the Earth (Continued)

avoided disagreeing with him. Consequently, during the later 1800s the acceptance of Darwin's views of long, slow rates of evolution began to decline, even among some of Darwin's strongest supporters. Many began to look for processes that could act at much faster rates of evolution to accommodate Kelvin's conclusion, even resurrecting a version of Lamarck's old theory of the inheritance of acquired characteristics (see Chapter 5).

We now know that the age of Earth is approximately 4.5 to 5 billion years based on radiometric dates. However, radioactivity, the source of Earth's internal heat, was not discovered until the late 1800s, late in Kelvin's life, and estimates of the age of Earth based on radioactive dating techniques did not start to become available until decades later. Initially, it was concluded that Earth was at least 3 billion years old based on dates reported by Ernest Rutherford and Arthur Holmes (of continental drift fame; **Box Figure 6.1A**).

However, in 1956 Clair Patterson at Cal Tech found the decay of radioactive isotopes in the Canyon Diablo meteorite (which formed Meteor Crater in northern Arizona) indicated an age for Earth of 4.56 billion years (Box Figure 6.1A). Patterson assumed meteorites were left over from the birth of the solar system (see Chapter 7). Patterson's dates were later corroborated by concordant ages obtained for crustal rocks from Earth using rubidium-strontium (Rb-Sr) and potassium-argon (K-Ar) isotope pairs (see Chapter 2) and by dates on Moon rocks brought back by the Apollo astronauts. Like meteorites, the Moon also formed as our solar system originated.

So, Darwin was basically right. Nevertheless, Kelvin maintained to his dying day that Earth could not be as old as Darwin or later scientists claimed. Today, Kelvin lies buried in Westminster Abbey, next to Sir Isaac Newton—and Charles Darwin.



Data from: Cloud, P. *Oasis in Space: Earth History from the Beginning*. New York, NY: W. W. Norton. Figure 4.6 (p. 89).

BOX FIGURE 6.1A Changing estimates of the age of the Earth.

TABLE 6.1

The Evolution of the Geologic Time Scale*

Early Subdivision				Modern Usage			
Arduino 1760	Lehmann 1756 Fochsel 1760–1773	Werner ca. 1800	English Equivalents	Eras	Periods	Epochs	Alternate Periods
Volcanic Alluvium Tertiary	Aufgeschwemmt- gebirge	Aufgeschwemmt- gebirge or Neues flötzgebirge	Alluvium Tertiary	Cenozoic Phillips 1841	Neogene Hoernes 1853	Holocene Pleistocene	Quaternary Desnoyers 1829
						Pliocene Miocene	Tertiary Arduino 1760
					Paleogene Naumann 1866	Oligocene Eocene Paleocene	
Secondary	Flötzgebirge	Flötzgebirge	Secondary	Mesozoic Phillips 1841	Cretaceous d'Halloy 1822		
					Jurassic von Humboldt 1799		
					Triassic von Alberti 1834		
				Paleozoic Sedgwick 1838	Permian Murchison 1841		
					Pennsylvanian Williams 1891	Carboniferous Conybeare and Phillips 1822	
					Mississippian Winchelll 1870		
Primitive	Ganggebirge	Übergangs- gebirge	Transition		Devonian Murchison, Sedgwick 1839		
					Silurian Murchison 1835		
					Ordovician Lapworth 1879		
					Cambrian Sedgwick 1835		
		Ürgebirge	Primary	Precambrian			

*Workers and the date of recognition of the most commonly used modern units are indicated.
Reproduced from: Mintz, L. W. 1977. *Historical Geology: The Science of a Dynamic Earth*, 2nd ed. Columbus, Ohio: Charles E. Merrill. 588 pp. (Figure 2.8, p. 14).

Faunal Succession (**Table 6.2**). Smith noticed that fossil assemblages always occurred in the same superpositional sequence, which led to his recognition of this principle. Smith was a surveyor responsible for the construction of canals in England as the Industrial Revolution grew; he therefore had ample opportunity to observe rocks and fossils over large areas and to test his hypothesis of faunal succession by predicting the sequences elsewhere. In reality, the Principle of Faunal Succession is based on the fact that fossil biotas have changed through time because of biologic evolution. Thus, life, unlike rocks, *does not tend to repeat itself*. The directionality of life (sometimes called Dollo's Law) is of course the result of biologic evolution; however, the recognition of Faunal Succession preceded Charles Darwin's *On the Origin of Species*, published in 1859, by nearly half a century.

Like superposition, fossils also give relative ages. However, fossils produce much finer subdivisions of the time scale than rocks alone (Table 6.1). Consequently, the primary is now called the **Precambrian**, which records the origin and development of Earth and its early life during its three main subdivisions or **eons**: the Hadean (from Hades, referring to Earth's early molten state), **Archeozoic** ("ancient life"), or just **Archean**, and **Proterozoic**, or "first life." Each of these eons is characterized by distinctive rock types and climate.

Many paleontologists concentrate their efforts somewhere within what used to be called the "Secondary," the "**Tertiary**," and the "**Quaternary**." Together, these intervals encompass

TABLE 6.2

Geologic Ages and Associated Biotic Events

Time Scale				Millions of Years Before Present (approx.)	Some Major Biotic Events
Eon	Era	Period	Epoch		
Phanerozoic	Cenozoic	Quaternary	Holocene (last 11,700 years)	0.01	Appearance of humans
			Pleistocene		
		Tertiary	Pliocene	2.8	Dominance of mammals and birds
			Miocene	5.3	Proliferation of bony fishes (telosts)
			Oligocene	23	Rise of modern groups of mammals and invertebrates
			Eocene	34	Dominance of flowering plants
			Paleocene	56	Radiation of primitive mammals
	Mesozoic	Cretaceous		65	First flowering plants Extinction of dinosaurs
		Jurassic		145	Rise of giant dinosaurs Appearance of first birds
		Triassic		200	Development of conifer plants
	Paleozoic	Permian		251	Proliferation of reptiles Extinction of many early forms (invertebrates)
		Carboniferous	Pennsylvanian	299	Appearance of early reptiles
			Mississippian	318	Development of amphibians and insects
		Devonian		359	Rise of fishes First land vertebrates
		Silurian		416	First land plants and land invertebrates
		Ordovician		443	Dominance of invertebrates First vertebrates
		Cambrian		488	Sharp increase in fossils of invertebrate phyla
Precambrian	Proterozoic	Neoproterozoic		542	Appearance of multicellular organisms
		Mesoproterozoic		1,000	Appearance of eukaryotic cells
		Paleoproterozoic		1,600	Appearance of planktonic prokaryotes
	Archean			2,500	Appearance of sedimentary rocks, stromatolites, and benthic prokaryotes
	Hadean			4,000	From the formation of Earth until first appearance of sedimentary rocks; no observable fossil organisms

Note: Dates derived mostly from Gradstein et al. *A Geologic Time Scale*. Cambridge University Press, 2004, and from Geologic Time Scale, available from http://www.stratigraphy.org, accessed August 2012.

about the last 540 million years. This interval is also called the **Phanerozoic** Eon, or the "time of apparent life," because it is when fossils are typically abundant. The distinctive changes in fossil assemblages of the Phanerozoic were recognized by Sir John Phillips to consist of three main **eras**, each now recognized to span tens to hundreds of millions of years. Phillips recognized that each era was represented by very distinct groups of fossils: **Paleozoic** ("ancient life"), **Mesozoic** ("middle life"), and **Cenozoic** ("recent life"; Table 6.1).

Many of the boundaries between the units of time scale correspond to major faunal, floral, and climatic change, including mass and minor extinctions (see Chapter 5). Each of the eras has its own distinct fossil assemblages or biotas that were later used to subdivide the eras into smaller units called **periods**. Periods are roughly tens of millions of years in duration. It is this sequence of fossils through the periods that Smith observed.

By the middle of the 19th century most of the geologic periods had been recognized in Europe based on fossil biotas (Table 6.1). Each geologic period's name was assigned based on characteristic features of the rocks, the area in which the fossils were first described, or both. The **Cambrian** is the first period of the Paleozoic and is an ancient name for Wales, whereas the next two periods, the **Ordovician** and **Silurian**, were named after ancient Welsh tribes. **Devonian** refers to Devonshire, England, and **Carboniferous** to coal-bearing units first recognized in England. The Carboniferous is often divided into the Early and Late Carboniferous in Europe, which correspond to the **Mississippian** and **Pennsylvanian** periods of the United States. The last period of the Paleozoic is the **Permian**, named for the Perm province in the Ural Mountains far to the east of Moscow in Russia, where they were described. Next is the Mesozoic Era, comprised of the **Triassic** and named for a distinctive, three-fold ("tri") sequence of rocks in eastern Germany; the **Jurassic**, named for the Jura Mountains of southeast France and Switzerland; and the **Cretaceous** for the abundant chalks ("creta") of this time. The Tertiary ("third") and Quaternary (meaning "fourth") follow.

All geologic periods are further subdivided into **epochs**. The most widely used epochs are those of the Tertiary and Quaternary periods. Epochs were first formally recognized by Lyell in the *Principles of Geology* based on rocks of the Cenozoic Era exposed in the vicinity of London and Paris. Lyell used the ratio of *extant* (or still-living) mollusks (mainly clams and snails) to extinct mollusks present in the rocks to recognize the epochs. From this fraction, he calculated the percentage of extant species also found as fossils. He found that as the rocks became older, the number of species still living today and found as fossils in the rocks decreased. Based on these percentages Lyell recognized the epochs **Eocene** ("dawn recent"), **Miocene** ("middle recent"), and Lower and Upper **Pliocene** ("more recent"). The Upper Pliocene was later renamed **Pleistocene** ("most recent") and represents the time of the "Ice Ages." About the last 10,000 years of the Pleistocene are often recognized as the **Holocene** ("wholly recent") for when human civilization spread over the globe. Other workers recognized the **Oligocene** ("few recent") and **Paleocene** ("ancient recent") epochs, which was split off from the lower Eocene based on fossil floras.

The Paleocene through Oligocene periods are often lumped together as the **Paleogene** and the Miocene to Recent into the **Neogene** because these two intervals represent fairly distinctive climate modes: the Paleogene was generally a warm interval with widespread seas until the Late Eocene and Oligocene, whereas the Neogene generally represents a time of widespread glaciers, colder conditions, and lower sea level. Geologic committees have recently recommended the use of the terms Paleogene and Neogene in place of the epochs. It has also recently been suggested that the epochs of the Cenozoic and the term "Tertiary" should be dropped and only the terms Paleogene, Neogene, and Pleistocene should be used. The date for the beginning of the Pleistocene has also been moved back to 2.8 Ma. We will continue to use the epoch terms, however, because they are well embedded in the literature and provide further subdivisions of the Cenozoic that are useful in further discussions in this text.

CONCEPT AND REASONING CHECKS

1. Why is the Principle of Faunal Succession an example of directionality in Earth's history?

6.5 Correlation

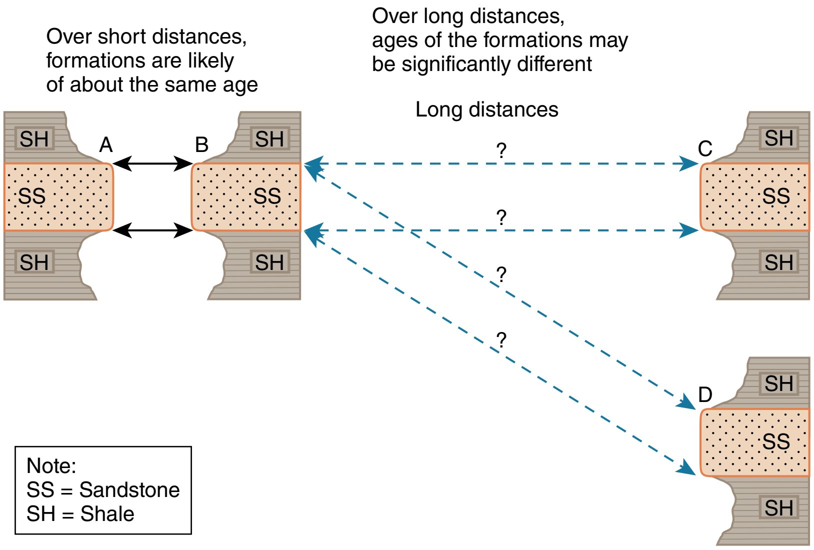
F As the geologic time scale began to be established, workers attempted to recognize rocks of the same fossil content and therefore age. The procedure that infers the age equivalence of rocks is called **correlation**. We can carry out correlation in a number of different ways.

6.5.1 Lithocorrelation

The study of the stratigraphic relationships of rocks based solely on lithology is called **lithostratigraphy**. Correlation using lithology, or rock type, alone is therefore called **lithocorrelation**. Sometimes we have no choice other than to correlate using lithology because fossils are absent.

Lithocorrelation is usually done in the field by the folksy-sounding process of **walking the outcrop** (or exposure), which means one maps the rock unit(s) in the field visually over the area in which they are exposed. In lithocorrelation, one assumes certain distinctive rock units, or **distinctive sequences** of rock units, are *contemporaneous*, meaning they were formed more or less at the same time (**Figure 6.4**). Such units could be a distinctively colored sandstone or a limestone that is very resistant to weathering or perhaps a distinctive sequence of rocks such as a shale overlain by a coal bed and then a limestone; such distinctive sequences are common in coal-bearing areas of the Carboniferous.

Another method of lithocorrelation uses distinctive **marker beds**, such as volcanic ash falls, which can range in thickness from a few centimeters to perhaps a meter or so in thickness, and are often spread over wide areas. Volcanic ashes are extremely useful because, geologically speaking,



Data from Levin, H. 2006. *The Earth Through Time*, 8th ed. Hoboken: NJ: John Wiley. Figure 6.38 (p. 105).

FIGURE 6.4 Lithocorrelation correlates rocks over relatively short distances (localities A and B in the diagram) by assuming that the rocks formed more or less simultaneously. Volcanic ashes can also form distinctive beds that can be correlated over large areas. Distinctive sequences of beds can also be used for correlation. However, lithocorrelation becomes unreliable over greater distances (localities C and D) because, unlike fossils, rocks tend to repeat themselves through geologic time. See text for further discussion.

they are instantaneous events that almost resemble the ticks of the second hand of a watch.

When rocks cannot be observed at the surface, another method of lithocorrelation involves matching distinctive shifts in **well-logs**. Well-logs are commonly used to infer the lithologies of subsurface strata and their pore fluids (water, oil, gas). The well-logs result from lowering remote-sensing instruments down wells and measuring the ability of the fluids in the well and the surrounding rocks to conduct electricity, emit radioactivity, or other features (**Figure 6.5**). Well-logging techniques are widely used in petroleum exploration to determine the thicknesses and pore fluids in subsurface rocks and to correlate subsurface rocks that conduct large volumes of water, or **aquifers**.

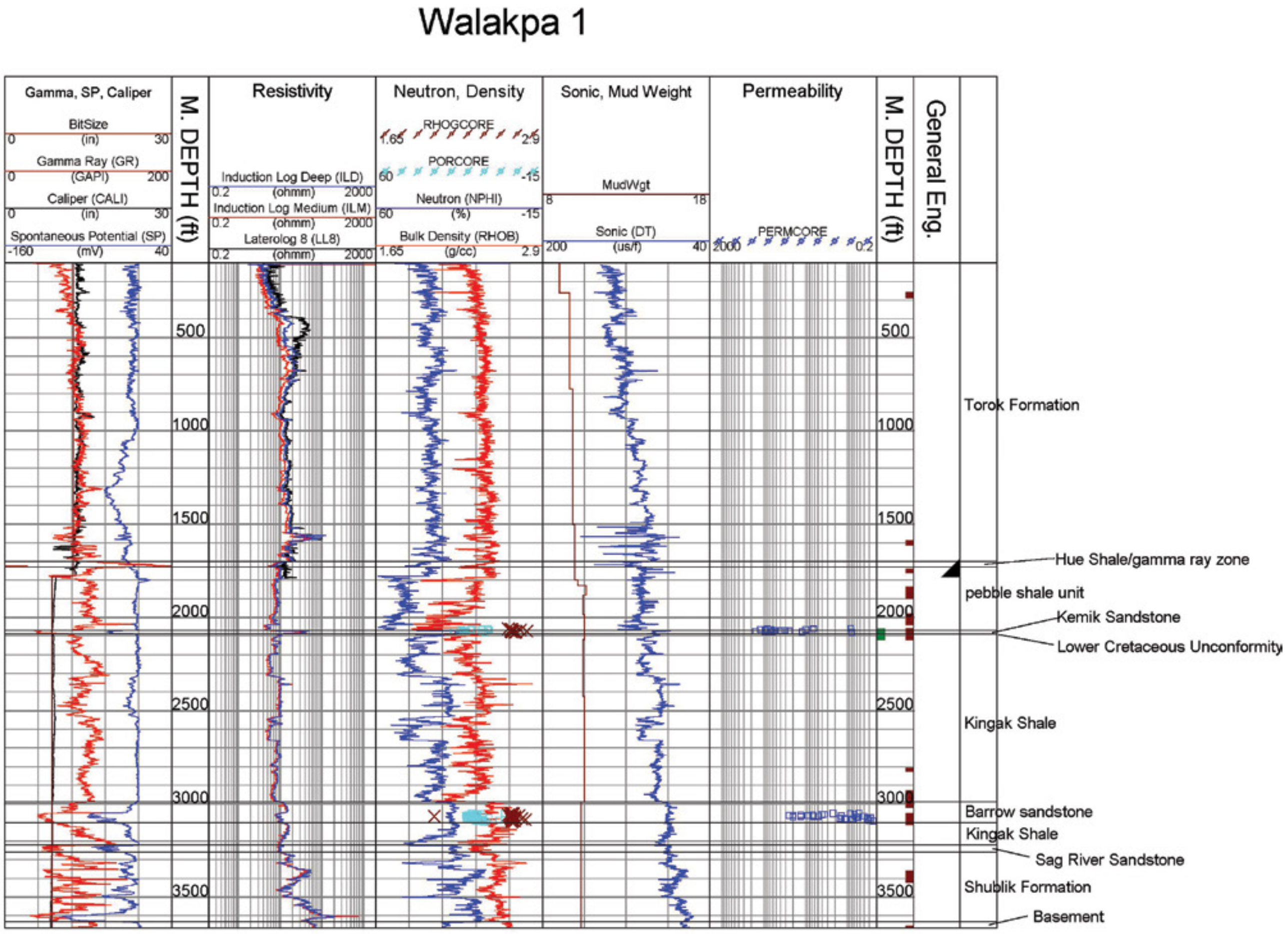
Another method of lithocorrelation uses the magnetic properties of rocks. As igneous rocks cool from a molten state, iron-rich mineral particles present in the magma align themselves with Earth's magnetic field, which acts much like a bar magnet (**Figure 6.6**). The temperature below which the alignments of the particles become fixed in the rock is called the **Curie point** (named after Marie Curie, one of the codiscoverers of radioactivity).

The Earth's magnetic field is not completely stable, however. The iron-rich particles in solid magma indicate past states of Earth's magnetic field. The modern Earth's magnetic field is said to be normal, and the north magnetic pole (which differs from Earth's geographic North Pole or axis of rotation) is today found in northern Canada (**Figure 6.7**) but is currently moving toward Russia at a rate of about 40 miles per year. Earth's magnetic field, which derives from the core, also flip-flops back and forth between "normal" and "reversed" polarity. In a reversed magnetic field, Earth's magnetic south polarity shifts to the northern hemisphere and the north magnetic polarity shifts to the southern hemisphere (Figure 6.7). The changes in magnetic polarity, or **magnetic reversals**, occur very quickly (geologically speaking) all over the world. Moreover, this behavior of iron-rich particles can occur not only in intrusive or extrusive rocks, but also sediments, both on land and on the seafloor. Because the reversals are recorded on land and in seafloor crust, both in igneous rocks and sediments, the changes in polarity can potentially be correlated between land and sea. In fact, paleomagnetic data and other types of datums are frequently integrated with what is called the oxygen isotope record of the Pleistocene Epoch to distinguish the different oxygen isotope stages, which reflect ice volume during the Pleistocene but which tend to resemble one another (see Chapter 15).

All these methods of lithocorrelation equate rock with time. Over short distances, equating rock with time is not a problem, and lithocorrelation is usually quite successful. However, over long distances, we cannot be sure that, for example, the sandstone one observes in an outcrop is the exact same sandstone far away (Figure 6.4). These sorts of problems led the originators of the early time scales awry. This is because, unlike fossils, rocks *repeat themselves through time*. Similarly, despite the great precision that oxygen isotope and paleomagnetic records offer for correlation over long distances, oxygen isotope stages and paleomagnetic reversals tend to look alike and they repeat themselves through time, just like rocks. Thus, we must distinguish and correlate different isotope stages or reversals by using other means such as fossils, which do not recur through time.

6.5.2 Formations and facies

G We have now recognized a fundamental principle of stratigraphy: *the same kinds of rocks repeat themselves*



Dr. Peter P. Mclaughlin, Delaware Geological Survey.

FIGURE 6.5 A typical well-log. The squiggles indicate the lithology and kinds of fluids such as water, oil, or gas that fill the pores of the rocks.

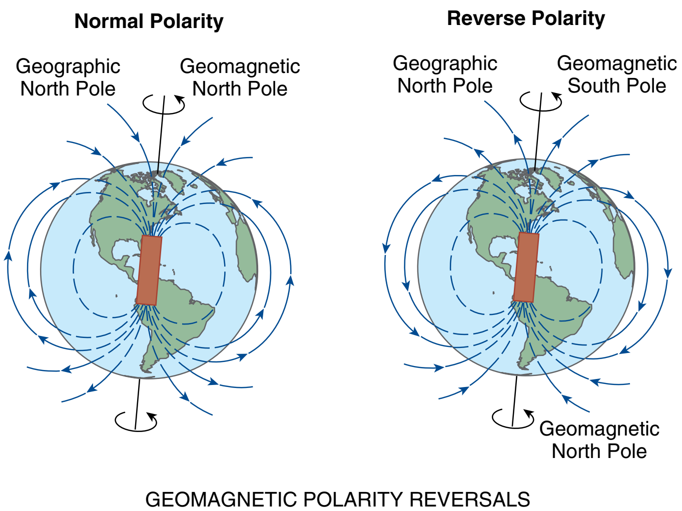


FIGURE 6.6 Changes in the Earth's magnetic field. The current orientation of the magnetic field is said to be normal, but it has flip-flopped through geologic time between normal and reversed states, with the south magnetic pole located in the northern hemisphere and the north magnetic pole located in the southern hemisphere.

through geologic time. Furthermore, *different types of rocks can occur at the same time*. With regard to sedimentary rocks these statements are sometimes referred to collectively as **Walther's Law**. We also can generalize the statements to include the environments in which the rocks were deposited.

The fact that rocks cannot be considered exactly equal to time is embodied by the concepts of formation and facies. A **formation** is a mappable unit of rock that is recognized based only on its lithology. A formation is therefore descriptive only, and there should be no interpretation of its age. An individual formation might range from only a few to hundreds of meters in thickness and might be traceable over areas of hundreds to thousands of square kilometers. Each formation is given a name based on the approximate location—or type locality—where it was originally recognized and described. Type localities can be towns, crossroads, rivers, streams, or some other geographic feature. Thus, formations bear names like Antietam Sandstone (found in the Appalachian Mountains), Niagara Limestone (of Niagara Falls), and Green River Shale (of Wyoming, which is famous for its fossil fish; see Chapter 14).

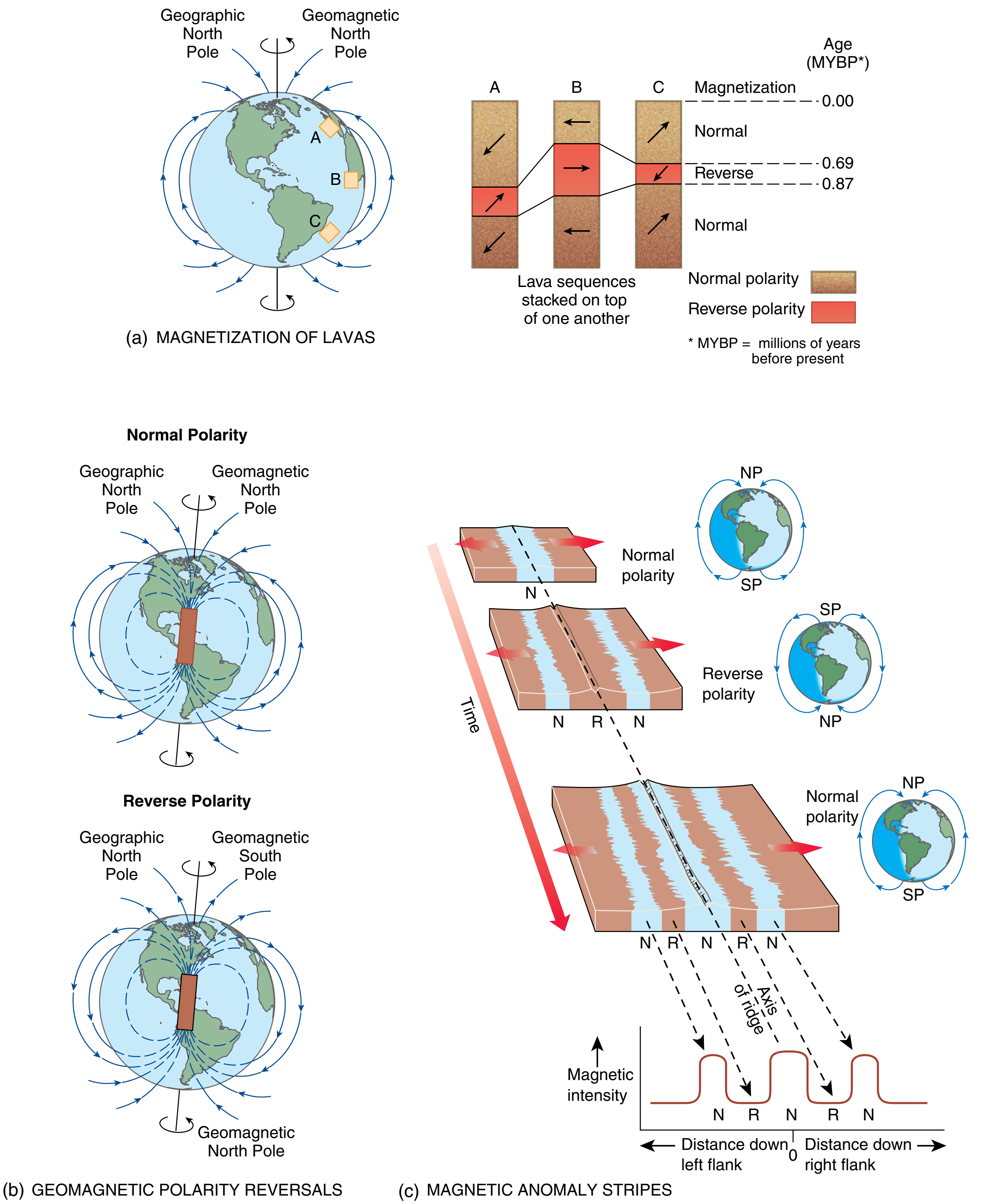


FIGURE 6.7 As igneous rocks cool from a molten state, iron-rich mineral particles that are present in the magma align themselves with the Earth's magnetic field as the temperature decreases below the Curie point to produce "magnetic stripes" (see Chapter 2). This behavior can occur in intrusive or extrusive rocks on land or in seafloor crust. Similar behavior is exhibited by iron-rich mineral grains as they are deposited in sediment on the ocean floor.

The concept of **facies** (meaning "aspect") recognizes that (1) different sedimentary rocks and the environments in which they were deposited can exist at the same time and (2) the same rocks (environments) have existed at different times. For example, when the limestones of a reef's crest are forming, biogenic or oolitic calcareous muds and sands might be deposited in the back reef lagoon adjacent to the core (**Figure 6.8**). Although these relationships are easily visualized in a diagram, they are less likely to actually be seen in outcrop. In the case of Figure 6.8, what would likely be observed in the geologic record are muds or sands cropping out in separate exposures over a large area, with the reef core cropping out in other exposures, most likely over a smaller area. The lithologies might be recognized as separate formations because they are relatively distinctive, but the fact that the sediments and their environments coexisted simultaneously would not be immediately obvious. Unless the interfingering of the two lithologies (called a **facies change**) was exposed in outcrop, the contemporaneity of the two lithologies could only be established by correlation.

A classic example of how formations and facies differ is provided by rocks at the base of the Grand Canyon in northern Arizona (**Figure 6.9**). Immediately above the Precambrian rocks at the base of the Grand Canyon are three formations that occur in an upward sequence: the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone. These three formations formed as parallel bands of sediment along the western margin of North America in the Early Cambrian, roughly about 540 million years ago. Because of the energy distribution of waves and currents, sandstones were found closest to shore and shales farther away; only the relatively coarse particles of the Tapeats Sandstone settled out in wave and current-swept environments, whereas the finer particles of the Bright Angel Shale settled in quiet water farther away from shore. The rocks of the Muav Limestone tended to form farthest from shore because the sediment supply was too low to dilute the accumulation of calcareous shells that resulted from the death of the organisms living there (see Chapter 4).

Sea level rose across the western part of North America during the Early Cambrian. As a result, the three environments represented by the Tapeats Sandstone, the Bright Angel Shale, and the Muav Limestone shifted inland as sea level rose (Figure 6.9). Now imagine three widely separated rock outcrops (X, Y, and Z) of these three formations (Figure 6.9). If we were to equate rock with time at sites X, Y, and Z, based on superposition we would have "sandstone-time" followed by "shale-time" followed by "limestone-time." Based on this interpretation, *all* the sandstone was deposited everywhere during the same interval of time, then all the shale everywhere on top of the sandstone, followed by all the limestone. The historical reconstruction of this area would then be as follows: (1) sea level rose and all the sandstone was deposited uniformly throughout the area, (2) then all the shale was deposited on top of the sandstone in deeper water over the entire area as sea level rose further, and (3) then all the limestone was deposited on top of the shale after the terrigenous sediment supply from land was shut off. In this reconstruction *rock has been equated with time* and the ages of each of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone are inferred to be the same throughout their whole extent.

But this isn't what happened. All three environments coexisted as facies (Figure 6.9). In other words these three types of rocks formed in different environments that existed *at the same time,* not at succeeding times. Thus, the time lines must not be drawn parallel to and separating the formations (Figure 6.9). Rocks normally "cut across time," so to speak. In this interpretation, the ages of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone at site X are different from their ages at site Z, even though the rock types are identical (Figure 6.9). This is because as sea level rose and fell, the three environments and their associated lithologies gradually shifted landward and seaward, respectively.

Thus, to equate rock and time can completely obliterate any notion of the true geologic history of a region and the processes and the rates involved. In the incorrect reconstruction, all the sand was deposited at once, then all the shale, and then all the limestone.

What does the incorrect interpretation say about sediment supply to the region through time? In this case, there must have been a rather large influx of sand into a very widespread and shallow marine setting while the Tapeats Sandstone was being deposited. This suggests an uplift nearby that resulted in extensive erosion and redeposition. Why, then, did sandstone deposition stop rather suddenly and give way to shale in this interpretation? Did the sea level rise so rapidly that coarse-grained sediments like sand were prevented from reaching the area? Or did the basin in which the sediments were accumulating suddenly deepen, which would also appear as a sudden sea-level rise? Or perhaps the source rocks for the sand were largely eroded by the end of "Tapeats time"?

Note that this last interpretation really doesn't make sense: the time it probably took for the Tapeats to be deposited—millions of years—was undoubtedly much shorter than it would take for the erosion of a mountain range given the slow rates of weathering. So, if we were leaning toward accepting the incorrect interpretation, we ought to have some intuitive realization of our mistake and begin to rethink the history of the area. In fact, other evidence suggests this region lay along a quiescent continental margin where mountain building was largely absent during this time, so it would seem that extensive uplift and erosion was unlikely.

The concept of facies is one of the most fundamental concepts in all of geology. The mistake of equating rock and time is perhaps no better exemplified than in the earliest geologic time scales (Table 6.1). The earliest time scales were essentially based on a kind of lithocorrelation: younger rocks lay on top of older rocks, and, with no evidence to the contrary, it was only natural for some workers to conclude that the succession of lithologies in the areas where they worked were characteristic of certain times in Earth's history. Hence, the subdivisions Primary, Secondary, and Tertiary of the earliest time scales were thought to apply to the whole Earth, like the layers of a cake (Table 6.1). However, to equate rock with time at the scale of the whole Earth is no more satisfactory than, in our example, equating rock with time in

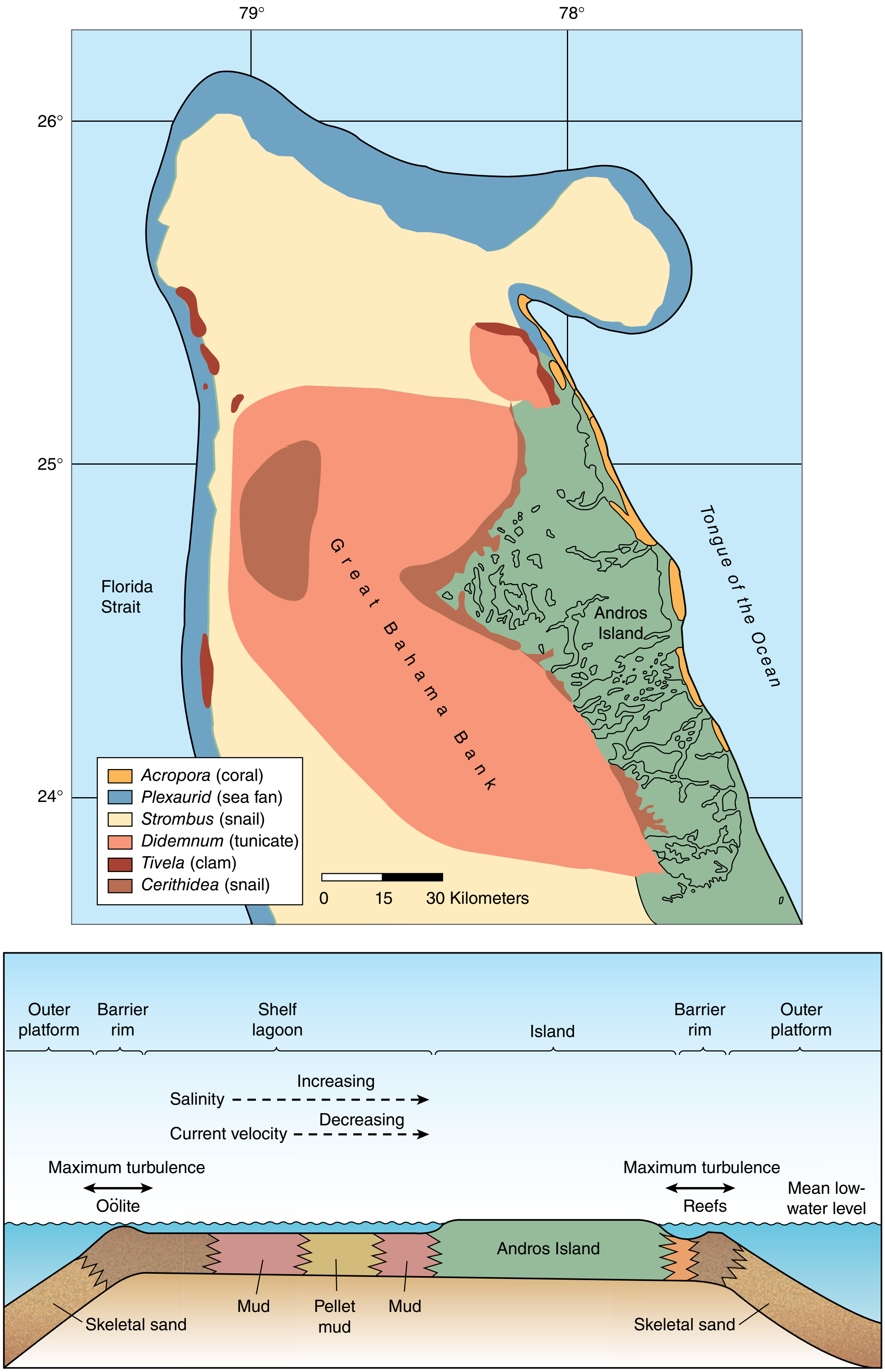
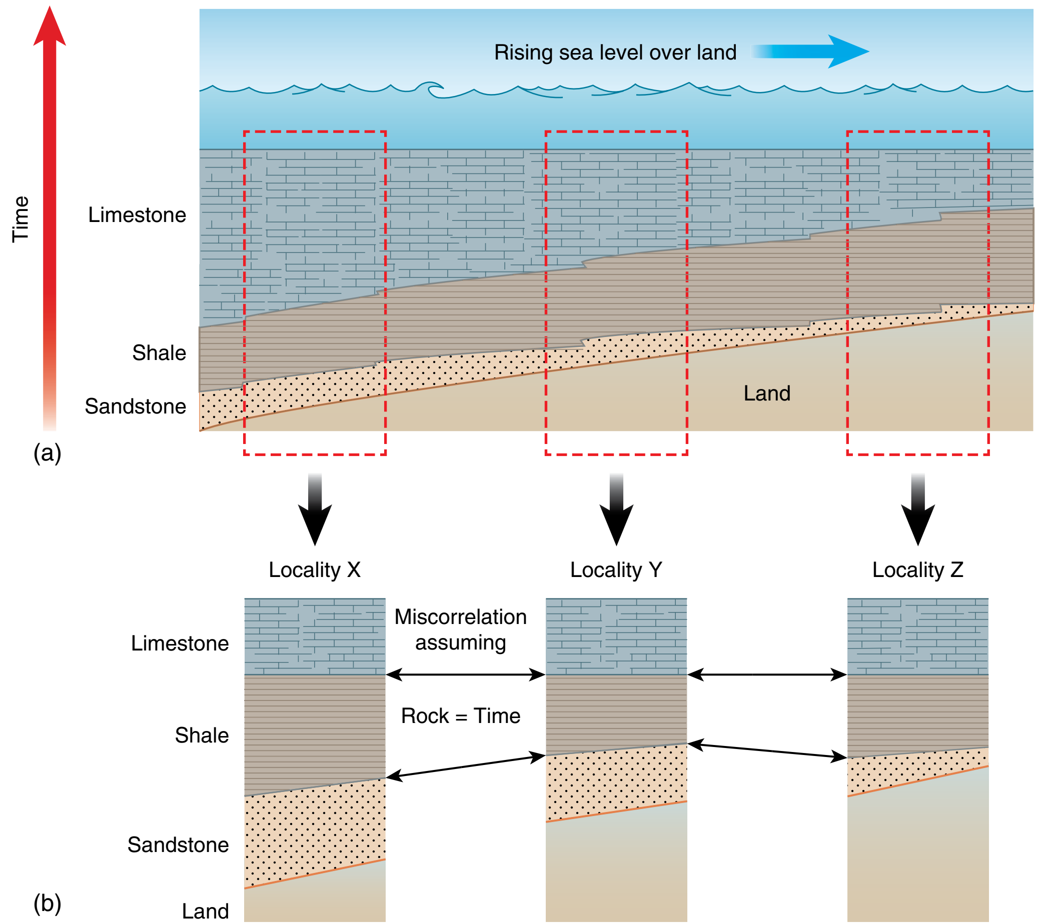


FIGURE 6.8 Map view and cross-section of modern environments on the Great Bahama Bank. A number of different environments and rock types exist at the same time. In the geologic record, these rock types would be recognized and mapped as formations, but the fact that they were deposited simultaneously would not be established until time lines were added.



Data from: Wicander, R., and Monroe, J. S. 2000. *Historical Geology: Evolution of Earth and Life Through Time*, 3rd ed. Pacific Grove, CA: Brooks/Cole. Figure 3.12 (p. 48).

FIGURE 6.9 The difference between facies and formations, illustrating that rock and time are not the same. **(a)** As sea level rises, the three formations represented by sandstone, shale, and limestone, move landward. All three environments exist through time, but the ages of each of the types of rocks, which are recognized as formations, differs over the area in which the rocks are exposed. **(b)** Miscorrelations result if rock and time are considered equal (arrows). The red and orange dots represent the extinctions of trilobites that are used instead to produce more accurate time lines for correlation (see section "6.5.3 Biostratigraphy" for further discussion). Note how the ages of the rocks are not the same between the localities, even within the same formation.

the field at the scale of a few outcrops at the base of the Grand Canyon.

CONCEPT AND REASONING CHECKS

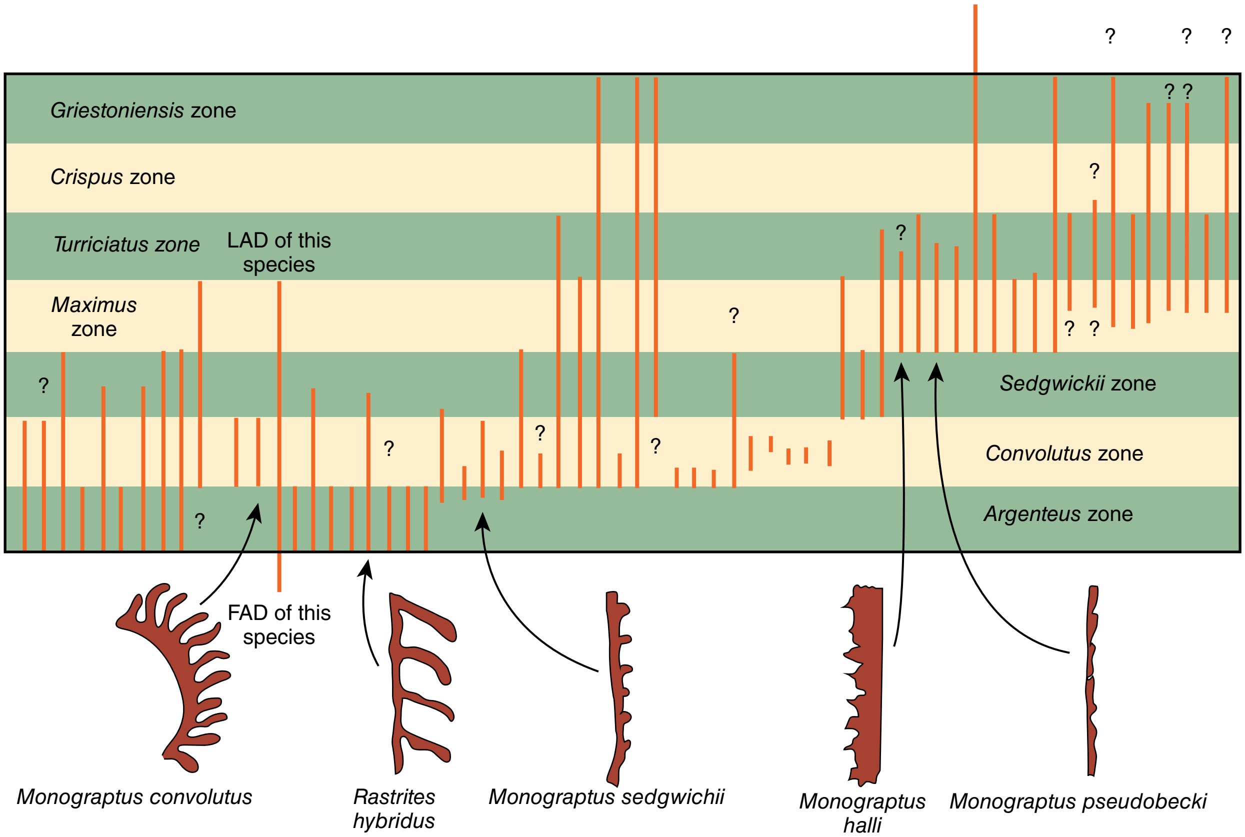
1. Why doesn't rock normally equal time?
2. Diagram the shift of facies in a transgressing and regressing seaway. Then, indicate the formations.

6.5.3 Biostratigraphy

H Very often, though, lithocorrelation works quite well. In fact, geologists use it all the time to correlate well-logs within relatively small areas. However, rock can only be confidently equated with time over relatively short distances. If we are to correlate successfully over longer distances and avoid making erroneous reconstructions of Earth history, we must use fossils because the succession of fossils can be equated with time.

The use of fossils to study the stratigraphic relationships of sedimentary rocks is called **biostratigraphy**. After formations have been identified and mapped, they can be correlated using their enclosed fossils. For example, the time lines in the example of the Grand Canyon were established using the extinctions of fossils called trilobites, which are distantly related to insects, crabs, lobsters, shrimp, and spiders.

The easiest way to conduct biostratigraphy is to use the **First Appearance Datums (FADs)** and **Last Appearance Datums (LADs)** of different fossil species (**Figure 6.10**). Usually, the FAD of a species represents the first evolutionary appearance of the species, and the LAD its extinction. The use of FADs and LADs was developed over the past few decades by the Deep Sea Drilling Program; its successor, the Ocean Drilling Program (now superseded by the Integrated Ocean Drilling Program), and petroleum companies. These groups needed methods that could be used in rapid biostratigraphic correlation of sediments in deep-sea cores and oil wells. In fact, of all the types of biostratigraphic datums, FADs and LADs are probably the most easily and rapidly



Data from: Martin, T. 1998. *One Long Experiment*. New York, NY: Columbia University Press. Figure 2.3 (p. 30), and Wicander, R., and Monroe, J. S. 2000. *Historical Geology: Evolution of Earth and Life Through Time*, 3rd ed. Pacific Grove, CA: Brooks/Cole. Figure 3.31 (p. 64).

FIGURE 6.10 First and Last Appearance Datums of different species of the extinct planktonic taxon called graptolites (see Chapter 11). The base of the range of each species (orange vertical lines) represents its First Appearance Datum (FAD) and the last (uppermost) occurrence its Last Appearance Datum (LAD). The overlapping ranges are then used to define biostratigraphic units called zones that are used for correlation, as discussed in the text.

determined. This is particularly advantageous when deep-sea cores or oil-well samples suddenly become available, especially in the middle of the night (because drilling continues around the clock). An age determination can be critical to determining whether to continue drilling, which takes time and costs money.

The use of FADs and LADs is really a highly simplified version of a much older process of biostratigraphic correlation. This process was developed by the German paleontologist, Albert Oppel, while he was working in the Jura Mountains in the 1850s. Instead of using just one species, as with FADs and LADs (Figure 6.10), Oppel plotted the stratigraphic ranges of multiple fossil species at each of many different localities. He used extinct fossils called *ammonites*, which are related to the modern octopus, squid, and pearly *Nautilus*. Oppel found that the ranges of the different ammonite species overlapped: some species were short ranging geologically, whereas others had intermediate to long ranges and spanned greater thicknesses of rock.

Oppel termed these intervals of overlap **overlapping** or **concurrent range zones** (Figure 6.10). Concurrent range zones consist of the ranges of individual species, each with their own FAD and LAD, within a biogeographic province. These individual ranges, called "teilzones," are plotted next to one another; an interval of overlapping teilzone ranges comprises a concurrent range zone. Thus, Oppel's method of using concurrent range zones was really the forerunner of the use of FADs and LADs. Oppel picked the upper and lower boundaries of each concurrent range zone where there were multiple appearances or disappearances of species (Figure 6.10). The technique of concurrent range zones produces zones as short as about 0.5 to 1 million years in duration, which is a substantial refinement of the ages provided by radiometric dates. However, the technique is labor intensive and time consuming, which is why FADs and LADs are now typically used.

An important aspect of biostratigraphy is that species are not uniformly distributed over Earth's surface because of differing tolerances to environmental factors (temperature, salinity, etc.) and barriers to migration and dispersal. An area on Earth's surface characterized by a particular group of marine species is called a biogeographic province (Chapter 3), and each ancient biogeographic province can have its own biostratigraphic zonation.

How, then, are the zonations of different provinces correlated? One method is to use more eurytopic species. Eurytopic species are fairly tolerant of environmental change, unlike stenotopic species (see Chapter 3). Eurytopic species are therefore more wide ranging geographically than stenotopic ones and more likely to occur in more than one province. One can also correlate between provinces by using the migration of a species from one province to another due to the dispersal of larvae, spores, pollen, or adults by atmospheric or oceanic currents.

No matter what the means, though, correlating zonations of different provinces is necessarily imprecise. Eurytopic species tend to have longer geologic ranges than stenotopic ones because they are more likely to survive environmental disturbances and therefore persist through time. In the case of migration, the appearance or extinction of a species in one province is unlikely to occur at exactly the same time as in another province. However, this is the best we can do.

Still, in many cases zonations of different provinces have been correlated. This has resulted in the recognition of what are called **index fossils**. An index fossil is a fossil species that is, ideally, easily identified, widespread, and abundant. All these traits make an index fossil especially useful for rapid determination of the approximate age of an outcrop and its correlation in the field. With index fossils there is a trade-off between eurytopy (being widespread) and rapid evolution and extinction that provide FADs and LADs for correlation. Index fossils are sufficiently eurytopic to be widespread and reasonably abundant but at the same time sufficiently stenotopic to undergo evolution and extinction fairly frequently and produce biostratigraphic markers.

Although Oppel did not originate the concept of index fossils, it is implicit in his work. The geologic range of an index fossil consists of the sum of the ranges of the same species in all the provinces in which it occurs, or its **total range zone**. By establishing the total range zone of a species, one establishes the total geologic range of an index fossil. The ranges of index fossils get down to about the epoch level of temporal resolution, or tens of millions of years. Although index fossils are not nearly as precise as using concurrent range zones, when finding an index fossil, we can be confident that we are dealing with rocks deposited within a particular interval of time. This provides a quick way of assessing the ages of rocks, especially if you are in the field, perhaps far removed from any form of civilization and no other resources are available.

CONCEPT AND REASONING CHECKS

1. What is the difference between the individual range zone of a species, concurrent range zones, and the total range zone of a species?
2. Diagram how the stratigraphic range of an index fossil is derived.

6.5.4 Integrating different stratigraphic datums

The different types of datums—lithologic, biostratigraphic, and so on—are by no means used separately. They are routinely integrated into standardized **chronostratigraphic** ("chrono" for time) frameworks into which absolute ages are incorporated to provide as high a time resolution as possible. Take, for example, a deep-sea core for which both FADs and LADs have been determined (**Figure 6.11**). These biostratigraphic datums yield relative dates. How can we determine the absolute ages for the datums? First, we can use a magnetometer to detect magnetic reversals that formed as the sediment was being deposited and that are recorded in the cores. If these same reversals can then be correlated to, say, igneous rocks on land, the reversals can be dated radiometrically and their absolute ages established.

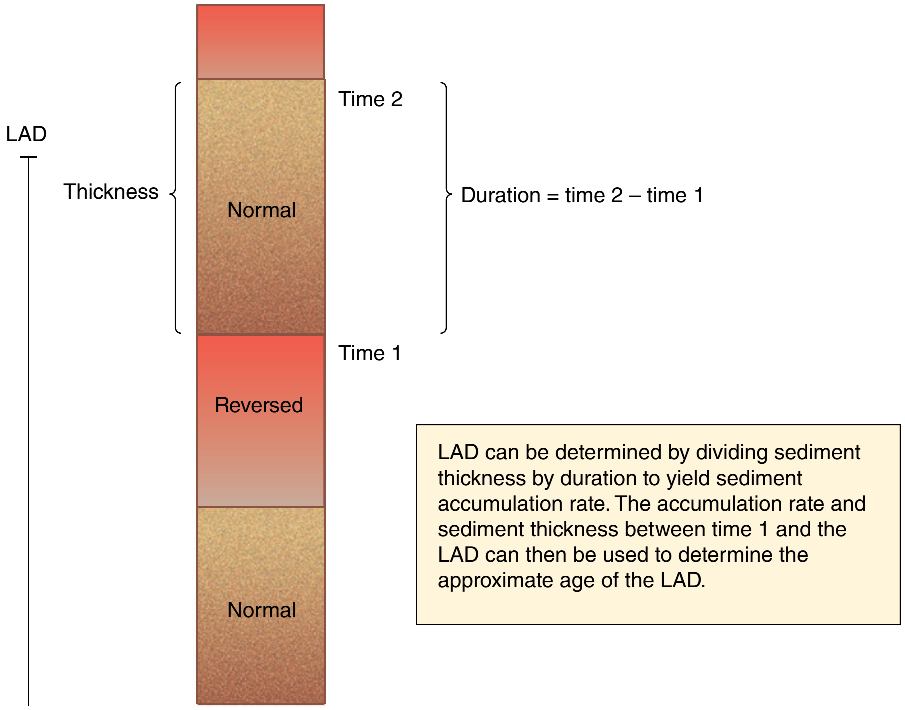
But what if the levels of the magnetic reversals in the cores don't match those of the biostratigraphic datums? Now what do we do? We can calculate the sedimentation rate in the core using the thicknesses of the relevant sections and the available absolute ages. This gives us an average sedimentation rate that we can use to calculate an approximate absolute age for the biostratigraphic datums at the levels where they occur in the core. We can then compare the ages for the biostratigraphic datums with those in other cores as they become available or when new data for magnetic reversals or absolute ages are determined. In this way the chronostratigraphic framework is progressively refined because the ages obtained for the biostratigraphic datums will begin to converge on a particular age.

6.6 How Complete Is the Geologic Record?

6.6.1 Unconformities and diastems

J The geologic record is by no means complete, and it does not record every event faithfully. Assume that a particular spot on Earth's surface started out with an uninterrupted sediment accumulation rate of 1 meter per thousand years or 1 kilometer per million years. This is not an unusual rate for relatively rapid sedimentation adjacent to a large delta depositing large amounts of sediment, for example. This would mean that over the course of the Phanerozoic, or about 540 million years, 540 kilometers of sediment would have accumulated. This thickness is many times greater than the sections of the thickest passive continental margins! Clearly, much of the sediment must have bypassed the site of deposition to deeper sites, was eroded, or the sediment was never deposited in the first place.

In fact, much of the geologic record is not represented by sediment at all but by surfaces of erosion or nondeposition called **unconformities** (**Figure 6.12**). Unconformities are only the most obvious expression of erosion or nondeposition of sediment and typically represent gaps in time on the order of hundreds of thousands to millions of years or more. It was a particular type of unconformity called an **angular unconformity** that Hutton observed at Siccar Point (see Chapter 1); an angular unconformity is also present at the base of parts of the Grand Canyon (refer to this chapter's frontispiece). Other types of unconformities are much more common. One type is a **disconformity** in which the erosional surface is overlain by more horizontal layers of sediment (Figure 6.12). Sometimes, a disconformity is so subtle it is not at first obvious, in which case it might be called a "paraconformity." Igneous and metamorphic rocks can also be eroded and sediments deposited on top to produce a **nonconformity** (Figure 6.12).



Data from: Tarbuck, E. J., and Lutgens, F. K. 2000. *Earth Science*, 9th ed. Upper Saddle River, NJ: Prentice-Hall. Figures 7.19 and 7.20 (p. 202).

FIGURE 6.11 Simplified example of how the absolute ages of biostratigraphic and other types of datums are determined and integrated. In this example, the FADs and LADs have been determined for a deep-sea core, yielding relative dates. Magnetic reversals recorded in volcanic rocks while the sediment was being deposited are determined with a magnetometer. If we can date the reversals radiometrically (from, say, intruded volcanic rocks or seafloor stripes), we can determine the sedimentation rate by using the thicknesses of the core section and the absolute ages. This yields an average sedimentation rate that we can use to calculate absolute ages for biostratigraphic datums in the core. The ages of the datums are refined by repeating this process over and over for the same datums in different cores from different areas.

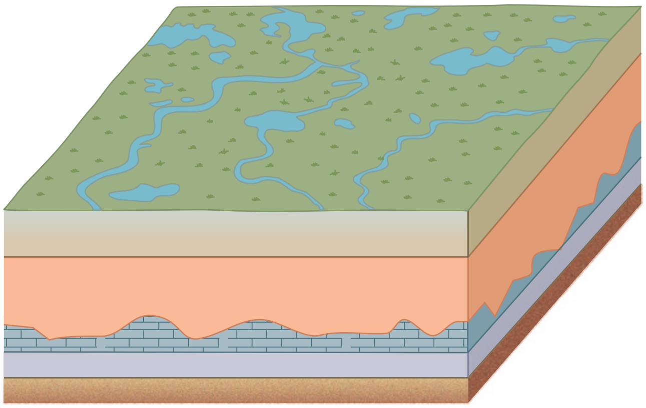
The time represented by the missing sediment is called a **hiatus** (Figure 6.12). The term "hiatus" is distinguished from an unconformity because even though no sediment was deposited during a particular interval of time or was later eroded, *time still passed.* Thus, not all time is represented by sediment in the geologic record.

At the other extreme from unconformities are **diastems**. Diastems are gaps in the stratigraphic record so short they are virtually undetectable. Much of the sedimentary record is missing more because of diastems than unconformities. Diastems are caused by very short-term changes in deposition. Sedimentation within a particular environment is not uniform everywhere and continuous throughout the same short interval of time, even during "normal" times, whereas short-term events such as storms can redistribute previously deposited sediment but leave no record of the storm. Inbetween, unconformities and diastems are stratigraphic gaps and hiatuses of all magnitudes and durations like those of the Grand Canyon (Figure 6.12).

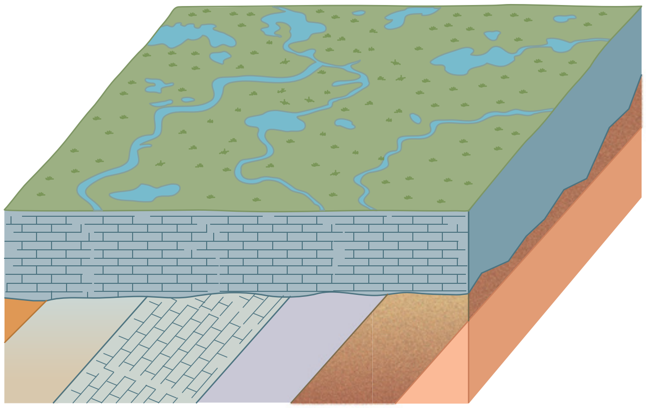
6.6.2 Sequence stratigraphy

Unconformities, especially disconformities, are the basis for the discipline of **sequence stratigraphy**. The basic unit of sequence stratigraphy is the **depositional sequence** that consists of rocks or sediments laid down relatively continuously but are bounded above and below by an unconformity. Each unconformity represents a **sequence boundary**.

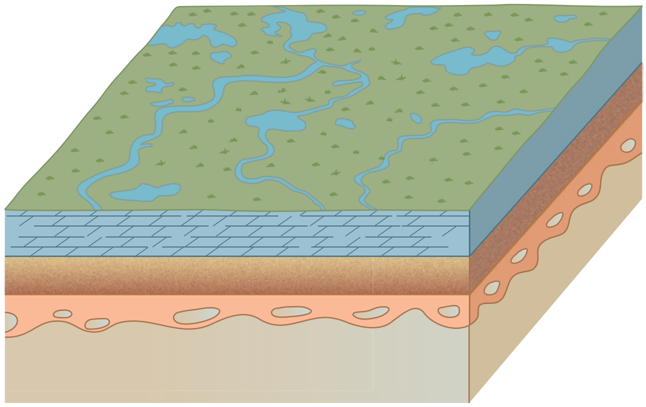
The concept of depositional sequences was first recognized by Lawrence Sloss, who related them to major sea-level rises, or **transgressions**, and falls, or **regressions** over the North American continent during the Phanerozoic (**Figure 6.13**). Each of Sloss's sequences is represented by numerous formations and environments, all of which comprise a thick sedimentary section spanning many tens of millions of years. Each of his sequences is bounded above and below by unconformities that can be traced over large portions of North America. The transgressions and regressions responsible for these sequences might have resulted



Disconformity
(a)

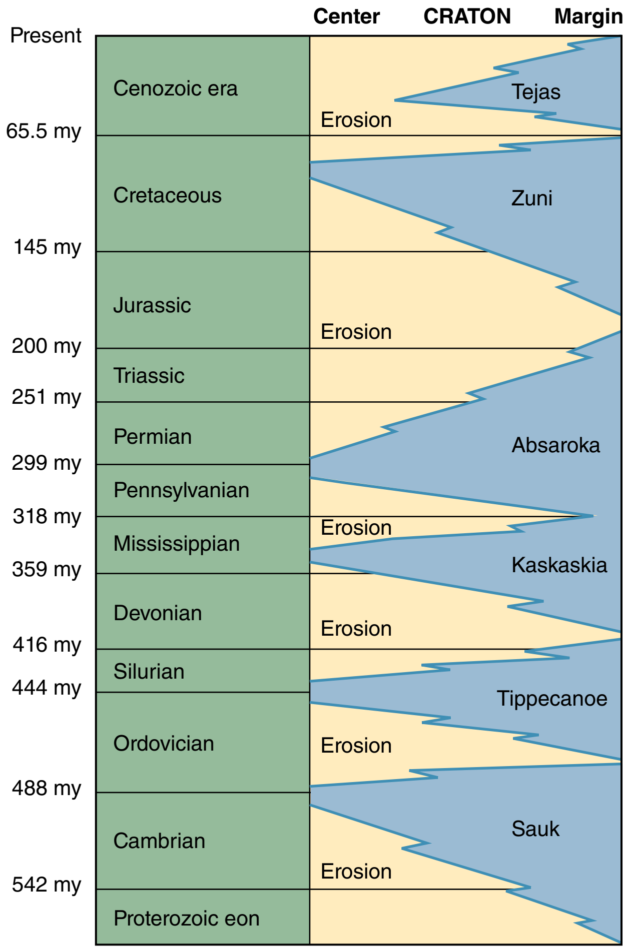


Angular unconformity
(b)



Nonconformity
(c) Data from: Monroe, J. S., and Wicander, R. 1997. *The Changing Earth: Exploring Geology and Evolution*, 2nd ed. Belmont CA: West/Wadsworth. Figure 17.10 (p. 418).

FIGURE 6.12 Types of unconformities. **(a)** A disconformity separating rocks of different ages. Sometimes, the disconformity is not particularly obvious, in which case it is called a paraconformity. **(b)** Angular unconformity. **(c)** A nonconformity involving erosion of an igneous intrusion, followed by deposition of sediment. Eroded fragments of the igneous rock body can be found in the overlying sediment.



Data from: Monroe, J. S., and Wicander, R. 1997. *The Changing Earth: Exploring Geology and Evolution*, 2nd ed. Belmont CA: West/Wadsworth. Figure 21.5 (p. 533).

FIGURE 6.13 The major depositional sequences recognized by Sloss for North America. The seas (blue) are shown to be moving gradually landward onto the continents (craton) and then retreating as the craton is eroded.

from changes in the size of large polar ice caps or changes in the volume of mid-ocean ridges, which would change the volume of water in the ocean basins by altering the volume of seafloor crust (see Chapter 3). The initial transgression in western North America that laid down the sequence of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone at the base of the Grand Canyon occurred as the basal part of the Sauk transgression or sequence.

Sloss's approach was further refined by Peter Vail, Robert Mitchum, and colleagues, who were former students of Sloss and had moved to the U.S. Gulf Coast. They developed sequence stratigraphy to better predict the location of oil and gas reservoir sands, but the technique of sequence stratigraphy is now widely used by all stratigraphers (see Chapter 17 for petroleum exploration). Like Sloss's sequences, their depositional sequences are cyclic in nature and caused mainly by sea-level fall and rise. However, their depositional sequences typically represent durations of tens of thousands to several hundred thousand years, depending on environmental setting and the mechanisms causing sea-level change. In the Gulf Coast, for example, the younger sequences are often related to sea-level change caused by

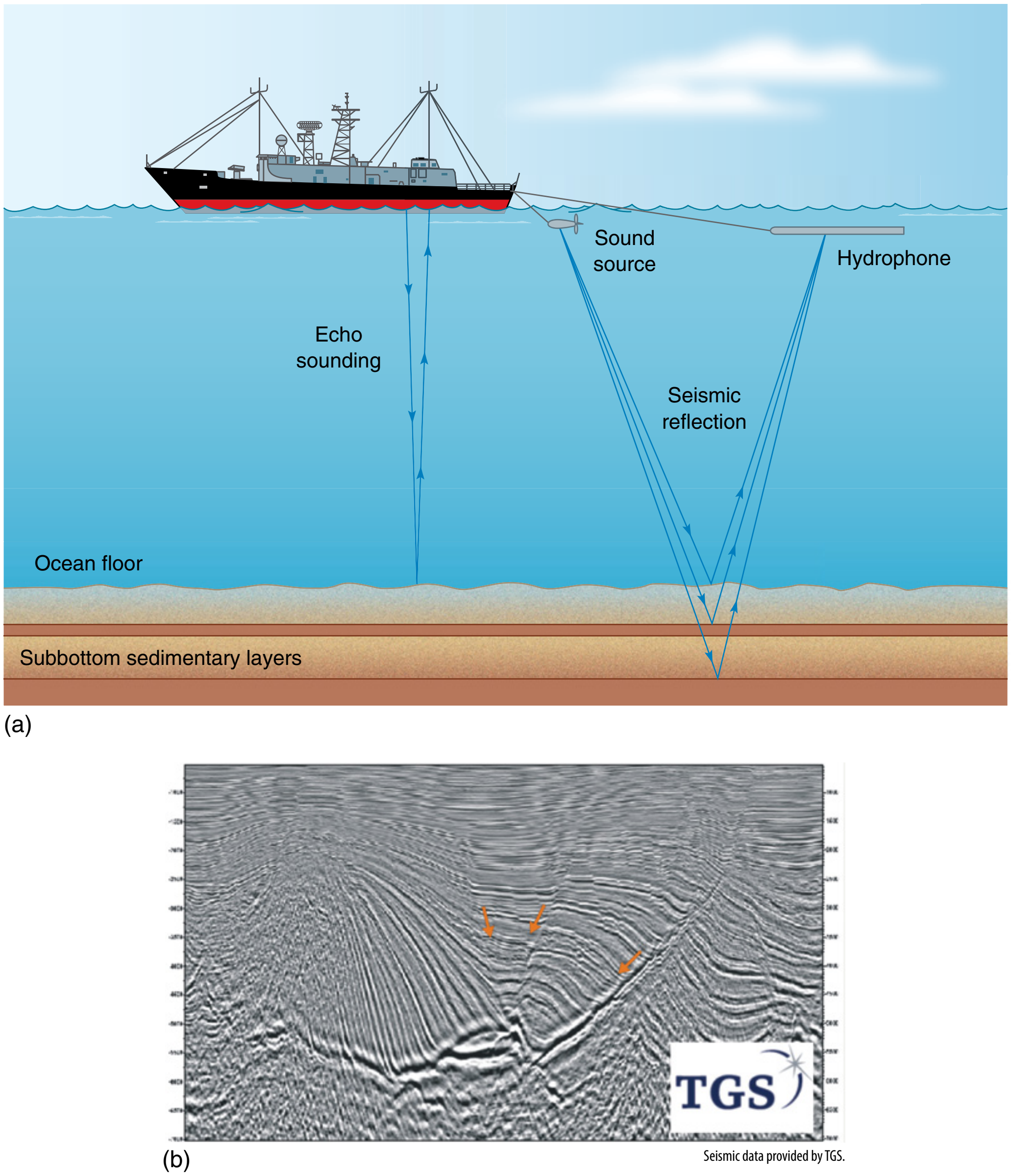


FIGURE 6.14 **(a)** The collection of seismic data. Pulses of energy are sent out at specified intervals from the ship. These energy pulses are either reflected back from the strata or travel through the rocks and then return to the surface. Here, the reflected energy is collected by special instruments called hydrophones which are being towed by the ship. A similar procedure is used on land. The data are recorded and then processed to produce a seismic section like that shown here. **(b)** Seismic section. Arrows indicate some of the major faults along which sediments have moved downward. Alternating dark and light layers roughly correspond to systems tracts (see Figure 6.15).

the waxing and waning of glaciers during the Neogene (**Figure 6.14**). Individual depositional sequences and their component systems tracts can be identified on seismic sections, which are produced by remote sensing techniques (Figure 6.14).

These depositional sequences are normally first recognized on seismic sections and later correlated to well-logs and biostratigraphic extinctions (called "tops" in oil industry parlance) seen in oil wells. At the base of each depositional sequence is a sequence boundary formed through erosion during sea level by regression (**Figure 6.15**). As sea level falls, river deltas prograde across the shelf; if sea level falls sufficiently, eventually the deltas dump sediment at or beyond the continental shelf edge to form a type of deposit called a **lowstand systems tract**, which consists of submarine fans. Very often, oil and gas are trapped in reservoirs formed by sand channels within the submarine fans.

Two other systems tracts occur above the lowstand systems tract in a complete depositional sequence. As sea level begins to rise and the deltas retreat shoreward, a **transgressive systems tract** forms over the shelf once occupied by the deltas (Figure 6.15). As the rate of sea-level rise slows and approaches its maximum height, a **highstand systems tract** develops (Figure 6.15). During this time, if there is enough sediment entering the system, the deltas build back out across the continental shelf. Ideally, all systems tracts are

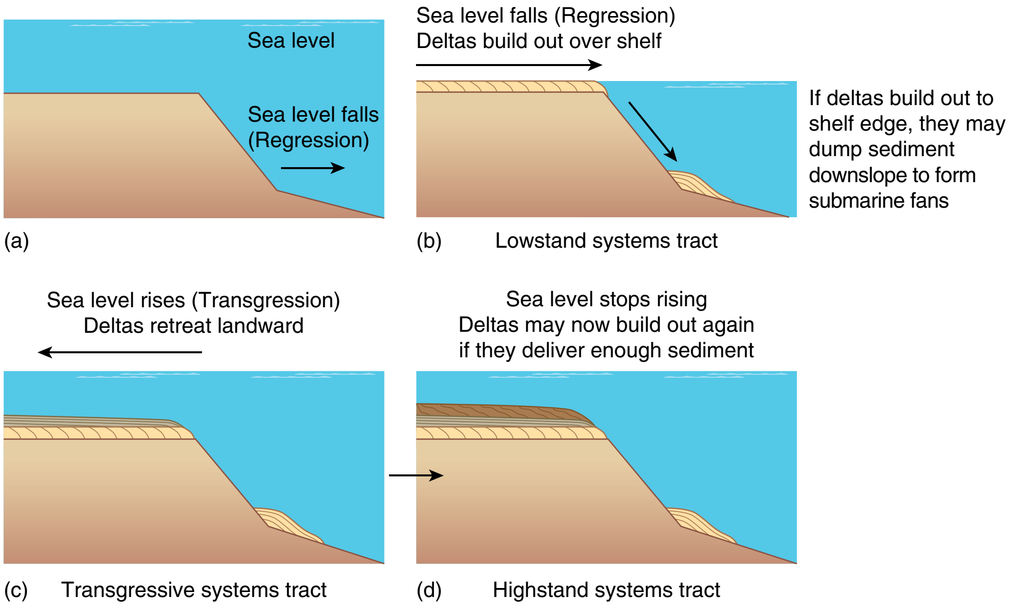


FIGURE 6.15 How a depositional sequence and its systems tracts form in response to sea-level transgression and regression.

preserved in a depositional sequence, but quite often parts of one or more of the system tracts are destroyed by erosion resulting from the next sea-level regression.

Despite the incompleteness of the stratigraphic record, the geologic record still provides a valuable means of understanding past environmental change on scales of time longer than those observable by humans. Because strata and fossil assemblages accumulate over relatively long periods of time, they are more likely to indicate longer-term environmental conditions, including unusual conditions that we might otherwise not detect on human time scales.

CONCEPT AND REASONING CHECKS

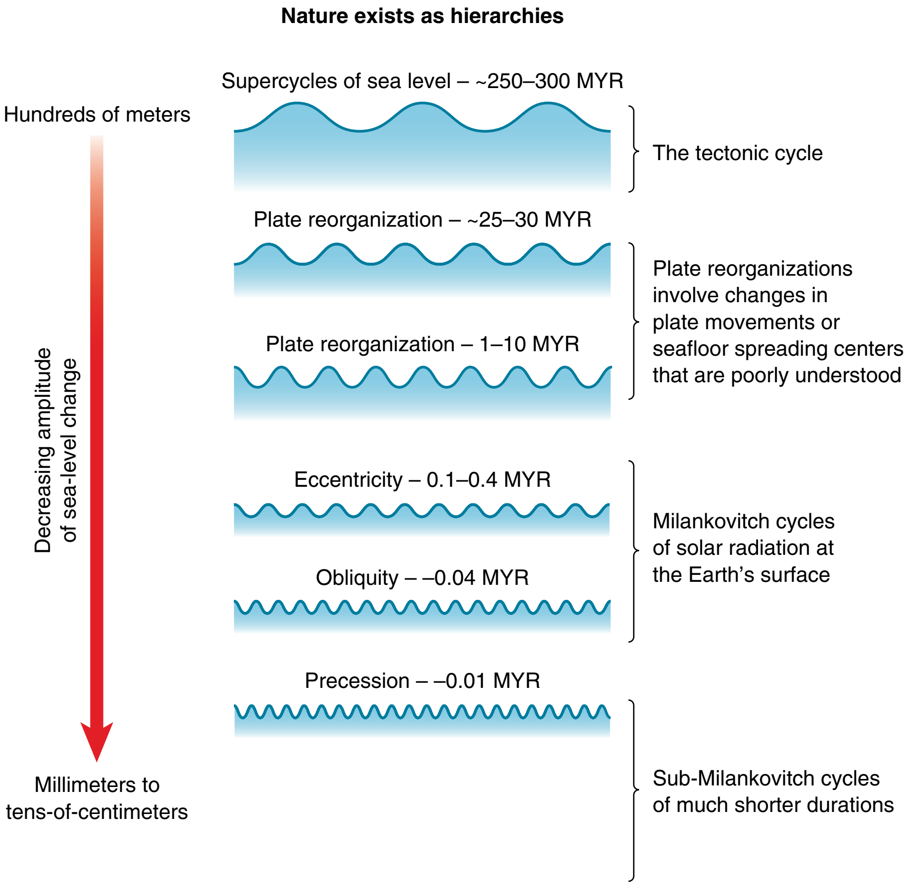
1. Diagram the formation of lowstand, transgressive, and highstand systems tracts in response to sea-level change.
2. Indicate the positions of disconformities on your diagram in question 1.
3. What sort of unconformity lies at the base of Siccar Point (see Chapter 1)?

6.7 Why Is Sea Level So Important?

K Sea level is important for several reasons, which we've already discussed. First, sea level determines the broad distribution of sedimentary facies and their fossils like those of Figure 6.9. It is the sedimentary rocks and fossils that record many of the changes in Earth's ancient climates. Second, sea level affects climate by affecting Earth's albedo, or surface reflectivity, which in turn affects global temperatures (see Chapter 3). Third, sea level is a broad indicator of the overall tectonic and climatic conditions on Earth. We have already alluded to this in our discussion of the causes of Sloss's sequences (Figure 6.13).

Indeed, the relative importance of the geologic processes that cause transgressions and regressions vary with the durations—or scales—of time involved (**Figure 6.16**). For example, if we were to take continuous measurements of the elevation of the ocean's surface at monitoring stations for a period of years, sea level would be seen to oscillate according to the tides (which are caused by the gravitational attraction of the moon on the ocean's surface). Such a monitoring network exists through tide gauges and satellite measurements. Other than the tidal fluctuations, however, sea level would appear to be relatively constant at each station from one year to the next.

Sea level also fluctuates on longer time scales, and the processes involved change accordingly. On time scales of decades or centuries, sea level can change by millimeters to centimeters. Although this does not sound like much, it is if your home is located in a low-lying area or along an eroding beach. These sea-level oscillations are most likely due to changes in water temperature and atmospheric circulation that are related to climate. Warmer temperatures cause ocean water to expand and global sea level to rise, whereas changes in the direction and speed of ocean currents, in response to changes in atmospheric circulation patterns, can cause sea level to fluctuate over large areas. On longer time scales of



Reproduced from: Vail, P. R. 1987. Seismic stratigraphic interpretation using sequence stratigraphy. In: Bally, A. W. (ed.) *Atlas of Seismic Stratigraphy*. Tulsa, OK: American Association of Petroleum Geologists Studies in Geology 27. Figure 1 (p. 2).

FIGURE 6.16 The hierarchy of processes that affect rates of sea-level change. A hierarchy is like a set of smaller and smaller boxes nested within one another, in this case involving shorter and shorter cyclic changes of sea level as one moves down the diagram. The processes that affect sea level also change with shorter durations of time (down the diagram), as shown. Eccentricity, obliquity, and precession refer to Milankovitch cycles of solar radiation reaching the Earth's surface; these cycles affect the advance and retreat of glaciers, which in turn affect sea level on these time scales (see Chapter 15). Even shorter "sub-Milankovitch cycles" of different durations occur, too (Chapter 16). If we use a "yardstick" (time scale) that is too short, such as observations made over human time scales (years, decades, centuries), the environment might appear relatively constant to us, with regard to longer-term processes like those nearer the top of the diagram. As the yardstick (time scale) lengthens, though, we are more likely to detect significant processes and changes on the Earth that cannot be observed or measured on human time scales and can only be detected in the rock and fossil record.

a few thousand years up to hundreds of thousands of years, sea-level change is more likely due to the advance and retreat of glaciers, like that described earlier for the formation of depositional sequences during the Plio-Pleistocene. In these cases, sea level might have oscillated up to 100 meters or so.

These particular cycles are called Milankovitch cycles and cause changes in the amount of solar radiation reaching the Earth's surface resulting from changes in the elliptical nature of the Earth's orbit around the Sun (eccentricity), changes in the angle of tilt of the Earth's axis of rotation, and shifts in where the seasons occur in the Earth's orbit (precession; see Chapter 15). On even longer time scales of many millions of years, sea-level change like that of the Sloss sequences is thought to also occur in response to changes in seafloor volume or the directions in which Earth's lithospheric plates are moving. As the plates change direction, the kinds of boundaries or the amount of seafloor crust produced at the boundaries can change; this alters the volume of the ocean basins and therefore the amount of water they can hold, causing sea level to go up or down. Finally, on scales of hundreds of millions of years, sea level fluctuates with the assembly and rifting of supercontinents, which affects mid-ocean ridge volume and the volume of water the ocean basins can hold (see Chapter 3). Changes in plate boundaries or mid-ocean ridge volume can cause sea level to fluctuate on the order of several hundred meters. Thus, the relative importance of the processes that affect sea level varies with time scale.

Conversely, our choice of time scale determines the processes that we observe or infer to affect sea level (Figure 6.16; see also Chapter 1). The choice of time scale is like selecting a measuring stick. If we were trying to measure sea-level change occurring in response to plate tectonic processes by using tide gauges on human time scales (a few years to decades or centuries), we would not see anything happening and sea level would appear constant. In fact, to determine that sea level has changed on long scales of time we would need to examine the sedimentary and fossil records; even the most sophisticated human instruments would be useless in this case because the "yardstick" (time scale) would be too short to detect any significant long-term change. Furthermore, detailed instrumental records like those from tide gauges are available only back to about the mid-19th century. The only records we have before this time, whatever the time scale or processes of interest, are the sedimentary and fossil records.

Again we see that Earth's history is an invaluable record of environmental change. Although not necessarily observable on human time scales, environmental change during Earth's evolution affects us because it determines the conditions under which we and other life on the planet exist.

CONCEPT AND REASONING CHECKS

1. Why is sea level important to geologists?
2. Would the rates of sea-level change occurring during a tectonic cycle (see Chapter 3) be discernable on human time scales? (Hint: Think about the rates of seafloor spreading discussed in Chapter 2.)

Summary

- Time is important to Earth scientists for two fundamental reasons. First, having "enough" time gives Earth scientists intellectual room to consider geologic processes and conditions not observed today. Second, time is important to establish the causes of phenomena or "effects" preserved in the geologic record.
- The geologic time scale has evolved. Early time scales equated rock with time; thus, distinctive types of rocks were concluded to have all formed at once. The most extreme version of this view was Neptunism, which stated that rocks were precipitated from a global ocean. However, with the recognition of the Principle of Faunal Succession by William Smith, fossils were used increasingly to subdivide rocks, especially those of the Phanerozoic, into smaller units called eras, periods, and epochs.
- We can determine the ages of rocks and fossils by using two different types of dates: relative dates from stratigraphic sequences of rocks and fossils and absolute ages from radiometric dates. Although absolute dates give ages in years, fossils, in particular the field of biostratigraphy, have been used to "interpolate" between dates and to recognize finer subdivisions of the geologic time scale.
- Time relationships of different events are established by the procedure of correlation. Correlation is done in two basic ways: correlation of rocks (lithocorrelation) and correlation of fossils (biostratigraphy). Lithocorrelation equates rock with time and normally works well over short distances but is prone to error over large distances because (1) similar kinds of sedimentary rocks and the environments in which they formed repeat themselves through time and (2) different kinds of sedimentary rocks (environments) have existed at the same time.
- These two points form the basis of the concept of facies. The concept of facies refers to the fact that different sedimentary rocks and the environments in which they were deposited can exist at the same time and that the same rocks (environments) have existed at different times.
- To distinguish rock from time, distinctive rock units are first recognized as formations, which are units of rock that we can recognize and map in the field based on their particular physical traits, such as color or grain size.
- Time lines are then determined by using fossils. The fossils within the formations are correlated between different areas using biostratigraphy. We can use biostratigraphic correlation over much longer distances because fossils are unique: when different groups of organisms go extinct they are gone forever. However, fossils can evolve and go extinct at different times in different places, so biostratigraphy is not simply a matter of "connecting the dots" represented by the first and last appearances of species. Also, the geographic distribution of organisms affects the types of fossils found in different places and their use in biostratigraphic correlation.
- The geologic record is not a continuous record of sediment deposition through time. Much sediment is lost through erosion or nondeposition to produce surfaces called unconformities. Thus, not all time is represented by the rock record. Unconformity-bounded sequences of rock are called depositional sequences and form the basis of sequence stratigraphy. Despite the incompleteness of the stratigraphic record, we can still use the geologic record to understand the longer-term state of the environment.
- Sea level determines the broad patterns of depositional environments and facies, which record much of the history of Earth in their sediments and entombed fossils.
- Without these records a great deal of Earth's history would be lost and our understanding of this planet's evolution would be far more fragmentary because sea level reflects and interacts with tectonics and climate to shape the Earth. The relative importance of the processes affecting sea-level change varies with the choice of time scale.

Key Terms

absolute ages
angular unconformity
aquifers
Archean
Archeozoic
biostratigraphy
blocking temperature
Cambrian
Carboniferous
Cenozoic
chronostratigraphic
closure
concordant
concurrent range zones
correlation
Cretaceous
Curie point
daughter
dendrochronology
depositional sequence
Devonian
diastems
disconformity
discordant
distinctive sequences
Eocene
eons
epochs
eras
facies
facies change
First Appearance Datums (FADs)
formation
half-life
hiatus
highstand systems tract
Holocene
index fossils
Jurassic
Last Appearance Datums (LADs)
lithocorrelation
lithostratigraphy
lowstand systems tract
magnetic reversals
marker beds
Mesozoic
Miocene
Mississippian
Neogene
Neptunism
nonconformity
Oligocene
Ordovician
overlapping
Paleocene
Paleogene
Paleozoic
parent isotope
Pennsylvanian
periods
Permian
Phanerozoic
Pleistocene
Pliocene
Precambrian
Principle of Cross Cutting Relationships
Principle of Faunal Succession
Principle of Original Horizontality
Principle of Superposition
Proterozoic
Quaternary
radiometric dates
regressions
relative ages
sequence boundary
sequence stratigraphy
Silurian
stratigraphy
Tertiary
total range zone
transgressions
transgressive systems tract
Triassic
unconformities
walking the outcrop
Walther's Law
well-logs

Review Questions

1. Why is time important in establishing cause and effect?
2. What is the difference between relative and absolute ages?
3. What were the important events in the development of the geologic time scale?
4. The half-life of ^{238}U is 4.5 billion years. How old is a rock containing a ratio of the daughter ^{206}Pb/^{238}U of 0.5? How old is a rock with a ratio of 0.75?
5. If the daughter isotope leaks from a mineral, will the leakage cause the age of the mineral to be too old or too young?
6. Why is it often incorrect to equate rock and time? Use labeled diagrams to explain your answer.
7. What is the difference between a formation and a facies? Use labeled diagrams in your answer.
8. Describe the different methods of lithocorrelation.
9. Compare FADs and LADs to overlapping range zones using labeled diagrams.
10. How do the biogeographic distributions of species affect their use in biostratigraphic correlation? Use labeled diagrams in your answer.
11. How do the environmental tolerances of species affect their use in biostratigraphic correlation?
12. What are the traits of an index fossil?
13. How is the geologic range of a fossil species determined so that we can use it as an index fossil?
14. What are the approximate durations of (a) overlapping range zones; (b) index fossils; (c) geologic epochs; (d) geologic periods; (e) geologic eras; (f) geologic eons?
15. Diagram a complete depositional sequence, label all systems tracts, and relate the systems tracts to sea-level cycles and sedimentation.
16. What is the difference between an unconformity and a hiatus?
17. How does sea level vary with process?

Food for Thought:
Further Activities In and Outside of Class

1. Why is knowing Earth's age important?
2. Determine the percentage of time each of the following represents: (a) Precambrian; (b) Hadean; (c) Archean; (d) Proterozoic; (e) Phanerozoic.
3. Why are radioactive elements with long half-lives required to date rocks billions of years old?
4. Why hasn't Lyell's method of subdivision of the Cenozoic been applied to the Paleozoic and Mesozoic?
5. How would you distinguish an igneous pluton from a nonconformity?
6. Compare and contrast the terms formation, facies, depositional sequence, and systems tract. Draw a depositional sequence with all the possible systems tracts, and then label what you consider to be formations and facies.
7. Divide into groups of several students. On large poster sheets, construct diagrams illustrating superposition, cross-cutting relationships with igneous intrusions and faults, unconformities, and radiometric dates. Challenge other groups to determine the sequence of events in your poster.

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