CHAPTER

3

Earth Systems: Processes and Interactions

Major Concepts and Questions Addressed in This Chapter

- **A** What is the rock cycle, and how is it related to plate tectonics and the tectonic cycle?
- **B** What are the major types of rocks, and how do we infer how and where they formed?
- **C** What are the major patterns of atmospheric circulation?
- **D** How does atmospheric circulation affect the distribution of heat and moisture over Earth's surface?
- **E** How fast do the oceans circulate?
- **F** How do the atmosphere and continental configuration affect ocean circulation?
- **G** What accounts for the distribution and diversity of plants and animals over Earth's surface?
- **H** How is the availability of energy related to the structure of biologic communities?
- **I** How are nutrients and other elements recycled, and why is nutrient recycling important?
- **J** How has the tectonic cycle affected the atmosphere and hydrosphere?

Chapter Outline

Yellowstone Gorge, Yellowstone National Park, Wyoming. The bright colors of the rocks result from lava flows and ash falls.

3.1 The Solid Earth System: Components and Processes

A Chapter 3 examines each of Earth's major systems in greater detail. As we proceed, recall the basic features of natural systems introduced in Chapter 1: (1) each major Earth system consists of a series of parts or compartments that comprise a larger integrated and complex whole, (2) each system is an open system that exchanges matter and energy with the environment, and (3) each system behaves in a cyclic manner because of the flow of matter and energy through the system.

The flows of matter and energy within and between systems are known as fluxes. This chapter emphasizes two major features of the fluxes of matter and energy:

1. Fluxes of matter and energy within systems and between systems are cyclic.
2. Systems interact with one another through the fluxes of matter and energy.

Recall, for example, that plate tectonics is driven by the flow of heat, which is itself produced by radioactive decay (Chapter 2). We will concentrate on how plate tectonics interacts with each of the other major Earth systems beginning with the rock cycle, and then move on to the behavior of the modern atmosphere, the hydrosphere, and biosphere. This will allow us to then examine how the tectonic cycle has broadly influenced the other systems through geologic time.

3.2 Rock Cycle

B The major cycle operating within the solid Earth system, especially the lithosphere, is the rock cycle (**Figure 3.1**). The rock cycle involves the formation and destruction of the three major rock types, or *lithologies*: **igneous**, **sedimentary**, and **metamorphic**. Igneous rocks are those that have cooled and solidified from magma (from the Latin, for "characterized by fire").

In an idealized example of the rock cycle, igneous rocks erode to produce sedimentary rocks that are later metamorphosed and then melted to produce igneous rocks (Figure 3.1). Usually, though, the rock cycle does not function this simply. Depending on conditions, all preexisting rocks, whether they are igneous, sedimentary, or metamorphic, can be subjected to any one or more of the processes of the rock cycle out of this sequence. Igneous rocks can, for example, be metamorphosed without first having been eroded; metamorphic rocks can erode to produce sedimentary rocks; sedimentary rocks can be metamorphosed; or sedimentary rocks can become caught up in a "sedimentary loop" in which they are recycled through the processes of erosion, transport, deposition, and lithification all over again to produce new sedimentary rocks.

3.2.1 Igneous rocks

Intrusive igneous rocks: occurrence, texture, and composition

Intrusive igneous rocks form beneath Earth's surface. Bodies of solidified magma beneath Earth's surface are referred to as **plutons** and vary substantially in size and shape. Gigantic plutons are called *batholiths*, whereas smaller dome-shaped

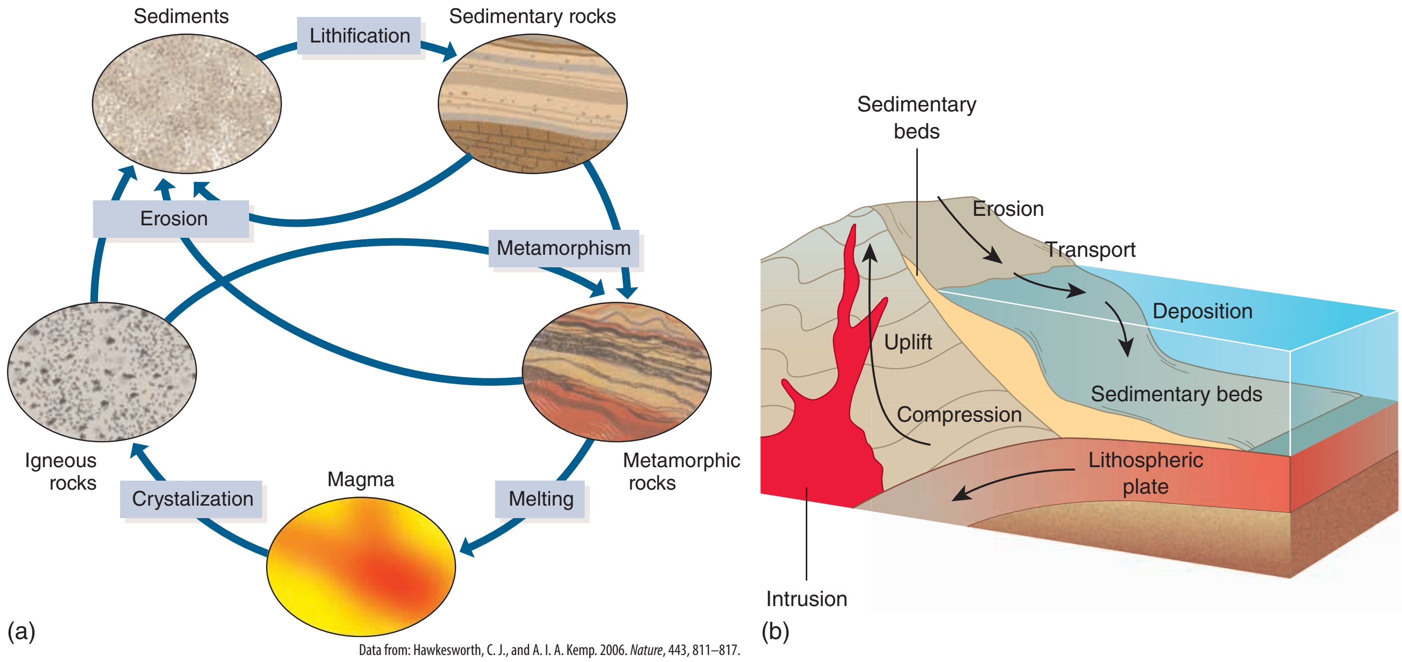
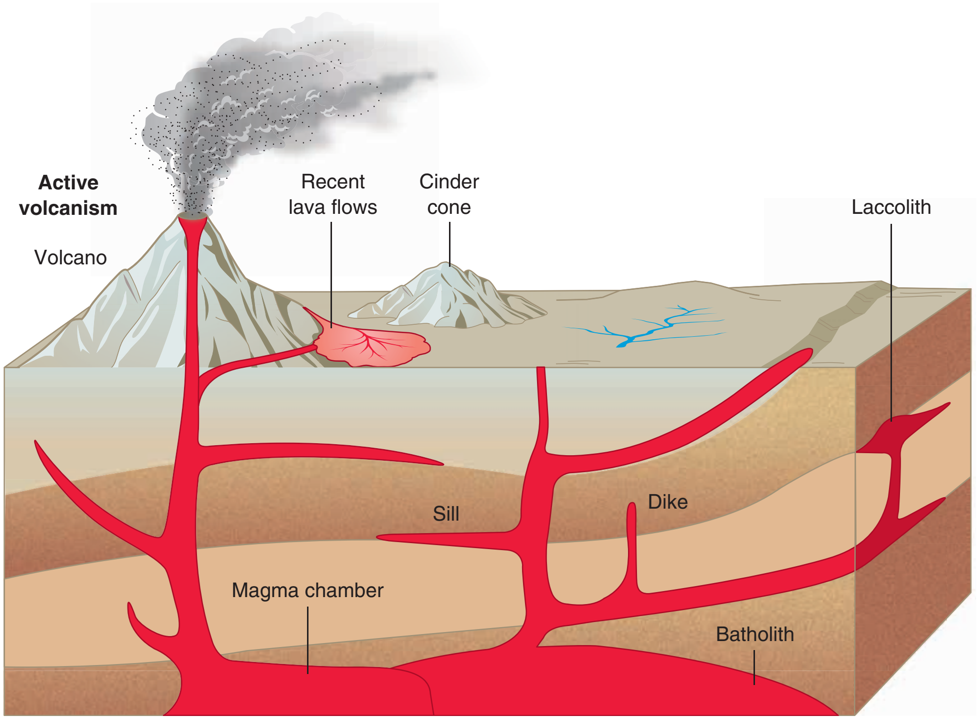


FIGURE 3.1 The rock cycle in relation to plate tectonics. The rock cycle involves the formation of molten magma and its intrusion into surrounding rocks or extrusion onto the Earth's surface as volcanoes; uplift, weathering and erosion, and redeposition to form sedimentary rocks; and metamorphism of preexisting rocks. Note the similarity of plate tectonics and the rock cycle.

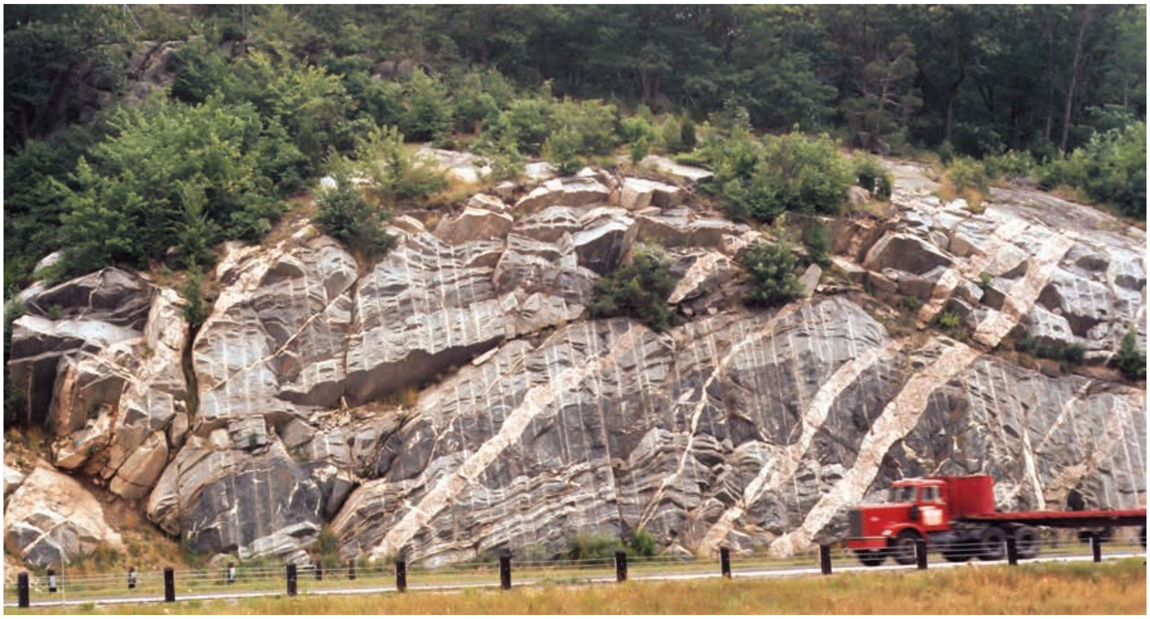
ones are called *laccoliths* (**Figure 3.2**). The dome shape of laccoliths occurs because the magma is still relatively thick and tends to collect in one spot, resulting in an igneous body with a relatively flat base and domed upper surface. Intrusive rocks can also occur as relatively thin bodies cutting across surrounding rocks (*dikes*) or injected parallel to strata (*sills*). One of the most spectacular sills is the Palisades Sill, located along the Hudson River, north of New York City; the Palisades are composed primarily of igneous rocks emplaced as the supercontinent Pangaea rifted apart (**Figure 3.3**).

Although no one has ever seen an intrusive igneous rock form, their emplacement beneath Earth's surface can be inferred from their coarse-grained, or **phaneritic**, texture ("phaneritic" means visible, referring to the visible mineral faces in the rock). The term *texture* refers to the size, shape, and arrangement of the grains in a rock. Phaneritic textures occur when minerals in the rock exhibit relatively large, blocky mineral faces that make them easily visible. This happens when the flux of heat from the magma to the surrounding environment occurs very slowly, giving the crystal faces sufficient time to grow into visible surfaces (**Figure 3.4**).



(a)

Reproduced from: U.S. Geological Survey (http://pubs.usgs.gov/of/2004/1007/volcanic.html). Accessed April 27, 2011.



(b)

Courtesy of Dr. Allan Thompson, University of Delaware.

FIGURE 3.2 **(a)** Intrusive igneous rock bodies: batholiths, laccoliths, dikes, and sills. **(b)** Igneous dikes cut across one another in this outcrop. We can use cross-cutting relationships like this to date rocks (see Chapter 5).

Courtesy of Fred Wehner, www.tug44.org.

FIGURE 3.3 The Palisades Sill along the Hudson River, north of New York City. These rocks are enriched in the mineral olivine and were intruded during the early rifting of the supercontinent Pangaea (see the section "Tectonic Cycle" in Chapter 2).

Intrusive igneous rocks also vary according to their chemical (mineralogic) composition. Rocks that are highly enriched in magnesium and iron, such as those within the mantle, are referred to as **ultramafic**. Rocks of the mantle are thought to consist mainly of peridotite. At shallower depths in the mantle, where lower pressures and temperatures are found, ultramafic rocks of the mantle give rise to mafic intrusive igneous rocks called **gabbros** (Figure 3.4). Gabbros are very dark in color because they contain relatively large amounts of iron and magnesium. Gabbros are probably common at the base of continental crust, and the boundary between ultramafic and gabbroic rocks is typically interpreted as the base of the oceanic crust. Diabase is a more medium-grained mafic igneous rock that is often found in dikes and sills.

Most continental crust is composed of granite, or rocks of "granitic" composition (Figure 3.4). The term "granitic" means the continental crust has an overall chemical composition similar, but not necessarily identical, to granite. Granites consist predominantly of the minerals potassium feldspar and silica-rich minerals such as quartz, and paper-like micas; hence, granitic rocks are sometimes referred to as being **felsic**.

Between gabbro and granite are igneous rocks of intermediate chemical composition. Like granite, these rocks also tend to be associated with continental crust. One of the most important of these rocks is **diorite**. Unlike granite, diorite does not have visible quartz crystals (Figure 3.4). Its white and dark grains tend to impart a salt-and-pepper appearance to it. Although diorite is sometimes involved in mountain building or other tectonic activity, granite is more commonly intruded as large felsic bodies. So, too, are **granodiorites**, which are grayish rocks with a composition intermediate between diorite and granite (Figure 3.4). Granodiorites, in part, form the enormous batholiths of the Sierra Nevada of

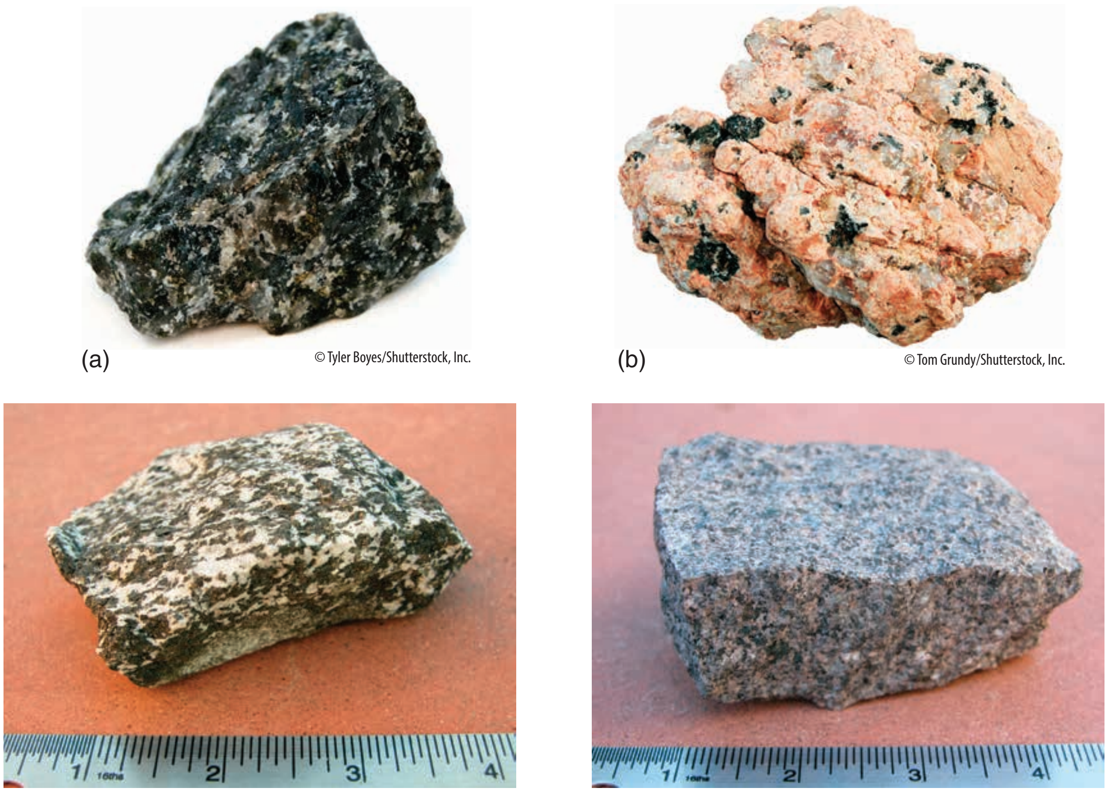


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FIGURE 3.4 Types of phaneritic or coarse-grained igneous rocks. These kinds of igneous rocks are emplaced deep within the Earth's crust, allowing them to cool slowly and develop their coarse-grained crystalline texture. **(a)** Gabbro. **(b)** Granite. **(c)** Diorite. **(d)** Granodiorite.

Courtesy of National Park Service.

FIGURE 3.5 Yosemite Valley in the Sierra Nevada of California. The Sierra Nevada consists of enormous batholiths of granodiorite that were later exposed by uplift and erosion. The U-shaped Yosemite Valley seen here was carved out much later by glaciers.

California (**Figure 3.5**). These granodiorites were originally emplaced within the Earth and brought to the surface by later uplift and erosion that formed the Sierra Nevada.

Extrusive igneous rocks: occurrence, texture, and composition

The magmas that form intrusive igneous rocks can also be extruded onto Earth's surface. Thus, granite, diorite, and gabbro each have an extrusive counterpart that is their chemical equivalent: rhyolite, andesite, and basalt, respectively (**Figure 3.6**). **Rhyolites**, **andesite**, and **basalt** can all occur on land, although basalts are more likely to erupt onto the seafloor. For this reason ocean crust is commonly referred to as being basaltic in composition. The texture of all three types of extrusive rocks is said to be fine-grained, or **aphanitic** ("without visible appearance"); aphanitic textures result from relatively rapid cooling and solidification on Earth's surface, leaving insufficient time for visible crystal faces to grow (Figure 3.6).

Extrusive igneous rocks form in association with volcanic activity and can form distinctive features at Earth's surface indicative of their mode of origin. On land and in the sea, extrusive igneous rocks are represented by **lava** and lava flows (**Figure 3.7**). In the sea, lava flows produce distinctive, bulbous *pillow lavas* as the hot magma is rapidly quenched by the much cooler seawater (Figure 3.7). Volcanoes can also pump large amounts of *volcanic ash* and gaseous *aerosols* high into the atmosphere, blocking sunlight and cooling the Earth, but the climate change is normally temporary, lasting only a few years (**Figure 3.8**). Eventually the ash rains down, sometimes blanketing large areas. Ash deposits are instantaneous in terms of geologic time and if sufficiently widespread are used to correlate, or "match," deposits in widely separated areas (see Chapter 6). In the case of *pumice*, the rock is so filled with vesicles, it floats (Figure 3.6)!

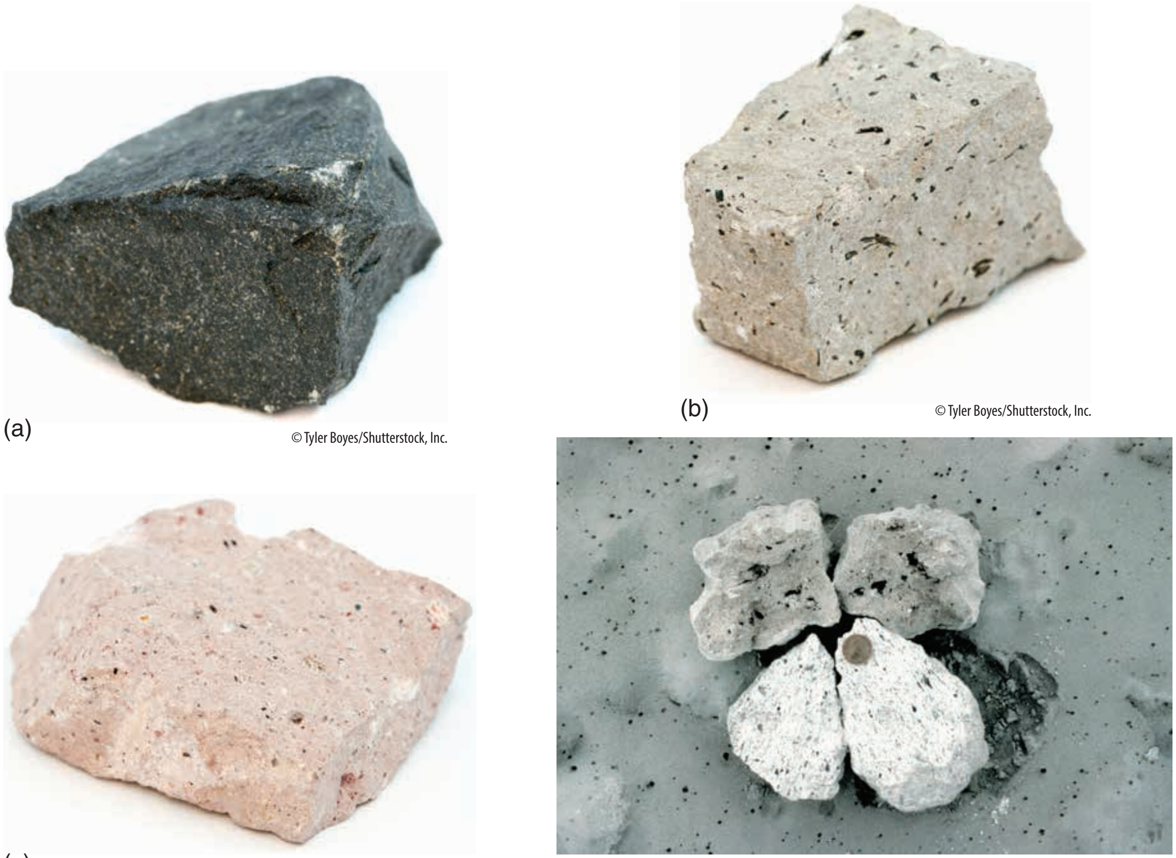

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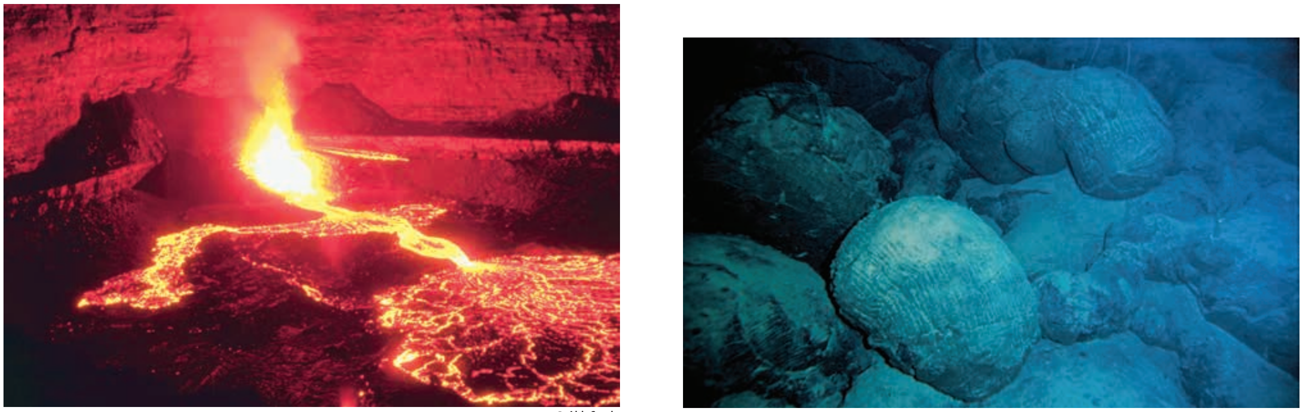
FIGURE 3.6 Types of aphanitic or fine-grained igneous rocks. These kinds of igneous rocks are extruded at or near the Earth's surface, allowing them to cool rapidly so that visible crystals do not have time to form. **(a)** Basalt. **(b)** Andesite. **(c)** Rhyolite. **(d)** Pumice.



(a) © AbleStock.

(b) Courtesy of NOAA/OAR/National Undersea Research Program (NURP).

FIGURE 3.7 Extrusive igneous rocks. **(a)** A lava flow on land. **(b)** Modern pillow lavas form during submarine volcanic eruptions.

If the volcanic vents or pipes that brought the magma to the surface fill with solidified magma, the resulting volcanic necks and dikes can form distinctive features at Earth's surface after erosion of the surrounding rock (**Figure 3.9**). Some magmas might also reach the surface through cracks or fissures in Earth's crust as relatively gentle *fissure eruptions*. Volcanic eruptions sometimes produce terrains that can be quite colorful, such as those of Yellowstone National Park (refer to this chapter's frontispiece). As we will see in coming chapters, enormous volcanic (including fissure) eruptions are thought to have been important agents of catastrophic climate change and mass extinction in Earth's ancient past. These fissure eruptions are thought to have injected enormous volumes of carbon dioxide into the atmosphere, rapidly altering Earth's surface temperature.

The styles of volcanic eruption—relatively gentle or explosive—differ because of the viscosity of the magma. Viscosity refers to the ability of a fluid to flow; molasses, for example, is much more viscous than water. The most important factor in determining viscosity is silica content; the greater the silica content, the more viscous the magma and the slower the flow. As a result, outpourings of basalt are common at Earth's surface, whereas the eruption of granitic magmas is less so. Granitic magmas have a greater concentration of silica than basaltic ones; thus as they near the surface and cool, they become less mobile. Consequently, granitic magmas are more likely to form large intrusions. If a volcano does spew magma of granitic composition, the magma will tend to block the release of gases (like carbon dioxide and water vapor) until they come near the surface. When it reaches the surface, the gas rapidly expands (because of the lowered pressure), producing explosive eruptions.

How do different kinds of magmas form?

The differing mineralogy and texture of igneous rocks leads to a fundamental question: how does granite, or at least crust with a granitic chemical composition, form? For that matter,

Courtesy of Ronald Martin, University of Delaware.

FIGURE 3.8 Volcanic ash layer at hammer approximately 400 million years old exposed in northern Pennsylvania.

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FIGURE 3.9 Shiprock, New Mexico, a volcanic vent exposed by erosion. The ridge is a feeder dike leading to the vent.

given that many magmas are thought to originate in the mantle, which is ultramafic to mafic in composition, how do magmas with andesitic or felsic compositions form?

Several processes are involved and are referred to collectively as **magmatic differentiation**. One of the most important is called **fractional crystallization** (**Figure 3.10**). For example, as basaltic magma ascends toward Earth's surface, it moves into zones of lower pressure and temperature. As the magma rises, the minerals in the magma with the highest melting points begin to crystallize and settle to the bottom, because as the magma temperature falls, those minerals with the highest melting points reach their crystallization temperature first. Thus, minerals with the lowest melting points are those that crystallize last from a magma. The minerals crystallize out in a definite sequence that has been demonstrated in laboratory experiments (called Bowen's Reaction Series after N. L. Bowen, who determined the sequence). As iron-, magnesium-, and calcium-rich minerals crystallize from magma and settle toward the bottom of the magma body, the magma left behind becomes progressively enriched in sodium-plagioclase and then potassium feldspar, micas, and leftover silica. Thus, the magma left behind becomes more felsic in composition and has a higher amount of silica and water than the original basaltic source.

Many magmas are thought to form through the process of **partial melting**. Partial melting occurs because of the different melting points of minerals and changing temperatures within the lithosphere. Ultramafic rocks consist predominantly of minerals with high melting points that are relatively low in silica, whereas more felsic rocks consist of minerals that melt at lower temperatures and have higher silica contents (Figure 3.10). Ultramafic rocks dominate in the mantle. Mantle rocks such as peridotites are normally under enormous temperatures and pressures from the overlying rocks, but the high pressure normally keeps them from melting. However, as mantle rocks move beneath mid-ocean ridges by upward convection, the pressure is released and melting begins. Minerals with lower melting points, like those in basalt, melt first, separate, and rise from the remaining magma, producing basalt.

Andesitic and more felsic magmas also likely form by other processes. Magma may **assimilate** (incorporate) more felsic rock—if present—through which it is rising, altering the chemical composition of the magma. **Magma mixing** might also occur when one body of magma overtakes another as it rises toward the surface and mixes with it.

More felsic magmas that generate granites are probably too enriched in silica to have been derived directly from mafic magmas. Rather, granitic magmas are probably generated by the differentiation of andesitic magmas or the partial melting of silica-rich continental rocks adjacent to the magma. The heat to melt the rocks likely comes from magma that has risen through the rocks after being generated by plate subduction.

The composition of extrusive igneous rocks—rhyolite, andesite, and basalt—also varies according to where volcanism occurs. We can use this feature to infer past tectonic activity and the types of plate margins. Ocean crust, for example, is composed of basalt, so volcanic eruptions associated with mid-ocean ridges are typically basaltic in composition. However, most of the 600 or so modern volcanoes occur where one lithospheric plate descends beneath another. If subduction of ocean crust occurs beneath the margin of another piece of ocean crust, magmas of either basaltic or andesitic (more silica-rich) composition are often produced. These magmas

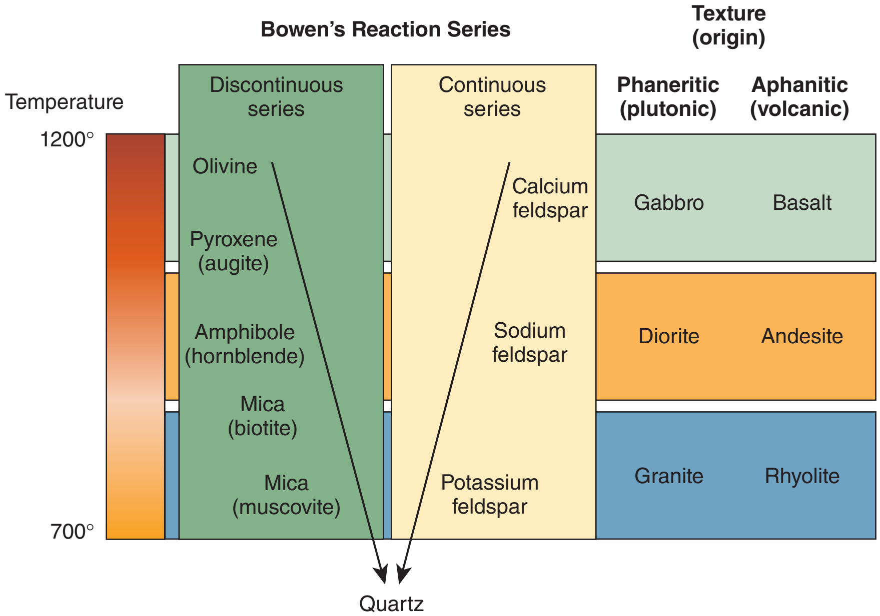

FIGURE 3.10 Bowen's Reaction Series shows the fractional crystallization of minerals and the resulting igneous rocks. The pattern of crystallization is Y-shaped. The branch called the continuous series represents the continuing enrichment of magma in sodium (Na) as calcium (Ca)-rich rocks crystallize out.

feed volcanic island arcs like the Aleutian Islands off Alaska. Because the volcanoes are fed by less viscous basalt, the volcanoes tend to occur at lower elevations and have a shield-like appearance because the lava flows more easily.

On the other hand, if subduction occurs beneath a continental margin, the remelting of crustal rocks and water-laden sediments tends to produce magmas of andesitic composition. These types of volcanoes include the Cascade Range of the Pacific Northwest and the Andes of South America ("andesite" derives from the fact that it is common in the Andes). If the magmas associated with plate subduction become sufficiently granitic in composition, rhyolites result. However, rhyolites are not as common as andesites because granitic magmas are less likely to be erupted; the magma that feeds volcanic chains on land is more silica-rich, so that the magmas are more viscous and flow less easily. Thus, volcanoes on land tend to build to higher elevations, giving them a steep, cone-like appearance.

By contrast to volcanism along plate margins, intraplate volcanism occurs within a plate. Examples include the Hawaiian islands. These islands also appear to be associated with a hotspot, where magma has reached the surface as if it had flowed through a pipe (see Chapter 2 for further discussion of the existence and behavior of hotspots). The types of extrusive rocks produced by intraplate volcanism vary from basalts to rhyolites. The magmas erupting in Hawaii are basaltic in composition, indicating they originate from the mantle or the base of the lithosphere. The low silica content of the basaltic magmas lowers their viscosity, making them flow more easily, accounting for the gentler slopes and shield-like appearances of these volcanoes.

CONCEPT AND REASONING CHECKS

1. Draw a table indicating the major types of intrusive igneous rocks and their extrusive counterparts.
2. What processes cause magmas to change composition?

3.2.2 Sedimentary rocks

A large proportion of Earth's surface is covered by **sedimentary rocks**, which form at Earth's surface. Sedimentary rocks are typically layered, or stratified. Rocks that are uplifted and exposed to the atmosphere slowly undergo physical and chemical weathering. Physical weathering transforms larger rocks into smaller grains, whereas chemical weathering attacks chemical bonds within minerals, breaking them down further. Physical and chemical weathering produce materials that are more easily removed and transported by the processes of erosion, which occurs by the action of landslides, streams and rivers, wind, and glaciers. The eroded grains are eventually deposited as loose sediment, which can eventually undergo **lithification** (consolidation or hardening) during the processes of burial, compaction, and cementation to form a sedimentary rock (Figure 3.1).

Not all sedimentary rocks form by erosion and deposition, however. Some form by chemical precipitation or from the accumulation of shells of dead organisms. Thus, sedimentary rocks frequently contain fossils, which are the remains (shell, bone) or traces (tracks, trails) of preexisting organisms. Sedimentary rocks and their preserved fossils represent an enormous archive of past interactions of Earth's systems because they are indicative of surface conditions such as sea level and related climatic feedbacks. For these reasons, we will postpone discussion of sedimentary rocks to Chapter 4, where we can more fully discuss their features and contained fossils.

3.2.3 Metamorphic rocks

All types of rocks can be subjected to changing temperatures and pressures that physically and chemically transform the rocks from one type to another. These processes are referred to as metamorphism ("meta," change; "morphos," form). Unlike igneous rocks, metamorphism might involve, at most, only partial remelting and rearrangement of grains in the rock. Metamorphism is frequently associated with the intense pressures and temperatures generated during mountain building, but metamorphism also occurs in or adjacent to subduction zones (where intense pressures and temperatures are also generated), in the solid rocks adjacent to magma, during the burial of rocks, or by the injection of hot fluids into rocks.

Metamorphic rocks: texture and mineralogy

During metamorphism, new textures and minerals form that are indicative of the intensity of the temperatures, pressures, and chemical conditions that occurred. Metamorphism occurs in a variety of settings: the localized alteration of rock adjacent to hot magma; the production of hot fluids by magma that are injected into the surrounding rock; or much broader, or regional, metamorphism associated with the generation of high temperatures and pressures during mountain building

The intensity, or grade, of metamorphism is reflected by the texture and mineralogy of the resulting rock. Let's consider texture first. A basic distinction between different types of metamorphic rocks is whether they are **foliated** or **nonfoliated**. Metamorphic rocks that exhibit a preferred orientation of their mineral grains are said to be foliated ("folium," leaf); foliation occurs in response to the increased pressure and other stresses of mountain building. Metamorphic rocks not exhibiting an orientation of mineral grains are said to be nonfoliated.

The lowest grade of metamorphism in foliated metamorphic rocks occurs in **slates**, which form from fine-grained, clay-rich sedimentary rocks called *shales* at relatively low temperatures and pressures (**Figure 3.11**). Slightly increased temperatures and pressures cause the tiny clay minerals in shales to react chemically. This in turn causes the minerals to reorganize and produce parallel arrangements of small mica flakes that cause the slate to break along preferred planes, or *slaty cleavage*. A **phyllite** forms from shale under conditions of higher temperature and pressure; phyllite is distinguished from slate by its shinier appearance, which is caused

FIGURE 3.11 Foliated metamorphic rocks and the rocks from which they form. Different types of foliated sedimentary rocks form under progressively more extreme conditions. **(a)** Slate forms under the least extreme conditions, when the platy clay minerals of a shale are compressed together and realigned. **(b)** In schists, which may develop from shales and sandstones, mica crystals grow in size to give the rock a scaly appearance. The small, red-colored dots are garnets, which recrystallize from the original minerals during metamorphism. **(c)** In gneisses, which can form from a variety of sedimentary and igneous rocks, including granites, higher-grade metamorphism causes the minerals to segregate into distinct bands. **(d)** Migmatites have a wavy, banded appearance and form by partial melting.

by slightly larger grain sizes and the presence of the micas muscovite and chlorite.

Under somewhat higher temperatures and pressures, minerals such as micas grow to produce larger crystals visible to the naked eye, giving the rock a scaly appearance. This kind of foliation is called *schistosity* and the rocks are called **schists**. There are a variety of schists, but most are mica schists consisting of muscovite and biotite (Figure 3.11). The mineral garnet, which only forms by metamorphism, can also form from the minerals present in the original rock.

Even more intense metamorphism causes the minerals in the original rock to recrystallize into distinct bands to produce **gneisses** (Figure 3.11). Gneisses can form from different rocks, including shales and alternating shales, sandstones, and even granite. Gneisses typically consist of light bands of quartz, feldspars, and muscovite alternating with darker bands of amphiboles and biotite. Garnet is often found in gneisses, as well (Figure 3.11).

Even more intense alteration produces **migmatites**. Migmatites (meaning "mixed igneous and metamorphic") form when partial—but not complete—melting occurs, producing a wavy, layered appearance (Figure 3.11). The wavy appearance results from the fact that light-colored silicate minerals like quartz and feldspar melt before more mafic minerals with higher melting points such as hornblende. Thus, the light-colored minerals with the lower melting points tend to segregate from the darker-colored minerals that have not melted, imparting a distinct "wavy" banding to migmatites.

Another type of foliated metamorphic rocks form under somewhat different conditions than those above. **Blueschist** forms in the thick sedimentary wedges associated with subduction zones, where relatively high pressures but low temperatures occur. In subduction zones, the ocean crust initially begins to cool as it descends, so that relatively little heat rises to the base of the rocks and sediments found in the subduction zone. By contrast, the pressures due to compression and burial increase dramatically.

Nonfoliated metamorphic rocks typically form from parent rocks that consisted of essentially one mineral. **Marble** is a nonfoliated metamorphic rock that forms during the recrystallization and interlocking of the individual calcite grains of limestones. Similarly, **quartzites** form by the recrystallization of individual quartz grains in sandstones. Minor impurities in the original rocks can impart distinctive coloration to marbles and quartzites.

The intensity of metamorphism is also indicated by the predominant minerals that compose the rocks. Chlorite is a greenish mica that is associated with greenschist, whereas sillimanite is associated with the highest metamorphic grade (not coincidentally, sillimanite is used to make temperature-resistant porcelains like those used in spark plugs). Various types of garnets characterize the different metamorphic grades between greenschist and sillimanite-bearing metamorphic rocks.

Types of metamorphism

Most metamorphic rocks are generated by **regional metamorphism** (**Figure 3.12**). As the term implies, regional metamorphism occurs over broad—or regional—scales, such as that associated with increased temperature and pressure and large-scale deformation during orogeny, or mountain building. We can use the intensity, or grade, of metamorphic rocks associated with regional metamorphism to infer the intensity of metamorphism, even after the mountains have long vanished. In the simplest, ideal case of regional metamorphism the metamorphic grades are expressed as successive zones of decreasing metamorphism away from the centers of mountain belts where the deformation is greatest and magma is most likely to have been emplaced. Thus, migmatites tend to occur closest to the center of mountain belts, with gneisses, schists, phyllites, and slates tending to occur progressively farther away (Figure 3.12). The mineralogic composition of the rocks parallels the gradation in foliation, with schist and gneiss occurring in the highest grade metamorphism and slate and phyllite occurring in the lower grades. Blueschist is associated with the high pressures that occur in the sedimentary wedges of subduction zones. However, in most cases, the patterns of metamorphism are more complex because of movement and deformation of the rocks during mountain building and erosion thereafter (see Chapter 2).

Another type of metamorphism important to the history of Earth's systems is **hydrothermal metamorphism**, or **hydrothermal weathering**, that occurs at seafloor spreading centers. Here, seawater percolates through hot ocean crust, altering the concentrations of certain dissolved ions in the seawater (**Figure 3.13**). Changes in the concentrations of these dissolved ions are recorded in the calcareous shells of fossil organisms and are used to infer past changes in rates of seafloor spreading and continental weathering.

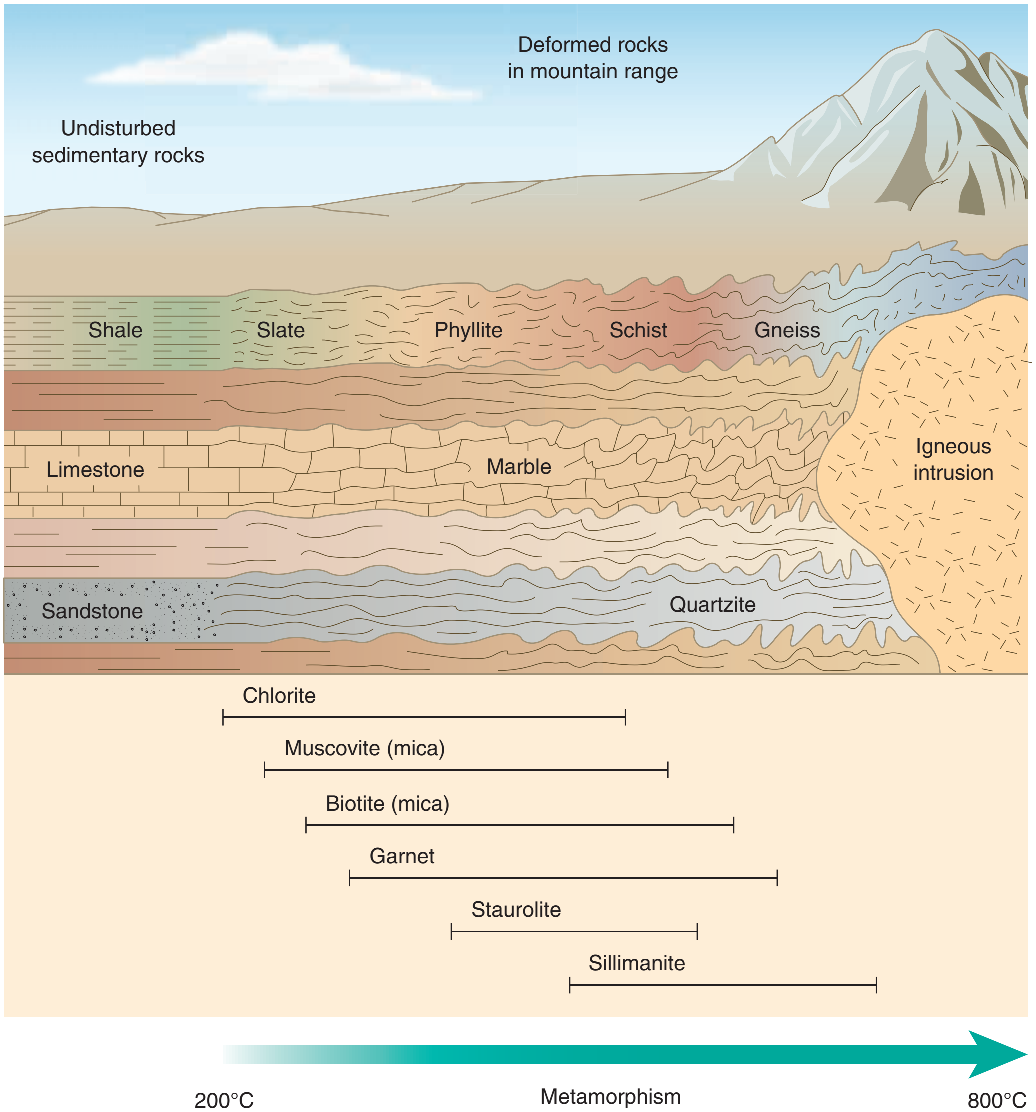

FIGURE 3.12 Changes in lithology and mineralogy that result during the metamorphism. Certain minerals are indicative of metamorphism and certain associations of these minerals are indicative of the intensity of metamorphism.

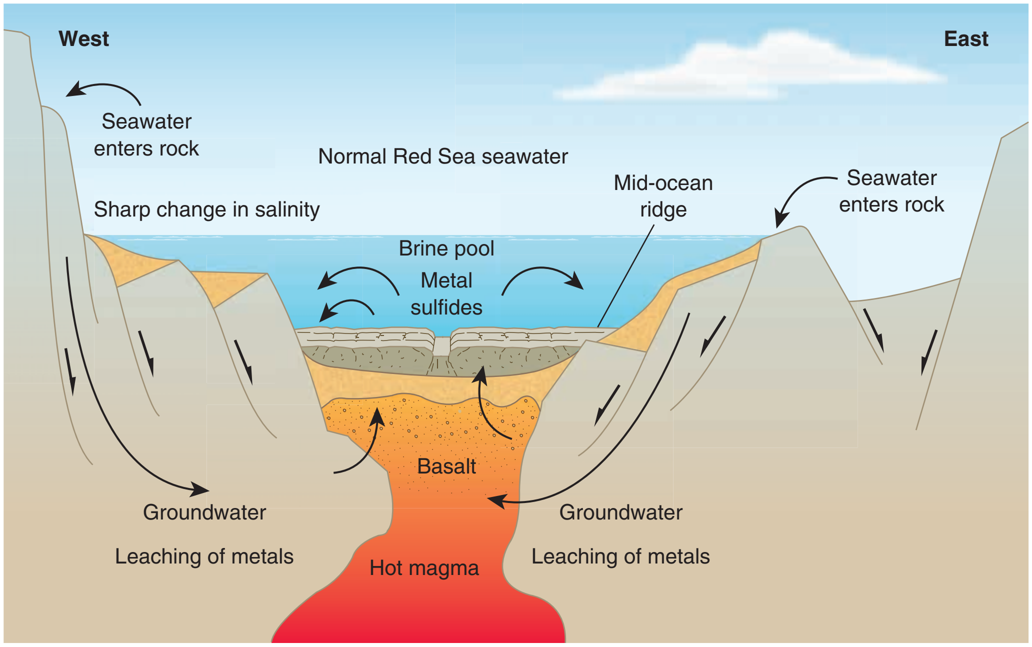

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FIGURE 3.13 Hydrothermal weathering occurs when seawater percolates through hot ocean crust at seafloor spreading centers, such as this one in the Red Sea. This mechanism alters the ionic composition of seawater. Magnesium ($Mg2^+$) ions from ocean crust dissolve into seawater as calcium ($Ca2^+$) ions move from seawater into the crust. The ratio of $Mg2^+/Ca2^+$ ions appears to be related to the mineralogy of the shells (calcite or aragonite) secreted by organisms living in the oceans.

Finally, there is **impact** or **shock metamorphism**, which occurs when an extraterrestrial body such as an asteroid hits the Earth (**Figure 3.14**). When an impact occurs, there is a tremendous and instantaneous increase in pressure and temperature to thousands of degrees. Projectiles consisting of melted rock called **tektites** can be ejected thousands of kilometers away from the site of impact (Figure 3.14). Shocked mineral assemblages also form from impact. Shocked minerals such as quartz have well-developed thin layers, or laminae, that represent rearrangements of the crystalline structure of the mineral (Figure 3.14). The only way known to generate such well-developed laminae is by the impact of an extraterrestrial object.

CONCEPT AND REASONING CHECKS

1. Diagram the sequence of metamorphic grades (phyllite, schist, gneiss, etc.) that one might encounter moving away from a batholith.
2. What are the different types of metamorphism?
3. Diagram the basic rock cycle on a subducting plate margin.

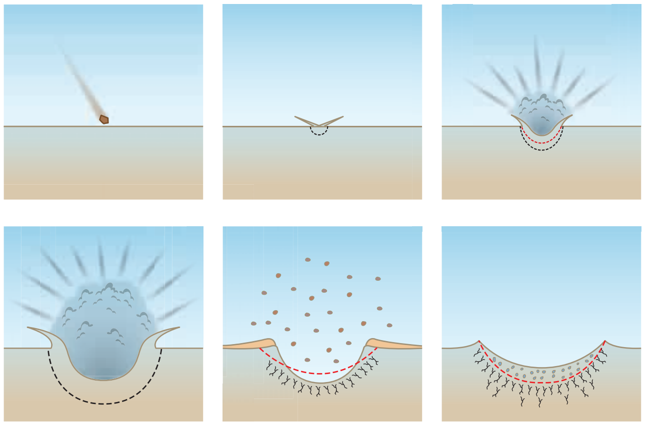
3.3 Atmosphere and Its Circulation

C The atmosphere comprises the gaseous envelope surrounding Earth. On the scale of the Earth, the atmosphere is only a thin veil that separates life on the planet from destruction, but without the atmosphere life as we know it on Earth would not exist. The atmosphere helps warm the Earth through the greenhouse effect (otherwise, life would freeze) and also protects Earth's surface from harmful cosmic radiation.

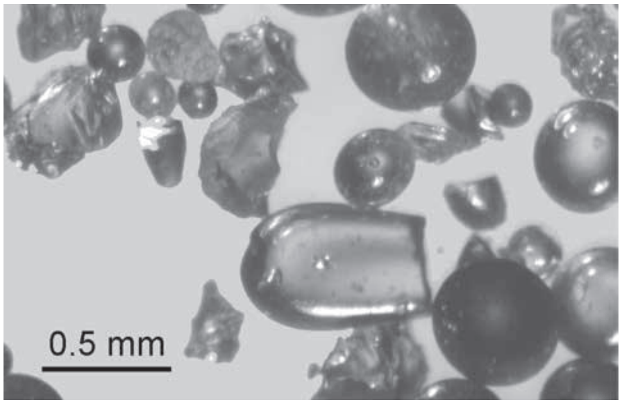
The lowest layer of the atmosphere, called the troposphere, is about 10 to 15 kilometers in thickness. Although the troposphere is quite thin, it is where about 80% of the gases and almost all water vapor are concentrated. As a result, it is the troposphere where most of our "weather" occurs. The top of the troposphere, for example, is marked by the anvil shapes of storm clouds. The composition of the modern atmosphere is dominated by several gases. Nitrogen (78%) and oxygen (21%) are by far the two most prominent components (**Figure 3.15**). Although carbon dioxide comprises only 0.038% of the atmosphere by volume, this relatively small amount of carbon dioxide is sufficient to warm Earth. Water vapor is also present and contributes substantially to warming.

Atmospheric circulation is driven, fundamentally, by the temperature contrast between the equator and the poles and results in turn from different fluxes of solar radiation reaching the Earth's surface. The atmosphere constantly attempts to "smooth out" this temperature gradient by transferring heat from the equator toward the poles by convection.

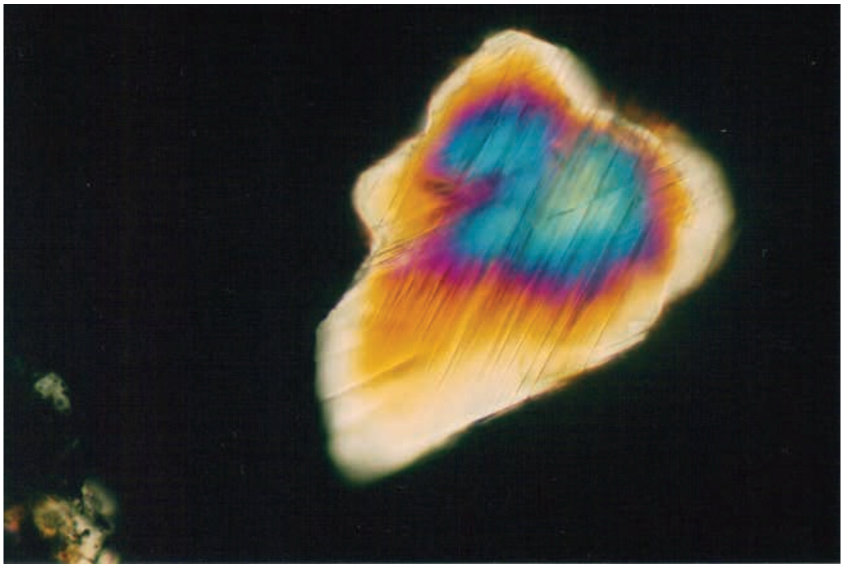
Let's look at a simplified model of atmospheric circulation (**Figure 3.16**). The sun's rays penetrate a thinner layer of atmosphere at the equator than at the poles because the rays penetrate the atmosphere at more-or-less right angles nearest the equator but more tangentially nearer the poles. Consequently, the sun's rays entering the atmosphere over the equator are less likely to collide with air molecules and



(a) Reproduced from: Christian Koeberl, "El'gygytgyn: a very special meteorite impact crater," Website of the FWF (Austrian Science Fund), project: P21821-N19 (http://lithosphere.univie.ac.at/impactresearch/elgygytgyn-crater/). Accessed April 19, 2011.

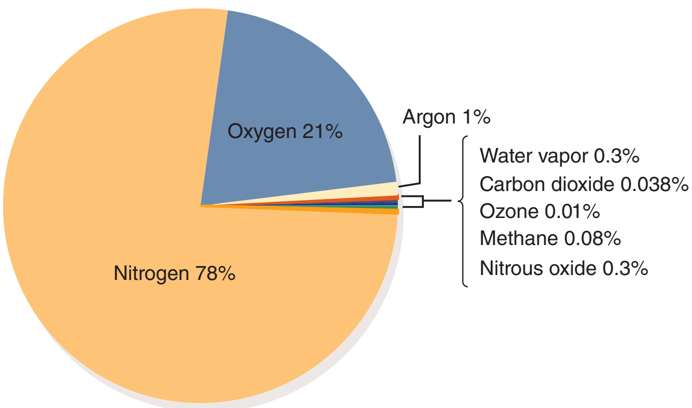


(b) Courtesy of Billy P. Glass, University of Delaware.



(c) Courtesy of Billy P. Glass, University of Delaware.

FIGURE 3.14 Impact metamorphism and its evidence. **(a)** Impact or shock metamorphism occurs when an extraterrestrial body such as an asteroid hits the Earth. When an extraterrestrial object hits the Earth, there is a tremendous and instantaneous increase in pressure and temperature to thousands of degrees. **(b)** Projectiles consisting of melted rock called tektites can be ejected thousands of kilometers. **(c)** Shocked quartz. The parallel laminations represent the rearrangement of the mineral's crystalline structure in response to sudden intense pressure and temperature generated by an impact. Well-developed shocked mineral assemblages are much better indicators of impact than iridium alone (see Chapter 1).



Data from: Mackenzie, F. T., and Mackenzie, J. A. 1995. *Our Changing Planet: An Introduction to Earth System Science and Global Environmental Change*. Englewood Cliffs, NJ: Prentice-Hall.

FIGURE 3.15 The composition of the modern Earth's atmosphere.

be scattered back to outer space than the rays that penetrate the atmosphere nearer the poles. The more intense heating at the equator causes the air to warm and rise there; because it is warm, the air can also hold more moisture. As the warm air rises it loses heat energy and cools, releasing its moisture as rain. It is for this reason rain forests occur in the tropics near the equator. As the air masses rise into the atmosphere, they begin to cool, so their density increases. Unlike the simple diagram in Figure 3.16a, however, the air masses stop rising and the air begins to spread parallel to Earth's surface toward either pole (Figure 3.16b and **Figure 3.17**). This air cools further as it flows parallel to Earth's surface. These air masses eventually cool sufficiently to further increase their density, causing them to descend back toward Earth before reaching the poles. Because these descending (high pressure) air masses have already lost their moisture, the land

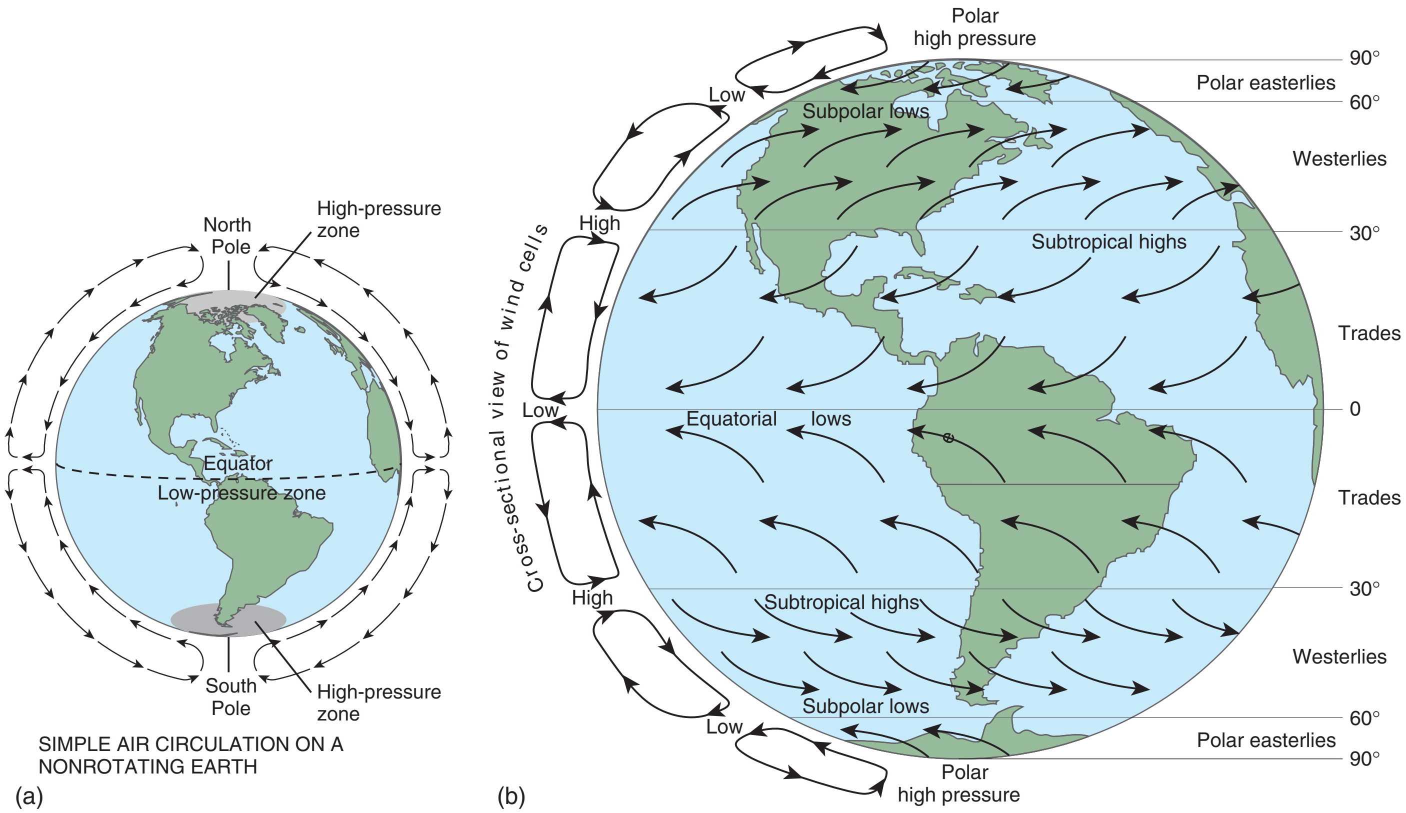
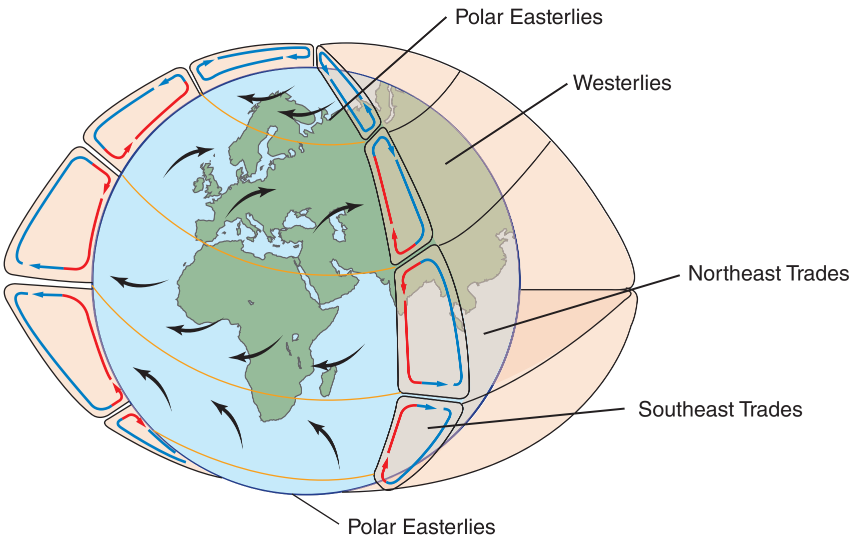


FIGURE 3.16 The structure and basic circulation of the atmosphere. **(a)** Cross-section of the Earth's atmosphere showing the basic components of highly simplified convection within the atmosphere as initially described in the text. Low-pressure zones are regions of ascending moist air and rainfall, whereas high-pressure zones consist of descending dry air masses. **(b)** Differences in heating between the equator and poles actually cause the formation of multiple convection cells in the atmosphere that determine the broad patterns of rainfall and dryness, as further discussed in the text.



Data from: National Weather Service. JetStream: Online School for Weather (http://www.srh.noaa.gov/jetstream/global/circ.htm). Accessed March 31, 2010.

FIGURE 3.17 Major wind systems of the Earth resulting from atmospheric convection and the Coriolis effect. The curvature of the airflow imparted by the Coriolis effect establishes the major wind patterns. As air descends at 30°E north and south latitude, it tends to move from east to west over the Earth's surface to produce the trade winds. Trade winds in the northern hemisphere flow from the northeast to southwest, whereas their counterparts in the southern hemisphere flow from southeast to northwest; northern and southern hemisphere trade winds meet at the Intertropical Convergence Zone above the equator. Warm air rising at about 60°E north and south latitude tends to flow from west to east (again because of the Coriolis effect) to produce the westerlies ("coming from the west") that move major weather systems over the United States and Europe. The polar easterlies ("coming from the east") lie toward the poles and move from east to west like the trade winds, meeting the warmer westerlies along a polar front.

beneath them often consists of deserts, such as the Sahara Desert in northern Africa.

After its descent, the air flows parallel to the Earth's surface. Some air flows back toward the equator to be incorporated into the rising air there, whereas the rest flows toward higher latitudes. As it does so, the dry air picks up moisture and warms once again, eventually rising into another convection cell. This pattern is repeated yet again in a third set of convection cells closest to the poles.

The flow of air within the convection cells is not simply straight up and down; it is actually curved. The curvature results from the **Coriolis effect**, which in turn results from the rotation of the Earth. The curvature of the airflow imparted by the Coriolis effect establishes the major wind patterns in Earth's atmosphere (Figures 3.16 and 3.17). The Coriolis effect exists because the atmosphere and the Earth move together as the Earth rotates eastward around its axis. As the Earth rotates, a point near the north pole moves around a circle that is much smaller in diameter than a point at the equator. In other words, during the same interval of time, the point near the north pole travels a shorter distance than the point at the equator. Thus, the point near the north pole moves more slowly than the point at the equator. Now imagine that an air molecule at the north pole is displaced toward the equator. Because of the physical phenomenon of inertia (which states that an object continues to move with the same speed and direction unless a force acts upon it), the air molecule maintains the original speed and direction that it had when it began to move south toward the equator. Consequently, the molecule moving from the north pole toward the equator will lag behind the one at the equator because the point at the equator is moving faster than the point coming from the north pole; thus, the point at the equator will have moved eastward away from where the point from the north pole will arrive. Conversely, a point moving from the equator toward the north pole will move ahead of the point at the pole. A similar phenomenon occurs in the southern hemisphere, but the movements are the reverse, or mirror image, of those in the northern hemisphere.

Because of the Coriolis effect, as air descends within the atmospheric convection cells at 30° north and south latitudes, the air masses tend to move from east to west over Earth's surface to produce the **trade winds**. Trade winds in the northern hemisphere flow from the northeast to southwest, whereas their counterparts in the southern hemisphere flow from southeast to northwest. Trade winds in the northern and southern hemispheres converge near the equator. Similar phenomena account for the well-known **westerlies** (coming from the west) that move major weather systems over the United States and Europe and the **polar easterlies** (which come from the northeast in the northern hemisphere and the southeast in the southern hemisphere) nearer the poles. As we will see below, the basic pattern of atmospheric circulation determines not only the broad pattern of precipitation over the planet but also the broad distribution of Earth's biotas while driving the major surface currents of the ocean. These patterns are in turn influenced by the distribution of the continents (discussed later in this Chapter) and the presence or absence of mountain ranges (**Box 3.1**).

CONCEPT AND REASONING CHECKS

1. What drives atmospheric circulation?
2. Diagram the circulation of the atmosphere, indicating the major wind belts.
3. Why does it rain so heavily in the tropics?
4. Diagram the orographic effect, indicating the processes involved.

3.4 The Hydrosphere

D The **hydrosphere** is critical to maintaining Earth's climate and life. The presence of water in sediments lowers the melting point of rocks in subduction zones and is therefore critical to maintaining the processes of plate tectonics. Water also provides habitat for countless numbers of organisms and is necessary for life as we know it; most organisms consist of more than 60% water, and some more than 90%. Water is also critical to life because water vapor is—like carbon dioxide—a greenhouse gas, affecting Earth's temperature and habitability.

3.4.1 Hydrologic cycle

Like other Earth systems, the hydrosphere is cyclic. The **hydrologic cycle** involves the flux of water through several **reservoirs** (**Figure 3.18**). **Precipitation** reaches the ground as rain or snow if the air just above the land is sufficiently cold, such as at high latitudes near the poles or at high elevations (mountains). Some precipitation may undergo **evaporation** or flow over Earth's surface as **runoff** in streams and rivers; as is described in Chapter 2, the occurrence of some of the major river systems of the world is determined by the presence of deep valleys within the Earth's crust that represent failed rift systems. Much of this water will of course reach the oceans, whereas some infiltrates the ground and flows through subterranean rocks and sediments as groundwater. The remaining water in the cycle is used by plants, which are technically part of the biosphere (**Figure 3.19**). Most land plants lose tremendous amounts of water out the bottom of the leaves through the process of **transpiration**. The water is lost through countless numbers of microscopic openings called stomata that allow the exchange of carbon dioxide and oxygen between the leaves and the environment during photosynthesis. The process of transpiration is tremendously important to the hydrologic cycle, because without transpiration many tropical regions would suffer from drought.

Some workers recognize a separate Earth system referred to as the **cryosphere**, that includes glaciers, both those of mountains (called alpine glaciers) and polar ice caps. The development of polar glaciers depends on the supply of moisture that is part of the overall hydrologic cycle.

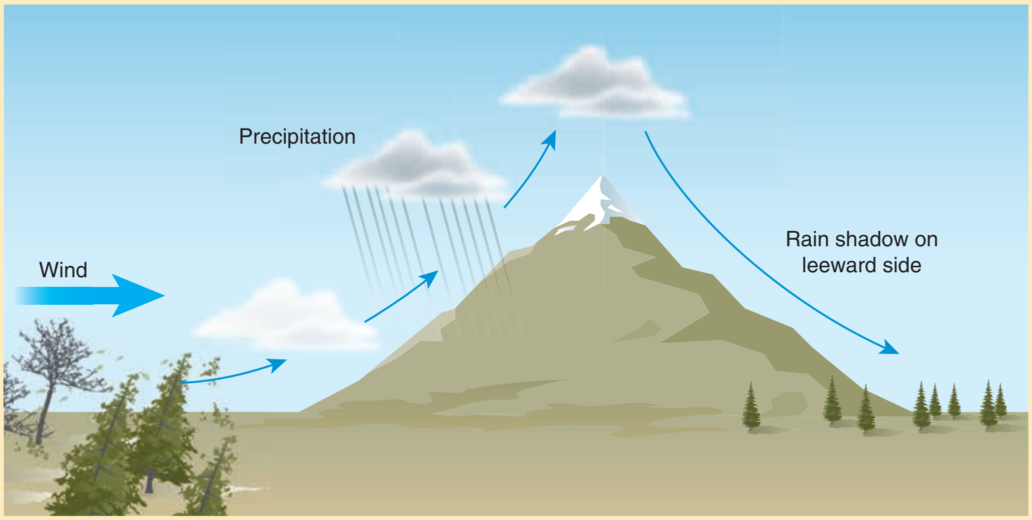
Box 3.1 Asian Monsoon: Influence of Large Land Masses on Atmospheric Circulation and the Hydrologic Cycle

Large land masses can profoundly influence the circulation of the atmosphere through the phenomenon of monsoons. The word "monsoon" is usually associated with torrential rainfall but actually refers to reversing airflow (**Box Figure 3.1A**).

Approximately 50 to 60 million years ago, the continent of India began to collide with the continent of Asia, resulting in the Himalayan Orogeny and leading to the Asian monsoon over Tibet and India. What we see today is that, as the summer sun warms the Tibetan Plateau to the north of India, warm air begins to rise, drawing warm moist air from the Indian Ocean over India. When this warm, moist air encounters the south side of the Himalayas, which form a narrow rampart along the southern margin of the Tibetan Plateau, the air is forced upward by the orographic effect. As the air rises it cools, and precipitation results on the southern side of the Himalayas, leaving Tibet high and dry. During the winter the reverse conditions hold: cold air, which is dense, descends over Tibet and southward over India. This airflow is also considered part of the monsoon.

But what exactly were the effects of the Himalayan Orogeny on climate and the Asian monsoon through geologic time? How, in other words, did the Asian monsoon evolve toward its present state? How can we tell what happened? One way to determine the effects of the Himalayan Orogeny on Asian climate, especially given the complex interactions of Earth's systems, is to use computer models of climate change. A model is a kind of sophisticated hypothesis (see Chapter 1) that tries to take into account all the components or processes of a system that are important to the system while excluding those that are not considered important. Using climate models, we can run experiments on complex systems under controlled conditions, like running experiments in a laboratory. This allows earth scientists to identify the mechanisms that cause variation in global climate because many factors can be held constant, whereas others are varied to examine their effect on the behavior of the model.

Based on climate models, as India collided with Asia the fluctuations in the climate of the Tibetan Plateau became more extreme because land was being uplifted higher into the atmosphere. Because of the increasing elevation of the plateau, the atmosphere over the plateau became progressively thinner. As a result, the sun warmed the air near



BOX FIGURE 3.1A A monsoon like that of the Indian subcontinent.

Box 3.1 Asian Monsoon: Influence of Large Land Masses on Atmospheric Circulation and the Hydrologic Cycle (Continued)

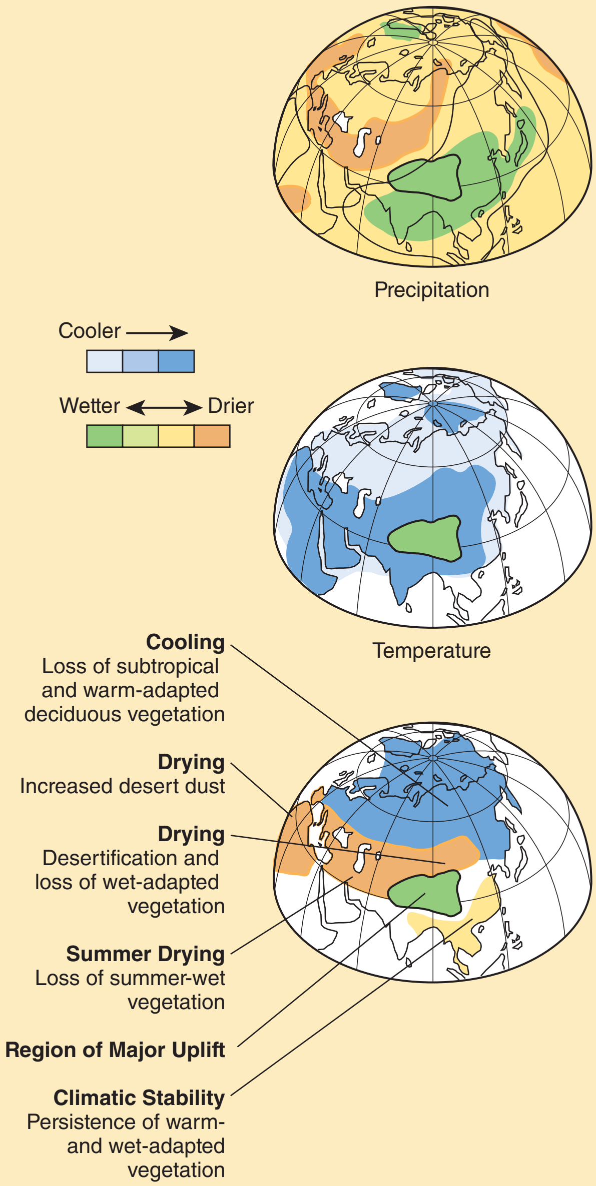
Earth's surface more rapidly during the summers, decreasing the air's density and allowing it to rise more easily. By contrast, during winters air masses cooled more readily, increasing their density and causing them to descend over the plateau. Because the air currents that feed into and out of the air masses over the plateau also flow over the Indian subcontinent, the slow rise of the plateau began to intensify the monsoonal airflow over India and Tibet (**Box Figure 3.1B**).

During this time, rainfall shifted from the north side of the Himalayas to the south side. Accordingly, over tens of millions of years, what was a warm, wet lowland in Tibet became a cool, desert-like plateau. The shift in rainfall to the south side of the Himalayas might in turn have fed back positively on erosion, uplift, and metamorphism in the region.

The results of a model—like those of a hypothesis—should be tested or at least constrained by the real data of the geologic record (see Chapter 1). If the results of the model agree with geologic evidence, we can be reasonably sure the model simulates what actually happened. If not, the model must be reexamined and modified or possibly even discarded. This approach is the same iterative one used in the scientific method.

One way is to construct arguments based on the record of rocks and fossils, reasoning backward to make predictions, and then look for evidence in the geologic record to corroborate or refute the predictions. In fact, the model results generally agree with the fossil record. Fossils collected from rock exposures in Tibet indicate that vegetation in Tibet before 30 million years ago was that of a subtropical-to-tropical forest like that of the southeastern United States today. However, by 5 to 10 million years ago these forests had given way to deciduous forest like that of temperate latitudes and eventually to grasses and scrubby vegetation. The changes in vegetation through time indicate that rainfall was decreasing.

The thinner atmosphere over uplifted areas intensifies airflow driven by temperature changes during the winter and summer. In the winter, cool air descends over the uplift and flows away, whereas in the summer, air warms and rises over the uplift, drawing air toward and over the uplift. Changes in the precipitation patterns in turn cause changes in vegetation.



Data from: Ruddiman, W. F., and Kutzbach, J. E. 1991. Plateau uplift and climatic change. *Scientific American*, 264, 5.

BOX FIGURE 3.1B Effect of the rise of the Himalayan Mountains on the Asian monsoon.

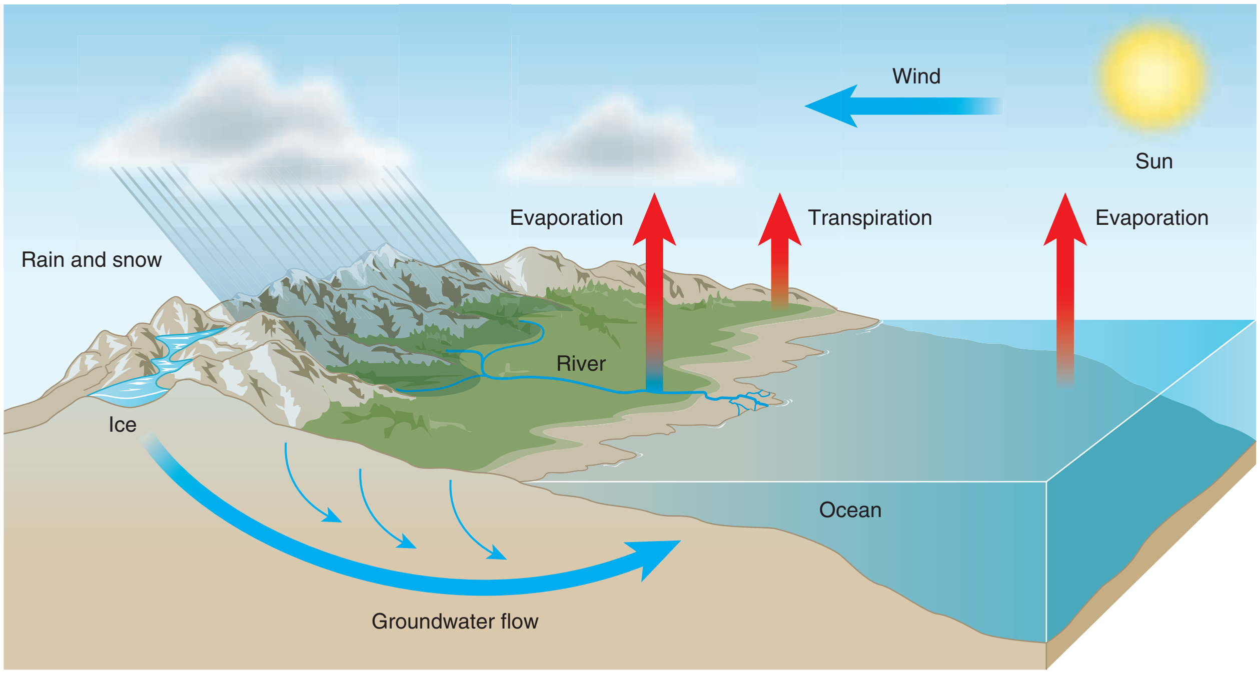
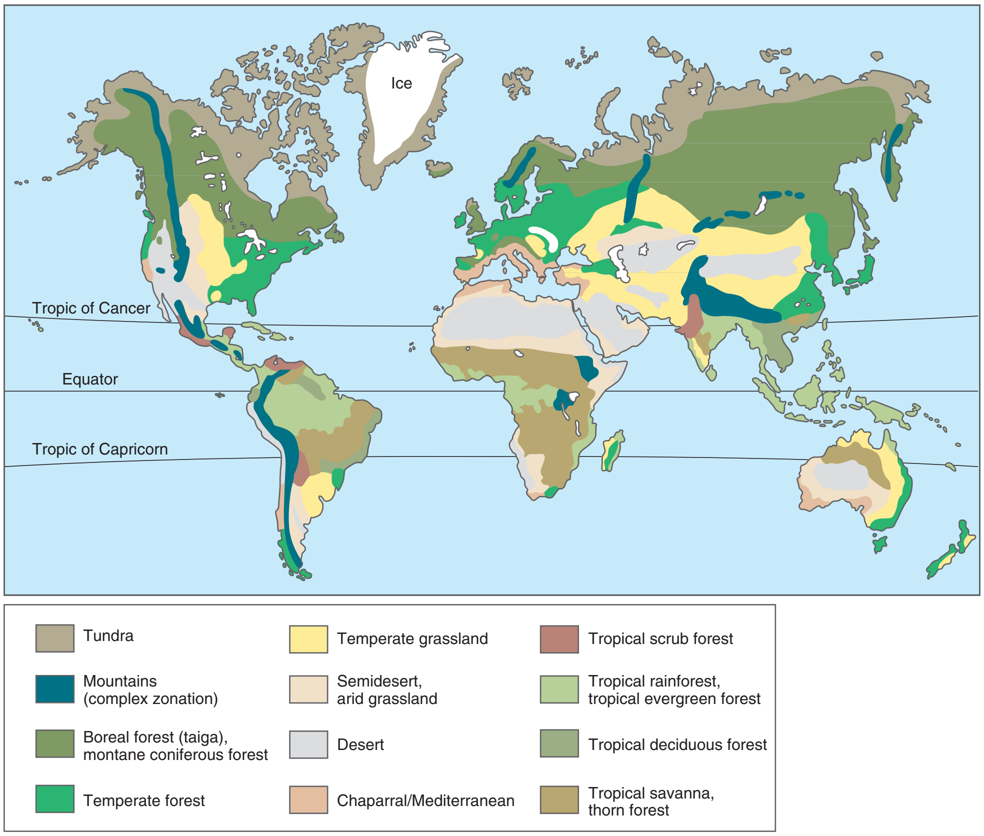


FIGURE 3.18 The hydrologic cycle. Note the involvement of the biosphere through the process of transpiration (water loss) through the microscopic stomata on the undersides of leaves. Note also the overlap of the hydrosphere and atmosphere: the atmosphere contains water vapor and also affects surface ocean circulation through the production of wind currents, as discussed in the text.



Data from: Earth Forum, The Houston Museum of Natural Science.

FIGURE 3.19 Convection cells within the atmosphere determine the major belts of precipitation, vegetation, and deserts over the Earth. Compare to Figure 3.17.

Glaciers in turn affect the return of moisture to the atmosphere because they store water. Today, about 90% of the world's freshwater is stored in Antarctic ice. Glaciers—at least polar ice caps—have not always been present during Earth's history, but when they have been present, they have exerted a profound impact on Earth's climate (such as during the Pleistocene "Ice Ages"; see Chapter 15).

3.4.2 Ocean circulation

E Unquestionably, the most dominant components of the hydrosphere are the oceans. The modern ocean basins have an average depth of 3.8 km and represent more than 70% of Earth's surface. The oceans store 96.5% of Earth's water, account for 86% of all evaporation, and receive 78% of all precipitation. Because of their area and volume, the oceans exert a tremendous influence on climate. Only about 2% of the heat generated by the greenhouse effect at Earth's surface is used to drive atmospheric circulation and those portions of the hydrologic cycle that occur in the atmosphere. Much of the rest of the heat is stored in the oceans. In fact, because of water's high specific heat capacity (the heat stored per unit volume), the oceans represent the largest reservoir and regulator of heat on Earth. In other words, after ocean waters have warmed up, they release the heat only slowly. This property allows ocean currents to retain heat for long periods of time, permitting them to redistribute heat over long distances—even to colder high latitudes—and affecting climate.

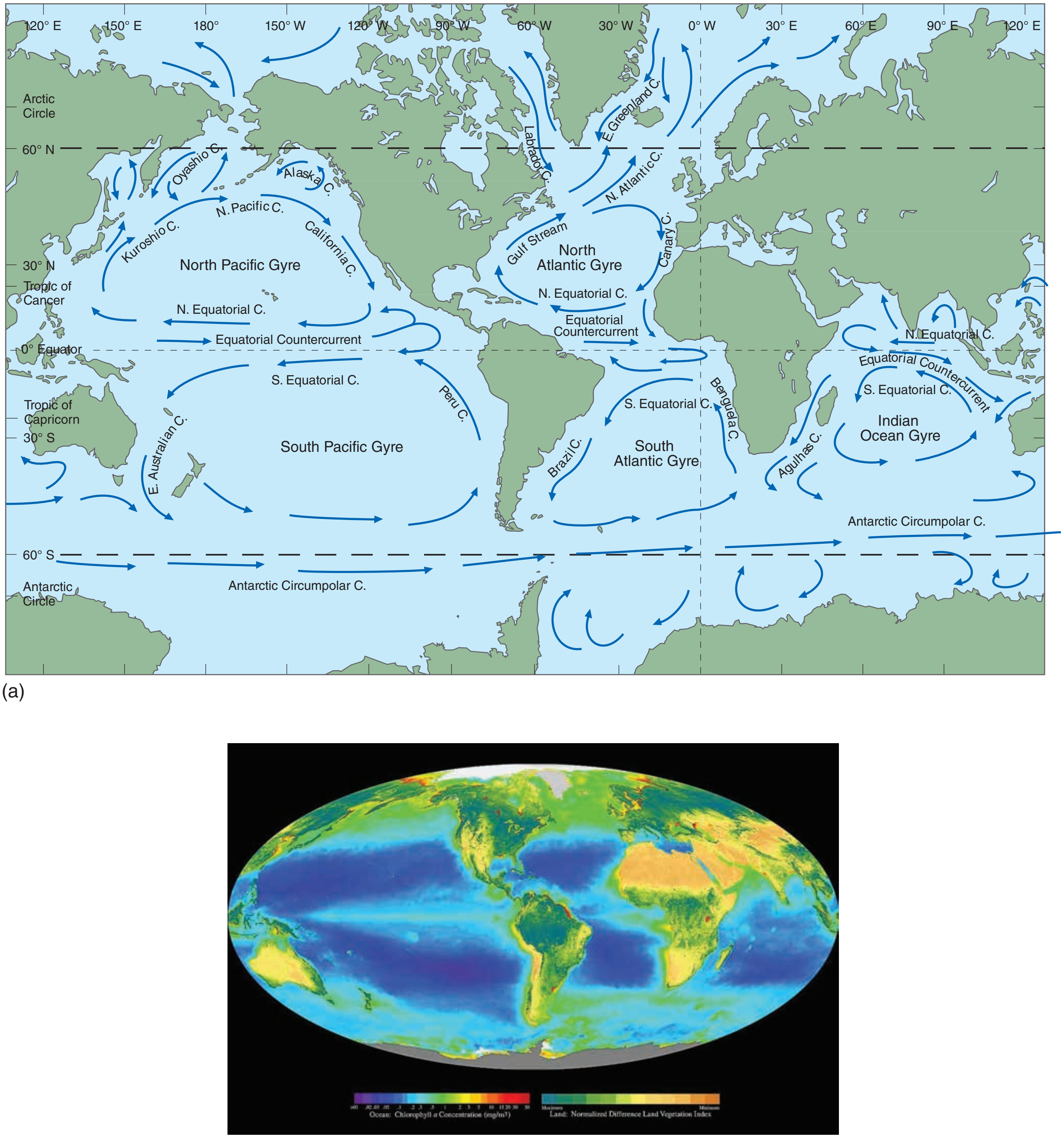
The major wind systems of Earth discussed earlier determine the patterns of major oceanic surface currents by pushing and dragging the water ahead of them (**Figure 3.20**). The oceanic surface currents normally flow down to about 100 to 200 meters. Some of the most pronounced surface currents belong to large, circular **gyres**, which result in part from the Coriolis effect. Surface water masses that flow from high to low latitudes in the gyres move along the western margins of continents. These currents flow more slowly than the water already at the equator, so these currents are "deflected" westward by the Coriolis effect relative to the currents already at the equator (compare Figures 3.17 and 3.20a). When it reaches the equator, the water continues to move westward, driven by the trade winds, and travels across the ocean. Upon reaching the eastern margins of continents, the water is deflected away from the equator back toward high latitudes. Because they are now flowing faster than the water already at higher latitudes, these currents are deflected eastward by the Coriolis effect. As they reach higher latitudes, the surface currents are moved eastward by the prevailing westerlies.

F G The behavior of the modern Earth's surface water masses must be distinguished from that of its deep water masses. The deep water masses circulate in what has been called an oceanic conveyor (**Figure 3.21**). To understand the oceanic conveyor, try to imagine releasing a colored water molecule at a particular spot in the ocean that is easily distinguished from all other water molecules. Assume that you could repeat this experiment a number of times by re-releasing the colored molecule each time it returned to the site of release, allowing the molecule to circulate through the oceans again. On average, it would take about 1,000 years for the colored molecule to return to the site of release. During this time the molecule, typically, would have circulated through the entire world ocean before returning back to its site of release. This rate of ocean circulation is relatively rapid and might even occur on the scale of centuries in separate ocean basins.

We know about the patterns and rates of modern ocean circulation based on the concentration of anthropogenic radioactive isotopes such as ^{14}C (carbon-14) and ^{3}H (tritium). Although ^{14}C and ^{3}H are both produced naturally in Earth's atmosphere by cosmic ray bombardment, their production peaked in the early 1960s because of nuclear weapons testing during the Cold War. Because they are radioactive, the amount of these isotopes in a water mass decreases as soon as the supply of radioactive parent in the atmosphere is cut off by the descent of surface water masses into the deep ocean. When the supply of radioactive parent in the atmosphere is cut off to the descending water mass, the amount of radioactive parent in the water mass begins to decline, giving a measure of time since the water mass became isolated from the atmospheric source.

The circulation of the modern oceanic conveyor has often been referred to as **thermohaline circulation**, meaning the circulation was thought to be driven by differences in the temperature and salinity of the different water masses. The deep water masses of the ocean tend to form in cold, high latitudes, especially near glaciers. Because cold water is denser than warm water, surface waters chilled by the glacial ice tend to sink. The deepest ocean water is quite cold, on the order of about 4°C. Also, the water taken up from the oceans into glacial ice is freshwater. This leaves the salt behind in the remaining ocean water near the ice, which also increases the water's density and causes it to sink.

There are two basic deep water masses produced in the oceans: **Antarctic Bottom Water (AABW)** and **North Atlantic Deep Water (NADW)** (Figure 3.21). As its name suggests, AABW forms off Antarctica but bathes the floors of ocean basins all over the world. Eventually, though, it appears to flow to the surface in the North Pacific and Indian Oceans and then returns along the ocean surface to Antarctica, where it cools and sinks again. NADW is produced mainly off the coasts of Greenland and Iceland in the North Atlantic (Figure 3.21). As the surface waters sink there, they are replaced by the northward flow of the Gulf Stream. As it flows northward, the Gulf Stream waters cool, releasing their heat to the environment (this is why the climates of countries such as England are relatively mild, despite the fact that they are located at relatively high, cool latitudes). Some of the Gulf Stream's water also evaporates, increasing the salinity. As it cools and becomes saltier, the Gulf Stream water eventually becomes dense enough to sink, thereby perpetuating the production of NADW and the oceanic conveyor. Today, the rate of NADW flow is about equal to that of 100 Sverdrups (named in honor of a famous oceanographer). One Sverdrup is equal to a flow rate of 10^6 cubic meters per second and 100 Sverdrups is about equal to the flow rate of the modern Amazon River! By contrast to AABW, NADW only flows within the Atlantic Basin, eventually returning to

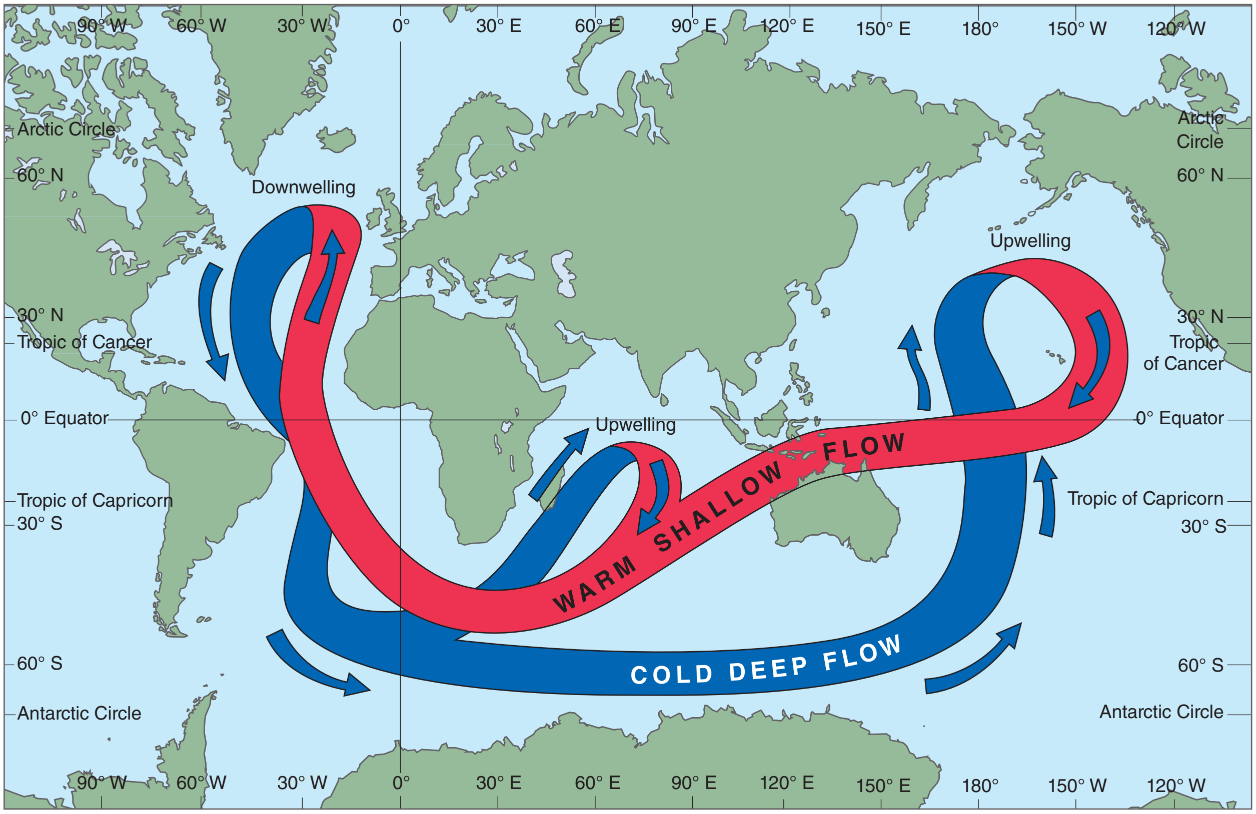


Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE.

FIGURE 3.20 Major ocean surface currents and oceanic production. **(a)** The major ocean surface currents are driven by atmospheric circulation. Compare Figure 3.17. **(b)** Primary production on the Earth as indicated by chlorophyll concentration. In the marine realm, the most productive regions are coastal regions shown in red, whereas the least productive regions are shown in deep blue and correspond to the oceanic gyres of Figure 3.20a. On land, productivity declines with lighter shades of green and yellow. The tropical rainforests of Brazil are highly productive, whereas the Arctic and Sahara Desert are among the least productive.

the ocean surface off Antarctica by the process of **upwelling**. It takes only about 200 years for NADW to circulate in the Atlantic Ocean basin based on the rates of radioactive decay of ^{14}C and other isotopes produced by nuclear bomb testing in the 1950s and 1960s. When it reaches the surface at Antarctica, NADW mixes with water around Antarctica, some of which will again descend as AABW, which takes much longer to circulate through the oceans.

Although density differences no doubt play a role in deep-ocean circulation, the concept of thermohaline circulation has been modified in recent years by the concept of **meridional ocean circulation**, so named because of

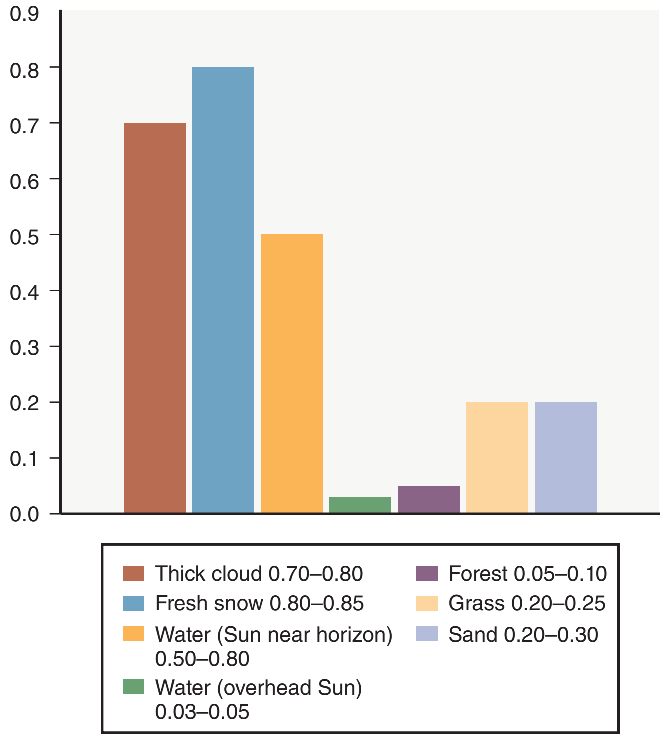


Data from: McCartney, M. S. 1994. Towards a model of Atlantic Ocean circulation. *Oceanus*, 37(1), 5–8.

FIGURE 3.21 The oceanic conveyor involves the thermohaline circulation of deep water masses due to differences in temperature and salinity. Two of the main water masses produced are Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW).

the movement of water masses north and south through the ocean basins parallel to the meridians of longitude. Although density differences due to temperature and salinity are still thought to be involved in the movement of these deep water masses, some workers now think that the density differences are not necessarily themselves the prime driver of deep-ocean circulation. Instead, winds are thought to produce the density differences in upper water masses of the top several hundred meters by evaporation and heat loss. These upper-water masses then become sufficiently dense to sink, driving the movement of deeper water masses.

The oceans also affect Earth's climate in a third way: by influencing Earth's **albedo**, or surface reflectivity, which in turn affects global temperatures. The oceans are dark compared with land, and darker surfaces tend to radiate the sun's energy back into the atmosphere as heat, which is trapped by carbon dioxide and water vapor, warming the Earth via the greenhouse effect (see Chapter 1). Thus, when oceans have been widespread—at many times even flooding most of the continents—Earth has tended to warm in part because of its decreased albedo. On the other hand, when the oceans have receded from land, more bare land increased Earth's albedo and cooled the planet. Other types of surfaces on land (ice, forests) also affect Earth's albedo (**Figure 3.22**). We examine the processes that cause sea level to rise and fall in Chapter 6.



Data from: Kump, L. R., Kasting, J. F., and Crane R. G. 1999. *The Earth System*. Upper Saddle River, NJ: Prentice-Hall.

FIGURE 3.22 Albedo (reflectivity) of various types of natural surfaces.

CONCEPT AND REASONING CHECKS

1. Diagram the hydrologic cycle.
2. How are the hydrologic cycle and atmospheric circulation related?
3. What drives surface ocean circulation?
4. What causes the deep oceans to circulate?
5. How do the oceans influence Earth's albedo?

3.5 The Biosphere

3.5.1 Biogeography: distribution of plants and animals over Earth's surface

H The **biosphere** is composed of the total living biota (living organisms) of Earth, ranging from the smallest bacteria to the largest trees and whales. However, organisms are not uniformly distributed over the planet. This basic observation was a cornerstone of Charles Darwin's theory of evolution (see Chapter 5).

Each type of organism—or *species*—has a certain range of physical environmental factors within which it can live and reproduce its own kind. It is this tolerance to environmental factors that largely determines the biogeographic distribution of different species. Temperature is considered to be the most important factor determining the distribution of different species because it affects the rates of biochemical pathways such as photosynthesis and respiration; such processes tend to be characteristic of each species. On land, rainfall is also important because animals and plants must make up for water loss due to respiration and transpiration. In the oceans the salinity and oxygen content of the water also affect the distribution of organisms, especially close to shore where large rivers enter. Modern species that, for example, live in temperate and higher latitudes—on land or in the oceans—tend to be **eurytopic** and more widely distributed—or **cosmopolitan**—because they must withstand greater extremes of temperature and other factors that change with the seasons. By contrast, many other species are **stenotopic**, or narrowly tolerant of environmental change. These taxa tend to be concentrated in, or endemic to, certain areas because of their narrower tolerances. Many tropical species of plants, insects, and corals are stenotopic and are endemic to certain regions of Earth.

Each continent, ocean basin, or sea tends to have its own distinctive biota. On land, larger regions of each continent are characterized by distinct bands of vegetation and deserts called **biomes** (**Figure 3.23**). These broad bands, which tend to circle the globe on land, tend to correspond to differences in the amount of solar radiation and precipitation reaching Earth's surface, as described earlier in the chapter. Each continent in turn represents a particular biogeographic **region**. Similarly, there is a steep temperature gradient in the surface waters of the open oceans. Surface water temperatures at the equator can reach 30°C, whereas those near the poles can be as low as 0°C, so that different species tend to characterize each water mass. The oceanic realm is in turn characterized by one or more smaller scale **provinces**, especially where different ocean currents encroach on land masses. Thus, in the marine realm species living closer to land occur in provinces whose boundaries correspond to changes in temperature and salinity between adjacent water masses impinging on the coasts.

These distinctive biotas have also changed through time as continents have changed position during tectonic cycles. In the process, populations of many different kinds of plants and animals have become separated from one another for tens to hundreds of millions of years, evolving their own distinctive faunas and floras, for example, the distinctive marsupial fauna of Australia. Rifting of a continent can, for example, lead to the evolution of what was once a single biota into two or more regions separated by new ocean basins. It was this type of evidence that was initially used to infer the former existence of the supercontinent Pangaea and to support the hypothesis of continental drift. These and other broad effects of the tectonic cycle on Earth systems and sedimentary environments will be discussed in the last part of this chapter.

3.5.2 Energy relationships

I The flux of matter and energy within ecosystems is determined by the characteristic **niches** of species within the ecosystem. The term "niche" refers to the particular role or function of a species within an ecosystem and is defined primarily by the **trophic (food, energy) relationships** of the species, or "who eats whom." The niches of the different species of a community can be diagrammed as "links" in a **food chain** or food web. It is these energetic relationships that organize the species inhabiting an area into communities and ecosystems.

The energetic relationships of food chains and webs can also be arranged into **food (or energy) pyramids** (**Figure 3.24**). The different levels of the food pyramid show how food (energy, matter) is passed from one group of organisms to another in a community. Plants (**autotrophs or producers**) occur at the base. During photosynthesis energy from light is used by plants (or producers) to combine carbon dioxide from the atmosphere with water to produce one molecule of sugar and oxygen, which is released as a byproduct into the atmosphere. Energy from sunlight is stored in the chemical bonds of the sugar, whereas carbon dioxide is taken out of the atmosphere and sequestered in the reservoirs of living and dead organic matter. **Herbivores** occur at the level immediately above producers. **Secondary consumers (carnivores)** occur at the next higher level above herbivores and **top carnivores** at the apex of the pyramid. Although the conversion of light energy to plant biomass varies, it is roughly about 10% efficient. Moreover, as the energy stored in plant biomass is passed from one level to the next of the pyramid, energy is lost, so that only so many levels can be supported. This means that only 10% of the original light energy received by the plant is converted to plant biomass. Now assume that each level of a food pyramid is only 10%

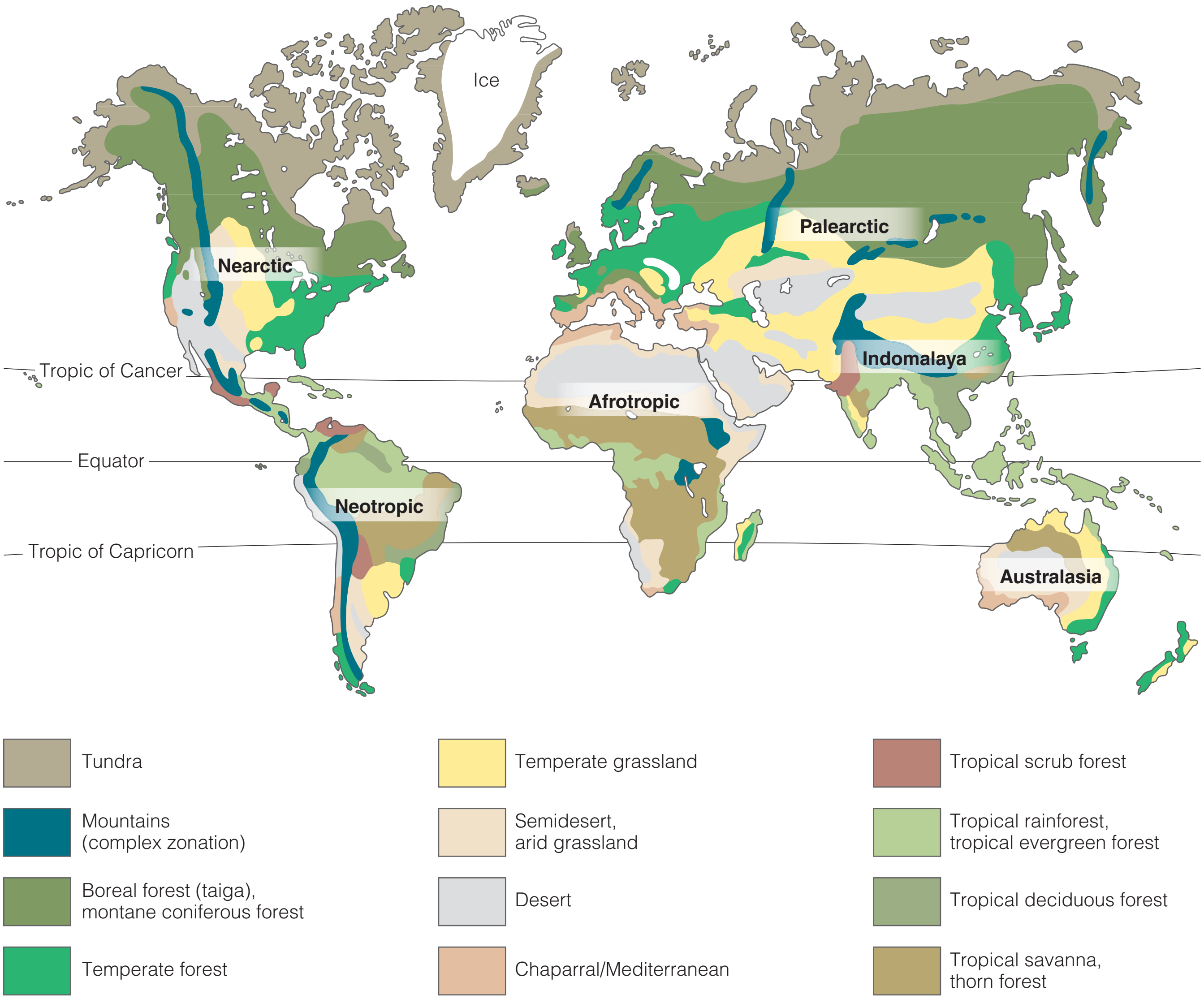


FIGURE 3.23 Major biogeographic regions and biomes on land. Compare with Figures 3.17 and 3.19.

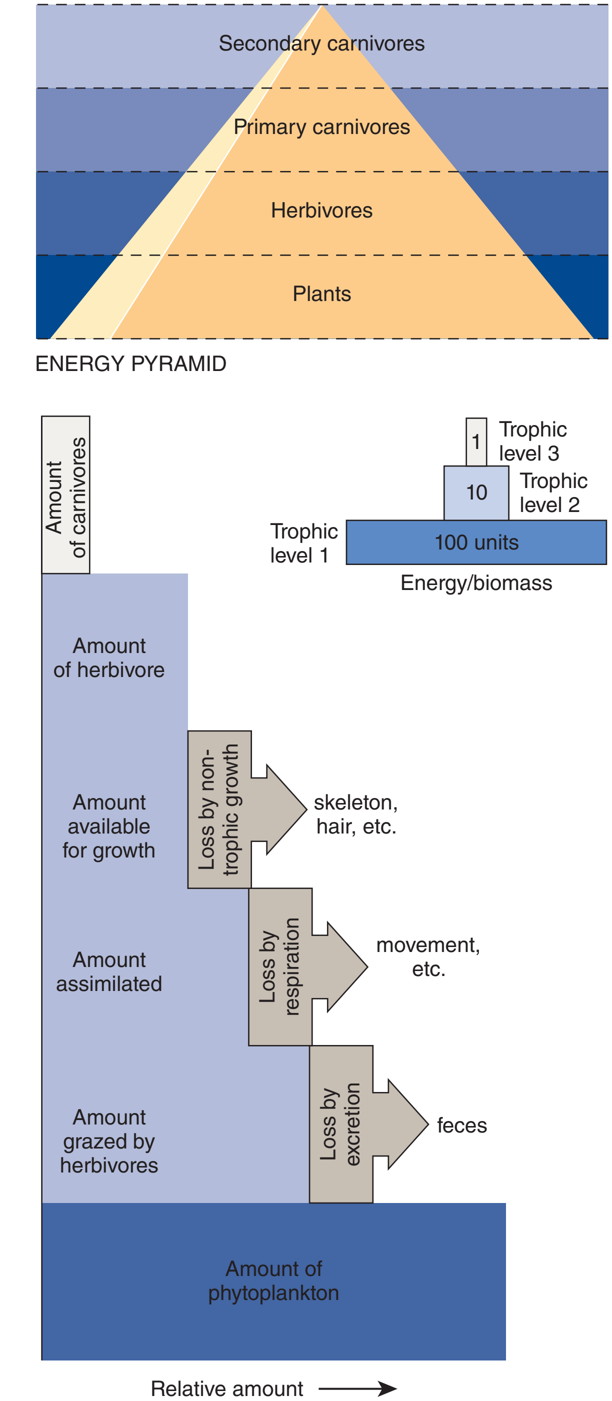
efficient in converting energy from the next lower level. Thus, only 10% of the energy stored in plant biomass (or about 1% of the energy originally received from the sun) at the base of the pyramid is converted into animal (herbivore) biomass at the next higher level; the rest of the energy is lost to the locomotion, body heat, and so on of the herbivores. At the next higher level only 10% of herbivore biomass is converted to carnivore biomass, or 0.1% of the original energy captured by plants (one-tenth of 1%). Ten percent of this primary carnivore biomass is converted to secondary carnivore biomass or 0.01% of the original energy in plant biomass (one-tenth of 0.1%). At this point the apex of the food pyramid has typically been reached, presumably because there is insufficient energy to support higher levels of the pyramid.

The level at which populations of organisms are no longer sustainable is called the **carrying capacity** of the environment. Carrying capacity therefore refers to the maximum population sizes (or biomass) that can be sustained by the environment. Carrying capacity is largely a function of energy (food availability) but also reflects other factors such as available habitat, mates, and nutrients (as you'll see in a moment).

3.5.3 Biogeochemical cycles

J The biosphere is intimately involved in the cycles of various chemical elements on different scales of time. Such cycles are called **biogeochemical cycles** because they involve the interplay of several of Earth's major systems. In Chapter 1, we were primarily concerned with the biogeochemical cycle of carbon.

During the cycle of organic carbon, as in other systems, matter and energy are transferred between reservoirs. The initial production of organic carbon by photosynthesis is referred to as gross primary production. Much of the gross primary production is used as an energy source at the base of food pyramids, as just described; that which is left is called net primary production. Net primary production can be incorporated into the reservoirs of living biomass or



Data from: Russell-Hunter, W. D. 1979. *Aquatic Productivity*. New York: MacMillan Publishers.

FIGURE 3.24 Most energy that is transferred upward through the levels of a food pyramid is lost as heat, thereby limiting the number of levels in a food pyramid or links in a food chain.

dead biomass, where it is stored until it is eventually broken down. The breakdown of dead organic matter and the release of energy stored in the chemical bonds occur by the process of respiration, which is essentially the reverse of photosynthesis. Bacteria, along with fungi and burrowing organisms like worms, act as **decomposers**, which initially break down—or **remineralize**—dead organic matter and **recycle** the nutrients trapped in the organic matter back to the ecosystem. **Nutrient** is any substance required by organisms for normal growth and maintenance (**Figure 3.25**). Without this recycling of nutrients from dead organic matter, ecosystems would quickly shut down.

This illustrates a very important point about ecosystems, communities, and the biosphere in general: they are all typically nutrient limited. Many nutrients like phosphorus (which is a critical component of DNA and other molecules of biologic systems) are originally derived from the weathering of continental rocks. However, the weathering of continental rocks is very slow, so that nutrient recycling is necessary to sustain ecosystems. Near the sediment surface, organic matter might be broken down by decomposers. Burrowers pump oxygen into the sediment, which oxidizes the organic matter to carbon dioxide, causing it to decay and release nutrients. As we will see in subsequent chapters, the availability of various nutrients has changed through time, affecting the flux of carbon between different reservoirs in the carbon cycle.

CONCEPT AND REASONING CHECKS

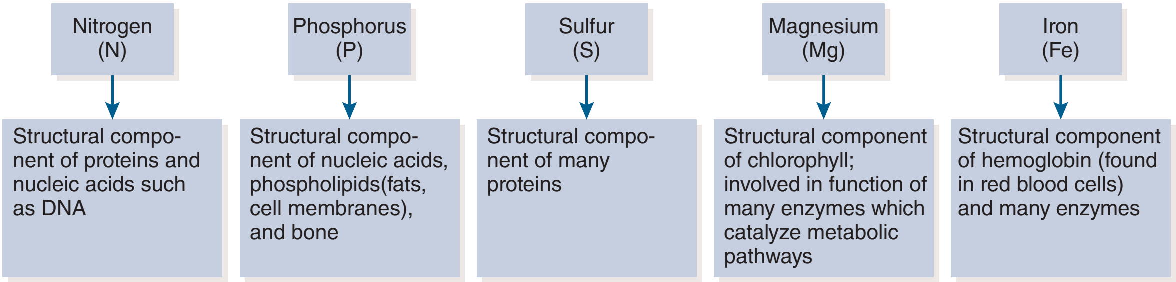
1. What factors determine the distribution of organisms over Earth's surface?

3.6 The Tectonic Cycle and Earth Systems

Earlier, we used the rise of the Himalayas to examine how continental movements and orogeny associated with the tectonic cycle can dramatically affect climate, the hydrologic cycle, and biotas over enormous regions—specifically, in case of the Himalayas, the origins of the Asian monsoon (Box 3.1).

The tectonic cycle has exerted similar effects on *global* scales by shifting the positions of the continents beneath atmospheric convection cells. The positions of the atmospheric cells have presumably remained relatively constant through geologic time, so we will move the continents beneath them and see what happens. For example, the movement of a portion of a continent beneath a low pressure cell will increase rainfall because as the air within the cell rises, it cools and loses its moisture, resulting in forests in temperate latitudes and tropical rainforests nearer the equator (**Table 3.1**). Conversely, moving a continent beneath a high pressure cell will likely result in a drier continental interior because the air within the high pressure cell picks up moisture as it descends toward the Earth's surface, potentially resulting in deserts or grasslands. Such conditions occurred in what is now the southwestern United States during the Jurassic Period, when thick, cross-bedded desert sands were deposited. On the other hand, the movement of a continent near or over a pole will result in the production of glaciers, increasing the latitudinal temperature gradient from poles to the equator while impacting the distribution of terrestrial vegetation, as occurs today.

The rifting and assembly of a supercontinent during a tectonic cycle also exert a tremendous impact on sea level,



Data from: Ricklefs, R. E., and Miller, G. L. 2000. *Ecology*, 4th ed. New York: W. H. Freeman.

FIGURE 3.25 The roles of nutrients essential to plants and animals.

patterns of surface ocean currents, and rates of deep-ocean circulation. Each tectonic cycle lasted approximately 250–300 million years and consisted of an initial "greenhouse" phase followed by an "icehouse" phase.

Let's begin with the rifting of a supercontinent like Pangaea during the Triassic Period, about 250 million years ago (see Chapter 13). A supercontinent insulates the Earth, slowing radiogenic heat loss from the core and mantle. Eventually heat buildup between continental crust becomes sufficient to cause doming, rifting, and breakup of the continent, followed by rapid seafloor spreading. Seafloor spreading centers (or mid-ocean ridges) amount to vast submarine mountain ranges, dwarfing even the Himalayas. During the Mesozoic, for example, the equatorial Tethyan Seaway (after Tethys, a daughter of the gods Uranus and Gaea) flowed around the Earth largely unimpeded. The Tethyan Seaway was a warm seaway because its currents, driven by the trade winds, flowed around the Earth largely unimpeded, all the while exposed to the heat of the sun in the tropics and subtropics (**Figure 3.26a**; **Table 3.2**). As mid-ocean ridges grew in volume, they also began to displace the oceans out of their basins onto the continents, much like when you sit in a bathtub full of water (also known as Archimedes' principle). At the same time, the warm crust forming at the spreading centers cooled as it spread away from the ridge and began to sink relative to the height of the oceans; this would have also caused the seas to flood the continents. In fact, during the Mesozoic Era, and especially the Cretaceous Period, sea levels were roughly several hundred meters higher than today (**Figure 3.27**). Increased rates of seafloor spreading would have also been associated with increased rates of subduction; thus, volcanism would have increased, as well, pumping more carbon dioxide into the atmosphere and promoting "greenhouse" conditions. These conditions would have been accentuated by decreased albedo related to the spread of relatively shallow epicontinental (or epeiric) seas. Warm conditions would have also intensified the hydrologic cycle on land; the increased heat likely increased the energy and rates of circulation of atmospheric convections cells.

These conditions continued until about the middle of the Cenozoic Era (late in the Paleogene period), when the Earth began to enter a prolonged "icehouse" phase (see Chapters 14 and 15). Why did the conditions begin to reverse themselves? Because the continents were now moving back toward one another and even colliding in some cases. The Himalayas, the Alps, and mountain ranges in western North and South America all began to form. This widespread uplift drove the seas off the continents as volcanism became less pronounced. By this time, too, Antarctica had moved the South Pole and massive ice sheets began to form, drawing sea level down and increasing Earth's albedo yet further.

A similar cycle of "greenhouse-to-icehouse" conditions occurred during the Paleozoic Era (see Chapters 11 and 12).

TABLE 3.1

Effects of the tectonic cycle on the hydrologic cycle and the distribution of terrestrial floras

Conditions	Supercontinent Present (Continents Clumped Together)	Continents Rifted (Continents Far Apart)
Tectonic style	Collision, orogeny, closing of ocean basins	Rifting
Relative latitudinal temperature gradient	High	Low
Relative area of continental interiors	High	Low
Relative climatic extremes	High	Low
Terrestrial vegetation: High (subpolar to polar) latitudes	Glaciers, taiga, and tundra	Deciduous forests
Terrestrial vegetation: Mid (temperate) latitudes	Deciduous forests and steppe	Tropical wet forests
Terrestrial vegetation: Low (subtropical to tropical) latitudes	Savannahs and deserts more likely present	Rainforests more likely, along with savannahs and deserts

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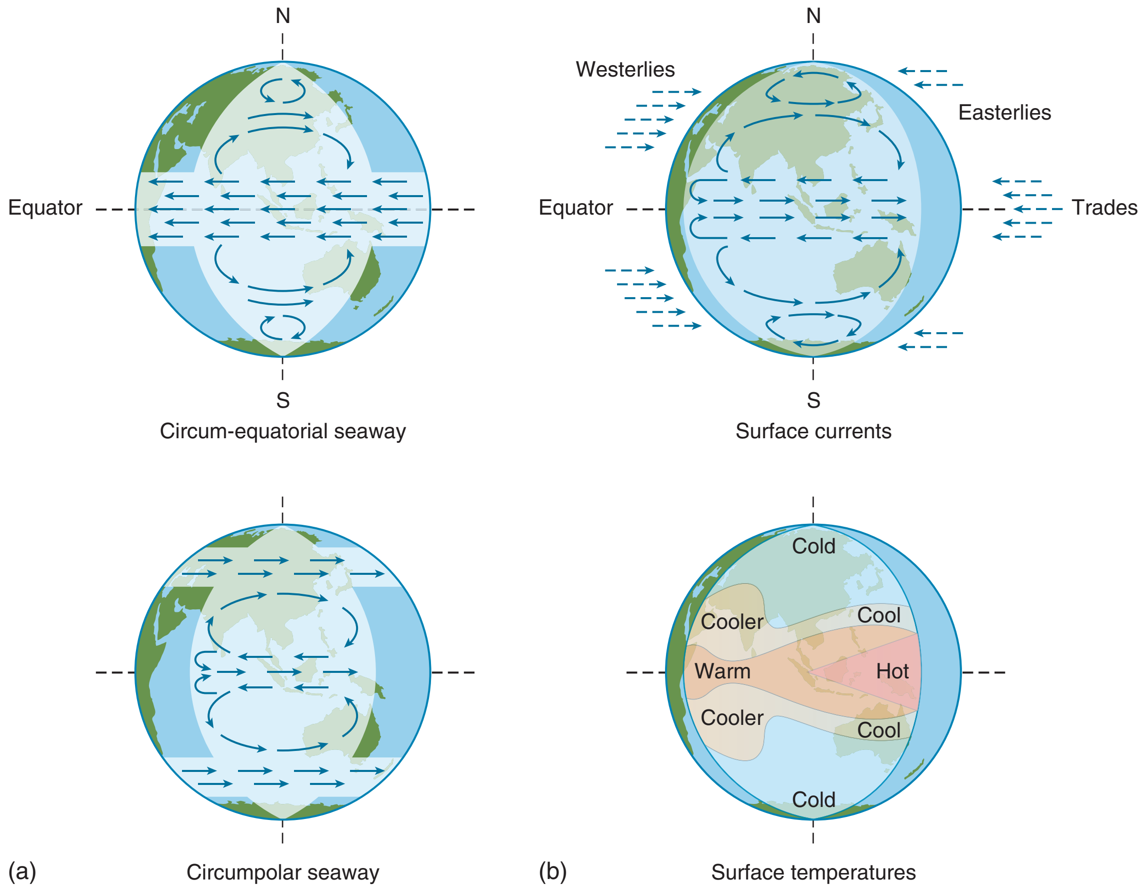

Data from: van Andel, Tj. H. *New Views on an Old Planet*. Cambridge, UK: Cambridge University Press 1985, 1994. Reprinted with the permission of Cambridge University Press.

FIGURE 3.26 The effects of the tectonic cycle on ocean circulation and global climate. **(a)** Effects on ocean circulation as a supercontinent rifts apart. A more even distribution of warm temperatures results if equatorial waters flow around the Earth more than once, warming the currents before they are eventually deflected to the north and south. As we will see, this was the basic situation during the existence of the Tethyan Seaway during the Mesozoic Era. If a continent is isolated over a pole by a surface current, then ice caps may start to grow, as eventually happened on Antarctica during the Neogene period. **(b)** Effects on ocean circulation and global temperature distributions as a supercontinent is assembled. Note how the temperatures of the surface waters mimic the flow of surface currents. Water in the equatorial current is moved westward by the trade winds, warming along the way because of exposure to the sun. Much of this water is deflected to the north and south by Pangaea and cools as it forms two large gyres. The rest of the water returns as an equatorial countercurrent and warms even further. Consequently, water in the western portion of the ocean is warm and that in the eastern portion is even warmer.

A different supercontinent called **Pannotia** began to rift during the Cambrian, the continents began to disperse, and the proto-Atlantic Ocean called the "Iapetus Ocean" (after Iapetus, a son of Oceanus and Gaea, and a brother of Tethys) formed between what was then North America (Laurentia) and Europe (Baltica). This particular greenhouse phase lasted until about the middle of the Paleozoic Era or so (Devonian Period). Then, continental collisions and associated orogenies began to assemble Pangaea during the last half of the Paleozoic Era (Mississippian-to-Permian periods). Supercontinent assembly is associated with the production of enormous mountain ranges and extremely large continental interiors that are prone to warming; during this time, Pangaea also lay astride the equator, where it was subject to warm, moisture-laden winds brought by the trade winds. Together, these conditions likely resulted in even more intense monsoons than those experienced over the Indian subcontinent today (see Chapter 12). Such conditions are indicated during the Late Paleozoic era, when widespread coal-forming swamps occurred in what is now the eastern half of North America and portions of Europe as the supercontinent Pangaea was being assembled (see Chapter 12).

So, what happened to ocean circulation when Pangaea began to block the warm ocean circulation of the earlier Paleozoic? The warm tropical surface currents would have been diverted to higher latitudes to the north and south, making it more likely that they would cool (**Figure 3.26b**). And like the Cenozoic Era, an enormous glacier formed on the Gondwana continents of the Southern Hemisphere, as the sea level gradually fell. This in turn likely imparted greater "continentality" to Pangaea, meaning greater seasonality and climatic extremes on the Earth.

The broad patterns of sedimentary environments responded to the broad cycles of sea-level change associated with the tectonic cycle, as we will see in later chapters. Both greenhouse phases were characterized by warm, and extensive, shallow seas several hundred meters or more higher than today's. These are prime conditions for the formation of

TABLE 3.2

Effects of the tectonic cycle on climate, sea level, and ocean circulation

Conditions	Icehouse State (Late Paleozoic; Oligocene-Recent)	Greenhouse State (Early-to-Middle Paleozoic; Cretaceous-Eocene)
Tectonic style	Collision, orogeny, closing of ocean basins	Rifting
Relative rates of seafloor spreading	Slow	Fast
Relative rates of ocean ridge formation, subduction, volcanism, and release of CO_2 to atmosphere	Low	High
Relative latitudinal temperature gradient	High	Low
Relative sea level	Low, due to decreased production of mid-ocean ridges; narrow continental shelves	High, sometimes hundreds of meters, due to increased mid-ocean ridge production; with broad epeiric seas covering the continents producing enormous continental shelves
Degree of stratification of oceans into distinct water masses	Ocean is highly stratified because of differences in temperature and salinity of distinct water masses	Much less stably stratified than icehouse state
Surface ocean temperatures	Great range due to large latitudinal temperature gradient: Surface water temperatures range from less than 2°C (at poles) to greater than 25°C at equator	Smaller range due to small latitiudinal temperature gradient: Surface water temperatures not much greater than icehouse phase at equator but much greater (12–15°C) at high latitudes
Deep ocean temperatures	Cold, ranging from about 1°C to 2°C, due to glaciation and production of deep-water masses nearer poles	Quite warm compared to present, ranging from 15°C near equator to about 10°C at poles, due to absence of glaciers
Rates of ocean circulation and oxygenation of deep-water masses	Relatively fast because of density differences between water masses; faster circulation moves oxygenated surface waters deeper into basins	Low-density surface water leads to slow deep water circulation and low oxygen content due to warm temperatures, often with widespread anoxia and black shales (warm water holds less oxygen than cold water)
Organic matter remineralization and nutrient cycling	Vigorous flow of strongly oxygenated bottom water, so relatively little organic matter preservation	Little remineralization of dead organic matter due to low oxygen conditions, so nutrient recycling may be much reduced
Primary productivity (marine photosynthesis)	Numerous, diverse marine environments and provinces, sometimes with high productivity due to upwelling	Low marine productivity, but good petroleum source beds because of organic matter preservation (due to low oxygen conditions)
Relative rates of erosion and mechanical versus chemical weathering	Fast, mechanical weathering tends to dominate	Slow, chemical weathering tends to dominate

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carbonate (limestone) platforms, in which reefs—formed by various taxa through time—thrived. Much of the world's petroleum also comes from rocks of the Cambrian-to-Devonian and Mesozoic eras; these intervals are characterized by widespread, carbon-rich black shales, which could have served as source beds for petroleum. These conditions have led some workers to suggest that ocean circulation was quite sluggish and conditions highly reducing ("anoxic" or without oxygen) during greenhouse phases because such conditions would have allowed the preservation of large amounts of dead organic matter in sediments to produce petroleum (Table 3.2). On the other hand, icehouse conditions would have been characterized by more rapid rates of ocean circulation and better oxygenation because of the presence of ice sheets at one or both poles.

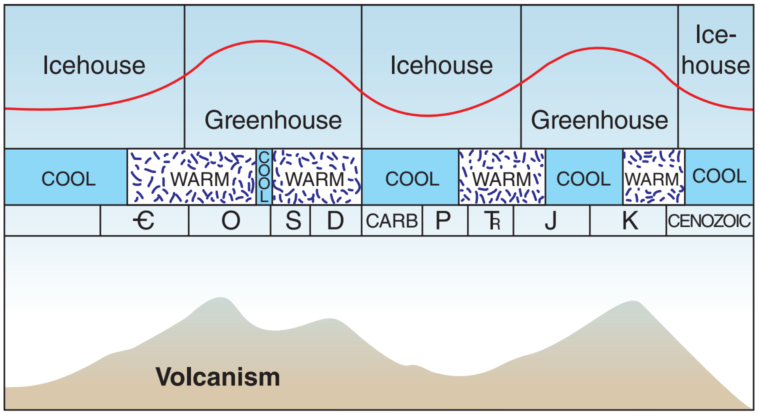

FIGURE 3.27 Cycles of continental configuration, sea level, and climate during the Phanerozoic Eon. During "greenhouses" (Cambrian through Devonian periods; Jurassic through Paleogene periods), continents dispersed and sea level rose as a result of increased sea floor spreading rates and mid-ocean ridge (MOR) volume. Increased volcanism (based on the volume of igneous rocks emplaced) resulted in increased atmospheric CO_2 levels that presumably caused the Earth's average surface temperature to rise during these intervals. Just the opposite conditions apparently prevailed during "icehouses" (Mississippian through Permian periods; Paleogene period to the recent): atmospheric CO_2 levels and sea level declined, presumably as a result of decreased spreading rates and MOR volume. *This figure and the associated discussion in the text serve as a framework for later discussion of Earth history in Chapters 11–15*.

Summary

- The solid Earth system involves the rock and tectonic cycles. The release of heat generated by radioactive decay from within the Earth drives the processes of plate tectonics: seafloor spreading, the movement of continents, mountain building, and the rock and tectonic cycles.
- As heat is brought toward Earth's surface by convection cells, igneous and metamorphic rocks are formed and mountain chains are uplifted. The mountains undergo weathering, erosion, deposition, and lithification to produce sedimentary rocks. Igneous and sedimentary rocks can change through the processes of metamorphism, as can metamorphic rocks.
- Circulation within the atmosphere results from differential heating of Earth's surface and the transfer of heat and moisture across latitudes via large convection cells. Coupled with the Coriolis effect, this results in the major wind systems of the Earth: trades, westerlies, and polar easterlies.
- The hydrosphere involves the hydrologic cycle. Precipitation produces rain, snow, and ice. Runoff from the land flows into rivers and streams, infiltrates the ground, evaporates to the atmosphere, and is lost by transpiration from plants during photosynthesis.
- The biosphere affects the carbon cycle and Earth's climate through photosynthesis and respiration, both of which help to regulate levels of the greenhouse gas carbon dioxide in the atmosphere.
- The biogeographic distribution of organisms is determined in part by their tolerance to environmental change. Widely distributed species tend to be eurytopic, or broadly tolerant of environmental change. By contrast, stenotopic species are less tolerant of environmental change and tend to be endemic to certain areas.
- Biomes are caused by differential heating of Earth's surface by the sun, which affects surface temperature and rainfall. Each continent is characterized by a particular biogeographic region. In the sea, subdivisions called provinces reflect changes in water masses, especially temperature related to ocean currents caused by atmospheric circulation and upwelling.
- The distribution of modern organisms is also determined by historical factors such as the movement of plates, which affect atmospheric and oceanic currents via rifting and orogeny.
- A biologic community coupled with its physical environment is called an ecosystem. The flow of energy from the sun to photosynthetic plants to consumers (herbivores and carnivores) establishes the trophic relationships and niches of food chains. Trophic relationships in turn link food chains into food webs that comprise biologic communities.
- Eventually, the availability of energy appears to run out because of the laws of thermodynamics, and further links in food chains and higher levels in food pyramids cannot be supported.

- Biogeochemical cycles transfer elements such as carbon, oxygen, and nutrients from one reservoir of Earth's systems to another. The reservoirs may be in the same system or in different systems. Biogeochemical cycles are critical to the functioning of Earth's systems because they help to recycle nutrients and other elements critical to life.
- The tectonic cycle has affected the broad patterns of sea level, ocean circulation, and climate of Earth on time scales of several hundred million years.

Key Terms

albedo
andesite
Antarctic Bottom Water (AABW)
aphanitic
assimilate
autotrophs or producers
basalt
biogeochemical cycles
biomes
biosphere
blueschist
carrying capacity
Coriolis effect
cosmopolitan
cryosphere
decomposers
diorite
eurytopic
evaporation
felsic
foliated
food chain
food (or energy) pyramids
fractional crystallization
gabbros
gneisses
granodiorites
gyres
herbivores
hydrologic cycle
hydrosphere
hydrothermal metamorphism
hydrothermal weathering
igneous
impact
lava
lithification
magma mixing
magmatic differentiation
marble
meridional ocean circulation
metamorphic
migmatites
niches
nonfoliated
North Atlantic Deep Water (NADW)
nutrient
Pannotia
partial melting
phaneritic
phyllite
plutons
polar easterlies
precipitation
provinces
quartzites
recycle
region
regional metamorphism
remineralize
reservoirs
rhyolites
runoff
schists
secondary consumers (carnivores)
sedimentary rocks
shock metamorphism
slates
stenotopic
tektites
thermohaline circulation
top carnivores
trade winds
transpiration
trophic (food, energy) relationships
ultramafic
upwelling
westerlies

Review Questions

1. Using labeled diagrams and in your own words, describe the reservoirs, processes, and fluxes of the each of the four basic Earth systems, including their cycles.
2. What are the ways by which different types of magmas form?
3. Diagram the sequence of crystallization of the different igneous rock types and their compositions and textures.
4. What does the texture and mineralogy of each of the following igneous rocks tell about how and where each rock formed: gabbro, basalt, granite, rhyolite, granodiorite, and andesite?
5. What does the texture and mineralogy of each of the following metamorphic rocks tell about how and where each rock formed: slate, phyllite, schist, gneiss, marble, and quartzite?
6. Using labeled diagrams and in your own words, describe how each of the following sets of systems interact via any processes and fluxes:
   Solid Earth-Atmosphere
   Atmosphere-Hydrosphere
   Solid Earth-Biosphere
   Atmosphere-Hydrosphere-Biosphere
   Biosphere-Hydrosphere
7. Diagram and discuss a monsoon.
8. Why is the heat capacity of the oceans important?
9. What factors determine the broad distribution of plants and animals?

10. What traits does an ecosystem share with other kinds of systems?
11. What are nutrients, and why are they important? Identify the different reservoirs and discuss the regeneration of nutrients in the oceans.
12. Construct a chart indicating how the tectonic cycle of greenhouse-icehouse conditions affects each of the following: global temperature, sea level, the hydrologic cycle, ocean currents, albedo, and the distribution of plants and animals? Indicate on the chart when these conditions occurred during geologic time.

Food for Thought:
Further Activities In and Outside of Class

1. Assume that you are an early geologist (like James Hutton; see Chapter 1) trying to determine how rocks form. Use inductive logic (see Chapter 1) to infer how each of the major types of rocks—igneous, sedimentary, metamorphic—forms. What sorts of evidence would you seek? Where would you go to look? How would you test your inferences?
2. In a few words, infer the conditions under which you believe each of the following rocks formed based on the description (in a few cases, there can be more than one interpretation):
   a. Phaneritic, abundant potassium feldspar, mica, and quartz
   b. Dark, with phaneritic texture
   c. Coarse-grained, banded rock containing quartz, feldspar, micas, and hornblende
   d. Shiny, generally fine-grained but with some coarser amphibole grains
   e. Dark, with aphanitic texture
3. Is the rock cycle a theory (see Chapter 1)? Explain.
4. Why does continental crust tend to be granitic in composition?
5. Granites and granodiorites are often involved in mountain building but diorites less so. Why? (Hint: Think about the processes by which magmas of different compositions form.)
6. The slopes of Hawaiian volcanoes are relatively gentle compared with those of the Cascades. Why?
7. The composition of the extrusives associated with the Snake River Plain west of Yellowstone Park range from basaltic to rhyolitic, but those nearer Yellowstone range from andesitic to rhyolitic. How might the composition of the extrusives located closer to Yellowstone have changed through time?
8. Imagine as you drive along a highway for many tens of miles that the rocks exposed in the outcrops change from granodiorites to gneisses and then phyllites. In what sort of geologic setting did these rocks originally form?
9. If you were looking for evidence of an ancient asteroid impact, for what sorts of evidence would you look?
10. Would the biosphere completely shut down if photosynthesis stopped?
11. The amount of time it takes for a particular substance to be replaced in a particular reservoir is called its residence time. The total inventory of phosphorus dissolved in all of the oceans is 89,910 terragrams (1 terragram [or Tg] = 1,012 grams). The amount of phosphorus delivered to the oceans by runoff (the flux) from land is about 1.9 Tg per year. What is the residence time of phosphorus in the oceans if it is replaced only by runoff from land?
12. The residence time of phosphorus in the surface layer of the ocean is only 2.6 days, which is quite rapid. Explain.
13. The phosphorus inventory of all the deep ocean water masses is 87,100 Tg and the amount of phosphorus coming into this reservoir from all sources is about 60 Tg per year. What is the residence time of phosphorus in this reservoir? Why do you suppose scientists are interested in ocean circulation and its effect on atmospheric carbon dioxide concentrations?

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