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Uplifted sediments at Moab, Utah. These sandstones and shales represent a former cycle of uplift, erosion, and sedimentation. Erosion of the ridges by streams that are tributary to the main river is part of the current cycle. [Breck P. Kent.]

CHAPTER
4

Rocks: Records of Geologic Processes

> *"The silly question is the first intimation of some totally new development."*
>
> ALFRED NORTH WHITEHEAD

A **rock** is a naturally occurring solid aggregate of minerals. Some rocks, such as white marble, are composed of just one mineral, in this case calcite. A few rocks are composed of nonmineral matter. These include the noncrystalline, glassy volcanic rocks, obsidian and pumice, and coal, which is compacted plant remains. In an aggregate, minerals are joined so they retain their individual identity (**Figure 4.1**). What determines the physical appearance of a rock? They vary in color, in the sizes of their crystals or grains, and in the kinds of minerals that make them up. Along a road cut, for example, we might find a smooth black rock composed of volcanic glass and crystals of pyroxene and feldspar, particles that are too small to be seen with the naked eye (**Figure 4.2**). Nearby we might see a brownish rock with many large glittering crystals of mica and some grains of quartz and feldspar. Overlying both the black rock and the brown one we might see the remains of a former beach: horizontal layers of light-brown rock that appear to be made up of sand grains cemented together.

The appearance of a rock is determined partly by its mineralogy and partly by its texture. **Mineralogy**—the relative proportions of a rock's constituent minerals—helps determine how it looks, as well as other properties, as you will recall from Chapter 3. So does a rock's **texture**—the sizes and shapes of its mineral crystals and the way they are put together. These crystals (or grains), only a few millimeters in diameter in most rocks, are categorized as *coarse,* if they are large enough to be seen with the naked eye, and *fine,* if they are not. The mineralogy and texture that determine a rock's appearance are themselves determined by the rock's geologic origin—where and how it was formed (see Figure 4.2).

The dark rock in our road cut, called basalt, was formed by a volcanic eruption. Its mineralogy and texture depend on the chemical composition of rocks that were melted deep in the Earth. All rocks that form by the solidification of molten rock are called **igneous rocks.**

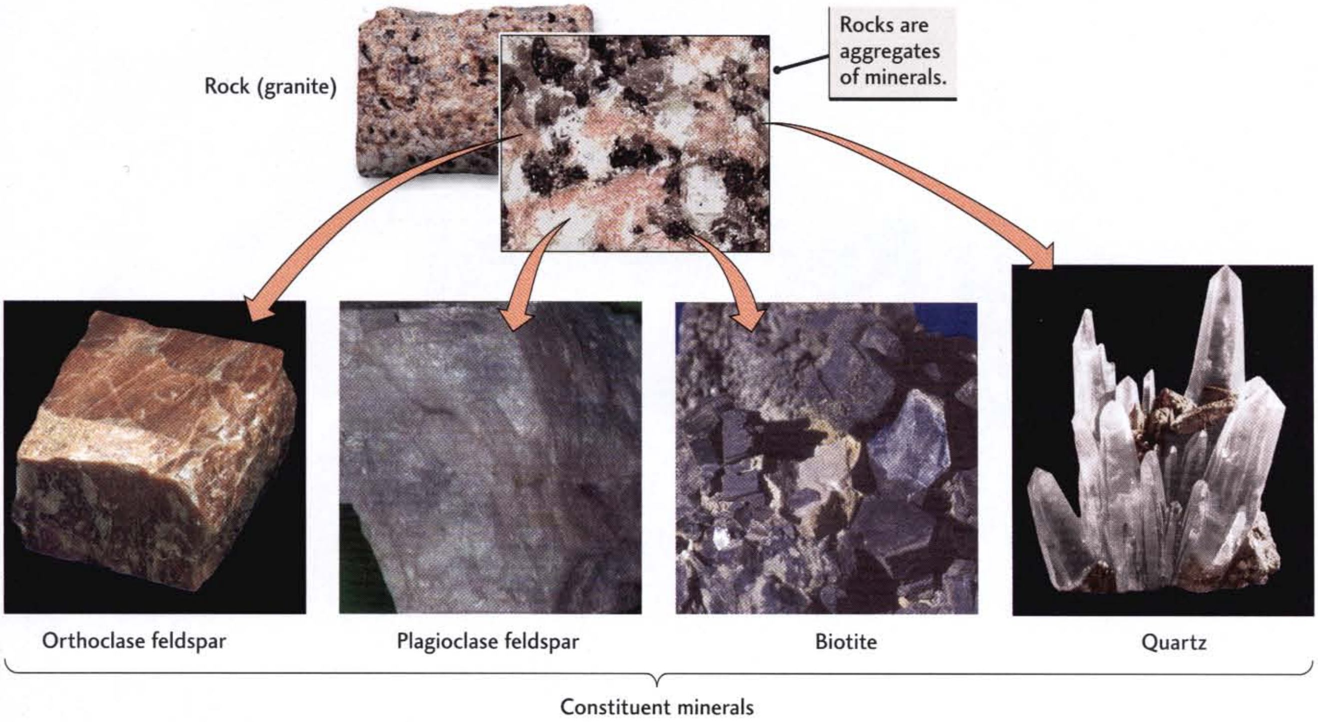


Figure 4.1 A rock is a naturally occurring aggregate of minerals. [*Clockwise from top:* J. Ramezani; J. Ramezani; José Manuel Sanchis Calvete/Corbis; Martin Miller/Visuals Unlimited; Arthur Hill/Visuals Unlimited; Chip Clark.]

The light-brown layered rock of the road cut, a sandstone, was formed as sand particles accumulated, perhaps on a beach, and eventually were covered over, buried, and cemented together. All rocks formed as the burial products of layers of sediments (such as sand, mud, and calcium carbonate shells), whether they were laid down on the land or under the sea, are called **sedimentary rocks.**

The brownish rock of our road cut, a schist, contains crystals of mica, quartz, and feldspar. It formed deep in Earth's crust as high temperatures and pressures transformed the mineralogy and texture of a buried sedimentary rock. All rocks formed by the transformation of preexisting solid rocks under the influence of high pressure and temperature are called **metamorphic rocks.**

A geologist's primary aim is to understand rock properties and to deduce their geologic origins from these properties. Such deductions further our understanding of the planet on which we live and provide important information about fuel reserves and solutions to environmental problems. For example, knowing that oil forms in certain kinds of sedimentary rocks that are rich in organic matter allows us to explore for new oil reserves more intelligently. Similarly, our knowledge of the properties of rocks will help us find new reserves of other useful and economically valuable mineral and energy resources, such as gas, coal, and metal ores.

Understanding how rocks form also guides us in solving environmental problems. Will this rock be prone to earthquake-triggered landslides? How might it transmit polluted waters in the ground? The underground storage of radioactive and other wastes depends on analysis of the rock to be used as a repository.

This chapter gives an overview of how geologists interpret the clues to understanding Earth provided by the three great families of rock: igneous, sedimentary, and metamorphic.

If rocks are the clues to many of the things we want to know about our planet, how do we go about interpreting them? We need a key, just as historians needed the Rosetta stone to crack the "code" of Egyptian hieroglyphs before they could read the inscriptions on temples and tombs. The first step in finding this key is to recognize the various kinds of rocks. The second step is to understand what their characteristics tell us about the surface and subsurface conditions under which they formed.

We will see what the appearance, texture, mineralogy, and chemical composition of a rock reveal about how and where it formed. We will look at how rock patterns found in subsurface drilling and in outcrops can help us reconstruct geologic history. Finally, we will trace the **rock cycle**—the set of geologic processes that convert each type of rock into

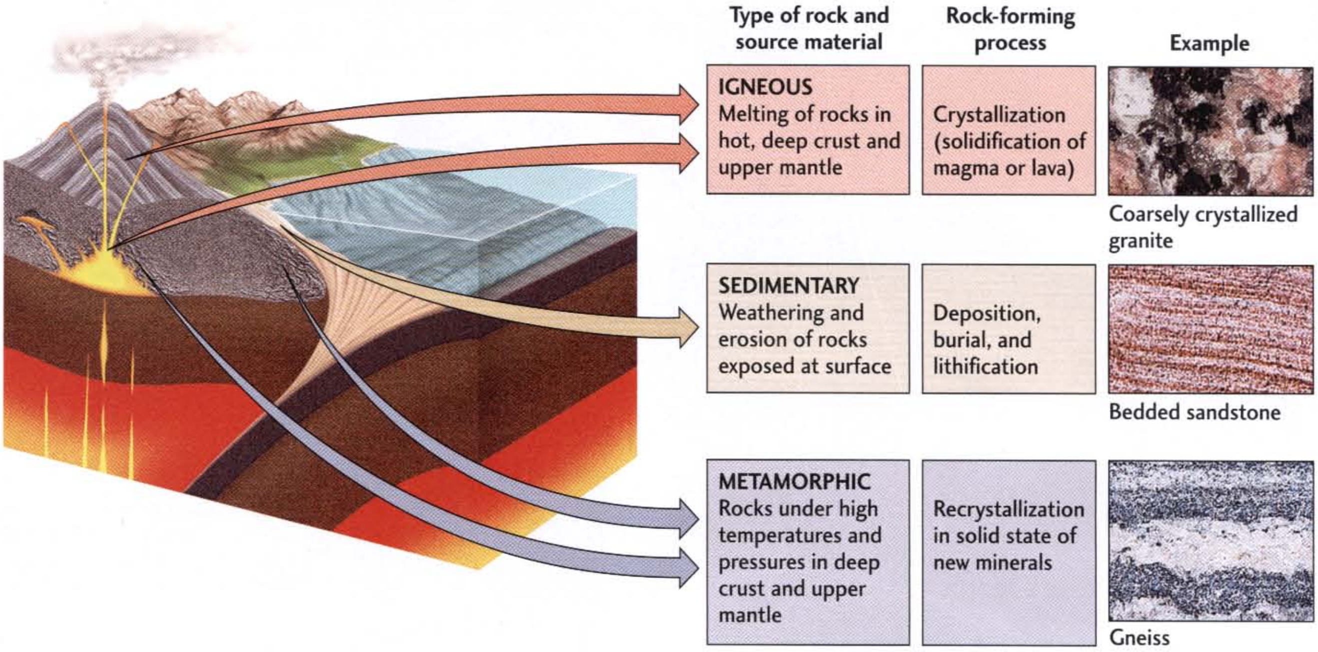


Figure 4.2 The minerals and textures of the three great rock groups are formed in different places in and on Earth by different geologic processes. As a result, geologists use mineralogical and chemical analyses to determine the origins of rocks and the processes that formed them. Granite, composed of quartz, feldspar, and mica crystals. [J. Ramezani.] Bedded sedimentary rock, made up of sandstones. [Breck P. Kent.] This crumpled and deformed metamorphic rock is a gneiss. [Breck P. Kent.]

the other two types—and see how these processes are all driven by plate tectonics and climate.

Igneous Rocks

Igneous rocks (from the Latin *ignis,* meaning "fire") form by crystallization from a magma, a mass of melted rock that originates deep in the crust or upper mantle. Here temperatures reach the 700°C or more needed to melt most rocks. When a magma cools slowly in the interior, microscopic crystals start to form. As the magma cools below the melting point, some of these crystals have time to grow to several millimeters or larger before the whole mass is crystallized as a coarse-grained igneous rock. But when a magma erupts from a volcano onto Earth's surface, it cools and solidifies so rapidly that individual crystals have no time to grow gradually. In that case, many tiny crystals form simultaneously, and the result is a fine-grained igneous rock. Geologists distinguish two major types of igneous rocks—intrusive and extrusive—on the basis of the sizes of their crystals.

Intrusive Igneous Rocks

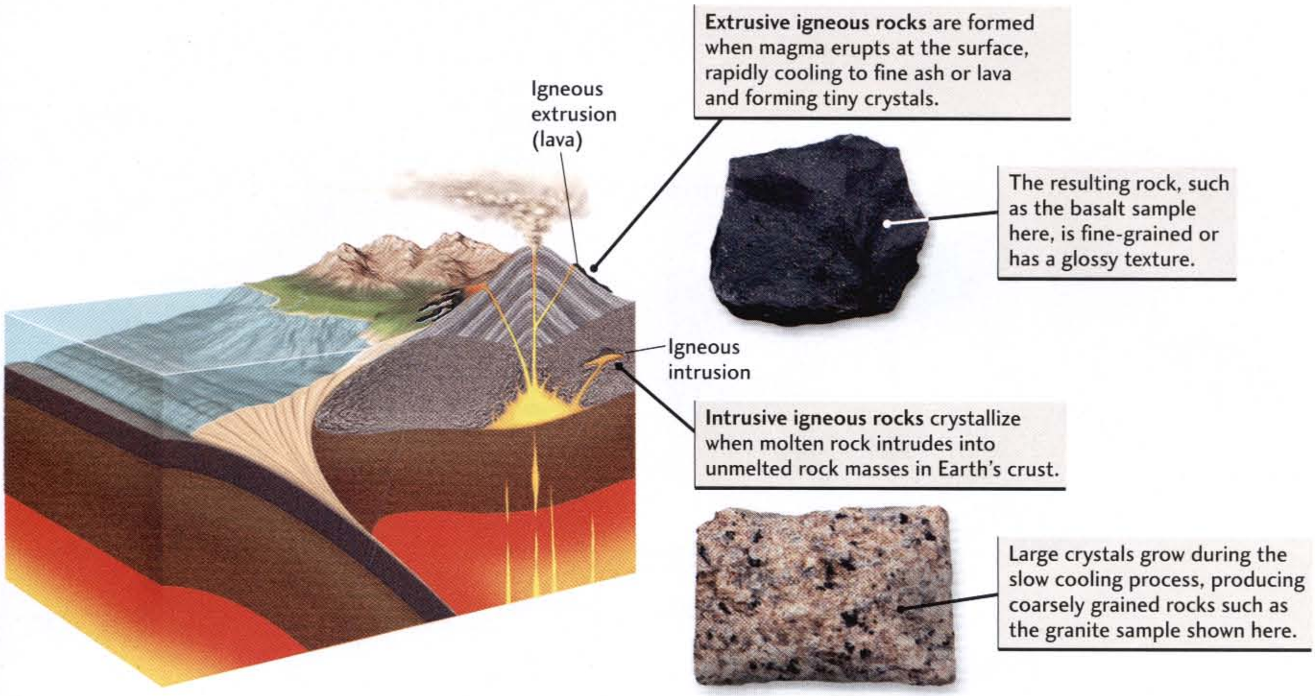
Intrusive igneous rocks crystallize when magma intrudes into unmelted rock masses deep in Earth's crust. Large crystals grow as the magma cools, producing coarse-grained rocks. Intrusive igneous rocks can be recognized by their interlocking large crystals, which grew slowly as the magma gradually cooled (**Figure 4.3**). *Granite* is an intrusive igneous rock.

Extrusive Igneous Rocks

Extrusive igneous rocks form from rapidly cooled magmas that erupt at the surface through volcanoes. Extrusive igneous rocks, such as *basalt,* are easily recognized by their glassy or fine-grained texture (see Figure 4.3).

Common Minerals

Most of the minerals of igneous rocks are silicates, partly because silicon is so abundant and partly because many silicate minerals melt at the high temperatures and pressures



Extrusive igneous rocks are formed when magma erupts at the surface, rapidly cooling to fine ash or lava and forming tiny crystals.

The resulting rock, such as the basalt sample here, is fine-grained or has a glossy texture.

Intrusive igneous rocks crystallize when molten rock intrudes into unmelted rock masses in Earth's crust.

Large crystals grow during the slow cooling process, producing coarsely grained rocks such as the granite sample shown here.

Figure 4.3 The formation of *extrusive igneous rocks* (basalt is shown here) [Chip Clark] and *intrusive igneous rocks* (granite is shown here) [J. Ramezani].

reached in deeper parts of the crust and in the mantle. The common silicate minerals found in igneous rocks include quartz, feldspar, mica, pyroxene, amphibole, and olivine (Table 4.1).

Table 4.1 Some Common Minerals of Igneous, Sedimentary, and Metamorphic Rocks

Igneous Rocks	Sedimentary Rocks	Metamorphic Rocks
Quartz*	Quartz*	Quartz*
Feldspar*	Clay minerals*	Feldspar*
Mica*	Feldspar*	Mica*
Pyroxene*	Calcite	Garnet*
Amphibole*	Dolomite	Pyroxene*
Olivine*	Gypsum	Staurolite*
	Halite	Kyanite*

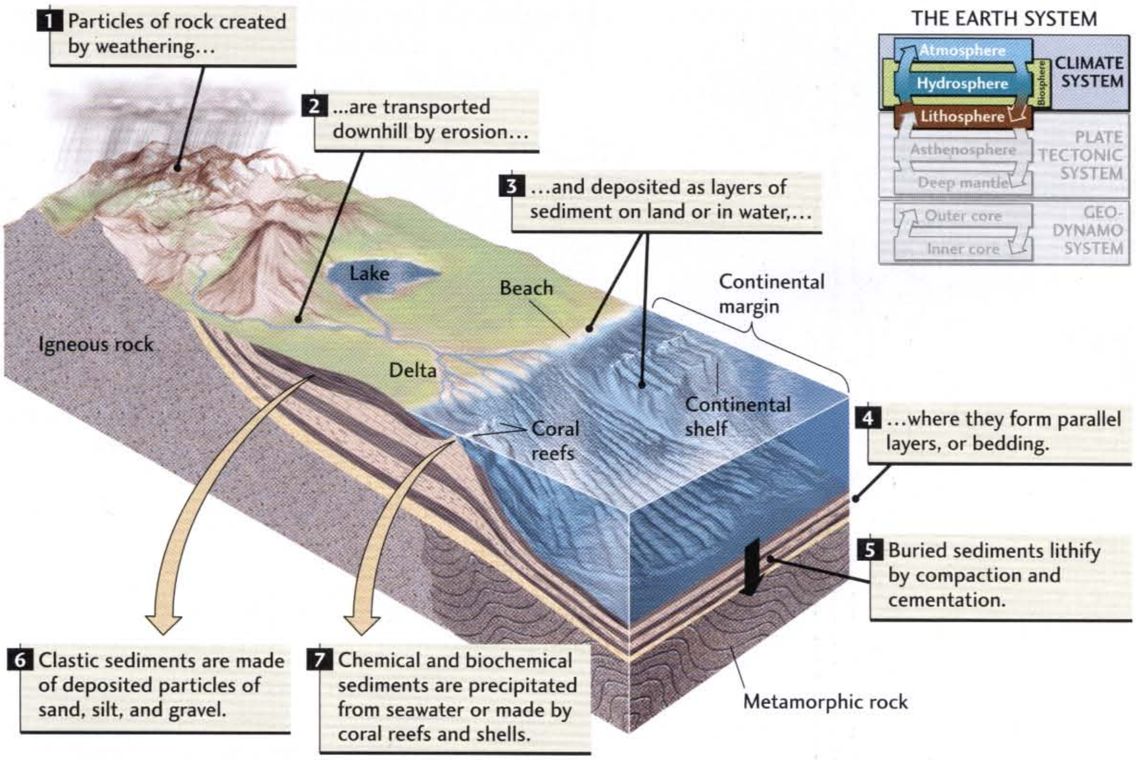
An asterisk indicates that a mineral is a silicate.

Sedimentary Rocks

Sediments, the precursors of sedimentary rocks, are found on Earth's surface as layers of loose particles, such as sand, silt, and the shells of organisms. These particles form at the surface as rocks undergo weathering and erosion. **Weathering** is all of the chemical and physical processes that break up and decay rocks into fragments of various sizes. The fragmented rock particles are then transported by **erosion,** the set of processes that loosen soil and rock and move them to the spot where they are deposited as layers of sediment (**Figure 4.4**). Weathering and erosion produce two types of sediments:

- **Clastic sediments** are physically deposited particles, such as grains of quartz and feldspar derived from a weathered granite. (*Clastic* is derived from the Greek word *klastos,* meaning "broken.") These sediments are laid down by running water, wind, and ice and form layers of sand, silt, and gravel.

- **Chemical and biochemical sediments** are new chemical substances that form by precipitation when some of a rock's components dissolve during weathering and are carried in river waters to the sea. These sediments include layers of such minerals as halite (sodium chloride) and calcite (calcium carbonate, most often found in the form of reefs and shells).



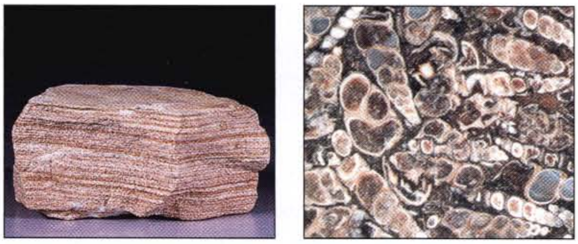


Figure 4.4 Weathering breaks down rock into smaller particles that are then carried downhill and downstream by erosion to be deposited as layers of sediment along continental margins. Other sediment is produced by biochemical precipitation, such as in the formation of coral reefs. As layers accumulate and are buried deeper and deeper, they lithify, hardening into sedimentary rock. (*left*) Laminated sandstone [Breck P. Kent]; (*right*) fossiliferous limestone [Peter Kresan].

From Sediment to Solid Rock

Lithification is the process that converts sediments into solid rock, and it occurs in one of two ways:

- By *compaction,* as grains are squeezed together by the weight of overlying sediment into a mass denser than the original.

- By *cementation,* as minerals precipitate around deposited particles and bind them together.

Sediments are compacted and cemented after burial under additional layers of sediment. Thus sandstone forms by the lithification of sand particles, and limestone forms by the lithification of shells and other particles of calcium carbonate.

Layers of Sediment

Sediments and sedimentary rocks are characterized by **bedding,** the formation of parallel layers of sediment as particles settle to the bottom of the sea, a river, or a land surface. Because sedimentary rocks are formed by surface processes, they cover much of Earth's land surface and seafloor. Although most rocks found at Earth's surface are sedimentary, their volume is small compared to the igneous and metamorphic rocks that make up the main volume of the crust because they are difficult to preserve (**Figure 4.5**).

Common Minerals

The common minerals of clastic sediments are silicates, because silicate minerals predominate in rocks that weather to form sedimentary particles (see Table 4.1). The most abundant minerals in clastic sedimentary rocks are quartz, feldspar, and clay minerals.

The most abundant minerals of chemically or biochemically precipitated sediments are carbonates, such as calcite, the main constituent of limestone. Dolomite, also found in limestone, is a calcium-magnesium carbonate formed by precipitation during lithification. Two other chemical sediments—gypsum and halite—form by precipitation as seawater evaporates.

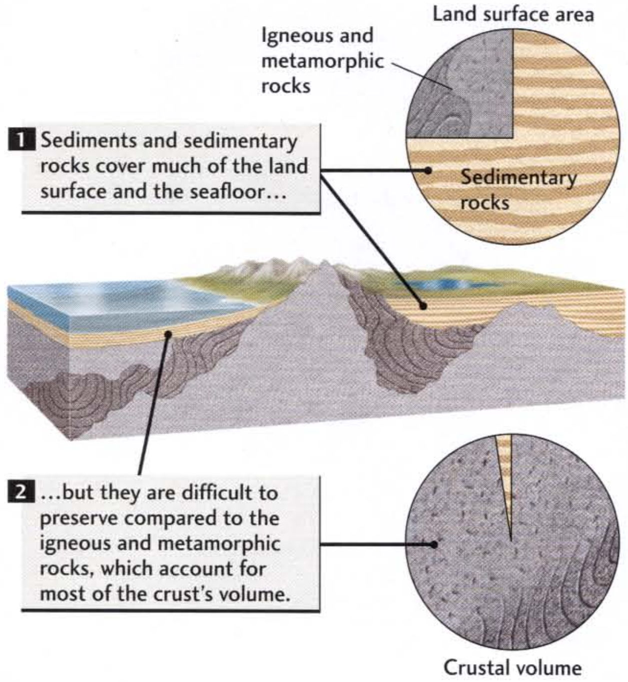


Figure 4.5 Sediments and sedimentary rocks cover much of Earth's land surface and the seafloor.

Metamorphic Rocks

Metamorphic rocks take their name from the Greek words for "change" (*meta*) and "form" (*morphe*). These rocks are produced when high temperatures and pressures deep in the Earth cause any kind of rock—igneous, sedimentary, or other metamorphic rock—to change its mineralogy, texture, or chemical composition while maintaining its solid form. The temperatures of metamorphism are below the melting points of the rocks (about 700°C) but high enough (above 250°C) for the rocks to change by recrystallization and chemical reactions.

Regional and Contact Metamorphism

Metamorphism may take place over a widespread area or a limited one (**Figure 4.6**). **Regional metamorphism** occurs where high pressures and temperatures extend over large regions, as happens where plates collide. Regional metamorphism accompanies plate collisions that result in mountain building and the folding and breaking of sedimentary layers that were once horizontal. Where high temperatures are restricted to smaller areas, such as the rocks near and in contact with an intrusion, rocks are transformed by **contact metamorphism.**

Many regionally metamorphosed rocks, such as schists, have characteristic **foliation,** wavy or flat planes produced when the rock was structurally deformed into folds. Granular textures are more typical of most contact metamorphic rocks and of some regional metamorphic rocks formed by very high pressure and temperature.

Common Minerals

Silicates are the most abundant minerals of metamorphic rocks because the parent rocks are also rich in silicates (see Table 4.1). Typical minerals of metamorphic rocks are quartz, feldspar, mica, pyroxene, and amphibole—the same kinds of silicates characteristic of igneous rocks. Several other silicates—kyanite, staurolite, and some varieties of garnet—are characteristic of metamorphic rocks alone. These minerals form under conditions of high pressure and temperature in the crust and are not characteristic of igneous rocks. They are therefore good indicators of metamorphism. Calcite is the main mineral of marbles, which are metamorphosed limestones.

Pressure-Temperature-Time Paths

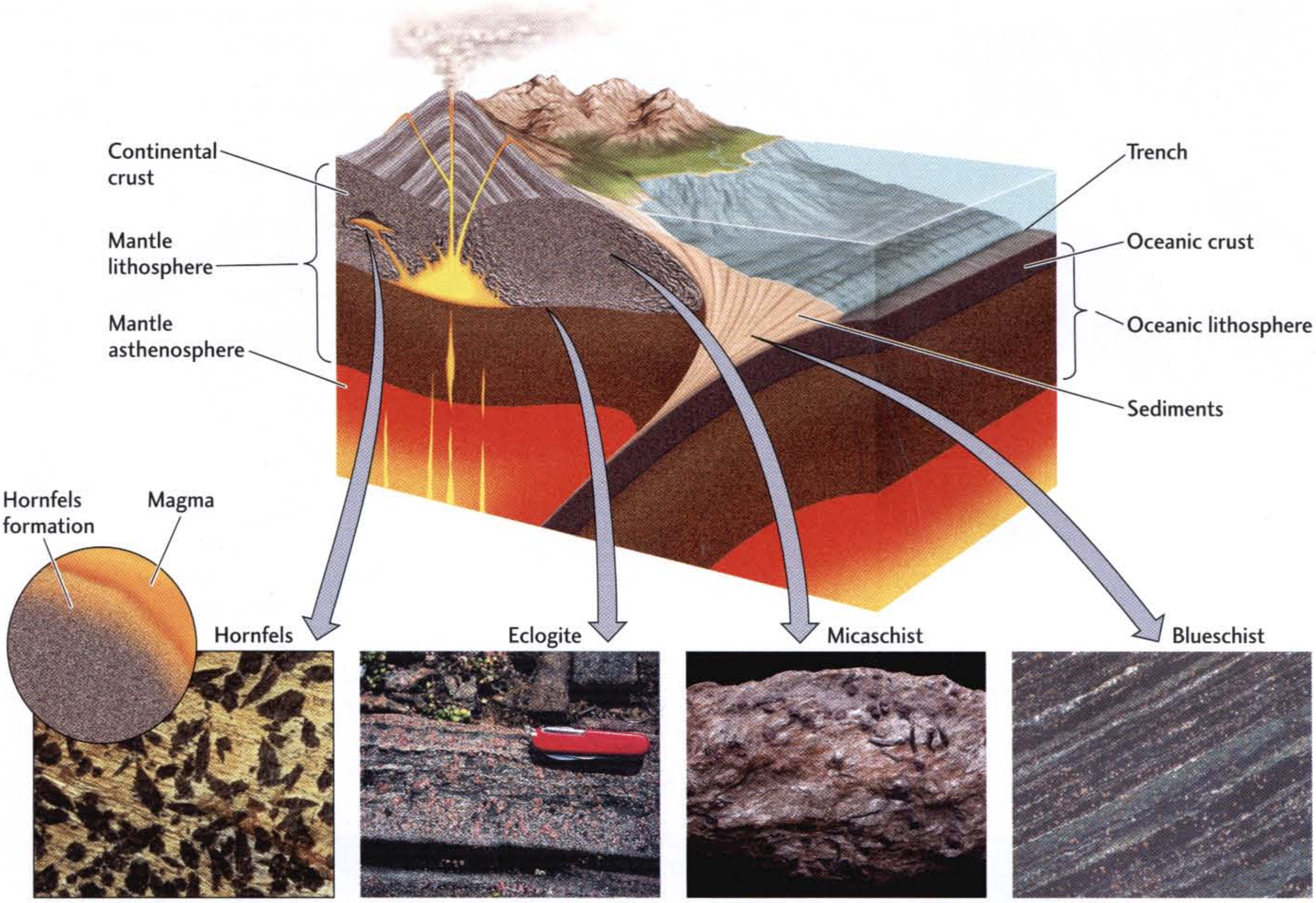
Plate tectonics makes regional metamorphism a dynamic process in which volumes of rock are subjected to changing conditions of pressure and temperature over time. Consequently, regionally metamorphosed rocks contain distinctive mineral assemblages in which earlier assemblages are overprinted by later assemblages. Such rocks thus record regimes of pressure and temperature which change in time. **Pressure-temperature-time paths** are recorded not only by changes in the assemblages of minerals but also by changes in the chemical compositions of the minerals themselves. Metamorphic pressure-temperature paths are discussed in detail in Chapter 9.

Where We See Rocks

Rocks are not found in nature conveniently divided into separate bodies—igneous here, sedimentary there, metamorphic in another place. Instead, we find them arranged in patterns determined by the geologic history of a region. Geologists map these patterns both at the surface and as projected into the interior, and they try to deduce the geologic past from the present variety and distribution of the rocks.

If we were to drill a hole into any spot on Earth, we would find rocks that represent the geologic history of that region. In the top few kilometers of most regions, we would probably find sedimentary rock. Drilling deeper, perhaps 6 to 10 km down, we would eventually penetrate an underlying area of older igneous and metamorphic rock.

In fact, thousands of relatively shallow holes have been drilled on the continents in the search for oil, water, and mineral resources. These holes are major sources of information, mainly about sedimentary rocks and their history. In the quest for more data on the deep continental crust, the governments of several countries—including the United States,



Contact metamorphism occurs in limited areas where magma intrusion metamorphoses neighboring rock by its heat, forming hornfels.

Ultra-high-pressure metamorphism occurs deep in the continental lithosphere and oceanic crust.

Regional metamorphism occurs where high pressures and temperatures extend over large regions.

High-pressure, low-temperature metamorphism occurs where oceanic crust subducts beneath the leading edge of a continental plate.

Figure 4.6 Metamorphic rocks form under four main conditions. Example of rocks shown here are (from left to right) *hornefels* [Biophoto Associates/Photo Researchers], *eclogite* [Julie Baldwin], *micaschist* [John Grotzinger], and *blueschist* [Mark Cloos].

Germany, and Russia—have drilled to great depths on the continents. The deepest hole, in Russia, is more than 12 km deep, exceeding the depth of any commercial drilling.

A large part of our knowledge about the rocks of the ocean floor comes from the hundreds of holes punched down by the Deep Sea Drilling Project, an ongoing program to drill the world's seafloor for geologic information. Started by the United States in the late 1960s, at the same time that plate tectonics swept the geological community, it is now an international venture (the Ocean Drilling Program) carried on with the cooperation of the major maritime countries of the world.

Even with all these sources of information about what lies beneath Earth's surface, geologists continue to rely on the rocks exposed in **outcrops,** places where **bedrock**—the underlying rock beneath the loose surface materials—is laid bare (**Figure 4.7**). Outcrops vary from region to region because they exemplify the geologic structure of the Earth at a particular spot. On a trip across North America, we might run across many kinds of outcrops (**Figure 4.8**). Starting at the Pacific, we would encounter sea cliffs from Mexico to Canada (Figure 4.8a). From the West Coast to the Rocky Mountain front, which stretches from New Mexico in the south to Alberta, Canada (Figure 4.8b), outcrops of all kinds of rock are abundant in the canyons, mountainsides, and cliffs of the relatively dry mountainous regions of the western third of the continent.

From the Rockies eastward to the Appalachian Mountains, the landscape is dominated by the plains and prairies of the American Midwest and the Prairie Provinces of

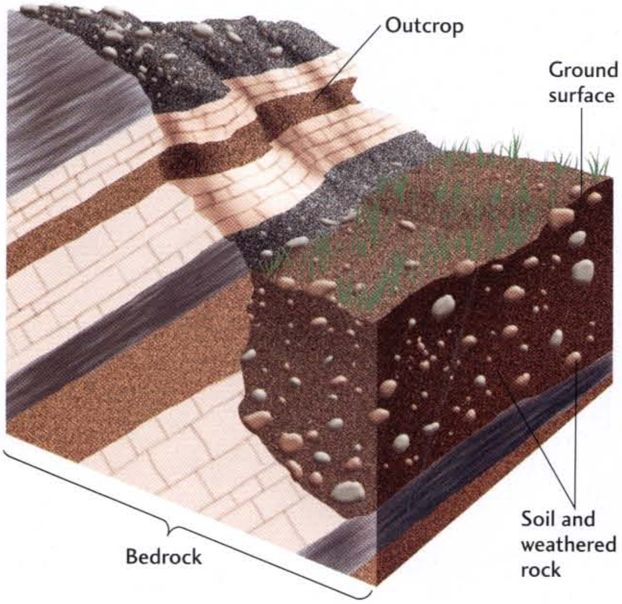
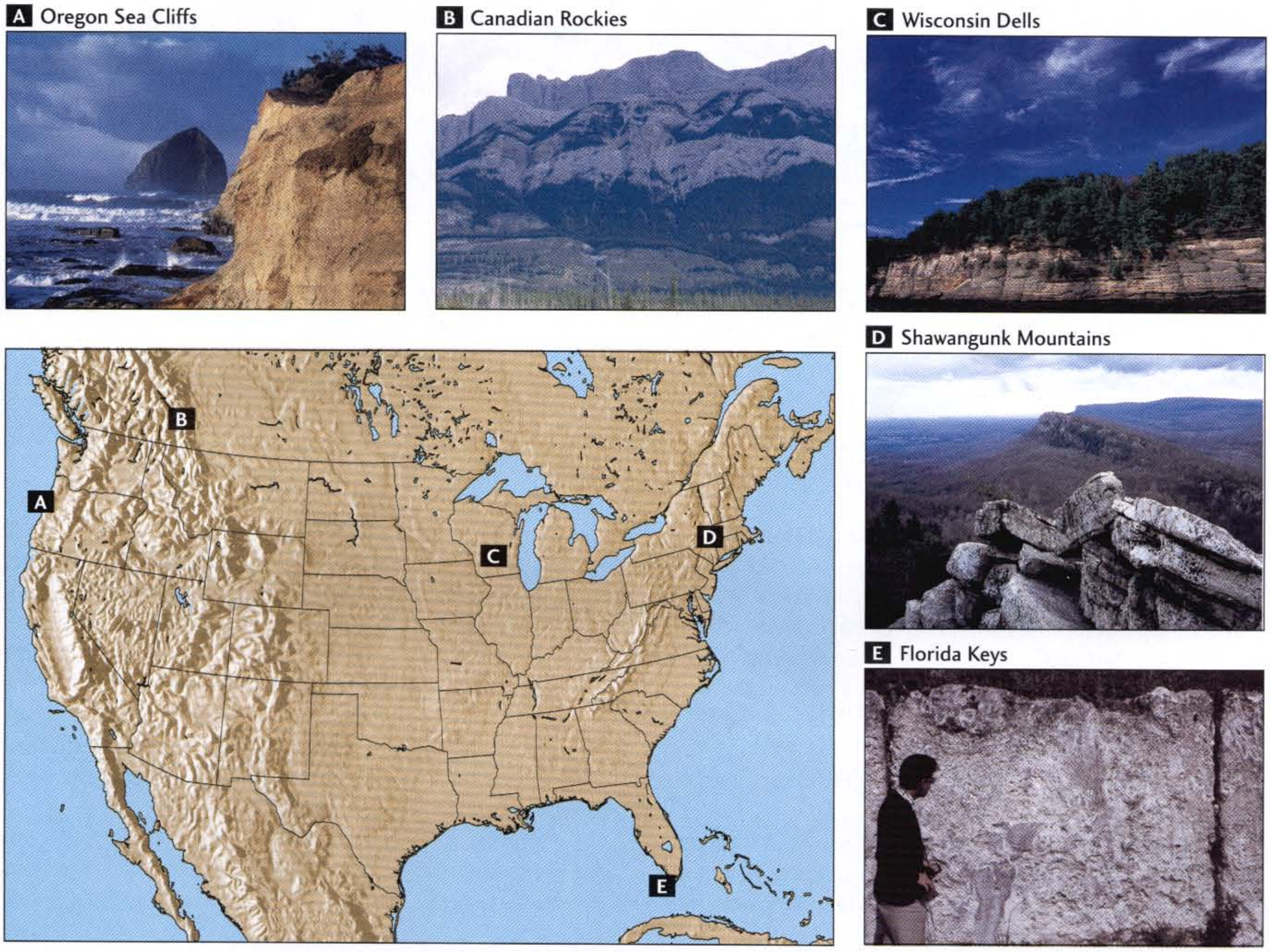


Figure 4.7 Outcrops are places where bedrock—the underlying rock beneath loose surface materials such as soil and boulders—is laid bare.

Canada. In this region, outcrops are scarce because most of the sedimentary bedrock is covered by soil and the sediments deposited by such rivers as the Missouri and their tributaries. Here outcrops occur in the low hills and gentle valleys (Figure 4.8c).

Low coastal plains cover the region from southeastern New Jersey to the Carolinas and Georgia in the east and Texas, Louisiana, Mississippi, and Alabama in the south. Here barely lithified, relatively soft sedimentary rocks are exposed in outcrops similar to those of the Great Plains. Good exposures can be found in the occasional bluffs along the shoreline. Farther south, in Florida, outcrops of limestone can be found in low hills and along the chain of islands called the Florida Keys (Figure 4.8d). To the north, outcrops become more numerous once we reach the Appalachians. In the hilly, rugged landscape of New England and the Maritime Provinces of Canada, we can find good outcrops, with the best exposures displayed along rocky coastlines. In this more humid climate, most of the rocks of the low ridges are covered by abundant vegetation and soil; however, there are many outcrops along rocky cliffs and ledges, especially on the higher ridges and mountains (Figure 4.8e).


A Oregon Sea Cliffs

B Canadian Rockies

C Wisconsin Dells

D Shawangunk Mountains

E Florida Keys

As this travelogue indicates, the presence and types of outcrops depend on the nature of the landscape, which in turn depends on the geologic structure of the region, its history, and its present climate. In later chapters, we will explore in more detail how rock types relate to geologic structures (Chapter 10) and to landscapes (Chapter 19). Now, however, we turn to the rock cycle, which—in combination with plate tectonics—reveals how the three groups of rocks interrelate and how they reflect geologic structure and history.

The Rock Cycle: Interactions Between the Plate Tectonic and Climate Systems

The rock cycle is the result of interactions between two of the three fundamental Earth systems: plate tectonics and climate. Driven by interactions between these two systems, material and energy are transferred among the Earth's interior, the land surface, the oceans, and the atmosphere. For example, the melting of subducting lithospheric slabs and the formation of magma result from processes operating within the plate tectonic system. When these molten rocks erupt, matter and energy are transferred to the land surface, where the material (newly formed rocks) is subject to weathering by the climate system. The same process injects volcanic ash and carbon dioxide gas high into the atmosphere, where they may affect global climate. As global climate changes, perhaps becoming warmer or cooler, the rate of rock weathering changes, which in turn influences the rate at which material (sediment) is returned to Earth's interior.

The idea of Earth as a system had not yet been proposed when the Scotsman James Hutton described the rock cycle in an oral presentation in 1785 before the Royal Society of Edinburgh. Ten years later, he presented the cycle in more detail in his book *Theory of the Earth with Proof and Illustrations.* As is often the case in the history of science, other scientists—both in England and on the European continent—also had recognized elements of the cyclic nature of geologic change. Hutton's role was that of synthesizer: he presented the larger picture that has enabled us to understand the process.

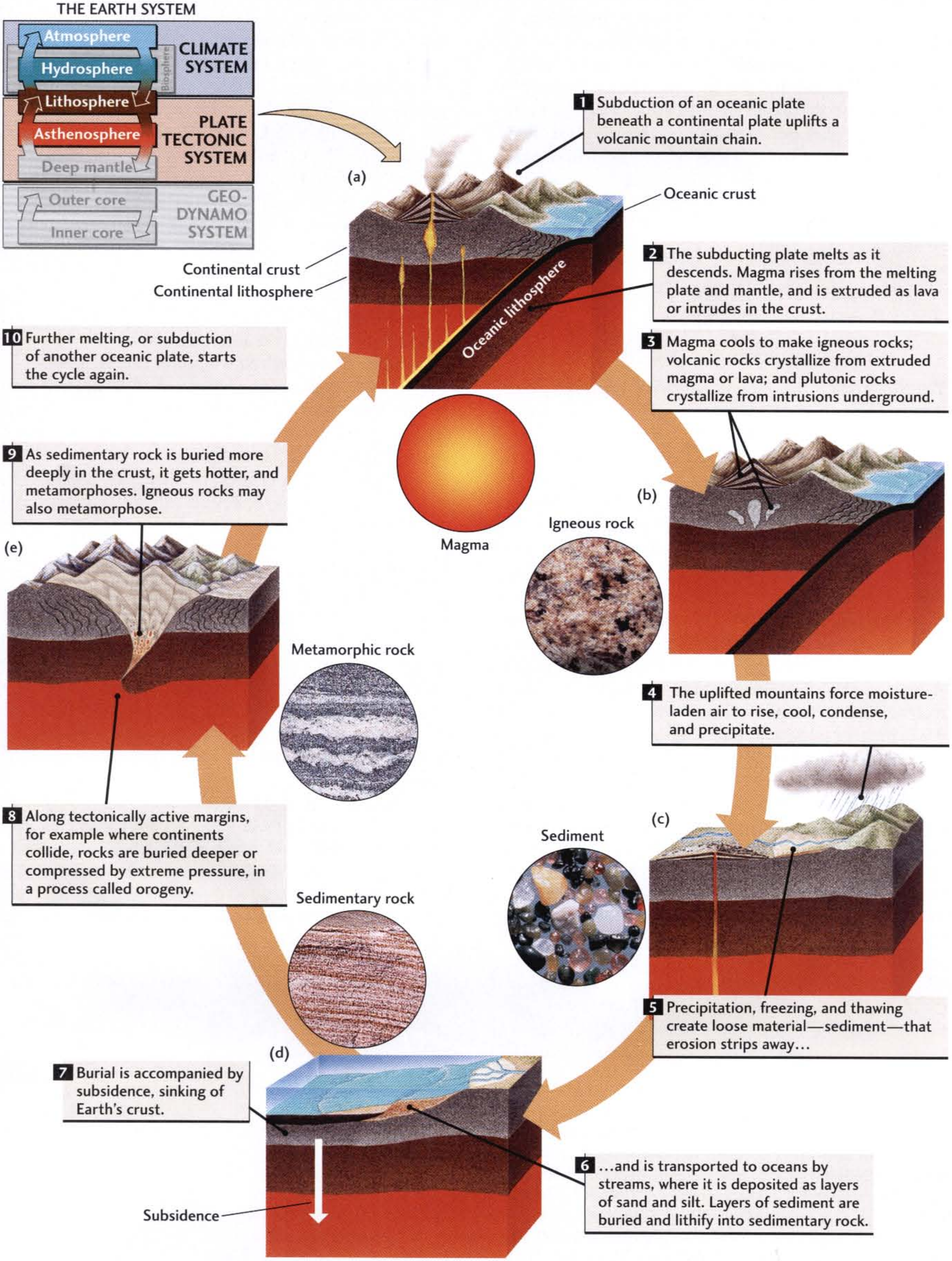
We give an account here of one particular cycle, recognizing that such cycles vary with time and place. We begin with a magma deep in the Earth, where temperatures and pressures are high enough to melt any kind of rock: igneous, metamorphic, or sedimentary (**Figure Story 4.9**). Hutton called the melting of rocks deep in Earth's crust the plutonic episode, after Pluto, the Roman god of the underworld. We now refer to all igneous intrusives as **plutonic rocks,** whereas the extrusives are known as **volcanic rocks.** When preexisting rocks melt, all their component minerals are destroyed and their chemical elements are homogenized in the resulting hot liquid. As the magma cools, crystals of new minerals grow and form new igneous rock. Melting and the formation of igneous rock take place mainly along the boundaries of colliding or diverging tectonic plates, as well as in mantle plumes, as you will see in later chapters.

The cycle begins with subduction of an oceanic plate beneath a continental plate. The igneous rocks that form at the boundaries where plates collide, together with associated sedimentary and metamorphic rocks, are then uplifted into a high mountain chain as a section of Earth's crust crumples and deforms. Geologists call this process, which begins with plate collision and ends in mountain building, **orogeny.** After uplift, the rocks of the crust overlying the uplifted igneous rock slowly weather. Weathering creates loose material that erosion then strips away, exposing the igneous rock at the surface.

The exposed igneous rock now weathers, and chemical changes occur in some of its minerals. Iron minerals, for example, may "rust" to form iron oxides. High-temperature minerals such as feldspars may become low-temperature clay minerals. Minerals such as pyroxene may dissolve completely as rain pours over them. The weathering of the igneous rock again produces various sizes and kinds of rock debris and dissolved material, which are carried away by erosion. Some of these materials are transported over land by water and wind. Much of the debris is transported by streams to rivers and ultimately to the ocean. In the ocean, debris is deposited as layers of sand, silt, and other sediments formed from dissolved material, such as the calcium carbonate from shells.

Figure 4.8 Outcrops found in North America. (a) Rocky cliffs on the Pacific coast at Cape Kiwanda, Oregon. Shoreline cliffs such as these provide ready accessibility to bedrock for the geologist. [Fred Hirschmann.] (b) The spectacular mountains of the Canadian Rockies afford both geologists and mountain climbers the opportunity to study rocks. [D. Robert Franz and Lorri Franz/Corbis.] (c) The Wisconsin Dells is a local favorite of Upper Midwest geologists. [David Dvorak, Jr.] (d) Shawangunk Mountains, New York. Even though these mountains are ancient (part of the Appalachian Mountain chain), excellent outcrops of bedrock are formed along steep slopes. [Carr Clifton.] (e) In Florida, some of the best outcrops occur in the Keys, where ancient reefs are exposed in the cores of the islands. [Robert N. Ginsburg.]

THE ROCK CYCLE IS THE INTERACTION OF PLATE TECTONIC AND CLIMATE SYSTEMS



1 Subduction of an oceanic plate beneath a continental plate uplifts a volcanic mountain chain.

2 The subducting plate melts as it descends. Magma rises from the melting plate and mantle, and is extruded as lava or intrudes in the crust.

3 Magma cools to make igneous rocks; volcanic rocks crystallize from extruded magma or lava; and plutonic rocks crystallize from intrusions underground.

4 The uplifted mountains force moisture-laden air to rise, cool, condense, and precipitate.

5 Precipitation, freezing, and thawing create loose material—sediment—that erosion strips away…

6 …and is transported to oceans by streams, where it is deposited as layers of sand and silt. Layers of sediment are buried and lithify into sedimentary rock.

7 Burial is accompanied by subsidence, sinking of Earth's crust.

8 Along tectonically active margins, for example where continents collide, rocks are buried deeper or compressed by extreme pressure, in a process called orogeny.

9 As sedimentary rock is buried more deeply in the crust, it gets hotter, and metamorphoses. Igneous rocks may also metamorphose.

10 Further melting, or subduction of another oceanic plate, starts the cycle again.

The sediments laid down in the sea, as well as those deposited on land by water and wind, are buried under successive layers of sediment, where they slowly lithify into sedimentary rock. Burial is accompanied by **subsidence**—a depression or sinking of the Earth's crust. As subsidence continues, additional layers of sediment can accumulate.

In some cases—for example, along tectonically active plate margins—subduction forces sedimentary rocks to descend to progressively greater depths (see Figure 4.6). As the lithified sedimentary rock is buried more deeply in the crust, it gets hotter. When the depth of burial exceeds 10 km and temperatures climb to more than 300°C, the minerals in the still-solid rock start to change into new minerals that are more stable at the higher temperatures and pressures of the deeper parts of the crust. The process that transforms the sedimentary rocks into metamorphic rocks is metamorphism. With further heating, the rocks may melt and form a new magma from which igneous rocks will crystallize, starting the cycle all over again.

As noted earlier, this series of processes is only one variation among the many that may take place in the rock cycle. Any type of rock—metamorphic, sedimentary, or igneous—can be uplifted during an orogeny and weathered and eroded to form new sediments. Some stages may be omitted: as a sedimentary rock is uplifted and eroded, for example, metamorphism and melting are skipped. And stages may take place out of sequence, as when an igneous rock formed in the interior is metamorphosed before it is uplifted. Also, as we know from deep drilling, some igneous rocks many kilometers deep in the crust may never have been uplifted or exposed to weathering and erosion.

The rock cycle never ends. It is always operating at different stages in various parts of the world, forming and eroding mountains in one place and laying down and burying sediments in another. The rocks that make up the solid Earth are recycled continuously, but we can see only the surface parts of the cycle. We must deduce the recycling of the deep crust and the mantle from indirect evidence.

One process that geologists were unaware of in Hutton's time is seafloor weathering or metasomatism, which was only recognized following the discovery of plate tectonics. The process involves chemical exchanges between seawater and the seafloor at mid-ocean ridges. It significantly supplements ordinary surface weathering in the return of important elements to Earth's interior. In the absence of seafloor metasomatism, the chemical composition of the ocean and atmosphere would be quite different.

Earth's Unique Systems and Rock Cycle

The rock cycle we have just described is unique to our planet because Earth's plate tectonic and climate systems differ from those on the other terrestrial planets. There are no sedimentary rocks on the Moon and Venus, for example, because they lack a hydrosphere and atmosphere and their climate is profoundly different from ours. All the rocks found on the surface of Venus have been affected and modified in various ways by the very high temperatures and the sulfuric-acid-rich atmosphere that characterize its present climate. The absence of water on the surface of Mars and the thin Martian atmosphere enable us to say that weathering and erosion on today's Mars follow a different path than they do on Earth. These examples show how the basic systems and the interactions among them that characterize a planet control how that planet works.

With this introduction to the rock world, we are ready to begin the study of rocks. In Chapters 5 and 6, we look at the geologic origin of magmas, the types of igneous rocks that form when magmas crystallize, the larger picture of plate tectonic control of igneous processes, and the dynamics of volcanoes and their eruptions. In Chapters 7 and 8, we explore weathering, the characteristics of sedimentary particles, and the ways in which various sediments and sedimentary rocks are produced. We complete our consideration of rocks in Chapter 9 by examining how high heat and pressure affect preexisting rocks, transforming them into metamorphic rocks, and how metamorphism relates to plate tectonics and orogeny.

SUMMARY

What determines the properties of the various kinds of rocks that form in and on Earth's surface? Mineralogy (the kinds and proportions of minerals that make up a rock) and texture (the sizes, shapes, and spatial arrangement of its crystals or grains) define a rock. The mineralogy and texture of a rock are determined by the geologic conditions, including chemical composition, under which it formed, either in the interior under various conditions of high temperature and pressure or at the surface, where temperatures and pressures are low.

Figure Story 4.9 The rock cycle, as proposed by James Hutton more than 200 years ago. Rocks subjected to weathering and erosion form sediments, which are deposited, buried, and lithified. After deep burial, the rocks undergo metamorphism, melting, or both. Through orogeny and volcanic processes, rocks are uplifted, only to be recycled again. [*Igneous* (granite): J. Ramezani. *Metamorphic* (gneiss): Breck P. Kent. *Sedimentary* (sandstone): Breck P. Kent. *Sediment* (loose sand and gravel): Rex Elliott.]

What are the three types of rock and how do they form? Igneous rocks form by the crystallization of magmas as they cool. Intrusive igneous rocks form in Earth's interior and have large crystals. Extrusive igneous rocks, which form at the surface where lavas and ash erupt from volcanoes, have a glassy or fine-grained texture. Sedimentary rocks form by the lithification of sediments after burial. Sediments are derived from the weathering and erosion of rocks exposed at Earth's surface. Metamorphic rocks form by alteration in the solid state of igneous, sedimentary, or other metamorphic rocks as they are subjected to high temperatures and pressures in the interior.

How does the rock cycle describe the formation of rocks as the products of geologic processes? The rock cycle relates geologic processes to the formation of the three types of rocks from one another. We can view the processes by starting at any point in the cycle. We began with the formation of igneous rocks by crystallization of a magma in the interior of the Earth. Igneous rocks then are uplifted to the surface in the mountain-building process. There, they are exposed to weathering and erosion, which produce sediment. The sediment is cycled back to the interior by burial and lithification into sedimentary rock. Deep burial leads to metamorphism or melting, at which point the cycle begins again. Plate tectonics is the mechanism by which the cycle operates.

Key Terms and Concepts

bedding (p. 79)
bedrock (p. 81)
chemical and biochemical sediments (p. 79)
clastic sediments (p. 79)
contact metamorphism (p. 80)
erosion (p. 79)
extrusive igneous rocks (p. 78)
foliation (p. 80)
igneous rocks (p. 75)
intrusive igneous rocks (p. 77)
lithification (p. 79)
metamorphic rocks (p. 77)
mineralogy (p. 75)
orogeny (p. 83)
outcrop (p. 81)
plutonic rocks (p. 83)
pressure-temperature-time path (p. 81)
regional metamorphism (p. 79)
rock (p. 75)
rock cycle (p. 77)
sedimentary rocks (p. 76)
sediments (p. 78)
subsidence (p. 83)
texture (p. 75)
volcanic rocks (p. 83)
weathering (p. 78)

Exercises

1. What are the differences between extrusive and intrusive igneous rocks?

2. What are the differences between regional and contact metamorphism?

3. What are the differences between clastic and chemical or biochemical sedimentary rocks?

4. List three common silicate minerals found in each group of rocks: igneous, sedimentary, and metamorphic.

5. Of the three groups of rocks, which form at Earth's surface and which in the interior of the crust?

6. Where on the continents can you see bare rock?

Thought Questions

MEDIA LINK *This icon indicates that there is an animation available on the Web site that may assist you in answering a question.*

1. What geologic processes transform a sedimentary rock into an igneous rock?

2. Name a mineral found only in sedimentary rocks that you might use to distinguish between a fine-grained sedimentary rock formed from lithified mud and an extrusive igneous rock.

3. As a magma cools, what might cause differences in the sizes of the crystals of two intrusive igneous rocks, one with crystals about 1 cm in diameter, the other with crystals about 2 mm in diameter?

4. Which igneous intrusion would you expect to have a wider contact metamorphic zone: one intruded by a very hot magma or one intruded by a cooler magma?

5. Describe the geologic processes by which an igneous rock is transformed into a metamorphic rock and then exposed to erosion.

6. Describe the kinds of outcrop that are found in various places in your hometown. If none, explain how you would determine the nature of the buried bedrock.

7. How does plate tectonics explain plutonism?

8. Using the rock cycle, trace the path from a magma to a granite intrusion to a metamorphic gneiss to a sandstone. Be sure to include the role of tectonics and the specific processes that create the rocks.

9. In the early history of Earth, there were no oceans and only a limited atmosphere. Plate tectonics either was not active or was far less developed during this period than it is now. How would these conditions, compared to those that exist today, affect the rock cycle and the incidence of the major rock types?

10. Although igneous, metamorphic, and sedimentary rocks differ markedly, they are all classified in much the same manner. What characteristics of rocks are common to the classification of all three rock types?

11. Where are igneous rocks most likely to be found? How could you be certain that the rock is igneous and not sedimentary or metamorphic?

12. On a field trip in Arizona you find a rock sample near a large outcrop and bring this sample back to the lab for identification. A thin section of the rock shows that the rock contains traces of quartz, feldspars, mica, and hornblende. Identify the rock and explain how you arrived at this conclusion.

Short-Term Team Projects

Identifying Building Stones

Building stones often are a clue to local geology. Local stone is both cost-effective and a source of community pride. With a partner, examine the building stones that you find on campus or in your community. Choose four to six types of stone that look different and note their locations on a local map. Draw each stone on a separate piece of paper and note such features as color, grain size, the presence or absence of layering, and whether the stone appears to contain one mineral or more than one. Also describe any evidence of chemical or physical weathering and judge how good the stone is for building. Then decide whether the stone is most likely to be igneous, metamorphic, or sedimentary, and explain why. Finally, compare a geologic map of the area with your findings in the field and explain why the stones that you described do or do not record the local geology. Submit an organized folder containing your drawings, observations, and inferences.

Suggested Readings

Blatt, H., and R. J. Tracy. 1996. *Petrology: Igneous, Sedimentary, and Metamorphic,* 2d ed. New York: W. H. Freeman.

Dietrich, R. V., and B. J. Skinner. 1980. *Rocks and Rock Minerals.* New York: Wiley.

Ernst, W. G. 1969. *Earth Materials.* Englewood Cliffs, N.J.: Prentice Hall.

Prinz, M., G. Harlow, and J. Peters. 1978. *Simon & Schuster's Guide to Rocks and Minerals.* New York: Simon & Schuster.

Spear, Frank. S. 1993. Metamorphic phase equilibria and pressure-temperature-time paths. Mineralogical Society of America, Monograph 22.