CHAPTER 6

Pages of Earth's Past: Sedimentary Rocks

The rugged landscape of the Grand Canyon exposes a blanket of sedimentary rock layers. These layers formed by the burial and hardening (lithification) of mud, shell accumulations, and sand. Beaches, reefs, mud flats, river floodplains, and desert sand dunes all existed here in the past.

Chapter Objectives

By the end of this chapter, you should know . . .

- how sediment produced by weathering and biologic activity at the Earth's surface can transform into sedimentary rock.
- how to interpret the past environment and sea level of the Earth by examining the composition, textures, and layering found in sedimentary rock.
- clues that geologists use to identify and classify different types of sedimentary rocks.
- where and why thick accumulations of sedimentary rocks form on Earth.

In every grain of sand there is a story of Earth.

—Rachel Carson (American marine biologist and conservationist, 1907–1964)

6.1 Introduction

On an isolated, windswept drilling platform in the North Sea off the coast of Scotland, a group of roughnecks ready a multimillion-dollar drilling rig—their plan is to penetrate the sea floor and see what layers lie beneath. The North Sea formed as a consequence of rifting that began tens of millions of years ago. During rifting, what was once dry land between Great Britain and continental Europe slowly sank or, in geologic parlance, "subsided." Rivers carried gravel, sand, and clay from the surrounding land into the newborn North Sea, and these sediments collected in layers. At certain stages in the process, salts precipitated from seawater and the shells of sea creatures settled and collected on the sea floor. As the drilling begins, a geologist stationed on the deck of the platform examines the material that has been flushed out of the lengthening drill hole. At first, drilling brings up soft mud and loose sand, silt, pebbles, and shell fragments. But as the hole goes deeper, the material coming up holds together in soft but coherent clumps. Eventually, when the hole has entered layers that now lie almost a kilometer below the sea floor, the drilling fluid flushes out chips and chunks of solid rock. When the geologist studies these fragments, she notes that the composition of fragments changes with depth. At some depths, fragments consist of grains of sand cemented together, or of tightly packed clay that is harder than pottery. At other depths, they consist of broken shell aggregates or of crystalline salt masses. The geologist has observed the transition of loose sediment into solid layers of sedimentary rock as burial depth progressively increases.

Formally defined, **sedimentary rock** is rock that forms at or near the surface of the Earth in one of several ways: by the cementing together of loose **clasts** (fragments or grains) produced by physical or chemical weathering of preexisting rock; by the growth of shell masses or the cementing together of shells and shell fragments; by the accumulation and subsequent alteration of organic matter from dead plankton or plants; or by the precipitation of minerals from water solutions. Layers of sedimentary rock are like the pages of a book, recording tales of ancient events and ancient environments on the ever-changing face of the Earth. They occur only in the upper part of the crust, and form a "cover" that buries the underlying "basement" of igneous and/or metamorphic rock (**Fig. 6.1 a, b**).

In Interlude B, we introduced the concept of weathering, and showed how it attacks bedrock, breaking it down into ions and loose sediment grains. What can happen next? Some of the sediment may become incorporated in soil, as we have seen. But some becomes buried and transformed into sedimentary rock. In this chapter, we discuss the various kinds of sedimentary rock and the ways in which they form, and we consider what sedimentary rocks can tell us about the history of the Earth System.

6.2 Classes of Sedimentary Rocks

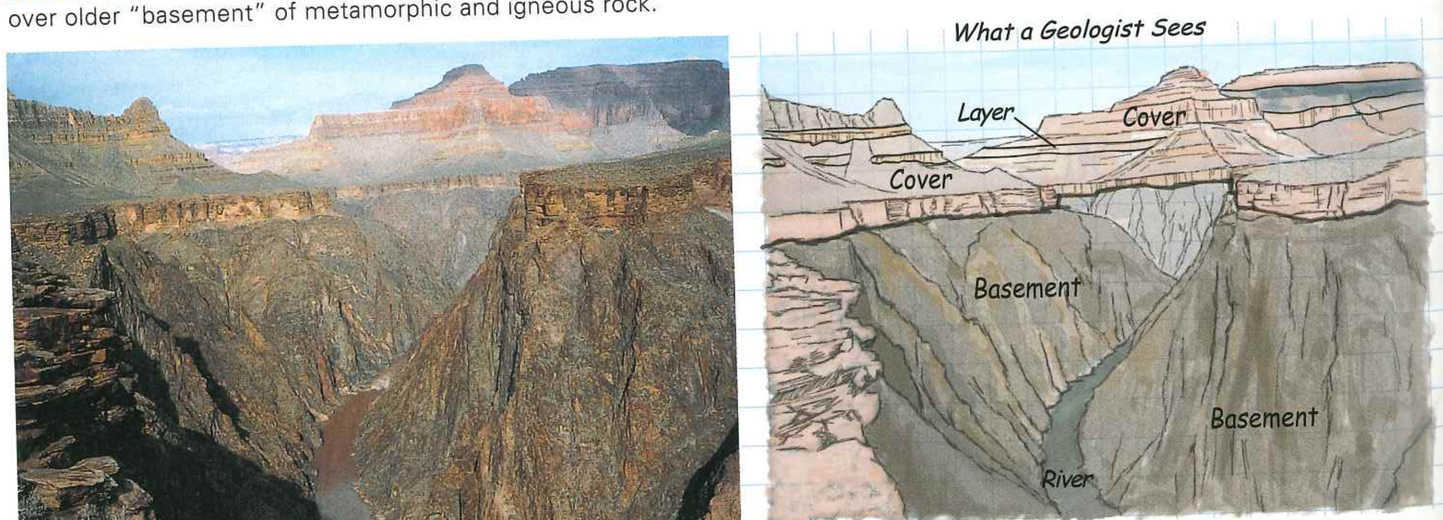
Geologists divide sedimentary rocks into four major classes, based on their mode of origin. (1) **Clastic sedimentary rock** consists of cemented-together clasts, solid fragments and grains broken off of preexisting rocks (the word comes from the Greek *klastos*, meaning broken); (2) **biochemical sedimentary rock** consists of shells; (3) **organic sedimentary rock** consists of carbon-rich relicts of plants or other organisms; and (4) **chemical sedimentary rock** is made up of minerals that precipitated directly from water solutions. Let's now look at these major classes in more detail.

Clastic Sedimentary Rocks

Formation. Nine hundred years ago, a thriving community of Native Americans inhabited the high plateau of Mesa Verde, Colorado. In hollows beneath huge overhanging ledges, they built multistory stone-block buildings that have survived to this day. Clearly, the blocks are solid and durable—they are, after all, rock. But if you were to rub your thumb along one, it would feel gritty, and small grains of quartz would break free and roll under your thumb, for the block consists of quartz sand grains cemented together. Geologists call such rock a **sandstone**.

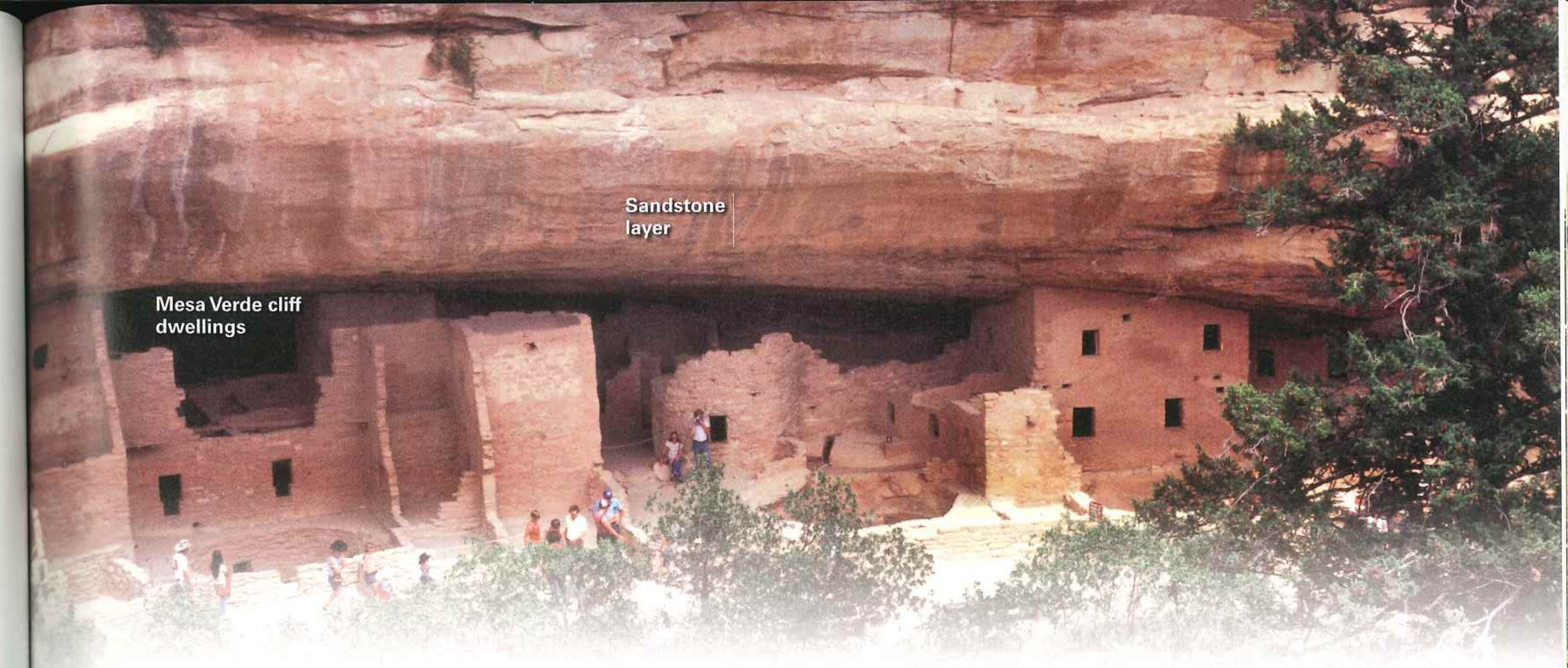
Sandstone is an example of clastic sedimentary rock. It consists of loose clasts, known as **detritus**, that have been stuck together to form a solid mass. The clasts can consist of individual minerals (such as grains of quartz or flakes of clay) or of fragments of rock (such as pebbles of granite). Formation of sediment and its transformation into clastic sedimentary rock takes place via the following five steps (**Fig. 6.2a, b**).

FIGURE 6.1 In this close-up of the inner gorge of the Grand Canyon, we see a sedimentary-rock blanket, that forms a "cover" over older "basement" of metamorphic and igneous rock.



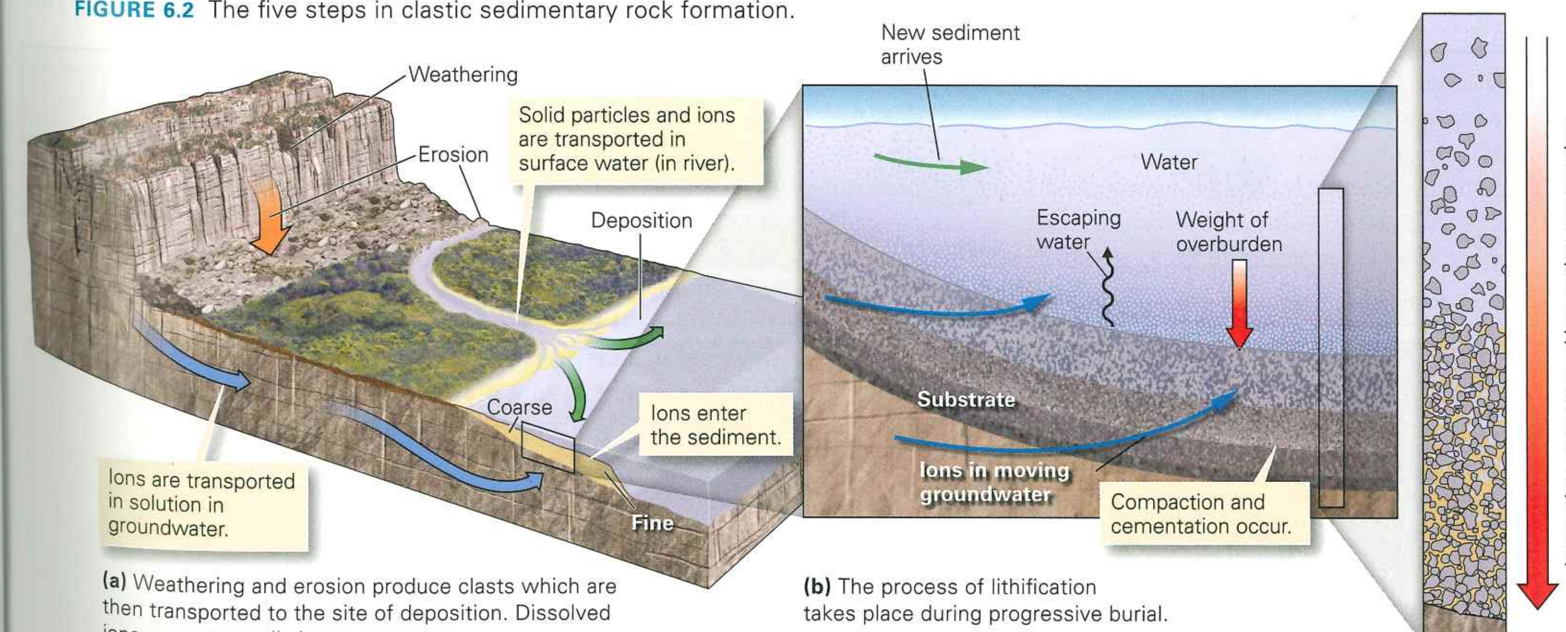
(a) Sedimentary cover here consists of horizontal layers but underlying metamorphic basement does not.

(b) A geologist's sketch emphasizes the contact between the sedimentary cover and basement.



- *Weathering*: Detritus forms by disintegration of bedrock into separate grains due to physical and chemical weathering.
- *Erosion*: **Erosion** refers to the combination of processes that separate rock or regolith (surface debris) from its substrate. Erosion involves abrasion, falling, plucking, scouring, and dissolution, and is caused by moving air, water, or ice.
- *Transportation*: Gravity, wind, water, or ice carry sediment. The ability of a medium to carry sediment depends on its viscosity and velocity. Solid ice can transport sediment of any size, regardless of how slowly the ice moves. Very fast-moving, turbulent water can transport coarse fragments (cobbles and boulders), moderately fast-moving water can carry only sand and gravel, and slow-moving water carries only silt and clay. Strong winds can move sand and dust, but gentle breezes carry only dust.
- *Deposition*: **Deposition** is the process by which sediment settles out of the transporting medium. Sediment settles out of wind or moving water when these fluids slow, because as the velocity decreases, the fluid no longer has the ability to carry sediment. Sediment is deposited by ice when the ice melts.
- *Lithification*: Geologists refer to the transformation of loose sediment into solid rock as **lithification**. The lithification of clastic sediment involves two steps. First, once the sediment has

FIGURE 6.2 The five steps in clastic sedimentary rock formation.



(a) Weathering and erosion produce clasts which are then transported to the site of deposition. Dissolved ions may eventually become cement.

(b) The process of lithification takes place during progressive burial.

been buried, pressure caused by the weight of overlying material squeezes out water and air that had been trapped between clasts, and clasts press together tightly, a process called **compaction**. Compacted sediment may then be stuck together to make coherent sedimentary rock by the process of **cementation**. Cement consists of minerals (commonly quartz or calcite) that precipitate from groundwater and fill the spaces between clasts.

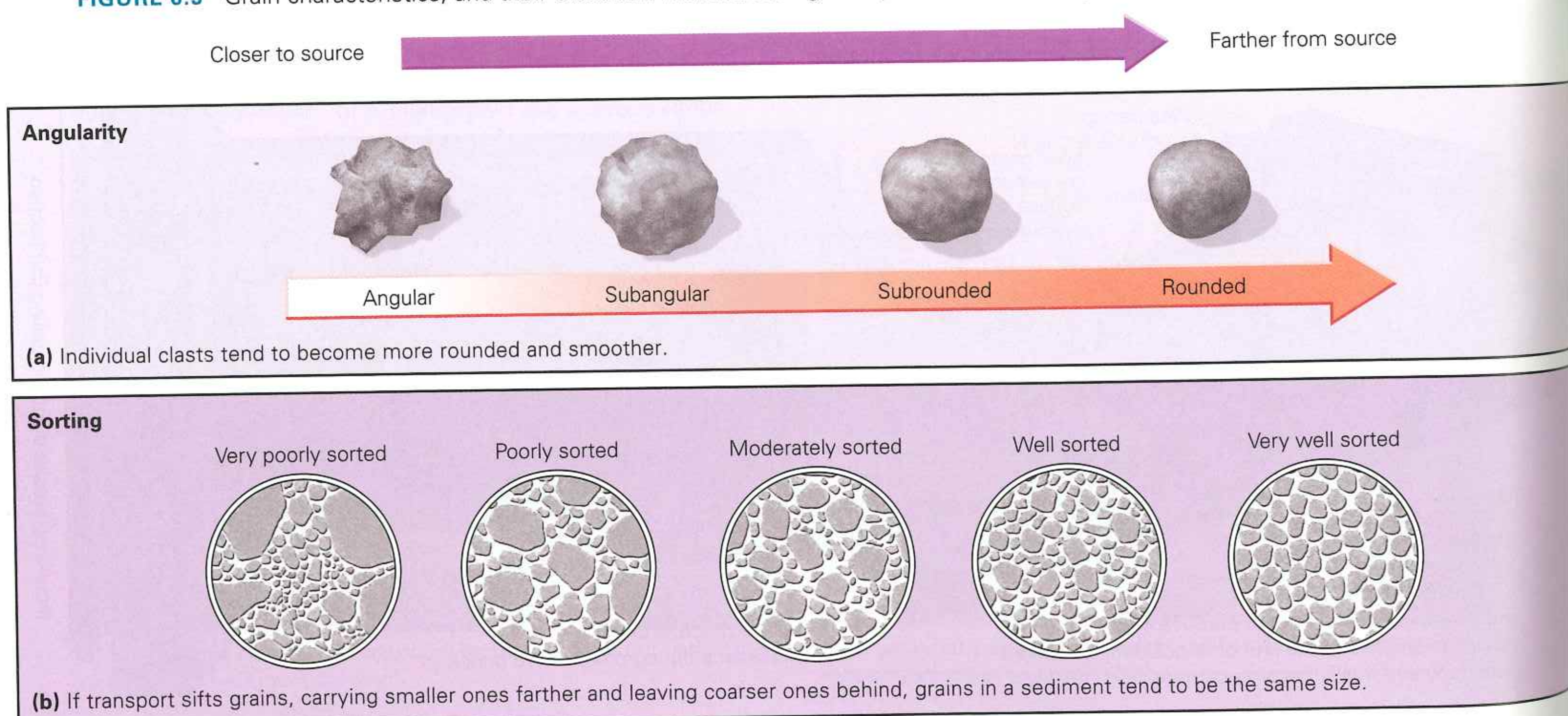
Classifying clastic sedimentary rocks. Say that you pick up a clastic sedimentary rock and want to describe it sufficiently so that, from your words alone, another person can picture the rock. What characteristics should you mention? Geologists find the following characteristics most useful.

- *Clast size.* Size refers to the diameter of fragments or grains making up a rock. Names used for clast size, listed in order from coarsest to finest, are: boulder, cobble, pebble, sand, silt, and clay (see Table B.1 in Interlude B).
- *Clast composition.* Composition refers to the makeup of clasts in sedimentary rock. Clasts may be composed of rock fragments or individual mineral grains.
- *Angularity and sphericity.* Angularity indicates the degree to which clasts have smooth or angular corners and edges (**Fig. 6.3a, b**). Sphericity, in contrast, refers to the degree to which the shape of a clast resembles a sphere.
- *Sorting.* **Sorting** of clasts indicates the degree to which the clasts in a rock are all the same size or include a variety of sizes. *Well-sorted* sediment consists entirely of sediment of the same size, whereas *poorly-sorted* sediment contains a mixture of more than one clast size.
- *Character of cement.* Not all clastic sedimentary rocks have the same kind of cement. In some, the cement consists predominantly of quartz, whereas in others, it consists predominantly of calcite.

With these characteristics in mind, we can distinguish among several common types of clastic sedimentary rocks, listed in **Table 6.1**. This table provides *common* rock names—specialists sometimes use other, more precise names based on more complex classification schemes.

The size, angularity, sphericity, and sorting of clasts depends on the medium (water, ice, or wind) that transports the clasts and, in the case of water or wind, on both the velocity of the medium and the distance of transport. The composition of the clasts depends on the composition of rock from which the clasts were derived, and on the degree of chemical weathering that the clasts have undergone. Thus, the type of clasts that accumulate in a sedimentary deposit varies with location. To see how, let's follow the fate of rock fragments as they gradually move from a cliff face in the mountains via a river to the seashore. Different kinds of sediment develop along the route. Each kind, if buried and lithified, would yield a different type of sedimentary rock.

FIGURE 6.3 Grain characteristics, and their evolution with increasing transport and weathering.



(a) Individual clasts tend to become more rounded and smoother.

(b) If transport sifts grains, carrying smaller ones farther and leaving coarser ones behind, grains in a sediment tend to be the same size.

TABLE 6.1 Classification of Clastic Sedimentary Rocks

Clast Size*	Clast Character	Rock Name (Alternative Name)
Coarse to very coarse	Rounded pebbles and cobbles	Conglomerate
	Angular clasts	Breccia
	Large clasts in muddy matrix	Diamictite
Medium to coarse	Sand-sized grains	Sandstone
	• quartz grains only	• quartz sandstone (quartz arenite)
	• quartz and feldspar sand	• arkose
	• sand-sized rock fragments	• lithic sandstone
	• quartz sand and sand-sized rock fragments in a clay-rich matrix	• wacke (informally called graywacke)
Fine	Silt-sized clasts	Siltstone
Very fine	Clay and/or very fine silt	Shale, if it breaks into platy sheets Mudstone, if it doesn't break into platy sheets

*For precise diameters, see Table B.1 on p. 150.

To start, imagine that some large blocks of granite tumble off a cliff and slam into other blocks already at the bottom. The impact shatters the blocks, producing a pile of angular fragments. If these fragments were to be cemented together before being transported very far, the resulting rock would be **breccia** (**Fig. 6.4a**). Later, a storm causes the fragments (clasts) to be carried away by a turbulent river. In the water, clasts bang into each other and into the riverbed, a process that shatters them into still smaller pieces and breaks off their sharp edges. As the clasts get carried downstream, they gradually become rounded pebbles and cobbles. When the river water slows, these clasts stop moving and form a mound or bar of gravel. Burial and lithification of these rounded clasts produces **conglomerate** (**Fig. 6.4b**).

Did you ever wonder . . . where beach sand comes from?

If the gravel stays put for a long time, it undergoes chemical weathering. As a consequence, cobbles and pebbles break apart into individual mineral grains, eventually producing a mixture of quartz, feldspar, and clay. Clay is so fine that flowing water easily picks it up and carries it downstream, leaving sand containing a mixture of quartz and some feldspar grains—this sediment, if buried and lithified, becomes **arkose** (**Fig. 6.4c**). Over time, feldspar grains in sand continue to weather into clay so that gradually, during successive events that wash the sediment downstream, the sand loses feldspar and ends up being composed almost entirely of durable quartz grains. Some of the sand may make it to the sea, where waves carry it to beaches, and some may end up in desert dunes. This sediment, when buried and lithified, becomes quartz sandstone (**Fig. 6.4d**). Meanwhile, silt and clay may accumulate in the flat areas bordering streams, regions called floodplains (see Chapter 14) that become inundated only during floods. And some silt and mud settles in a wedge, called a delta, at the mouth of the river, or in lagoons or mudflats along the shore. The silt, when lithified, becomes **siltstone**, and the mud, when lithified, becomes **shale** or **mudstone** (**Fig. 6.4e**).

Biochemical Sedimentary Rocks

The Earth System involves many interactions between living organisms and the physical planet. Numerous organisms have evolved the ability to extract dissolved ions from seawater to make solid shells. When the organisms die, the solid material in their shells survives. This material, when lithified, comprises biochemical sedimentary rock. Geologists recognize several different types of biochemical sedimentary rocks, which we now describe.

Limestone (biochemical). A snorkeler gliding above a reef sees an incredibly diverse community of coral and algae, around which creatures such as clams, oysters, snails (gastropods), and lampshells (brachiopods) live, and above which plankton float (**Fig. 6.5a**). Though they look so different from each other, many of these organisms share an important characteristic: they make solid shells of calcium carbonate ($CaCO_3$). The $CaCO_3$ crystallizes either as calcite or aragonite. (These minerals have the same composition, but different crystal structures.) When the organisms die, the shells remain and may accumulate.

Rocks formed dominantly from this material are the biochemical version of **limestone**. Since the principal compound making up limestone is $CaCO_3$, geologists refer to limestone as a type of carbonate rock.

Limestone comes in a variety of textures, because the material that forms it accumulates in a variety of ways. For example, limestone can originate from reef builders (such as coral) that grew in place, from shell debris that was broken up and transported, from carbonate mud, or from plankton shells that settled like snow out of water. Because of this variety, geologists distinguish among *fossiliferous limestone*, consisting of visible fossil shells or shell fragments (**Fig. 6.5b**); *micrite*, consisting of very fine carbonate mud; and *chalk*, consisting of plankton shells. Experts recognize many other types as well.

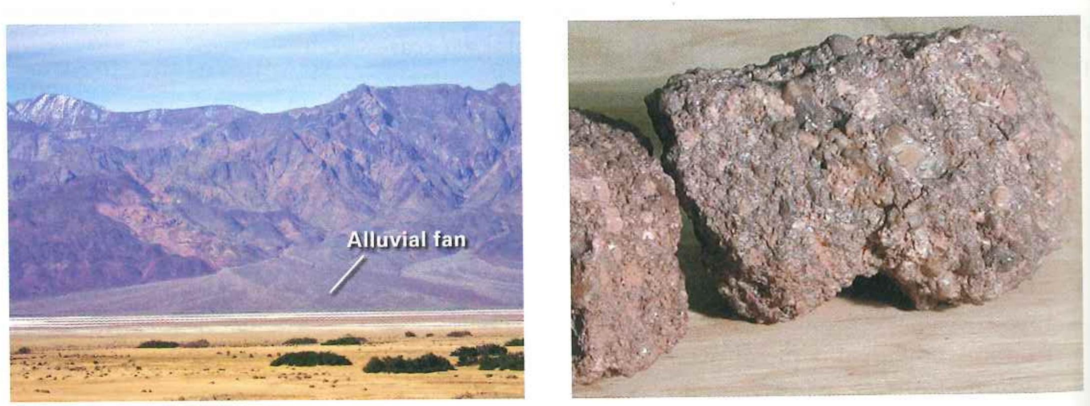
Typically, limestone is a massive light-gray to dark-bluish-gray rock that breaks into chunky blocks—it doesn't look much like a pile of shell fragments (**Fig. 6.5c**). That's because several processes change the texture of the rock over time. For example, water passing through the rock not only precipitates cement but also dissolves some carbonate grains and causes new ones to grow.

FIGURE 6.4 Different kinds of clasts lithify into different kinds of sedimentary rocks.

Sediment → Lithification → Sedimentary rock

(a) Lithification of an accumulation of angular clasts yields breccia.

(b) Layers of river gravel lithify into conglomerate.



(c) Sediment deposited in an alluvial fan, close to its source in an arid climate, can be feldspar rich. Lithification of this sediment yields arkose.

Sediment → Lithification → Sedimentary rock

(d) Layers of beach or dune sand lithify into sandstone.

(e) Layers of mud, exposed beneath marsh grass, lithify to form shale. Here, the thin-bedded shale is interbedded with sandstone.

Chert (biochemical). If you walk beneath the northern end of the Golden Gate Bridge in California, you will find outcrops of reddish, almost porcelain-like rock occurring in 3- to 15-cm-thick layers (**Fig. 6.6a**). Hit it with a hammer, and the rock would crack to form smooth, spoon-shaped (conchoidal) fractures. Geologists call this rock biochemical chert; it's made from cryptocrystalline quartz (*crypto* is Greek for hidden), meaning quartz grains that are too small to be seen without the extreme magnification of an electron microscope. The chert beneath the Golden Gate Bridge formed from the shells of silica-secreting plankton that accumulated on the sea floor. Gradually, after burial, the shells dissolved, forming a silica-rich gel. Chert then formed when this gel solidified.

Organic Sedimentary Rocks

We've seen how the mineral shells of organisms ($CaCO_3$ or SiO_2) can accumulate and lithify to become *biochemical* sedimentary rocks. What happens to the "guts" of the organisms—the cellulose, fat, carbohydrate, protein, and other organic compounds that make up living matter? Commonly, this organic debris gets eaten by other organisms or decays at the Earth's surface. But in some environments, the organic debris settles along with other sediment and eventually gets buried. When lithified, organic-rich sediment becomes organic sedimentary rock.

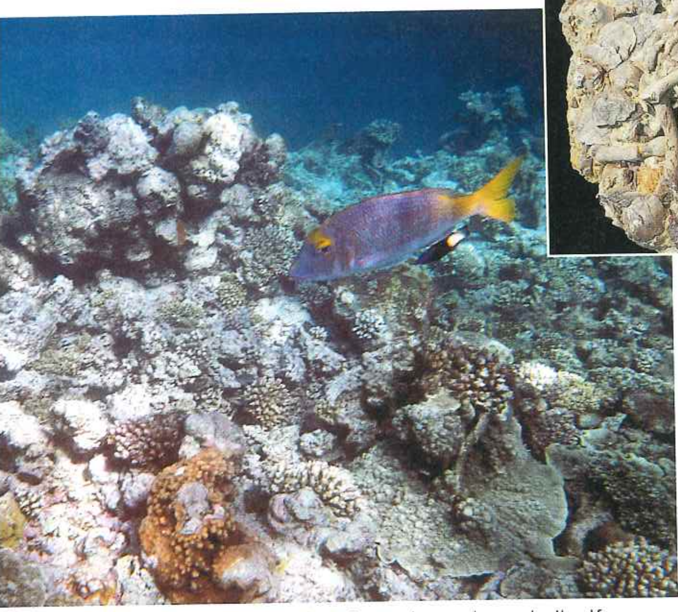
Since the dawn of the industrial revolution in the early 19th century, coal, one type of organic sedimentary rock, has provided the fuel of modern industry and transportation, for the organic chemicals in the rock yield energy when burned. Coal is a black, combustible rock consisting of over 50 to 90% carbon. The remainder consists of oxygen, nitrogen, hydrogen, sulfur, silica, and minor amounts of other elements. Typically, the carbon in coal occurs in large, complex organic molecules made of many rings—note that the carbon does *not* occur in $CaCO_3$. As discussed further in Chapter 12, coal forms when plant remains have been buried deeply enough and long enough for the material to become compacted and to lose significant amounts of volatiles (hydrogen, water, CO_2, and ammonia); as the volatiles seep away, a concentration of carbon remains (**Fig. 6.6b**).

Chemical Sedimentary Rocks

The colorful terraces, or mounds, that grow around the vents of hot-water springs; the immense layers of salt that underlie the floor of the Mediterranean Sea; the smooth, sharp point of an ancient arrowhead—these materials all have something in common. They all consist of rock formed primarily by the precipitation of minerals from water solutions. We call such rocks chemical sedimentary rocks. They typically have a crystalline texture, partly formed during their original precipitation and partly when, at a later time, new crystals grow at the expense of old ones through a process called recrystallization. In some examples, crystals are coarse. In others, they are too small to see. Geologists distinguish among many types of chemical sedimentary rocks, primarily on the basis of composition.

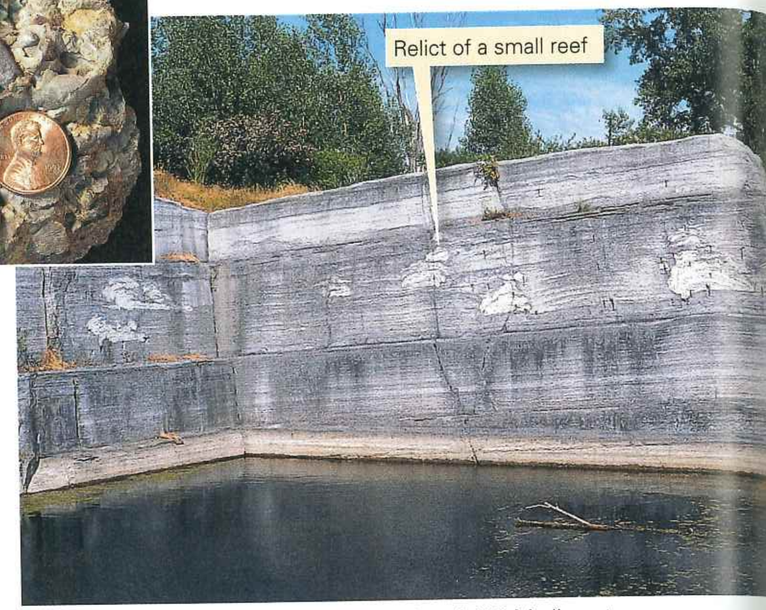
Evaporites: the products of saltwater evaporation. In 1965, two daredevil drivers in jet-powered cars battled to be the first to set the land speed record of 600 mph. On November 7, Art Arfons, in the *Green Monster*, peaked at 576.127 mph; but eight days later Craig Breedlove, driving the *Spirit of America*, reached 600.601 mph. Traveling at such speeds, a driver must maintain an absolutely straight line; any turn will catapult the vehicle out of control. Thus, high-speed trials take place on extremely long and flat racecourses. Not many places can provide such conditions—the Bonneville Salt Flats of Utah do. The salt flats formed when an ancient salt lake evaporated. Under the heat of the Sun, the water turned

FIGURE 6.5 The formation of carbonate rocks (limestone).



(a) In this modern coral reef, corals produce shells. If buried and preserved, these become limestone.

(b) Wave energy breaks up shells, forming carbonate clasts that later become cemented together.



(c) A Vermont quarry shows the gray color of 400-Ma limestone. The white mounds are relicts of small reefs.

to vapor and drifted up into the atmosphere, but the salt that had been dissolved in the water stayed behind.

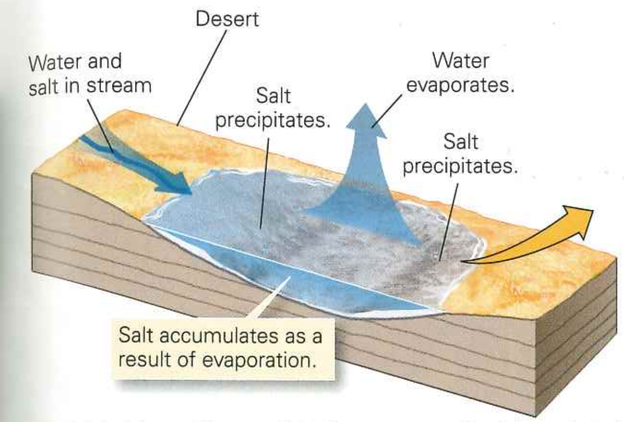
Salt precipitation occurs where saltwater becomes supersaturated, meaning that it has exceeded its capacity to contain more dissolved ions. In supersaturated saltwater, ions bond to form solid grains that either settle out of the water or grow on the floor of the water body. Supersaturated saltwater develops where evaporation removes water from a water body faster than the rate at which new water enters. This process takes place in desert lakes and along the margins of restricted seas (Fig. 6.7a, b). For thick deposits of salt to form, large volumes of water must evaporate. Because salt deposits form as a consequence of evaporation, geologists refer to them as **evaporites**. The specific type of salt minerals comprising an evaporite depends on the amount of evaporation. When 80% of the water evaporates, gypsum forms; and when 90% of the water evaporates, halite precipitates.

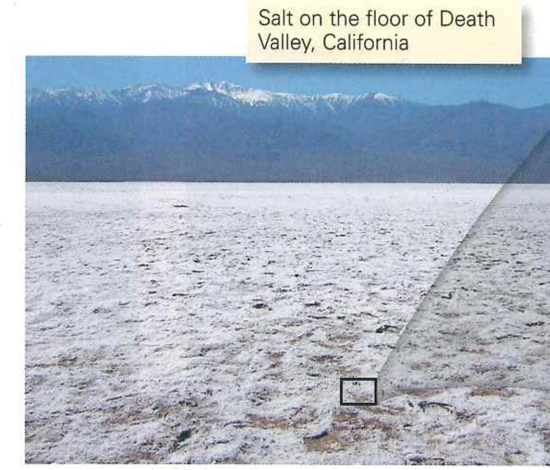
FIGURE 6.6 Examples of biochemical and organic sedimentary rocks.

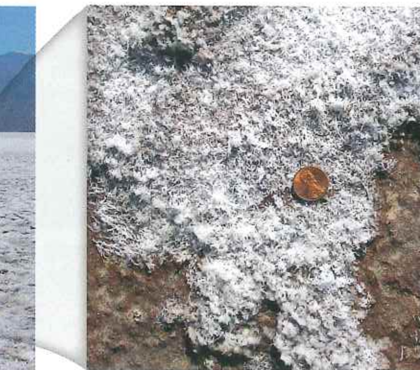
(a) This bedded chert developed on the deep-sea floor by the deposition of plankton that secrete silica shells.

(b) Coal is deposited in layers (beds), just like other kinds of sedimentary rocks.

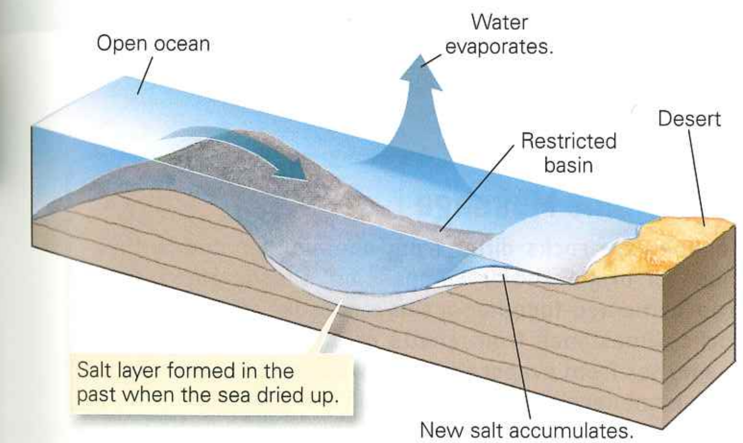
FIGURE 6.7 The formation of evaporite deposits.







(a) In lakes with no outlet, tiny amounts of salt brought in by streams stay behind as the water evaporates. When the water evaporates entirely, a white crust of salt remains.



(b) Salt precipitation can also occur along the margins of a restricted marine basin, if saltwater evaporates faster than it can be resupplied.

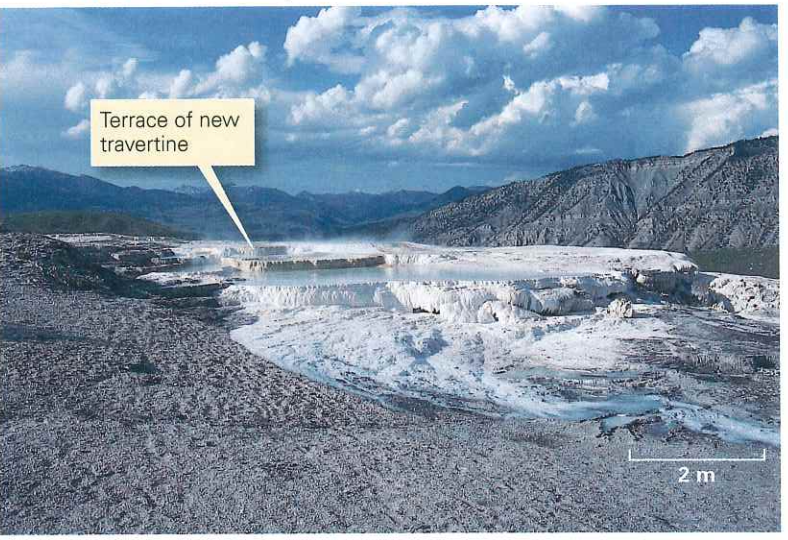
Travertine (chemical limestone). **Travertine** is a rock composed of crystalline calcium carbonate ($CaCO_3$) formed by chemical precipitation from groundwater that has seeped out at the ground surface either in hot- or cold-water springs, or on the walls of caves. What causes this precipitation? It happens, in part, when the groundwater degasses, meaning that some of the carbon dioxide that had been dissolved in the groundwater bubbles out of solution, for removal of carbon dioxide encourages the precipitation of carbonate. Precipitation also occurs when water evaporates, thereby increasing the concentration of carbonate. Various kinds of microbes live in the environments in which travertine accumulates, so biologic activity may also contribute to the precipitation process. Travertine produced at springs forms terraces and mounds that are meters or even hundreds of meters thick, such as those at Mammoth Hot Springs (Fig. 6.8a). Travertine also grows on the walls of caves where groundwater seeps out (Fig. 6.8b). In cave settings, travertine builds up beautiful and complex growth forms called speleothems (see Chapter 16).

Dolostone. Another carbonate rock, **dolostone**, differs from limestone in that it contains the mineral dolomite ($CaMg[CO_3]_2$), which contains equal amounts of calcium and magnesium. Where does the magnesium come from? Most dolostone forms by a chemical reaction between solid calcite and magnesium-bearing groundwater. Much of the dolostone you may find in an outcrop actually originated as limestone but later changed into dolostone as dolomite crystals replaced calcite. This change may take place beneath lagoons along a shore soon after the limestone formed, or a long time later, after the limestone has been buried deeply.

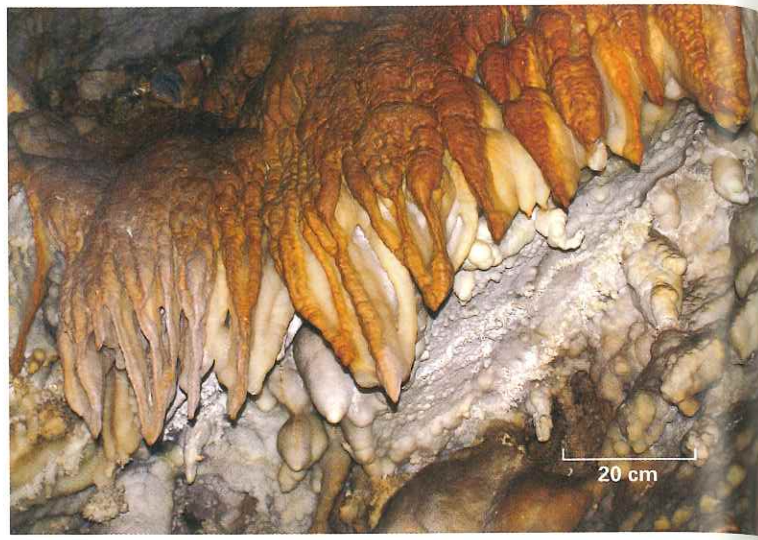
Chert (replacement). A tribe of Native Americans, the Onondaga, once lived off the land in eastern New York State. Here, outcrops of limestone contain layers or nodules (lenses or lumps) of a black chert (Fig. 6.9a). Because of the way it breaks, the tribe's artisans could fashion sharp-edged tools (arrowheads and scrapers) from this chert, so the Onondaga collected it for their own toolmaking industry and for use in trade with other people. Unlike the deep-sea (biochemical) chert described earlier, the chert collected by the Onondaga formed when cryptocrystalline quartz gradually *replaced* calcite crystals within a body of limestone long after the limestone was deposited; geologists call such material "replacement chert."

Did you ever wonder . . .
how flint used for arrowheads first formed?

FIGURE 6.8 Examples of travertine (chemical limestone) deposits.



(a) Travertine accumulates in terraces at Mammoth Hot Springs in Yellowstone Park, Wyoming.

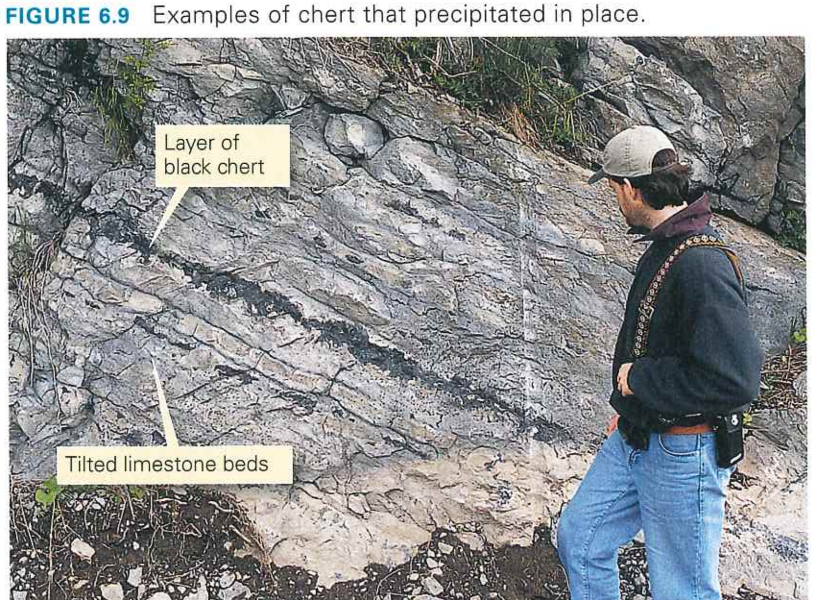


(b) Travertine speleothems form as calcite-rich water drips from the ceiling of Timpanogos Cave in Utah.

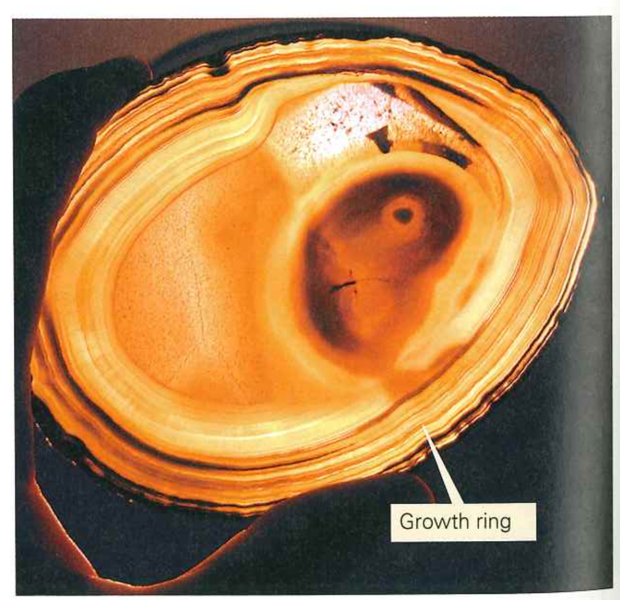
Chert comes in many colors (black, white, red, brown, green, gray), depending on the impurities it contains. Petrified wood is chert that forms when silica-rich sediment, such as ash from a volcanic eruption, buries a forest. The silica dissolves in groundwater, and then later precipitates as cryptocrystalline quartz within wood, gradually replacing the wood's cellulose. The chert deposit retains the shape of the wood and the growth rings within it. Some chert, known as agate, precipitates in concentric rings inside hollows in a rock and ends up with a striped appearance, caused by variations in the content of impurities incorporated in the chert (**Fig. 6.9b**).

> **Take-Home Message**
>
> **Sedimentary rocks differ from one another due to their mode of origin and/or composition. Clastic rocks form from cemented-together grains that broke off pre-existing rocks, limestones from shells or chemical precipitates, evaporites from evaporating salt water, and organic rocks from plant debris and other organic matter.**

FIGURE 6.9 Examples of chert that precipitated in place.



(a) Replacement chert forms as layers of nodules between tilted limestone beds in New York.



(b) A thin slice of Brazilian agate, lit from the back, shows growth rings.

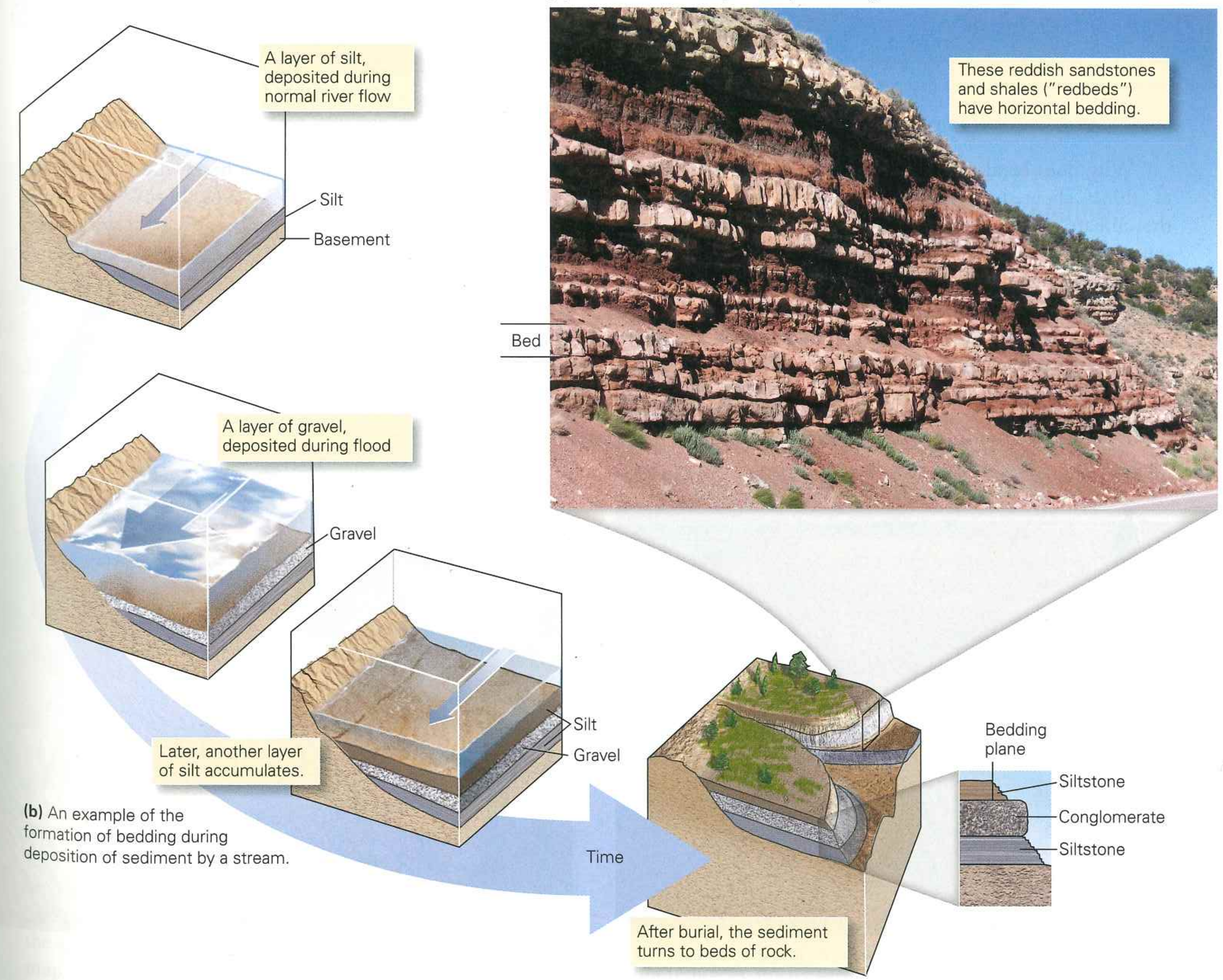
6.3 Sedimentary Structures

Geologists use the term **sedimentary structure** for the layering of sedimentary rocks, for surface features on layers formed during deposition, and for the arrangement of grains within layers. Here, we examine some of the more important types.

Bedding and Stratification

Let's start by introducing the jargon for discussing sedimentary layers. A single layer of sediment or sedimentary rock with a recognizable top and bottom is called a **bed**; the boundary between two beds is a bedding plane; several beds together constitute **strata** (singular stratum, from the Latin *stratum*, meaning pavement); and the overall arrangement of sediment into a sequence of beds is bedding, or stratification. From the word strata, we derive other words, such as stratigrapher (a geologist who specializes in studying strata) and stratigraphy (the study of the record of Earth history preserved in strata). In some outcrops, stratification can be quite subtle. But commonly, successive beds have different colors, textures, and resistance to erosion, so bedding gives outcrops a striped appearence (**Fig. 6.10a**).

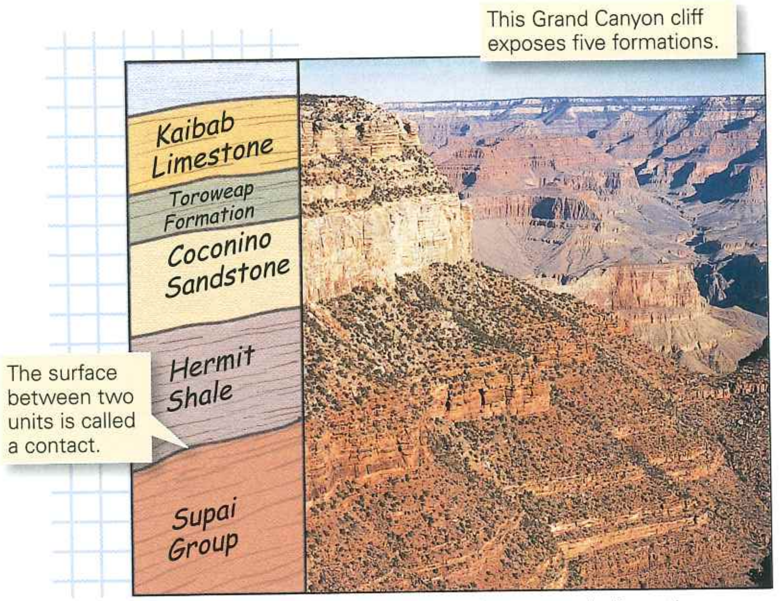
FIGURE 6.10 Bedding in sedimentary rocks.



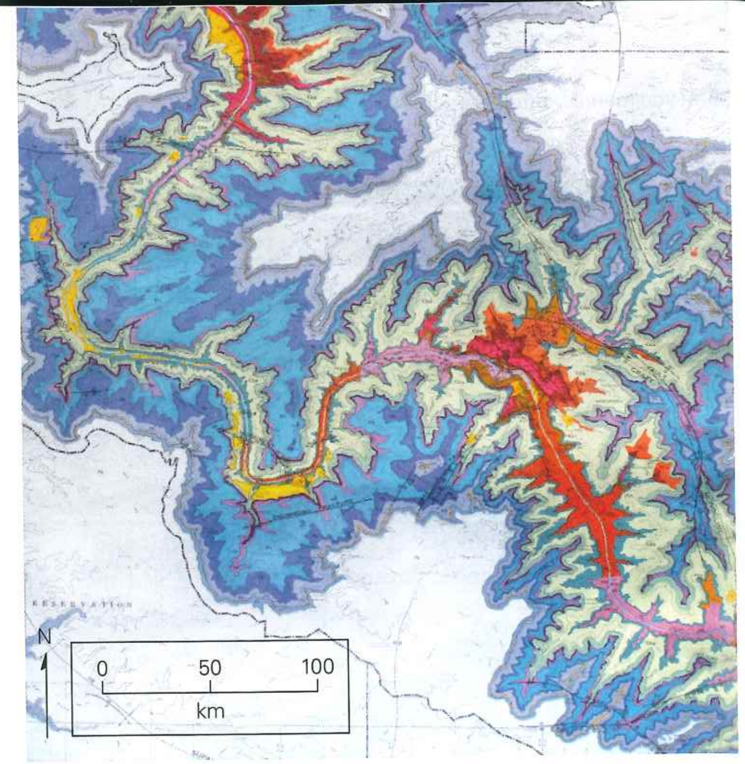
(a) Beds of sedimentary rock exposed along a road in Utah.

(b) An example of the formation of bedding during deposition of sediment by a stream.

FIGURE 6.11 The concept of a stratigraphic formation.



(a) The names of formations consisting of one rock type may indicate the rock type (e.g., Kaibab Limestone). The name of a formation including more than one rock type includes the word *formation* (Toroweap Formation). Several related formations comprise a group (Supai Group).



(b) A geologic map portrays the distribution of formations in a portion of the Grand Canyon. Each color band is a specific formation.

Why does bedding form? To find the answer, we need to think about how sediment accumulates. Changes in the climate, water depth, current velocity, or the sediment source control the type of sediment deposited at a location at a given time. For example, on a normal day a slow-moving river may carry only silt, which collects on the riverbed (**Fig. 6.10b**). During a flood, the river flows faster and carries sand and pebbles, so a layer of sandy gravel forms over the silt layer. Then, when the flooding stops, more silt buries the gravel. If this succession of sediments become lithified and exposed for you to see, they appear as alternating beds of siltstone and sandy conglomerate.

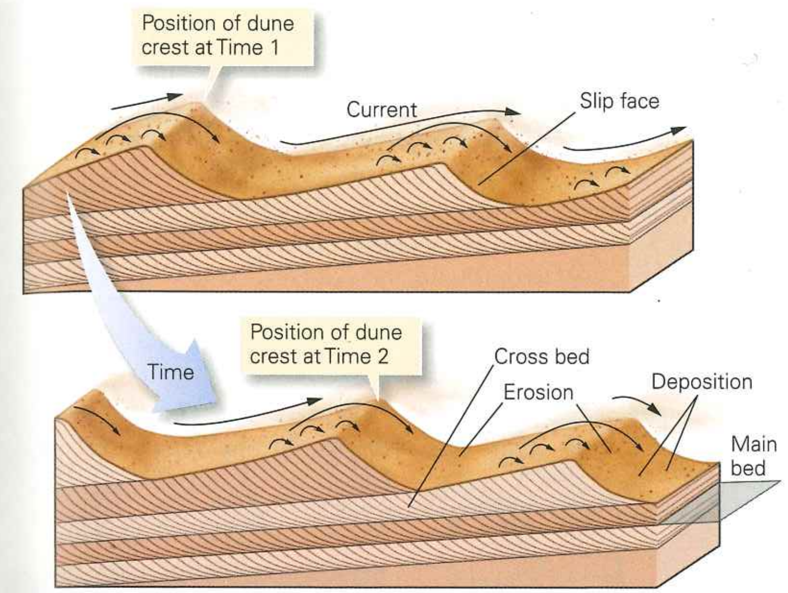
During geologic time, long-term changes in a depositional environment can take place. Thus, a given sequence of strata may differ markedly from sequences of strata above or below.

FIGURE 6.12 Ripple marks, a type of sedimentary structure, are visible on the surface of modern and ancient beds.

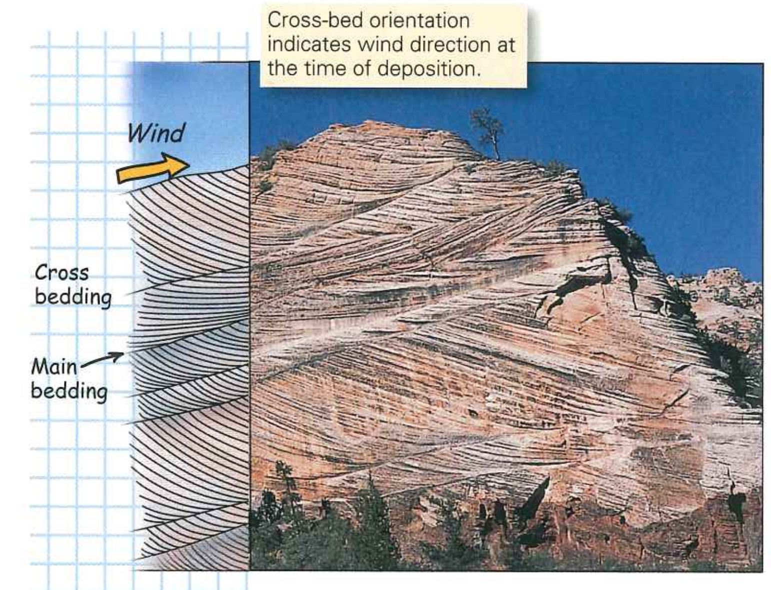
(a) Modern ripples exposed at low tide along a sandy beach on the shore of Cape Cod, Massachusetts.

(b) These 145-million-year-old ripples are preserved on a tilted bed of solid sandstone at Dinosaur Ridge, Colorado.

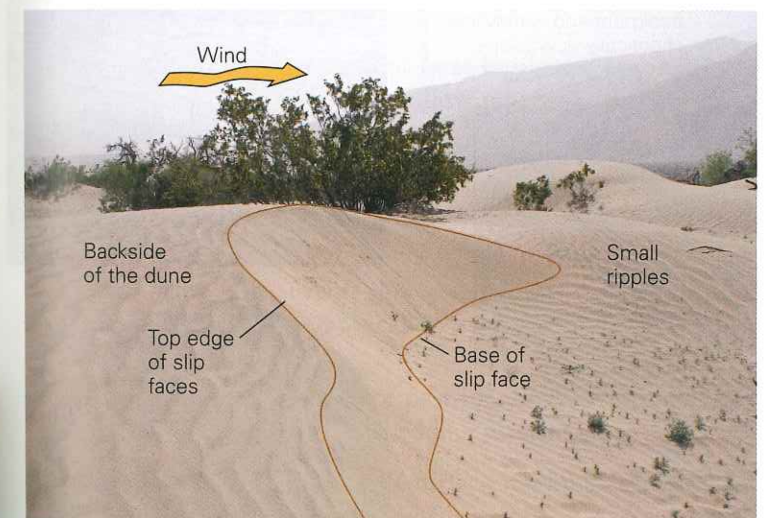
FIGURE 6.13 Cross bedding, a type of sedimentary structure within a bed.



(a) Cross beds form as sand blows up the windward side of a dune or ripple and then accumulates on the slip face. With time, the dune crest moves.



(b) A cliff face in Zion National Park, Utah, displays large cross beds formed between 200 and 180 million years ago, when the region was a desert with large sand dunes.



(c) A steep slip face occurs on the leeward side of a small dune. The edges of the slip face are highlighted.

A sequence of strata that is distinctive enough to be traced as a unit across a fairly large region is called a **stratigraphic formation**, or simply a formation (**Fig. 6.11a**). For example, a region may contain a succession of alternating sandstone and shale beds deposited by rivers, overlain by beds of marine limestone deposited later when the region was submerged by the sea. A stratigrapher might identify the sequence of sandstone and shale beds as one formation and the sequence of limestone beds as another. Formations are often named after the locality where they were first found and studied. A map that portrays the distribution of stratigraphic formations is called a **geologic map** (**Fig. 6.11b**).

Ripple Marks, Dunes, and Cross Bedding: Consequences of Deposition in a Current

Many clastic sediments accumulate in moving fluids (wind, rivers, or waves). Fascinating sedimentary structures develop at the interface between the sediment and the fluid. These structures are called bedforms. Bedforms that develop at a given location reflect such factors as the velocity of the flow and the size of the clasts. Though there are many types of bedforms, we'll focus on only two—ripple marks and dunes. The growth of both produces cross bedding, a special type of lamination within beds.

Ripple marks are relatively small (generally no more than a few centimeters high), elongated ridges that form on a bed surface at right angles to the direction of current flow. You can find ripples on modern beaches and preserved on bedding planes of ancient rocks (**Fig. 6.12a, b**). Dunes are relatively large, elongate ridges built of sediment transported by a current. In effect, dunes are "mega-ripples." Dunes on the bed of a stream may be tens of centimeters high, and wind-formed dunes of deserts may be tens to over 100 meters high.

If you examine a vertical slice cut into a ripple or dune, you will find distinct internal laminations that are inclined at an angle. Such laminations are called **cross beds**. To see how cross beds develop, imagine a current of air or water moving uniformly in one direction (**Fig. 6.13a**). The current erodes and picks up clasts from the upstream part of the bedform and deposits them on the downstream or leeward face of the crest. Sediment builds up until gravity causes it to slip down the leeward face. With time, the dune or ripple builds in the downstream direction. The surface of the slip face establishes the shape of the cross beds. Eventually, a new cross-bedded layer builds out over a preexisting one. The boundary between two successive layers is called the "main bedding," and the internal curving surfaces within the layer constitute the cross bedding (Fig. 6.13b, c).

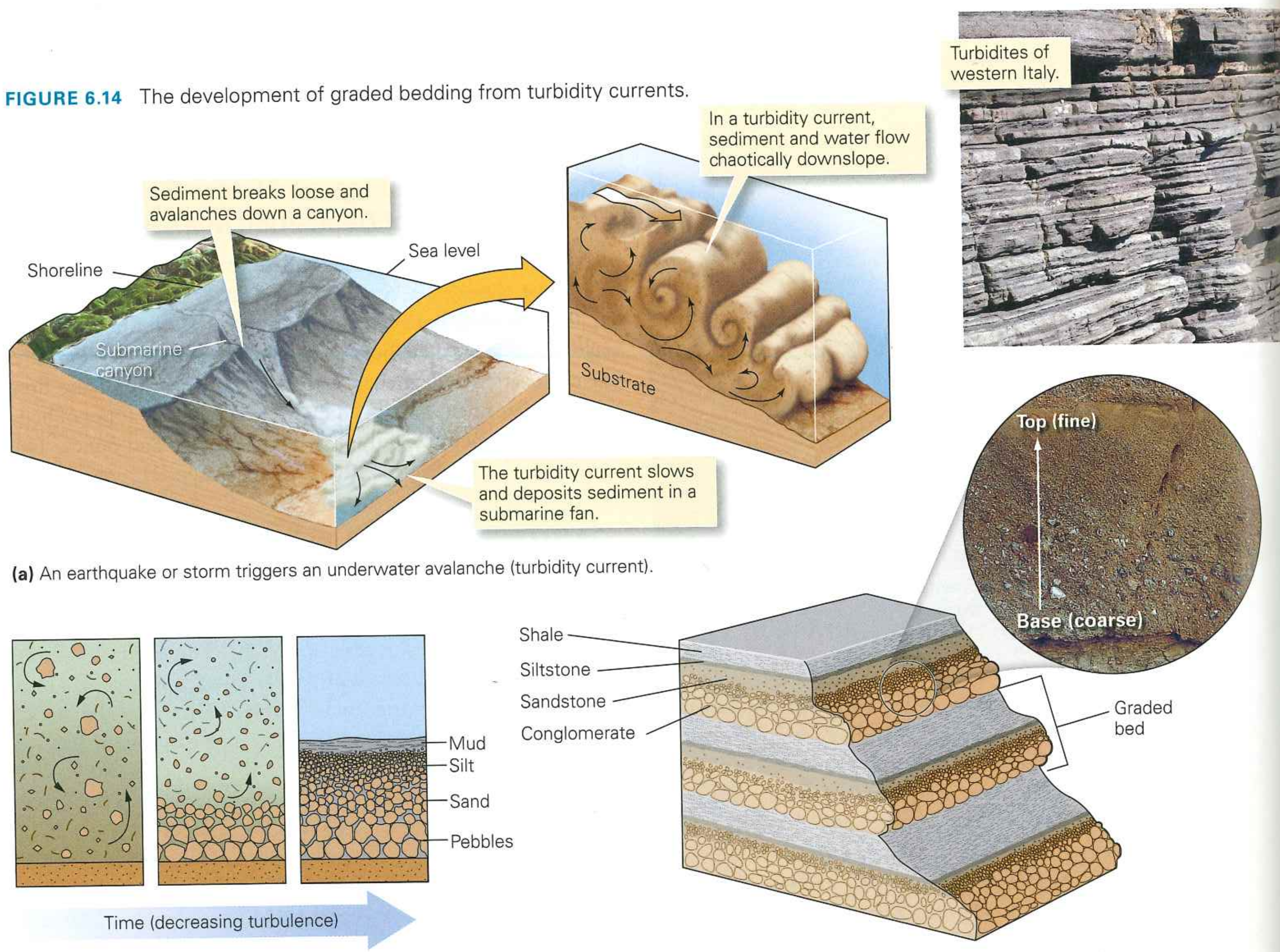
Turbidity Currents and Graded Beds

Sediment deposited on a submarine slope tends to be unstable. For example, an earthquake or storm might disturb this sediment and cause it to slip downslope and mix with water to create a murky, turbulent cloud. This cloud is denser than clear water and thus flows downslope like an underwater avalanche (Fig. 6.14a–c). We call this moving submarine suspension of sediment a **turbidity current**. Downslope, the turbidity current slows, and the sediment that it has carried starts to settle out. Larger grains sink faster through a fluid than do finer grains, so the coarsest sediment settles out first. Progressively finer grains accumulate on top, with the finest sediment (clay) settling out last. This process forms a **graded bed**—that is, a layer of sediment in which grain size varies from coarse at the bottom to fine at the top. Geologists refer to a deposit from a turbidity current as a turbidite.

Bed-Surface Markings

A number of features develop on the surface of a bed as a consequence of events that happen during deposition or

FIGURE 6.14 The development of graded bedding from turbidity currents.

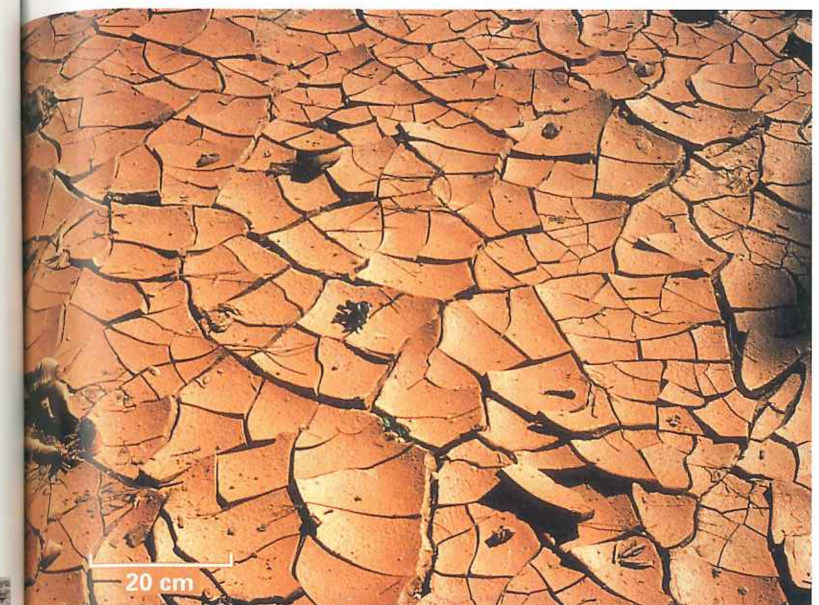


(a) An earthquake or storm triggers an underwater avalanche (turbidity current).

(b) As the turbidity current slows, larger grains settle first, followed by progressively finer grains.

(c) As the process repeats, a succession of graded beds accumulates.

FIGURE 6.15 Mud cracks, a sedimentary structure formed when mud dries out.



(a) Mud cracks in red mud at Bryce Canyon, Utah. Note how the edges of the mud plates curl up.

(b) Mud cracks preserved in a 410-million-year-old bed exposed on the base of a cliff in New York.

soon after, while the sediment layer remains soft. Such bed-surface markings include the following.

- *Mud cracks*: If a mud layer dries up after deposition, it cracks into roughly hexagonal plates that typically curl up at their edges. We refer to the openings between the plates as mud cracks (Fig. 6.15a, b).
- *Scour marks*: As currents flow over a sediment surface, they may erode small troughs, called scour marks, parallel to the current flow.
- *Fossils*: Fossils are relicts of past life. Some fossils are shell imprints or footprints on a bedding surface (see Interlude E).

Burial and lithification of bed-surface markings can preserve them in the stratigraphic record.

Why Study Sedimentary Structures?

Sedimentary structures are not just a curiosity, but are important clues that help geologists understand the environment in which sedimentary beds were deposited. For example, the presence of ripple marks and cross bedding indicates that layers were deposited in a current, the presence of mud cracks indicates that the sediment layer was exposed to the air and dried out, and graded beds indicate deposition by turbidity currents. Also, fossil types can tell us whether sediment was deposited along a river or in the deep sea, for different species of organisms live in different environments. In the next section of this chapter, we examine these environments in greater detail.

Take-Home Message

Sedimentary rocks occur in beds, because as conditions of deposition and/or sediment source change over time, sediment character changes. Geologists refer to a succession of strata traceable over a region as a stratigraphic formation. The action of currents can produce sedimentary structures such as ripples, scours, and cross beds.

6.4 How Do We Recognize Depositional Environments?

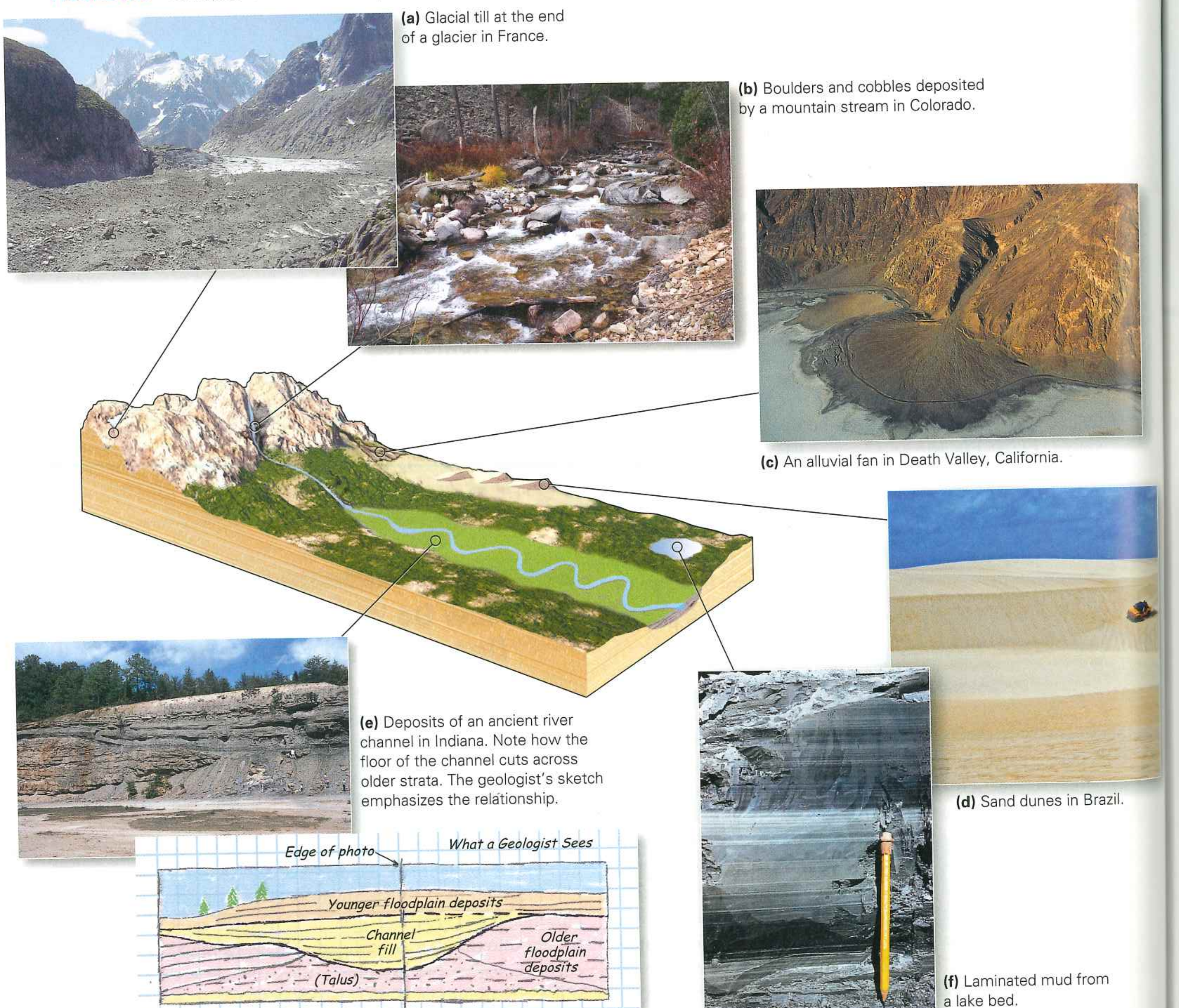
Geologists refer to the conditions in which sediment was deposited as the **depositional environment**. Examples include beach, glacial, and river environments. To identify depositional environments, geologists, like crime scene investigators, look for clues. Detectives may seek fingerprints and bloodstains to identify a culprit. Geologists examine grain size, composition, sorting, bed-surface marks, cross bedding, and fossils to identify a depositional environment. Geological clues can tell us if the sediment was deposited by ice, strong currents, waves, or quiet water, and in some cases can provide insight into the climate at the time of deposition. With experience, geologists can examine a succession of beds and determine if it accumulated on a river floodplain, along a beach, in shallow water just offshore, or on the deep ocean floor.

Let's now explore some examples of different depositional environments and the sediments deposited in them, by imagining that we are taking a journey from the mountains to the sea, examining sediments as we go (see **Geology at a Glance** on pp. 180–181 and **See for Yourself F**). We will see that geologists distinguish among three basic categories of depositional environments: terrestrial, coastal, and marine.

Terrestrial (Nonmarine) Sedimentary Environments

We begin our exploration with terrestrial depositional environments, those that develop inland, far enough away from the shoreline that they are not affected by ocean tides and waves. The sediments settle on dry land, or under and adjacent to freshwater.

FIGURE 6.16 Examples of nonmarine depositional environments.



(a) Glacial till at the end of a glacier in France.

(b) Boulders and cobbles deposited by a mountain stream in Colorado.

(c) An alluvial fan in Death Valley, California.

(d) Sand dunes in Brazil.

(e) Deposits of an ancient river channel in Indiana. Note how the floor of the channel cuts across older strata. The geologist's sketch emphasizes the relationship.

(f) Laminated mud from a lake bed.

In some settings, oxygen in surface water or groundwater reacts with iron to produce rust-like iron-oxide minerals in terrestrial sediments, which give the sediment an overall reddish hue. Strata with this hue are informally called redbeds.

Glacial environments. High in the mountains, where it's so cold that more snow collects in the winter than melts away, glaciers—rivers or sheets of ice—develop and slowly flow. Because ice is a solid, it can move sediment of any size. So as a glacier moves down a valley in the mountains, it carries along *all* the sediment that falls on its surface from adjacent cliffs or gets plucked from the ground at its base or sides. At the end of the glacier, where the ice finally melts away, the sediment that had been in or on the ice accumulates as "glacial till" (**Fig. 6.16a**). Till is unsorted and unstratified—it contains clasts ranging from clay size to boulder size all mixed together.

Mountain stream environments. As we walk down beyond the end of the glacier, we enter a realm where turbulent streams rush downslope in steep-sided valleys. This fast-moving water has the power to carry large clasts; in fact, during floods, boulders and cobbles can tumble down the stream bed. Between floods, when water flow slows, the largest clasts settle out to form gravel and boulder beds, while the stream carries finer sediments like sand and mud farther downstream (**Fig. 6.16b**). Sedimentary deposits of a mountain stream would, therefore, include breccia and conglomerate.

Alluvial-fan environments. Our journey now takes us to the mountain front, where the fast-moving stream empties onto a plain. In arid regions, where there is not enough water for the stream to flow continuously, the stream deposits its load of sediment near the mountain front, producing a wedge-shaped apron of gravel and sand called an alluvial fan (**Fig. 6.16c**). Deposition takes place here because when the stream pours from a canyon mouth and spreads out over a broader region, friction with the ground causes the water to slow down, and slow-moving water does not have the power to move coarse sediment. The sand here still contains feldspar grains, for these have not yet weathered into clay. Alluvial-fan sediments become arkose and conglomerate.

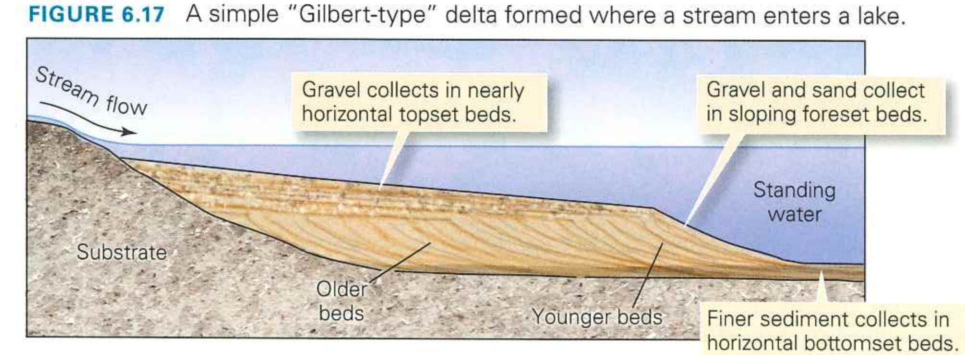
Sand-dune environments. If the climate is very dry, few plants can grow and the ground surface lies exposed. Strong winds can move dust and sand. The dust gets carried away, and the resulting well-sorted sand can accumulate in dunes. Thus, thick layers of well-sorted sandstone, in which we can find large cross beds, are relicts of desert sand-dune environments (**Fig. 6.16d**).

River (fluvial) environments. In climates where streams flow, we find several distinctive depositional environments. Rivers transport gravel, sand, silt, and mud. The coarser sediments tumble along the bed in the river's channel and collect in cross-bedded, rippled layers while the finer sediments drift along, suspended in the water. This fine sediment settles out along the banks of the river, or on the floodplain, the flat land on either side of the river that is covered with water only during floods. On the floodplain, mud layers dry out between floods, leading to the formation of mud cracks. River sediments lithify to form sandstone, siltstone, and shale. Typically, the coarser sediments of channels are surrounded by layers of fine-grained floodplain deposits, so in cross section, the channel has a lens-like shape (**Fig. 6.16e**). Geologists commonly refer to river deposits as fluvial sediments, from the Latin word *fluvius*, for river.

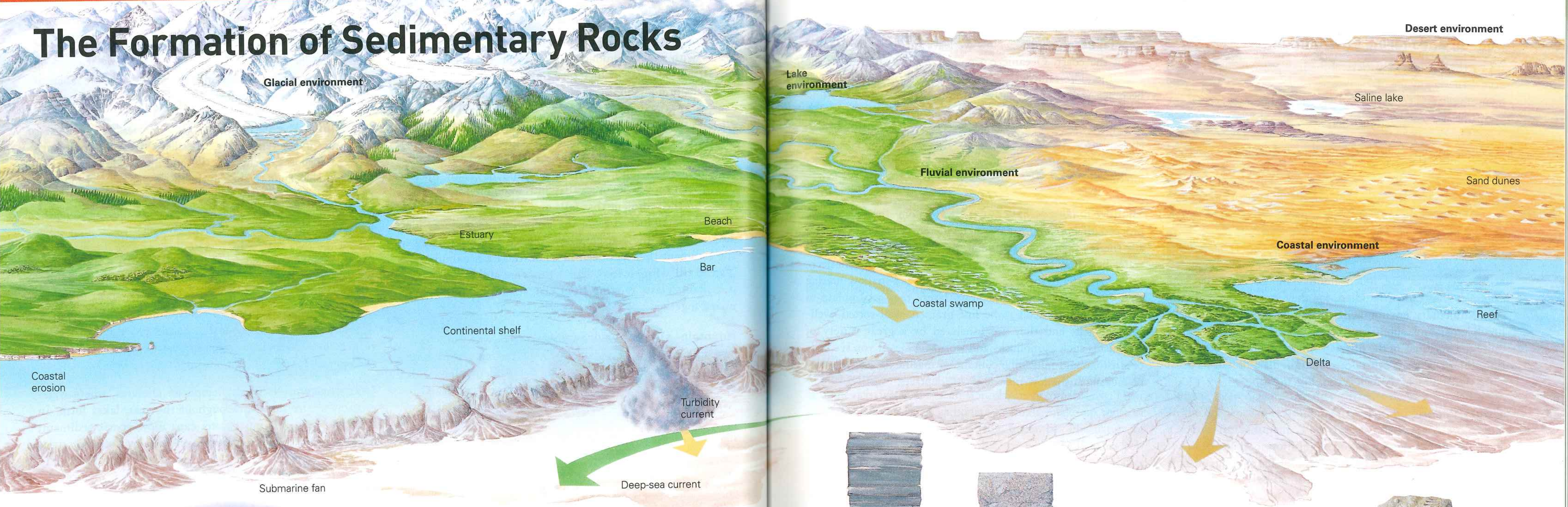
Lake environments. In temperate climates, where water remains at the surface throughout the year, lakes form. In lakes, the relatively quiet water can't move coarse sediment; any coarse sediment brought into the lake by a stream settles out at the stream's outlet. Only fine clay makes it out into the center of the lake, where it settles to form mud on the lake bed. Thus, lake sediments typically consist of finely laminated shale (**Fig. 6.16f**).

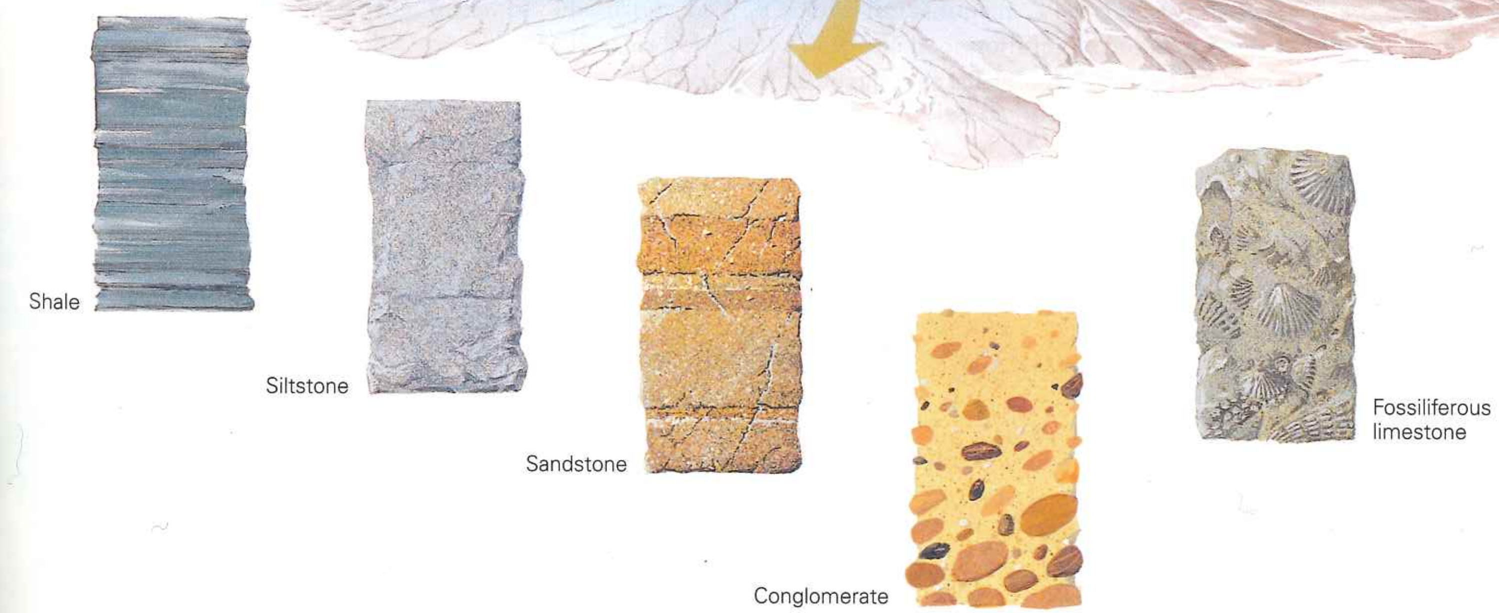
At the mouths of streams that empty into lakes, small deltas may form. A **delta** is a wedge of sediment that accumulates where moving water enters standing water. Deltas were so named because the map shape of some deltas resembles the Greek letter *delta* (Δ), as we discuss further in Chapter 14. In 1885, an American geologist named G. K. Gilbert showed that such deltas contain three components (**Fig. 6.17**): topset beds composed of gravel, foreset beds of gravel and sand, and silty bottomset beds.

FIGURE 6.17 A simple "Gilbert-type" delta formed where a stream enters a lake.



The Formation of Sedimentary Rocks





Categories of sedimentary rocks include clastic sedimentary rocks, chemical sedimentary rocks (formed from the precipitation of minerals out of water), and biochemical sedimentary rocks (formed from the shells of organisms). Clastic sedimentary rocks develop when grains (clasts) break off preexisting rock by weathering and erosion and are transported to a new location by wind, water, or ice; the grains are deposited to create sediment layers, which are then cemented together. We distinguish among types of clastic sedimentary rocks on the basis of grain size.

The character of a sedimentary rock depends on the composition of the sediment and on the environment in which it accumulated. For example, glaciers carry sediment of all sizes, so they leave deposits of poorly sorted (different-sized) till; streams deposit coarser grains in their channels and finer ones on floodplains; a river slows down at its mouth and deposits an immense pile of silt in a delta. Fossiliferous limestone develops on coral reefs. In desert environments, sand accumulates into dunes and evaporates precipitate in saline lakes. Offshore, submarine canyons channel avalanches of sediment, or turbidity currents, out to the deep-sea floor.

Sedimentary rocks tell the history of the Earth. For example, the layering, or bedding, of sedimentary rocks is initially horizontal. So where we see layers bent or folded, we can conclude that the layers were deformed during mountain building. Where horizontal layers overlie folded layers, we have an unconformity: for a time, sediment was not deposited, and/or older rocks were eroded away.

Coastal and Marine Environments

Along the seashore, a variety of distinct coastal environments occur; the character of each reflects the nature of the sediment supply and the climate. Marine environments start at the high-tide line and extend offshore, to include the deep ocean floor. The type of sediment deposited at a location depends on the climate, water depth, and whether or not clastic grains are available.

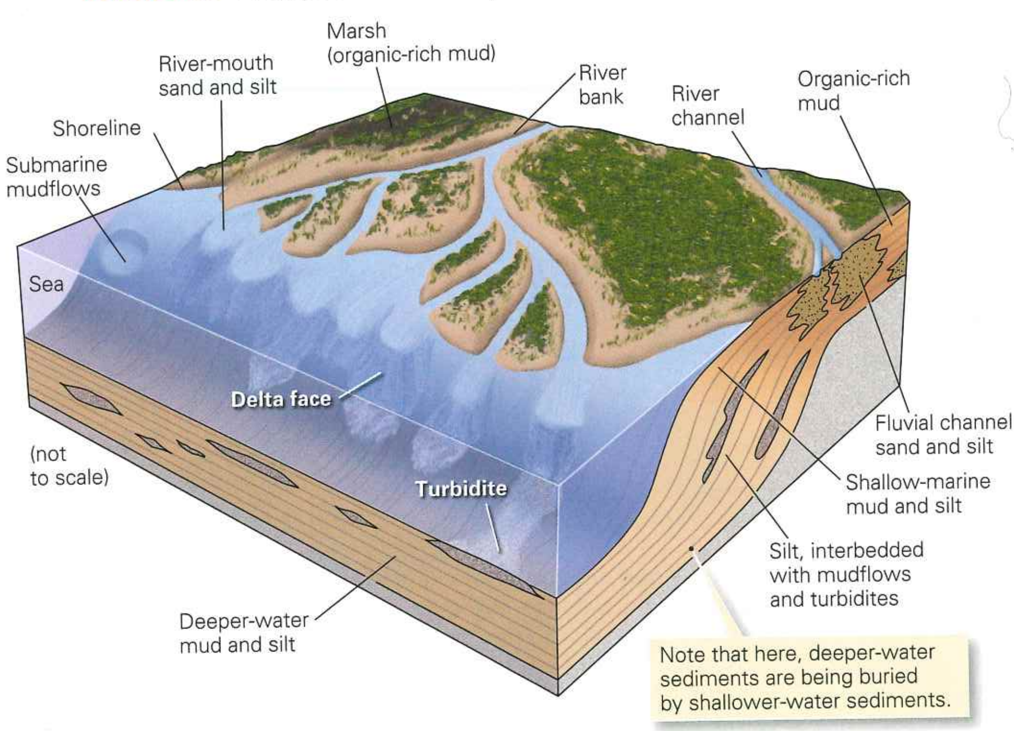
Marine delta deposits. After following the river downstream for a long distance, we reach its mouth, where it empties into the sea. Here, the river builds a delta of sediment out into the sea. River water stops flowing when it enters the sea, so sediment settles out.

Large deltas are much more complex than the lake examples that Gilbert studied, for they include many different sedimentary environments including swamps, channels, floodplains, and submarine slopes. Sea-level changes may cause the positions of the different environments to move with time. Thus, deposits of an ocean-margin delta produce a great variety of sedimentary rock types (Fig. 6.18a).

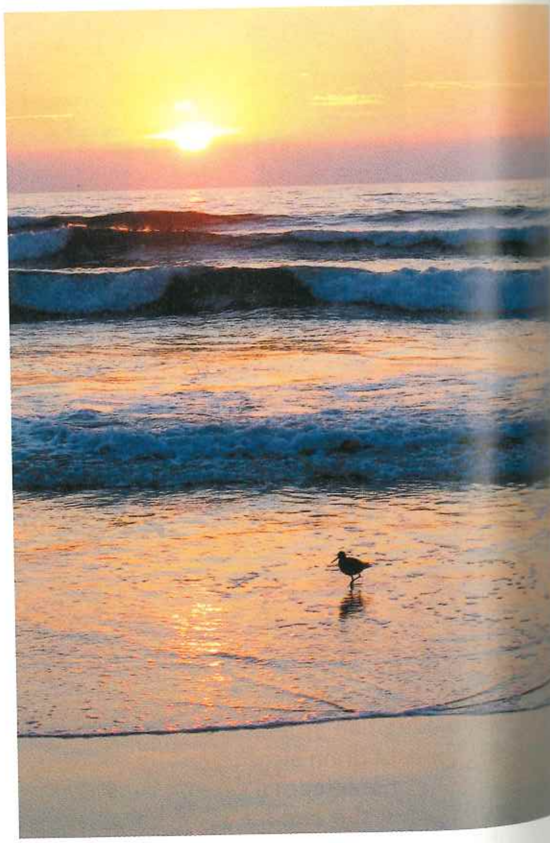
Coastal beach sands. Now we leave the delta and wander along the coast. Oceanic currents transport sand along the coastline. The sand washes back and forth in the surf, so it becomes well sorted (waves winnow out silt and clay) and well rounded, and because of the back-and-forth movement of ocean water over the sand, the sand surface may become rippled (Fig. 6.18b). Thus, if you find well-sorted, medium-grained sandstone, perhaps with ripple marks, you may be looking at the remnants of a beach environment.

Shallow-marine clastic deposits. From the beach, we proceed offshore. In deeper water, where wave energy does not stir the sea floor, finer sediment can accumulate. Because the water here may be only meters to a few tens of meters deep, geologists refer to this depositional setting as a shallow-marine environment. Clastic sedimentary layers that accumulate in this environment tend to be fine-grained, well-sorted, well-rounded silt, and they are inhabited by a great variety of organisms such as mollusks and worms. Thus, if you see beds of siltstone and mudstone containing marine fossils, you may be looking at shallow-marine clastic deposits.

FIGURE 6.18 Examples of coastal depositional environments.

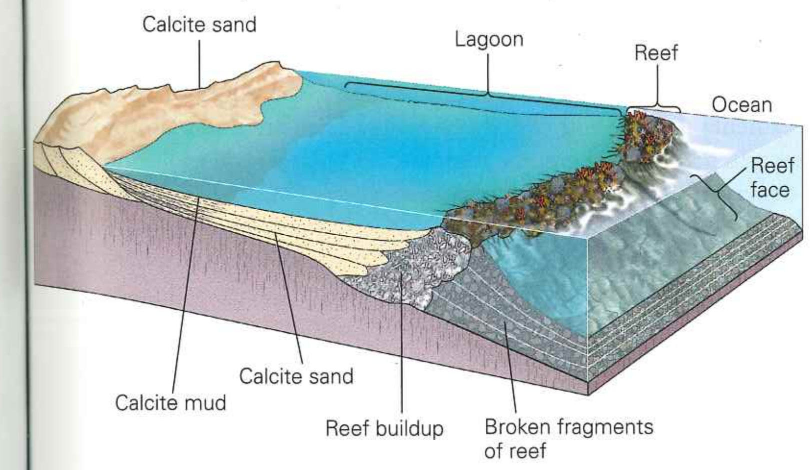


(a) A major river delta along an ocean coast is a complex depositional environment. Sea-level changes affect locations of depositional settings.



(b) Waves on this California beach wash and sort the sand.

FIGURE 6.19 Reef environments for the deposition of carbonate rocks.



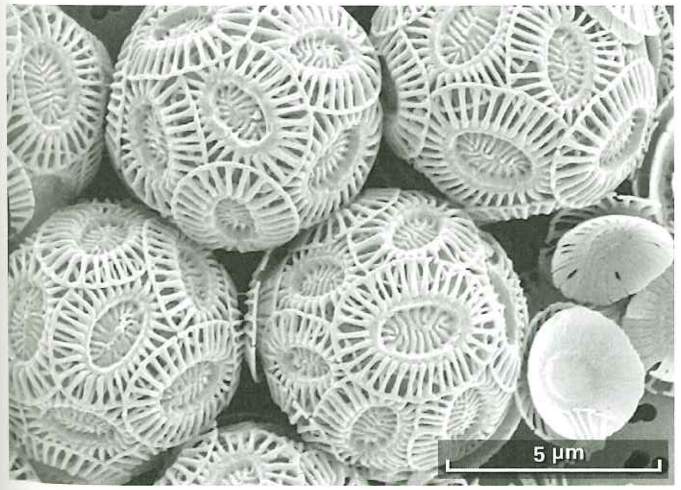
(a) Carbonate reefs form along shorelines in warm-water environments. In detail, reefs include many distinct depositional environments.

(b) A dramatic reef surrounds an island in the tropical Pacific. Deeper water is darker. Note the surf along the edge of the reef.

Shallow-water carbonate environments. In shallow-marine settings relatively free of clastic sediment, warm, clear, nutrient-rich water hosts an abundance of organisms. Their shells, which consist of carbonate minerals, make up most of the sediment that accumulates (Fig. 6.19a, b). The nature of carbonate sediment depends on the water depth. Beaches collect sand composed of shell fragments; lagoons (protected bodies of quiet water) are sites where carbonate mud accumulates; and reefs consist of coral and coral debris. Farther offshore of a reef, we can find a sloping apron of reef fragments. Shallow-water carbonate environments transform into various kinds of limestone.

Deep-marine deposits. We conclude our journey by sailing far offshore. Along the transition between coastal regions and the deep ocean, turbidity currents deposit graded beds. In the deep-ocean realm, only fine clay and plankton provide a source for sediment. The clay eventually settles out onto the deep-sea floor, forming deposits of finely laminated mudstones, and plankton shells settle to form chalk (from calcite shells; Fig. 6.20a, b) or chert (from siliceous shells). Thus, deposits of mudstone, chalk, or bedded chert indicate a deep-marine origin.

FIGURE 6.20 Examples of deep-marine sediment.



(a) These plankton shells, which make up some kinds of deep-marine sediment, are so small that 50 could fit in the eye of a needle.

(b) The chalk cliffs of southeastern England consist of plankton shells deposited on the sea floor tens of millions of years ago.

Take-Home Message

Different types of sedimentary rocks accumulate in different depositional environments. Thus, strata deposited along a river differs from strata deposited by ocean waves, by glaciers, or in the deep sea. By studying sedimentary rocks at a location, geologists can deduce environments that existed at the locality in the past.

6.5 Sedimentary Basins

The sedimentary veneer on the Earth's surface varies greatly in thickness. If you stand in central Siberia or south-central Canada, you will find yourself on igneous and metamorphic basement rocks that are over a billion years old—sedimentary rocks are nowhere in sight. Yet if you stand along the southern coast of Texas, you would have to drill through over 15 km of sedimentary beds before reaching igneous and metamorphic basement. *Thick accumulations of sediment form only in special regions* where the surface of the Earth's lithosphere sinks, providing space in which sediment collects. Geologists use the term **subsidence** to refer to the process by which the surface of the lithosphere sinks, and the term **sedimentary basin** for the sediment-filled depression. In what geologic settings do sedimentary basins form? An understanding of plate tectonics theory provides the answers.

Categories of Basins in the Context of Plate Tectonics Theory

Geologists distinguish among different kinds of sedimentary basins in the context of plate tectonics theory. Let's consider a few examples (Fig. 6.21).

- *Rift basins*: These form in continental rifts, regions where the lithosphere is stretching horizontally, and therefore thins vertically. As the rift grows, slip on faults drops blocks of crust down, producing low areas bordered by narrow mountain ridges. These troughs fill with sediment.
- *Passive-margin basins*: These form along the edges of continents that are not plate boundaries. They are underlain by stretched lithosphere, the remnants of a rift whose evolution successfully led to the formation of a mid-ocean ridge and subsequent growth of a new ocean basin. Passive-margin basins form because subsidence of stretched lithosphere continues long after rifting ceases. They fill with sediment carried to the sea by rivers and with carbonate rocks formed in coastal reefs.
- *Intracontinental basins*: These develop in the interiors of continents, initially because of subsidence over a rift. They may continue to subside in pulses even hundreds of millions of years after they formed, for reasons that are not well understood.
- *Foreland basins*: These form on the continent side of a mountain belt because the forces produced during convergence or collision push large slices of rock up faults and onto the surface of the continent. The weight of these slices pushes down on the surface of the lithosphere, producing a wedge-shaped depression adjacent to the mountain range that fills with sediment eroded from the range. Fluvial and deltaic strata accumulate in foreland basins.

Transgression and Regression

Sea-level changes, relative to the land surface, control the succession of sediments that we see in a sedimentary basin. At times during Earth history, sea level has risen by as much as a couple of hundred meters, creating shallow seas that submerge the interiors of continents. At other times, sea level has fallen by a couple of hundred meters, exposing the continental shelves to air. Global sea-level changes may be due to a number of factors, including climate change, which controls the amount of ice stored in polar ice caps and causes changes in the volume of ocean basins. Sea level at a location may also be due to the local uplift or sinking of the land surface.

When relative sea level rises, the shoreline migrates inland. We call this process **transgression**. When relative sea level falls, the coast migrates seaward. We call this process **regression** (Fig. 6.22). The process of transgression and regression leads to the formation of broad blankets of sediment.

FIGURE 6.21 The geologic setting of sedimentary basins.

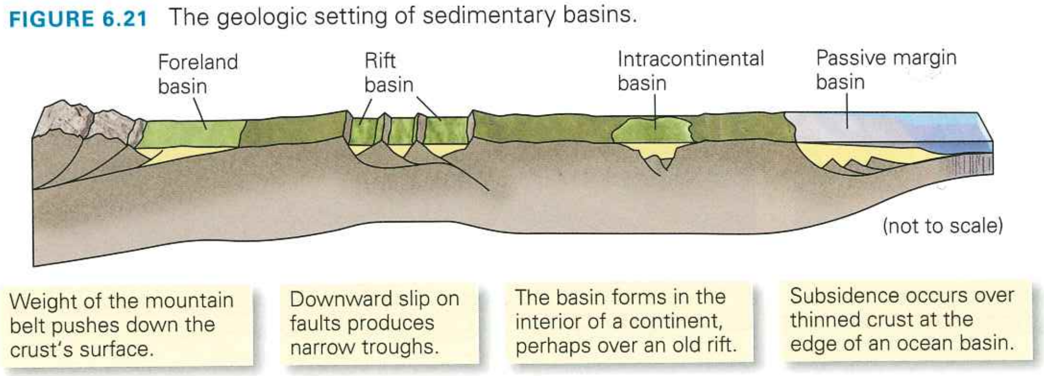
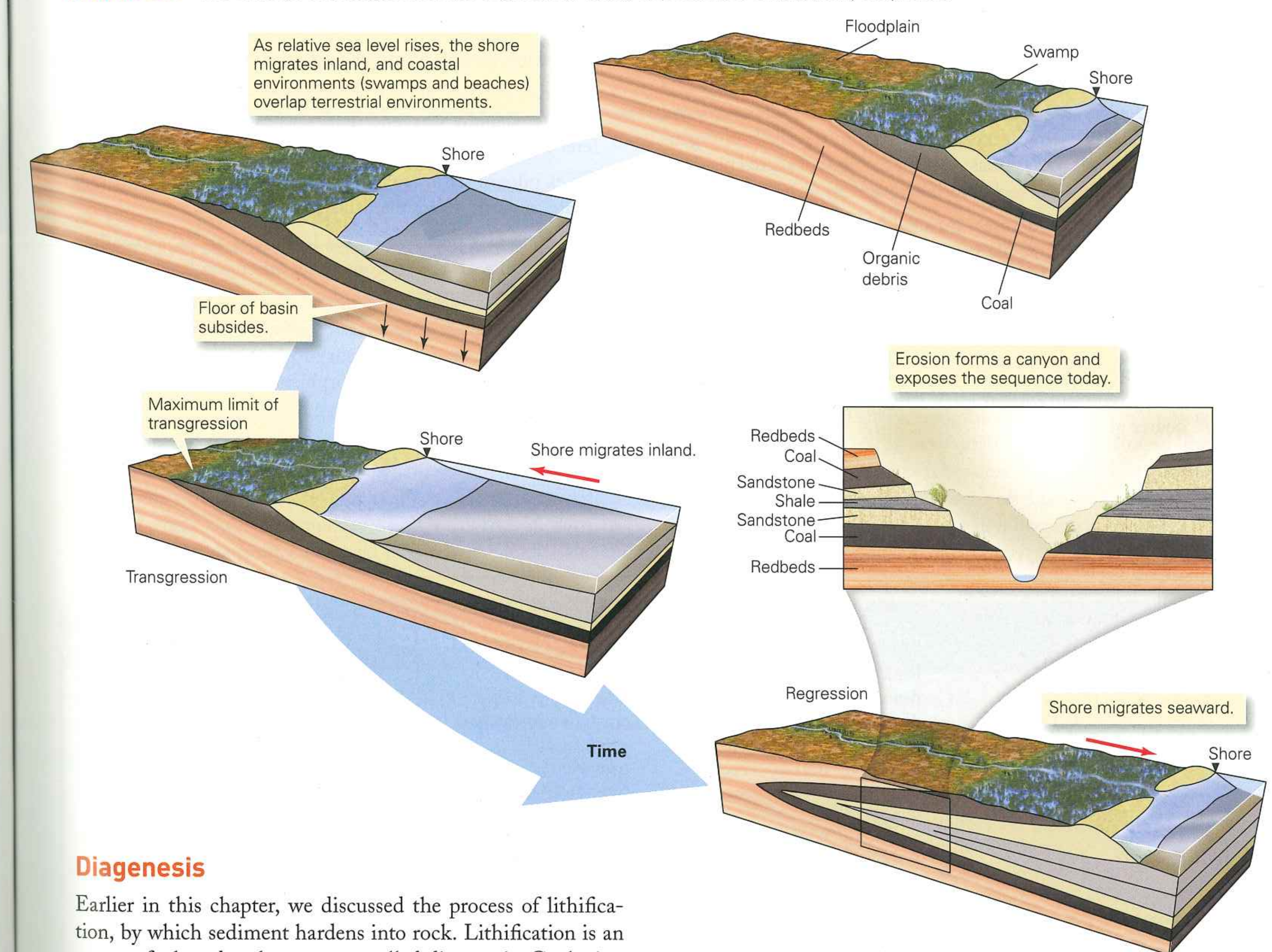


FIGURE 6.22 The concept of transgression and regression, during deposition of sedimentary sequence.



Diagenesis

Earlier in this chapter, we discussed the process of lithification, by which sediment hardens into rock. Lithification is an aspect of a broader phenomenon called diagenesis. Geologists use the term **diagenesis** for all the physical, chemical, and biological processes that transform sediment into sedimentary rock and that alter characteristics of sedimentary rock after the rock has formed.

In sedimentary basins, sedimentary rocks may become very deeply buried. As a result, the rocks endure higher pressures and temperatures and come in contact with warm groundwater. Diagenesis, under such conditions, can cause chemical reactions in the rock that produce new minerals and can also cause cement to dissolve or precipitate.

As temperature and pressure increase still deeper in the subsurface, the changes that take place in rocks become more profound. At sufficiently high temperature and pressure, metamorphism begins, in that a new assemblage of minerals forms, and/or mineral grains become aligned parallel to each other. The transition between diagenesis and metamorphism in sedimentary rocks is gradational and occurs between temperatures of 150°C and 300°C. In the next chapter, we enter the realm of true metamorphism.

Take-Home Message

In certain geologic settings, Earth's surface sinks (subsides) to form a depression that fills with sediment. The depression with its thick fill of sediment is a sedimentary basin. As sea level rises and falls, the coast, and therefore depositional environments, can migrate.

CHAPTER 6 REVIEW

Chapter Summary

- Geologists recognize four major classes of sedimentary rocks. Clastic rocks form from cemented-together grains that were first produced by weathering, then were transported, deposited, and lithified. Biochemical rocks develop from the shells of organisms. Organic rocks consist of plant debris or of altered plankton remains. Chemical rocks precipitate directly from water.
- Sedimentary structures include bedding, cross bedding, graded bedding, ripple marks, dunes, and mud cracks. They serve as clues to depositional settings.
- Biochemical and organic rocks form from materials produced by living organisms.
- Limestone consists dominantly of calcite, chert forms from silica, coal from carbon, shale from clay, and sandstone from quartz grains.
- Evaporites consist of minerals precipitated from water.
- Glaciers, streams, alluvial fans, deserts, rivers, lakes, deltas, beaches, shallow seas, and deep seas each accumulate a different, distinctive assemblage of sedimentary strata.
- Thick piles of sedimentary rocks accumulate in sedimentary basins, regions where the lithosphere subsides.
- Transgressions occur when sea level rises and the coastline migrates inland. Regressions occur when sea level falls and the coastline migrates seaward.
- Diagenesis involves processes leading to lithification and processes that alter sedimentary rock at temperatures lower than those that cause metamorphism.

Key Terms

arkose (p. 167)
bed (p. 173)
biochemical sedimentary rock (p. 164)
breccia (p. 167)
cementation (p. 166)
chemical sedimentary rock (p. 164)
clastic sedimentary rock (p. 164)
clast (p. 164)
coal (p. 169)
compaction (p. 166)
conglomerate (p. 167)
cross bed (p. 175)
delta (p. 179)
deposition (p. 165)
depositional environment (p. 177)
detritus (p. 164)
diagenesis (p. 185)
dolostone (p. 171)
erosion (p. 165)
evaporite (p. 170)
geologic map (p. 175)
graded bed (p. 176)
limestone (p. 168)
lithification (p. 165)
mudstone (p. 167)
organic sedimentary rock (p. 164)
regression (p. 184)
ripple mark (p. 175)
sandstone (p. 164)
sedimentary basin (p. 184)
sedimentary rock (p. 164)
sedimentary structure (p. 173)
shale (p. 167)
siltstone (p. 167)
sorting (p. 166)
strata (p. 173)
stratigraphic formation (p. 175)
subsidence (p. 184)
transgression (p. 184)
travertine (p. 171)
turbidity current (p. 176)

Review Questions

1. Describe how a clastic sedimentary rock forms from its unweathered parent rock.
2. Explain how biochemical sedimentary rocks form.
3. How do grain size and shape, sorting, sphericity, and angularity change as sediments move downstream?
4. Describe the two different kinds of chert. How are they similar? How are they different?
5. Do all chemical sedimentary rocks have the same composition? What conditions produce evaporites?
6. How does dolostone differ from limestone, and how does dolostone form?
7. What are cross beds, and how do they form? How can you read the current direction from cross beds?
8. Describe how a turbidity current forms and moves. How does it produce graded bedding?
9. Compare deposits of an alluvial fan with those of a deep-marine deposit.
10. Why don't sediments accumulate everywhere? What types of tectonic conditions are required to create basins?
11. How is it possible for sandstone derived from sediment deposited in a beach environment to comprise a formation that blankets a broad region?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on sedimentary rocks and structures.
- A video exercise on the characteristics of canyons.
- An animation exercise on the formation of cross-bedding.

On Further Thought

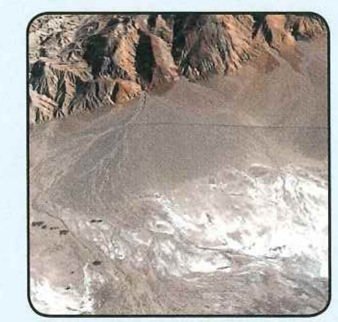
12. Recent exploration of Mars by robotic vehicles suggests that layers of sedimentary rock cover portions of the planet's surface. On the basis of examining images of these layers, some researchers claim that the layers contain cross bedding and relicts of gypsum crystals. At face value, what do these features suggest about depositional environments on Mars in the past?
13. The Gulf Coast of the United States is a passive-margin basin that contains a very thick accumulation of sediment. Drilling reveals that the base of the sedimentary succession in this basin consists of redbeds. These are overlain by a thick layer of evaporite. The evaporite, in turn, is overlain by deposits composed of sandstone and shale. In some intervals, sandstone occurs in channels and contains ripple marks, and the shale contains mud cracks. In other intervals, the sandstone and shale contain fossils of marine organisms. Be a sedimentary detective, and explain the succession of sediment in the basin.
14. Examine the Bahamas with *Google Earth*™ or NASA World Wind. (You can find a high-resolution image at Latitude 23°58′40.98″N, Longitude 77°30′20.37″W.) Note that broad expanses of very shallow water surround the islands, that white-sand beaches occur along the coast of the islands, and that small reefs occur offshore. What does the sand consist of, and what rock will it become if it eventually becomes buried and lithified?

SEE FOR YOURSELF F . . . Sedimentary Rocks

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet F of our **Geotours Workbook**.

Shallow marine environments, Red Sea, Egypt
Latitude 22°38′17.70″N,
Longitude 36°13′21.27″E

From 4 km, the desert sands of the Sahara abut the blue waters of the Red Sea. What types of sedimentary rocks would form if the sediments visible in this view were to be buried and preserved?



Alluvial fans and evaporites, Death Valley, California
Latitude 36°24′20.49″N,
Longitude 116°51′12.63″W
Elev. 1.5 km (oblique, looking east)

Death Valley is a narrow rift whose floor lies below sea level; from 1.5 km, you can see alluvial fans and white evaporites.

Murray River flood plain, Australia
Latitude 34°7′4.68″S,
Longitude 140°46′9.75″E

From 15 km, you see the Murray River meanders across the flat-lying landscape of South Australia. In this view, the water is restricted to the channel, exposing the sand and silt deposits that have covered its floodplain.

Grand Canyon, Arizona
Latitude 36° 8′8.94″N,
Longitude 112°15′48.56″W

Looking along the Grand Canyon, from 15 km above you can see the spectacular color banding caused by the succession of stratigraphic formations exposed on its walls. Some of these units are light gray limestone, some are tan sandstone, some are red shale.