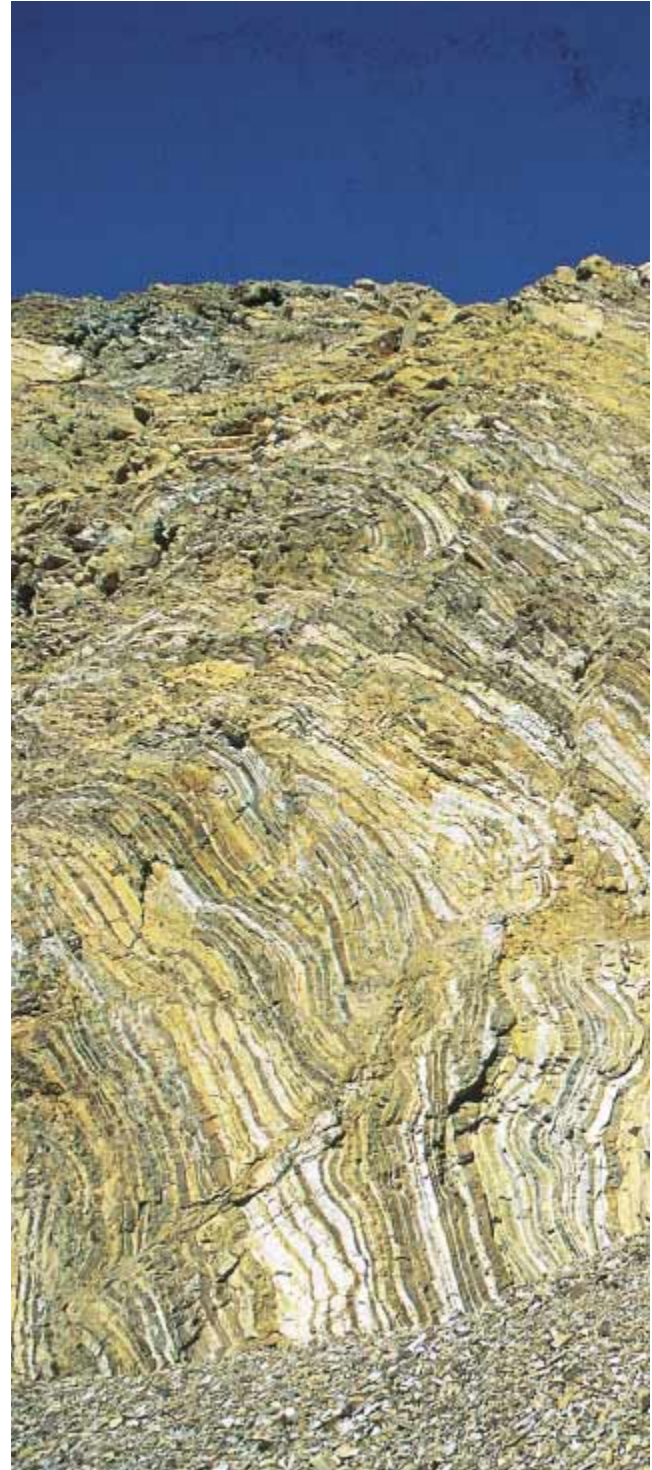


Geologic Structures, Mountain Ranges, and Continents

Mountains form some of the most majestic landscapes on Earth. People find peace in the high mountain air and quiet valleys. But mountains also project nature's power. Storms swirl among the silent peaks that were lifted skyward millions of years ago by tectonic processes. Rocks have been folded as if squeezed by a giant's hand. In the first portion of this chapter, we will study how rocks behave when tectonic forces stress them. In the second portion, we will learn how tectonic forces raise mountains.



Tectonic forces contorted these once-horizontal sedimentary rocks near Carlin, Nevada, into tight folds. (David Matherly/Visuals Unlimited)



Geologic Structures

► 12.1 ROCK DEFORMATION

STRESS

Recall from Chapter 10 that stress is a force exerted against an object. Tectonic forces exert different types of stress on rocks in different geologic environments. The first, called **confining stress** or **confining pressure**, occurs when rock or sediment is buried (Fig. 12–1a). Confining pressure merely compresses rocks but does not distort them, because the compressive force acts equally in all directions, like water pressure on a fish. As you learned in Chapter 7, burial pressure compacts sediment and is one step in the lithification of sedimentary rocks. Confining pressure also contributes to metamorphism during deep burial in sedimentary basins.

In contrast, **directed stress** acts most strongly in one direction. Tectonic processes create three types of directed stress. Compression squeezes rocks together in one direction. It frequently acts horizontally, shortening the distance parallel to the squeezing direction (Fig. 12–1b). **Compressive stress** is common in convergent plate boundaries, where two plates converge and the rock crumples, just as car fenders crumple during a head-on collision. **Extensional stress** (often called **tensional stress**) pulls rock apart and is the opposite of tectonic compression (Fig. 12–1c). Rocks at a divergent plate boundary stretch and pull apart because they are subject to extensional stress. **Shear stress** acts in parallel but opposite directions (Fig. 12–1d). Shearing deforms rock by causing one part of a rock mass to slide past the other part, as in a transform fault or a transform plate boundary.

STRAIN

Strain is the deformation produced by stress. As explained in Chapter 10, a rock responds to tectonic stress by elastic deformation, plastic deformation, or brittle fracture. An elastically deformed rock springs back to its original size and shape when the stress is removed. During plastic deformation, a rock deforms like putty and retains its new shape. In some cases a rock will deform plastically and then fracture (Fig. 12–2).

Factors That Control Rock Behavior

Several factors control whether a rock responds to stress by elastic or plastic deformation or fails by brittle fracture:

1. *The nature of the material.* Think of a quartz crystal, a gold nugget, and a rubber ball. If you strike quartz with a hammer, it shatters. That is, it fails by

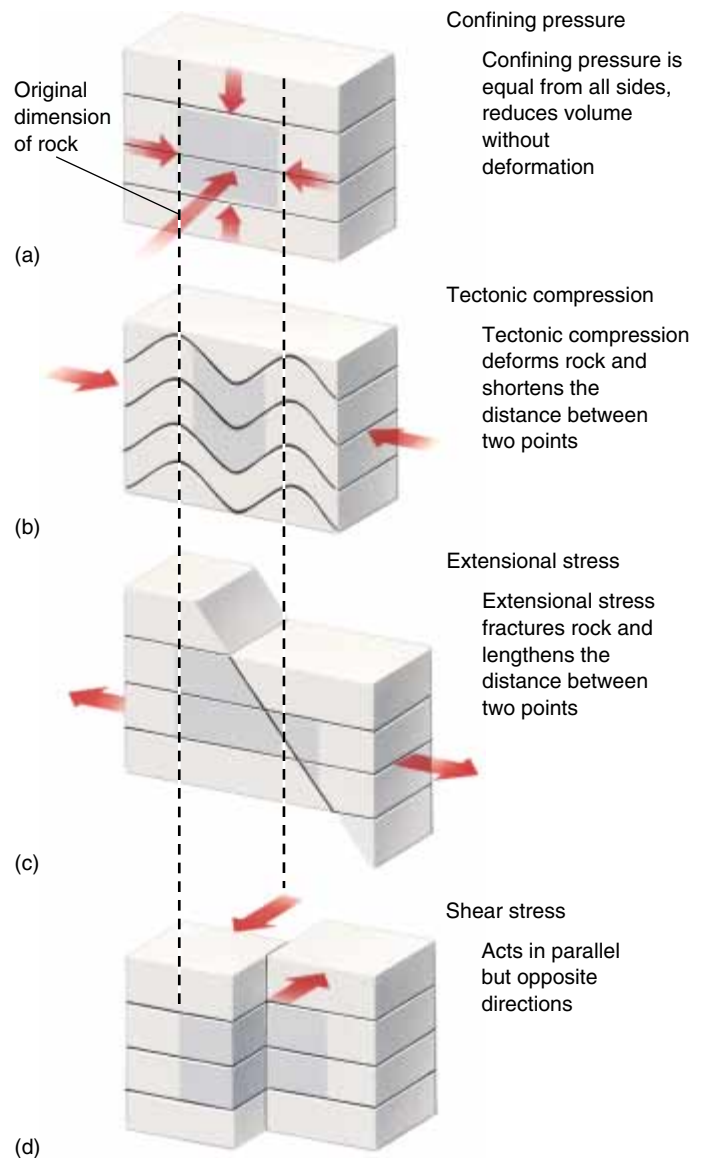


Figure 12–1 (a) Confining pressure acts equally on all sides of a rock. Thus, the rock is compressed much as a balloon is compressed if held under water. Rock volume decreases without deformation. (b) Tectonic compression shortens the distance parallel to the stress direction. Rocks fold or fracture to accommodate the shortening. (c) Extensional stress lengthens the distance parallel to the stress direction. Rocks commonly fracture to accommodate the stretching. (d) Shear stress deforms the rock parallel to the stress direction.

brittle fracture. In contrast, if you strike the gold nugget, it deforms in a plastic manner; it flattens and stays flat. If you hit the rubber ball, it deforms elastically and rebounds immediately, sending the hammer flying back at you. Initially, all rocks react to stress by deforming elastically. Near the Earth's



Figure 12-2 This rock (in the Nahanni River, Northwest Territories, Canada) folded plastically and then fractured.

surface, where temperature and pressure are low, different types of rocks behave differently with continuing stress. Granite and quartzite tend to behave in a brittle manner. Other rocks, such as shale, limestone, and marble, have greater tendencies to deform plastically.

2. **Temperature.** The higher the temperature, the greater the tendency of a rock to behave in a plastic manner. It is difficult to bend an iron bar at room temperature, but if the bar is heated in a forge, it becomes plastic and bends easily.
3. **Pressure.** High confining pressure also favors plastic behavior. During burial, both temperature and pressure increase. Both factors promote plastic deformation, so deeply buried rocks have a greater tendency to bend and flow than shallow rocks.
4. **Time.** Stress applied over a long time, rather than suddenly, also favors plastic behavior. Marble park benches in New York City have sagged plastically under their own weight within 100 years. In contrast, rapidly applied stress, such as the blow of a hammer, to a marble bench causes brittle fracture.

► 12.2 GEOLOGIC STRUCTURES

Enormous compressive forces can develop at a convergent plate boundary, bending and fracturing rocks in the tectonically active region. In some cases the forces deform rocks tens or even hundreds of kilometers from the plate boundary. Because the same tectonic processes create great mountain chains, rocks in mountainous regions are commonly broken and bent. Tectonic forces also deform rocks at divergent and transform plate boundaries.



Figure 12-3 A fold is a bend in rock. These are in quartzite in the Maria Mountains, California. (W. B. Hamilton, USGS)

A **geologic structure** is any feature produced by rock deformation. Tectonic forces create three types of geologic structures: folds, faults, and joints.

FOLDS

A **fold** is a bend in rock (Fig. 12-3). Some folded rocks display little or no fracturing, indicating that the rocks deformed in a plastic manner. In other cases, folding occurs by a combination of plastic deformation and brittle fracture. Folds formed in this manner exhibit many tiny fractures.

If you hold a sheet of clay between your hands and exert compressive stress, the clay deforms into a sequence of folds (Fig. 12-4). This demonstration illustrates three characteristics of folds:



Figure 12-4 Clay deforms into a sequence of folds when compressed.

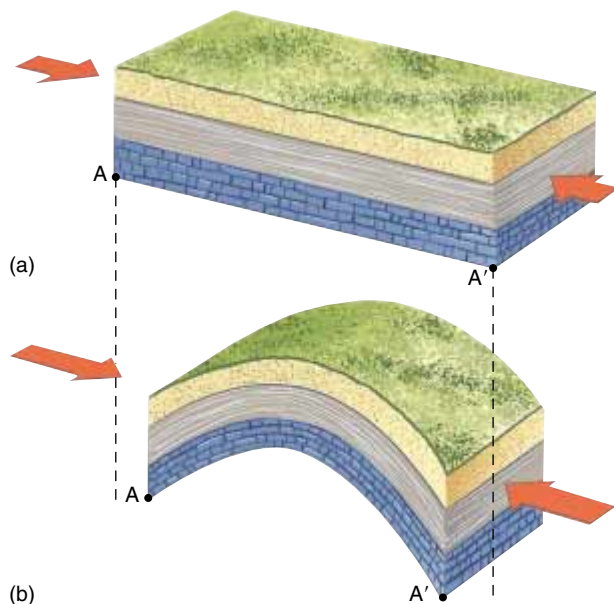
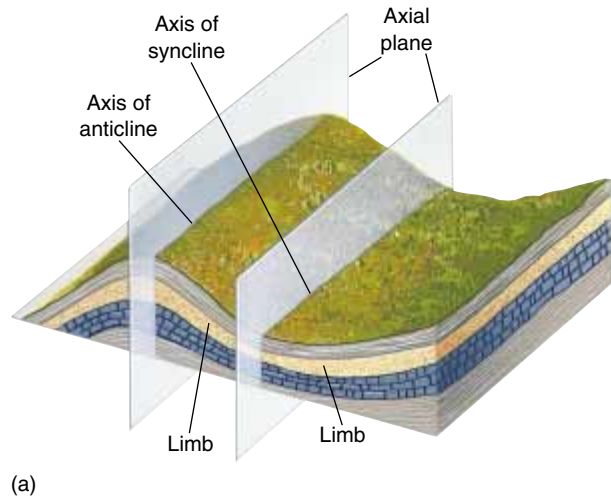


Figure 12-5 (a) Horizontally layered sedimentary rocks. (b) A fold in the same rocks. The forces that folded the rocks are shown by the arrows. Notice that points A and A' are closer after folding.

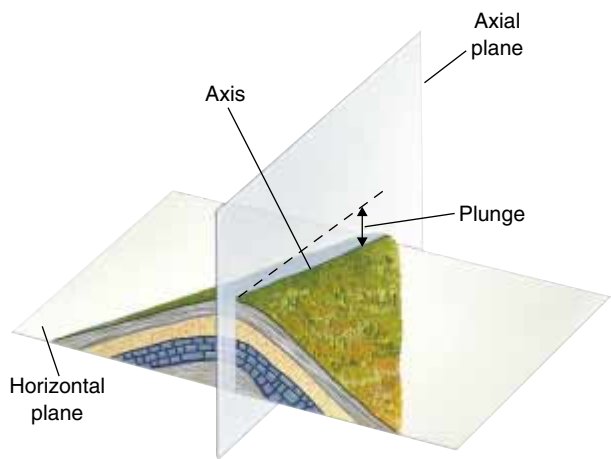
1. Folding usually results from compressive stress. For example, tightly folded rocks in the Himalayas indicate that the region was subjected to compressive stress.
2. Folding always shortens the horizontal distances in rock. Notice in Figure 12-5 that the distance between two points, A and A', is shorter in the folded rock than it was before folding.
3. Folds usually occur as a repeating pattern of many folds as in the illustration using clay.

Figure 12-6 shows that a fold arching upward is called an **anticline** and one arching downward is a **syncline**.¹ The sides of a fold are called the **limbs**. Notice that a single limb is shared by an anticline-syncline pair. A line dividing the two limbs of a fold and running along the crest of an anticline or the trough of a syncline is the fold **axis**. The **axial plane** is an imaginary plane that runs through the axis and divides a fold as symmetrically as possible into two halves.

In many folds, the axis is horizontal, as shown in Figure 12-6a. If you were to walk along the axis of a



(a)



(b)



(c)

Figure 12-6 (a) An anticline, a syncline, and the parts of a fold. (b) A plunging anticline. (c) A syncline in southern Nevada.

¹Properly, an upward-arched fold is called an anticline only if the oldest rocks are in the center and the youngest are on the outside of the fold. Similarly, a downward-arched fold is a syncline only if the youngest rocks are at the center and the oldest are on the outside. The age relationships become reversed if the rocks are turned completely upside down and folded. If the age relationships are unknown, as sometimes occurs, an upward-arched fold is called an *antiform*, and a downward-arched one is called a *synform*.



Figure 12-7 A syncline lies beneath the mountain peak and an anticline forms the low point, or saddle, in the Canadian Rockies, Alberta.

horizontal anticline, you would be walking on a level ridge. In other folds, the axis is inclined or tipped at an angle called the **plunge**, as shown in Figure 12-6b. A fold with a plunging axis is called a **plunging fold**. If you were to walk along the axis of a plunging fold, you would be traveling uphill or downhill along the axis.

Even though an anticline is structurally a high point in a fold, anticlines do not always form topographic

ridges. Conversely, synclines do not always form valleys. Landforms are created by combinations of tectonic and surface processes. In Figure 12-7, the syncline lies beneath the peak and the anticline forms the saddle between two peaks.

Figure 12-8 summarizes the characteristics of five common types of folds. A special type of fold with only one limb is a **monocline**. Figure 12-9 shows a monocline

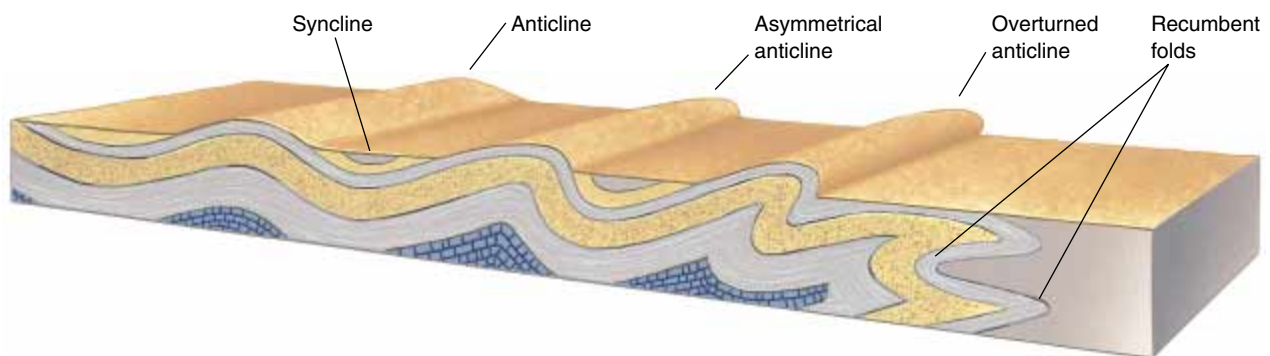
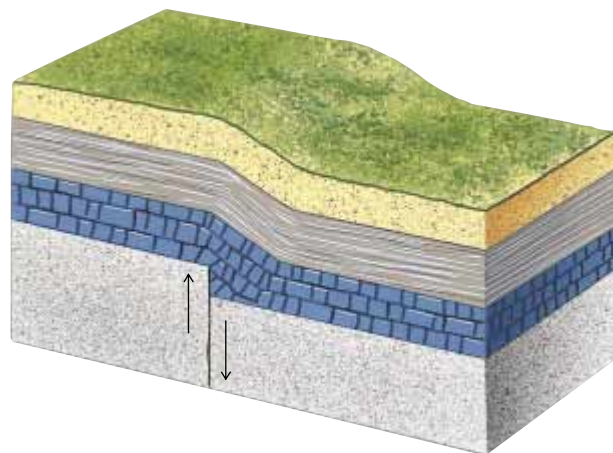


Figure 12-8 Cross-sectional view of five different kinds of folds. Folds can be symmetrical, as shown on the left, or asymmetrical, as shown in the center. If a fold has tilted beyond the perpendicular, it is overturned.



(a)



(b)

Figure 12-9 (a) A monocline formed where near-surface sedimentary rocks sag over a fault. (b) A monocline in southern Utah.

that developed where sedimentary rocks sag over an underlying fault.

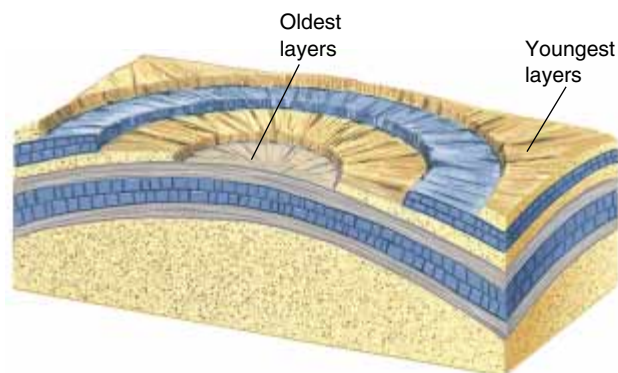
A circular or elliptical anticlinal structure is called a **dome**. Domes resemble inverted bowls. Sedimentary layering dips away from the center of a dome in all directions (Fig. 12-10). A similarly shaped syncline is called a **basin**. Domes and basins can be small structures only a few kilometers in diameter or less. Frequently, however, they are very large and are caused by broad upward or downward movement of the continental crust. The Black Hills of South Dakota are a large structural dome. The Michigan basin covers much of the state of Michigan, and the Williston basin covers much of eastern Montana, northeastern Wyoming, the western Dakotas, and southern Alberta and Saskatchewan.

Although most folds form by compression, less commonly, crustal extension can also fold rocks. Figure 12-11 shows a block of rock that dropped down along a curved fault as the crust pulled apart. The block developed a syncline as it rotated and deformed while sliding downward. Folds formed by extension are usually broad, open folds in contrast to tight folds commonly formed by compression.

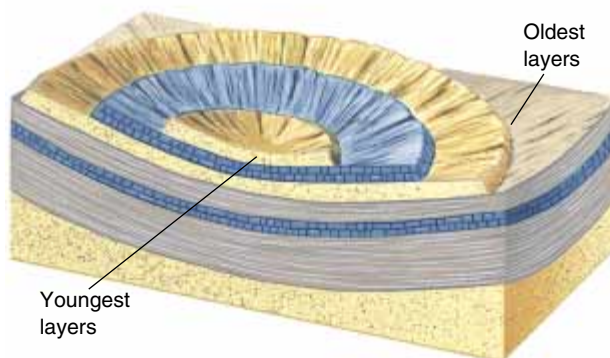
FAULTS

A **fault** is a fracture along which rock on one side has moved relative to rock on the other side (Fig. 12-12). **Slip** is the distance that rocks on opposite sides of a fault have moved. Movement along a fault may be gradual, or the rock may move suddenly, generating an earthquake. Some faults are a single fracture in rock; others consist of numerous closely spaced fractures called a **fault zone** (Fig. 12-13). Rock may slide hundreds of meters or many kilometers along a large fault zone.

Rock moves repeatedly along many faults and fault zones for two reasons: (1) Tectonic forces commonly persist in the same place over long periods of time (for example, at a tectonic plate boundary), and (2) once a fault forms, it is easier for movement to occur again



(a) Dome



(b) Basin

Figure 12-10 (a) Sedimentary layering dips away from a dome in all directions, and the outcrop pattern is circular or elliptical. (b) Layers dip toward the center of a basin.

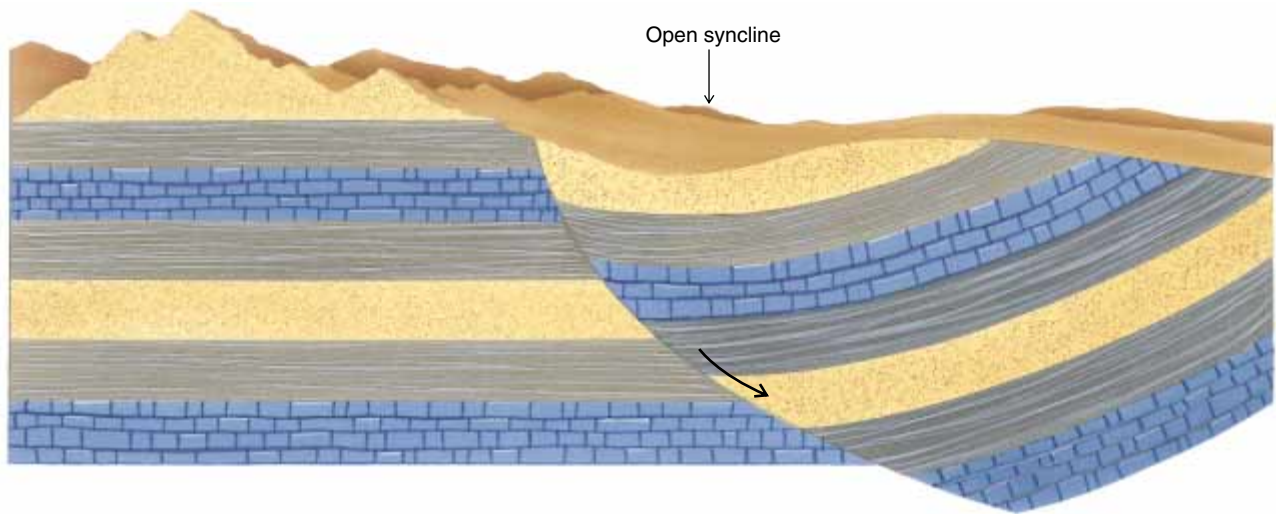


Figure 12-11 Folds can form by crustal extension. A syncline has developed in a down-dropped block of sedimentary rock as it slid down and rotated along a curved normal fault.



Figure 12-12 A small fault has dropped the right side of these volcanic ash layers downward about 60 centimeters relative to the left side. (Ward's Natural Science Establishment, Inc.)

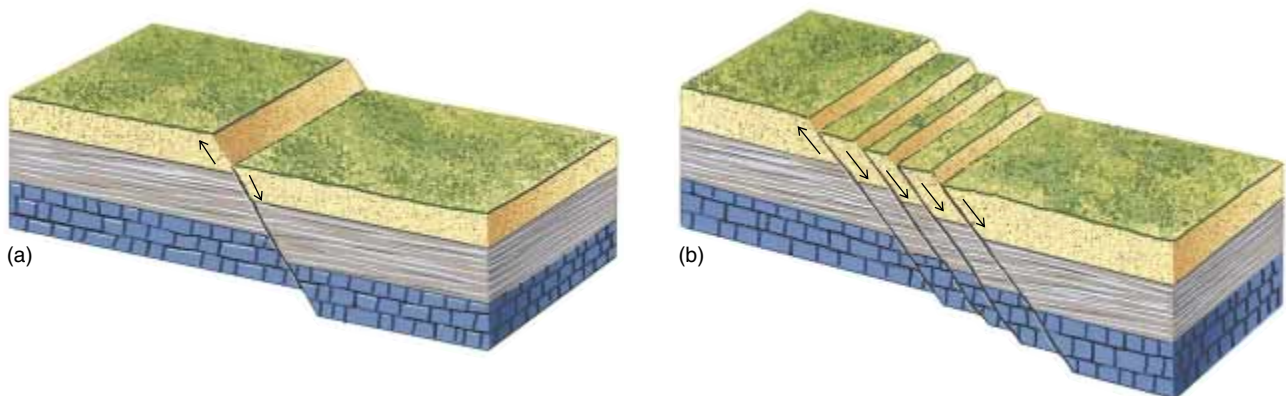


Figure 12-13 (a) Movement along a single fracture surface characterizes faults with relatively small slip. (b) Movement along numerous closely spaced faults in a fault zone is typical of faults with large slip.

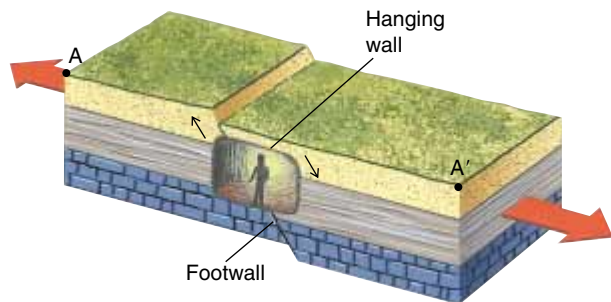


Figure 12-14 A normal fault accommodates extension of the Earth's crust. Large arrows show extensional stress direction. The overlying side of the fault is called the hanging wall, and the side beneath the fault is the footwall.

along the same fracture than for a new fracture to develop nearby.

Hydrothermal solutions often precipitate in faults to form rich ore veins. Miners then dig shafts and tunnels along veins to get the ore. Many faults are not vertical but dip into the Earth at an angle. Therefore, many veins have an upper side and a lower side. Miners referred to the side that hung over their heads as the **hanging wall** and the side they walked on as the **footwall**. These names are commonly used to describe both ore veins and faults (Fig. 12-14).

A fault in which the hanging wall has moved down relative to the footwall is called a **normal fault**. Notice that the horizontal distance between points on opposite sides of the fault, such as A and A' in Figure 12-14, is greater after normal faulting occurs. Hence, a normal fault forms where tectonic tension stretches the Earth's crust, pulling it apart.

Figure 12-15 shows a wedge-shaped block of rock called a **graben** dropped downward between a pair of normal faults. The word *graben* comes from the German word for “grave” (think of a large block of rock settling downward into a grave). If tectonic forces stretch the crust over a large area, many normal faults may develop, allowing numerous grabens to settle downward between the faults. The blocks of rock between the downdropped grabens then appear to have moved upward relative to the grabens; they are called **horsts**.

Normal faults, grabens, and horsts are common where the crust is rifting at a spreading center, such as the mid-oceanic ridge and the East African rift zone. They are also common where tectonic forces stretch a single plate, as in the Basin and Range of Utah, Nevada, and adjacent parts of western North America.

In a region where tectonic forces squeeze the crust, geologic structures must accommodate crustal shortening. A fold accomplishes shortening. A **reverse fault** is another structure that accommodates shortening (Fig. 12-16). In a reverse fault, the hanging wall has moved up relative to the footwall. The distance between points A and A' is shortened by the faulting.

A **thrust fault** is a special type of reverse fault that is nearly horizontal (Fig. 12-17). In some thrust faults, the rocks of the hanging wall have moved many kilometers over the footwall. For example, all of the rocks of Glacier National Park in northwestern Montana slid 50 to 100 kilometers eastward along a thrust fault to their present location. This thrust is one of many that formed from about 180 to 45 million years ago as compressive tectonic forces built the mountains of western North America. Most of those thrusts moved large slabs of rock, some even larger than that of Glacier Park, from west to east in a zone reaching from Alaska to Mexico.

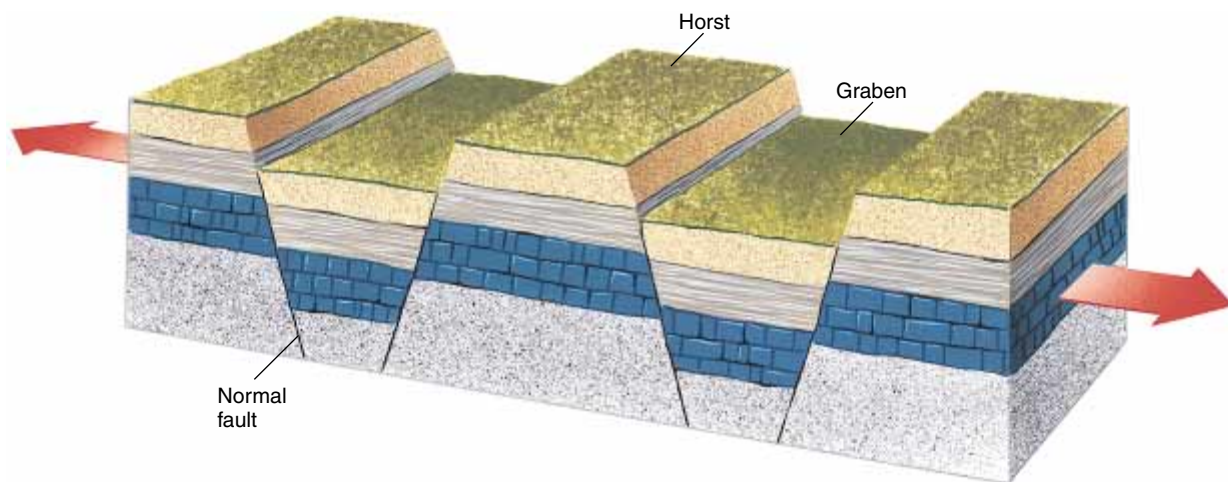
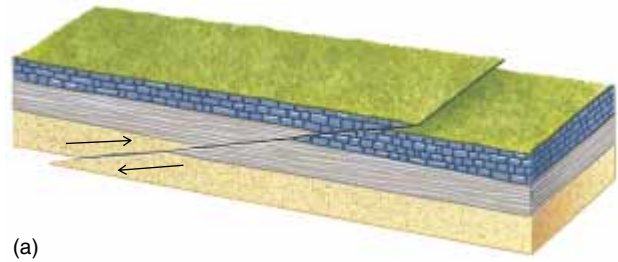
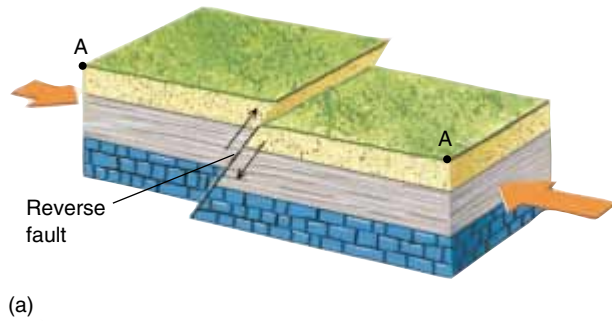


Figure 12-15 Horsts and grabens commonly form where tectonic forces stretch the Earth's crust.



(b)

Figure 12-17 (a) A thrust fault is a low-angle reverse fault. (b) A small thrust fault near Flagstaff, Arizona. (Ward's Natural Science Establishment, Inc.)

Figure 12-16 (a) A reverse fault accommodates crustal shortening and reflects squeezing of the crust, shown by large arrows. (b) A small reverse fault in Zion National Park, Utah.

A **strike-slip fault** is one in which the fracture is vertical, or nearly so, and rocks on opposite sides of the fracture move horizontally past each other (Fig. 12-18). A transform plate boundary is a strike-slip fault. As explained previously, the famous San Andreas fault zone is a zone of strike-slip faults that form the border between the Pacific plate and the North American plate.

JOINTS

A **joint** is a fracture in rock and is therefore similar to a fault, except that in a joint rocks on either side of the fracture have not moved. We have already discussed columnar joints in basalt (Chapter 5) and jointing caused

by unloading and exfoliation (Chapter 6). Tectonic forces also fracture rock to form joints (Fig. 12-19). Most rocks near the Earth's surface are jointed, but joints become less abundant with depth because rocks become more plastic at deeper levels in the crust.

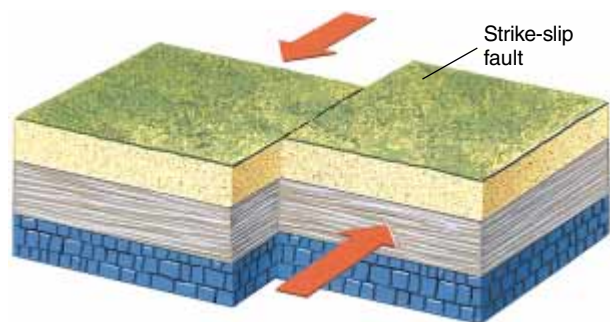


Figure 12-18 A strike-slip fault is nearly vertical, but movement along the fault is horizontal. The large arrows show direction of movement.

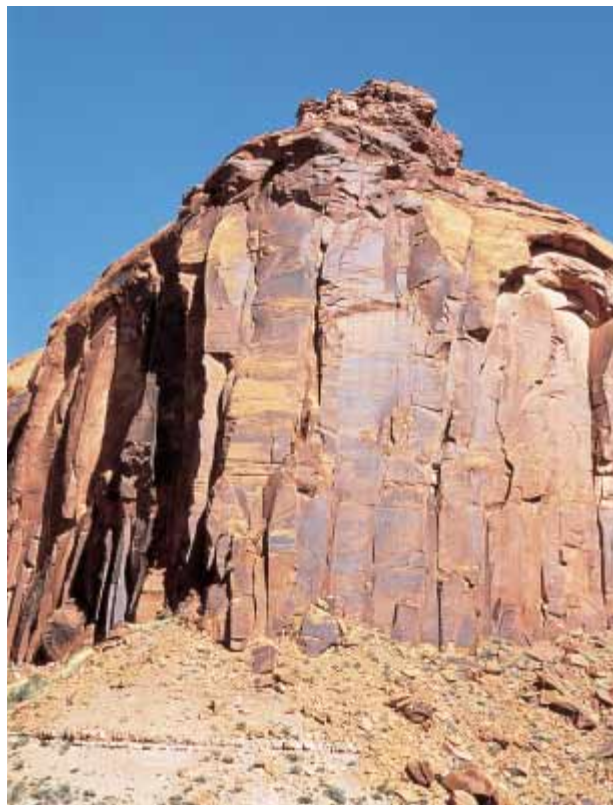


Figure 12-19 Joints, such as those in this sandstone along the Escalante River in Utah, are fractures along which the rock has not slipped.

Joints and faults are important in engineering, mining, and quarrying because they are planes of weakness in otherwise strong rock. A dam constructed in jointed rock often leaks, not because the dam has a hole but because water follows the fractures and seeps around the dam. You can commonly see seepage caused by such leaks in the walls of a canyon downstream from a dam.

Strike and Dip

Faults, joints, sedimentary beds, slaty cleavage, and a wide range of other geologic features are planar surfaces in rock. Field geologists describe the orientations of sedimentary beds or other planes with two measurements called **strike** and **dip**. To understand these concepts, recall from elementary geometry that two planes intersect in a straight line. Strike is the compass direction of the line produced by the intersection of a tilted rock or structure with a horizontal plane. For example, if the line runs exactly north–south, the strike is 0° (you could also call it 180°). If the line points east, the strike is 90° . Dip is the angle of inclination of the tilted layer, also measured from the horizontal plane. In Figure 12-20 the dip is 45° .

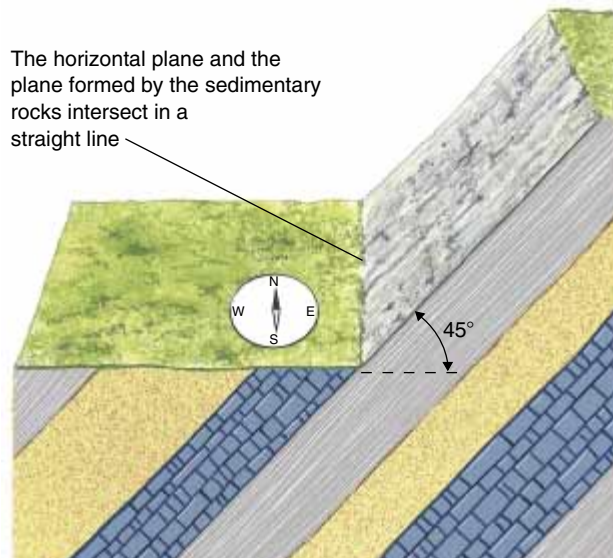


Figure 12-20 Strike is the compass direction of the intersection of a horizontal plane with a sedimentary bed or other planar feature in rock. Dip is the angle between a horizontal plane and the layering.

GEOLOGIC STRUCTURES AND PLATE BOUNDARIES

Each of the three different types of plate boundaries produces different tectonic stresses and therefore different kinds of structures. Extensional stress at a divergent boundary (mid-oceanic ridges and continental rift boundaries) produces normal faults, and sometimes grabens, but little or no folding of rocks.

Where a transform boundary crosses continental crust, shear stress bends and fractures rock. Frictional drag between both sides of the fault may fold, fault, and uplift nearby rocks. Forces of this type have formed the San Gabriel Mountains along the San Andreas fault zone, as well as mountain ranges north of the Himalayas.

In contrast, compressive stress commonly dominates a convergent plate boundary. The compression produces folds, reverse faults, and thrust faults. These structures are common features of many mountain ranges formed at convergent plate boundaries. For example, subduction along the west coast of North America formed extensive regions of folded and thrust-faulted rocks in the western mountains. Similar structures are common in the Appalachian Mountains of eastern North America (Fig. 12-21), the Alps, and the Himalayas, all of which formed as the result of continent–continent collisions.

Although plate convergence commonly creates compressive stress, in some instances crustal extension and normal faulting are common. The Andes of western South America formed, and continue to grow today, by subduction of the Nazca plate beneath the western edge of



Figure 12-21 These sedimentary rocks in New Jersey were folded during the Appalachian orogeny. (Breck P. Kent)

the South American plate. The two plates are converging, yet large grabens west of the mountains reflect crustal extension.

Mountain Ranges and Continents

► 12.3 MOUNTAINS AND MOUNTAIN RANGES

MOUNTAIN-BUILDING PROCESSES

Mountains grow along each of the three types of tectonic plate boundaries. As you learned in Chapter 11, the world's largest mountain chain, the mid-oceanic ridge, formed at divergent plate boundaries beneath the ocean. Mountain ranges also originate at divergent plate boundaries on land. Mount Kilimanjaro and Mount Kenya, two volcanic peaks near the equator, lie along the East African rift. Other ranges, such as the San Gabriel Mountains of California, form at transform plate boundaries. However, the great continental mountain chains, including the Andes, Appalachians, Alps, Himalayas, and Rockies, all rose at convergent plate boundaries. Folding and faulting of rocks, earthquakes, volcanic eruptions, intrusion of plutons, and metamorphism all occur at a convergent plate boundary. The term **orogeny** refers to the process of mountain building and includes all of these activities.

Because plate boundaries are linear, mountains most commonly occur as long, linear, or slightly curved ranges and chains. For example, the Andes extend in a narrow band along the west coast of South America, and the Appalachians form a linear uplift along the east coast of North America.

Several processes thicken continental crust as tectonic forces build a mountain range. A subducting slab

generates magma, which cools within the crust to form plutons or rises to the surface to form volcanic peaks. Both the plutons and volcanic rocks thicken the continental crust over a subduction zone by adding new material to it. In addition, the magmatic activity heats the lithosphere in the region above the subduction zone, causing it to become less dense and to rise isostatically. In a region where two continents collide, one continent may be forced beneath the other. This process, called **underthrusting**, can double the thickness of continental crust in the collision zone. Finally, compressive forces fold and crumple rock, squeezing the continent and increasing its thickness. Thus, addition of magma, heating, underthrusting, and folding all combine to thicken continental crust and lithosphere. As they thicken, the surface of the continent rises isostatically to form a mountain chain.

Opposing forces act on a rising mountain chain; the processes just described may continue to raise the mountains at the same time that other processes lower the peaks (Fig. 12-22). As a mountain chain grows higher and heavier, eventually the underlying rocks cannot support the weight of the mountains. The crustal rocks and

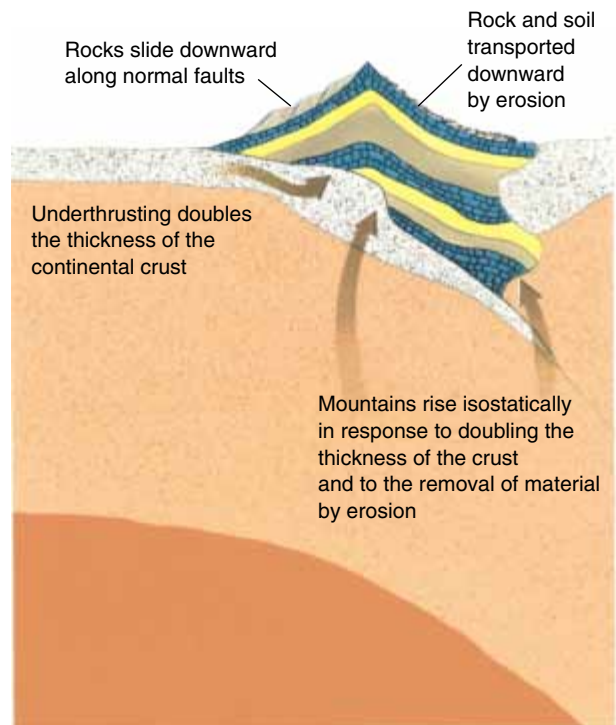


Figure 12-22 Several factors affect the height of a mountain range. Today the Himalayas are being uplifted by continued underthrusting. At the same time, erosion removes the tops of the peaks, and the sides of the range slip downward along normal faults. As these processes remove weight from the range, the mountains rise by isostatic adjustment.

underlying lithosphere become so plastic that they flow outward from beneath the mountains. As an analogy, consider pouring cold honey onto a table top. At first, the honey piles up into a high, steep mound, but soon it begins to flow outward under its own weight, lowering the top of the mound.

Streams, glaciers, and landslides erode the peaks as they rise, carrying the sediment into adjacent valleys. When rock and sediment erode, the mountain becomes lighter and rises isostatically, just as a canoe rises when you step out of it. Eventually, however, the mountains erode away completely. The Appalachians are an old range where erosion is now wearing away the remains of peaks that may once have been the size of the Himalayas.

With this background, let us look at mountain building in three types of convergent plate boundaries.

► 12.4 ISLAND ARCS: MOUNTAIN BUILDING DURING CONVERGENCE BETWEEN TWO OCEANIC PLATES

As described in Chapter 11, an island arc is a volcanic mountain chain formed at an oceanic subduction zone. During subduction, one of the plates dives into the mantle, forming an oceanic trench and generating magma. This magma rises to the sea floor, where it erupts to

build submarine volcanoes. These volcanoes may eventually grow above sea level, creating an arc-shaped volcanic island chain next to the trench.

A layer of sediment a half kilometer or more thick commonly covers the basaltic crust of the deep sea floor. Some of the sediment is scraped from the subducting slab and jammed against the inner wall (the wall toward the island arc) of the trench. Occasionally, slices of rock from the oceanic crust, and even pieces of the upper mantle, are scraped off and mixed in with the sea-floor sediment. The process is like a bulldozer scraping soil from bedrock and occasionally knocking off a chunk of bedrock along with the soil. The bulldozer process folds, shears, and faults sediment and rock. The rocks added to the island arc in this way are called a **subduction complex** (Fig. 12–23).

Growth of the subduction complex occurs by addition of the newest slices at the bottom of the complex. Consequently, this underthrusting forces the subduction complex upward, forming a sedimentary basin called a **forearc basin** between the subduction complex and the island arc. This process is similar to holding a flexible notebook horizontally between your two hands. If you move your hands closer together, the middle of the notebook bends downward to form a topographic depression analogous to a forearc basin. In addition, underthrusting thickens the crust, leading to isostatic uplift. The forearc

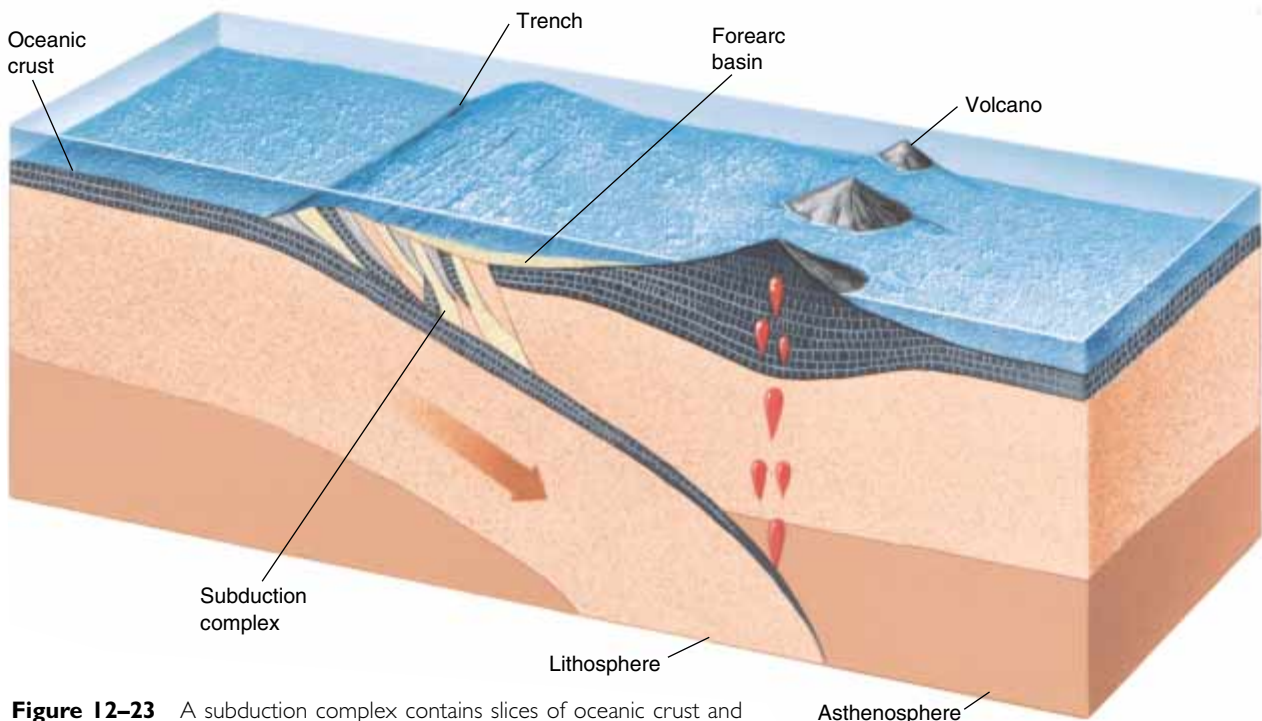


Figure 12–23 A subduction complex contains slices of oceanic crust and upper mantle scraped from the upper layers of a subducting plate.



Figure 12–24 The Cordillera Apolobamba in Bolivia rises over 6000 meters.

basin fills with sediment derived from erosion of the volcanic islands and also becomes a part of the island arc.

Island arcs are abundant in the Pacific Ocean, where convergence of oceanic plates is common. The western Aleutian Islands and most of the island chains of the southwestern Pacific are island arcs.

► 12.5 THE ANDES: SUBDUCTION AT A CONTINENTAL MARGIN

The Andes are the world's second highest mountain chain, with 49 peaks above 6000 meters (nearly 20,000 feet) (Fig. 12–24). The highest peak is Aconcagua, at 6962 meters. The Andes rise almost immediately from the Pacific coast of South America and thus start nearly at sea level. Igneous rocks make up most of the Andes, although the chain also contains folded sedimentary rocks, especially in the eastern foothills.

The supercontinent that Alfred Wegener called Pangea broke apart at the end of the Triassic Period. In the early Jurassic, the lithospheric plate that included South America started moving westward. To accommodate the westward motion, oceanic lithosphere began to dive into the mantle beneath the west coast of South America, forming a subduction zone by early Cretaceous time, 140 million years ago (Fig. 12–25a).

By 130 million years ago, vast amounts of basaltic magma were forming (Fig. 12–25b). Some of this magma rose to the surface to cause volcanic eruptions. Most of the remainder melted portions of the lower crust to form andesitic and granitic magma, as explained in Chapter 4.

This intrusive and volcanic activity occurred along the entire length of western South America, but in a band only a few tens of kilometers wide, directly over the zone of melting. As the oceanic plate sank beneath the continent, slices of sea-floor mud and rock were scraped from the subducting plate, forming a subduction complex similar to that of an island arc.

The rising magma heated and thickened the crust beneath the Andes, causing it to rise isostatically and form great peaks. When the peaks became sufficiently high and heavy, the weak, soft rock oozed outward under its own weight. This spreading formed a great belt of thrust faults and folds along the east side of the Andes (Fig. 12–25c).

The Andes, then, are a relatively narrow mountain chain consisting predominantly of igneous rocks formed by subduction at a continental margin. The chain also contains extensive sedimentary rocks on both sides of the mountains; these rocks formed from sediment eroded from the rising peaks. The Andes are a good general example of subduction at a continental margin, and this type of plate margin is called an **Andean margin**.

► 12.6 THE HIMALAYAN MOUNTAIN CHAIN: A COLLISION BETWEEN CONTINENTS

The world's highest mountain chain, the Himalayas, separates China from India and includes the world's highest peaks, Mount Everest and K2 (Fig. 12–26). If you were

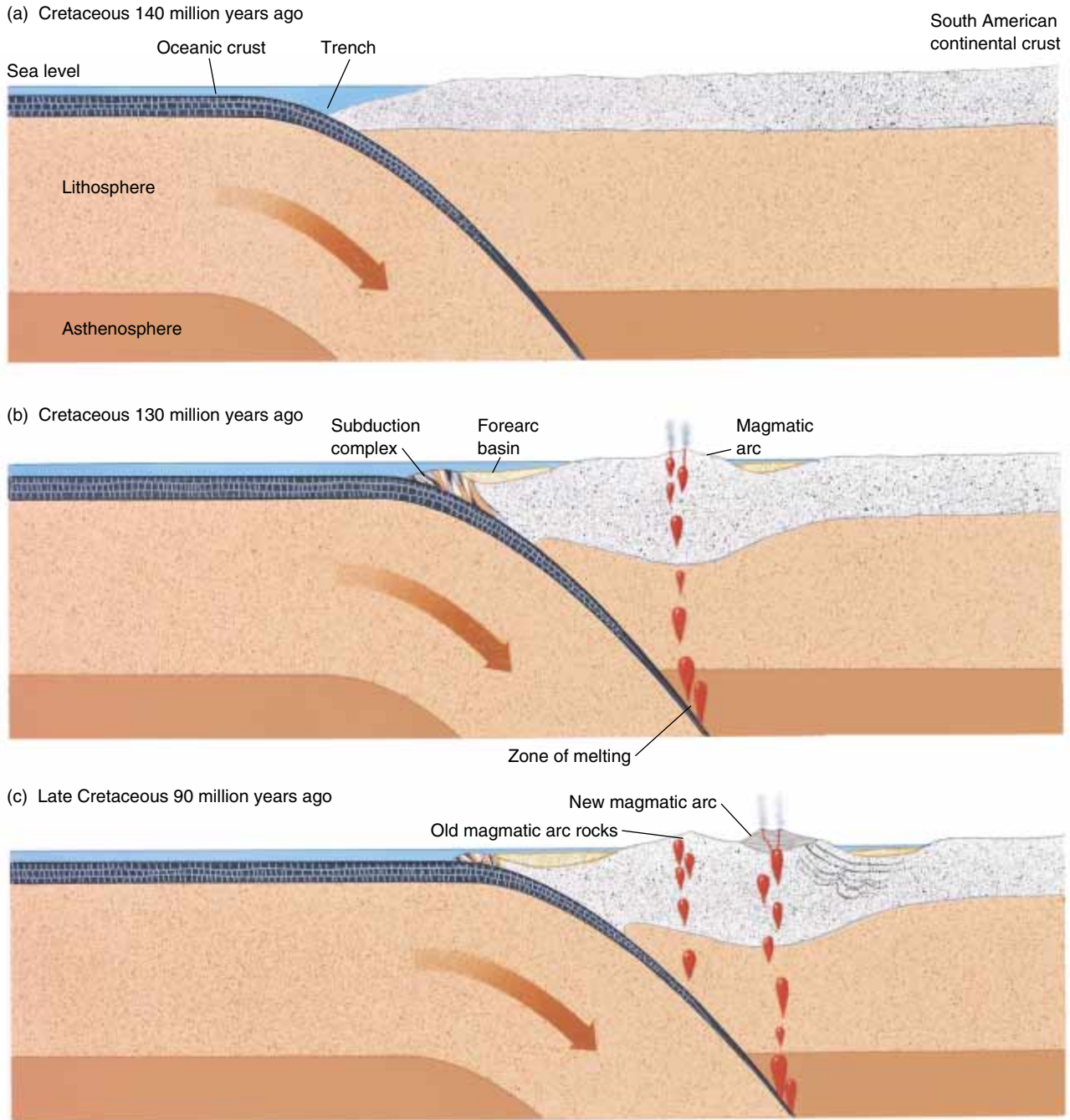


Figure 12-25 Development of the Andes, seen in cross section looking northward. (a) As the South American lithospheric plate moved westward in early Cretaceous time, about 140 million years ago, a subduction zone and a trench formed at the west coast of the continent. (b) By 130 million years ago, igneous activity began and a subduction complex and forearc basin formed. (c) In late Cretaceous time, the trench and region of igneous activity had both migrated eastward. Old volcanoes became dormant and new ones formed to the east.

to stand on the southern edge of the Tibetan Plateau and look southward, you would see the high peaks of the Himalayas. Beyond this great mountain chain lie the rainforests and hot, dry plains of the Indian subconti-

nent. If you had been able to stand in the same place 100 million years ago and look southward, you would have seen only ocean. At that time, India was located south of the equator, separated from Tibet by thousands of kilo-

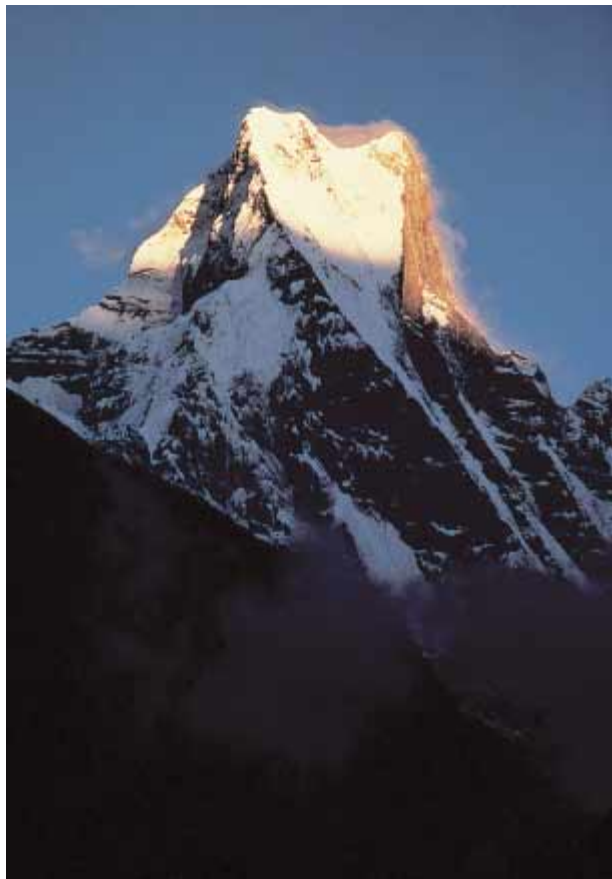


Figure 12–26 Machapuchare is a holy mountain in Nepal.

meters of open ocean. The Himalayas had not yet begun to rise.

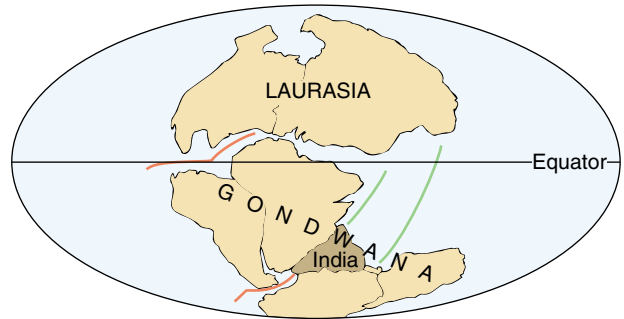
FORMATION OF AN ANDEAN-TYPE MARGIN

About 120 million years ago, a triangular piece of lithosphere that included India split off from a large mass of continental crust near the South Pole. It began drifting northward toward Asia at a high speed, geologically speaking—perhaps as fast as 20 centimeters per year (Fig. 12–27a). As the Indian plate started to move, oceanic crust sank beneath Asia’s southern margin, forming a subduction zone (Fig. 12–28b). As a result, volcanoes erupted, and granite plutons rose into southern Tibet. At this point, southern Tibet was an Andean-type continental margin, and it continued to be so from about 120 to 55 million years ago, while India drew closer to Asia.

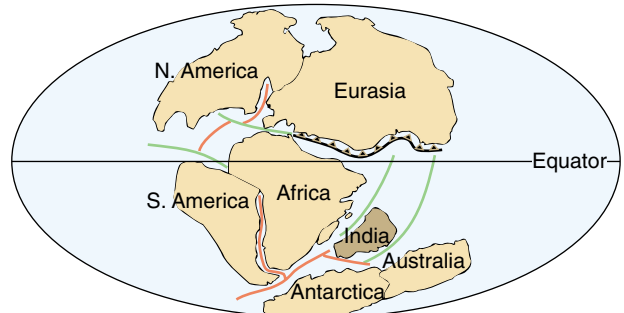
CONTINENT–CONTINENT COLLISION

By about 55 million years ago, subduction had consumed all of the oceanic lithosphere between India and Asia (Fig. 12–28c). Then the two continents collided. Because both are continental crust, neither could sink deeply into the mantle. Igneous activity then ceased because subduction had stopped. The collision did not stop the northward movement of India, but it did slow it down to about 5 centimeters per year.

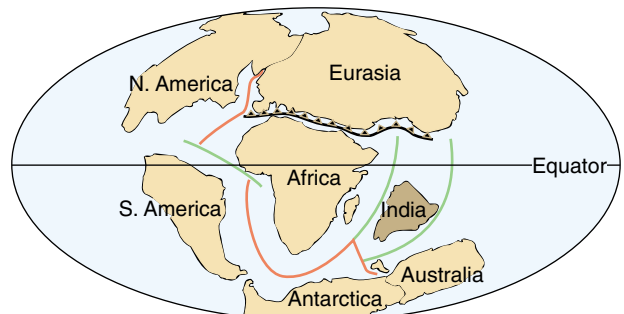
Continued northward movement of India was accommodated in two ways. The leading edge of India



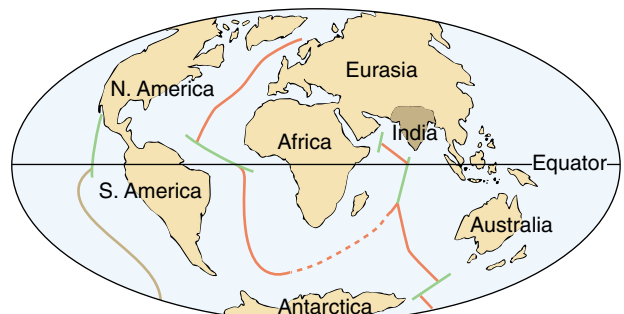
(a) 200 million years ago



(b) 120 million years ago



(c) 80 million years ago



(d) 40 million years ago

Figure 12–27 (a) Gondwanaland and Laurasia formed shortly after 200 million years ago as a result of the early breakup of Pangea. Notice that India was initially part of Gondwanaland. (b) About 120 million years ago, India broke off from Gondwanaland and began drifting northward. (c) By 80 million years ago, India was isolated from other continents and was approaching the equator: (d) By 40 million years ago, it had moved 4000 to 5000 kilometers northward and collided with Asia.

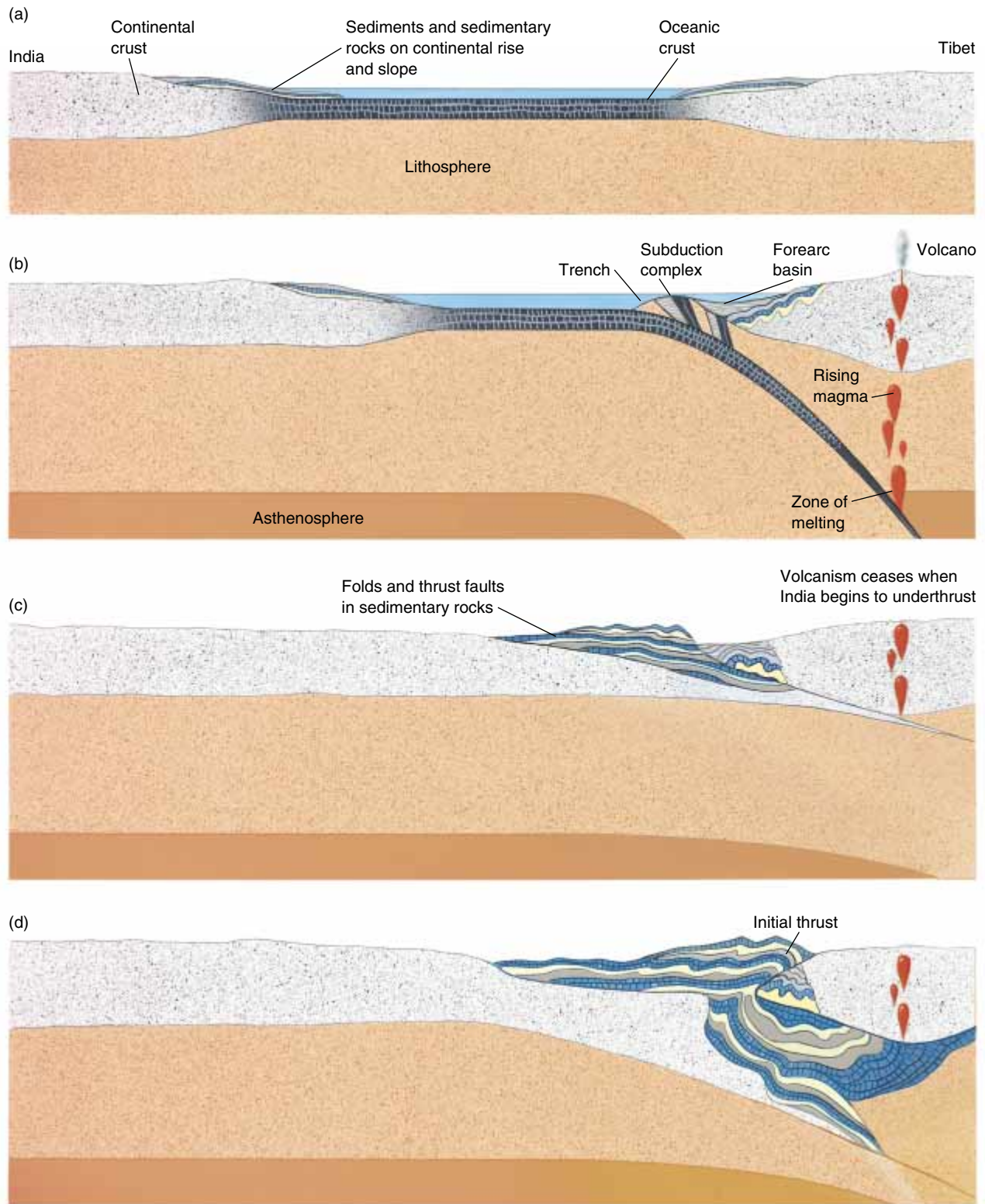


Figure 12-28 These cross-sectional views show the Indian and Asian plates before and during the collision between India and Asia. (a) Shortly before 120 million years ago, India, southern Asia, and the intervening ocean basin were parts of the same lithospheric plate. (In this figure, the amount of oceanic crust between Indian and Asian continental crust is abbreviated to fit the diagram on the page.) (b) When India began moving northward, the plate broke and subduction began at the southern margin of Asia. By 80 million years ago, an oceanic

trench and subduction complex had formed. Volcanoes erupted, and granite plutons formed in the region now called Tibet. (c) By 40 million years ago, India had collided with Tibet. The leading edge of India was underthrust beneath southern Tibet. (d) Continued underthrusting and collision between the two continents has crushed Tibet and created the high Himalayas by folding and thrust faulting the sedimentary rocks. India continues to underthrust and crush Tibet today.

began to underthrust beneath Tibet. As a result, the thickness of continental crust in the region doubled. Thick piles of sediment that had accumulated on India's northern continental shelf were scraped from harder basement rock as India slid beneath Tibet. These sediments were pushed into folds and thrust faults (Fig. 12–28d). Some of the deeper thrusts extend downward into the basement rocks.

The second way in which India continued moving northward was by crushing Tibet and wedging China out of the way along huge strike-slip faults. India has pushed southern Tibet 1500 to 2000 kilometers northward since the beginning of the collision. These compressional forces have created major mountain ranges and basins north of the Himalayas.

THE HIMALAYAS TODAY

Today, the Himalayas contain igneous, sedimentary, and metamorphic rocks (Fig. 12–29). Many of the sedimentary rocks contain fossils of shallow-dwelling marine organisms that lived in the shallow sea of the Indian continental shelf. Plutonic and volcanic Himalayan rocks

formed when the range was an Andean margin. Rocks of all types were metamorphosed by the tremendous stresses and heat generated during the mountain building process.

The underthrusting of India beneath Tibet and the squashing of Tibet have greatly thickened continental crust and lithosphere under the Himalayas and the Tibetan Plateau to the north. Consequently, the region floats isostatically at high elevation. Even the valleys lie at elevations of 3000 to 4000 meters, and the Tibetan Plateau has an average elevation of 4000 to 5000 meters. One reason the Himalayas contain all of the Earth's highest peaks is simply that the entire plateau lies at such a high elevation. From the valley floor to the summit, Mount Everest is actually smaller than Alaska's Denali (Mount McKinley), North America's highest peak. Mount Everest rises about 3300 meters from base to summit, whereas Denali rises about 4200 meters. The difference in elevation of the two peaks lies in the fact that the base of Mount Everest is at about 5500 meters, but Denali's base is at 2000 meters.

Comparisons of older surveys with newer ones show that the tops of some Himalayan peaks are now rising rapidly—perhaps as fast as 1 centimeter per year. If this



Figure 12–29 Wildly folded sedimentary rocks on the Nuptse–Lhotse Wall from an elevation of 7600 meters on Mount Everest. (Galen Rowell/Mountain Light)

rate were to continue, Mount Everest would double its height in about 1 million years, a short time compared with many other geologic events. However, normal faulting throughout the range is evidence that the mountains are oozing outward at the same time that they are rising. If the newly formed, steep mound of honey discussed earlier were covered with a layer of brittle chocolate frosting, the frosting would crack and slip apart in normal faults as the honey spread outward. The upper few kilometers of rocks of a rapidly rising mountain chain such as the Himalayas are like the frosting, and normal faulting is common in such regions. As blocks of rock slide off the mountains, they compress adjacent rock near the margins of the chain. In this way, normal faults in one region frequently form thrust faults and folds in a nearby region. But, at the same time, tectonic forces resulting from the continent–continent collision continue to push the mountains upward. No one knows when India will stop its northward movement or how high the mountains will become. However, we are certain that when the rapid uplift ends, the destructive forces—normal faulting and erosion—will lower the lofty peaks to form rolling hills.

THE TWO STEPS OF HIMALAYAN GROWTH

The Himalayan chain developed first as an Andean-type margin as oceanic crust sank beneath southern Asia. At that time, the geology of southern Asia was similar to the present geology of the Andes. Only later, after subduction had consumed all the oceanic crust between the two continents, did India and Asia collide. The two-step nature of the process is common to all continent–continent collisions because an ocean basin separating two continents must first be consumed by subduction before the continents can collide.

The Himalayan chain is only one example of a mountain chain built by a collision between two continents. The Appalachian Mountains formed when eastern North America collided with Europe, Africa, and South America between 470 and 250 million years ago. The European Alps formed during repeated collisions between northern Africa and southern Europe beginning about 30 million years ago. The Urals, which separate Europe from Asia, formed by a similar process about 250 million years ago.

► 12.7 THE ORIGIN OF CONTINENTS

Most geologists agree that the Earth formed by accretion of planetesimals, about 4.6 billion years ago. However, little evidence remains to trace our planet's earliest history. Some geologists argue that the entire Earth melted and was covered by an extensive magma ocean. Others

contend that it was largely, but not completely, molten. In either scenario, the Earth was hot and active about 4.5 billion years ago. Magma rose to the surface and then cooled to form the earliest crust. From the evidence of a few traces of old ocean crust combined with calculations of the temperature and composition of the earliest upper mantle, geologists surmise that the first crust was composed of a type of ultramafic rock called **komatiite**. Komatiite is the volcanic equivalent of peridotite—the rock that now makes up the upper mantle. (Recall from Chapter 4 that ultramafic rocks have even higher magnesium and iron concentrations than basalt, which is a mafic rock.)

According to one hypothesis, heat-driven convection currents in a hot, active mantle initiated plate movement in this early crust. Dense komatiites dove into the mantle in subduction zones, where partial melting of the uppermost mantle created basaltic magma. As a result, the oceanic crust gradually became basaltic.

When did the earliest continental crust form? The 3.96-billion-year-old Acasta gneiss in Canada's Northwest Territories is the Earth's oldest known rock. It is metamorphosed granitic rock, similar to modern continental crust, and implies that at least some granitic crust had formed by that time.

Geologists have found grains of a mineral called zircon in a sandstone in western Australia. Although the sandstone is younger, the zircon gives radiometric dates of 4.2 billion years. Zircon commonly forms in granite. Geologists infer that the very old zircon initially formed in granite, which later weathered and released the zircon grains as sand. Eventually, the zircon became part of the younger sedimentary rock. Thus, these zircon grains suggest that granitic rocks existed 4.2 billion years ago. Geologists have also found granitic rocks nearly as old as the Acasta gneiss and the Australian zircon grains in Greenland and Labrador.

According to one model, the earliest continental crust formed by partial melting in oceanic subduction zones. Recall that island arcs form today by a similar mechanism. Thus, the first continents probably consisted of small granitic or andesitic blobs, like island arcs or microcontinents, sitting in a vast sea of basaltic crust.

Modeling suggests that about 40 percent of the present continental crust had formed by 3.8 billion years ago, and 50 percent had formed by 2.5 billion years ago. Thus, continental crust accumulated rapidly early in Earth history and more slowly after the end of Archean time. Geologists cannot calculate the rate of formation of continental crust precisely because they are not certain how much continental crust is recycled back into the mantle at subduction zones.

Most new continental crust now forms in subduction zones; a small amount forms over mantle plumes. Does

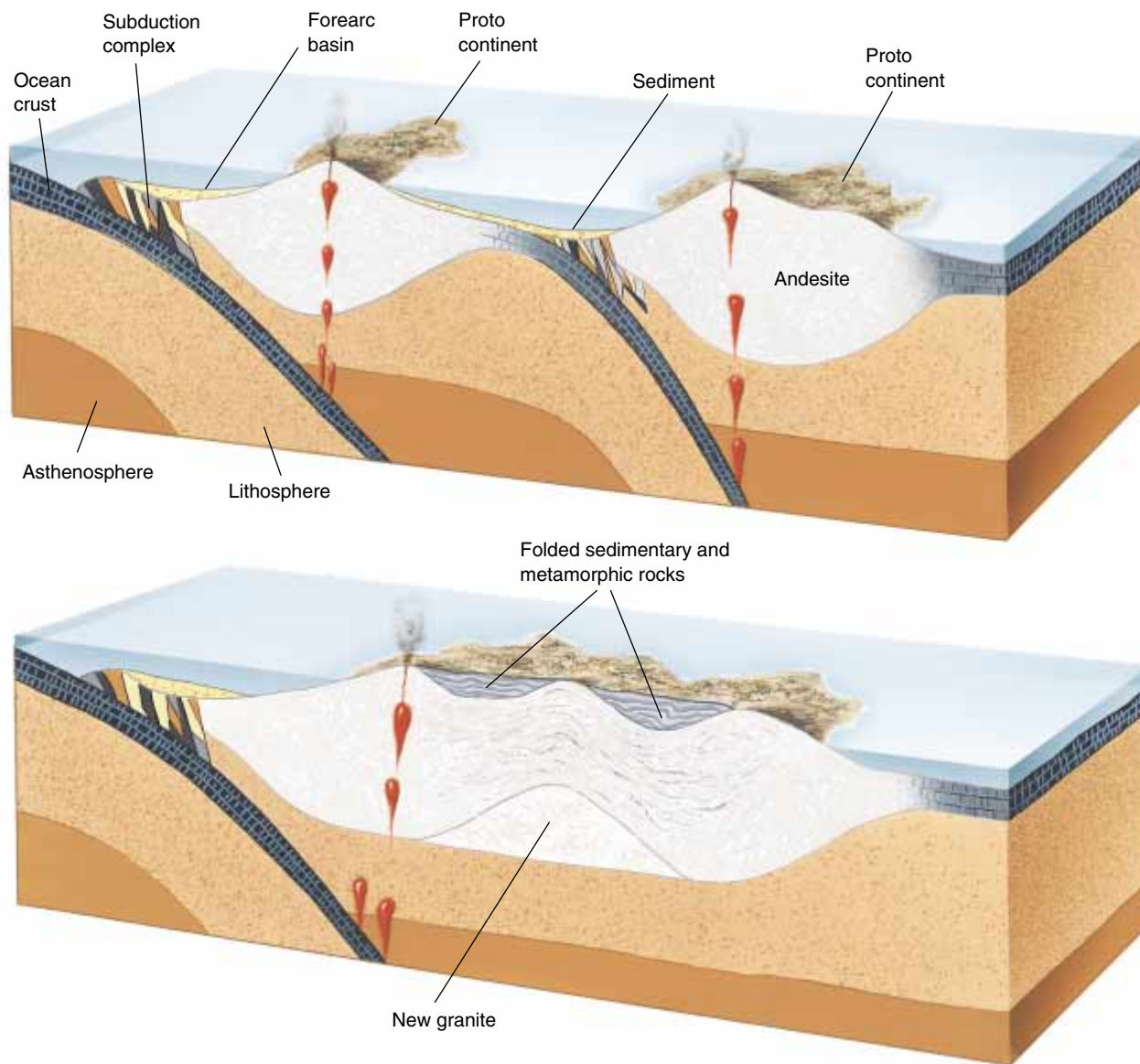


Figure 12-30 According to one model, the modern continents formed as island arcs sutured together. During the suturing, sediments eroded from the original islands were compressed, folded, and uplifted. Some were subjected to so much heat and pressure that they metamorphosed. New granite formed from partial melting of the crust at the subduction zone.

the evolution of continental crust early in Archean time suggest that modern-style plate tectonics had begun that early? Again, conflicting models have been proposed. Some geologists stress that the early Archean mantle was 200 to 400 degrees hotter than today's mantle. The high temperature should have caused rapid convection in the mantle and fast plate movements involving many small tectonic plates. In support of this model, some geologists point out that most Archean rocks are folded and sheared—a style of deformation that forms at modern convergent plate boundaries. They infer from this reasoning that horizontal plate movement has dominated tectonic activity from the beginning of Archean time to the present (Fig. 12-30).

However, other calculations and scant paleomagnetic evidence suggest that Archean plates moved at about the same speed as modern plates—between 1 and 16 centimeters per year. If Archean plates moved as slowly as modern plates do, how did the volume of Archean continental crust grow so rapidly? Another model suggests that early growth of continental crust, and perhaps even of oceanic crust, occurred mainly by “plume tectonics”—production of both basaltic and granitic magma over rising mantle plumes (Fig. 12-31). “Horizontal tectonics” became the dominant process only in late Archean time, after the mantle had cooled and convection slowed. Modern plate tectonics is dominated by horizontal plate movements.

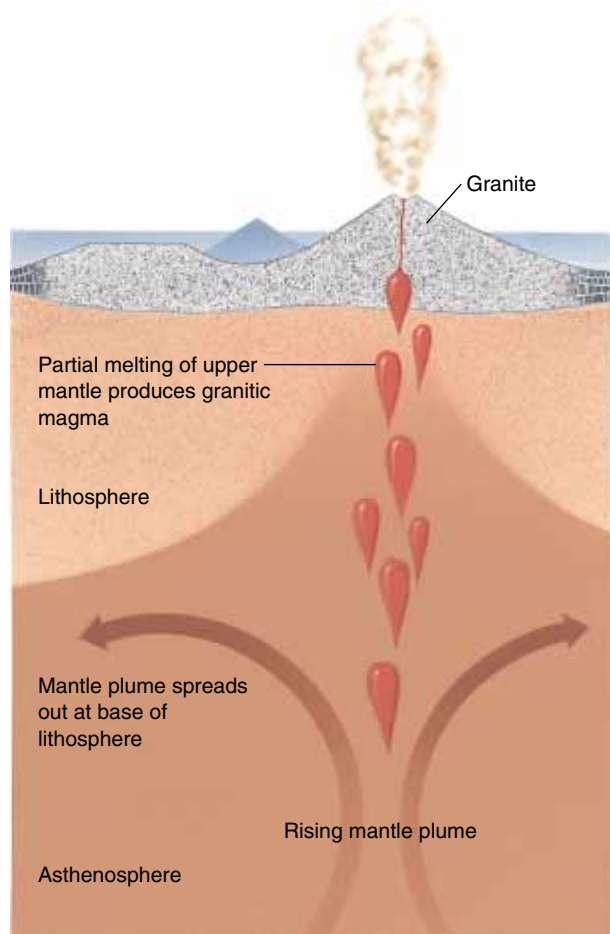


Figure 12-31 Another hypothesis contends that early continental crust formed over rising mantle plumes, in a process called “plume tectonics.”

SUMMARY

Tectonic stress can be **confining stress**, **tectonic compression**, **extensional stress**, or **shear stress**. **Strain** is the distortion or deformation that results from stress.

When tectonic stress is applied to rocks, the rocks can deform in an **elastic** or **plastic** manner, or they may rupture by **brittle fracture**. The nature of the material, temperature, pressure, and rate at which the stress is applied all affect rock behavior under stress.

A **geologic structure** is any feature produced by deformation of rocks. Geologic structures consist of **folds**, which reflect predominant plastic rock behavior, and **faults** and **joints**, which form by rupture. Folds usually form when rocks are compressed.

Normal faults are usually caused by extensional stress, **reverse** and **thrust faults** are caused by compressional stress, and **strike-slip faults** form by shear stress, where blocks of crust slip horizontally past each other along vertical fractures. **Strike** is the direction in which rock layers are tilted, and **dip** is the angle of the bedding plane measured from the horizontal.

Mountains form when the crust thickens and rises isostatically. They become lower when crustal rocks flow

outward or are worn away by erosion. If two converging plates carry oceanic crust, a volcanic **island arc** forms. If one plate carries oceanic crust and the other carries continental crust, an **Andean margin** develops. Andean margins are dominated by granitic plutons and andesitic volcanoes. They also contain rocks of a **subduction complex** and sedimentary rocks deposited in a **forearc basin**.

When two plates carrying continental crust converge, an Andean margin develops first as oceanic crust between the two continental masses is subducted. Later, when the two continents collide, one continent is underthrust beneath the other. The geology of mountain ranges formed by continent–continent collisions such as the **Himalayan chain** is dominated by vast regions of folded and thrust-faulted sedimentary and metamorphic rocks and by earlier formed plutonic and volcanic rocks.

The Earth’s earliest crust was thin, ultramafic oceanic crust. According to one model, the first continental crust formed by partial melting in subduction zones or over mantle plumes.

KEY WORDS

confining stress 200
confining pressure 200
directed stress 200
compressive stress 200
extensional stress 200
tensional stress 200
shear stress 200
geologic structure 201
fold 201
anticline 202

syncline 202
limbs 202
axis 202
axial plane 202
plunge 203
plunging fold 203
monocline 203
dome 204
basin 204
fault 204

slip 204
fault zone 204
hanging wall 206
footwall 206
normal fault 206
graben 206
horst 206
reverse fault 206
thrust fault 206
strike-slip fault 207

joint 207
strike 208
dip 208
orogeny 209
underthrusting 209
subduction complex 210
forearc basin 210
Andean margin 211
komatiite 216

REVIEW QUESTIONS

1. What is tectonic stress? Explain the main types of stress.
2. Explain the different ways in which rocks can respond to tectonic stress. What factors control the response of rocks to stress?
3. What is a geologic structure? What are the three main types of structures? What type(s) of rock behavior does each type of structure reflect?
4. At what type of tectonic plate boundary would you expect to find normal faults?
5. Explain why folds accommodate crustal shortening.
6. Draw a cross-sectional sketch of an anticline-syncline pair and label the parts of the folds. Include the axis and axial plane. Draw a sketch with a plunging fold.
7. Draw a cross-sectional sketch of a normal fault. Label the hanging wall and the footwall. Use your sketch to explain how a normal fault accommodates crustal extension. Sketch a reverse fault and show how it accommodates crustal shortening.
8. Explain the similarities and differences between a fault and a joint.
9. In what sort of a tectonic environment would you expect to find a strike-slip fault, a normal fault, and a thrust fault?
10. What mountain chain has formed at a divergent plate boundary? What are the main differences between this chain and those developed at convergent boundaries? Explain the differences.
11. Explain why erosion initially causes a mountain range to rise and then eventually causes the peak heights to decrease.
12. Describe the similarities and differences between an island arc and the Andes. Why do the differences exist?
13. Describe the similarities and differences between the Andes and the Himalayan chain. Why do the differences exist?
14. Draw a cross-sectional sketch of an Andean-type plate boundary to a depth of several hundred kilometers.
15. Draw a sequence of cross-sectional sketches showing the evolution of a Himalayan-type plate boundary. Why does this type of boundary start out as an Andean-type boundary?
16. What are the oldest Earth materials found to date? How old are they? What information do they provide us (what information can we infer from the data)?
17. Briefly outline one model for the formation of the continents.

DISCUSSION QUESTIONS

1. Discuss the relationships among types of lithospheric plate boundaries, predominant tectonic stress at each type of plate boundary, and the main types of geologic structures you might expect to find in each environment.
2. Why are thrust faults, reverse faults, and folds commonly found together?
3. Why do most major continental mountain chains form at convergent plate boundaries? What topographic and geologic features characterize divergent and transform plate boundaries in continental crust? Where do these types of boundaries exist in continental crust today?
4. Explain why extensional forces act on mountains rising in a tectonically compressional environment.
5. Explain why many mountains contain sedimentary rocks even though subduction leads to magma formation and the formation of igneous rocks.
6. Give a plausible explanation for the formation of the Ural Mountains, which lie in an inland portion of Asia.
7. Compare and explain the similarities and differences between the Andes and the Himalayan chain. How would the Himalayas, at their stage of development about 60 million years ago, have compared with the modern Andes?
8. Where would you be most likely to find large quantities of igneous rocks in the Himalayan chain: in the northern parts of the chain near Tibet or southward near India? Discuss why.
9. Where would you be most likely to find very old rocks: the sea floor, at the base of a growing mountain range, or within the central portion of the continent?