Convergent Boundaries: Origin of Mountains

CHAPTER 14

Elk Mountains, west of Snowmass, Colorado. (Photo by Michael Collier)

Mountains are often spectacular features that rise abruptly above the surrounding terrain (Figure 14.1). Some occur as isolated masses; the volcanic cone Kilimanjaro, for example, stands almost 6000 meters (20,000 feet) above sea level, overlooking the expansive grasslands of East Africa. Other peaks are parts of extensive mountain belts, such as the American Cordillera, which runs almost continuously from the tip of South America through Alaska. Chains such as the Himalayas consist of youthful, towering peaks that are still rising, whereas others, including the Appalachian Mountains in the eastern United States, are much older and have been eroded far below their original lofty heights.

Most major mountain belts show evidence of enormous horizontal forces that have folded, faulted, and generally deformed large sections of Earth's crust. Although folded and faulted strata contribute to the majestic appearance of mountains, much of the credit for their beauty must be given to weathering and mass-wasting processes and to the erosional work of running water and glacial ice, which sculpt these uplifted masses in an unending effort to lower them to sea level. In this chapter, we will examine the nature of mountains and the mechanisms that generate them.

FIGURE 14.1 Uplift along high-angle faults created Mount Sneffels in the Colorado Rockies. (Photo by Art Wolfe, Inc.)

Mountain Building

Convergent Boundaries
▸ **Introduction**

Mountain building has occurred during the recent geologic past in several locations around the world. Young mountain belts include the American Cordillera, which runs along the western margin of the Americas from Cape Horn to Alaska and includes the Andes and Rocky Mountains; the Alpine–Himalaya chain, that extends from the Mediterranean through Iran to northern India and into Indochina; and the mountainous terrains of the western Pacific, which include volcanic island arcs such as Japan, the Philippines, and Sumatra. Most of these young mountain belts have come into existence within the last 100 million years. Some, including the Himalayas, began their growth as recently as 45 million years ago.

In addition to these young mountain belts, several chains of Paleozoic- and Precambrian-age mountains exist on Earth as well. Although these older structures are deeply eroded and topographically less prominent, they clearly possess the same structural features found in younger mountains. The Appalachians in the eastern United States and the Urals in Russia are classic examples of this older group of mountain belts.

Over the last few decades, geologists have learned a great deal about the tectonic processes that generate mountains. The term for the processes that collectively produce a mountain belt is **orogenesis,** (*oros* = mountain, *genesis* = to come into being). Some mountain belts, including the Andes, are constructed predominantly of lavas and volcanic debris that erupted on the surface, as well as massive amounts of intrusive igneous rocks that have solidified at depth. However, most major mountain belts display striking visual evidence of great tectonic forces that have shortened and thickened the crust. These *compressional mountains* tend to contain large quantities of preexisting sedimentary rocks and crystalline crustal fragments that have been contorted into a series of folds (Figure 14.2). Although folding and thrust faulting are often the most conspicuous signs of orogenesis, metamorphism and igneous activity are always present in varying degrees.

Over the years, several hypotheses have been put forward regarding the formation of Earth's major mountain belts (Figure 14.3). One early proposal suggested that mountains are simply wrinkles in Earth's crust, produced as the planet cooled from its original semimolten state. As Earth lost heat, it contracted and shrank. In response to this process, the crust was deformed similar to how the peel of an orange wrinkles as the fruit dries out. However, neither this nor any other early hypothesis was able to withstand careful scrutiny.

With the development of the theory of plate tectonics, a model for orogenesis with excellent explanatory power has emerged. According to this model, most mountain building occurs at convergent plate boundaries. Here, the subduction of oceanic lithosphere triggers partial melting of mantle rock, providing a source of magma that intrudes the crustal rocks that form the margin of the overlying plate. In addition, colliding plates provide the tectonic forces that fold, fault, and metamorphose the thick accumulations of sediments that have been deposited along the flanks of landmasses. Together, these processes thicken and shorten the continental crust, thereby elevating rocks that may have formed near the ocean floor, to lofty heights.

To unravel the events that produce mountains, researchers examine ancient mountain structures as well as sites where orogenesis is currently active. Of particular

Students Sometimes Ask . . .

You mentioned that most mountains are the result of crustal deformation. Are there areas that exhibit mountainous topography but have been produced without crustal deformation?

Yes. Plateaus—areas of high-standing rocks that are essentially horizontal—are one example of a feature that can be deeply dissected by erosional forces into rugged, mountainlike landscapes. Although these highlands resemble mountains topographically, they lack the structures associated with orogenesis. The opposite situation also exists. For instance, the Piedmont section of the eastern Appalachians exhibits topography that is nearly as subdued as that seen in the Great Plains. Yet because this region is composed of deformed metamorphic rocks, it is clearly part of the Appalachian Mountains.

FIGURE 14.2 Highly deformed sedimentary strata exposed on the face of Alberta's Mount Kidd. These sedimentary rocks are continental shelf deposits that were displaced toward the interior of Canada by low-angle thrust faults. (Photo by Peter French/DRK Photo)

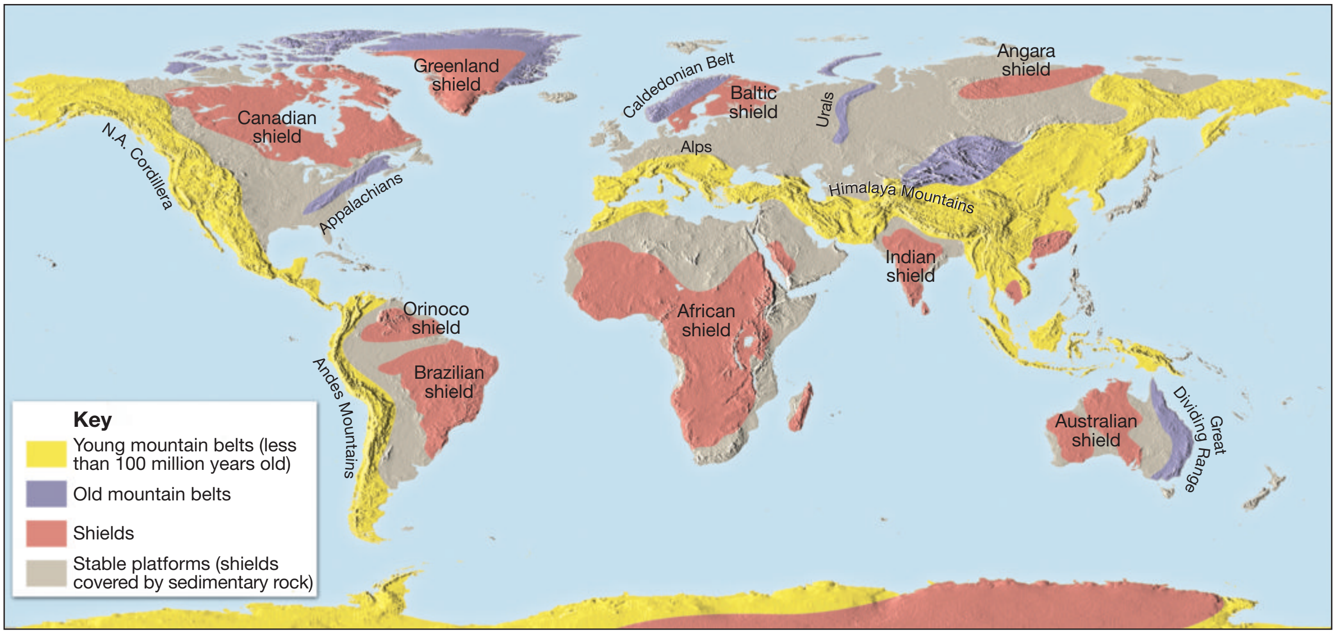


FIGURE 14.3 Earth's major mountain belts.

interest are active subduction zones, where lithospheric plates are converging. Here the subduction of oceanic lithosphere generates Earth's strongest earthquakes and most explosive volcanic eruptions, as well as playing a pivotal role in generating many of Earth's mountain belts.

Convergence and Subducting Plates

As discussed in Chapter 13, upwelling of partially melted mantle rock along divergent plate boundaries results in the formation of new oceanic lithosphere. By contrast, subduction zones located along convergent boundaries are the sites of plate destruction—places where slabs of oceanic lithosphere bend and plunge back into the mantle. As oceanic lithosphere slowly sinks, higher temperatures and pressures gradually alter these rigid slabs until they are fully assimilated into the mantle.

Major Features of Subduction Zones

Subduction zones can be roughly divided into four regions that include: (1) a *deep-ocean trench,* which forms where a subducting slab of oceanic lithosphere bends and descends into the asthenosphere; (2) a *volcanic arc,* which is built upon the overlying plate; (3) a region located between the trench and the volcanic arc (*forearc region*) and; (4) a region on the side of the volcanic arc opposite the trench (*backarc region*). Although all subduction zones exhibit these features, a great deal of variation exists—along the length of an individual subduction zone, as well as among different subduction zones (Figure 14.4).

Subduction zones can also be placed into one of two categories—those in which oceanic lithosphere is subducted beneath another oceanic slab and those in which oceanic lithosphere descends beneath a continental block. (An exception is the Aleutian subduction zone, where the western part is an oceanic–oceanic subduction zone, while subduction along the eastern section occurs under the Alaskan mainland.)

Volcanic Arcs Perhaps the most obvious structure generated by subduction is a *volcanic arc,* which is built upon the overlying plate. Where two oceanic slabs converge, one is subducted beneath the other, initiating partial melting of the mantle wedge located above the subducting plate. This eventually leads to the growth of a **volcanic island arc,** or simply an **island arc,** on the ocean floor. Examples of active island arcs include the Mariana, New Hebrides, Tonga, and Aleutian arcs (Figure 14.5).

In locations where oceanic lithosphere is subducted beneath a continental block, a **continental volcanic arc** results. Here the volcanic arc builds upon the higher topography of older continental rocks, resulting in volcanic peaks that may reach 6000 meters (nearly 20,000 feet) above sea level.

Deep-Ocean Trenches Another major feature associated with subduction is a deep-ocean trench. Trench depth appears to be strongly related to the age and hence the temperature of the subducting oceanic slab. In the western Pacific, where oceanic lithosphere is cold, relatively dense oceanic slabs descend into the mantle and produce deep trenches. A well-known example is the Mariana Trench, where the deepest area is more than 11,000 meters (36,000 feet) below sea level. By contrast, the Cascadia subduction zone lacks a well-defined trench. Here the warm, buoyant Juan de Fuca plate is actively subducting at a very low angle beneath southwestern Canada and the northwestern United States. The Peru–Chile subduction zone, on the other hand, displays

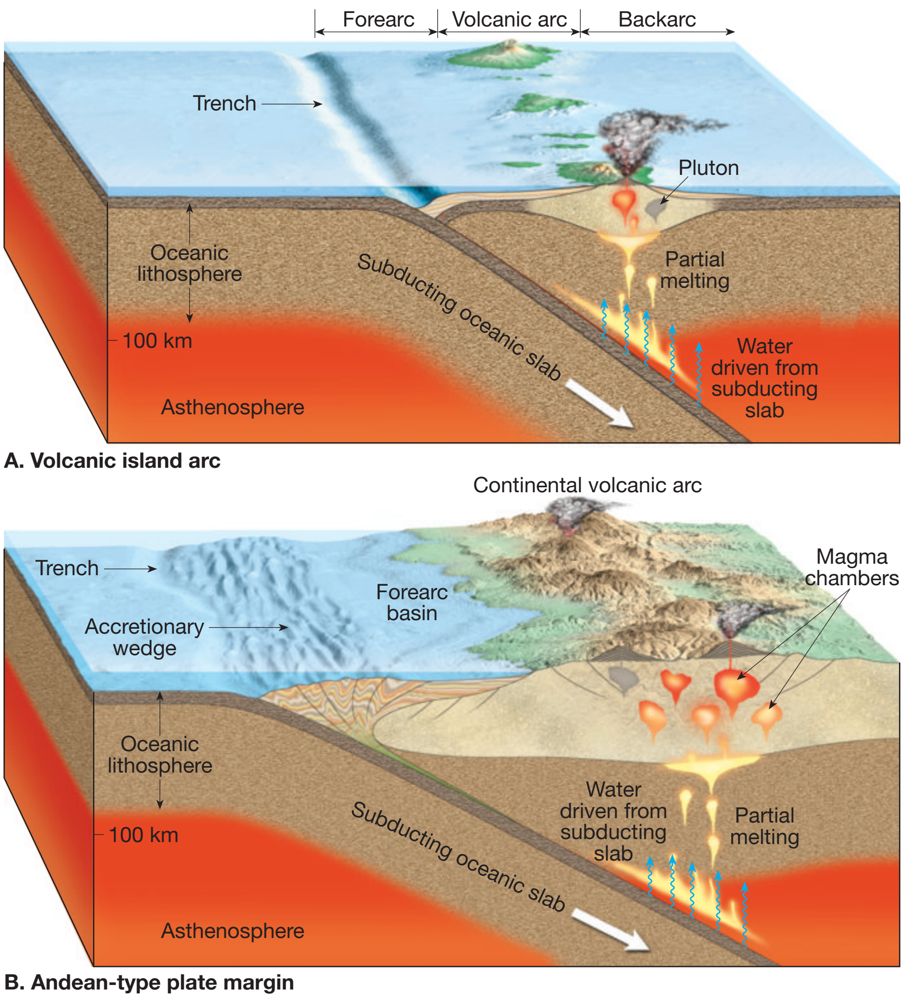


FIGURE 14.4 Diagrammatic comparison of a volcanic island arc and an Andean-type plate margin.

trench depths between these extremes. Much of this trench is 2 to 3 kilometers shallower than those in the western Pacific, averaging between 7 and 8 kilometers deep. One exception occurs in central Chile, where the plate boundary has a very shallow dip, making the trench virtually nonexistent.

Forearc and Backarc Regions Located between developing volcanic arcs and deep-ocean trenches are the *forearc* regions (Figure 14.4). Here pyroclastic material from the volcanic arc as well as sediments eroded from the adjacent landmass accumulate. In addition, ocean-floor sediments are carried to the forearc region by the subducting plate.

Another site where sediments and volcanic debris may accumulate is the *backarc* region, which is located on the side of the volcanic arc opposite the trench. In these regions, tensional forces often dominate, causing the crust to be stretched and thinned.

Dynamics at Subduction Zones

Because subduction zones form where two plates are converging, it is natural to assume that large compressional forces are at work to deform the plate margins. Indeed, this is the case along many convergent plate boundaries. However, convergent margins are not always regions dominated by compressional forces.

Extension and Backarc Spreading Along some convergent plate margins, the overlying plates are under tension, which causes stretching and thinning of the crust. But how do extensional processes operate where two plates are moving together?

The age of the subducting oceanic slab is thought to play a significant role in determining the dominant forces acting on the overriding plate. Recall that when a relatively cold, dense slab subducts, it does *not* follow a fixed path into the asthenosphere. Rather, it sinks vertically as it descends, causing the trench to retreat, or "roll back," as shown in Figure 14.6. As the subducting plate sinks, it creates a flow (*slab suction*) in the asthenosphere that "pulls" the upper plate toward the retreating trench. (Visualize what would happen if you were sitting in a lifeboat near the *Titanic* as it sank!) As a result, the overriding plate is under tension and may be elongated and thinned. If tension is maintained long enough, a **backarc basin** may form.

Recall from Chapter 13 that thinning and rifting of the lithosphere results in upwelling of hot mantle rock and accompanying decompression melting. Continued extension initiates a type of seafloor spreading that generates new ocean crust, thereby increasing the size of a developing backarc basin.

Active backarc basins are found behind the Mariana and Tonga islands, whereas inactive basins contain the South

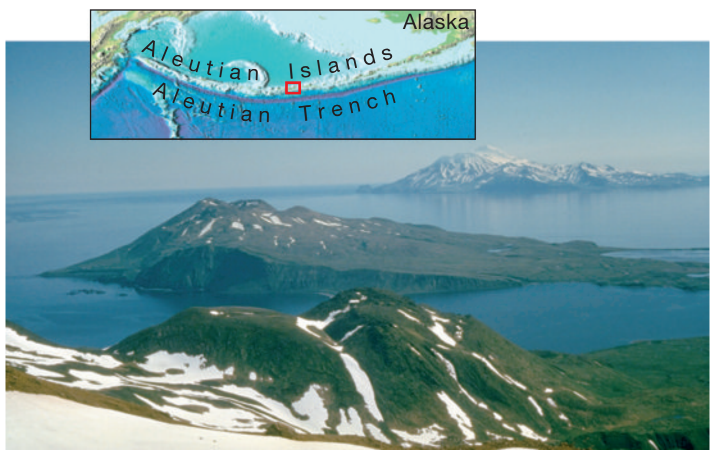


FIGURE 14.5 Three of many volcanic islands that comprise the Aleutian arc. This narrow band of volcanism results from the subduction of the Pacific plate. In the distance is the Great Sitkin volcano (1772 meters), which the Aleuts call the "Great Emptier of Bowels" because of its frequent activity. (Photo by Bruce D. Marsh)

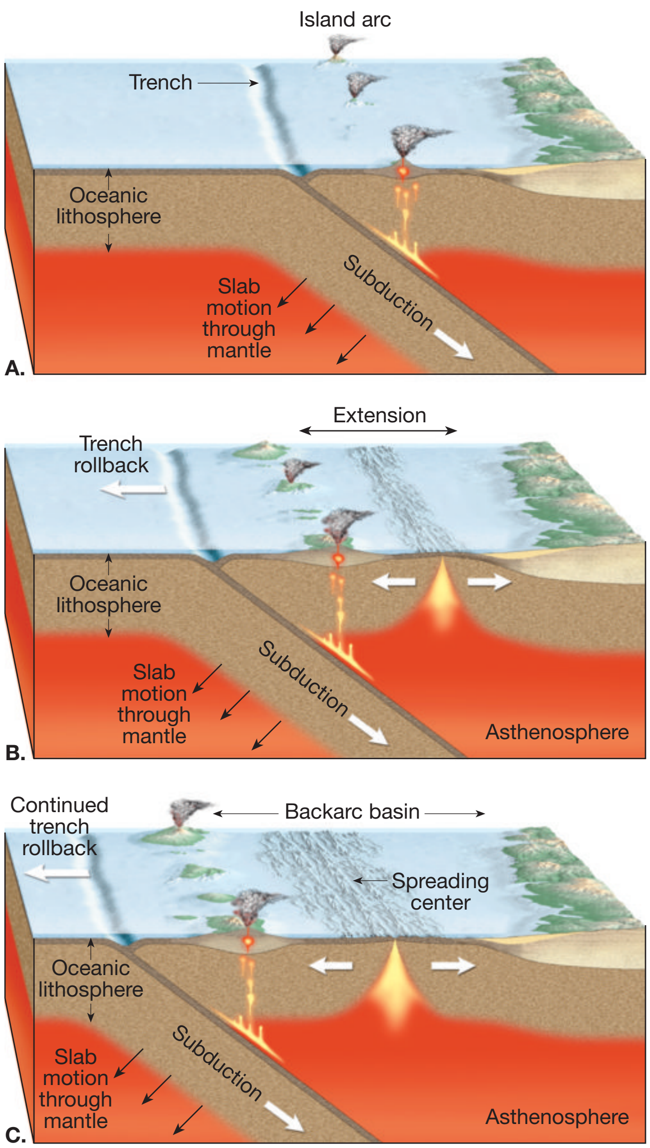


FIGURE 14.6 Model showing the formation of a backarc basin. Subduction and "roll back" of an oceanic slab creates flow in the mantle that "pulls" the upper plate toward the retreating trench.

China Sea and the Sea of Japan. Backarc spreading that formed the Sea of Japan is thought to have rifted a small piece of continental crust from Asia. Gradually, this crustal fragment migrated seaward along with the retreating trench. Seafloor spreading, in turn, created the oceanic crust that floors the Sea of Japan.

Compressional Regimes At some subduction zones compressional forces are dominant (see Box 14.1). This appears to be the case in the central Andes, where an episode of deformation began about 30 million years ago. During this span, the western margin of South America has been actively overrunning the subducting Nazca plate at a rate of about 3 centimeters per year. Put another way, the South American plate has been advancing toward the Peru–Chile trench at a rate faster than the trench has been retreating, because of slab sinking. Thus, in the case of the Andes, the descending slab of oceanic lithosphere serves as a "wall" that resists the westward motion of the South American plate. The resulting tectonic forces have shortened and thickened the western margin of South America. (It is important to note that continental crust is generally weaker than oceanic crust, hence most deformation occurs in the continental blocks.) In this region, the Andean crustal block has its greatest thickening, about 70 kilometers (40 miles), and a mountainous topography that occasionally exceeds 6000 meters (20,000 feet) in elevation.

Subduction and Mountain Building

As noted earlier, the subduction of oceanic lithosphere gives rise to two different types of mountain belts. Where *oceanic lithosphere* subducts beneath an *oceanic plate*, an island arc and related tectonic features develop. Subduction beneath a *continental block*, on the other hand, results in the formation of a volcanic arc along the margin of a continent. Plate boundaries that generate continental volcanic arcs are often referred to as **Andean-type plate margins.**

Island Arcs

Island arcs represent what are perhaps the simplest mountain belts. These structures result from the steady subduction of oceanic lithosphere, which may last for 100 million years or more. Somewhat sporadic volcanic activity, the emplacement of plutonic bodies at depth, and the accumulation of sediment that is scraped from the subducting plate gradually increase the volume of crustal material capping the upper plate. Some mature volcanic island arcs, such as Japan, appear to have been built upon a preexisting fragment of continental crust.

The continued development of a mature volcanic island arc can result in the formation of mountainous topography consisting of belts of igneous and metamorphic rocks. This activity, however, is viewed as just one phase in the development of a major mountain belt. As you will see later, some volcanic arcs are carried by a subducting plate to the margin of a large continental block, where they become involved in a major mountain-building episode.

Mountain Building along Andean-type Margins

The first stage in the development of an Andean-type mountain belt occurs prior to the formation of the subduction zone. At this time, the continental margin is a **passive margin**; that is, it is not a plate boundary but a part of the same plate as the adjoining oceanic crust. The East Coast of the United States provides a present-day example of a passive continental margin. In such settings, deposition of sediment on the continental shelf produces a thick platform of shallow-water sandstones, limestones, and shales (Figure 14.7A). Beyond the continental shelf, turbidity currents deposit sediments on the floor of the deep-ocean basin (see

BOX 14.1 ▶ UNDERSTANDING EARTH

Earthquakes in the Pacific Northwest

Seismic studies have shown that the Cascadia subduction zone exhibits less earthquake activity than any other subduction zone along the margin of the Pacific basin. Does this mean that earthquakes pose no major threat to the population centers of the Pacific Northwest (Figure 14.A)? For some time, that was the conventional wisdom. However, that view changed with the discovery of buried marshes and coastal forests that are best explained by the rapid subsidence that accompanies a large earthquake.

The Cascadia subduction zone is very similar to the convergent margin in central Chile, where the oceanic slab descends at a shallow angle of about 10–15 degrees. In Chile, the effects of large compressional forces are being felt regularly in the form of strong earthquakes. The strongest earthquake ever recorded occurred there in 1960, Mw 9.5. Research predicts that subduction at shallow dip angles results in an environment that is conducive to great earthquakes (Mw 8.0 or greater). A partial explanation lies in the fact that in such settings, a large area of contact exists between the upper plate and the subducting slab.

FIGURE 14.A Scene outside a historic Pioneer Square building following the February 28, 2001, Seattle earthquake. (Photo by Tim Crosby/Newsmakers/Liaison Agency, Inc.)

Like the central Chilean subduction zone, the Cascadia boundary has a gently dipping plate and lacks a trench. This suggests that the Cascadia subduction zone is capable of great earthquakes. Evidence for past events of great magnitude include buried peat deposits found in some bay areas. These discoveries are consistent with episodes of rapid subsidence similar to what occurred during the 1964 Alaskan Earthquake (see Chapter 11). In addition, a fault near Seattle apparently ruptured about 1100 years ago, producing a large tsunami.

However, evidence has also been uncovered suggesting that a great earthquake is not very likely, at least over the short term. Geodetic studies conducted along coastal areas of the Pacific Northwest over the past few decades indicate that elastic strain is not accumulating to any great extent.

Which view is correct? Is a major earthquake in the Pacific Northwest imminent or unlikely? Hopefully further research will resolve this question. In the meantime, those living in the region bordering the Cascadia subduction zone should become aware of the precautions that can be taken to mitigate the effects of a great earthquake.

Chapter 13). In this environment, three distinct structural elements of a developing mountain belt gradually take form: volcanic arcs, accretionary wedges, and forearc basins (Figure 14.7).

Building a Volcanic Arc Recall that as oceanic lithosphere descends into the mantle, increasing temperatures and pressures drive volatiles (mostly water) from the crustal rocks. These mobile fluids migrate upward into the wedge-shaped piece of mantle located between the subducting slab and upper plate. Once the sinking slab reaches a depth of about 100 kilometers (60 miles), these water-rich fluids reduce the melting point of hot mantle rock sufficiently to trigger some melting (Figure 14.7B). Partial melting of mantle rock (principally peridotite) generates *primary magmas*, with basaltic compositions. Because they are less dense than the rocks from which they originated, these newly formed basaltic magmas will buoyantly rise. Upon reaching the base of the continental crust, which consists of low-density, rocky components, these basaltic magmas typically collect, or pond. However, recent volcanism at modern arcs—the eruption of Mount Etna, for example—indicates that some magma must reach the surface.

In order to continue to ascend, magma bodies must remain buoyant relative to the crust. In subduction zones, this is generally achieved through magmatic differentiation, in which heavy iron-rich minerals crystallize and settle out, leaving the remaining melt enriched in silica and other "light" components (see Chapter 4). Hence, through magmatic differentiation, a comparatively dense basaltic magma

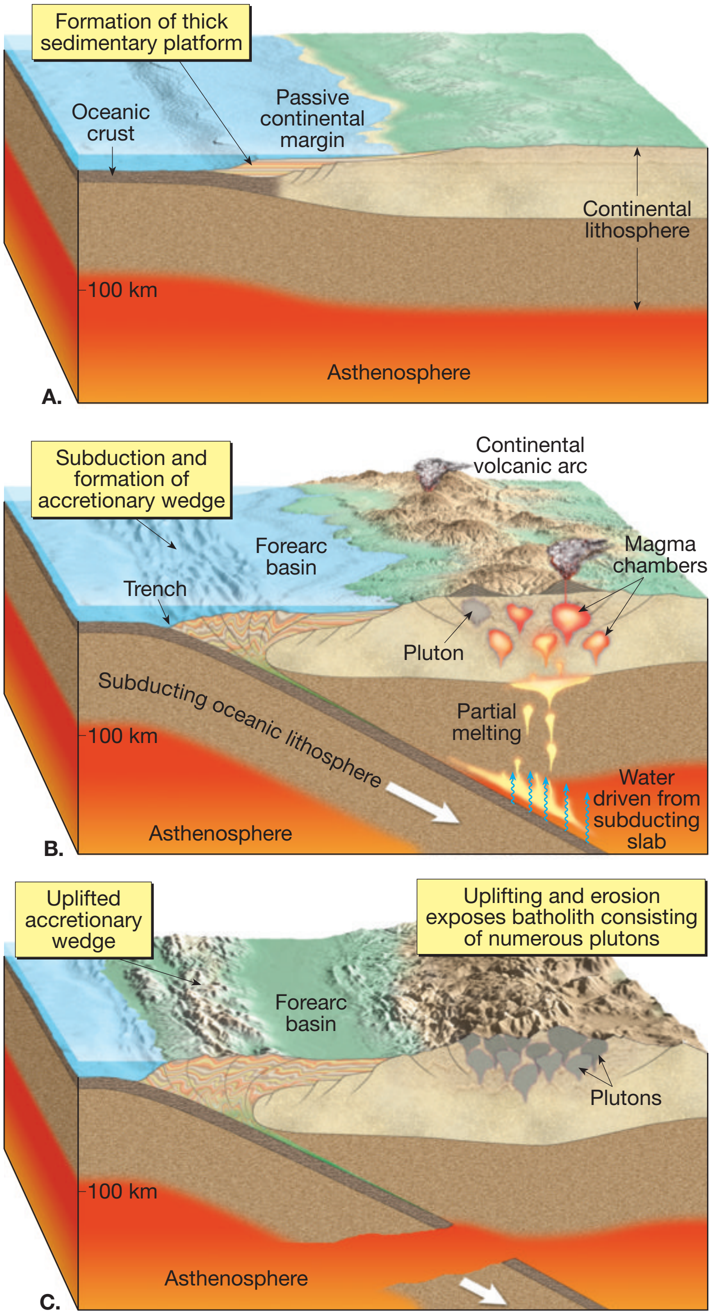


FIGURE 14.7 Orogenesis along an Andean-type subduction zone. **A.** Passive continental margin with an extensive platform of sediments. **B.** Plate convergence generates a subduction zone, and partial melting produces a volcanic arc. Continued convergence and igneous activity further deform and thicken the crust, elevating the mountain belt, while an accretionary wedge develops. **C.** Subduction ends and is followed by a period of uplift and erosion.

can generate low-density, buoyant melts that have an andesitic (intermediate) or even a rhyolitic (felsic) composition.

Volcanism along continental arcs is dominated by the eruption of lavas and pyroclastic materials of andesitic composition, whereas lesser amounts of basaltic and rhyolitic rocks may be generated. Because water driven from the subducting plate is necessary for melting, these mantle-derived magmas are enriched in water and other volatiles (the gaseous component of magma). It is these gas-laden andesitic magmas that produce the explosive eruptions that characterize continental volcanic arcs and mature island arcs.

Emplacement of Plutons Thick continental crust greatly impedes the ascent of magma. Consequently, a high percentage of the magma that intrudes the crust never reaches the surface—instead, it crystallizes at depth to form plutons. The emplacement of these massive igneous bodies will metamorphose the host rock by the process called contact metamorphism (see Chapter 8).

Eventually, uplifting and erosion exhume these igneous bodies and associated metamorphic rocks. Once they are exposed at the surface, these massive structures are called *batholiths* (Figure 14.7C). Composed of numerous plutons, batholiths form the core of the Sierra Nevada in California and are prevalent in the Peruvian Andes. Most batholiths are composed of intrusive igneous rocks with an intermediate to felsic composition, such as diorite and granodiorite, although granites have been observed. (Granite is sparse in the batholiths along the western margin of North America, but significant amounts occur in the core of the Appalachian Mountains.)

Development of an Accretionary Wedge During the development of volcanic arcs, sediments that are carried on the subducting plate, as well as fragments of oceanic crust, may be scraped off and plastered against the edge of the overriding plate. The resulting chaotic accumulation of deformed and thrust-faulted sediments and scraps of ocean crust is called an **accretionary wedge** (Figure 14.7B). The processes that deform these sediments have been likened to what happens to a wedge of soil as it is scraped and pushed in front of an advancing bulldozer.

Some of the sediments that comprise an accretionary wedge are muds that accumulated on the ocean floor and were subsequently carried to the subduction zone by plate motion. Other materials are derived from the adjacent volcanic arc and consist of volcanic ash and other pyroclastic materials, as well as sediments eroded from these elevated landforms.

Some subduction zones have minimal accretionary wedges or lack them all together. The Mariana Trench, for example, lacks an accretionary wedge, partly because of the distance to a significant source region. (Another proposed explanation for the lack of an accretionary wedge is that much of the available sediment is subducted.) By contrast, the Cascadia subduction zone has a large accretionary wedge. Here, the Juan de Fuca plate has a 3-kilometer- (2-mile-) thick mantle of sediments, contributed mainly by the Columbia River.

Prolonged subduction, in regions where sediment is plentiful, may thicken an accretionary wedge enough so it protrudes above sea level. This has occurred along the southern end of the Puerto Rico Trench, where the Orinoco River Basin of Venezuela is a major source region. The resulting wedge emerges to form the island of Barbados.

Not all the available sediment becomes part of the accretionary wedge; rather, some is subducted to great depths. As these sediments descend, pressure steadily increases, but the temperatures within the sediments remain relatively low, because they are in contact with the cool, plunging plate. This activity generates a suite of high-pressure, low-temperature metamorphic minerals. Because of their low density, some of the subducted sediments and associated metamorphic components will buoyantly rise toward the surface. This "backflow" tends to mix and churn the sediment within the accretionary wedge. Thus, an accretionary wedge evolves into a complex structure consisting of faulted and folded sedimentary rocks and scraps of oceanic crust that may be intermixed with metamorphic rocks formed during the subduction process. The unique structure of accretionary wedges has greatly aided geologists in their efforts to piece together the events that have generated our modern continents.

Forearc Basins As the accretionary wedge grows upward, it tends to act as a barrier to the movement of sediment from the volcanic arc to the trench. As a result, sediments begin to collect between the accretionary wedge and volcanic arc. This region, which is composed of relatively undeformed layers of sediment and sedimentary rocks, is called a **forearc basin** (Figure 14.7B). Subsidence, and continued sedimentation in forearc basins, can generate a sequence of horizontal, sedimentary strata that is several kilometers thick.

FIGURE 14.8 Map of mountains and landform regions in the western United States. (After Thelin and Pike, U.S. Geological Survey)

Sierra Nevada and Coast Ranges

During the Jurassic period, when the North Atlantic began to open, a subduction zone formed along the western margin of the North American plate. Evidence for this episode of subduction is found in a nearly continuous belt of igneous plutons that include Mexico's Baja batholith, the Sierra Nevada and Idaho batholiths found in the western United States, and the Coast Range batholith in Canada (see Figure 5.36).

Part of what formed this convergent plate boundary is now an excellent example of an inactive Andean-type orogenic belt. It includes the Sierra Nevada and the Coast Ranges in California (Figure 14.8). These parallel mountain belts were produced by the subduction of a portion of the Pacific basin (Farallon plate) under the western margin of California.

The Sierra Nevada batholith is a remnant of the continental volcanic arc that was produced by many surges of magma over tens of millions of years. The Coast Ranges represent an accretionary wedge that formed when sediments scraped from the subducting plate and provided by the eroding continental volcanic arc were intensely folded and faulted. (Portions of the Coast Ranges are composed of a chaotic mixture of sedimentary and metamorphic rocks, plus fragments of oceanic crust called the Franciscan Formation.)

Beginning about 30 million years ago, subduction gradually ceased along much of the margin of North America as the spreading center that produced the Farallon plate entered the California trench (see Figure 13.26). Both the spreading center and subduction zone were subsequently destroyed. Uplifting and erosion that followed this event have removed most of the evidence of past volcanic activity and exposed a core of crystalline, igneous, and associated metamorphic rocks that make up the Sierra Nevada. The Coast Ranges were uplifted only recently, as evidenced by the young, unconsolidated sediments that still mantle portions of these highlands.

California's Great Valley is a remnant of the forearc basin that formed between the developing Sierra Nevada and the Coast Ranges. Throughout much of its history, portions of the Great Valley lay below sea level. This sediment-laden basin contains thick marine deposits and debris eroded from the continental volcanic arc.

From this example, we can see that Andean-type mountain belts are composed of two roughly parallel zones of deformation. A continental volcanic arc, which forms along the continental margins, consists of volcanoes and large intrusive igneous bodies and associated metamorphosed rocks. Seaward of the continental volcanic arc, where subducting plates descend beneath the continent, an accretionary wedge is generated. This feature consists mainly of sediments and volcanic debris that have been folded, faulted, and in some places metamorphosed (Figure 14.7). Between these regions of deformation lies a forearc basin, composed mostly of horizontal marine strata.

In summary, the growth of mountain belts at subduction zones is a response to crustal thickening caused by the addition of mantle-derived igneous rocks. In addition, crustal shortening and thickening may occur along the continental margins as a result of convergence.

Continental Collisions

Convergent Boundaries
▸ Continental Collisions

As you have seen, when a slab of oceanic lithosphere subducts beneath a continental margin, an Andean-type mountain belt develops. If the subducting plate also contains a continent, continued subduction eventually carries the continental block to the trench. Although oceanic lithosphere is relatively dense and readily subducts, continental crust contains significant amounts of low-density materials and is too buoyant to undergo appreciable subduction. Consequently, the arrival of continental lithosphere at the trench results in a collision with the margin of the overlying continental block and an end to subduction (Figure 14.9).

Continental collisions result in the development of mountains that are characterized by shortened and thickened crust. Thicknesses of 50 kilometers (30 miles) are common, and some regions have crustal thicknesses in excess of 70 kilometers (40 miles). In these settings, crustal thickening is typically achieved through folding and faulting.

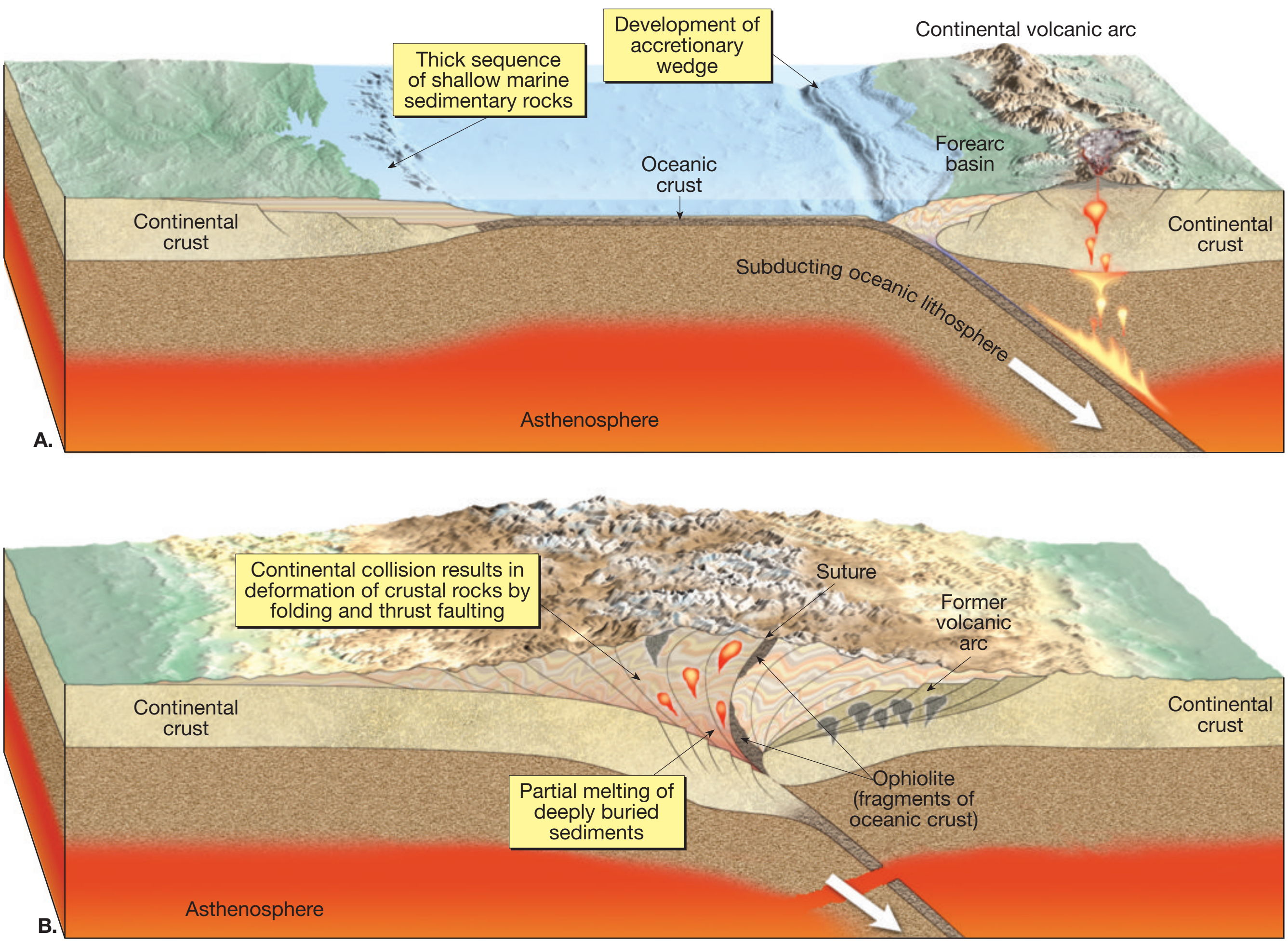


FIGURE 14.9 Illustration showing the formation of the major features of a compressional mountain belt, including the fold-and-thrust belt.

Noteworthy features of most mountain ranges that result from continental collisions are **fold-and-thrust belts.** These mountainous terrains often result from deformation of thick sequences of shallow marine sedimentary rocks similar to those that make up the passive continental margins of the Atlantic. During a continental collision, these sedimentary rocks are pushed inland, away from the core of the developing mountain belt and over the stable continental interior. In essence, crustal shortening is achieved by displacement along thrust faults (low angle reverse faults), where once relatively flat-lying strata are stacked one upon another as illustrated in Figure 14.9. During this displacement, material caught between the thrust faults is often folded, thereby forming the other major structure of a fold-and-thrust belt. Excellent examples of fold-and-thrust belts are found in the Appalachian Valley and Ridge province, the Canadian Rockies, the Lesser (southern) Himalayas, and the northern Alps.

The zone where two continents collide is called the **suture.** This portion of the mountain belt often preserves slivers of the oceanic lithosphere that were entrapped between the colliding plates. As a result of their unique ophiolite structure (see Chapter 13), these pieces of oceanic lithosphere help identify the location of the collision boundary. It is along suture zones that continents are described as being "welded" together.

We will take a closer look at two examples of collision mountains—the Himalayas and the Appalachians. The Himalayas are the youngest collision mountains on Earth and are still rising. The Appalachians are a much older mountain belt, in which active mountain building ceased about 250 million years ago.

The Himalayas

The mountain-building episode that created the Himalayas began roughly 45 million years ago when India began to collide with Asia. Prior to the breakup of Pangaea, India was a part of Gondwana in the Southern Hemisphere (see Figure 2.A, p. 42). Upon splitting from that continent, India moved rapidly, geologically speaking, a few thousand kilometers in a northward direction (see Figure 2.A).

The subduction zone that facilitated India's northward migration was located near the southern margin of Asia. Continuing subduction along Asia's margin created an Andean-type plate margin that contained a well-developed volcanic arc and accretionary wedge. India's northern margin, on the other hand, was a passive continental margin consisting of a thick platform of shallow-water sediments and sedimentary rocks.

Although the details remain somewhat sketchy, one, or perhaps more, small continental fragments were positioned on the subducting plate somewhere between India and Asia. During the closing of the intervening ocean basin, a relatively small crustal fragment, which now forms southern Tibet, reached the trench. This event was followed by the docking of India itself. The tectonic forces involved in the collision of India with Asia were immense and caused the more deformable materials located on the seaward edges of these landmasses to be highly folded and faulted. The shortening and thickening of the crust elevated great quantities of crustal material, thereby generating the spectacular Himalayan mountains (Figure 14.10).

In addition to uplift, crustal shortening produced a thick mass of material in which the lower layers experienced elevated temperatures and pressures (Figure 14.9). Partial melting within the deepest and most deformed region of the developing mountain belt produced plutons that intruded and further deformed the overlying rocks. It is in such environments that the metamorphic and igneous core of compressional mountains are generated.

The formation of the Himalayas was followed by a period of uplift that raised the Tibetan Plateau. Evidence from seismic studies suggests that a portion of the Indian subcontinent was thrust beneath Tibet a distance of perhaps 400 kilometers. If so, the added crustal thickness would account for the lofty landscape of southern Tibet, which has an average elevation higher than Mount Whitney, the highest point in the contiguous United States. Other researchers disagree with this scenario. Instead, they suggest that extensive thrust faulting and folding within the upper crust, as well as uniform ductile deformation of the lower crust and underlying lithospheric mantle, produced the great crustal thickness that accounts for this extremely high plateau. Further research is necessary to resolve this issue.

The collision with Asia slowed but did not stop the northward migration of India, which has since penetrated at least 2000 kilometers (1200 miles) into the mainland of Asia. Some of this motion can be accounted for by crustal shortening. Much of the remaining penetration into Asia is thought to have resulted in the lateral displacement of large

FIGURE 14.10 Himalaya Mountains with Mount Everest in the background (left center) and Nuptse in the foreground (right center). (Photo by David Woodfall/DRK Photo)

blocks of the Asian crust by a mechanism described as *continental escape.* As shown in Figure 14.11, as India collided with Asia, parts of Asia were "squeezed" eastward out of the collision zone. These displaced crustal blocks included much of present-day Indochina and sections of mainland China.

Why has the interior of Asia deformed to such a large degree while India proper has remained essentially undisturbed? The answer lies in the nature of these diverse crustal blocks. Much of India is a shield composed mainly of crystalline Precambrian rocks (see Figure 14.3). This thick, cold slab of crustal material has been intact for more than 2 billion years. By contrast, Southeast Asia was assembled more recently from several smaller crustal fragments—during and even after the formation of Pangaea. Consequently, it is still relatively "warm and weak" from recent periods of mountain building. The deformation of Asia has been re-created in the laboratory with a rigid block representing India pushed into a mass of deformable modeling clay as shown in Figure 14.11. India continues to be thrust into Asia at an estimated rate of a few centimeters each year.

The Appalachians

The Appalachian Mountains provide great scenic beauty near the eastern margin of North America from Alabama to Newfoundland. In addition, mountains that formed contemporaneously with the Appalachians are found in the British Isles, Scandinavia, northwestern Africa, and Greenland (see Figure 2.6, p. 40). The orogeny that generated this extensive mountain system lasted a few hundred million years and was one of the stages in assembling the supercontinent of Pangaea. Detailed studies in the central and southern Appalachians indicate that the formation of this mountain belt was more complex than once thought. Rather than forming during a single continental collision, the Appalachians resulted from three distinct episodes of mountain building.

This oversimplified scenario begins roughly 750 million years ago with the breakup of a pre-Pangaea supercontinent (Rodinia), which rifted North America from Europe and Africa. This episode of continental rifting and seafloor spreading generated the ancestral North Atlantic. Located within this developing ocean basin was a fragment of continental crust that had been rifted from North America (Figure 14.12A).

Then, about 600 million years ago, plate motion dramatically changed and the ancestral North Atlantic began to close. Two subduction zones probably formed. One of these was located seaward of the coast of Africa and gave rise to a volcanic arc similar to those that presently rim the western Pacific. The other developed on the continental fragment that lay off the coast of North America, as shown in Figure 14.12.

Between 450 and 500 million years ago, the marginal sea located between this crustal fragment and North America began to close. The ensuing collision deformed the continental shelf and sutured the crustal fragment to the North American plate. The metamorphosed remnants of the continental fragment are recognized today as the crystalline rocks of the Blue Ridge and western Piedmont regions of the Appalachians (Figure 14.12B). In addition to the pervasive regional metamorphism, igneous activity placed numerous plutonic bodies along the entire continental margin, particularly in New England.

A second episode of mountain building occurred about 400 million years ago. In the southern Appalachians, the continued closing of the ancestral North Atlantic resulted in the collision of the developing volcanic arc with North America (Figure 14.12C). Evidence for this event is visible in the Carolina Slate Belt of the eastern Piedmont, which contains metamorphosed sedimentary and volcanic rocks characteristic of an island arc.

The final orogeny occurred somewhere between 250 and 300 million years ago, when Africa collided with North America. At some locations the total landward displacement of the Blue Ridge and Piedmont provinces may have exceeded 250 kilometers (155 miles). This event displaced and further deformed the shelf sediments and sedimentary rocks that had once flanked the eastern margin of North America (Figure 14.12D). Today these folded and thrust-faulted sandstones, limestones, and shales make up the largely unmetamorphosed rocks of the Valley and Ridge Province. Outcrops of the fold-

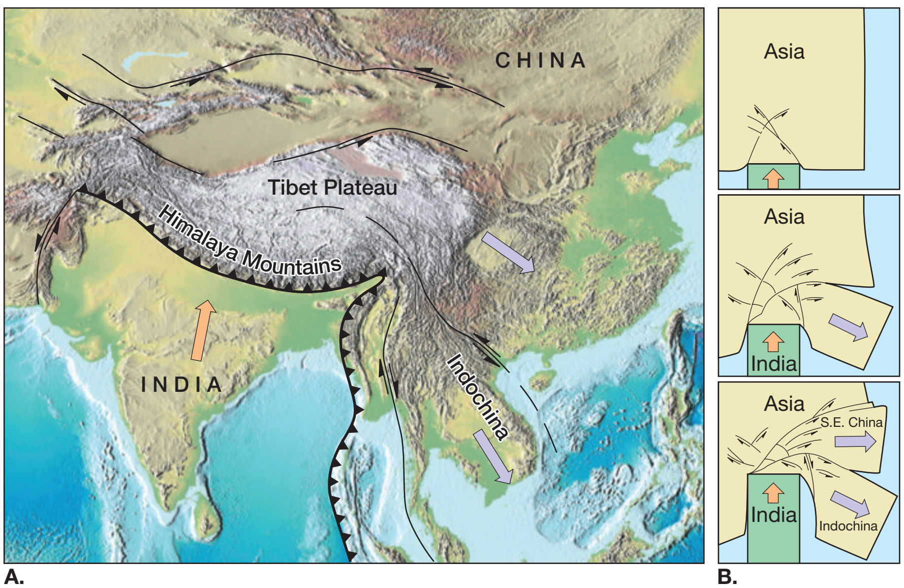


FIGURE 14.11 The collision between India and Asia that generated the Himalayas and Tibetan Plateau also severely deformed much of Southeast Asia. **A.** Map view of some of the major structural features of Southeast Asia thought to be related to this episode of mountain building. **B.** Re-creation of the deformation of Asia, with a rigid block representing India pushed into a mass of deformable modeling clay.

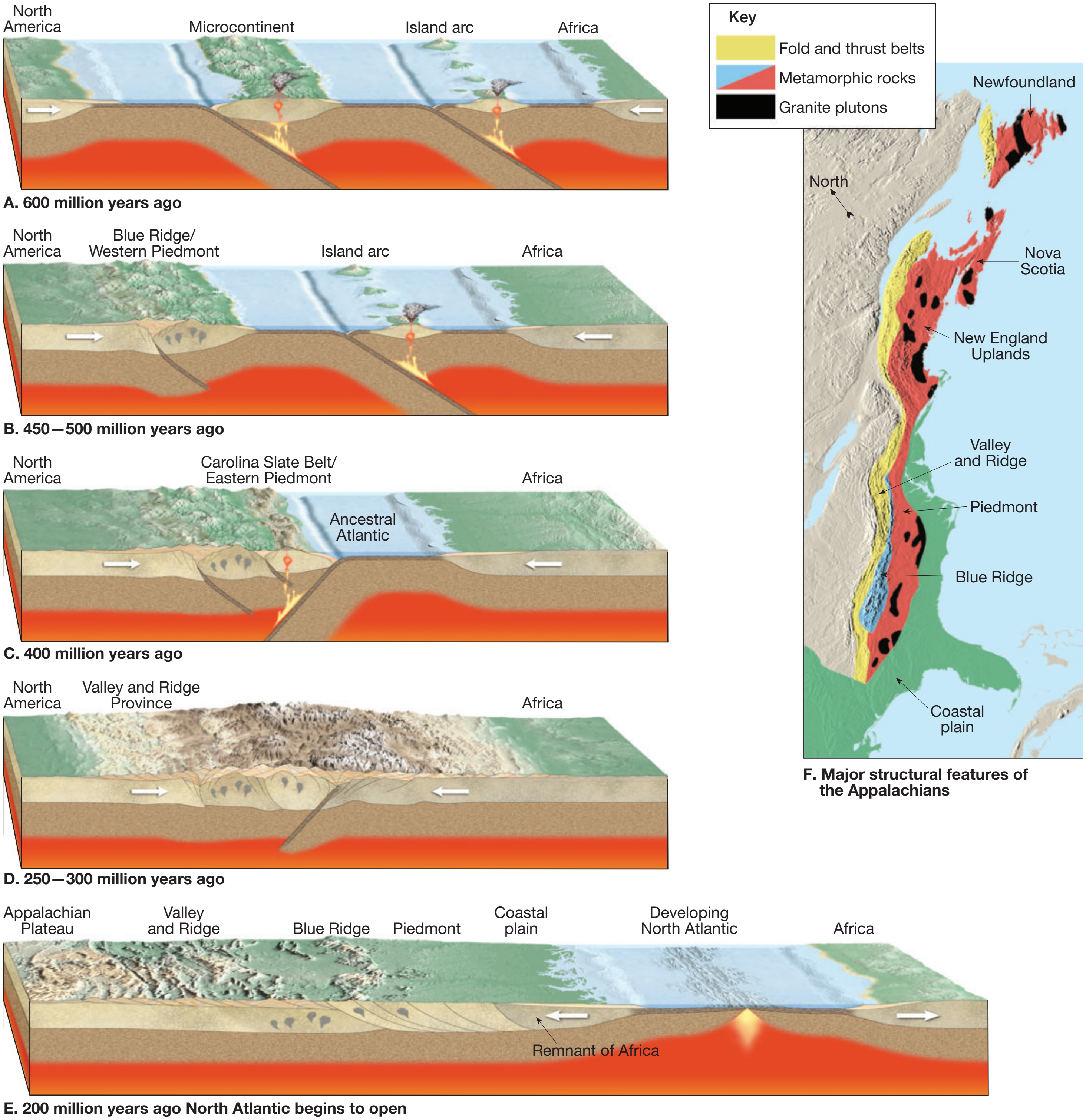


FIGURE 14.12 These simplified diagrams depict the development of the southern Appalachians as the ancient North Atlantic was closed during the formation of Pangaea. Three separate stages of mountain-building activity spanned more than 300 million years. (After Zve Ben-Avraham, Jack Oliver, Larry Brown, and Frederick Cook)

ed thrust-faulted structures that characterize collision mountains are found as far inland as central Pennsylvania and western Virginia (Figure 14.13).

Geologically speaking, shortly after the formation of the Appalachian Mountains, the newly formed supercontinent of Pangaea began to break into smaller fragments. Because this new zone of rifting occurred east of the suture that formed between Africa and North America, a remnant of Africa remains "welded" to the North American plate (Figure 14.12E).

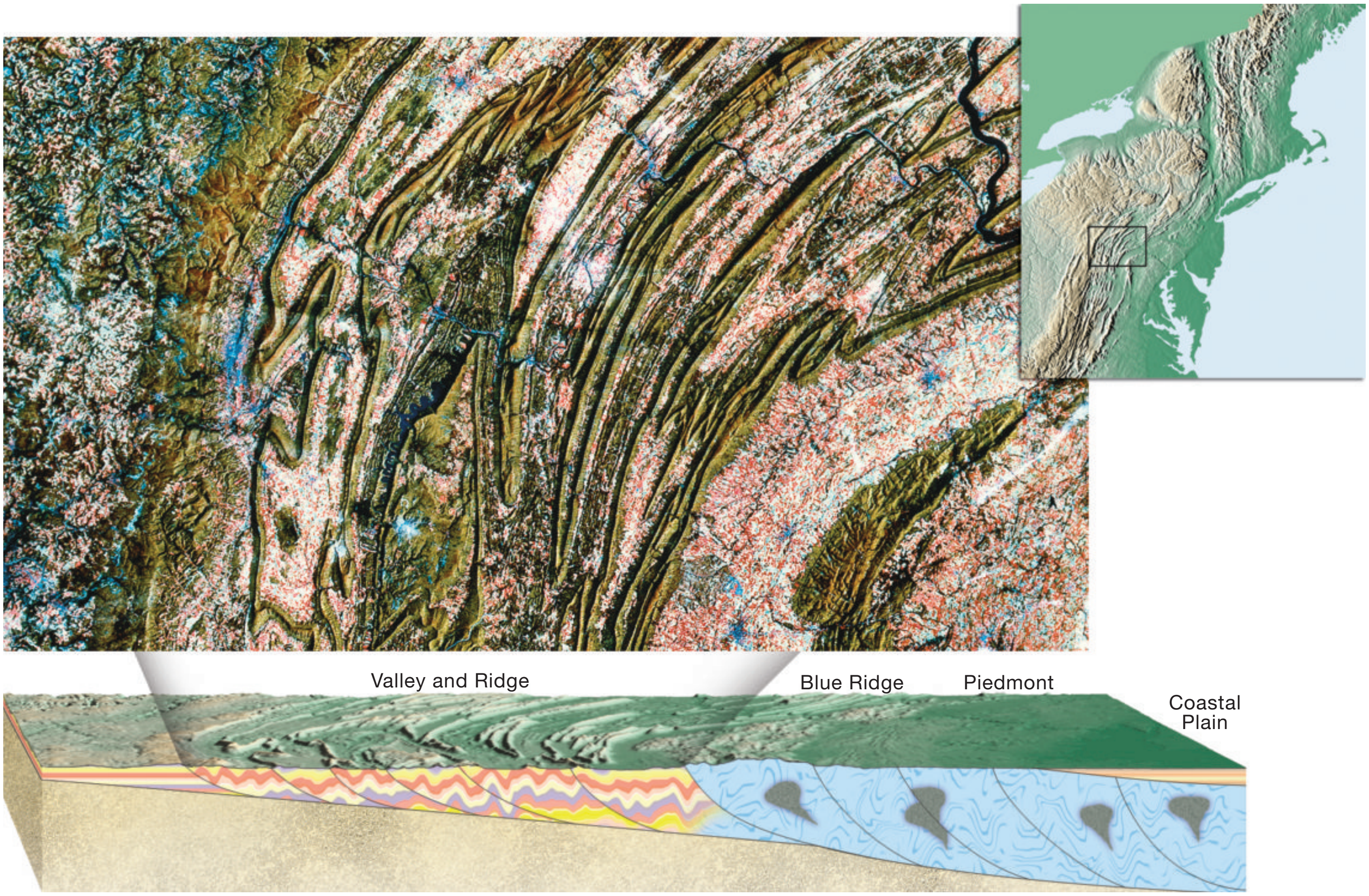


FIGURE 14.13 The Valley and Ridge Province. This portion of the Appalachian Mountains consists of folded and faulted sedimentary strata that were displaced landward with the closing of the proto-Atlantic. (LANDSAT image, courtesy of Phillips Petroleum Company, Exploration Projects Section)

Other mountain ranges that exhibit evidence of continental collisions include the Alps and the Urals. The Alps are thought to have formed as a result of a collision between Africa and Europe during the closing of the Tethys Sea. The Urals, on the other hand, formed during the assembly of Pangaea when Baltica (northern Europe) and Siberia (northern Asia) collided.

Terranes and Mountain Building

Convergent Boundaries
▸ Crustal Fragments and Mountain Building

Mountain belts can also develop as a result of the collision and merger of an island arc, or some other small crustal fragment, to a continental block. The process of collision and accretion (joining together) of comparatively small crustal fragments to a continental margin has generated many of the mountainous regions rimming the Pacific.

The Nature of Terranes

Geologists refer to these accreted crustal blocks as terranes. Simply, the term **terrane** refers to any crustal fragment that has a geologic history distinct from that of the adjoining terranes. Terranes come in varied shapes and sizes.

What is the nature of these crustal fragments, and from where do they originate? Research suggests that prior to their accretion to a continental block, some of the fragments may have been **microcontinents** similar to the present-day island of Madagascar, located east of Africa in the Indian Ocean. Many others were island arcs similar to Japan, the Philippines, and the Aleutian Islands. Still others may have been submerged crustal fragments, such as those occurring on the floor of the western Pacific (see Figure 13.10). More than 100 of these comparatively small crustal fragments are presently known to exist. Their origins vary. Some are submerged fragments consisting mainly of continental crust, whereas others are extinct volcanic islands, such as the Hawaiian Island–Emperor Seamount chain. Still others are

Students Sometimes Ask . . .

What's the difference between a terrane and a terrain?

The term *terrane* is used to designate a distinct and recognizable series of rock formations that has been transported by plate-tectonic processes. Since geologists who mapped these rocks were unsure where they came from, these rocks were sometimes called "exotic," "suspect," "accreted," or "foreign" terranes. Don't confuse this with the term *terrain*, which describes the shape of the surface topography or "lay of the land."

submerged oceanic plateaus created by massive outpourings of basaltic lavas associated with hot-spot activity.

Accretion and Orogenesis

The widely accepted view is that as oceanic plates move, they carry embedded oceanic plateaus, volcanic island arcs, and microcontinents to an Andean-type subduction zone. When an oceanic plate contains a chain of small seamounts, these structures are generally subducted along with the descending oceanic slab. However, very thick units of oceanic crust, such as the Ontong Java Plateau, or a mature island arc composed of abundant "light" igneous rocks produced by magmatic differentiation, may render the oceanic lithosphere too buoyant to subduct. In these situations, a collision between the crustal fragment and the continent occurs.

The sequence of events that occurs when a mature island arc reaches an Andean-type margin is shown in Figure 14.14. Because of its buoyancy, a mature island arc will not subduct beneath the continental plate. Instead, the upper portions of these thickened zones are peeled from the descending plate and thrust in relatively thin sheets upon the adjacent continental block. In some settings continued subduction may carry another crustal fragment to the continental margin. When this fragment collides with the continental margin, it displaces the accreted island arc further inland, adding to the zone of deformation and to the thickness and lateral extent of the continental margin.

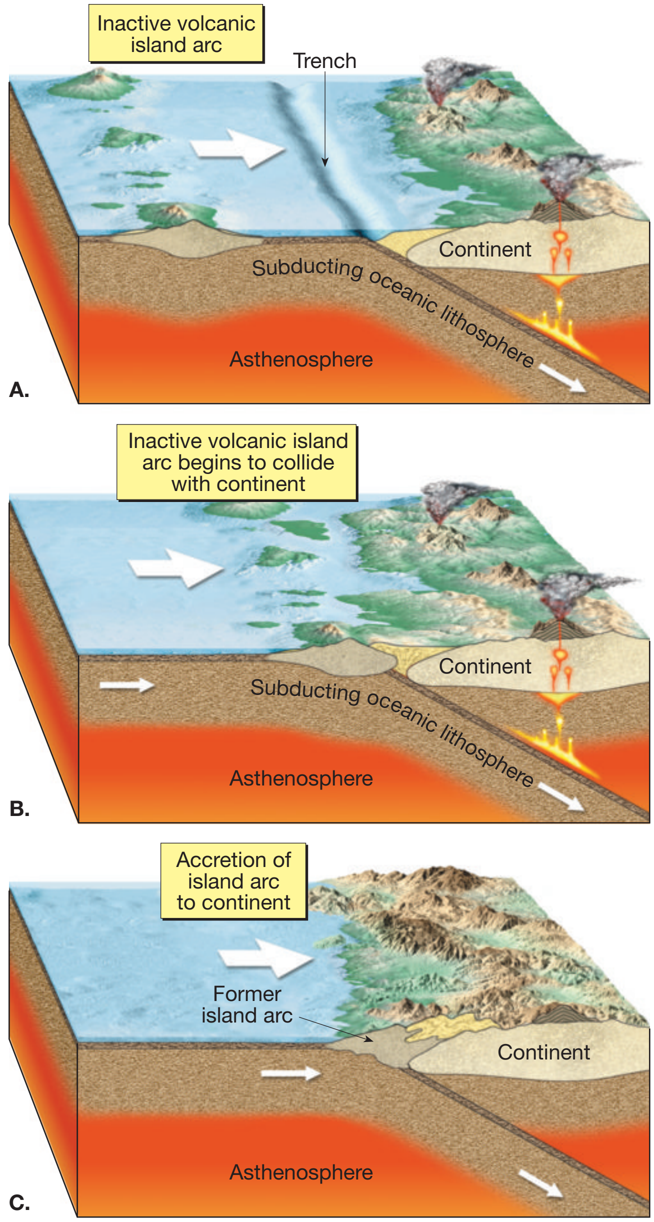


FIGURE 14.14 Sequence of events showing the collision and accretion of an island arc to a continental margin.

The North American Cordillera The idea that mountain building occurs in association with the accretion of crustal fragments to a continental mass arose principally from studies conducted in the North American Cordillera (Figure 14.15). Here it was determined that some mountainous areas, principally those in the orogenic belts of Alaska and British Columbia, contain fossil and paleomagnetic evidence indicating that these strata once lay nearer the equator.

It is now assumed that many of the other terranes found in the North American Cordillera were once scattered throughout the eastern Pacific, much as we find island arcs and oceanic plateaus distributed in the western Pacific today (see Figure 13.10). Since before the breakup of Pangaea, the eastern portion of the Pacific basin (Farallon plate) has been subducting under the western margin of North America. Apparently, this activity resulted in the piecemeal addition of crustal fragments to the entire Pacific margin of the continent—from Mexico's Baja Peninsula to northern Alaska (Figure 14.15). In a like manner, many modern microcontinents will eventually be accreted to active continental margins, producing new orogenic belts.

Fault-Block Mountains

Most mountain belts, including the Alps, Himalayas, and Appalachians, form in compressional environments, as evidenced by the predominance of large thrust faults and folded strata. However, other tectonic processes, such as

BOX 14.2 ▶ UNDERSTANDING EARTH

The Southern Rockies

The portion of the Rocky Mountains that extends from southern Montana to New Mexico was produced by a period of deformation known as the *Laramide Orogeny.* This event, which created some of the most picturesque scenery in the United States, peaked about 60 million years ago (Figure 14.B). The mountain ranges generated during the Laramide Orogeny include the Front Range of Colorado, the Sangre de Cristo of New Mexico and Colorado, and the Bighorns of Wyoming.

These mountains are structurally much different from the northern Rockies, which include the Canadian Rockies and those portions of the Rockies found in Idaho, western Wyoming, and western Montana. The northern Rockies are compressional mountains, composed of thick sequences of sedimentary rocks that were deformed by folding and low-angle thrust faulting. Most investigators agree that the collision of one or more microcontinents with the western margin of North America generated the driving force behind the formation of the northern Rockies.

FIGURE 14.B The spectacular Maroon Bells are part of the Colorado Rockies. (Photo by Peter Saloutos/The Stock Market)

The southern Rockies, on the other hand, formed when deeply buried crystalline rock was lifted nearly vertically along steeply dipping faults, upwarping the overlying layers of younger sedimentary rocks. The resulting mountainous topography consists of large blocks of ancient basement rocks that are separated by sediment-filled basins. Since their formation, much of the sedimentary cover has been eroded from the highest portions of the uplifted blocks, exposing their igneous and metamorphic cores. Examples include a number of granitic outcrops that project as steep summits, such as Pike's Peak and Long's Peak in Colorado's Front Range. In many areas, remnants of the sedimentary strata that once covered this region are visible as prominent angular ridges, called *hogbacks,* flanking the crystalline cores of the mountains (Figure 14.C).

It was once assumed that like other regions of mountainous topography, the southern Rockies stood tall because the crust had been thickened by past tectonic events. However, seismic studies conducted across the American Southwest revealed a crustal thickness no greater than that found below Denver. These data ruled out crustal buoyancy as the cause for the abrupt 2-kilometer (1.2-mile) jump in elevation that occurs where the Great Plains meet the Rockies.

Although the southern Rockies have been extensively studied for more than a century, there is still a good deal of debate regarding the mechanisms that led to uplift. One hypothesis proposes that this period of uplift started with the nearly horizontal subduction of the Farallon plate eastward beneath North America as far inland as the Black Hills of South Dakota. As the subducted slab scraped beneath the continent, compressional forces initiated a period of tectonic activity. As the comparatively cool Farallon plate sank, it was replaced by hot rock that upwelled from the mantle. Thus, according to this scenario, the hot mantle provided the buoyancy to raise the southern Rockies, as well as the Colorado Plateau and the mountains of the Basin and Range.

Others disagree, maintaining that there is no need to invoke the process of buoyant subduction. Rather, they suggest that plate convergence and the collision of one or more microcontinents to the western margin of North America generated the driving force behind the Laramide Orogeny (see the section entitled "Terranes and Mountain Building").

It should be pointed out that neither of these proposals has gained widespread support. As one geologist familiar with this region put it, "We just don't know."

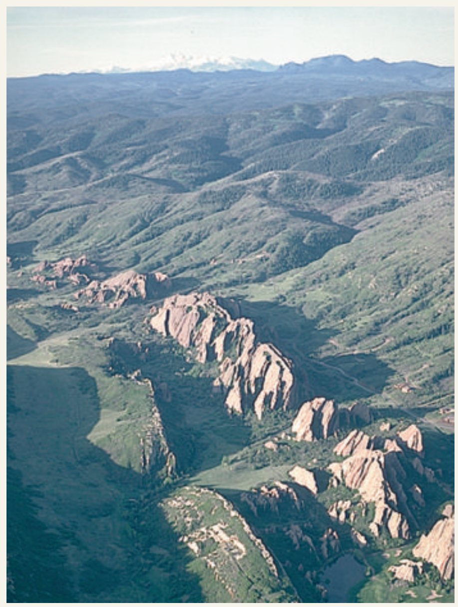


FIGURE 14.C Hogback ridges in the Rocky Mountains of Colorado. Shown is a view looking south along the east flank of the Front Range. These upturned sedimentary rocks are remnants of strata that once covered the Precambrian igneous and metamorphic core of the mountains to the west (right). (Photo by Tom Till/DRK Photo)

FIGURE 14.15 Map showing terranes that have been added to western North America during the past 200 million years. Paleomagnetic studies and fossil evidence indicate that some of these terranes originated thousands of kilometers to the south of their present location. (After D. R. Hutchinson and others)

continental rifting, can also produce uplift and the formation of topographic mountains. The mountains that form in these settings, termed **fault-block mountains,** are bounded by high-angle normal faults that gradually flatten with depth. Most fault-block mountains form in response to broad uplifting, which causes elongation and faulting. Such a situation is exemplified by the fault blocks that rise high above the rift valleys of East Africa.

Mountains in the United States in which faulting and gradual uplift have contributed to their lofty stature include the Sierra Nevada of California and the Grand Tetons of Wyoming. Both are faulted along their eastern flanks, which were uplifted as the blocks tilted downward to the west. Looking west from Owens Valley, California, and Jackson Hole, Wyoming, the eastern fronts of these ranges (the Sierra Nevada and the Tetons, respectively) rise more than 2 kilometers, making them two of the most imposing mountain fronts in the United States (Figure 14.16).

Students Sometimes Ask . . .

What are some modern-day examples of material that may wind up as terranes in the future?

The southwestern Pacific Ocean is a good place to find pieces and fragments of land that may one day become terranes. Here there are many island arcs, oceanic plateaus, and microcontinents that will likely become accreted to the edges of a continent. One of the best-known terranes is the area west of the San Andreas Fault, which includes southwest California and the Baja California peninsula of Mexico. Already named the "California Terrane," it is moving to the northwest and will probably detach from North America in about 50 million years. Continued movement toward the northwest will bring it to southern Alaska, where it will become the next in a long procession of terranes that have rafted toward and "docked" against Alaska during the past 200 million years.

Basin and Range Province

Located between the Sierra Nevada and Rocky Mountains is one of Earth's largest regions of fault-block mountains—the Basin and Range Province. This region extends in a roughly north to south direction for nearly 3000 kilometers (2000 miles) and encompasses all of Nevada and portions of the surrounding states, as well as parts of southern Canada and western Mexico. Here, the brittle upper crust has literally been broken into hundreds of fault blocks. Tilting of these faulted structures (half-grabens) gave rise to nearly parallel mountain ranges, averaging about 80 kilometers in length, which rise above adjacent sediment-laden basins (see Figure 10.22).

Extension in the Basin and Range Province began about 20 million years ago and appears to have "stretched" the crust as much as twice its original width. Figure 14.17 shows a rough outline of the boundaries of the western states before and after this period of extension. High heat flow in the region, three times average, and several episodes of volcanism provide strong evidence that mantle upwelling caused doming of the crust, which in turn contributed to extension in the region.

It has also been suggested that the change in the nature of the plate boundary along the western margin of California may have contributed to the formation of the Basin and Range. About 40 million years ago the dominant forces acting on the western margin of North America were compressional, caused by the buoyant subduction of a segment of the Pacific basin (Figure 14.18). Subduction gradually ceased along the coast of California as the convergent boundary separating the Pacific and North American plates turned into the transform boundary we call the San

FIGURE 14.16 The Grand Tetons of Wyoming are an example of fault-block mountains. (Photo by Art Wolfe, Inc.)

Andreas Fault. Approximately 20 million years ago, a warm, rising mantle plume began to uplift and fault the crust between the Sierra Nevada and Rocky Mountains. According to one model, these elevated crustal blocks began to gravitationally slide off their lofty perches to generate the fault-block topography of the Basin and Range Province (Figure 14.18).

Vertical Movements of the Crust

In addition to the large crustal displacements driven mainly by plate tectonics, gradual up-and-down motions of the continental crust are observed at many locations around the globe. Although much of this vertical movement occurs along plate margins and is associated with active mountain building, some of it is not.

FIGURE 14-17 Extension in the Basin and Range Province has "stretched" the crust in some locations by as much as twice its original width. Shown here is a rough outline of the western states before (left) and after (right) extension.

Evidence for crustal uplift occurs along the West Coast of the United States. When the elevation of a coastal area remains unchanged for an extended period, a wavecut platform develops (see Figure 20.11). In parts of California, ancient wave-cut platforms can now be found as terraces hundreds of meters above sea level (Figure 14.19). Such evidence of crustal uplift is easy to find; unfortunately, the reason for uplift is not always as easy to determine.

Isostasy

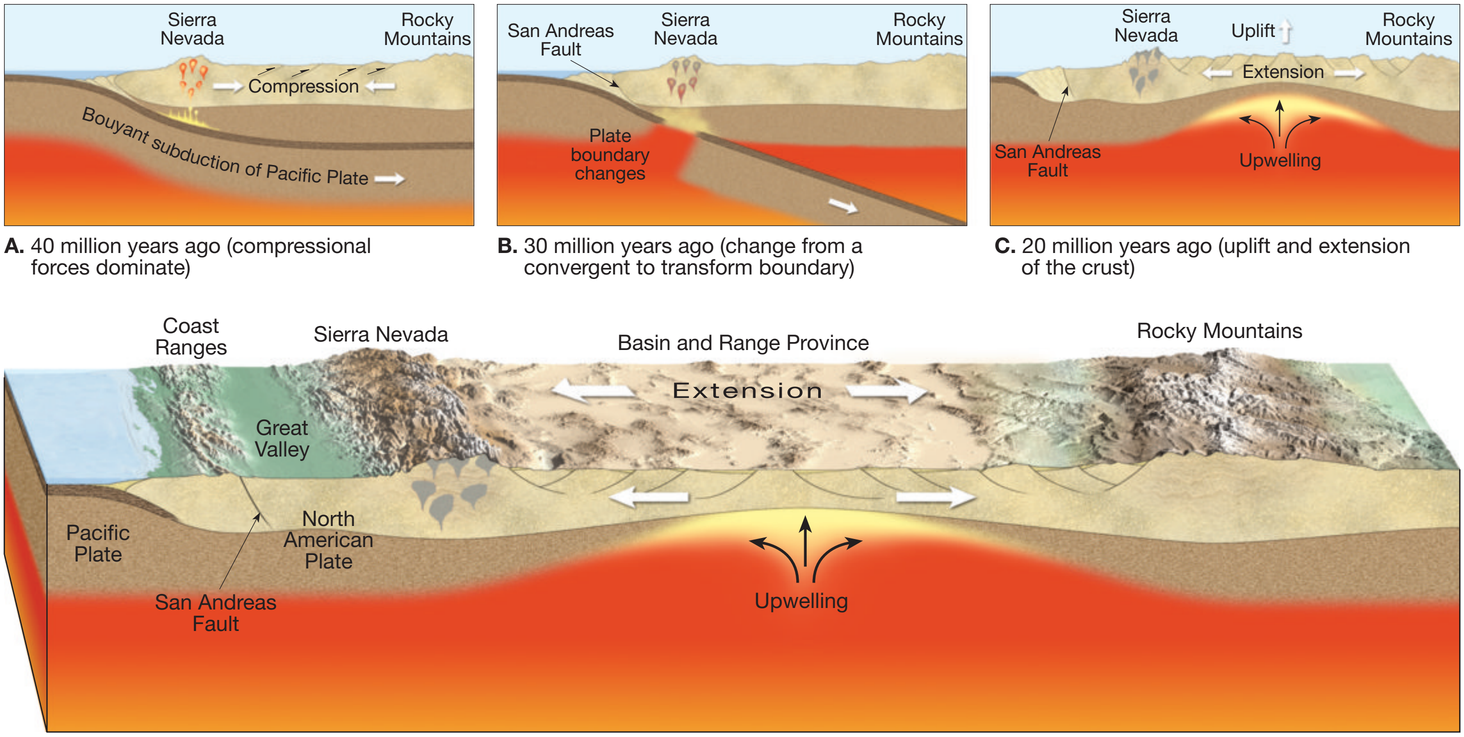
Early workers discovered that Earth's less-dense crust floats on top of the denser and deformable rocks of the mantle. The concept of a floating crust in gravitational balance is called **isostasy** (*iso* = equal, *stasis* = standing). Perhaps the easiest way to grasp the concept of isostasy is to envision a series of wooden blocks of different heights floating in water, as shown in Figure 14.20. Note that the thicker wooden blocks float higher than the thinner blocks.

Similarly, many mountain belts stand high above the surrounding terrain because of crustal thickening. These compressional mountains have buoyant crustal "roots" that extend deep into the supporting material below, just like the thicker wooden blocks shown in Figure 14.20 (see Box 14.3).

Isostatic Adjustment Visualize what would happen if another small block of wood were placed atop one of the blocks in Figure 14.20. The combined block would sink until a new isostatic (gravitational) balance was reached. However, the top of the combined block would actually be higher than before, and the bottom would be lower. This process of establishing a new level of gravitational equilibrium is called **isostatic adjustment.**

Applying the concept of isostatic adjustment, we should expect that when weight is added to the crust, it will respond by subsiding, and when weight is removed, the crust will rebound. (Visualize what happens to a ship as cargo is being loaded and unloaded.) Evidence for crustal subsidence followed by crustal rebound is provided by Ice Age glaciers. When continental ice sheets occupied portions of North America during the Pleistocene epoch, the added weight of 3-kilometer-thick masses of ice caused downwarping of Earth's crust by hundreds of meters. In the 8000 years since the last ice sheet melted, uplifting of as much as 330 meters (1000 feet) has occurred in Canada's Hudson Bay region, where the thickest ice had accumulated (see Figure 18.26).

One of the consequences of isostatic adjustment is that as erosion lowers the summits of mountains, the crust will rise in response to the reduced load (Figure 14.21). However, each episode of isostatic uplift is somewhat less than the elevation loss due to erosion. The processes of uplifting and erosion will continue until the mountain block reaches



A. 40 million years ago (compressional forces dominate)

B. 30 million years ago (change from a convergent to transform boundary)

C. 20 million years ago (uplift and extension of the crust)

D. 20 million years ago to present (uplift and gravitational sliding creates the topography of the Basin and Range)

FIGURE 14.18 The Basin and Range Province consists of numerous fault-block mountains that were generated during the last 20 million years of Earth history. Upwelling of hot mantle rock and perhaps gravitational collapse (crustal sliding) contributed to considerable stretching and thinning of the crust.

"normal" crustal thickness. When this occurs, the mountains will be eroded to near sea level, and the once deeply buried interior of the mountain will be exposed at the surface. In addition, as mountains are worn down, the eroded sediment is deposited on adjacent landscapes, causing these areas to subside (Figure 14.21).

How High Is Too High? Where compressional forces are great, such as those driving India into Asia, mountains such as the Himalayas result. But is there a limit on how high a mountain can rise? As mountaintops are elevated, gravity-driven processes such as erosion and mass wasting accelerate, carving the deformed strata into rugged landscapes. Just as important, however, is the fact that gravity also acts on the rocks within these mountainous masses. The higher the mountain, the greater the downward force on the rocks near the base. (Visualize a group of cheerleaders at a sporting event building a human pyramid.) At some point the rocks deep within the developing mountain, which are comparatively warm and weak, will begin to flow laterally, as shown in Figure 14.22. This is analogous to what happens when a ladle of very thick pancake batter is poured on a hot griddle. As a result, the mountain will experience a **gravitational collapse,** which involves normal faulting and subsidence in the upper, brittle portion of the crust and ductile spreading at depth.

You then might ask, What keeps the Himalayas standing? Simply, the horizontal compressional forces that are driving India into Asia are greater than the vertical force of gravity. However, once India's northward trek ends, the downward pull of gravity will become the dominant force acting on this mountainous region.

FIGURE 14.19 Former wave-cut platforms now exist as a series of elevated terraces on the west side of San Clemente Island off the southern California coast. Once at sea level, the highest terraces have risen about 400 meters. (Photo by John S. Shelton)

Mantle Convection: A Cause of Vertical Crustal Movement

Based on studies of Earth's gravitational field, it became clear that up-and-down convective flow in the mantle also affects the elevation of Earth's major landforms. The buoyancy of hot rising material accounts for broad upwarping in the overlying lithosphere, while downward flow causes downwarping.

BOX 14.3 ▶ UNDERSTANDING EARTH

Do Mountains Have Roots?

One of the major advances in determining the structure of mountains occurred in the 1840s when Sir George Everest (after whom Mount Everest is named) conducted the first topographical survey in India. During this survey the distance between the towns of Kalianpur and Kaliana, located south of the Himalayan range, was measured using two different methods. One method employed the conventional surveying technique of triangulation, and the other method determined the distance astronomically. Although the two techniques should have given similar results, the astronomical calculations placed these towns nearly 150 meters closer to each other than did the triangulation survey.

The discrepancy was attributed to the gravitational attraction exerted by the massive Himalayas on the plumb bob used for leveling the astronomical instrument. (A plumb bob is a metal weight suspended by a cord, used to determine a vertical orientation.) It was suggested that the deflection of the plumb bob would be greater at Kaliana than at Kalianpur because it is closer to the mountains (Figure 14.D).

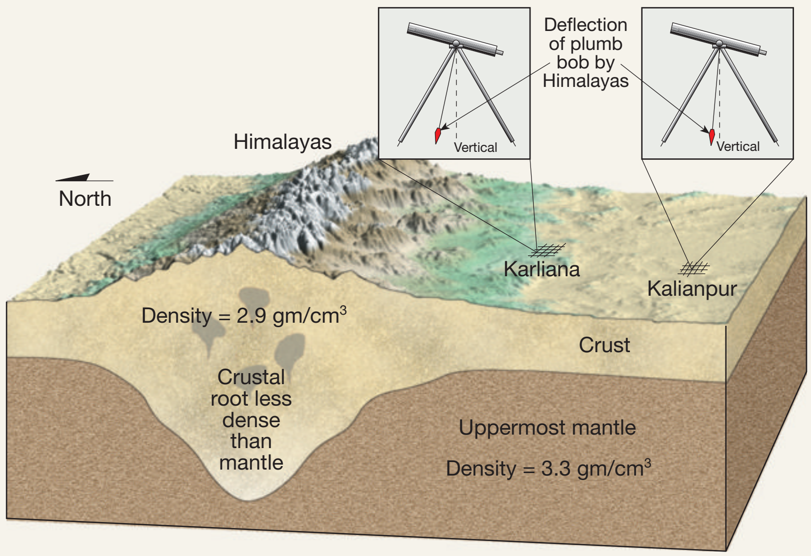


FIGURE 14.D During the first survey of India, an error in measurement occurred because the plumb bob on an instrument was deflected by the massive Himalayas. Later work by George Airy predicted that the mountains have roots of light crustal rocks. Airy's model explained why the plumb bob was deflected much less than expected.

A few years later, J. H. Pratt estimated the mass of the Himalayas and calculated the error that should have been caused by the gravitational influence of the mountains. To his surprise, Pratt discovered that the mountains should have produced an error three times larger than was actually observed. Simply stated, the mountains were not "pulling their weight." It was as if they had a hollow central core.

A hypothesis to explain the apparent "missing" mass was developed by George Airy. Airy suggested that Earth's lighter crustal rocks float on the denser, more easily deformed mantle. Further, he correctly argued that the crust must be thicker under mountains than beneath the adjacent lowlands. In other words, mountainous terrains are supported by light crustal material that extends as "roots" into the denser mantle (Figure 14.D). This phenomenon is exhibited by icebergs, which are buoyed up by the weight of the displaced water. If the Himalayas do have roots of light crustal rocks that extend far beneath them, then these mountains would exert less gravitational attraction, as Pratt had calculated. Hence, Airy's model explained why the plumb bob was deflected much less than expected.

Seismological and gravitational studies have confirmed the existence of crustal roots under some mountain ranges. The thickness of continental crust is normally about 35 kilometers, but crustal thicknesses exceeding 70 kilometers have been determined for some mountain belts.

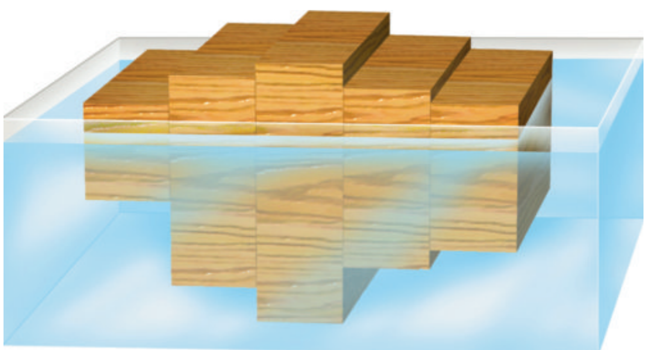


FIGURE 14.20 This drawing illustrates how wooden blocks of different thicknesses float in water. In a similar manner, thick sections of crustal material float higher than do thinner crustal slabs.

Uplifting Whole Continents Southern Africa is one region where large-scale vertical motion is evident. Here much of the region exists as an expansive plateau having an average elevation of nearly 1500 meters (5000 feet). Geologic studies have shown that southern Africa and the surrounding seafloor have been slowly rising for the past 100 million years, even though it has not experienced a plate collision for nearly 400 million years.

Evidence from seismic tomography (see Figure 12.20, p. 341) indicates that a large, mushroom-shaped mass of hot mantle rock is centered below the southern tip of Africa. This *superplume* extends upward about 2900 kilometers (1800 miles) from the mantle–core boundary and spreads out over several thousand kilometers. Researchers have concluded that the upward flow of this huge mantle plume is sufficient to elevate southern Africa.

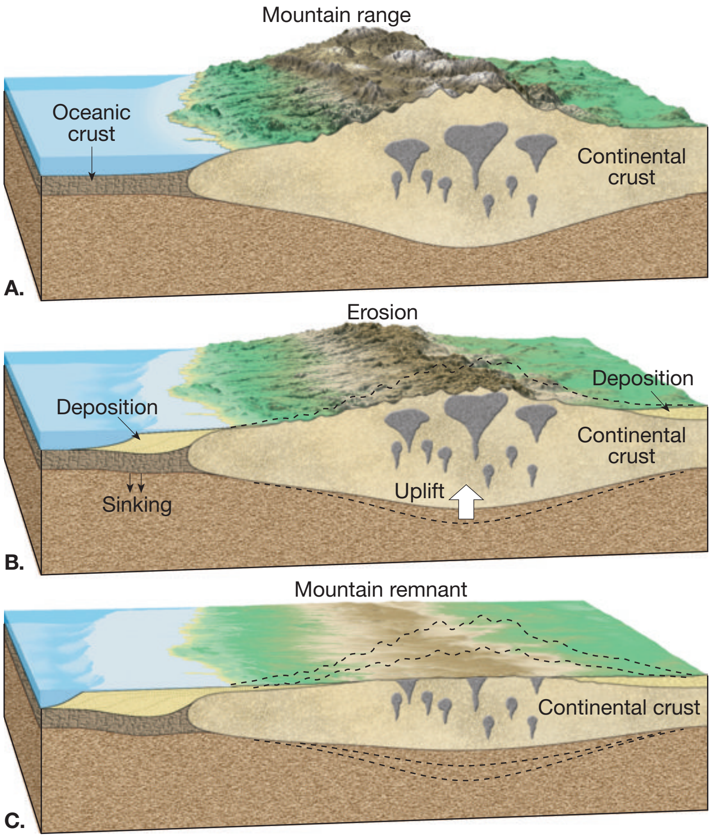


FIGURE 14.21 This sequence illustrates how the combined effects of erosion and isostatic adjustment result in a thinning of the crust in mountainous regions. **A.** When mountains are young, the continental crust is thickest. **B.** As erosion lowers the mountains, the crust rises in response to the reduced load. **C.** Erosion and uplift continue until the mountains reach "normal" crustal thickness.

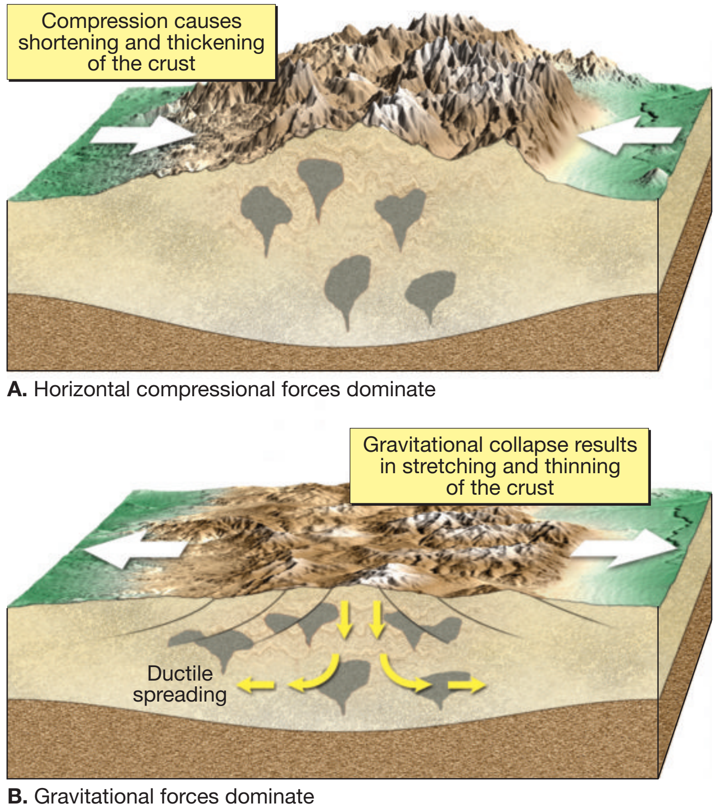


FIGURE 14.22 Block diagram of a mountain belt that is collapsing under its own "weight." Gravitational collapse involves normal faulting in the upper, brittle portion of the crust and ductile spreading at depth.

Crustal Subsidence Extensive areas of downwarping have also been discovered. For example, large, nearly circular basins are found in the interiors of some continents. Studies indicate that many major episodes of crustal downwarping are not caused by the weight of accumulating sediments. Rather, they show that the formation of basins promoted the accumulation of vast quantities of sediments. Several of these downwarped structures exist in the United States, including the large basins of Michigan and Illinois.

Similar episodes of large-scale downwarping are known on other continents, including Australia. The cause of these downward movements followed by rebound may be linked to the subduction of slabs of oceanic lithosphere. One proposal suggests that when subduction ceases along a continental margin, the subducting slab detaches from the trailing lithosphere and continues its descent into the mantle. As this detached lithospheric slab sinks, it creates a downward flow in its wake that tugs on the base of the overriding continent. In some situations the crust is apparently pulled down sufficiently to allow the ocean to extend inland. As the oceanic slab sinks deeper into the mantle, the pull of the trailing wake weakens and the continent "floats" back into isostatic balance.

Summary

- The name for the processes that collectively produce a *compressional mountain belt* is *orogenesis*. Most compressional mountains consist of folded and faulted sedimentary and volcanic rocks, portions of which have been strongly metamorphosed and intruded by younger igneous bodies.
- Plate convergence can result in a subduction zone consisting of four regions: (1) a *deep-ocean trench* that forms where a subducting slab of oceanic lithosphere bends and descends into the asthenosphere; (2) a *volcanic arc*, which is built upon the overlying plate; (3) a region located between the trench and the volcanic arc (*forearc region*); and (4) a region on the side of the volcanic arc opposite the trench (*backarc region*). Along some subduction zones backarc spreading results in the formation of *backarc basins*, such as those that floor the Sea of Japan and China Sea.
- Subduction of oceanic lithosphere under a continental block gives rise to an *Andean-type plate margin* that is

characterized by a continental volcanic arc and associated igneous plutons. In addition, sediment derived from the land, as well as material scraped from the subducting plate, becomes plastered against the landward side of the trench, forming an *accretionary wedge.* An excellent example of an inactive Andean-type mountain belt is found in the western United States and includes the Sierra Nevada and the Coast Range in California.

- Continued subduction of oceanic lithosphere beneath an Andean-type continental margin will eventually close an ocean basin. The result will be a *continental collision* and the development of compressional mountains that are characterized by shortened and thickened crust as exhibited by the Himalayas. The development of a major mountain belt is often complex, involving two or more distinct episodes of mountain building. A common feature of compressional mountains are *fold-and-thrust belts.* Continental collisions have generated many mountain belts, including the Alps, Urals, and Appalachians.
- Mountain belts can develop as a result of the collision and merger of an island arc, oceanic plateau, or some other small crustal fragment to a continental block. Many of the mountain belts of the North American Cordillera, principally those in Alaska and British Columbia, were generated in this manner.
- Although most mountains form along convergent plate boundaries, other tectonic processes, such as continental rifting, can produce uplift and the formation of topographic mountains. The mountains that form in these settings, termed *fault-block mountains,* are bounded by high-angle normal faults that gradually flatten with depth. The Basin and Range Province in the western United States consists of hundreds of faulted blocks that give rise to nearly parallel mountain ranges that stand above sediment-laden basins.
- Earth's less dense crust floats on top of the denser and deformable rocks of the mantle, much like wooden blocks floating in water. The concept of a floating crust in gravitational balance is called *isostasy.* Most mountainous topography is located where the crust has been shortened and thickened. Therefore, mountains have deep crustal roots that isostatically support them. As erosion lowers the peaks, *isostatic adjustment* gradually raises the mountains in response. The processes of uplifting and erosion will continue until the mountain block reaches "normal" crustal thickness. Gravity also causes elevated mountainous structures to collapse under their own "weight."
- Convective flow in the mantle contributes to the up-and-down bobbing of the crust. The upward flow of a large superplume located beneath southern Africa is thought to have elevated this region during the last 100 million years. Crustal subsidence has produced large basins and may have allowed the ocean to invade the continents several times in the geologic past.

Review Questions

1. In the plate tectonics model, which type of plate boundary is most directly associated with mountain building?
2. List the four main structures of a subduction zone, and describe where each is located relative to the others.
3. Briefly describe how backarc basins form.
4. Describe the process that generates most basaltic magma at subduction zones.
5. How are magmas that exhibit an intermediate to felsic composition thought to be produced from mantle-derived basaltic magmas at Andean-type plate margins?
6. What is a batholith? In what modern tectonic setting are batholiths being generated?
7. In what ways are the Sierra Nevada and the Andes similar? How are they different?
8. What is an accretionary wedge? Briefly describe its formation.
9. What is a passive margin? Give an example. Give an example of an active continental margin.
10. The formation of mountainous topography at a volcanic island arc, such as Japan, is considered just one phase in the development of a major mountain belt. Explain.
11. What tectonic structure is exhibited by the Coast Ranges of California?
12. Suture zones are often described as the place where continents are "welded" together. Why might that statement be misleading?
13. During the formation of the Himalayas, the continental crust of Asia was deformed more than India proper. Why do we think that happened?
14. Where might magma be generated in a newly formed collision mountain?
15. Suppose a sliver of oceanic crust was discovered in the interior of a continent. Would this support or refute the theory of plate tectonics? Explain.
16. How can the Appalachian Mountains be considered a collision-type mountain range when the nearest continent is 5000 kilometers (3000 miles) away?
17. How does the plate tectonics theory help explain the existence of fossil marine life in rocks atop compressional mountains?
18. In your own words, briefly describe the stages in the formation of a major mountain belt according to the plate tectonics model.
19. Define the term *terrane.* How is it different from the term *terrain?*

20. In addition to microcontinents, what other structures are thought to be carried by the oceanic lithosphere and eventually accreted to a continent?
21. Briefly describe the major differences between the evolution of the Appalachian Mountains and the North American Cordillera.
22. Compare the processes that generate fault-block mountains to those associated with most other major mountain belts.
23. Give one example of evidence that supports the concept of crustal uplift.
24. What happens to a floating object when weight is added? Subtracted? How does this principal apply to changes in the elevations of mountains? What term is applied to the adjustment that causes crustal uplift of this type?
25. How do some researchers explain the elevated position of southern Africa?

Key Terms

accretionary wedge (p. 384)
Andean-type plate margins (p. 382)
backarc basin (p. 381)
continental volcanic arc (p. 380)
fault-block mountains (p. 393)
fold-and-thrust belts (p. 387)
forearc basin (p. 385)
gravitational collapse (p. 395)
island arcs (p. 380)
isostasy (p. 394)
isostatic adjustment (p. 394)
microcontinent (p. 390)
orogenesis (p. 379)
passive margin (p. 382)
suture (p. 387)
terrane (p. 390)
volcanic island arc (p. 380)

Web Resources

The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

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