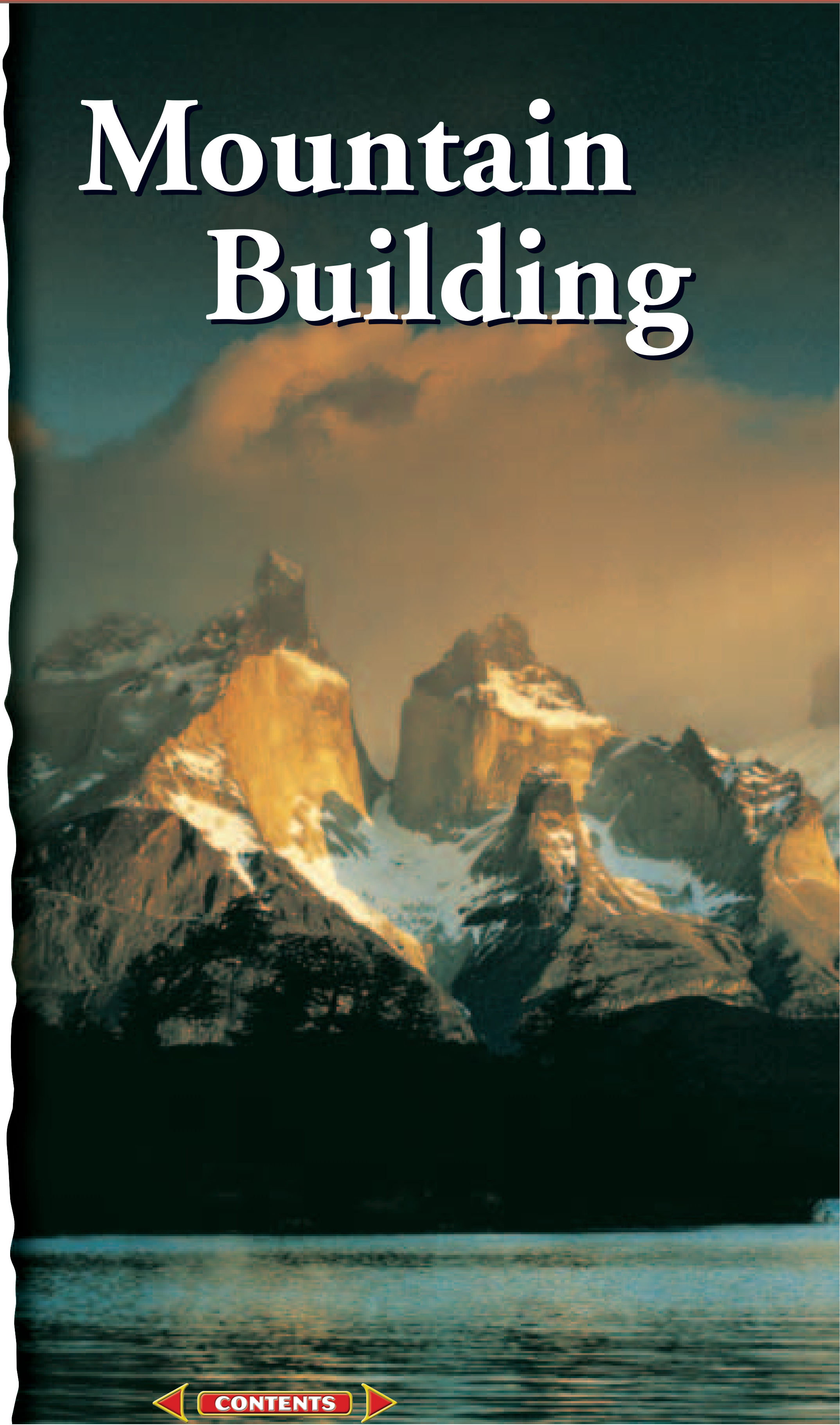
Chapter 20

# Mountain Building



## What You'll Learn

- Why Earth's crust displaces the mantle on which it rests.
- How different processes create mountains that rise above Earth's surface.

## Why It's Important

All mountains rise above the surrounding land, yet each of these awesome structures is unique. Understanding the various processes involved in mountain building is critical to our understanding of the dynamic planet on which we live.

Earth Science Online

To learn more about mountain building, visit the Earth Science Web Site at earthgeu.com



CONTENTS

# Discovery Lab

## Model Crustal Differences

Continental and oceanic crust have different densities. In this activity, you will model how both kinds of crust displace the mantle.

1. Obtain three wood blocks from your teacher. Determine the mass and volume of each. Calculate the density of each block. Record all of these values in a data table.
2. Half-fill a clear, plastic container with water. Place both of the 2-cm-thick blocks in the container.
3. Use a ruler to measure how much of each block is above the water surface. Record the measurements.
4. Replace the hardwood block with the 4-cm-thick softwood block.
5. Measure and record how much of each block is above the water surface.

***CAUTION: Always wear safety goggles and an apron in the lab.***

**Analyze and Conclude** Use your data to answer the following questions in your science journal. How does density affect the height of flotation? How does thickness affect the height of flotation? Which block represents oceanic crust? Continental crust?

# SECTION 20.1 *Crust-Mantle Relationships*

**OBJECTIVES**

- **Describe** *the elevation distribution of Earth's surface.*
- **Explain** *isostasy and how it pertains to Earth's mountains.*
- **Describe** *how Earth's crust responds to the addition and removal of mass.*

**VOCABULARY**

*isostasy*
*isostatic rebound*

Mountains are spectacular features of Earth's crust that rise high above their surroundings. Mountains can occur as individual peaks such as the Towers of Paine in southern South America, which are shown on the facing page, or as immense ranges that snake for many kilometers along the landscape. Why do these geologic wonders rise high above Earth's surface, and how are such vast masses of rock supported? The answers to these questions lie in the relationships between Earth's crust and the underlying mantle.

## Earth's Topography

When you look at a globe or a map of Earth's surface, you immediately notice the oceans and continents. From these models of Earth, you can estimate that about 70 percent of Earth's surface is below sea level, and that the remaining 30 percent lies above the ocean's surface. What isn't obvious from most maps and globes, however, is the change in elevation, or topography, of the crust. Look at ***Figure 20-1*** on the next page, which is a map of the general topography of Earth's crust. Where are

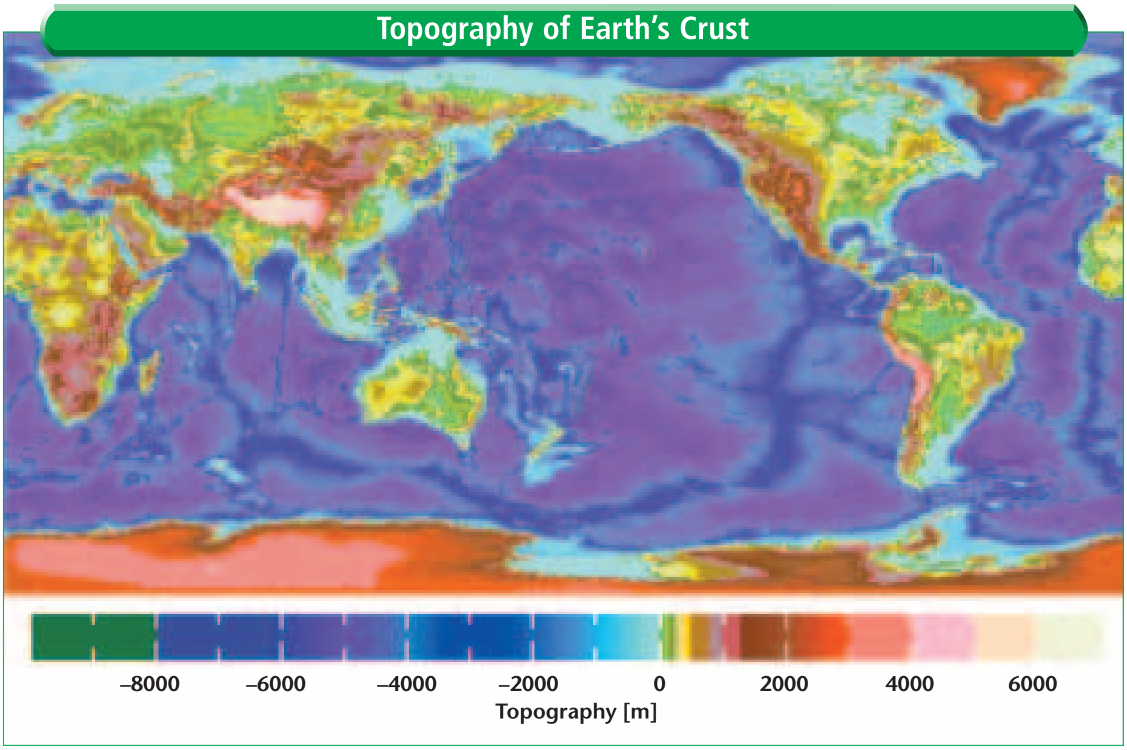



**Figure 20-1** The highest point on Earth is Mt.Everest in Asia. The lowest point on Earth is the Mariana Trench, which is in the Pacific Ocean.

Earth's highest elevations? Where are Earth's lowest elevations?

When Earth's topography is plotted on a graph, a pattern in the distribution of elevations emerges, as shown in ***Figure 20-2.*** Note that there are two main elevation modes. Most of Earth's elevations cluster around these two modes: 0 to 1 km above sea level and 4 to 5 km below sea level. These two modes dominate Earth's topography and reflect the basic differences in density and thickness between continental and oceanic crust.

You observed in the *Discovery Lab* at the beginning of this chapter that blocks of wood with different densities displaced different amounts of water, and thus floated at various heights above the surface of the water. The block with the greatest density displaced the most water and floated lower in the water than the less-dense blocks. The results of this simple experiment are similar to the relationship that exists between Earth's crust and mantle. Recall from Chapter 1 that oceanic crust is composed mainly of basalt and that continental crust is composed primarily of granite. The average density of basalt is about 2.9 g/cm$^3$, while the average density of granite is about 2.8 g/cm$^3$. The slightly higher density of oceanic crust causes it to displace more of the mantle—which has a density of about 3.3 g/cm$^3$—than the same thickness of continental crust does.

Differences in elevation, however, are not caused by density differences alone. Recall from the *Discovery Lab* what happened when the

**Using Math**

**Using Numbers**
Suppose a mountain is being uplifted at a rate of 1 m every 1000 years. It is also being eroded at a rate of 1 cm/y. Is this mountain rising faster than it is being eroded? Explain.

thicker wood block was placed in the water. It displaced more water than the other two blocks, but, because of its density, it floated higher in the water than the other two blocks. Continental crust, which is thicker and less dense than oceanic crust, behaves similarly. It extends deeper into the mantle because of its thickness, and it rises higher above Earth's surface than oceanic crust because of its lower density, as shown in ***Figure 20-3.***

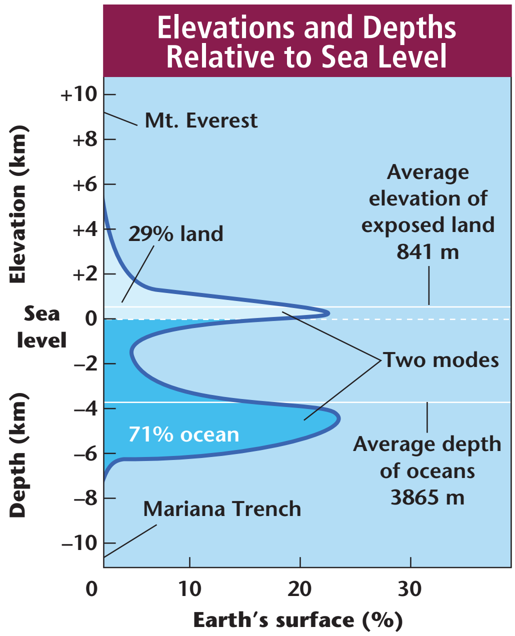



**Figure 20-2** About 29% of Earth is land; 71% of Earth is water. Two elevations dominate Earth's surface: 0 to 1 km above sea level and 4 to 5 km below sea level. The average elevation above sea level is 841 m. The average depth of Earth's oceans is 3865 m.

## ISOSTASY

The displacement of the mantle by Earth's continental and oceanic crust is a condition of equilibrium called **isostasy.** The crust and mantle are in equilibrium when the force of gravity on the mass of crust involved is balanced by the upward force of buoyancy. This balance is familiar to you if you have ever watched people get in and out of a small boat. As the people boarded the boat, it sank deeper into the water. Conversely, as the people got out of the boat, it displaced less water and floated higher in the water.

A similar sinking and rising that result from the addition and removal of mass occurs with the crust that makes up Earth's mountains. Gravitational and seismic studies have detected thick roots of continental material that extend into the mantle below Earth's mountain ranges. According to the principle of isostasy, parts of the crust will rise or subside until these parts are buoyantly supported by their roots. In other words, a mountain range requires large roots to counter the enormous mass of the range above Earth's surface. Continents and mountains are said to float on the mantle because they are less dense than the underlying mantle and therefore project into the mantle to

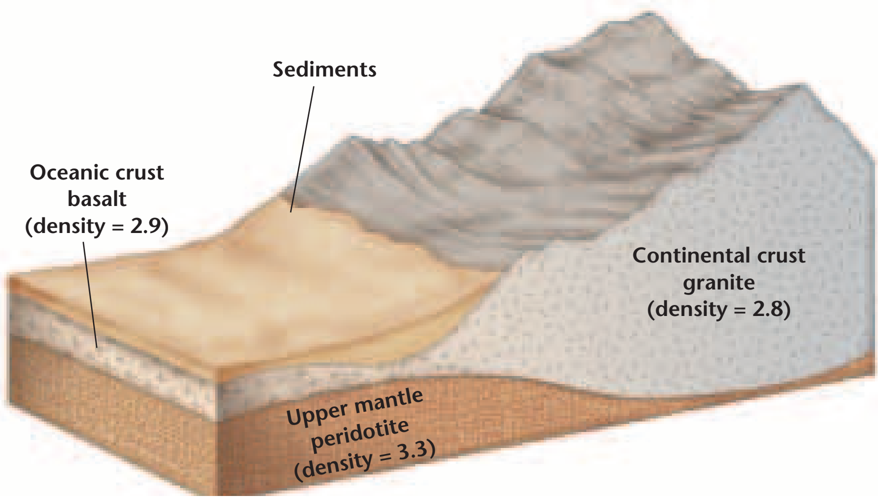



**Figure 20-3** Continental crust is less dense and thicker than oceanic crust, and it thus extends higher above Earth's surface and deeper into the mantle than oceanic crust.

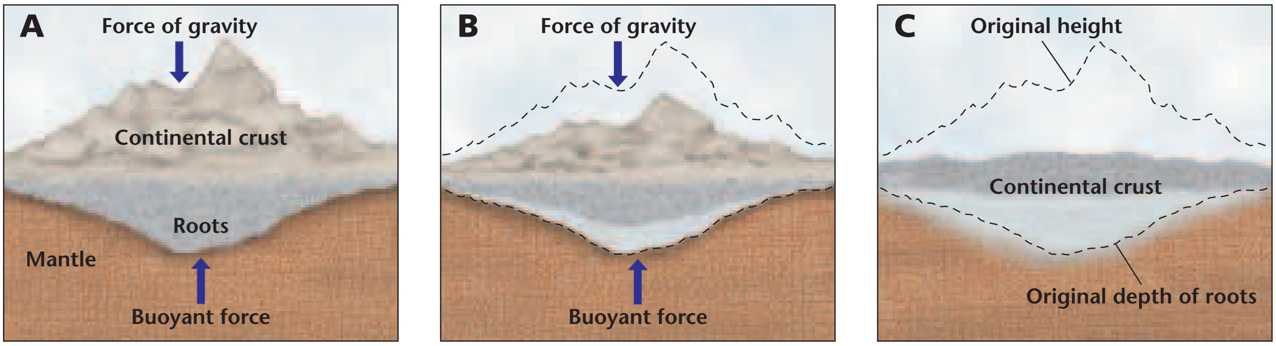



**Figure 20-4** Mountains are underlain by massive roots that extend into the mantle **(A).** As erosion takes place, mass is lost from the mountain, causing the root to rise in response to this decrease in mass **(B).** When the mountain has been eroded to the average continental thickness, the root that once supported it is also gone **(C).**

provide the necessary buoyant support. What do you think happens when mass is removed from a mountain or mountain range?

**Isostasy and Erosion** You might recall from Chapter 17 that the Appalachian Mountains formed millions of years ago when the North American continent collided with the European continent. Rates of erosion on land are such that these mountains should have been completely eroded long ago. Why, then, do these mountains still exist? As mountains rise above Earth's surface, deep roots form until isostatic equilibrium is achieved and the mountains are buoyantly supported. As peaks are eroded, mass decreases, and the roots become smaller, as shown in ***Figure 20-4.*** A balance between erosion and the decrease in the size of the root will continue for hundreds of millions of years until both the mountains and their roots disappear. This slow process of the

## Problem-Solving Lab

### Making and Interpreting Graphs

**Graph isostatic rebound** The rate of isostatic rebound changes over time. An initially rapid rate often declines to a very slow rate. Use the data in the table to generate a graph of isostatic rebound with time.

**Isostatic Rebound Data**

| Years Before Present | Total Amount of Rebound (m) |
|---|---|
| 8000 | 54 |
| 6000 | 80 |
| 4000 | 93 |
| 2000 | 100 |
| 0 | 104 |

**Analysis**

1. How much of the total rebound occurred during the first 2000 years?

**Thinking Critically**

2. Predict how much rebound will still occur. Approximately how long will this take?
3. Study your graph. Describe how the rate of isostatic rebound decreases with time.

crust's rising as the result of the removal of overlying material is called **isostatic rebound.** You can explore how the rate of isostatic rebound changes with time in the *Problem-Solving Lab* on page 526.

Crustal movements resulting from isostasy are not restricted to Earth's continents. Individual volcanic mountains called seamounts can form on the ocean floor as a result of a plate's moving over a hot spot in Earth's mantle. On the geologic time scale, these mountains form very quickly. What do you think happens to the seafloor after these seamounts form? The seamounts are added mass. As a result of isostasy, the oceanic crust around these peaks displaces the underlying mantle until equilibrium is achieved.

You've just learned that the elevation of Earth's crust depends upon the thickness of the crust as well as its density. You also learned that a mountain peak is countered by a root. Mountain roots can be many times as deep as a mountain is high. Mt. Everest, shown in ***Figure 20-5,*** towers nearly 9 km above sea level and is the tallest peak in the Himalayan Mountains. Some parts of the Himalayas are underlain by crustal roots nearly 80 km thick! You'll learn more about Mt. Everest in the *Science & Math* feature at the end of this chapter. Where do the immense forces required to produce such crustal thickening originate? You'll find out in the next section.

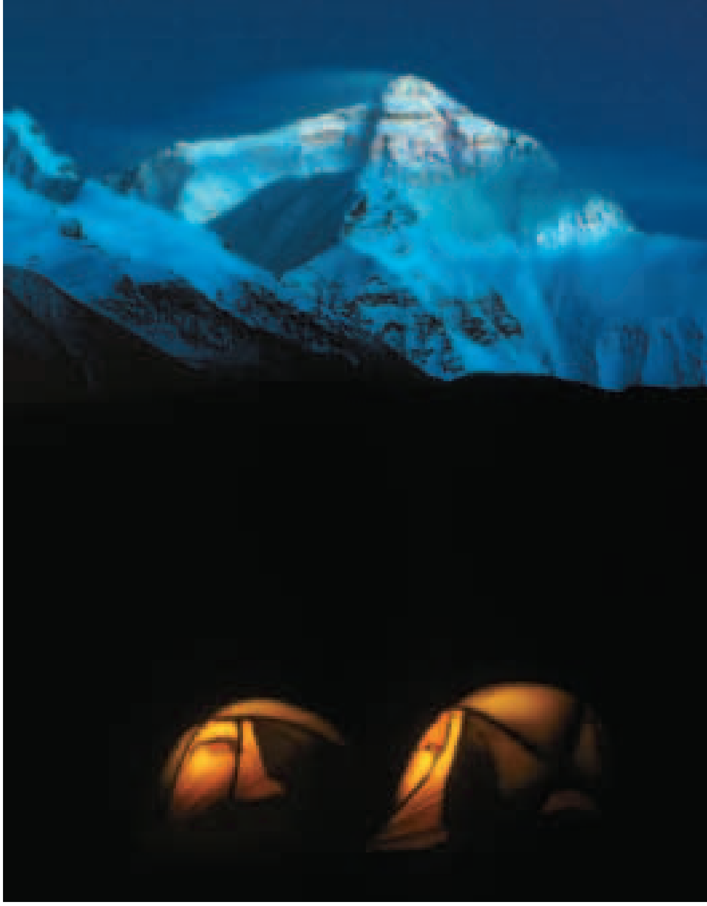


**Figure 20-5** Mt. Everest, a peak in Asia, is currently the highest mountain on Earth. It is underlain by a very deep crustal root that supports its mass.

## SECTION ASSESSMENT

1. If continental crust were thinner than its average thickness of 40 km, would it depress the mantle more or less than it does now? Explain.
2. What is isostasy?
3. Describe the distribution of Earth's elevations and explain what causes this distribution.
4. Why is the crust thicker beneath continental mountain ranges than it is under flat-lying stretches of landscape?
5. **Thinking Critically** The area around the Great Lakes was once covered by thick sheets of ice. Use the principle of isostasy to explain how the melting of these ice sheets has affected the land around the lakes.

### SKILL REVIEW

6. **Recognizing Cause and Effect** Explain what happens in terms of isostasy to the land surrounding a mountain range as sediments are eroded from the mountains onto the nearby land. For more help, refer to the *Skill Handbook.*

# SECTION 20.2 Convergent-Boundary Mountains

**OBJECTIVES**

- **Compare** *and* **contrast** *the different types of mountains that form along convergent plate boundaries.*
- **Explain** *how the Appalachian Mountains formed.*

**VOCABULARY**

*orogeny*

A quick glance at a world map will show that Earth's landscape is dotted with numerous mountain peaks and ranges. The Cascades and the Appalachians, for example, run north-south on either side of the United States. The Andes form the western border of South America, and the majestic Himalayas separate Nepal from Tibet. Mt. Kilimanjaro is a volcano that rises high above the African continent. Mauna Loa, another volcanic peak, is located in Hawaii. Most of these ranges and peaks, like most earthquakes and volcanoes, have formed as a result of tectonic interactions.

## OROGENY

The processes that form all mountain ranges are called **orogeny.** Orogeny results in broad, linear regions of deformation known as orogenic belts. Most orogenic belts, as shown in ***Figure 20-6,*** are associated with plate boundaries. The greatest variety and the tallest of these belts are found at convergent boundaries. The compressive forces at these

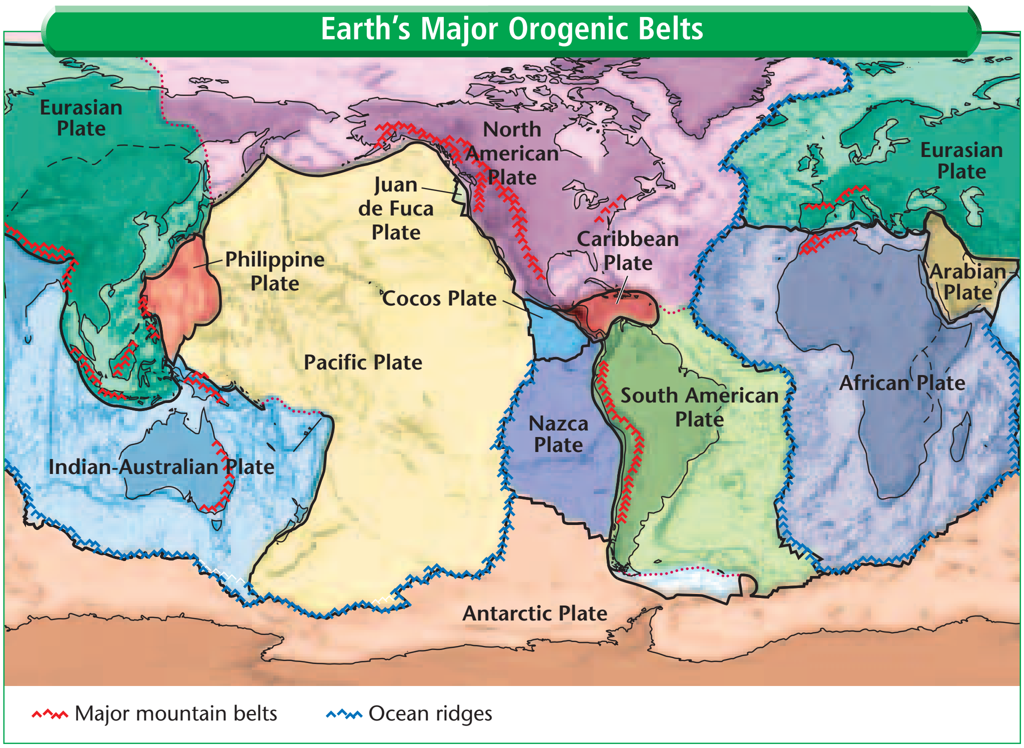



**Figure 20-6** Most of Earth's mountain ranges have formed along plate boundaries.

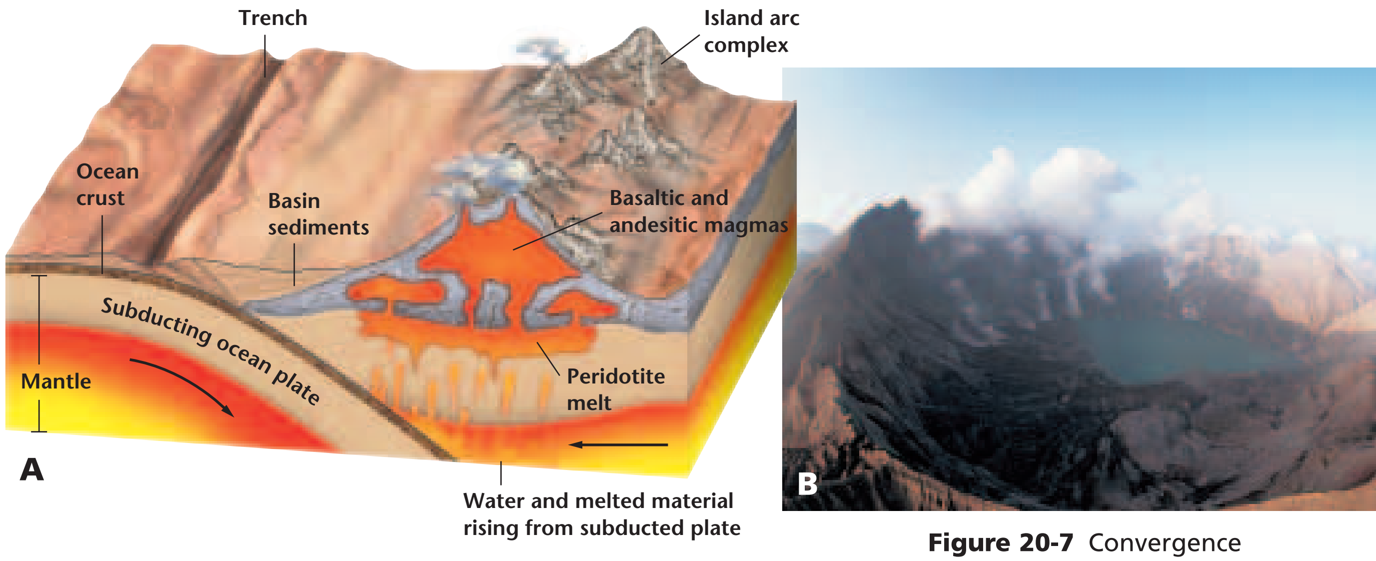



**Figure 20-7** Convergence between two oceanic plates results in the formation of individual volcanic peaks that make up an island arc complex **(A).** Mt. Pinatubo, shown here **(B),** is one of several volcanic peaks that make up the island arc complex known as the Philippine Islands.

boundaries may cause the intense deformation—folding, faulting, metamorphism, and igneous intrusions—that is characteristic of orogenic belts. Interactions at each type of convergent boundary create different types of mountain ranges.

**Oceanic-Oceanic Convergence** When an oceanic plate converges with another oceanic plate, one plate descends into the mantle to create a subduction zone. As parts of the subducted plate melt, magma is forced upward to form a series of volcanic peaks called an island arc complex. The tectonic relationships and processes associated with oceanic-oceanic convergence are detailed in ***Figure 20-7A.*** Note that the crust along the island arc thickens to form a root. According to the principle of isostasy, it is the displacement of the mantle by this root that provides the necessary buoyancy for a mountain peak.

What kinds of rocks make up island arc complexes? Recall from Chapter 19 that seismic studies indicate that much of the mantle is made of an igneous rock called peridotite. The water released from a subducted plate and the sediments it carries causes the peridotite to melt. The melted rocks, along with bits of the subducted plate, are forced upward toward the surface, where more melting occurs. As the melted material comes into contact with the crust, magmas with different compositions form. Eventually, basaltic and andesitic magmas rise to the surface and erupt to form the island arc complex.

In addition to the volcanic rocks that make up an island arc complex, some large complexes contain sedimentary rocks. Between an island arc and a trench is a depression, or basin, which fills with sediments eroded from the island arc. If subduction continues for a long enough period of time, some of these sediments can be uplifted,

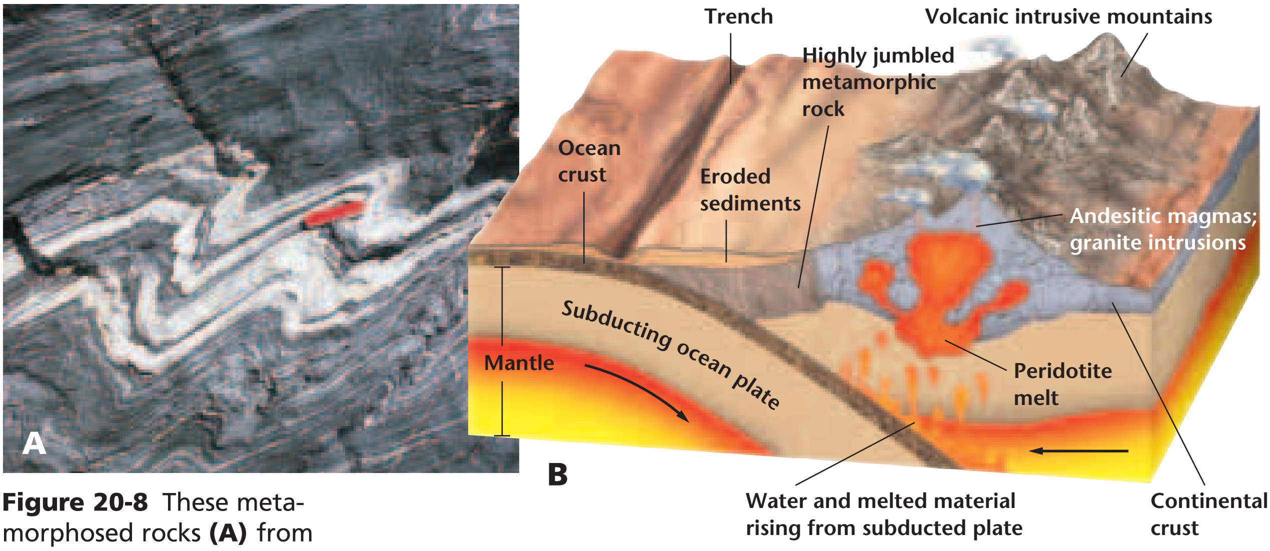



**Figure 20-8** These metamorphosed rocks **(A)** from Catalina Island, California, formed as the result of convergence of an oceanic plate with a continental plate. At an oceanic-continental boundary **(B)** compression causes continental crust to fold and thicken. Igneous activity and metamorphism are also common along such boundaries.

folded, faulted, and thrust against the island arc to form a complex mass of sedimentary and island-arc volcanic rocks.

**Oceanic-Continental Convergence** Oceanic-continental boundaries are very similar to oceanic-oceanic boundaries in that convergence along both creates subduction zones and trenches. The similarity ends there, however, because convergence between oceanic and continental plates can produce major mountain belts. When an oceanic plate converges with a continental plate, the descending oceanic plate forces the edge of the continental plate upward. This uplift marks the beginning of orogeny, as detailed in ***Figure 20-8B.*** In addition to uplift, compressive forces may cause the continental crust to fold and thicken. As the crust thickens, higher and higher mountains form. Deep roots develop to support these enormous masses of rocks.

Another important orogenic process that occurs along an oceanic-continental boundary is the formation of magma, as illustrated in ***Figure 20-8B.*** As the subducting plate sinks into the mantle, parts of the plate begin to melt. As the magma moves upward through the continental crust, the magma becomes rich in silica and gives rise to granitic intrusions and volcanoes fueled by andesitic magma.

Sediments eroded from volcanic intrusive mountains may fill the low areas between the trench and the coast. These sediments, along with ocean sediments and material scraped off the descending plate, are shoved against the edge of the continent to form a jumble of highly folded, faulted, and metamorphosed rocks. The metamorphosed rocks shown in ***Figure 20-8A*** formed when the Pacific Plate subducted beneath the North American Plate millions of years ago.

Earth Science Online

**Topic: Mt. Everest**
To take a virtual tour of Mt. Everest, visit the Earth Science Web Site at earthgeu.com

**Activity: High Altitudes**
Research the effects of high altitudes on climbers. How does the density of air at 29 000 feet affect the human body? How do climbers cope with this effect?

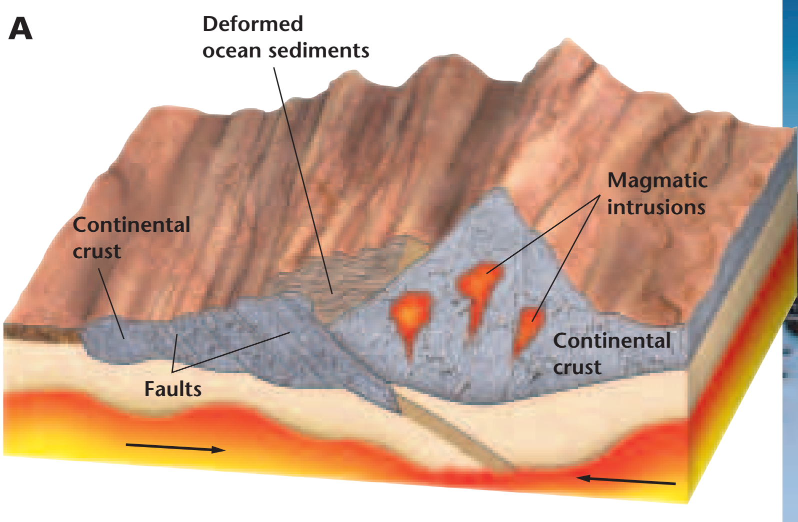
**Continental-Continental Convergence** Earth's tallest mountain ranges, including the Himalayas, are formed at continental-continental plate boundaries. Because of its relatively low density, continental crust cannot be subducted into the mantle when two plates converge. Instead, the energy associated with the collision is transferred to the crust involved, which becomes highly folded and faulted, as shown in ***Figure 20-9A.*** Compressional forces break the crust into thick slabs that are thrust onto each other along low-angle faults. This process can double the thickness of the deformed crust. Deformation can also extend laterally for hundreds of kilometers into the continents involved. The magma that forms as a result of continental-continental mountain building hardens beneath Earth's surface to form granite batholiths.

Another common characteristic of mountains that form when two continents collide is the presence of marine sedimentary rock near the mountains' summits. Where do you think this rock comes from? Such rock forms from the sediments deposited in the ocean basin that existed between the continents before their collision. Mount Godwin Austen, also known as K2 in the western Himalayas, for example, is composed of thousands of meters of marine limestone that sits upon a granite base. The limestone represents the northern portions of the old continental margin of India that were pushed up and over the rest of the continent when India began to collide with Asia about 50 million years ago.

NATIONAL GEOGRAPHIC

To learn more about Mt. Everest, the tallest peak in the Himalayas, go to the **National Geographic Expedition** on page 864.

**Figure 20-9** Intense folding and faulting along continental-continental boundaries produce some of the highest mountain ranges on Earth **(A).** K2, shown here **(B),** is the second-highest peak in the Himalayas; only Mt. Everest is taller.




## The Appalachian Mountains–A Case Study

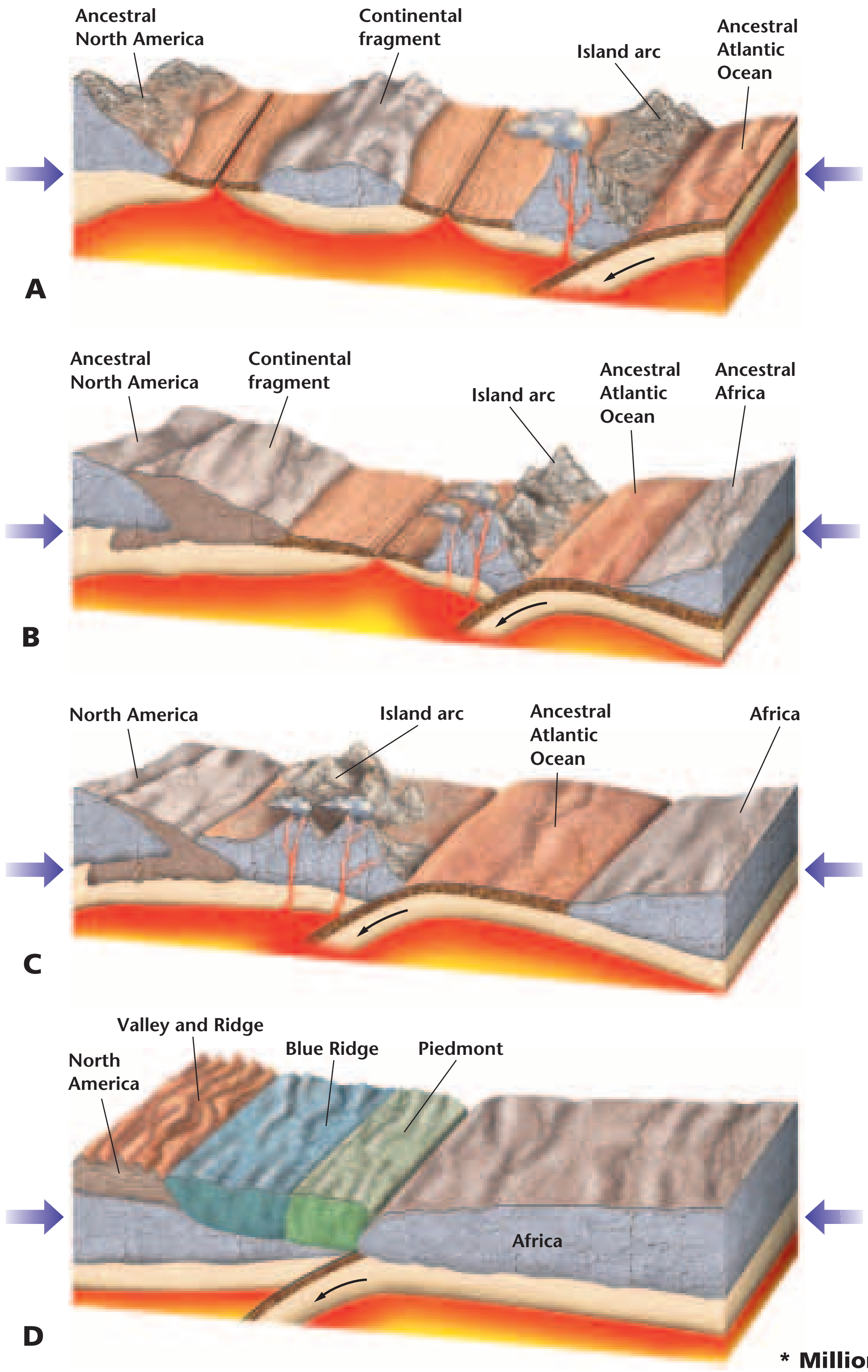
Recall from Chapter 17 that Alfred Wegener used the matching rocks and geologic structures in the Appalachians and mountains in Greenland and northern Europe to support his hypothesis of continental drift. In addition to Wegener, many other scientists have studied the Appalachians. In fact, the geology of this mountain range, which is located in the eastern United States, has been the subject of many studies for more than a hundred years. Based on these studies, geologists have divided the Appalachian Mountain Belt into several distinct regions, including the Valley and Ridge, the Blue Ridge, and the Piedmont Provinces. Each region is characterized by rocks that show different degrees of deformation. Rocks of the Valley and Ridge Province, for example, some of which are shown in ***Figure 20-10,*** are highly folded; most of the rocks that make up the Piedmont Province are not. Why are these regions so different? What kinds of processes led to their formation?

**The Early Appalachians** The tectonic history of the Appalachian Mountains began about 700 to 800 million years ago when ancestral North America separated from ancestral Africa along two divergent boundaries to form two oceans. The ancestral Atlantic Ocean was located off the western coast of ancestral Africa. A shallow, marginal sea formed along the eastern coast of ancestral North America. A continental fragment was located between the two divergent boundaries.

About 700 to 600 million years ago, the directions of plate motions reversed. The ancestral Atlantic Ocean began to close as the plates converged. This convergence resulted in the formation of a subduction zone and a volcanic island arc east of ancestral North America, as shown in ***Figure 20-11A.***

**Figure 20-10** These folded rocks in West Virginia are part of the Valley and Ridge Province of the Appalachian Mountains.

**Figure 20-11** The Appalachians formed millions of years ago as a result of convergence.




**700-600 M.Y.B.P.*** Convergence causes the ancestral Atlantic Ocean to begin to close. An island arc develops east of ancestral North America.

**500-400 M.Y.B.P.** The continental fragment, which eventually becomes the Blue Ridge Province, becomes attached to ancestral North America.

**400-300 M.Y.B.P.** The island arc becomes attached to ancestral North America and the continental fragment is thrust farther onto ancestral North America. The arc becomes the Piedmont Province.

**300-260 M.Y.B.P.** Ancestral Africa collides with ancestral North America to close the ancestral Atlantic Ocean. Compression forces the Blue Ridge and Piedmont rocks farther west and the folded Valley and Ridge Province forms.

*** Million Years Before Present**

**Figure 20-12** The metamorphosed rocks in the foreground are parts of the Blue Ridge Province of North Carolina.

About 200 million years passed before the continental fragment became attached to ancestral North America, as shown in ***Figure 20-11B*** on page 533. These highly metamorphosed rocks, some of which are shown in ***Figure 20-12,*** were thrust over younger rocks to become the Blue Ridge Province.

### The Final Stages of Formation

Between about 400 and 300 million years ago, the island arc became attached to North America, as shown in ***Figure 20-11C*** on page 533. Evidence of this event is preserved in the Piedmont Province as a group of metamorphic and igneous rocks. These rocks were also faulted over the continent, pushing the Blue Ridge rocks farther west.

Between about 300 and 260 million years ago, the ancestral Atlantic Ocean closed as ancestral Africa, Europe, and South America collided with ancestral North America to form Pangaea. This collision resulted in extensive folding and faulting, as illustrated in ***Figure 20-11D*** on page 533, to form the Valley and Ridge Province. When rifting caused Pangaea to break apart about 200 million years ago, the modern Atlantic Ocean formed.

The Appalachian Mountains are only one example of the many mountain ranges that have formed along convergent boundaries. In the next section, you'll find out about the orogeny that takes place along divergent plate boundaries, as well as some of the types of mountains that form far from plate margins.

## SECTION ASSESSMENT

1. Describe how mountains form along a continental-continental plate boundary.
2. How do the mountains that form at oceanic-oceanic plate boundaries differ from the mountains that form at oceanic-continental plate boundaries?
3. **Thinking Critically** Locate the Aleutian Islands on the map shown in ***Figure 20-6.*** How do you think these mountain peaks formed?

### SKILL REVIEW

4. **Sequencing** Sequence the events that resulted in the formation of the Appalachian Mountains. For more help, refer to the *Skill Handbook.*

# SECTION 20.3 Other Types of Mountains

When ocean ridges were first discovered, they caused quite a stir in the scientific community simply because of their size. These mountains form a continuous chain that snakes along Earth's ocean floor for over 65 000 km! In addition to their being much longer and taller than most of their continental counterparts, these mountains formed as a result of different orogenic processes.

## DIVERGENT-BOUNDARY MOUNTAINS

Ocean ridges are regions of very broad uplift that seems to be related to the rising convection cells that form deep in the mantle beneath these ridges. As matter is heated, it expands, which results in a decrease in density. Magma is less dense than surrounding mantle material, and thus it is forced upward, where it warms the overlying lithosphere. As a result of this increase in temperature, the lithosphere along a divergent boundary bulges upward and stands higher than the surrounding ocean crust to form a gently sloping mountain range, as shown in ***Figure 20-13.*** As newly formed lithosphere moves away from the central rift, it cools, contracts, and becomes more dense.

Ocean ridge mountain ranges can be thousands of kilometers wide. In the *MiniLab* on page 536, you will compare the size of one ocean ridge, the Mid-Atlantic Ridge, with the size of the continental United States.

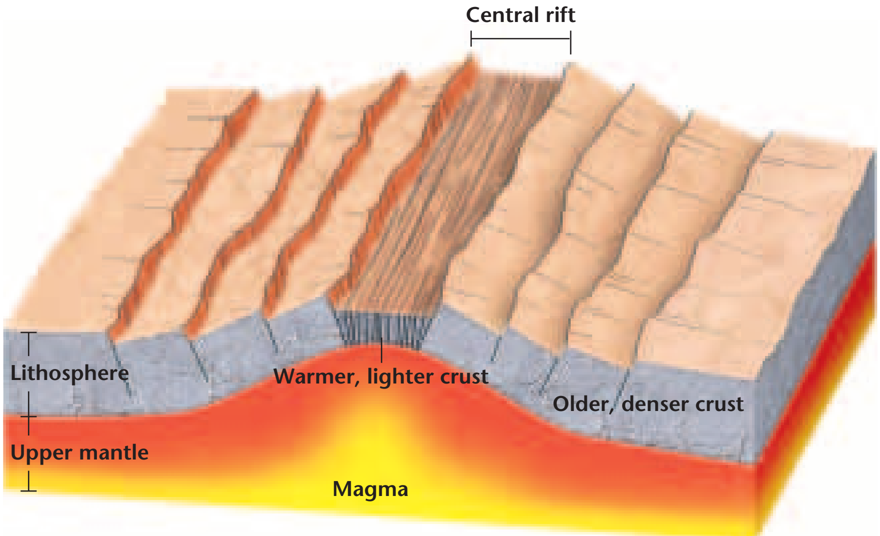



**Figure 20-13** An ocean ridge is a broad, topographic high that forms as lithosphere bulges upward due to an increase in temperature along a divergent boundary.

### OBJECTIVES

- **Describe** *the mountain ranges that form along ocean ridges.*
- **Compare** *and* **contrast** *uplifted and fault-block mountains.*
- **Describe** *the mountains that form as a result of hot spots in Earth's mantle.*

### VOCABULARY

*pillow basalt*
*uplifted mountain*
*fault-block mountain*

## MiniLab

### How large is an ocean ridge?

**Compare** the width of part of an ocean ridge with the size of the United States.

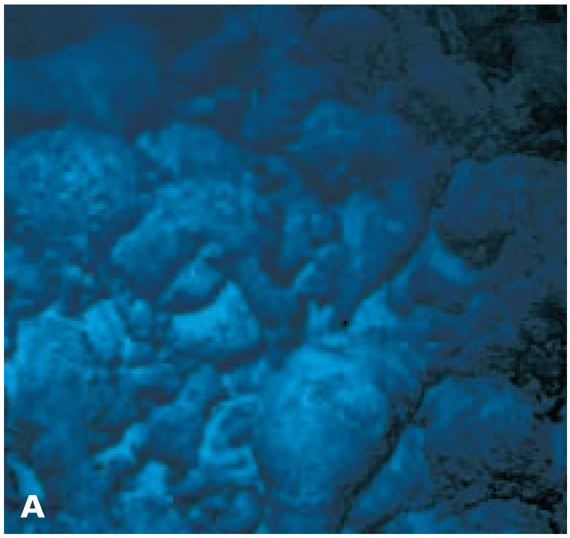
### Procedure

1. Obtain physiographic maps of the Atlantic Ocean floor and North America.
2. Use tracing paper to copy the general outline of a section of the Mid-Atlantic Ridge. The length of the section should be long enough to stretch from San Francisco to New York City. Mark the ridge axis on your tracing.
3. Place the same tracing paper on the map of North America with the ridge axis running east-west. Trace the general outline of the United States onto the paper.

### Analyze and Conclude

1. How wide is the Mid-Atlantic Ridge?
2. Are there any parts of the United States that are not covered by your tracing?
3. If a mountain range the size of the Mid-Atlantic Ridge were located in the United States as you have drawn it, how would it affect the major river drainage patterns and climates in various parts of North America?

**Ocean–Ridge Rocks** Ocean ridges are composed mainly of igneous rocks. Recall from Chapter 17 that as tectonic plates separate along an ocean ridge, hot mantle material is forced upward. The partial melting of this material results in a mixture that accumulates in a magma chamber beneath the ridge. From the chamber, the mixture intrudes into the overlying rock to form a series of vertical dikes that resemble a stack of index cards standing on edge, as shown in ***Figure 20-14B.*** Some of the magma also pushes through the dikes and erupts onto the seafloor to form igneous rocks called **pillow basalts,** which, as you can see in ***Figure 20-14A,*** resemble a pile of sandbags.



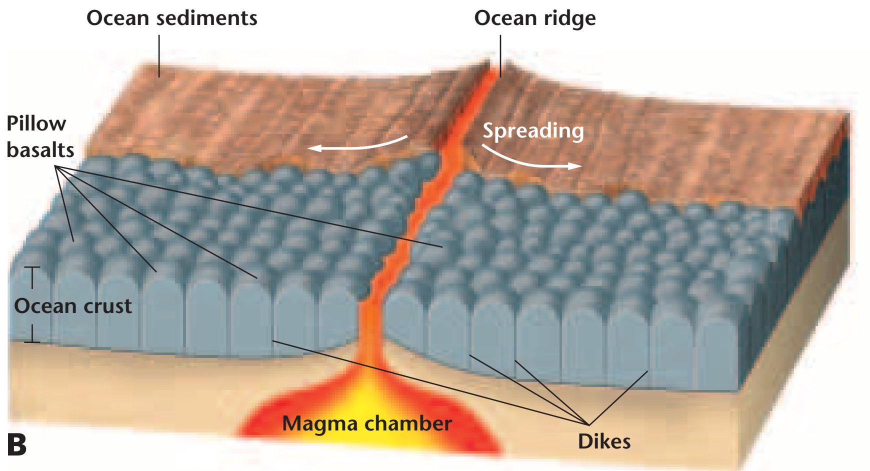




**Figure 20-14** Vertical dikes overlain by pillow basalts, which are shown in the photo **(A),** are characteristic of ocean-ridge rocks **(B).**

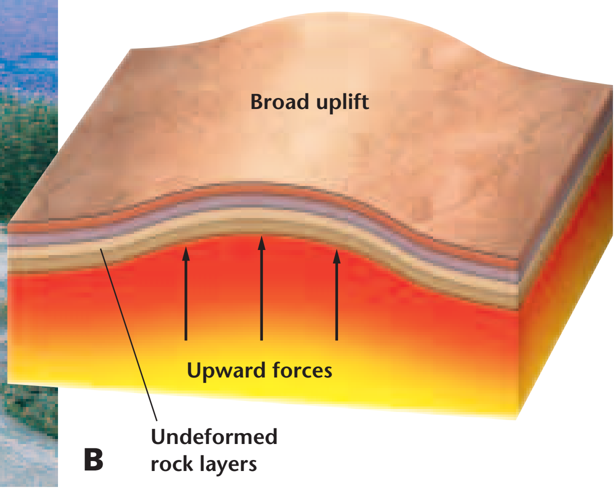
## Nonboundary Mountains

You've just learned that island arc complexes, intrusive volcanic mountain ranges, highly folded continental mountains, and ocean ridges are all associated with plate boundaries. While these types of mountains make up the majority of ranges and peaks on Earth, some mountains and peaks form in places far removed from tectonic boundaries. Three nonboundary types of mountains are uplifted mountains, fault-block mountains, and some volcanoes.

**Uplifted Mountains** As shown in ***Figure 20-15B,*** some mountains form when large regions of Earth have been slowly forced upward as a unit; these mountains are called **uplifted mountains.** The Adirondack Mountains in New York State, shown in ***Figure 20-15A,*** are uplifted mountains. Generally, the rocks that make up uplifted mountains undergo less deformation than rocks associated with plate boundary orogeny, which are highly folded, faulted, and metamorphosed.

The cause of large-scale regional uplift is not well understood. It is possible that warmer regions of the mantle heat these portions of the lithosphere. The heat causes the density of the crust to decrease, resulting in slow uplift as that section rebounds in response to isostasy. Another possible cause is upward movement in the mantle, which lifts regions of the crust without causing much deformation. Regional uplift can form broad plateaus, such as the Colorado Plateau, which extends through Colorado, Utah, Arizona, and New Mexico. Erosional forces eventually carve uplifted areas to form mountains, valleys, and canyons.

**Figure 20-15** The Adirondack Mountains of New York State, shown in the photo **(A),** are uplifted mountains. Uplifted mountains form when large sections of Earth's crust are forced upward without much structural deformation **(B).**

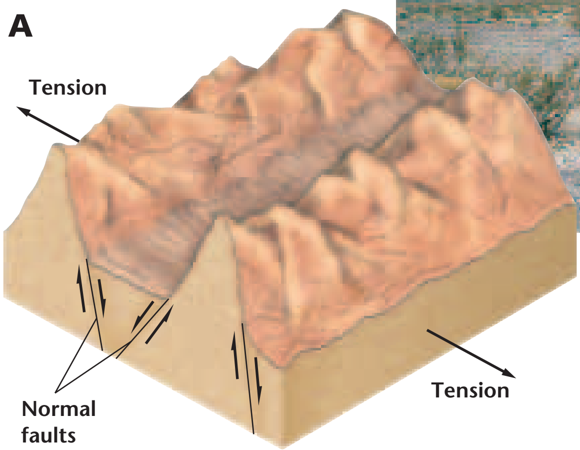




**Figure 20-16** Fault-block mountains are areas of Earth's crust that are higher than the surrounding landscape as the result of faulting **(A).** The Basin and Range Province consists of hundreds of mountains separated by normal faults **(B).**

**Fault-Block Mountains** Another type of mountain that is not necessarily associated with plate boundaries is a fault-block mountain. **Fault-block mountains** form when large pieces of crust are tilted, uplifted, or dropped downward between large faults, as shown in ***Figure 20-16A.*** The Basin and Range Province of the southwestern United States and northern Mexico, a part of which is shown in ***Figure 20-16B,*** consists of hundreds of nearly parallel mountains separated by normal faults. The Grand Tetons in Wyoming are also fault-block mountains. You'll explore the topography of this range in the *Mapping Geolab* at the end of this chapter.

**Volcanic Peaks** Volcanoes that form along oceanic-continental convergent margins are usually parts of large mountain ranges. Volcanoes that form over hot spots, however, are generally solitary peaks that form far from tectonic plate boundaries. Recall from Chapter 18 that a hot spot is a region in Earth's mantle that is much hotter than the surrounding area. As a tectonic plate moves over a hot spot, plumes of mantle material are forced through the crust to form a volcanic peak. As the plate continues to move over the hot spot, a chain of volcanoes forms. The shield volcanoes that make up the state of Hawaii are volcanic peaks that formed as the Pacific Plate moved over a hot spot in the mantle. Mauna Kea, which is shown in ***Figure 20-17,*** is one of these volcanic peaks.

**Figure 20-17** Mauna Kea, and the small volcanoes that dot its flanks are some of the many volcanic peaks that make up the Hawaiian Islands, which formed as the Pacific Plate moved over a hot spot in Earth's mantle.

While all mountains are similar in that they tower high above the surrounding land, individual peaks and chains are unique, as you have discovered in this chapter. Some peaks and chains form along tectonic plate boundaries, while others form far from these boundaries. Some mountains are produced by faulting and folding; others form as the result of igneous activity and crustal uplift. No matter how they form, all mountains are evidence that Earth, unlike some of its neighbors, is truly a dynamic planet.

## SECTION ASSESSMENT

1. What kinds of rocks are associated with ocean ridges?
2. Explain why an ocean ridge is higher than the surrounding crust.
3. How do volcanoes that form when a plate moves over a hot spot in the mantle differ from volcanoes that form along convergent plate boundaries?
4. Compare and contrast the formation of uplifted and fault-block mountains.
5. **Thinking Critically** Would you expect a volcano that forms on a continent to depress the crust as much as a volcano that forms on the ocean floor? Explain your reasoning.

### SKILL REVIEW

6. **Concept Mapping** Use the following terms to construct a concept map that contrasts the mountain types discussed in this section. For more help, refer to the *Skill Handbook.*

uplifted mountains

solitary volcanoes

form as a result of hot spots

result from tension

form at divergent boundaries

show little structural deformation

ocean ridges

fault-block mountains

Mapping GeoLab

# Making a Map Profile

*A map profile, which is also called a cross section, is a side view of a geographic or geologic feature constructed from a topographic map. You will construct and analyze a profile of the Grand Tetons, a mountain range in Wyoming that formed when enormous blocks of rocks were faulted along their eastern flanks, causing the blocks to tilt to the west.*

## Preparation

### Problem
How do you construct a map profile?

### Materials
metric ruler
graph paper
sharp pencil

## Procedure

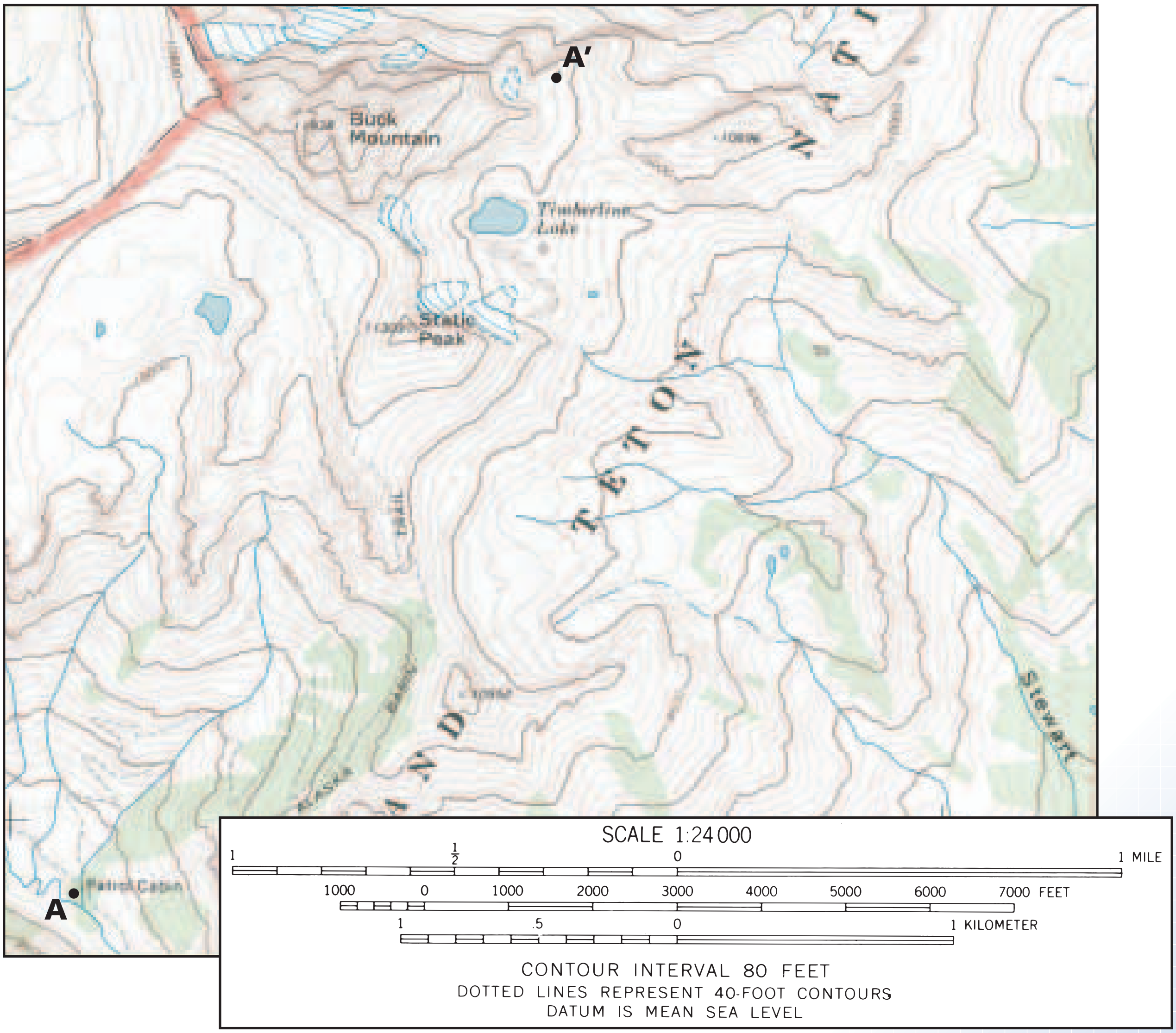
1. On the graph paper, make a grid like the one shown on the facing page.
2. Place the edge of a paper strip along the profile line AA' and mark where each major contour line intersects the strip.
3. Label each intersection point with the correct elevation.
4. Transfer the points from the paper strip to the profile grid.
5. Connect the points with a smooth line to construct a profile of the mountain range along line AA'.
6. Label the major geographic features on your profile.

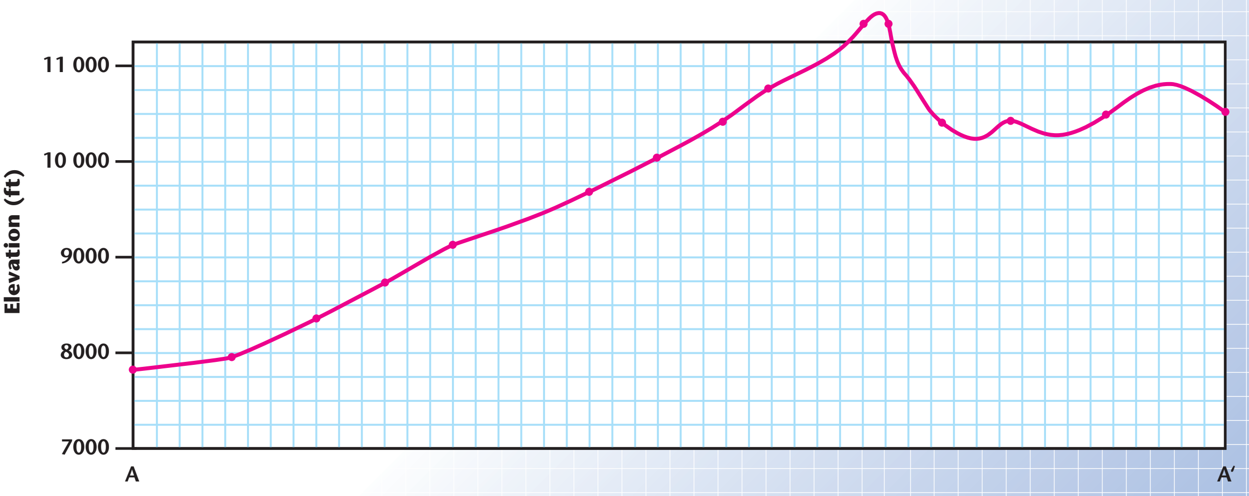
## Analyze

1. Describe how the map profile changes with distance from point A.
2. What is the elevation of the highest point on the map profile? The lowest point?
3. What is the average elevation shown in the profile?
4. Calculate the total relief shown in the profile.

## Conclude & Apply

1. Is your map profile a scale model of the topography along line AA'? Explain.
2. What determined the scale of this map profile?
3. Why are map profiles made from topographic maps often exaggerated vertically?

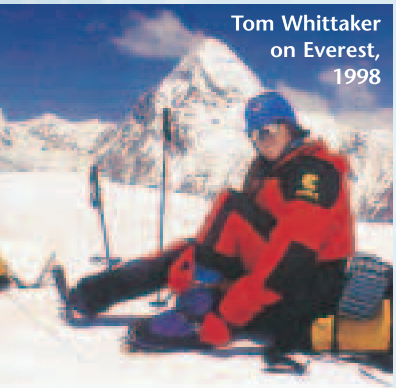

A′
Buck Mountain
Timberline Lake
Static Peak
TETON
Stewart
A
SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER
CONTOUR INTERVAL 80 FEET
DOTTED LINES REPRESENT 40-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL


11 000
10 000
9000
8000
7000
Elevation (ft)
A
A′



CONTENTS

# Science & Math



Tom Whittaker on Everest, 1998

## The Roof of the World

*Since 1953, more than 600 people have reached the summit of Mt. Everest to stand nearly 9 km above sea level on Earth's highest point. Brutal cold, oxygen deprivation, and treacherous conditions have claimed the lives of hundreds who attempted the climb. Preserved from decay by the dry, cold conditions and high altitude, most of their bodies remain on Everest, silent witnesses to the awesome forces that continue to build this mountain.*

Since British surveyor Sir George Everest first measured the height of this Himalayan peak in 1852, many explorers have dreamed of reaching Mt. Everest's summit. One hundred years would pass from the initial measurement to the first successful attempt to reach the summit by Sir Edmund Hillary and Tenzing Norgay. An explorer named George Mallory led the first attempts to scale Everest during the 1920s. He did not return from his last attempt. The discovery of his body by climbers in 1999 reminded many of Mallory's reply when asked why he was trying to reach Mt. Everest's peak. His famous answer, "Because it's there," echoes the sentiments of many who have followed in his footsteps.

### Measuring a Mountain

Some of those who have climbed Mt. Everest in the past 50 years have had another reason to scale this peak: to measure the elevation of Earth's tallest point. In 1954, an elevation of nearly 8848 m was determined by averaging altitude measurements taken from 12 different points around the mountain. Climbers with the Millennium Expedition, which took place from 1998 to 2000, utilized the highly accurate Global Positioning System to calculate an elevation of 8850 m for Earth's highest point.

Is Mt. Everest getting taller, or is the difference in elevation a result of the different instruments used to measure this mountain? The answer could be both. The collision between two tectonic plates is forcing the Indian subcontinent beneath Asia, causing Everest to rise at a rate of about 5 to 8 mm/y. Readings from GPS instruments on the mountain also suggest that Everest and other peaks in the range are moving toward China at about 6 cm/y.

### Technology—Then and Now

The elevation determined in 1954 by the Survey of India was calculated by picking the unweighted mean of altitudes determined from the 12 survey stations around the mountain. These measurements varied by about 5 m. The data gathered by the GPS to calculate the elevation have a margin of error of just over 2 m.

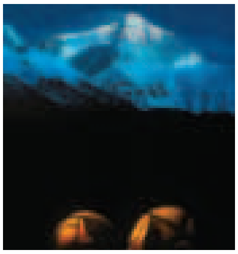
### Activity

Is Mt. Everest actually 2 m taller than it was in 1954? Use an average rate of uplift of 6.5 mm/y to determine how much Mt. Everest has risen since it was first measured. How does this compare with the newly calculated elevation?

# Summary

## SECTION 20.1

### Crust-Mantle Relationships



**Main Ideas**

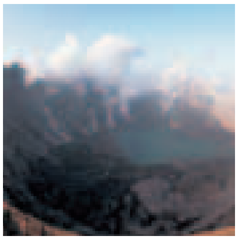
- Earth's elevations cluster around two intervals: 0 to 1 km above sea level and 4 to 5 km below sea level. These modes reflect the differences in density and thickness of the crust.
- Isostasy is a condition of equilibrium. According to this principle, the mass of a mountain above Earth's surface is supported by a root that projects into the mantle. The root provides buoyancy for the massive mountain.
- The addition of mass to Earth's crust depresses the crust; the removal of mass from the crust causes the crust to rebound in a process called isostatic rebound.

**Vocabulary**

isostasy (p. 525)
isostatic rebound (p. 527)

## SECTION 20.2

### Convergent-Boundary Mountains



**Main Ideas**

- Orogeny is the cycle of processes that form mountain belts. Most mountain belts are associated with plate boundaries.
- Island arc complexes are volcanic mountains that form as a result of the convergence of two oceanic plates.
- Highly deformed mountains with deep roots may form as a result of the convergence of an oceanic plate and a continental plate.
- Earth's tallest mountains form along continental-continental plate boundaries, where the energy of the collision causes extensive deformation of the rocks involved.
- The Appalachian Mountains, which are located in the eastern United States, formed millions of years ago mainly as the result of convergence between two tectonic plates.

**Vocabulary**

orogeny (p. 528)

## SECTION 20.3

### Other Types of Mountains

**Main Ideas**

- At a divergent boundary, newly formed lithosphere moves away from the central rift, cools, contracts, and becomes more dense to create a broad, gently sloping mountain range called an ocean ridge. Rocks that make up ocean ridges include dikes and pillow basalts.
- Regional uplift can result in the formation of uplifted mountains that are made of nearly horizontal, undeformed layers of rock.
- Fault-block mountains form when large pieces of the crust are tilted, uplifted, or dropped downward between normal faults.
- Most solitary volcanic peaks form as a tectonic plate moves over a hot spot in Earth's mantle.

**Vocabulary**

fault-block mountain (p. 538)
pillow basalt (p. 536)
uplifted mountain (p. 537)

earthgeu.com/vocabulary_puzzlemaker

CHAPTER 20

# Assessment

## Understanding Main Ideas

1. What causes differences in elevation on Earth?
   **a.** density and thickness of the crust
   **b.** vertical dikes and pillow basalts
   **c.** seamounts and hot spots
   **d.** uplifted and faulted mountains

2. Which of the following is *not* associated with orogeny at convergent boundaries?
   **a.** island arcs
   **b.** highly folded and faulted ranges
   **c.** ocean ridges
   **d.** deformed sedimentary rocks

3. What type of mountains are generally made up of undeformed rocks?
   **a.** fault-block mountains
   **b.** uplifted mountains
   **c.** convergent-boundary mountains
   **d.** continental mountains

4. What type of mountain would you expect to find at a convergent boundary involving two oceanic plates?
   **a.** fault-block mountain
   **b.** volcanic mountain
   **c.** uplifted mountain
   **d.** an ocean ridge

5. What is isostasy?
   **a.** a convergent-boundary mountain
   **b.** a condition of equilibrium
   **c.** a fault-block mountain
   **d.** a difference in crustal densities

6. Adding mass to the crust causes
   **a.** the crust to rebound.
   **b.** the mantle to rebound.
   **c.** the crust to become depressed.
   **d.** the mantle to displace the crust.

7. Explain why continental crust can displace more of the mantle than oceanic crust can.

8. What happens to a mountain's root as the mountain is eroded?

9. What type of plate boundary is most often associated with orogenic belts? Why?

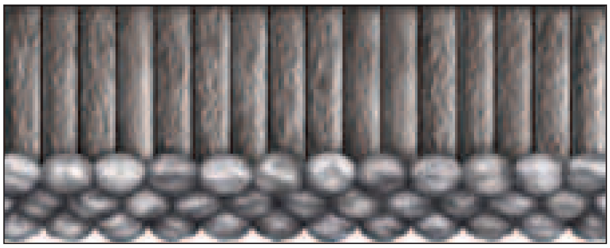
10. Describe three mechanisms of crustal thickening that occur at convergent boundaries.

11. Explain why ocean ridges rise high above the surrounding ocean floor.

12. What processes might be responsible for regional uplift of continental crust?

13. Discuss the processes involved in the formation of the Appalachian Mountains.

**Use the figure below to answer questions 14–16.**



14. A geologist observed these two igneous rock beds in a coastal mountain range. Based on what you've learned in this chapter, where did these rocks form?

15. Explain how the two rock beds formed.

16. Are the rock beds in their original positions? Explain.

## Test-Taking Tip

**TEST YOURSELF** Have a classmate make a practice test for you that covers the material discussed in this chapter. Take the test under test-like conditions. Show your practice test to one of your teachers for an objective assessment of your performance.

## Applying Main Ideas

17. If Earth's mantle were denser than it is now, would continental crust displace more or less of it? Explain.
18. Explain what caused an island arc to develop east of the North American continent early in the tectonic history of the Appalachian Mountains.
19. Refer to ***Figure 20-11.*** Describe how the deformation due to orogeny changes among the provinces of the Appalachian Mountains.
20. What type of faulting occurs at a continental-continental convergent boundary? Explain your answer.
21. How are ocean ridges and fault-block mountains similar? How do they differ?

## Thinking Critically

22. Thick ice sheets once covered the Great Lakes region. The area north of the Great Lakes has rebounded more than areas south of the lakes. What conclusion can you make about the thickness of the ice in these two areas? Explain your reasoning.
23. Suppose a mountain range is 4 km high. Explain why more than 4 km of material would have to be eroded before the mountain would be completely level.
24. When does the isostatic rebound of an area stop?
25. Why are dikes rather than sills common along ocean ridges?
26. The Appalachians mark the western side of the convergent boundary between North America and Africa. What kinds of structures do you think would be found on the eastern side of this boundary? Where would you look for these structures?

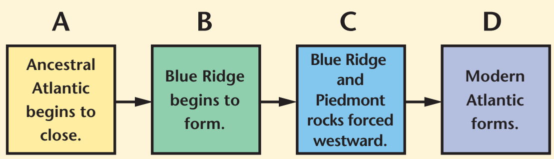
## Standardized Test Practice

1. Why would a certain thickness of continental crust displace less of the mantle than the same thickness of oceanic crust?
   **a.** Continental crust is more dense.
   **b.** Continental crust is less dense.
   **c.** Continental crust is mainly basalt.
   **d.** Continental crust is closer to the mantle.

2. Which of the following can NOT form as the result of oceanic-oceanic convergence?
   **a.** rift zones
   **b.** trenches
   **c.** subduction zones
   **d.** island arc complexes

3. Which type of mountains form as the result of uplift far from plate boundaries?
   **a.** ocean ridges
   **b.** uplifted mountains
   **c.** faulted mountains
   **d.** volcanic ranges

**INTERPRETING DIAGRAMS** Use the diagram and ***Figure 20-11*** to answer questions 4 and




4. Which of the following occurred between events B and C?
   **a.** The island arc attached to North America.
   **b.** Plate motions reversed.
   **c.** Africa collided with North America.
   **d.** The island arc developed.

5. Approximately when did event C occur?
   **a.** 800 to 700 M.Y.B.P.
   **b.** 700 to 600 M.Y.B.P.
   **c.** 500 to 400 M.Y.B.P.
   **d.** 300 to 200 M.Y.B.P.

UNIT 5

GeoDigest

For a **preview** of Unit 5, study this GeoDigest before you read the chapters in the unit. After you have studied these chapters, you can use the GeoDigest to **review** the unit.

# The Dynamic Earth

## Plate Tectonics

**Drifting Continents and Seafloor Spreading** Continental drift, first hypothesized by Alfred Wegener, states that Earth's continents were once joined as a single landmass that broke up and drifted apart. Wegener used matching coastlines of Earth's continents, similar rocks and fossils, and ancient climatic data to support his hypothesis. Wegener, however, couldn't explain how or why the continents moved. The answer, seafloor spreading, was found by studying ocean-floor rocks and sediments. Magnetic patterns of ocean-floor rocks are symmetric in relation to ocean ridges, which indicates that oceanic crust on either side of the ridge is moving away from the ridge. Seafloor spreading occurs as magma rises toward the crust, cools and hardens to fill the gap that forms, and becomes a new section of oceanic crust.

**The Theory of Plate Tectonics** Earth's crust and the top of the upper mantle are broken into large slabs of rock called plates, which move at different rates over Earth's surface. Interactions occur at plate boundaries. At a divergent boundary, plates move apart; high heat flow, volcanism, and earthquakes are associated with divergent boundaries. At a convergent boundary, plates come together; deep-sea trenches, island arcs, and folded mountain ranges are associated with this type of boundary. At a transform boundary, plates slide past one another horizontally; faults and shallow earthquakes are associated with transform boundaries. Convection currents in Earth's mantle are related to plate movements. Convection currents transfer energy through the movement of matter. Heat causes matter to expand and decrease in density. Warm matter is thus forced upward and cool matter is pulled downward. Ridge push is a tectonic process that occurs when the weight of an ocean ridge pushes a plate toward a subduction zone. Slab pull is a tectonic process that occurs when the weight of the subducting plate pulls a plate into a subduction zone.

Soufrière, a composite cone in the West Indies

## Volcanic Activity

**Magma** The composition of magma is affected by temperature, pressure, and the presence of water. There are three main types of magma—basaltic, andesitic, and rhyolitic— that differ in the source rock from which they form, and also in composition, viscosity, silica content, amount of dissolved gases, and explosiveness.

# GeoDigest

**Intrusive Activity** Magma can affect the crust in several ways. Magma can force overlying rock apart and enter the fissures formed, can cause blocks of rock to break off and sink into the magma chamber, and can melt the rock into which it intrudes. Plutons, which include batholiths, stocks, sills, dikes, and laccoliths, are classified according to their size, shape, and relationship to surrounding rocks.

**Volcanoes** A volcano forms when lava repeatedly flows out through a vent and accumulates. A crater is a depression that forms around the vent at the summit of a volcano; a caldera is a large crater that forms when a volcano collapses during or after an eruption. There are three types of volcanoes—shield volcanoes, cinder-cone volcanoes, and composite volcanoes. Shield volcanoes are large, gently sloping volcanoes composed of basalt. Cinder-cone volcanoes have steep sides and are made of volcanic fragments. Composite volcanoes have relatively steep slopes and are made of layers of volcanic fragments that alternate with lava. Most volcanoes form along subduction zones and rifts, but they may also form over hot spots, which are especially hot areas in Earth's mantle.

**Hot Spring, Africa**

## Earthquakes

**Forces Within Earth** Stresses exist within Earth. Stress is the forces per unit area that act on a material. Strain is the deformation of a material in response to stress. Stress is released at breaks in Earth's crust called faults. Reverse faults form as a result of horizontal compression; normal faults as a result of horizontal tension; and strike-slip faults as a result of horizontal shear. Movements along many faults cause earthquakes. Earthquakes generate waves that pass through Earth in specific ways. P-waves squeeze and pull rocks in the same direction in which the waves travel. S-waves cause rocks to move at right angles to the direction of the waves. Surface waves cause both up-and-down and side-to-side motions. Seismic waves are reflected and refracted as they strike different materials. Analysis of these different waves have enabled scientists to infer the structure of Earth's interior.

**Measuring and Locating Earthquakes** Most earthquakes occur along plate boundaries in areas called seismic belts. Earthquake epicenters are located with data from at least three seismic stations. Magnitude is a measurement of the energy released during an earthquake and is measured on the Richter scale or the moment-magnitude scale. Intensity is the measure of the damage caused by an earthquake as measured on the modified Mercalli scale.

### Vital Statistics

**Highest Peak per Continent**

| | | |
|---|---|---|
| Africa | Kilimanjaro | 5895 m |
| Antarctica | Vinson Massif | 4897 m |
| Asia | Everest | 8850 m |
| Australia | Kosciusko | 2228 m |
| Europe | Elbrus | 5642 m |
| North America | McKinley | 6194 m |
| South America | Aconcagua | 6960 m |

# GeoDigest

Earthquake damage, Guatemala

**Earthquakes and Society** Earthquakes can cause buildings and other structures to collapse, soil to behave like quicksand, fissures and fault scarps to form, uplift and subsidence of the crust, and tsunamis to form. The type of subsurface, the height and structure of buildings, the distance to the epicenter, and the depth of the earthquake's focus all affect the extent of damage done by an earthquake. The probability of an earthquake is determined by the history of earthquakes in an area and the rate at which strain builds up in the rocks.

## Mountain Building

**Isostasy** According to the principle of isostasy, the mass of a mountain above Earth's surface is supported by a root that projects into the mantle. The root provides buoyancy for the mountain. Adding mass to Earth's crust results in a depression of the crust. Removing mass causes the crust to rebound. Earth's elevations cluster around two intervals: 0 to 1 km above sea level and 4 to 5 km below sea level. These modes reflect the differences in density and thickness of Earth's two kinds of crust.

**Types of Mountains** The cycle of processes that forms mountain belts is called orogeny. Island-arc complexes are volcanic mountains that form as the result of convergence of two oceanic plates. When an oceanic plate converges with a continental plate, highly deformed mountains with deep roots form. When two continental plates converge and collide, very tall mountains result, along with extensive deformation of the rocks involved. Ocean ridges are mountains that form on ocean floors along divergent boundaries; they form topographic highs as the result of density differences—crust along the ridges is warmer and less dense than older, cooler crust farther from the ridges. Some mountains form far from plate boundaries. Uplifted mountains are made of nearly horizontal, undeformed layers of rock and form as the result of regional uplift. Fault-block mountains form when large pieces of the crust are tilted, uplifted, or dropped downward between large faults. Solitary volcanic peaks form as a result of a plate's moving over a hot spot in Earth's mantle.

### FOCUS ON CAREERS

**Volcanologist**

**A volcanologist is a scientist who studies volcanoes. A volcanologist must have at least a bachelor's degree, but often pursues a master's or doctoral degree in order to specialize in a specific aspect of volcanology. Some volcanologists work close to active volcanoes; others study data in labs, perhaps searching for relationships that will allow the prediction of eruptions.**

# GeoDigest

## ASSESSMENT

### Understanding Main Ideas

1. The study of which of the following led to the proposal of seafloor spreading?
   **a.** ocean rocks and sediments
   **b.** soil liquefaction
   **c.** seismic wave travel times
   **d.** P-wave motions

2. Which of the following is the probable cause of plate movements?
   **a.** ocean currents
   **b.** topographic highs
   **c.** convection currents in the mantle
   **d.** strain

3. In addition to temperature and pressure, what other factor affects the composition of magma?
   **a.** seismic gap
   **b.** the presence of water
   **c.** explosiveness
   **d.** seismic waves

4. What are batholiths, stocks, sills, dikes, and laccoliths?
   **a.** types of plutons
   **b.** kinds of magma chambers
   **c.** seismic wave types
   **d.** topographic lows

5. Which of the following forms when a volcano collapses during an eruption?
   **a.** a vent
   **b.** a crater
   **c.** a lava pipe
   **d.** a caldera

6. Which type of fault forms as a result of horizontal tension?
   **a.** reverse
   **b.** normal
   **c.** strike-slip
   **d.** shear

7. Which of the following is not caused by earthquakes?
   **a.** collapse of buildings
   **b.** flood basalt
   **c.** soil liquefaction
   **d.** tsunamis

8. How is earthquake magnitude measured?
   **a.** on the modified Mercalli scale
   **b.** by seismic gaps
   **c.** on the Richter scale
   **d.** by the earthquake history of an area

9. Which type of mountain forms when large pieces of Earth's crust are tilted, uplifted, or dropped down between large faults?
   **a.** uplifted mountains
   **b.** island arcs
   **c.** fault-block mountains
   **d.** hot spot volcanoes

10. What is stress?
    **a.** the deformation of a material
    **b.** the force that acts on a material
    **c.** a series of P-waves
    **d.** a series of S-waves

### Thinking Critically

1. Describe the process of seafloor spreading.
2. How do scientists determine the probability of an earthquake?

**Sierra Nevada, California**



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