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CHAPTER 7

PLATE TECTONICS
Will California eventually slide into the ocean as some predict? Have continents really drifted apart over the centuries? Answers to these questions and many others that have intrigued geologists for decades are now being provided by an exciting theory on large-scale movements taking place within Earth. This theory, called plate tectonics, represents the real frontier of the Earth sciences, and its implications are so far-reaching that it can be considered the framework from which most other geological processes should be viewed.

Early in this century, most geologists thought that the geographic positions of the ocean basins and continents were fixed. During the last few decades, however, vast amounts of new data have dramatically changed our understanding of the nature and workings of our planet. Earth scientists now realize that the continents gradually migrate across the globe. Where landmasses split apart, new ocean basins are created between the diverging blocks. Meanwhile, older portions of the seafloor are carried back into the mantle in regions where trenches occur in the deep-ocean floor. Because of these movements, blocks of continental material eventually collide and form Earth’s great mountain ranges (Figure 7.1). In short, a revolutionary new model of Earth’s tectonic processes has emerged.

This profound reversal of scientific understanding has been appropriately described as a scientific revolution. Like other scientific revolutions, considerable time elapsed between the idea’s inception and its general acceptance. The revolution began early in the twentieth century as a relatively straightforward proposal that the continents drift about the face of Earth. After many years of heated debate, the idea of drifting continents was rejected by the vast majority of Earth scientists. However, during the 1950s and 1960s, new evidence rekindled interest in this proposal. By 1968, these new developments led to the unfolding of a far more encompassing theory than continental drift—a theory known as plate tectonics.

Continental Drift: An Idea Before Its Time

The idea that continents, particularly South America and Africa, fit together like pieces of a jigsaw puzzle originated with improved world maps. However, little

*Tectonics refers to the deformation of Earth’s crust and results in the formation of structural features such as mountains.
significance was given this idea until 1915, when Alfred Wegener, a German meteorologist and geophysicist, published *The Origin of Continents and Oceans*. In this book, Wegener set forth his radical hypothesis of continental drift.*

Wegener suggested that a supercontinent he called **Pangaea** (meaning all land) once existed (Figure 7.2). He further hypothesized that about 200 million years ago this supercontinent began breaking into smaller continents, which then drifted to their present positions (see Box 7.1).

Wegener and others collected substantial evidence to support these claims. The fit of South America and Africa and the geographic distribution of fossils, rock structures, and ancient climates all seemed to support the idea that these now separate landmasses were once joined. Let us examine their evidence.

**Evidence: The Continental Jigsaw Puzzle**

Like a few others before him, Wegener first suspected that the continents might have been joined when he noticed the remarkable similarity between the coastlines on opposite sides of the South Atlantic. However, his use of present-day shorelines to make a fit of the continents was challenged immediately by other Earth scientists. These opponents correctly argued that shorelines are continually modified by erosional processes, and even if continental displacement had taken place, a good fit today would be unlikely. Wegener appeared to be aware of this problem, and, in fact, his original jigsaw fit of the continents was only very crude.

A much better approximation of the true outer boundary of the continents is the continental shelf. Today, the seaward edge of the continental shelf lies submerged, several hundred meters below sea level. In the early 1960s, scientists produced a map that attempted to fit the edges of the continental shelves at a depth of 900 meters. The remarkable fit that was obtained is shown in Figure 7.3. Although the continents overlap in a few places, these are regions where streams have deposited large quantities of sediment, thus enlarging the continental shelves. The overall fit was even better than what the supporters of continental drift suspected it would be.

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*Wegener’s ideas were actually preceded by those of an American geologist, F. B. Taylor, who in 1910 published a paper on continental drift. Taylor’s paper provided little supporting evidence for continental drift, which may have been the reason that it had a relatively small impact on the scientific community.*

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**STUDENTS SOMETIMES ASK...**

If all the continents were joined during the time of Pangaea, what did the rest of Earth look like?

When all the continents were together, there must also have been one huge ocean surrounding them. This ocean is called **Panthalassa** (pan = all, thalassa = sea). About 200 million years ago the supercontinent of Pangaea began to split apart, and the various continental masses we know today started to drift toward their present geographic positions. Today all that remains of Panthalassa is the Pacific Ocean, which has been decreasing in size since the breakup of Pangaea.
Evidence: Fossils Match Across the Seas

Although Wegener was intrigued by the jigsaw fit of the continental margins that lie on opposite sides of the Atlantic, he at first thought the idea of a mobile Earth improbable. Not until he came across an article citing fossil evidence for the existence of a land bridge connecting South America and Africa did he begin to take his own idea seriously. Through a search of the literature, Wegener learned that most paleontologists were in agreement that some type of land connection was needed to explain the existence of identical fossils on the widely separated landmasses.

Mesosaurus. To add credibility to his argument for the existence of the supercontinent of Pangaea, Wegener cited documented cases of several fossil organisms that had been found on different landmasses but that could not have crossed the vast oceans presently separating the continents. The classic example is Mesosaurus, a presumably aquatic, snaggle-toothed reptile whose fossil remains are limited to eastern South America and southern Africa (Figure 7.4). If Mesosaurus had been able to swim well enough to cross the vast South Atlantic Ocean, its remains should be more widely distributed. As this is not the case, Wegener argued that South America and Africa must have been joined somehow.

How did scientists explain the discovery of identical fossil organisms separated by thousands of kilometers of open ocean? The idea of land bridges was the most widely accepted solution to the problem of migration (Figure 7.5). We know, for example, that during the most recent glacial period, the lowering of sea level allowed animals to cross the narrow Bering Strait between Asia and North America. Was it possible, then, that one or more land bridges once connected Africa and South America? We are now quite certain that land bridges of this magnitude did not exist, for their remnants should still lie below sea level. But they are nowhere to be found.

Present-Day Organisms. In his book, Wegener also cited the distribution of present-day organisms as evidence to support the concept of drifting continents. For example, modern organisms with similar ancestries clearly had to evolve in isolation during the last few tens of millions of years. Most obvious of these are the Australian marsupials, which have a direct fossil link to the marsupial opossums found in the Americas.

Evidence: Rock Types and Structures Match

Anyone who has worked a picture puzzle knows that, in addition to the pieces fitting together, the picture must also be continuous. The picture that must match in the Continental Drift Puzzle is one of rock types and mountain belts. If the continents were once together to form Pangaea, the rocks found in a particular region on one continent should closely match in age and type those in adjacent positions on the adjoining continent.

Such evidence exists in the form of several mountain belts that terminate at one coastline, only to reappear on a landmass across the ocean. For instance, the mountain belt that includes the Appalachians trends...
Figure 7.A  Several views of the breakup of Pangaea over a period of 200 million years.
northeastward through the eastern United States and disappears off the coast of Newfoundland (Figure 7.6A). Mountains of comparable age and structure are found in the British Isles and Scandinavia. When these landmasses are reassembled as in Figure 7.6B, the mountain chains form a nearly continuous belt. Numerous other rock structures exist that appear to have formed at the same time and were subsequently split apart.

Wegener was very satisfied that the similarities in rock structure on both sides of the Atlantic linked these landmasses. In his own words, “It is just as if we were to refit the torn pieces of a newspaper by matching their edges and then check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined in this way.”

Evidence: Ancient Climates

Because Alfred Wegener was a meteorologist by training, he was keenly interested in obtaining paleoclimatic (ancient climatic) data in support of continental drift. His efforts were rewarded when he found evidence for dramatic global climatic changes. For instance, glacial deposits indicate that near the end of the Paleozoic era (between 220 million and 300 million years ago), ice sheets covered extensive areas of the Southern Hemisphere. Layers of glacial till were found in southern Africa and South America, as well as in India and Australia. Below these beds of glacial debris lay striated and grooved bedrock. In some locations the striations and grooves indicated that the ice had moved from what is now the sea onto land. Much of the land area containing evidence of this late Paleozoic glaciation presently lies within 30 degrees of the equator in a subtropical or tropical climate.

Could Earth have gone through a period sufficiently cold to have generated extensive continental glaciers in what is presently a tropical region? Wegener rejected this explanation because, during the late Paleozoic, large tropical swamps existed in the Northern Hemisphere. The lush vegetation of these swamps eventually became the major coal fields of the eastern United States, Europe, and Siberia.

Fossils from these coal fields indicate that the tree ferns that produced the coal deposits had large fronds.

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This indicates a tropical setting. Furthermore, unlike trees in colder climates, the tree trunks lacked growth rings. Growth rings do not form in tropical plants, because there are minimal seasonal fluctuations in temperature.

Wegener believed that a better explanation for the paleoclimatic regimes he observed is provided by fitting together the landmasses as a supercontinent, with South Africa centered over the South Pole (Figure 7.7). This would account for the conditions necessary to generate extensive expanses of glacial ice over much of the Southern Hemisphere. At the same time, this geography would place the northern landmasses nearer the tropics and account for their vast coal deposits.

Wegener was so convinced that his explanation was correct that he wrote, “This evidence is so compelling that by comparison all other criteria must take a back seat.”

How does a glacier develop in hot, arid Australia? How do land animals migrate across wide expanses of open water? As compelling as this evidence may have been, 50 years passed before most of the scientific community would accept it and the logical conclusions to which it led.

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**Figure 7.5** These sketches by John Holden illustrate various explanations for the occurrence of similar species on landmasses that are presently separated by vast oceans. (Reprinted with permission of John Holden)

**Figure 7.6** Matching mountain ranges across the North Atlantic. A. The Appalachian Mountains trend along the eastern flank of North America and disappear off the coast of Newfoundland. Mountains of comparable age and structure are found in the British Isles and Scandinavia. B. When these landmasses are placed in their predrift locations, these ancient mountain chains form a nearly continuous belt. These folded mountain belts formed roughly 300 million years ago as the landmasses collided during the formation of the supercontinent of Pangaea.
The Great Debate: Rejecting an Hypothesis

Wegener’s proposal did not attract much open criticism until 1924 when his book was translated into English. From this time on, until his death in 1930, his drift hypothesis encountered a great deal of hostile criticism. To quote the respected American geologist T. C. Chamberlin, Wegener’s hypothesis takes considerable liberty with our globe, and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories. Its appeal seems to lie in the fact that it plays a game in which there are few restrictive rules and no sharply drawn code of conduct.

One of the main objections to Wegener’s hypothesis stemmed from his inability to provide a mechanism that was capable of moving the continents across the globe. Wegener proposed that the tidal influence of the Moon was strong enough to give the continents a westward motion. However, the prominent physicist Harold Jeffreys quickly countered with the argument that tidal friction of the magnitude that’s needed to displace the continents would bring Earth’s rotation to a halt in a matter of a few years.

Wegener also proposed that the larger and sturdier continents broke through the oceanic crust, much like ice breakers cut through ice. However, no evidence existed to suggest that the ocean floor was weak enough to permit passage of the continents without themselves being appreciably deformed in the process.

Although most of Wegener’s contemporaries opposed his views, even to the point of open ridicule, a few considered his ideas plausible. For these few geologists who continued the search for additional evidence,
the exciting concept of continents in motion held their interest. Others viewed continental drift as a solution to previously unexplainable observations.

Plate Tectonics: The New Paradigm

During the years that followed Wegener’s proposal, major strides in technology permitted mapping of the ocean floor. Moreover, extensive data on seismic activity and Earth’s magnetic field became available. By 1968, these developments led to the unfolding of a far more encompassing theory than continental drift, known as plate tectonics. The implications of plate tectonics are so far-reaching that this theory is today the framework within which to view most geologic processes.

Earth’s Major Plates

According to the plate tectonics model, the uppermost mantle, along with the overlying crust, behaves as a strong, rigid layer, known as the lithosphere. This outermost shell overlies a weaker region in the mantle known as the asthenosphere. Further, the lithosphere is broken into numerous segments called plates, which are in motion and are continually changing in shape and size. As shown in Figure 7.8, seven major lithospheric plates are recognized. They are the North American, South American, Pacific, African, Eurasian, Australian-Indian, and Antarctic plates. The largest is the Pacific plate, which is located mostly within the Pacific Ocean. Notice from Figure 7.8 that several of the large plates include an entire continent plus a large area of seafloor (for example, the South American plate). This is a major departure from Wegener’s continental drift hypothesis, which proposed that the continents moved through the ocean floor, not with it. Note also that none of the plates are defined entirely by the margins of a continent.

Intermediate-sized plates include the Caribbean, Nazca, Philippine, Arabian, Cocos, and Scotia plates. In addition, there are over a dozen smaller plates that have been identified but are not shown in Figure 7.8.

The lithospheric plates move relative to each other at a very slow but continuous rate that averages about 5 centimeters (2 inches) per year. This movement is ultimately driven by the unequal distribution of heat within Earth. Hot material found deep in the mantle moves slowly upward and serves as one part of our planet’s internal convection system. Concurrently, cooler, denser slabs of oceanic lithosphere descend into the mantle, setting Earth’s rigid outer shell into motion. Ultimately, the titanic, grinding movements of Earth’s lithospheric plates generate earthquakes, create volcanoes, and deform large masses of rock into mountains.

Plate Boundaries

Lithospheric plates move as coherent units relative to all other plates. Although the interiors of plates may experience some deformation, all major interactions among individual plates (and therefore most deformation) occur along their boundaries. In fact, the first attempts to outline plate boundaries were made using locations of earthquakes. Later work showed that plates are bounded by three distinct types of boundaries, which are differentiated by the type of movement they exhibit. These boundaries are depicted at the bottom of Figure 7.8 and are briefly described here:

1. Divergent plate boundaries (constructive margins)—where two plates move apart, resulting in upwelling of material from the mantle to create new seafloor (Figure 7.8A).

2. Convergent plate boundaries (destructive margins)—where two plates move together, resulting in oceanic lithosphere being thrust beneath an overriding plate, eventually to be reabsorbed into the mantle (Figure 7.8B). Convergence can also result in the collision of two continental plates to create a mountain system.

3. Transform fault boundaries (conservative margins)—where two plates grind past each other without the production or destruction of lithosphere (Figure 7.8C).

Each plate is bounded by a combination of these three types of boundaries. For example, as shown in Figure 7.8, the Nazca plate has a divergent zone on the west, a convergent boundary on the east, and numerous transform faults, which offset segments of the divergent boundary. Although the total surface area of Earth does not change, individual plates may diminish or grow in an area depending on the distribution of convergent and divergent boundaries. The Antarctic and African plates are almost entirely bounded by spreading centers and hence are growing larger. By contrast, the Pacific plate is being consumed into the mantle along its northern and western flanks and is therefore diminishing in size.

Furthermore, new plate boundaries can be created in response to changes in the forces acting on these rigid slabs. For example, a relatively new divergent boundary is located in Africa, in a region known as the East African Rift Valleys. If spreading continues there, the African plate will split into two plates separated by a new ocean basin. At other locations, plates carrying continental crust are presently moving toward each other. Eventually, these continents may collide and be sutured together. Thus, the boundary that once separated two plates disappears as the plates become one. The result
Figure 7.8  A mosaic of rigid plates constitutes Earth's outer shell.
Figure 7.8  Continued
of such a continental collision is a majestic mountain range such as the Himalayas.

In the following sections we will briefly summarize the nature of the three types of plate boundaries.

Divergent Plate Boundaries

Most divergent (di = apart, vergere = to move) plate boundaries are located along the crests of oceanic ridges and can be thought of as constructive plate margins since this is where new oceanic lithosphere is generated (Figure 7.9). Here, as the plates move away from the ridge axis, the fractures created are filled with molten rock that wells up from the hot mantle below. Gradually, this magma cools to produce new slivers of seafloor. In a continuous manner, spreading and upwelling of magma adds oceanic lithosphere between the diverging plates. As we shall see later, divergent boundaries can also form on the continents (Figure 7.10).

Oceanic Ridges and Seafloor Spreading

Along well-developed divergent plate boundaries, the seafloor is elevated forming the oceanic ridge. The interconnected ocean ridge system is the longest topographic feature on Earth’s surface, exceeding 70,000 kilometers (43,000 miles) in length with crests commonly 2 to 3 kilometers higher than the adjacent ocean basins. Representing 20 percent of Earth’s surface, the ocean ridge system winds through all major ocean basins in a manner similar to the seam on a baseball. The term “ridge” may be misleading, as these features are not narrow but have widths from 1000 to 4000 kilometers. Further, along the axis of some segments are deep down-faulted structures called rift valleys.

The mechanism that operates along the oceanic ridge system to create new seafloor is appropriately called seafloor spreading. Typical rates of spreading average around 5 centimeters (2 inches) per year. Comparatively slow spreading rates of 2 centimeters per year are found in the North Atlantic, whereas spreading rates exceeding 15 centimeters (6 inches) have been measured along...
sections of the East Pacific Rise. Although these rates of lithospheric production are slow on a human time scale, they are nevertheless rapid enough so that all of Earth’s ocean basins could have been generated within the last 200 million years. In fact, none of the ocean floor that has been dated exceeds 180 million years in age.

During seafloor spreading, the magma that is injected into newly developed fractures forms dikes that tend to cool from their outer borders inward toward their centers. Because the warm interiors of these newly formed dikes are weak, continued spreading produces new fractures that split these young rocks roughly in half. As a result, new material is added about equally to the two diverging plates. Consequently, new ocean floor grows symmetrically on each side of a centrally located ridge crest. Indeed, the ridge systems of the Atlantic and Indian oceans are located near the middle of these water bodies and as a consequence are called mid-ocean ridges. However, the East Pacific Rise is situated far from the center of the Pacific Ocean. Despite uniform spreading along the East Pacific Rise, much of the Pacific Basin that once lay east of this spreading center has been overridden by the westward migration of the American plates.

**Spreading Rates and Ridge Topography**

When various segments of the oceanic ridge system were studied in detail, some topographic differences came to light. Most of these differences appear to be

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**Figure 7.10**

A. Rising magma forces the crust upward, causing numerous cracks in the rigid lithosphere. B. As the crust is pulled apart, large slabs of rock sink, generating a rift zone. C. Further spreading generates a narrow sea. D. Eventually, an expansive ocean basin and ridge system are created.
controlled by spreading rates. At comparatively slow spreading rates of 1 to 5 centimeters per year, such as occur at the Mid-Atlantic and Mid-Indian ridges, a prominent rift valley develops along the ridge crest. This structure is usually 30 to 50 kilometers across and between 1500 to 3000 meters deep. Here, the displacement of large slabs of oceanic crust along nearly vertical faults and outpourings of pillow lavas contribute to the characteristically rugged topography of these rift valleys.

Along the Galapagos ridge and the northernmost section of the East Pacific Rise, an intermediate spreading rate of 5 to 9 centimeters per year is the norm. In these settings the rift valleys that develop are shallow, often less than 200 meters deep, and their topography is relatively smooth.

At faster spreading rates (greater than 9 centimeters per year), such as those which occur along much of the East Pacific Rise, no median rift valleys develop. Here oceanic ridges are usually narrow (roughly 10 kilometers wide) topographic highs. These elevated structures are extensively faulted and exhibit topography consisting of numerous horsts and grabens (see Chapter 9). Faulting is the primary cause of topographic variations along fast spreading centers, whereas the buildup of volcanic structures is significant at slow spreading centers.

**Continental Rifts**

Spreading centers can also develop within a continent, in which case the landmass may split into two or more smaller segments, as Alfred Wegener had proposed for the breakup of the Pangaea. Examples of active continental rifts include the East African rift valleys, the Baikal Rift (south central Siberia), the Rhine Valley (Northwest Europe), the Rio Grande Rift, and the Basin and Range province in the western United States. Whether any of these rifts will continue to develop and eventually split a continent is a matter of much speculation.

The most widely accepted model for continental splitting suggests that extensional forces must be acting on the lithospheric plate. These forces are thought to arise from the “pull” of cold lithospheric plates as they subduct along the margins of a continent. It appears that by themselves these extensional forces are not great enough to actually tear the lithosphere apart. Rather, the rupture of the lithosphere is initiated only in those settings where plumes of hot rock rise from the mantle.

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**Figure 7.11** East African rift valleys and associated features.
effect of this hot-spot activity is weakening of the lithosphere and doming of the crust directly above the hot rising plume. Uplifting stretches and thins the crust, as shown in Figure 7.10A. Extension is accompanied by alternating episodes of faulting and volcanism that result in the development of a rift valley that resembles those found along the axes of some ridges (Figure 7.10B).

The East African rift valleys may represent the initial stage in the breakup of a continent as described above (Figure 7.11). Large volcanic mountains such as Kilimanjaro and Mount Kenya exemplify the extensive volcanic activity that accompanies continental rifting.

In those settings where the extensional forces are maintained, the rift valley will lengthen and deepen, eventually extending out to the margin of the plate and splitting it in two (Figure 7.10C). At this point the rift becomes a narrow linear sea with an outlet to the ocean, similar to the Red Sea (Figure 7.11). The Red Sea formed...
when the Arabian Peninsula rifted from Africa, an event that began about 20 million years ago. Consequently, the Red Sea provides oceanographers with a view of how the Atlantic Ocean may have looked in its infancy.

Not all rift valleys develop into full-fledged spreading centers. Running through the central United States is a failed rift extending from Lake Superior to Oklahoma. This once active rift valley is filled with volcanic rock that was extruded onto the crust more than a billion years ago. Why one rift valley develops into an active spreading center while others are abandoned is not yet known.

**Convergent Plate Boundaries**

Although new lithosphere is constantly being added at the oceanic ridges, our planet is not growing larger—it's total surface area remains constant. To accommodate the newly created lithosphere, older portions of oceanic plates return to the mantle along convergent (con = together, vergere = to move) plate boundaries. (Because lithosphere is “destroyed” at convergent boundaries, they are also called **destructive plate margins**.) As two plates slowly converge, the leading edge of one is bent downward, allowing it to slide beneath the other. The surface expression produced by the descending plate is an ocean **trench**, like the Peru–Chile trench (Figure 7.12, on previous page). Trenches formed in this manner may be thousands of kilometers long, 8 to 12 kilometers deep, and between 50 and 100 kilometers wide (Figure 7.13). Destructive plate margins where oceanic crust is being consumed in the mantle are called **subduction (sub = under, duct = lead) zones**.

The average angle at which oceanic lithosphere descends into the mantle is about 45 degrees. However, depending on its buoyancy, a plate might descend at an angle as small as a few degrees or it might plunge vertically (90 degrees) into the mantle. When a spreading center is located near a subduction zone, the litho-

![Figure 7.13](image_url)  
**Figure 7.13** Distribution of the world’s oceanic trenches, ridge system, and transform faults. Where transform faults offset ridge segments, they permit the ridge to change direction (curve) as can be seen in the Atlantic Ocean.
sphere is young and, therefore, warm and buoyant. Thus, the angle of descent is small. This is the situation along parts of the Peru–Chile trench. Low dip angles are usually associated with a strong coupling between the descending slab and the overriding plate. Consequently, these regions experience great earthquakes. By contrast, some subduction zones, such as the Mariana trench, have steep angles of descent and few strong earthquakes.

Although all convergent zones have the same basic characteristics, they are highly variable features. Each is controlled by the type of crustal material involved and the tectonic setting. Convergent boundaries can form between two oceanic plates, one oceanic and one continental plate, or two continental plates. All these situations are illustrated in Figure 7.12.

**Oceanic-Continental Convergence**

Whenever the leading edge of a continental plate converges with an oceanic plate, the buoyant continental plate remains floating, whereas the denser oceanic slab sinks into the asthenosphere (Figure 7.12A). When a descending plate reaches a depth of about 100 to 150 kilometers, heat drives water and other volatile components from the subducted sediments into the overlying mantle. These substances act as a flux does at a foundry, inducing partial melting of mantle rocks at reduced temperatures. The partial melting of mantle rock generates magmas having a basaltic or occasionally an andesitic composition. The newly formed magma, being less dense than the rocks of the mantle, will buoyantly rise. Often the magma, being more dense than continental rocks, will pond beneath the overlying continental crust where it may melt some of the silica-enriched rocks. Eventually some of this silica-rich magma may migrate to the surface, where it can give rise to volcanic eruptions, some of which are explosive.

The volcanoes of the Andean arc located along the western flank of South America are the product of magma generated as the Nazca plate descends beneath the continent (see Figure 7.8). In the central section of the southern Andes the subduction angle is very shallow, which probably accounts for the lack of volcanism in that area. As the South American plate moves westward, it overruns the Nazca plate. The result is a seaward migration of the Peru–Chile trench and a reduction in the size of the Nazca plate.

Mountains such as the Andes, which are produced in part by volcanic activity associated with the subduction of oceanic lithosphere, are called continental volcanic arcs. Another active continental volcanic arc is located in the western United States. The Cascade Range of Washington, Oregon, and California consists of several well-known volcanic mountains, including Mount Rainier, Mount Shasta, and Mount St. Helens. As the continuing activity of Mount St. Helens testifies, the Cascade Range is still active. The magma here arises from melting triggered by the subduction of the Juan de Fuca plate—a small remaining remnant of a once large plate.

A remnant of a formerly extensive continental volcanic arc is California’s Sierra Nevada, in which Yosemite National Park is located. The Sierra Nevada is much older than the Cascade Range, and has been inactive for several million years as evidenced by the absence of volcanic cones. Here erosion has stripped away most of the obvious traces of volcanic activity and left exposed the large, crystallized magma chambers that once fed lofty volcanoes.

**Oceanic-Oceanic Convergence**

When two oceanic slabs converge, one descends beneath the other, initiating volcanic activity in a manner similar to that which occurs at an oceanic-continental boundary. In this case, however, the volcanoes form on the ocean floor rather than on a continent (Figure 7.12B). If this activity is sustained, it will eventually build a chain of volcanic structures that emerge as islands. The volcanic islands are spaced about 80 kilo-
meters apart and are built upon submerged ridges a few hundred kilometers wide. This newly formed land consisting of an arc-shaped chain of small volcanic islands is called a **volcanic island arc**. The Aleutian, Mariana, and Tonga islands are examples of volcanic island arcs (see Box 7.2). Island arcs such as these are generally located 200 to 300 kilometers from the trench axis. Located adjacent to the island arcs just mentioned are the Aleutian trench, the Mariana trench, and the Tonga trench (Figure 7.13).

Only two volcanic island arcs are located in the Atlantic, the Lesser Antilles arc adjacent to the Caribbean

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**BOX 7.2**

I discovered geology the summer that I worked doing trail maintenance in the North Cascades mountains of Washington State. I had just finished my freshman year in college and had never before studied Earth Science. But a coworker (now my best friend) began to describe the geological features of the mountains that we were hiking in—the classic cone shape of Mount Baker volcano, the U-shaped glacial valleys, the advance of active glaciers, and other wonders. I was hooked and went back to college that fall with a geology passion that hasn’t abated. As an undergraduate, I worked as a field assistant to a graduate student and did a senior thesis project on rocks from the Aleutian island arc. From that initial spark, island arcs have remained my top research interest, on through Ph.D. research at Stanford University, postdoctoral work at the University of Hawaii, and as a faculty member at San Jose State University and Western Washington University.

Especially the deep crust of arcs, the material that lies close to the Mohorovičić discontinuity (fondly known as the Moho). What kinds of processes are occurring down there at the base of the crust in island arcs? What is the source of magmas that make their way to the surface (the mantle? the deep crust itself?). How do these magmas interact with the crust as they make their way upwards? What do these early magmas look like chemically? Are they very different from what is erupted at the surface?

Obviously, geologists cannot go down to the base of the crust (typically 20 to 40 kilometers beneath Earth’s surface). So what they do is play a bit of a detective game. They must use rocks that are now exposed at the surface that were originally formed in the deep crust of an island arc. The rocks must have been brought to the surface rapidly along fault zones to preserve their original features. Thus, I can walk on rocks of the deep crust without really leaving the Earth’s surface! There are a few places around the world where these rare rocks are exposed. Some of the places that I have worked include the Chugach Mountains of Alaska, the Sierras Pampeanas of Argentina, the Karakorum range in Pakistan, Vancouver Island’s west coast, and the North Cascades of Washington. Fieldwork has involved hiking most commonly, but also extensive use of mules and trucks.

I also went looking for exposed pieces of the deep crust of island arcs in a less obvious place, in one of the deepest oceanic trenches of the world, the Izu Bonin trench (Figure 7.B). Here I dove into the ocean in a submersible called the **Shinkai 6500** (pictured to my right in the background). The **Shinkai 6500** is a Japanese submersible that has the capability to dive to 6500 meters below the surface of the ocean (approximately 4 miles). My plan was to take rock samples from the wall of the trench at its deepest levels using the submersible’s mechanical arm. Because preliminary data suggested that vast amounts of rock were exposed for several kilometers in a vertical sense, this could be a great way to sample the deep arc basement. I dove in the submersible three times, reaching a maximum depth of 6497 meters. Each dive lasted 9 hours, spent in a space no bigger than the front seat of a Honda, shared with two of the Japanese pilots that controlled the submersible’s movements. It was an exhilarating experience!

I am now on the faculty at Western Washington University where I continue to do research on the deep roots of volcanic arcs, and get students involved as well. I am also involved in Science Education training for K–12 teachers, hoping to get young people motivated to ask questions about the fascinating world that surrounds them!

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**Figure 7.B**  Susan DeBari photographed with the Japanese submersible, **Shinkai 6500**, which she used to collect rock samples from the Izu Bonin trench. (Photo courtesy of Susan DeBari)
Sea, and the Sandwich Islands in the South Atlantic. The Lesser Antilles are a product of the subduction of the Atlantic beneath the Caribbean plate. Located within this arc is the island of Martinique where Mount Pelé erupted in 1902, destroying the town of St. Pierre and killing an estimated 28,000 people, and the island of Montserrat, where volcanic activity has occurred very recently.

Relatively young island arcs are fairly simple structures that are underlain by crust that is generally less than 20 kilometers (12 miles) thick. Examples include the arcs of Tonga, the Aleutians, and the Lesser Antilles. By contrast, older island arcs are more complex and are underlain by crust that ranges in thickness from 20 to 35 kilometers. Examples include the Japanese and Indonesian arcs, which are built upon material generated by earlier episodes of subduction. In a few places, volcanic island arcs are gradually transformed into an Andean-type volcanic chain. For example, the western section of the Aleutian arc consists of numerous volcanic islands built on oceanic crust whereas the volcanoes at the eastern end of the chain are part of the Alaskan Peninsula—a piece of continental crust.

**Continental–Continental Convergence**

As you saw earlier, when an oceanic plate is subducted beneath continental lithosphere, an Andean-type volcanic arc develops along the margin of the continent. However, if the subducting plate also contains conti-

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**Figure 7.14** The ongoing collision of India and Asia, starting about 45 million years ago, produced the majestic Himalayas. A. Converging plates generated a subduction zone, while partial melting triggered by the subducting oceanic slab produced a continental volcanic arc. Sediments scraped from the subducting plate were added to the accretionary wedge. B. Position of India in relation to Eurasia at various times. (Modified after Peter Molnar) C. Eventually the two landmasses collided, deforming and elevating the accretionary wedge and continental shelf deposits. In addition, slices of the Indian crust were thrust up onto the Indian plate.
Plate Tectonics

Continental lithosphere, continued subduction eventually brings the two continents together (Figure 7.12C). Whereas oceanic lithosphere is relatively dense and sinks into the asthenosphere, continental lithosphere is buoyant, which prevents it from being subducted to any great depth. The result is a collision between the two continental blocks (Figure 7.14).

Such a collision occurred when the subcontinent of India rammed into Asia and produced the Himalayas—the most spectacular mountain range on Earth (Figure 7.14). During this collision, the continental crust buckled, fractured, and was generally shortened and thickened. In addition to the Himalayas, several other major mountain systems, including the Alps, Appalachians, and Urals, formed during continental collisions.

Prior to a continental collision, the landmasses involved are separated by an ocean basin. As the continental blocks converge, the intervening seafloor is subducted beneath one of the plates. Subduction initiates partial melting in the overlying mantle rocks, which in turn results in the growth of a volcanic arc. Depending on the location of the subduction zone, the volcanic arc could develop on either of the converging landmasses, or if the subduction zone developed several hundred kilometers seaward from the coast, a volcanic island arc would form. Eventually, as the intervening seafloor is consumed, these continental masses collide. This folds and deforms the accumulation of sediments along the continental margin as if they were placed in a gigantic vise. The result is the formation of a new mountain range, composed of deformed and metamorphosed sedimentary rocks, fragments of the volcanic arc, and possibly slivers of oceanic crust.

After continents collide, the subducted oceanic plate may separate from the continental block and continue its downward movement. However, because of its buoyancy, continental lithosphere cannot be carried very far into the mantle. In the case of the Himalayas, the leading edge of the Indian plate was forced partially under Asia, generating an unusually great thickness of continental lithosphere. This accumulation accounts, in part, for the high elevation of the Himalayas and may help explain the elevated Tibetan Plateau to the north.

Transform Fault Boundaries

The third type of plate boundary is the transform fault, where plates grind past one another without the production or destruction of lithosphere. Transform faults were first identified where they join offset segments of an ocean ridge. At first it was erroneously assumed that the ridge system originally formed a long and continuous chain that was later offset by horizontal displacement along these large faults. However, the displacement along these faults was found to be in the exact opposite direction required to produce the offset ridge segments.

The true nature of transform faults was discovered in 1965 by a Canadian researcher who suggested that these large faults connect the global active belts (convergent boundaries, divergent boundaries, and other transform faults) into a continuous network that divides Earth’s outer shell into several rigid plates. Thus, he became the first to suggest that Earth was made of individual plates, while at the same time identifying the faults along which relative motion between the plates is made possible.

Most transform faults join two segments of a mid-ocean ridge (Figure 7.15). Here, they are part of prominent linear breaks in the oceanic crust known as fracture zones that include both the transform fault as well as their inactive extension into the plate interior. These fracture zones are present approximately every 100 kilometers along the trend of a ridge axis. As shown in Figure 7.15, active transform faults lie only between the two offset
ridge segments. Here seafloor produced at one ridge axis moves in the opposite direction as seafloor is produced at an opposing ridge segment. Thus, between the ridge segments these adjacent slabs of oceanic crust are grinding past each other along a transform fault. Beyond the ridge crests are the inactive zones, which are preserved as linear topographic scars. These fracture zones tend to curve such that small segments roughly parallel the direction of plate motion at the time of their formation.

In another role, transform faults provide the means by which the oceanic crust created at ridge crests can be transported to a site of destruction, the deep-ocean trenches. Figure 7.16 illustrates this situation. Notice that the Juan de Fuca plate moves in a southeasterly direction, eventually being subducted under the West Coast of the United States. The southern end of this relatively small plate is bounded by the Mendocino transform fault. This transform fault boundary connects the Juan de Fuca ridge to the Cascade subduction zone (Figure 7.16). Therefore, it facilitates the movement of the crustal material created at the ridge crest to its destination beneath the North American continent (Figure 7.16).

Another example of a ridge-trench transform fault is found southeast of the tip of South America. Here transform faults on the north and south margins of the Scotia plate connect the trench to a short spreading axis (see Figure 7.8).

Although most transform faults are located within the ocean basins, a few cut through continental crust. Two examples are the earthquake-prone San Andreas Fault of California and the Alpine Fault of New Zealand. Notice in Figure 7.16 that the San Andreas Fault connects a spreading center located in the Gulf of California to the Cascade subduction zone and the Mendocino transform fault located along the northwest coast of the United States. Along the San Andreas Fault, the Pacific plate is moving toward the northwest, past the North American plate. If this movement continues,
that part of California west of the fault zone, including the Baja Peninsula, will become an island off the West Coast of the United States and Canada. It could eventually reach Alaska. However, a more immediate concern is the earthquake activity triggered by movements along this fault system.

**STUDENTS SOMETIMES ASK...**

**If the continents move, do other features like segments of the oceanic ridge also move?**

That’s a good observation, and yes, they do! It is interesting to note that very little is really fixed in place on Earth’s surface. When we talk about movement of features on Earth, we must consider the question, “Moving relative to what?” Certainly, the oceanic ridge does move relative to the continents (which sometimes causes segments of the oceanic ridges to be subducted beneath the continents). In addition, the oceanic ridge is moving relative to a fixed location outside Earth. This means that an observer orbiting above Earth would notice, after only a few million years, that all continental and seafloor features—as well as plate boundaries—are indeed moving. The exception to this are hot spots, which seem to be relatively stationary and can be used to determine the motions of other features.

**Testing the Plate Tectonics Model**

With the birth of the plate tectonics model, researchers from all of the Earth sciences began testing it. Some of the evidence supporting continental drift and seafloor spreading has already been presented. Some of the evidence that was instrumental in solidifying the support for this new concept follows. Note that some of the evidence was not new; rather, it was a new interpretation of old data that swayed the tide of opinion.

**Evidence: Paleomagnetism**

Probably the most persuasive evidence to the geologic community for the acceptance of the plate tectonics theory comes from the study of Earth’s magnetic field. Anyone who has used a compass to find direction knows that the magnetic field has a north pole and a south pole. These magnetic poles align closely, but not exactly, with the geographic poles. (The geographic poles are simply the top and bottom of the spinning sphere we live on, the points through which passes the imaginary axis of rotation.)

In many respects the magnetic field is very much like that produced by a simple bar magnet. Invisible lines of force pass through Earth and extend from one pole to the other. A compass needle, itself a small magnet free to move about, becomes aligned with these lines of force and thus points toward the magnetic poles.

The technique used to study ancient magnetic fields relies on the fact that certain rocks contain minerals that serve as fossil compasses. These iron-rich minerals, such as magnetite, are abundant in lava flows of basaltic composition. When heated above a certain temperature called the Curie point, these magnetic minerals lose their magnetism. However, when these iron-rich grains cool below their Curie point (about 580°C), they become magnetized in the direction parallel to the existing magnetic field. Once the minerals solidify, the magnetism they possess will remain frozen in this position. In this regard, they behave much like a compass needle inasmuch as they point toward the existing magnetic poles. Then, if the rock is moved or if the magnetic pole changes position, the rock magnetism will, in most instances, retain its original alignment. Rocks formed thousands of millions of years ago thus remember the location of the magnetic poles at the time of their formation and are said to possess fossil magnetism, or **paleomagnetism**.

**Polar Wandering**. A study of lava flows conducted in Europe in the 1950s led to an amazing discovery. The magnetic alignment in the iron-rich minerals in lava flows of different ages was found to vary widely. A plot of the apparent positions of the magnetic north pole revealed that during the past 500 million years, the location of the pole had gradually wandered from a spot near Hawaii northward through eastern Siberia and finally to its present site (Figure 7.17A). This was clear evidence that either the magnetic poles had migrated through time, an idea known as **polar wandering**, or that the lava flows had moved—in other words, the continents had drifted.

Although the magnetic poles are known to move, studies of the magnetic field indicated that the average positions of the magnetic poles correspond closely to the positions of the geographic poles. This is consistent with our knowledge of Earth’s magnetic field, which is generated in part by the rotation of Earth about its axis. If the geographic poles do not wander appreciably, which we believe is true, neither can the magnetic poles. Therefore, a more acceptable explanation for the apparent polar wandering is provided by the plate tectonics theory. **If the magnetic poles remain stationary, their apparent movement was produced by the drifting of the continents.**

Further evidence for plate tectonics came a few years later when polar wandering curves were constructed for North America and Europe (Figure 7.17A). To nearly everyone’s surprise, the curves for North America and Europe had similar paths, except that they were separated by about 24 degrees of longitude. When these rocks solidified, could there have been two magnetic north poles that migrated parallel to each other? This is very unlikely. The differences in these migration paths, however, can be reconciled if the two presently...
Magnetic Reversals and Seafloor Spreading. Another discovery came when geophysicists learned that Earth’s magnetic field periodically reverses polarity; that is, the north magnetic pole becomes the south magnetic pole, and vice versa. A rock solidifying during one of the periods of reverse polarity will be magnetized with the polarity opposite that of rocks being formed today.

When rocks exhibit the same magnetism as the present magnetic field, they are said to possess **normal polarity**, whereas those rocks exhibiting the opposite magnetism are said to have **reverse polarity**. Evidence for magnetic reversals was obtained from lavas and sediments from around the world.

Once the concept of magnetic reversals was confirmed, researchers set out to establish a time scale for polarity reversals. Many areas exist where volcanic activity has occurred sporadically for periods of millions of years (Figure 7.18). The task was to measure the directions of paleomagnetism in numerous lava flows of various ages. These data were collected from several places and were used to determine the dates when the polarity of Earth’s magnetic field changed. Figure 7.19 shows the time scale of the polarity reversals established for the last few million years.

A significant relationship was uncovered between the magnetic reversals and the seafloor-spreading hypothesis. Very sensitive instruments called **magnetometers** were towed by research vessels across a segment of the ocean floor located off the West Coast of the United States. Here workers from the Scripps Institute of Oceanography discovered alternating strips of high- and low-intensity magnetism that trended in roughly a north-south direction. This relatively simple pattern of magnetic variation defied explanation until 1963, when it was tied to the concept of seafloor spreading. The strips of high-intensity magnetism are regions where the paleomagnetism of the ocean crust is of the normal type. Consequently, these positively magnetized rocks enhance the existing magnetic field. Conversely, the low-intensity strips represent regions where the ocean crust is polarized in the reverse direction and, therefore, weaken the existing magnetic field. But how do parallel strips of normally and reversely magnetized rock become distributed across the ocean floor?

As new basalt is added to the ocean floor at the oceanic ridges, it becomes magnetized according to the existing magnetic field (Figure 7.20). Because new rock is added in approximately equal amounts to the trailing edges of both plates, we should expect strips of equal size and polarity to parallel both sides of the ocean ridges, as shown in Figure 7.20. This explanation of the alternating strips of normal and reverse polarity, which lay as mirror images across the ocean ridges, was the strongest evidence so far presented in support of the concept of seafloor spreading.

Now that the dates of the most recent magnetic reversals have been established, the rate at which spreading occurs at the various ridges can be determined accurately. In the Pacific Ocean, for example, the magnetic strips are much wider for corresponding time intervals than those of the Atlantic Ocean. Hence, we
conclude that a faster spreading rate exists for the spreading center of the Pacific as compared to the Atlantic. When we apply absolute dates to these magnetic events, we find that the spreading rate for the North Atlantic Ridge is only 2 centimeters per year. The rate is somewhat faster for the South Atlantic. The spreading rates for the East Pacific Rise generally range between 6 and 12 centimeters per year, with a maximum rate exceeding 15 centimeters (6 inches) per year in one segment. Thus, we have a magnetic tape recorder that records changes in Earth's magnetic field. This recorder also permits us to determine the rate of seafloor spreading.

**Evidence: Earthquake Patterns**

By 1968, the basic outline of global tectonics was firmly established. In that same year, three seismologists published papers demonstrating how successfully the new plate tectonics model accounted for the global distribution of earthquakes (Figure 7.21). In particular, these scientists were able to account for the close association between deep-focus earthquakes and ocean trenches. Furthermore, the absence of deep-focus earthquakes along the oceanic ridge system was also shown to be consistent with the new theory.

The close association between plate boundaries and earthquakes can be seen by comparing the distribution of earthquakes shown in Figure 7.21 with the map of plate boundaries in Figure 7.8 and trenches in Figure 7.13. In trench regions where dense slabs of lithosphere plunge into the mantle, this association is especially striking. When the depths of earthquake foci and their locations within the trench systems are plotted, an interesting pattern emerges. Figure 7.22, which shows the distribution of earthquakes in the vicinity of the Japan trench, is an example. Here most shallow-focus earthquakes occur within, or adjacent to, the trench, whereas intermediate- and deep-focus earthquakes occur toward the mainland.

In the plate tectonics model, deep-ocean trenches are produced where cool, dense slabs of oceanic litho-
Figure 7.20  As new basalt is added to the ocean floor at the oceanic ridges, it is magnetized according to Earth’s existing magnetic field. Hence, it behaves much like a tape recorder as it records each reversal of the planet’s magnetic field.

Figure 7.21  Distribution of shallow-, intermediate-, and deep-focus earthquakes. Note that intermediate- and deep-focus earthquakes only occur in association with subduction zones. (Data from NOAA)

sphere plunge into the mantle. Shallow-focus earthquakes are produced as the descending plate interacts with the overriding lithosphere. As the slab descends farther into the asthenosphere, deeper-focus earthquakes are generated (Figure 7.22). Because the earthquakes occur within the rigid subducting plate rather than in the plastic mantle, they provide a method for tracking the plate’s descent. Very few earthquakes have been recorded below 700 kilometers (435 miles), possibly because the slab has been heated sufficiently to lose its rigidity.

Evidence: Ocean Drilling
Some of the most convincing evidence confirming the plate tectonics theory has come from drilling directly
into ocean-floor sediment. From 1968 until 1983, the source of these important data was the Deep Sea Drilling Project, an international program sponsored by several major oceanographic institutions and the National Science Foundation. A new drilling ship was built. The Glomar Challenger represented a significant technological breakthrough, because this ship could lower drill pipe thousands of meters to the ocean floor and then drill hundreds of meters into the sediments and underlying basaltic crust.

Operations began in August 1968, in the South Atlantic. At several sites, holes were drilled through the entire thickness of sediments to the basaltic rock below. An important objective was to gather samples of sediment from just above the igneous crust as a means of dating the seafloor at each site. (Radiometric dates of the ocean crust itself are unreliable because seawater alters basalt.)

When the oldest sediment from each drill site was plotted against its distance from the ridge crest, it was revealed that the age of the sediment increased with increasing distance from the ridge. This finding agreed with the seafloor-spreading hypothesis, which predicted that the youngest oceanic crust would be found at the ridge crest and that the oldest oceanic crust would be at the continental margins.

The data from the Deep Sea Drilling Project also reinforced the idea that the ocean basins are geologically youthful, because no sediment with an age in excess of 180 million years was found. By comparison, some continental crust has been dated at 3.9 billion years.

During its 15 years of operation, the Glomar Challenger drilled 1092 holes and obtained more than 96 kilometers (60 miles) of invaluable core samples. The Ocean Drilling Program has succeeded the Deep Sea Drilling Project and, like its predecessor, is a major international program. A more technologically advanced drilling ship, the JOIDES Resolution, now continues the work of the Glomar Challenger (Figure 7.23).

Evidence: Hot Spots

Mapping of seafloor volcanoes (called seamounts) in the Pacific revealed a chain of volcanic structures extending from the Hawaiian Islands to Midway Island and then continuing northward toward the Aleutian trench (Figure 7.24). Radiometric dates of volcanoes in this chain showed that the volcanoes increase in age with increasing distance from Hawaii. Suiko Seamount, which is located near the Aleutian trench, is 65 million years old, Midway Island is 27 million years old, and the island of Hawaii was built up from the seafloor less than a million years ago (Figure 7.24).

Researchers are in agreement that a rising plume of mantle material is located below the island of Hawaii. Decompression melting of this hot rock as it enters the low-pressure environment near the surface generates a volcanic area, or hot spot. As the Pacific plate moved over the hot spot, successive volcanic mountains have been built. The age of each volcano indicates the time when it was situated over the relatively stationary mantle plume.

This pattern is shown in Figure 7.24. Kauai is the oldest of the large islands in the Hawaiian chain. Five million years ago, when it was positioned over the hot spot, Kauai was the only Hawaiian island in existence.
Visible evidence of the age of Kauai can be seen by examining its extinct volcanoes, which have been eroded into jagged peaks and vast canyons. By contrast, the south slopes of the relatively youthful island of Hawaii consist of fresh lava flows, and two of Hawaii’s volcanoes, Mauna Loa and Kilauea, remain active.

This evidence supports the fact that the plates do indeed move relative to Earth’s interior. The hot spot tracks also trace the direction of plate motion. Notice, for example, in Figure 7.24 (lower left) that the Hawaiian Island–Emperor Seamount chain bends. This particular bend in the trace occurred about 40 million years ago when the motion of the Pacific plate changed from nearly due north to its present northwesterly path.

Measuring Plate Motion

A number of methods have been employed to establish the direction and rate of plate motion. As noted earlier, hot spot “tracks” like those of the Hawaiian Island–Emperor Seamount chain trace the movement of the Pacific Plate relative to the mantle below. Further, by measuring the length of this volcanic chain and the time interval between the formation of the oldest structure (Suiko Seamount) and youngest structure (Hawaii), an average rate of plate motion can be calculated. In this case the volcanic chain is roughly 3000 kilometers long and has formed over the past 65 million years—making the average rate of movement about 9 centimeters per year.
(4 inches) per year. The accuracy of this calculation hinges on the hot spot maintaining a fixed position in the mantle. Based on current evidence, this appears to be a reasonable assumption.

Recall that the magnetic stripes measured on the floor of the ocean also provide a method to measure rates of plate motion—at least as averaged over millions of years. Using paleomagnetism and other indirect techniques, researchers have been able to work out relative plate velocities as shown on the map in Figure 7.25.

It is currently possible, with the use of space-age technology, to directly measure the relative motion between plates. This is accomplished by periodically establishing the exact locations, and hence the distance between two observing stations situated on opposite sides of a plate boundary. Two of the methods used for this calculation are Very Long Baseline Interferometry (VLBI) and a satellite positioning technique that employs the Global Positioning System (GPS). The Very Long Baseline Interferometry system utilizes large radio telescopes to record signals from very distant quasars (quasi-stellar objects) (Figure 7.26). Quasars lie billions of light-years from Earth, so they act as stationary reference points. The millisecond differences in the arrival times of the same signal at different earthbound observatories provide a means of establishing the precise distance between receivers. A typical survey may take a day to perform and involves two widely spaced radio telescopes observing perhaps a dozen quasars, 5 to 10 times each. This scheme provides an estimate of the distance between these observatories, which is accurate to about 2 centimeters. By repeating this experiment at a later date, researchers can establish the relative motion of these sites. This method has been particularly useful in establishing large-scale plate motions, such as the separation that is occurring between the United States and Europe (see Box 7.3).

You may be familiar with GPS, which uses 21 satellites to accurately locate any individual who is equipped with a handheld receiver. By using two spaced receivers, signals obtained by these instruments can be used to calculate their relative positions with considerable accuracy. Techniques using GPS receivers have been shown to be useful in establishing small-scale crustal movements such as those that occur along local faults in regions known to be tectonically active.

Confirming data obtained from these and other techniques leave little doubt that real plate motion has been detected (Figure 7.25). Calculations show that Hawaii is moving in a northwesterly direction and is approaching Japan at 8.3 centimeters per year. A site located in Maryland is retreating from one in England at a rate of about 1.7 centimeters per year—a rate that is close to the 2.3-centimeters-per-year spreading rate that was established from paleomagnetic evidence.

The Driving Mechanism

The plate tectonics theory describes plate motion and the effects of this motion. Therefore, acceptance of this model does not rely on the mechanism that drives plate motion. This is fortunate, because none of the driving

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**Figure 7.25** This map illustrates directions and rates of plate motion in centimeters per year. Seafloor-spreading velocities (as shown with black arrows and labels) are based on the spacing of dated magnetic stripes (anomalies). The colored arrows show Very Long Baseline Interferometry (VLBI) data of plate motion at selected locations. The data obtained by these methods are typically consistent. (Seafloor data from DeMets and others, VLBI data from Ryan and others.)
mechanisms yet proposed can account for all major facets of plate tectonics. Nevertheless, researchers generally agree on the following:

1. Convective flow in the rocky 2900-kilometer-thick mantle—in which warm, less dense rock rises and cooler, more dense material sinks—is the basic driving force for plate movement.

2. Mantle convection and plate tectonics are part of the same system. Oceanic plates represent the cold downward-moving portion of convective flow.

3. The slow movements of the plates and mantle are driven by the unequal distribution of heat within Earth’s interior. This flow is the mechanism that transports heat away from Earth’s interior.

What is not known with any large degree of certainty is the precise nature of this convective flow.

Some researchers have argued that the mantle is like a giant layer cake, divided at a depth of 660 kilometers. Convection operates in both layers, but mixing between layers is minimal. At the other end of the spectrum is a model that loosely resembles a pot of just barely boiling water, churning ever so slowly from top to bottom over eons of geologic time. Neither model fits all of the available data. We will first look at some of the processes that are thought to contribute to plate motion and then examine a few of the models that have been proposed to describe plate-mantle convection.

**Slab-Pull, Ridge-Push, and Mantle Plumes**

Several mechanisms generate forces that contribute to plate motion. One relies on the fact that old oceanic crust, which is relatively cool and dense, sinks into the asthenosphere and “pulls” the trailing lithosphere along. This mechanism, called **slab-pull**, is thought to be the primary downward arm of the convective flow operating in the mantle. By contrast, **ridge-push** results from the elevated position of the oceanic ridge system and causes oceanic lithosphere to gravitationally slide down the flanks of the ridge. Ridge-push, although apparently active in some spreading centers, is probably less important than slab-pull.

Most models suggest that hot, buoyant plumes of rock are the upward flowing arms in the convective mechanism at work in the mantle. These rising **mantle plumes** manifest themselves on Earth’s surface as hot spots with their associated volcanic activity. Mapping of Earth’s interior using seismic tomography indicates that at least some of these hot plumes extend upward from the vicinity of the mantle-core boundary. Others, however, appear to originate higher in the mantle. Further, some upward flow in the mantle is not related to plumes and occurs just below the ridge crests as a result of seafloor spreading.

**Models of Plate-Mantle Convection**

Any model describing mantle convection must be consistent with the observed physical and chemical properties of the mantle. In particular, these models must explain why basalts that erupt along the oceanic ridge are fairly homogeneous in composition and depleted in certain trace elements. It is assumed that these ridge basalts are derived from rocks located in the upper mantle that experienced an earlier period of chemical differentiation, in which trace elements were removed. By contrast, higher concentrations of these elements are evident in basaltic eruptions associated with hot-spot volcanism. Because basalts that erupted in different settings have different concentrations of trace elements, they are assumed to be derived from chemically distinct regions of the mantle. Basalts associated with mantle plumes are thought to come from a primitive (less differentiated) source, which more closely resembles the average chemical composition of the early mantle.

**Layering at 660 Kilometers.** Earlier we referred to the “layer cake” version of mantle convection. As shown in Figure 7.27A, one of these layered models has two zones of convection—a thin, convective layer above 660 kilometers and a thick one located below. This model successfully explains why the basalts that erupt along the oceanic ridges have a somewhat different composition than those that erupt in Hawaii as a result of hot-spot activity. The oceanic ridge basalts come from the upper convective layer, which is well mixed, whereas the mantle plume that feeds the Hawaiian volcanoes taps a deeper, more primitive source that resides in the lower convective layer.

Despite evidence that supports this model, recent seismic imaging has shown that subducting slabs of cold oceanic lithosphere are able to penetrate the 660-kilometer boundary. The subducting lithosphere serves to mix the upper and lower layers together. As a result, the layered mantle structure is lost.
Two geologists, Robert Dietz and John Holden, extrapolated present-day plate movements into the future. Figure 7.C illustrates where they envision Earth’s landmasses will be 50 million years from now if present plate movements persist for this time span.

In North America we see that the Baja Peninsula and the portion of southern California that lies west of the San Andreas Fault will have slid past the North American plate. If this northward migration takes place, Los Angeles and San Francisco will pass each other in about 10 million years, and in about 60 million years Los Angeles will begin to descend into the Aleutian trench.

Significant changes are seen in Africa, where a new sea emerges as East Africa parts company with the mainland. In addition, Africa will have moved slowly into Europe, perhaps initiating the next major mountain-building stage on our dynamic planet. Meanwhile, the Arabian Peninsula continues to diverge from Africa, allowing the Red Sea to widen and close the Persian Gulf.

In other parts of the world, Australia is now astride the equator and, along with New Guinea, is on a collision course with Asia. Meanwhile, North and South America are beginning to separate, while the Atlantic and Indian oceans continue to grow at the expense of the Pacific Ocean.

These projections into the future, although interesting, must be viewed with caution because many assumptions must be correct for these events to unfold as just described. Nevertheless, changes in the shapes and positions of continents that are equally profound will undoubtedly occur for millions of years to come.

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**Whole-Mantle Convection.** Because of problems with the layered model, researchers began to favor whole-mantle convection. In a whole-mantle convection model, slabs of cold oceanic lithosphere descend into the lower mantle, providing the downward arm of convective flow (Figure 7.27B). Simultaneously, hot mantle plumes originating near the mantle-core boundary transport heat toward the surface. It was also suggested that at extremely slow rates of convection, primitive (undepleted) mantle rock would exist at depth in quantities sufficient to feed the rising mantle plumes.

Recent work, however, has shown that whole mantle mixing would cause the lower mantle to become appreciably mixed in a matter of a few hundred million years. This mixing would tend to eliminate the source of primitive magma observed in hot-spot volcanism.

**Deep-Layer Model.** A remaining possibility is layering deeper in the mantle. One deep-layer model has been described as analogous to a lava lamp on a low setting. As shown in Figure 7.27C, the lower perhaps one-third of the mantle is like the colored fluid in the bottom layer of a lava lamp. Like a lava lamp on low, heat from Earth’s interior causes the two layers to slowly swell and shrink in complex patterns without substantial mixing. A small amount of material from the lower layer flows upward as mantle plumes to generate hot-spot volcanism at the surface.

This model provides the two chemically different mantle sources for basalt that are required by observational data. Further, it is compatible with seismic images that show cold lithospheric plates sinking deep into the mantle. Despite its attractiveness, there is little
Figure 7.27  Proposed models for mantle convection. A. The model shown in this illustration consists of two convection layers—a thin, convective layer above 660 kilometers and a thick one below. B. In this whole-mantle convection model, cold oceanic lithosphere descends into the lowermost mantle while hot mantle plumes transport heat toward the surface. C. This deep-layer model suggests that the mantle operates similar to a lava lamp on a low setting. Earth’s heat causes these layers of convection to slowly swell and shrink in complex patterns without substantial mixing. Some material from the lower layer flows upward as mantle plumes.
seismic evidence to suggest that a deep mantle layer of this nature exists, except for the very thin layer located at the mantle-core boundary.

Although there is still much to be learned about the mechanisms that cause plates to move, some facts are clear. The unequal distribution of heat in Earth generates some type of thermal convection that ultimately drives plate-mantle motion. Furthermore, the descending lithospheric plates are active components of downwelling, and they serve to transport cold material into the mantle. Exactly how this convective flow operates is yet to be determined.

Chapter Summary

- In the early 1900s Alfred Wegener set forth his continental drift hypothesis. One of its major tenets was that a supercontinent called Pangaea began breaking apart into smaller continents about 200 million years ago. The smaller continental fragments then drifted to their present positions. To support the claim that the now separate continents were once joined, Wegener and others used the fit of South America and Africa, the distribution of ancient climates, fossil evidence, and rock structures.

- One of the main objections to the continental drift hypothesis was its inability to provide an acceptable mechanism for the movement of continents.

- The theory of plate tectonics, a far more encompassing theory than continental drift, holds that Earth’s rigid outer shell, called the lithosphere, consists of about seven large and numerous smaller segments called plates that are in motion relative to each other. Most of Earth’s seismic activity, volcanism, and mountain building occur along the dynamic margins of these plates.

- A major departure of the plate tectonics theory from the continental drift hypothesis is that large plates contain both continental and ocean crust and the entire plate moves. By contrast, in continental drift, Wegener proposed that the sturdier continents drifted by breaking through the oceanic crust, much like ice breakers cut through ice.

- Divergent plate boundaries occur where plates move apart, resulting in upwelling of material from the mantle to create new seafloor. Most divergent boundaries occur along the axis of the oceanic ridge system and are associated with seafloor spreading, which occurs at rates of 2 to 15 centimeters per year. New divergent boundaries may form within a continent (for example, the East African rift valleys) where they may fragment a landmass and develop a new ocean basin.

- Convergent plate boundaries occur where plates move together, resulting in the subduction of oceanic lithosphere into the mantle along a deep oceanic trench. Convergence between an oceanic and continental block results in subduction of the oceanic slab and the formation of a continental volcanic arc such as the Andes of South America. Oceanic–oceanic convergence results in an arc-shaped chain of volcanic islands called a volcanic island arc. When two plates carrying continental crust converge, both plates are too buoyant to be subducted. The result is a “collision” resulting in the formation of a mountain belt such as the Himalayas.

- Transform fault boundaries occur where plates grind past each other without the production or destruction of lithosphere. Most transform faults join two segments of an oceanic ridge. Others connect spreading centers to subduction zones and thus facilitate the transport of oceanic crust created at a ridge crest to its site of destruction, at a deep-ocean trench. Still others, like the San Andreas Fault, cut through continental crust.

- The theory of plate tectonics is supported by (1) paleomagnetism, the direction and intensity of Earth’s magnetism in the geologic past; (2) the global distribution of earthquakes and their close association with plate boundaries; (3) the ages of sediments from the floors of the deep-ocean basins; and (4) the existence of island groups that formed over hot spots and that provide a frame of reference for tracing the direction of plate motion.

- Three basic models for mantle convection are currently being evaluated. Mechanisms that contribute to this convective flow are slab-pull, ridge-push, and mantle plumes. Slab-pull occurs when cold, dense oceanic lithosphere is subducted and pulls the trailing lithosphere along. Ridge-push results when gravity sets the elevated slabs astride oceanic ridges in motion. Hot, buoyant mantle plumes are considered the upward flowing arms of mantle convection. One model suggests that mantle convection occurs in two layers separated at a depth of 660 kilometers. Another model proposes whole-mantle convection that stirs the entire 2900-kilometer-thick rocky mantle. Yet another model suggests that the bottom third of the mantle gradually bulges upward in some areas and sinks in others without appreciable mixing.

Key Terms

- asthenosphere (p. 199)
- continental drift (p. 192)
- continental volcanic arc (p. 207)
- convergent plate boundary (p. 199)
- divergent plate boundary (p. 199)
- hot spot (p. 216)
- lithosphere (p. 199)
- mantle plume (p. 219)
- normal polarity (p. 213)
Review Questions

1. Who is credited with developing the continental drift hypothesis?
2. What was probably the first evidence that led some to suspect the continents were once connected?
3. What was Pangaea?
4. List the evidence that Wegener and his supporters gathered to substantiate the continental drift hypothesis.
5. Explain why the discovery of the fossil remains of Mesosaurus in both South America and Africa, but nowhere else, supports the continental drift hypothesis.
6. Early in this century, what was the prevailing view of how land animals migrated across vast expanses of ocean?
7. How did Wegener account for the existence of glaciers in the southern landmasses, while at the same time areas in North America, Europe, and Siberia supported lush tropical swamps?
8. On what basis were plate boundaries first established?
9. What are the three major types of plate boundaries? Describe the relative plate motion at each of these boundaries.
10. What is seafloor spreading? Where is active seafloor spreading occurring today?
11. What is a subduction zone? With what type of plate boundary is it associated?
12. Where is lithosphere being consumed? Why must the production and destruction of lithosphere be going on at approximately the same rate?
13. Briefly describe how the Himalaya Mountains formed.
14. Differentiate between transform faults and the other two types of plate boundaries.
15. Some predict that California will sink into the ocean. Is this idea consistent with the theory of plate tectonics?
16. Define the term paleomagnetism.
17. How does the continental drift hypothesis account for the apparent wandering of Earth’s magnetic poles?
18. Describe the distribution of earthquake epicenters and foci depths as they relate to oceanic trench systems.
19. What is the age of the oldest sediments recovered by deep-ocean drilling? How do the ages of these sediments compare to the ages of the oldest continental rocks?
20. How do hot spots and the plate tectonics theory account for the fact that the Hawaiian Islands vary in age?
21. With what type of plate boundary are the following places or features associated (be as specific as possible): Himalayas, Aleutian Islands, Red Sea, Andes Mountains, San Andreas Fault, Iceland, Japan, Mount St. Helens?
22. Briefly describe the three models proposed for mantle-plate convection. What is lacking in each of these models?

Examining the Earth System

1. As an integral subsystem of the Earth system, plate tectonics has played a major role in determining the events that have taken place on Earth since its formation about 4.5 billion years ago. Briefly comment on the general effect that the changing positions of the continents and the redistribution of land and water over Earth’s surface have had on the atmosphere, hydrosphere, and biosphere through time. You may want to review plate tectonics by investigating the topic on the Internet using a search engine such as HotBot (http://www.hotbot.com/) or Yahoo (http://www.yahoo.com/) and visiting the United States Geological Survey’s (USGS) This Dynamic Earth: The Story of Plate Tectonics Website at http://pubs.usgs.gov/publications/text/dynamic.html.
2. Assume that plate tectonics did not cause the breakup of the supercontinent Pangaea. Using Figure 7.2, describe how the climate (atmosphere), vegetation and animal life (biosphere), and geological features (solid Earth) of those locations currently occupied by the cities of Seattle, WA; Chicago, IL; New York, NY; and your college campus location would be different from the conditions that exist today.

Web Resources

The Earth Science Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by Earth science instructors, this site will help improve your understanding of Earth science. Visit http://www.prenhall.com/tarbuck and click on the cover of Earth Science 10e to find:

- On-line review quizzes.
- Web-based critical thinking and writing exercises.
- Links to chapter-specific Web resources.
- Internet-wide key term searches.

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