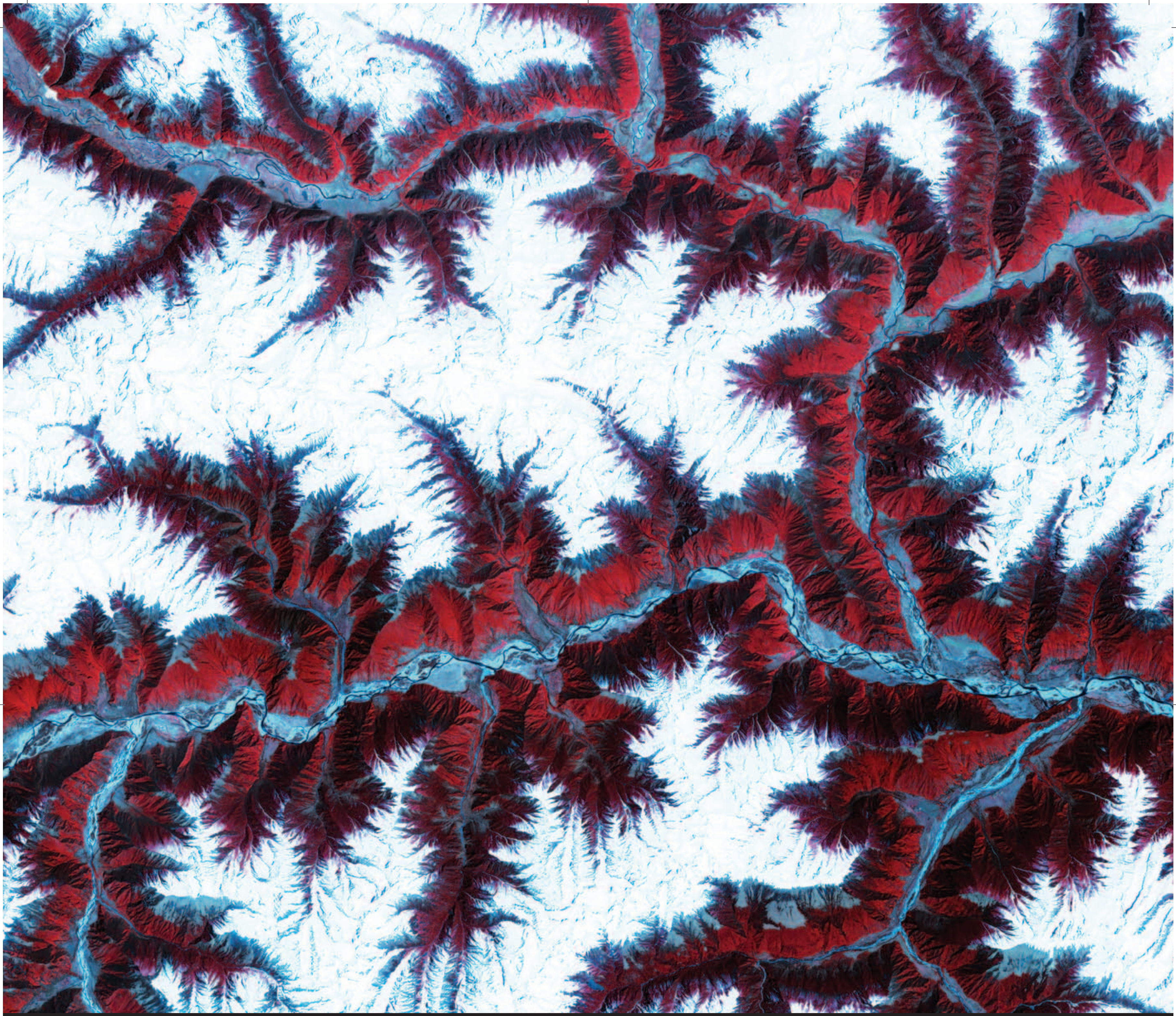
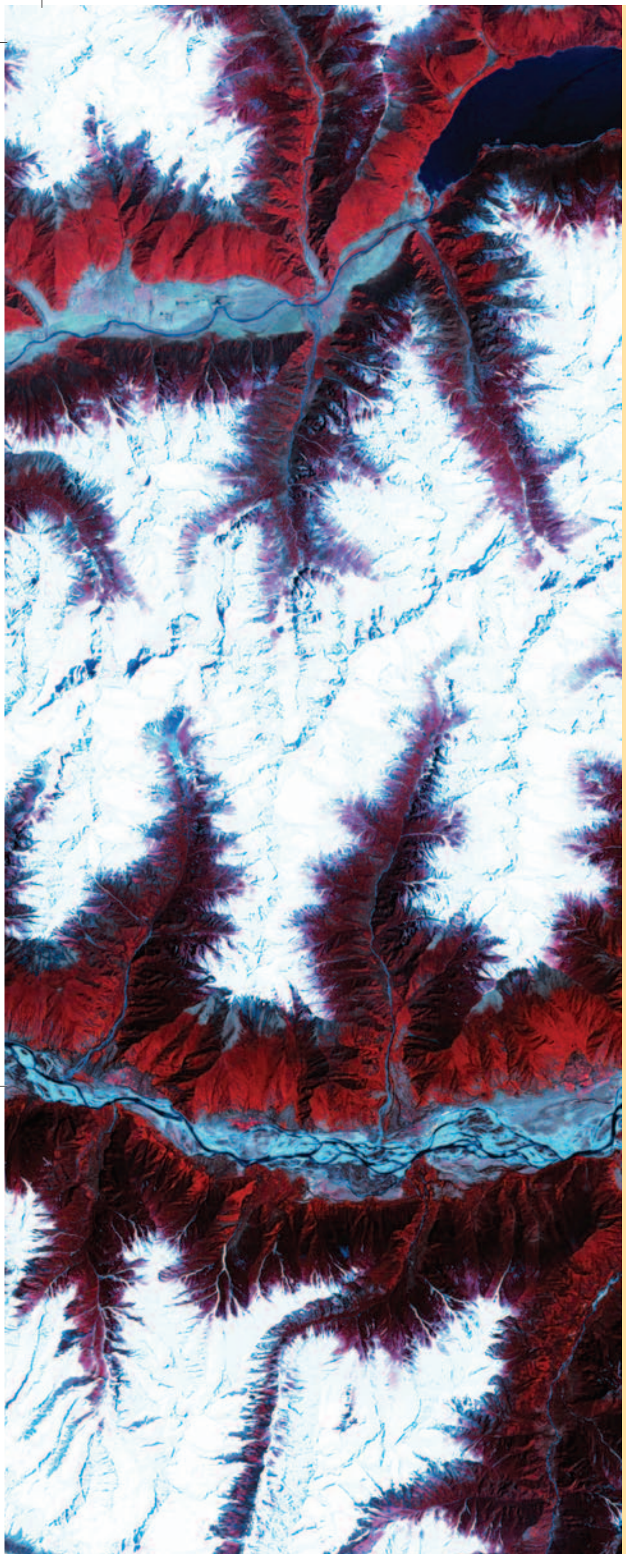


Chapter 2

Plate Tectonics: A Unifying Theory



USGS/NASA

The Himalayas, Southwestern China
Ruby and sapphire veins spread over white like fossils of ferns on rock.
This satellite image of the Himalayas reveals an ever-changing tapestry of peaks, ridges, and rivers woven by Earth millions of years ago when India collided with Asia.

—A. W.

ESSENTIAL QUESTIONS TO ASK

2.1 Introduction
- *Why should you know about plate tectonics?*

2.2 Continental Drift
- *What were some early ideas about Earth's past geography?*
- *What is the continental drift hypothesis and who proposed it?*

2.3 Evidence for Continental Drift
- *What is the evidence for continental drift?*

2.4 Paleomagnetism and Polar Wandering
- *What is paleomagnetism?*
- *What is the Curie point and why is it important?*
- *How can the apparent wandering of the magnetic poles be best explained?*

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- *What evidence is there that Earth's magnetic field has reversed in the past?*
- *What is the theory of seafloor spreading, and how does it validate continental drift?*
- *How was the theory of seafloor spreading confirmed?*

2.6 Plate Tectonics: A Unifying Theory
- *What are the main tenets of plate tectonic theory?*
- *Why is plate tectonics a unifying theory of geology?*
- *What is the supercontinent cycle?*

2.7 The Three Types of Plate Boundaries
- *What are the three types of plate boundaries?*
- *What are divergent boundaries?*
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- *What are convergent boundaries?*
- *How can ancient subduction zones be recognized in the geologic record?*
- *What are transform boundaries?*

2.8 Hot Spots: An Intraplate Feature
- *What are hot spots and what do they tell us about plate movement?*

2.9 Plate Movement and Motion
- *How can the rate and direction of plate movement be determined?*

2.10 The Driving Mechanism of Plate Tectonics
- *What drives plates?*
- *How do thermal convection cells move plates?*
- *Can plate movement be gravity driven?*

2.11 Plate Tectonics and the Distribution of Natural Resources
- *How does plate tectonic theory relate to the origin and distribution of natural resources?*
- *What is the relationship between plate boundaries and various metallic mineral deposits?*

GEOLOGY MATTERS

GEOLOGY IN FOCUS:
Oil, Plate Tectonics, and Politics

GEOLOGY IN UNEXPECTED PLACES:
A Man's Home Is His Castle

GEOLOGY AND CULTURAL CONNECTIONS:
The Struggle toward Scientific Progress

GEOLOGY AT WORK:
The Geologic Exploration of Mars

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2.1 Introduction

Imagine it is the day after Christmas, December 26, 2004, and you are vacationing on a beautiful beach in Thailand. You look up from the book you're reading to see the sea suddenly retreat from the shoreline, exposing a vast expanse of seafloor that had moments before been underwater and teeming with exotic and colorful fish. It is hard to believe that within minutes of this unusual event, a powerful tsunami will sweep over your resort and everything in its path for several kilometers inland. Within hours, the coasts of Indonesia, Sri Lanka, India, Thailand, Somalia, Myanmar, Malaysia, and the Maldives will be inundated by the deadliest tsunami in history. More than 220,000 people will die, and billions of dollars in damage will be wreaked on the region.

One year earlier, on December 26, 2003, violent shaking from an earthquake awakened hundreds of thousands of people in the Bam area of southeastern Iran. When the magnitude-6.6 earthquake was over, an estimated 43,000 people were dead, at least 30,000 were injured, and approximately 75,000 survivors were left homeless. At least 85% of the structures in the Bam area were destroyed or damaged. Collapsed buildings were everywhere, streets were strewn with rubble, and all communications were knocked out.

Now go back another 12½ years to June 15, 1991, when Mount Pinatubo in the Philippines erupted violently, discharging huge quantities of ash and gases into the atmosphere. Fortunately, in this case, warnings of an impending eruption were broadcast and heeded, resulting in the evacuation of 200,000 people from areas around the volcano. Unfortunately, the eruption still caused at least 364 deaths not only from the eruption but also from ensuing mudflows.

What do these three recent tragic events have in common? They are part of the dynamic interactions involving Earth's plates. When two plates come together, one plate is pushed or pulled under the other plate, triggering large earthquakes such as the one that shook India in 2001, Iran in 2003, and Pakistan in 2005. If conditions are right, earthquakes can produce a tsunami such as the one in 2004 or the 1998 Papua New Guinea tsunami that killed more than 2200 people.

As the descending plate moves downward and is assimilated into Earth's interior, magma is generated. Being less dense than the surrounding material, the magma rises toward the surface, where it may erupt as a volcano such as Mount Pinatubo did in 1991 and others have since. It therefore should not be surprising that the distribution of volcanoes and earthquakes closely follows plate boundaries.

As we stated in Chapter 1, **plate tectonic theory** has had significant and far-reaching consequences in all fields of geology because it provides the basis for relating many seemingly unrelated phenomena. The interactions between moving plates determine the locations of continents, ocean basins, and mountain systems, which in turn affect atmospheric and oceanic circulation patterns that ultimately determine global climate (see Table 1.3). Plate movements have also profoundly influenced the geographic distribution, evolution, and extinction of plants and animals. Furthermore, the formation and distribution of many geologic resources, such as metal ores, are related to plate tectonic processes, so geologists incorporate plate tectonic theory into their prospecting efforts.

■ *Why should you know about plate tectonics?*

If you're like most people, you probably have no idea or only a vague notion of what plate tectonic theory is. Yet plate tectonics affects all of us. Volcanic eruptions, earthquakes, and tsunami are the result of interactions between plates. Global weather patterns and oceanic currents are caused, in part, by the configuration of the continents and ocean basins. The formation and distribution of many natural resources are related to plate movement and thus have an impact on the economic well-being and political decisions of nations. It is therefore important to understand this unifying theory, not only because it affects us as individuals and as citizens of nation-states but also because it ties together many aspects of the geology you will be studying.

Section 2.1 Summary

- Plate tectonic theory is the unifying theory of geology. It affects all of us because it explains where and why such natural disasters as earthquakes, volcanic eruptions, and tsunami occur as well as the formation and distribution of many economically valuable natural resources.

2.2 Continental Drift

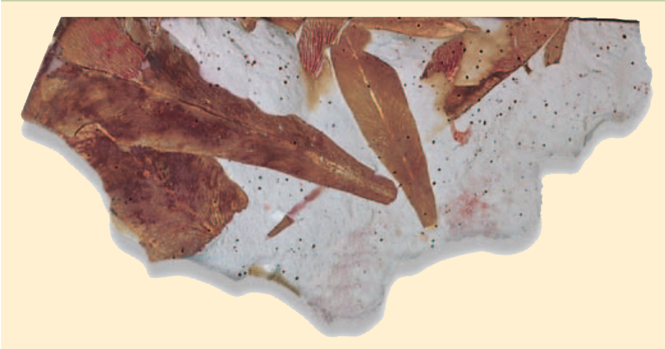
■ *What were some early ideas about Earth's past geography?*

The idea that Earth's past geography was different from today is not new. The earliest maps showing the east coast of South America and the west coast of Africa probably provided people with the first evidence that continents may have once been joined together, then broken apart and moved to their present locations.

During the late 19th century, the Austrian geologist Edward Suess noted the similarities between the Late Paleozoic plant fossils of India, Australia, South Africa, and South America as well as evidence of glaciation in the rock sequences of these southern continents. The plant fossils make up a unique flora in the coal layers just above the glacial deposits of these southern continents. This flora is very different from the contemporaneous coal swamp flora of the northern continents and is collectively known as the ***Glossopteris* flora,** after its most conspicuous genus (▶ Figure 2.1).

In his book, *The Face of the Earth*, published in 1885, Suess proposed the name *Gondwanaland* (or **Gondwana** as we will use here) for a supercontinent composed of the

▶ **Figure 2.1 Fossil *Glossopteris* Leaves** Plant fossils, such as these *Glossopteris* leaves from the Upper Permian Dunedoo Formation in Australia, are found on all five Gondwana continents. The presence of these fossil plants on continents with widely varying climates today is evidence that the continents were at one time connected. The distribution of the plants at that time was in the same climatic latitudinal belt.



Courtesy of Patricia G. Gensel, University of North Carolina

aforementioned southern continents. Abundant fossils of the *Glossopteris* flora are found in coal beds in Gondwana, a province in India. Suess thought these southern continents were at one time connected by land bridges over which plants and animals migrated. Thus, in his view, the similarities of fossils on these continents were due to the appearance and disappearance of the connecting land bridges.

The American geologist Frank Taylor published a pamphlet in 1910 presenting his own theory of continental drift. He explained the formation of mountain ranges as a result of the lateral movement of continents. He also envisioned the present-day continents as parts of larger polar continents that eventually broke apart and migrated toward the equator after Earth's rotation was supposedly slowed by gigantic tidal forces. According to Taylor, these tidal forces were generated when Earth captured the Moon about 100 million years ago.

Although we now know that Taylor's mechanism is incorrect, one of his most significant contributions was his suggestion that the Mid-Atlantic Ridge, discovered by the 1872–1876 British HMS *Challenger* expeditions, might mark the site along which an ancient continent broke apart to form the present-day Atlantic Ocean.

■ *What is the continental drift hypothesis and who proposed it?*

Alfred Wegener, a German meteorologist (▶ Figure 2.2), is generally credited with developing the hypothesis of **continental drift.** In his monumental book, *The Origin of Continents and Oceans* (first published in 1915), Wegener proposed that all landmasses were originally united in a single supercontinent that he named **Pangaea,** from the Greek meaning "all land." Wegener portrayed his grand concept of continental movement in a series of maps showing the breakup of Pangaea and the movement of the various continents to their present-day locations. Wegener amassed a tremendous amount of geologic, paleontologic, and climatologic evidence in support of continental drift, but the initial reaction of scientists to his then-heretical ideas can best be described as mixed.

Opposition to Wegener's ideas became particularly widespread in North America after 1928, when the American Association of Petroleum Geologists held an international symposium to review the hypothesis of continental drift. After each side had presented its arguments, the opponents of continental drift were clearly in the majority, even though the evidence in support of continental drift, most of which came from the Southern Hemisphere, was impressive and difficult to refute. The main problem with the hypothesis was its lack of a mechanism to explain how continents, composed of granitic rocks, could seemingly move through the denser basaltic oceanic crust.

Nevertheless, the eminent South African geologist Alexander du Toit further developed Wegener's arguments and gathered more geologic and paleontologic evidence in support of continental drift. In 1937 du Toit published *Our Wandering Continents*, in which he contrasted the glacial deposits of Gondwana with coal deposits of the same age found in the continents of the Northern Hemisphere. To resolve this apparent

▶ **Figure 2.2 Alfred Wegener** Alfred Wegener, a German meteorologist, proposed the continental drift hypothesis in 1912 based on a tremendous amount of geologic, paleontologic, and climatologic evidence. He is shown here waiting out the Arctic winter in an expedition hut in Greenland.

Bildarchiv Preussischer Kulturbestiz

climatologic paradox, du Toit moved the Gondwana continents to the South Pole and brought the northern continents together such that the coal deposits were located at the equator. He named this northern landmass **Laurasia.** It consisted of present-day North America, Greenland, Europe, and Asia (except for India).

Despite what seemed to be overwhelming evidence, most geologists still refused to accept the idea that the continents moved. Not until the 1960s, when oceanographic research provided convincing evidence that the continents had once been joined together and subsequently separated, did the hypothesis of continental drift finally become widely accepted.

Section 2.2 Summary

- The idea that continents have moved in the past is not new and probably goes back to the first maps, in which one could see that the east coast of South America looks like it fits into the west coast of Africa.
- The continental drift hypothesis was first articulated by Alfred Wegener in 1912. He proposed that a single supercontinent, Pangaea, consisting of a northern landmass (later named Laurasia) and a southern landmass (previously named Gondwana), broke apart into what would become Earth's current continents, which then moved across Earth's surface to their present locations.

2.3 Evidence for Continental Drift

■ *What is the evidence for continental drift?*

What, then, was the evidence Wegener, du Toit, and others used to support the hypothesis of continental drift? It includes the fit of the shorelines of continents, the appearance of the same rock sequences and mountain ranges of the same age on continents now widely separated, the matching of glacial deposits and paleoclimatic zones, and the similarities of many extinct plant and animal groups whose fossil remains are found today on widely separated continents. Wegener and his supporters argued that this vast amount of evidence from a variety of sources surely indicated that the continents must have been close together in the past.

Continental Fit

Wegener, like some before him, was impressed by the close resemblance between the coastlines of continents on opposite sides of the Atlantic Ocean, particularly South America and Africa. He cited these similarities as partial evidence that the continents were at one time joined together as a supercontinent that subsequently split apart. As his critics pointed out, though, the configuration of coastlines results from erosional and depositional processes and therefore is continuously being modified. So, even if the continents had separated during the Mesozoic Era, as Wegener proposed, it is not likely that the coastlines would fit exactly.

▶ **Figure 2.3 Continental Fit** When continents are placed together based on their outlines, the best fit isn't along their present-day coastlines, but rather along the continental slope at a depth of about 2000 m. **Why is this?** *Because the coastlines are continuously being modified by erosional and depositional processes, and thus one would not expect them to be the same today as they were at any time in the geologic past.*

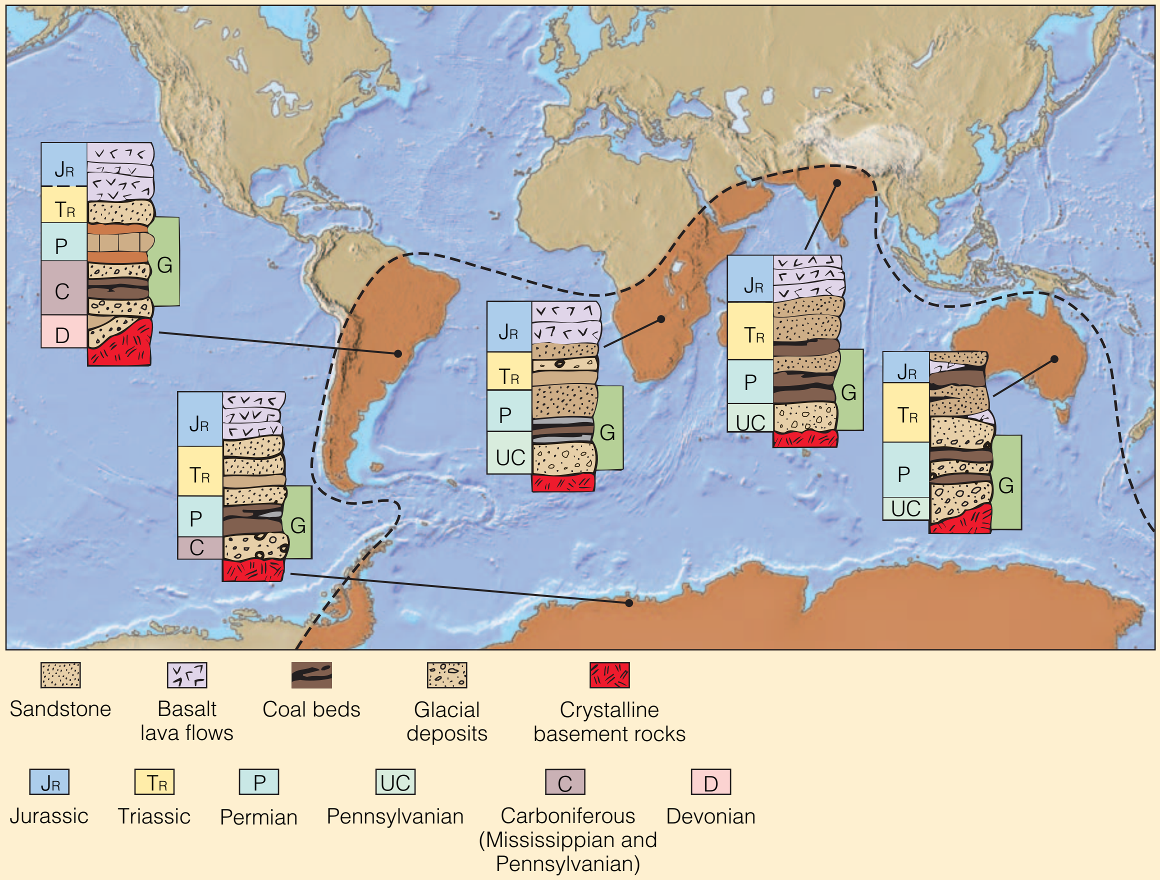
A more realistic approach is to fit the continents together along the continental slope, where erosion would be minimal. In 1965 Sir Edward Bullard, an English geophysicist, and two associates showed that the best fit between the continents occurs at a depth of about 2000 m (▶ Figure 2.3). Since then, other reconstructions using the latest ocean basin data have confirmed the close fit between continents when they are reassembled to form Pangaea.

Similarity of Rock Sequences and Mountain Ranges

If the continents were at one time joined, then the rocks and mountain ranges of the same age in adjoining locations on the opposite continents should closely match. Such is the case for the Gondwana continents (▶ Figure 2.4). Marine, nonmarine, and glacial rock sequences of Pennsylvanian to Jurassic age are almost identical on all five Gondwana continents, strongly indicating that they were joined at one time.

The trends of several major mountain ranges also support the hypothesis of continental drift. These mountain ranges seemingly end at the coastline of one continent only to apparently continue on another continent across the ocean. The folded Appalachian Mountains of North America, for example, trend northeastward through the eastern United

▶ **Figure 2.4 Similarity of Rock Sequences on the Gondwana Continents** Sequences of marine, nonmarine, and glacial rocks of Pennsylvanian (UC) to Jurassic (JR) age are nearly the same on all five Gondwana continents (South America, Africa, India, Australia, and Antarctica). These continents are widely separated today and have different environments and climates ranging from tropical to polar. Thus the rocks forming on each continent are very different. When the continents were all joined together in the past, however, the environments of adjacent continents were similar and the rocks forming in those areas were similar. The range indicated by G in each column is the age range (Carboniferous–Permian) of the *Glossopteris* flora.



States and Canada and terminate abruptly at the Newfoundland coastline. Mountain ranges of the same age and deformational style are found in eastern Greenland, Ireland, Great Britain, and Norway. In fact, the same red sandstones used in the construction of many English and Scottish castles are used in various buildings throughout New York. So, even though the Appalachian Mountains and their equivalent-age mountain ranges in Great Britain are currently separated by the Atlantic Ocean, they form an essentially continuous mountain range when the continents are positioned next to each other as they were during the Paleozoic Era.

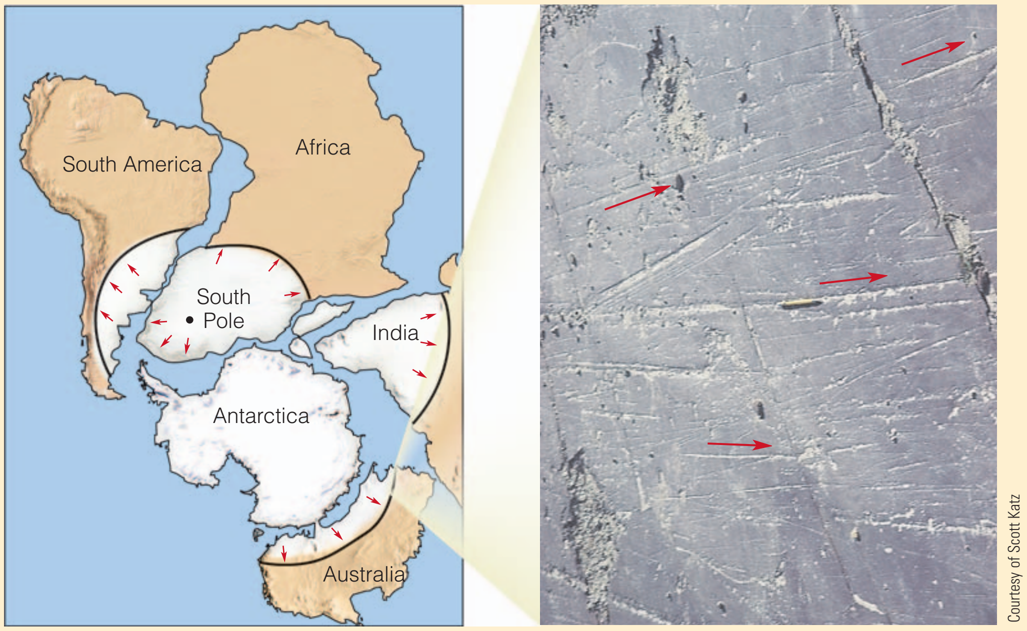
Glacial Evidence

During the Late Paleozoic Era, massive glaciers covered large continental areas of the Southern Hemisphere. Evidence for this glaciation includes layers of till (sediments deposited by glaciers) and striations (scratch marks) in the bedrock beneath the till. Fossils and sedimentary rocks of the same age from the Northern Hemisphere, however, give no indication of glaciation. Fossil plants found in coals indicate that the Northern Hemisphere had a tropical climate during the time the Southern Hemisphere was glaciated.

All the Gondwana continents except Antarctica are currently located near the equator in subtropical to tropical climates. Mapping of glacial striations in bedrock in Australia, India, and South America indicates that the glaciers moved from the areas of the present-day oceans onto land. This would be highly unlikely because large continental glaciers (such as occurred on the Gondwana continents during the Late Paleozoic Era) flow outward from their central area of accumulation toward the sea.

If the continents did not move during the past, one would have to explain how glaciers moved from the oceans onto land and how large-scale continental glaciers formed near the equator. But if the continents are reassembled as a single landmass with South Africa located at the South Pole, the direction of movement of Late Paleozoic continental glaciers makes sense (▶ Figure 2.5). Furthermore, this geographic arrangement places the northern continents nearer the tropics, which is consistent with the fossil and climatologic evidence from Laurasia.

PHYSICAL Geology Now™ ▶ **Geo-focus Figure 2.5 Glacial Evidence Indicating Continental Drift**



a When the Gondwana continents are placed together so that South Africa is located at the South Pole, the glacial movements indicated by striations (red arrows) found on rock outcrops on each continent make sense. In this situation, the glacier (white area) is located in a polar climate and has moved radially outward from its thick central area toward its periphery.

b Glacial striations (scratch marks) on an outcrop of Permian-age bedrock exposed at Hallet's Cove, Australia, indicate the general direction of glacial movement more than 200 million years ago. As a glacier moves over a continent's surface, it grinds and scratches the underlying rock. The scratch marks that are preserved on a rock's surface (glacial striations) thus provide evidence of the direction (red arrows) the glacier moved at that time.

Fossil Evidence

Some of the most compelling evidence for continental drift comes from the fossil record. Fossils of the *Glossopteris* flora are found in equivalent Pennsylvanian- and Permian-aged coal deposits on all five Gondwana continents. The ***Glossopteris* flora** is characterized by the seed fern *Glossopteris* (▶ Figure 2.1) as well as by many other distinctive and easily identifiable plants. Pollen and spores of plants can be dispersed over great distances by wind, but *Glossopteris*-type plants produced seeds that are too large to have been carried by winds. Even if the seeds had floated across the ocean, they probably would not have remained viable for any length of time in saltwater.

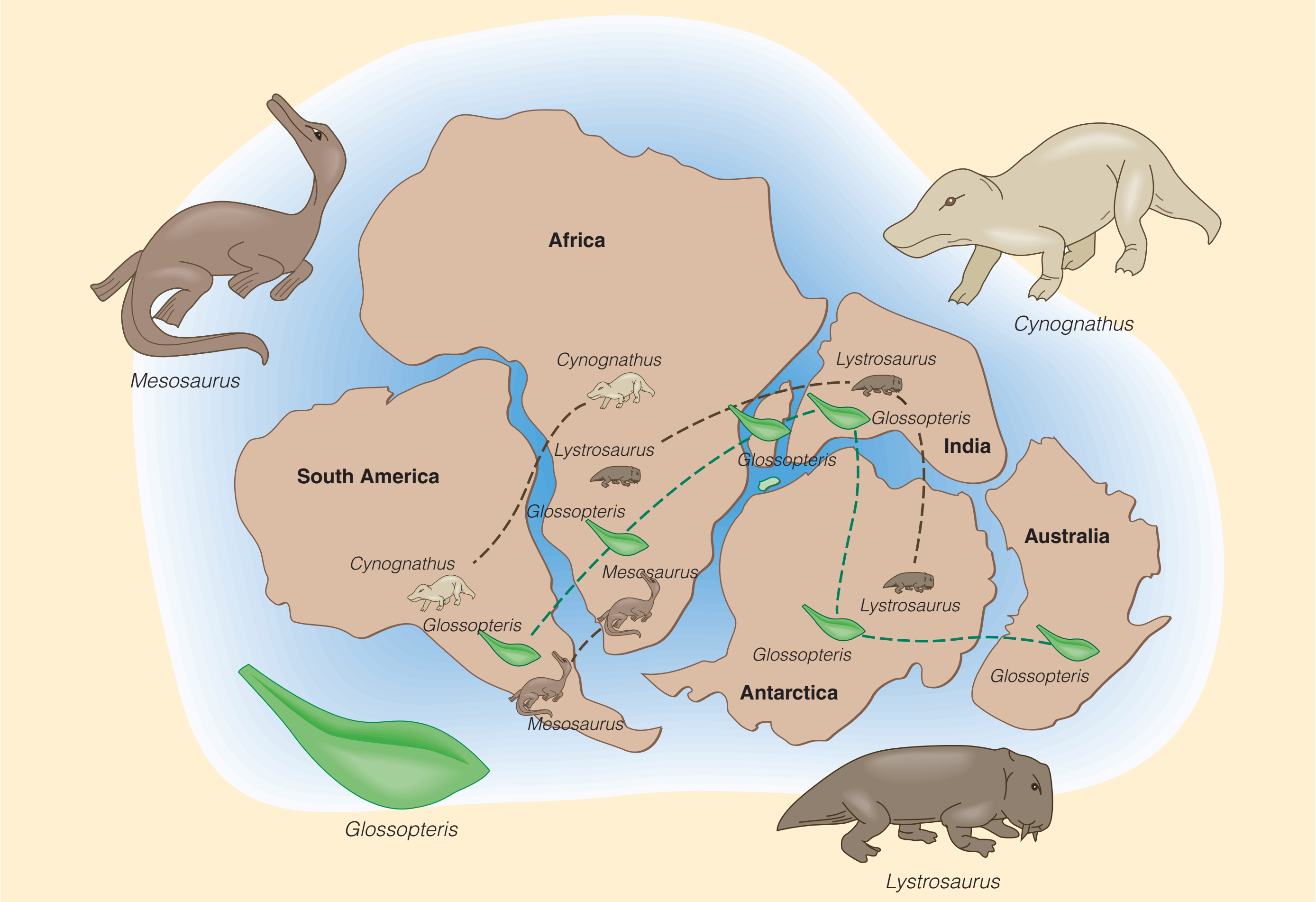
The present-day climates of South America, Africa, India, Australia, and Antarctica range from tropical to polar and are much too diverse to support the type of plants in the *Glossopteris* flora. Wegener therefore reasoned that these continents must once have been joined so that these widely separated localities were all in the same latitudinal climatic belt (▶ Figure 2.6).

The fossil remains of animals also provide strong evidence for continental drift. One of the best examples is *Mesosaurus*, a freshwater reptile whose fossils are found in Permian-aged rocks in certain regions of Brazil and South Africa and nowhere else in the world (▶ Figure 2.6). Because the physiologies of freshwater and marine animals are completely different, it is hard to imagine how a freshwater reptile could have swum across the Atlantic Ocean and found a freshwater environment nearly identical to its former habitat. Moreover, if *Mesosaurus* could have swum across the ocean, its fossil remains should be widely dispersed. It is more logical to assume that *Mesosaurus* lived in lakes in what are now adjacent areas of South America and Africa but were then united into a single continent.

Lystrosaurus and *Cynognathus* are both land-dwelling reptiles that lived during the Triassic Period; their fossils are found only on the present-day continental fragments of Gondwana (▶ Figure 2.6). Because they are both land animals, they certainly could not have swum across the oceans currently separating the Gondwana continents. Therefore, it is logical to assume that the continents must once have been connected. Recent discoveries of dinosaur fossils in Gondwana continents further solidifies the argument that these landmasses were close to each other during the Early Mesozoic Era.

Notwithstanding all of the empirical evidence presented by Wegener and later by du Toit and others, most geologists simply refused to entertain the idea that continents might have moved during the past. The geologists were not necessarily being obstinate about accepting new ideas; rather, they found the evidence for continental drift inadequate and unconvincing. In part, this was because no one could provide a

▶ **Figure 2.6 Fossil Evidence Supporting Continental Drift** Some of the plants and animals whose fossils are found today on the widely separated continents of South America, Africa, India, Australia, and Antarctica. During the Late Paleozoic Era, these continents were joined together to form Gondwana, the southern landmass of Pangaea. Plants of the *Glossopteris* flora are found on all five continents, which today have widely different climates, but during the Pennsylvanian and Permian periods, they were all located in the same general climatic belt. *Mesosaurus* is a freshwater reptile whose fossils are found only in similar nonmarine Permian-age rocks in Brazil and South Africa. *Cynognathus* and *Lystrosaurus* are land reptiles that lived during the Early Triassic Period. Fossils of *Cynognathus* are found in South America and Africa, whereas fossils of *Lystrosaurus* have been recovered from Africa, India, and Antarctica. It is hard to imagine how a freshwater reptile and land-dwelling reptiles could have swum across the wide oceans that presently separate these continents. It is more logical to assume that the continents were at one time connected.



suitable mechanism to explain how continents could move over Earth's surface. Interest in continental drift waned until new evidence from oceanographic research and studies of Earth's magnetic field showed that the present-day ocean basins were not as old as the continents but were geologically young features that resulted from the breakup of Pangaea.

Section 2.3 Summary

- The evidence for continental drift is impressive. It includes the fact that the continents show a close fit along the continental slope at a depth of about 2000 m.
- Furthermore, several major mountain ranges that currently end at the coastline form a continuous range when the present-day continents are assembled into a single landmass.
- Marine, nonmarine, and glacial rock sequences of Pennsylvanian to Jurassic age are nearly identical on the five Gondwana continents, suggesting that these continents were joined together during this time interval.
- Glacial deposits and striations indicate that massive glaciers covered large areas of the Gondwana continents during the Late Paleozoic Era. Placing these continents together with South Africa located at the South Pole shows that the glaciers moved in a radial pattern from a thick central area toward their periphery, as would be expected in such a configuration.
- The distribution of plant and animal fossils also provides strong evidence for continental drift because it is hard to imagine land animals being able to swim across the Atlantic Ocean and the same plants occupying tropical, moderate, and polar environments.

2.4 Paleomagnetism and Polar Wandering

■ *What is paleomagnetism?*

Interest in continental drift revived during the 1950s as a result of evidence from paleomagnetic studies, a relatively new discipline at the time. **Paleomagnetism** is the remanent magnetism in ancient rocks recording the direction and intensity of Earth's magnetic field at the time of the rock's formation. Earth can be thought of as a giant dipole magnet in which the magnetic poles essentially coincide with the geographic poles (▶ Figure 2.7). This arrangement means that the strength of the magnetic field is not constant but varies, being weakest at the equator and strongest at the poles. Earth's magnetic field is thought to result from the different rotation speeds of the outer core and mantle.

■ *What is the Curie point and why is it important?*

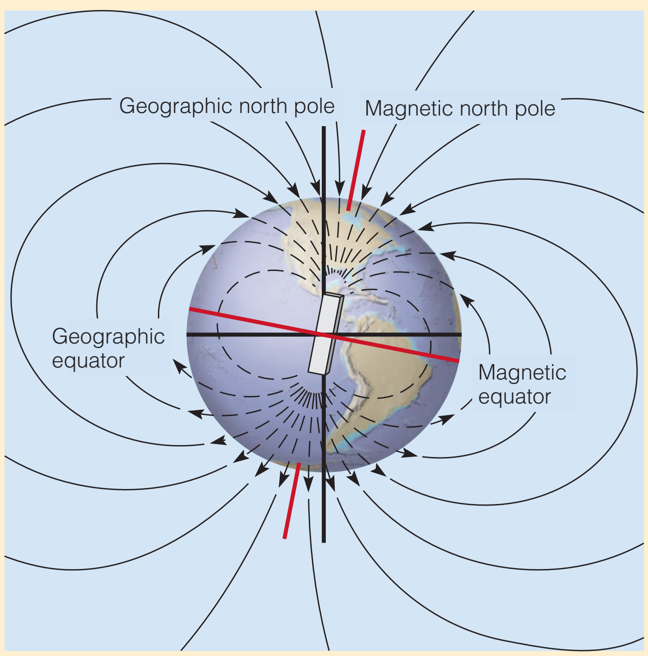
When magma cools, the magnetic iron-bearing minerals align themselves with Earth's magnetic field, recording both its direction and its strength. The temperature at which iron-bearing minerals gain their magnetization is called the **Curie point.** As long as the rock is not subsequently heated above the Curie point, it will preserve that remanent magnetism. Thus an ancient lava flow provides a record of the orientation and strength of Earth's magnetic field at the time the lava flow cooled.

■ *How can the apparent wandering of the magnetic poles be best explained?*

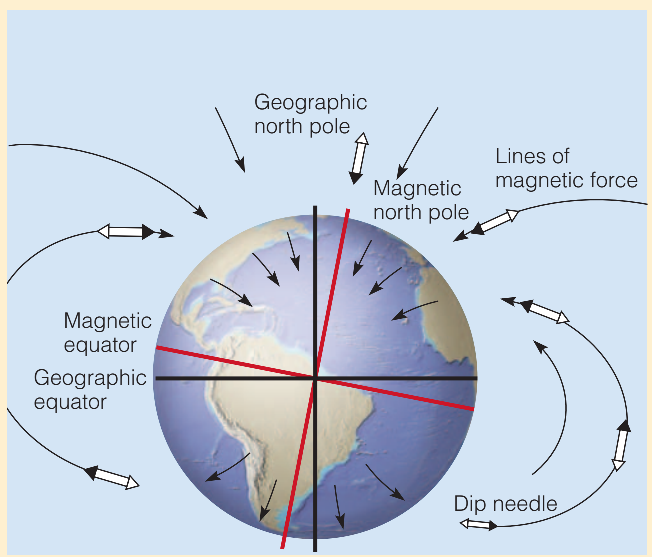
As paleomagnetic research progressed during the 1950s, some unexpected results emerged. When geologists measured the paleomagnetism of geologically recent rocks, they found it was generally consistent with Earth's current magnetic field. The paleomagnetism of ancient rocks, though, showed different orientations. For example, paleomagnetic studies of Silurian lava flows in North America indicated that the north magnetic pole was located in the western Pacific Ocean at that time, whereas the paleomagnetic evidence from Permian lava flows pointed to yet another location in Asia. When plotted on a map, the paleomagnetic readings of numerous lava flows from all ages in North America trace the apparent movement of the magnetic pole (called *polar wandering*) through time (▶ Figure 2.8). This paleomagnetic evidence from a single continent could be interpreted in three ways: The continent remained fixed and the north magnetic pole moved; the north magnetic pole stood still and the continent moved; or both the continent and the north magnetic pole moved.

Upon additional analysis, magnetic minerals from European Silurian and Permian lava flows pointed to a different magnetic pole location from those of the same age in North

▶ **Figure 2.7 Earth's Magnetic Field**

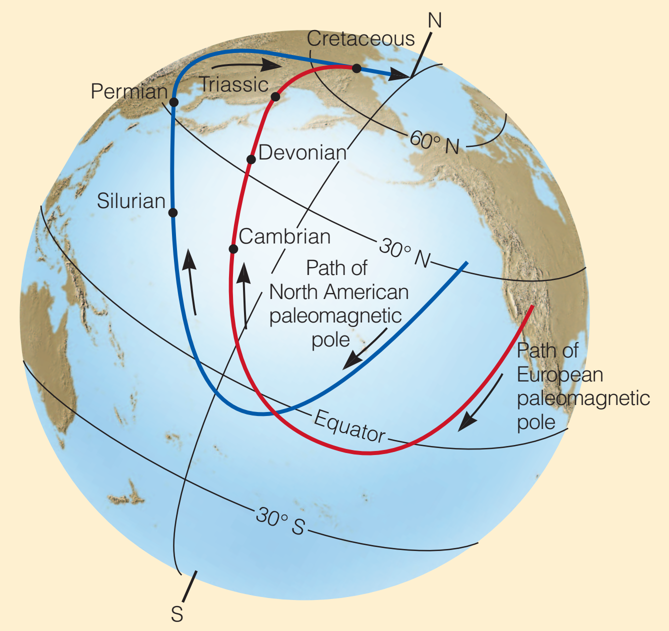


a Earth's magnetic field has lines of force like those of a bar magnet.



b The strength of the magnetic field changes from the magnetic equator to the magnetic poles. This change in strength causes a dip needle (a magnetic needle that is balanced on the tip of a support so that it can freely move vertically) to be parallel to Earth's surface only at the magnetic equator, where the strength of the magnetic north and south poles are equally balanced. Its inclination or dip with respect to Earth's surface increases as it moves toward the magnetic poles, until it is at 90 degrees or perpendicular to Earth's surface at the magnetic poles.

▶ **Figure 2.8 Polar Wandering** The apparent paths of polar wandering for North America and Europe. The apparent location of the north magnetic pole is shown for different time periods on each continent's polar wandering path. If the continents have not moved through time, and because Earth has only one magnetic pole, the paleomagnetic readings for the same time in the past taken on different continents should all point to the same location. However, the north magnetic pole has different locations for the same time in the past when measured on different continents, indicating multiple north magnetic poles. The logical explanation for this dilemma is that the magnetic north pole has remained at the same approximate geographic location during the past, and the continents have moved.



America (▶ Figure 2.8). Furthermore, analysis of lava flows from all continents indicated that each continent seemingly had its own series of magnetic poles. Does this really mean there were different north magnetic poles for each continent? That would be highly unlikely and difficult to reconcile with the theory accounting for Earth's magnetic field.

The best explanation for such data is that the magnetic poles have remained near their present locations at the geographic north and south poles and the continents have moved. When the continental margins are fitted together so that the paleomagnetic data point to only one magnetic pole, we find, just as Wegener did, that the rock sequences and glacial deposits match and that the fossil evidence is consistent with the reconstructed paleogeography.

Section 2.4 Summary

- Paleomagnetism is the remanent magnetism in ancient rocks recording the direction and intensity of Earth's magnetic field at the time of the rock's formation.

- Earth's magnetic field is not constant. Being strongest at the poles and weakest at the equator, Earth's magnetic field is thought to result from the different rotation speeds of the outer core and mantle. Earth's magnetic poles closely coincide with its geographic poles.

- The Curie point is the temperature at which iron-bearing minerals gain their magnetism and align themselves with Earth's magnetic field.

- Polar wandering is the apparent movement of the magnetic poles through time. The best explanation for such apparent movement is that the magnetic poles have remained near their present polar locations and the continents have moved.

2.5 Magnetic Reversals and Seafloor Spreading

■ *What evidence is there that Earth's magnetic field has reversed in the past?*

Geologists refer to Earth's present magnetic field as being normal—that is, with the north and south magnetic poles located approximately at the north and south geographic poles. At various times in the geologic past, however, Earth's magnetic field has completely reversed. The existence of such **magnetic reversals** was discovered by dating and determining the orientation of the remanent magnetism in lava flows on land (▶ Figure 2.9).

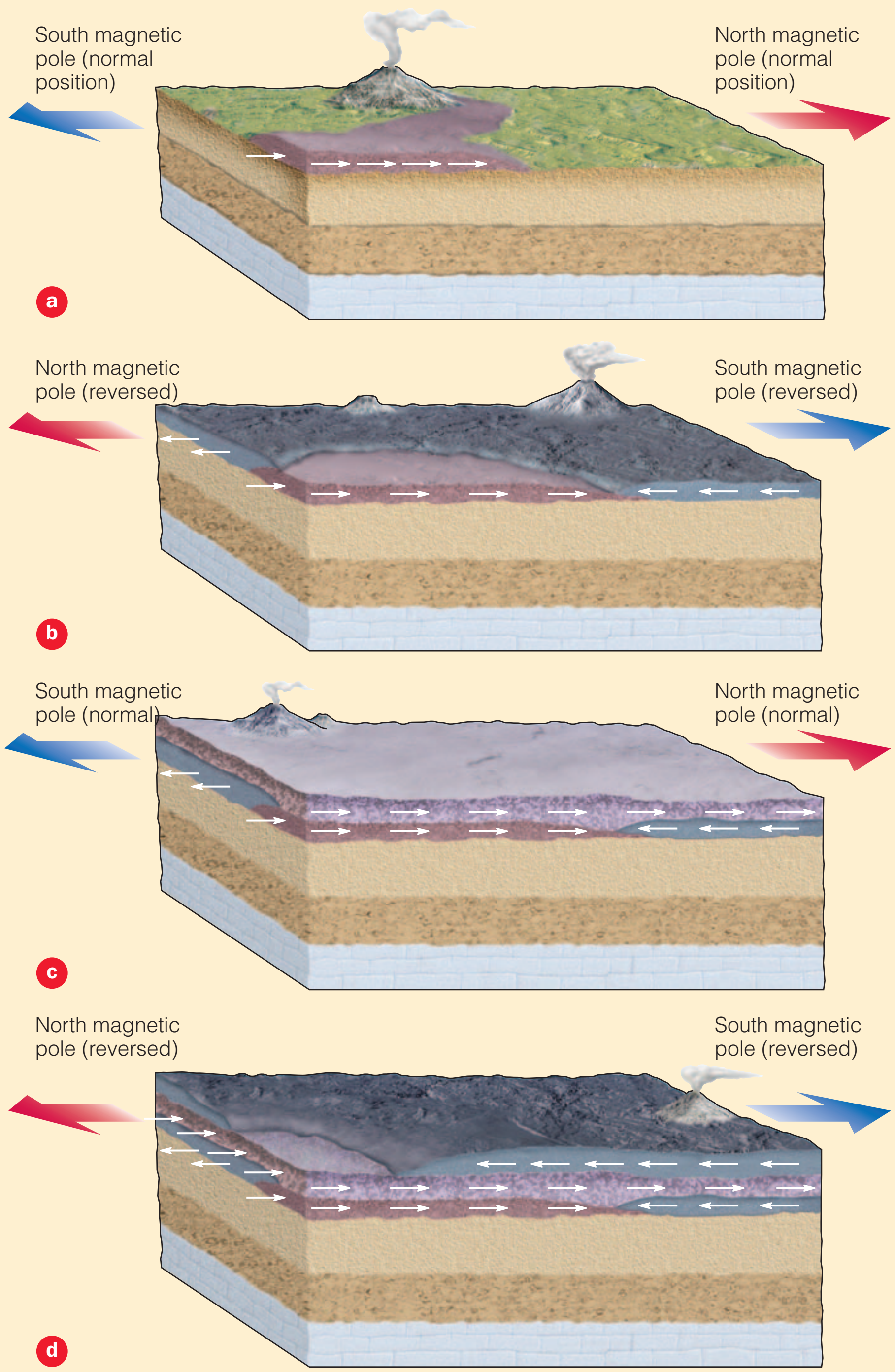
Once magnetic reversals were well established for continental lava flows, magnetic reversals were also discovered in igneous rocks in the oceanic crust as part of the large scale mapping of the ocean basins during the 1960s. Although the cause of magnetic reversals is still uncertain, their occurrence in the geologic record is well documented.

■ *What is the theory of seafloor spreading, and how does it validate continental drift?*

A renewed interest in oceanographic research led to extensive mapping of the ocean basins during the 1960s. Such mapping revealed an oceanic ridge system more than 65,000 km long, constituting the most extensive mountain range in the world. Perhaps the best-known part of the ridge system is the Mid-Atlantic Ridge, which divides the Atlantic Ocean basin into two nearly equal parts (▶ Figure 2.10).

As a result of the oceanographic research conducted during the 1950s, Harry Hess of Princeton University proposed the theory of **seafloor spreading** in 1962 to account for continental movement. He suggested that continents do not move across oceanic crust, but rather the continents and oceanic crust move together. Thus the theory of seafloor spreading answered a major objection of the opponents of continental drift—namely, how could continents move through oceanic crust? In fact, the continents moved with the oceanic crust as part of a lithospheric system.

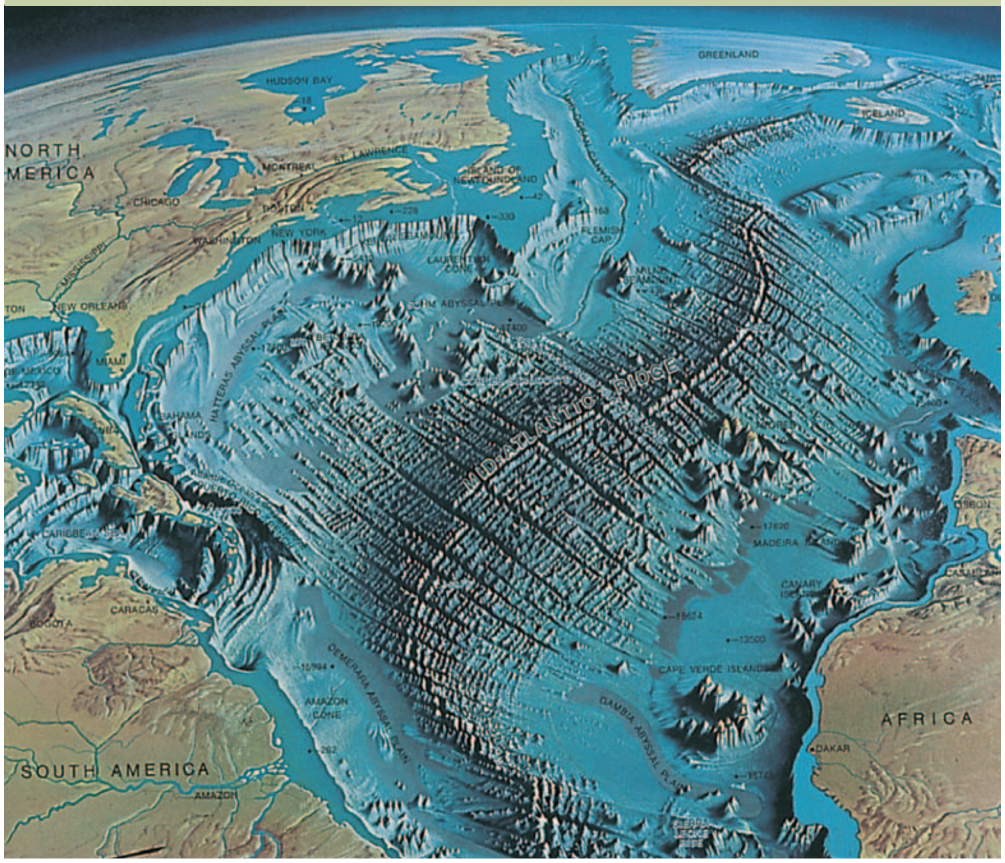
PHYSICAL Geology Now™ ▶ **Geo-focus Figure 2.9 Magnetic Reversals** During the time period shown **(a–d),** volcanic eruptions produced a succession of overlapping lava flows. At the time of these volcanic eruptions, Earth's magnetic field completely reversed; that is, the magnetic north pole moved to the geographic south pole, and the magnetic south pole moved to the geographic north pole. Thus the end of the needle on a magnetic compass that today would point to the North Pole would point to the South Pole if the magnetic field should again suddenly reverse. We know that Earth's magnetic field has reversed numerous times in the past because when lava flows cool below the Curie point, magnetic minerals within the flow orient themselves parallel to the magnetic field at the time. They thus record whether the magnetic field was normal or reversed at that time. The white arrows in this diagram show the direction of the north magnetic pole for each individual lava flow, thus confirming that Earth's magnetic field has reversed in the past.



Hess postulated that the seafloor separates at oceanic ridges, where new crust is formed by upwelling magma. As the magma cools, the newly formed oceanic crust moves laterally away from the ridge.

As a mechanism to drive this system, Hess revived the idea (proposed in the 1930s and 1940s by Arthur Holmes and others) of **thermal convection cells** in the mantle; that is, hot magma rises from the mantle, intrudes along frac-

▶ **Figure 2.10 Topography of the Atlantic Ocean Basin** Artistic view of what the Atlantic Ocean basin would look like without water. The major feature is the Mid-Atlantic Ridge, an oceanic ridge system that is longer than 65,000 km and divides the Atlantic Ocean basin in half. It is along such oceanic ridges that the seafloor is separating and new oceanic crust is forming from upwelling magma in Earth's interior.



ALCOA

tures defining oceanic ridges, and thus forms new crust. Cold crust is subducted back into the mantle at oceanic trenches, where it is heated and recycled, thus completing a thermal convection cell (see Figure 1.10).

Paleomagnetic Data

■ *How was the theory of seafloor spreading confirmed?*

Magnetic surveys of the oceanic crust revealed striped **magnetic anomalies** (deviations from the average strength of Earth's magnetic field) in the rocks that are both parallel to and symmetric around the oceanic ridges (▶ Figure 2.11). Furthermore, the pattern of oceanic magnetic anomalies matches the pattern of magnetic reversals already known from studies of continental lava flows (▶ Figure 2.9). When magma wells up and cools along a ridge summit, it records Earth's magnetic field at that time as either normal or reversed. As new crust forms at the summit, the previously formed crust moves laterally away from the ridge. These magnetic stripes represent times of normal and reversed polarity at oceanic ridges (where upwelling magma forms new oceanic crust), conclusively confirming Hess's theory of seafloor spreading.

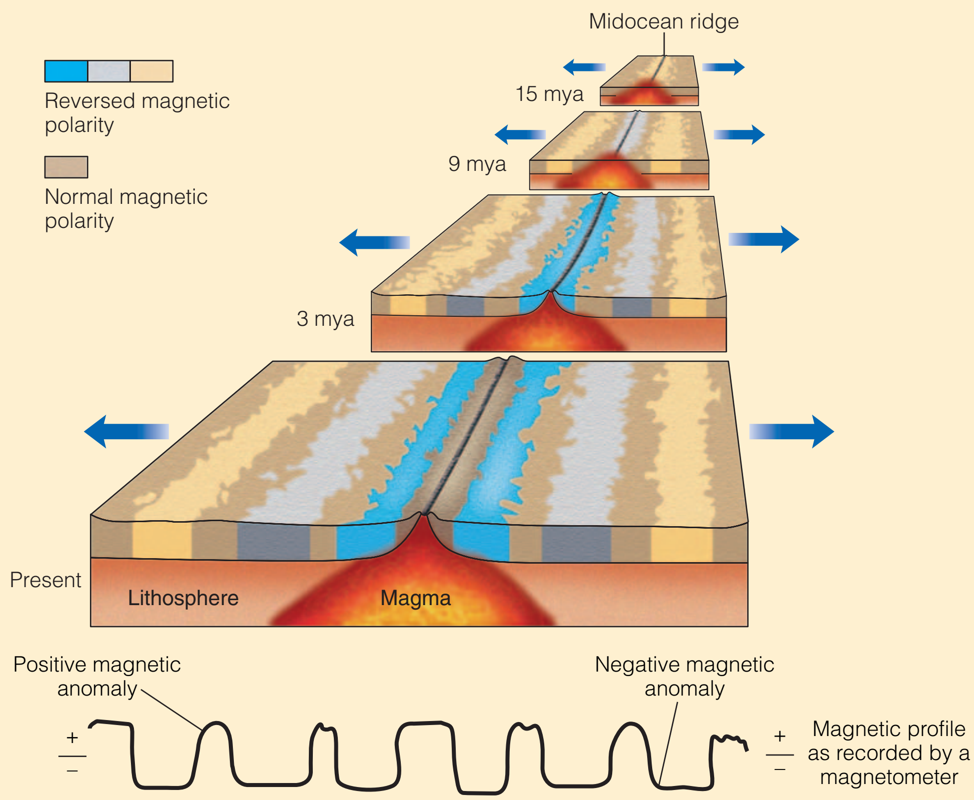
The seafloor spreading theory also confirms that ocean basins are geologically young features whose openings and closings are partially responsible for continental movement (▶ Figure 2.12). Radiometric dating reveals that the oldest oceanic crust is somewhat less than 180 million years old, whereas the oldest continental crust is 3.96 billion years old. Although geologists do not universally accept the idea of thermal convection cells as a driving mechanism for plate movement, most accept that plates are created at oceanic ridges and destroyed at deep-sea trenches, regardless of the driving mechanism involved.

Deep-Sea Drilling Project Results

For many geologists, the paleomagnetic data amassed in support of continental drift and seafloor spreading were convincing. Results from the Deep-Sea Drilling Project (see Chapter 12) confirmed the interpretations made from earlier paleomagnetic studies. Cores of deep-sea sediments and seismic profiles obtained by the *Glomar Challenger* and other research vessels have provided much of the data that support the seafloor spreading theory.

According to this theory, oceanic crust is continuously forming at mid-oceanic ridges, moves away from these

PHYSICAL Geology Now™ ▶ **Active Figure 2.11 Magnetic Anomalies and Seafloor Spreading** The sequence of magnetic anomalies preserved within the oceanic crust is both parallel to and symmetric around oceanic ridges. Basaltic lava intruding into an oceanic ridge today and spreading laterally away from the ridge records Earth's current magnetic field or polarity (considered by convention to be normal). Basaltic intrusions 3, 9, and 15 million years ago record Earth's reversed magnetic field at that time. This schematic diagram shows how the solidified basalt moves away from the oceanic ridge (or spreading center), carrying with it the magnetic anomalies that are preserved in the oceanic crust. Magnetic anomalies are magnetic readings that are either higher (positive magnetic anomalies) or lower (negative magnetic anomalies) than Earth's current magnetic field strength. The magnetic anomalies are recorded by a magnetometer, which measures the strength of the magnetic field. Modified from Kious and Tilling, USGS and Hyndman & Hyndman *Natural Hazards and Disasters,* Brooks/Cole, 2006, p. 15, Fig. 2.6b.



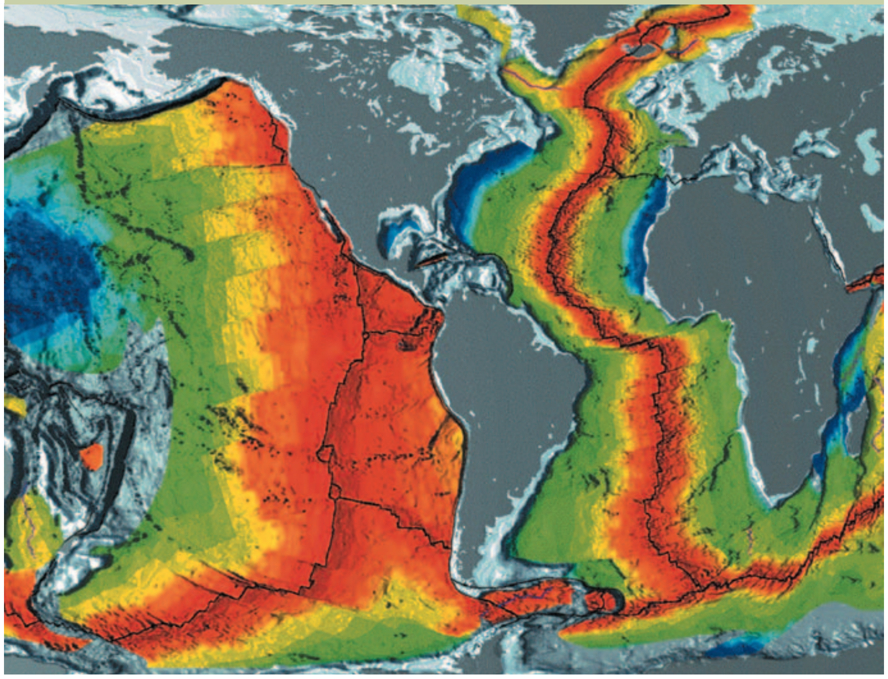
ridges by seafloor spreading, and is consumed at subduction zones. If this is the case, then oceanic crust should be youngest at the ridges and become progressively older with increasing distance away from them. Moreover, the age of the oceanic crust should be symmetrically distributed about the ridges. As we have just noted, paleomagnetic data confirm these statements. Furthermore, fossils from sediments overlying the oceanic crust and radiometric dating of rocks found on oceanic islands both substantiate this predicted age distribution.

Sediments in the open ocean accumulate, on average, at a rate of less than 0.3 cm in 1000 years. If the ocean basins were as old as the continents, we would expect deep-sea sediments to be several kilometers thick. However, data from numerous drill holes indicate that deep-sea sediments are at most only a few hundred meters thick and are thin or absent at oceanic ridges. Their near-absence at the ridges should come as no surprise because these are the areas where new crust is continuously produced by volcanism and seafloor spreading. Accordingly, sediments have had little time to accumulate at or very close to spreading ridges where the oceanic crust is young, but their thickness increases with distance away from the ridges (▶ Figure 2.13).

Section 2.5 Summary

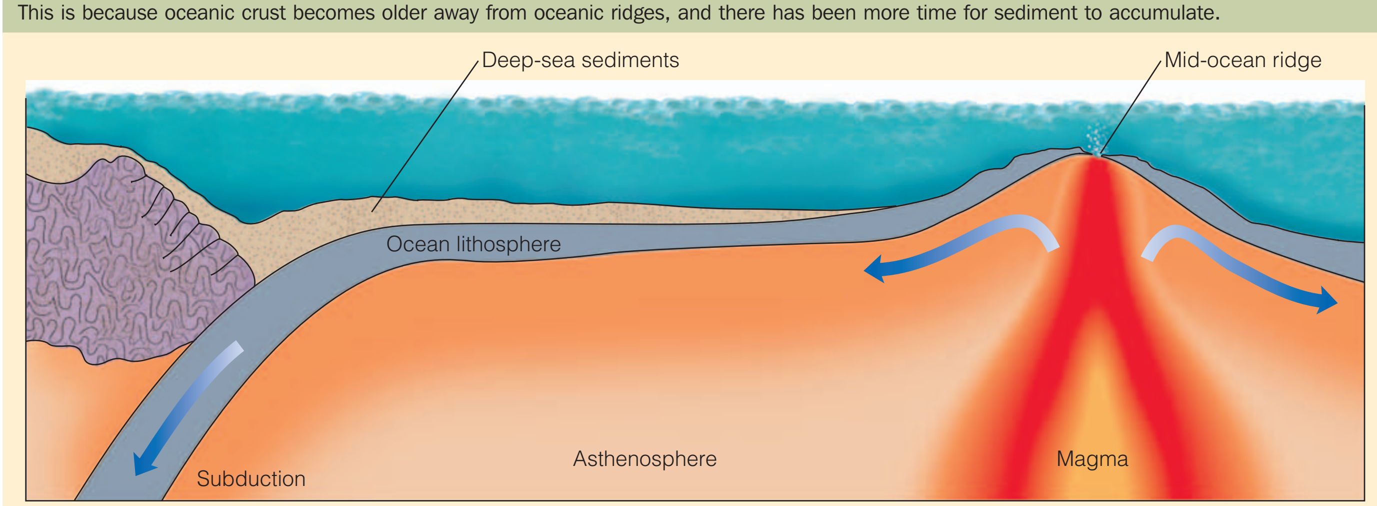
- According to the theory of seafloor spreading, seafloor separates at oceanic ridges where new crust is formed by upwelling magma generated by thermal convection cells within the mantle. As the magma cools, the newly formed oceanic crust moves laterally away from the ridge.
- Earth's magnetic field has periodically reversed during the past.

▶ **Figure 2.12 Age of the World's Ocean Basins** The age of the world's ocean basins have been determined from magnetic anomalies preserved in oceanic crust. The red colors adjacent to the oceanic ridges are the youngest oceanic crust. Moving laterally away from the ridges, the red colors grade to yellow at 48 million years, to green at 68 million years ago, and to dark blue some 155 million years ago. The darkest blue color is adjacent to the continental margins and is just somewhat less than 180 million years old. **How does the age of the oceanic crust confirm the seafloor spreading theory?** *Based on magnetic anomalies, the age of the oceanic crust gets progressively older away from the oceanic ridges where it is being formed. This means it is moving away from the oceanic ridges; that is, the seafloor is spreading.*



NOAA-NGDC

▶ **Figure 2.13 Deep-Sea Sediments and Seafloor Spreading** The total thickness of deep-sea sediments increases away from oceanic ridges. This is because oceanic crust becomes older away from oceanic ridges, and there has been more time for sediment to accumulate.



• Magnetic anomalies in oceanic crust, which are parallel to and symmetric around oceanic ridges, match the pattern of magnetic reversals seen in continental lava flows, thus confirming that new oceanic crust is forming along oceanic ridges and moving the seafloor laterally away from them.

• Cores of deep-sea sediments also confirm the theory of seafloor spreading in that the sediments directly overlying the oceanic crust get older with increasing distance from oceanic ridges, and the sediments become thicker moving away from the ridge.

2.6 Plate Tectonics: A Unifying Theory

■ *What are the main tenets of plate tectonic theory?*

Plate tectonic theory is based on a simple model of Earth. The rigid lithosphere, composed of both oceanic and continental crust as well as the underlying upper mantle, consists of many variable-sized pieces called **plates** (▶ Figure 2.14). The plates vary in thickness; those composed of upper mantle and continental crust are as much as 250 km thick, whereas those of upper mantle and oceanic crust are up to 100 km thick.

The lithosphere overlies the hotter and weaker semiplastic asthenosphere. It is thought that movement resulting from some type of heat-transfer system within the asthenosphere causes the overlying plates to move. As plates move over the asthenosphere, they separate, mostly at oceanic ridges; in other areas, such as at oceanic trenches, they collide and are subducted back into the mantle.

An easy way to visualize plate movement is to think of a conveyor belt moving luggage from an airplane's cargo hold to a baggage cart. The conveyor belt represents convection currents within the mantle, and the luggage represents Earth's lithospheric plates. The luggage is moved along by the conveyor belt until it is dumped into the baggage cart in the same way plates are moved by convection cells until they are subducted into Earth's interior. Although this analogy allows you to visualize how the mechanism of plate movement takes place, remember that this analogy is limited. The major limitation is that, unlike the luggage, plates consist of continental and oceanic crust, which have different densities; only oceanic crust, because it is denser than continental crust, is subducted into Earth's interior.

■ *Why is plate tectonics a unifying theory of geology?*

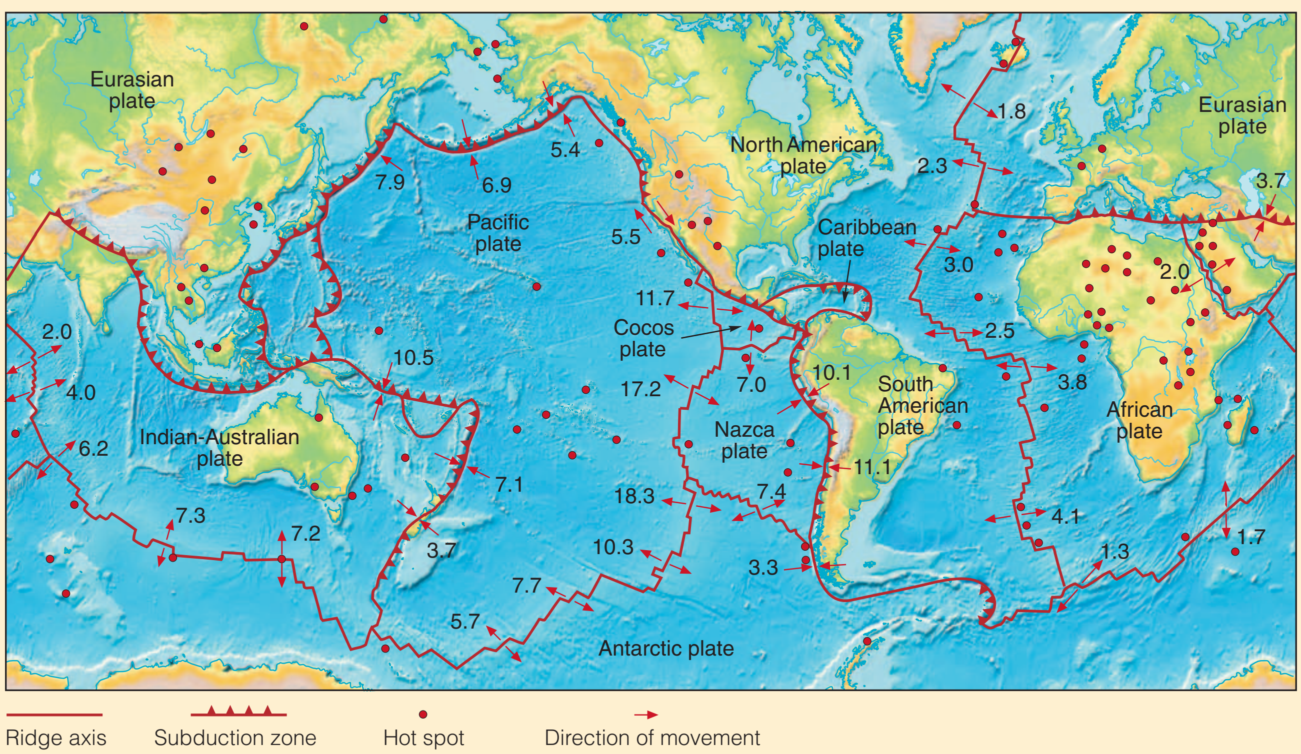
Most geologists accept plate tectonic theory, in part because the evidence for it is overwhelming and it ties together many seemingly unrelated geologic features and events and shows how they are interrelated. Consequently, geologists now view such geologic processes as mountain building, earthquake activity, and volcanism from the perspective of plate tectonics. Furthermore, because all the inner planets have had a similar origin and early history, geologists are interested in determining whether plate tectonics is unique to Earth or whether it operates in the same way on other planets (see "Tectonics of the Terrestrial Planets" on pp. 50–51).

■ *What is the supercontinent cycle?*

As a result of plate movement, all of the continents came together to form the supercontinent Pangaea by the end of the Paleozoic Era. Pangaea began fragmenting during the Triassic Period and continues to do so, thus accounting for the present distribution of continents and ocean basins. It has been proposed that supercontinents, consisting of all or most of Earth's landmasses, form, break up, and re-form in a cycle spanning about 500 million years.

The *supercontinent cycle hypothesis* is an expansion on the ideas of the Canadian geologist J. Tuzo Wilson. During the early 1970s, Wilson proposed a cycle (now known as the Wilson cycle) that includes continental fragmentation, the

▶ **Figure 2.14 Earth's Plates** A world map showing Earth's plates, their boundaries, their relative motion and rates of movement in centimeters per year, and hot spots.



opening and closing of an ocean basin, and re-assembly of the continent. According to the supercontinent cycle hypothesis, heat accumulates beneath a supercontinent because the rocks of continents are poor conductors of heat. As a result of the heat accumulation, the supercontinent domes upward and fractures. Basaltic magma rising from below fills the fractures. As a basalt-filled fracture widens, it begins subsiding and forms a long, narrow ocean such as the present-day Red Sea. Continued rifting eventually forms an expansive ocean basin such as the Atlantic.

One of the most convincing arguments for the proponents of the supercontinent cycle hypothesis is the "surprising regularity" of mountain building caused by compression during continental collisions. These mountain-building episodes occur about every 400 to 500 million years and are followed by an episode of rifting about 100 million years later. In other words, a supercontinent fragments and its individual plates disperse following a rifting episode, an interior ocean forms, and then the dispersed fragments reassemble to form another supercontinent.

The supercontinent cycle is yet another example of how interrelated the various systems and subsystems of Earth are and how they operate over vast periods of geologic time.

Section 2.6 Summary

- The main tenets of plate tectonic theory are that the rigid lithosphere consists of numerous variable-sized pieces called plates. These plates move over the hotter and weaker semiplastic asthenosphere as a result of some type of heat-transfer system within the asthenosphere. Plates separate, mostly at oceanic ridges, and collide, usually at oceanic trenches, where they are subducted back into the mantle.
- Plate tectonics is considered a unifying theory of geology because it explains how many geologic features, processes, and events are interrelated.
- In the supercontinent cycle, all or most of Earth's landmasses come together to form a supercontinent, such as Pangaea, then break up, producing ocean basins, and then re-form in a cycle spanning about 500 million years.

2.7 The Three Types of Plate Boundaries

■ *What are the three types of plate boundaries?*

Because it appears that plate tectonics have operated since at least the Proterozoic Eon, it is important that we understand how plates move and interact with each other and how ancient plate boundaries are recognized. After all, the movement of plates has profoundly affected the geologic and biologic history of this planet.

Geologists recognize three major types of plate boundaries: *divergent*, *convergent*, and *transform* (Table 2.1). Along these boundaries new plates are formed, are consumed, or slide laterally past each other. Interaction of plates at their boundaries accounts for most of Earth's volcanic eruptions and earthquakes as well as the formation and evolution of its mountain systems.

■ *What are divergent boundaries?*

Divergent plate boundaries or *spreading ridges* occur where plates are separating and new oceanic lithosphere is forming. Divergent boundaries are places where the crust is extended, thinned, and fractured as magma, derived from the partial melting of the mantle, rises to the surface. The magma is almost entirely basaltic and intrudes into vertical fractures to form dikes and pillow lava flows (see Figure 5.7). As successive injections of magma cool and solidify, they form new oceanic crust and record the intensity and orientation of Earth's magnetic field (▶ Figure 2.11). Divergent boundaries most commonly occur along the crests of oceanic ridges—the Mid-Atlantic Ridge, for example. Oceanic ridges are thus characterized by rugged topography with high relief resulting from the displacement of rocks along large fractures, shallow-depth earthquakes, high heat flow, and basaltic flows or pillow lavas.

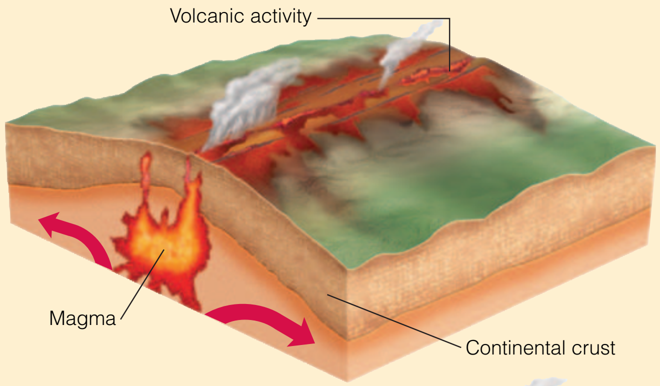
Divergent boundaries are also present under continents during the early stages of continental breakup. When magma wells up beneath a continent, the crust is initially elevated, stretched, and thinned, producing fractures, faults, rift valleys, and volcanic activity (▶ Figure 2.15). As magma intrudes into faults and fractures, it

Table 2.1

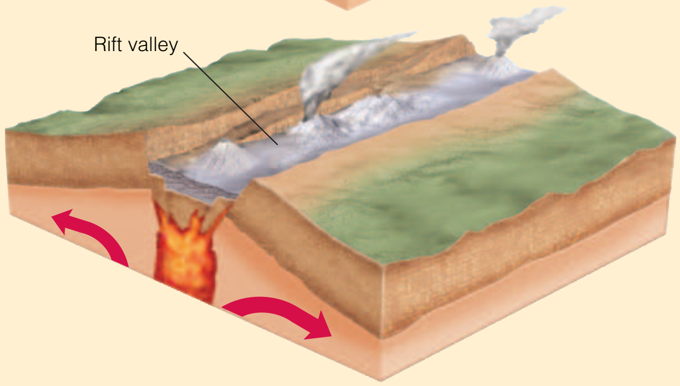
Types of Plate Boundaries

Type	Example	Landforms	Volcanism
Divergent			
Oceanic	Mid-Atlantic Ridge	Mid-oceanic ridge with axial rift valley	Basalt
Continental	East African Rift Valley	Rift valley	Basalt and rhyolite, no andesite
Convergent			
Oceanic–oceanic	Aleutian Islands	Volcanic island arc, offshore oceanic trench	Andesite
Oceanic–continental	Andes	Offshore oceanic trench, volcanic mountain chain, mountain belt	Andesite
Continental–continental	Himalayas	Mountain belt	Minor
Transform	San Andreas fault	Fault valley	Minor

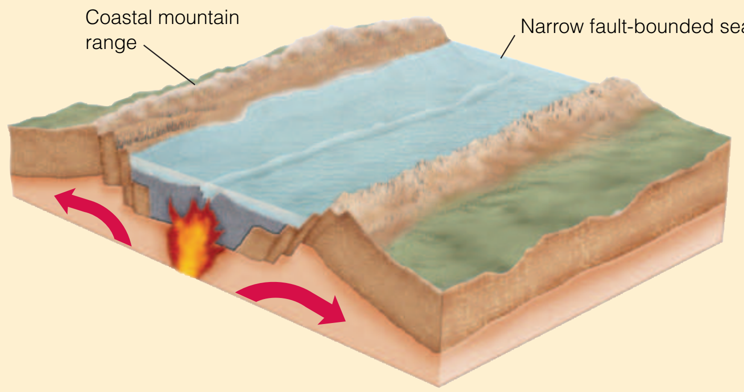
PHYSICAL Geology Now™ ▶ **Geo-focus/Active Figure 2.15 History of a Divergent Plate Boundary**



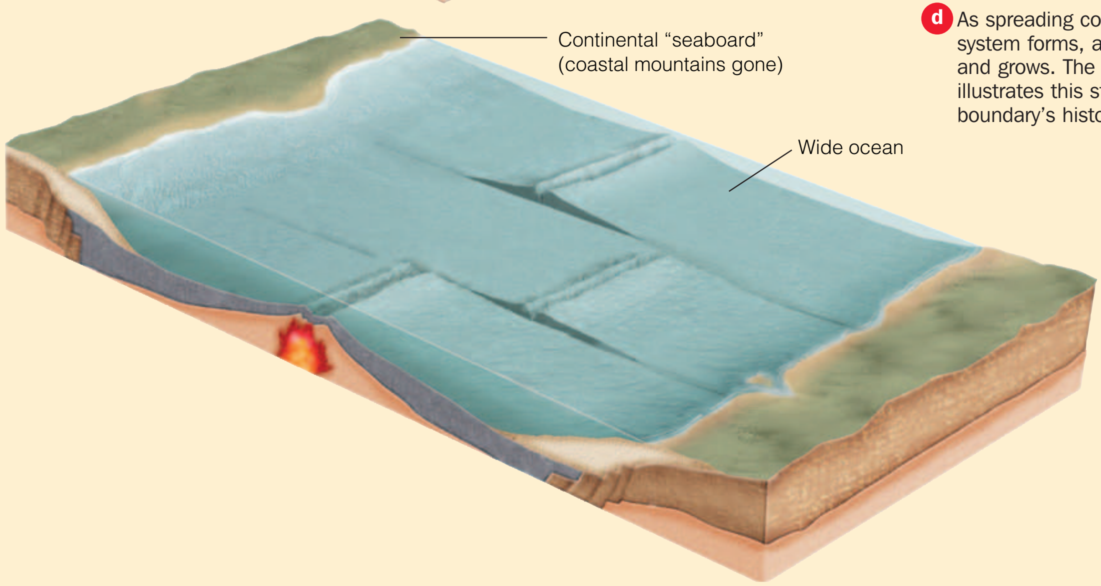
a Rising magma beneath a continent pushes the crust up, producing numerous fractures, faults, rift valleys, and volcanic activity.



b As the crust is stretched and thinned, rift valleys develop and lava flows onto the valley floors, such as seen today in the East African Rift Valley.



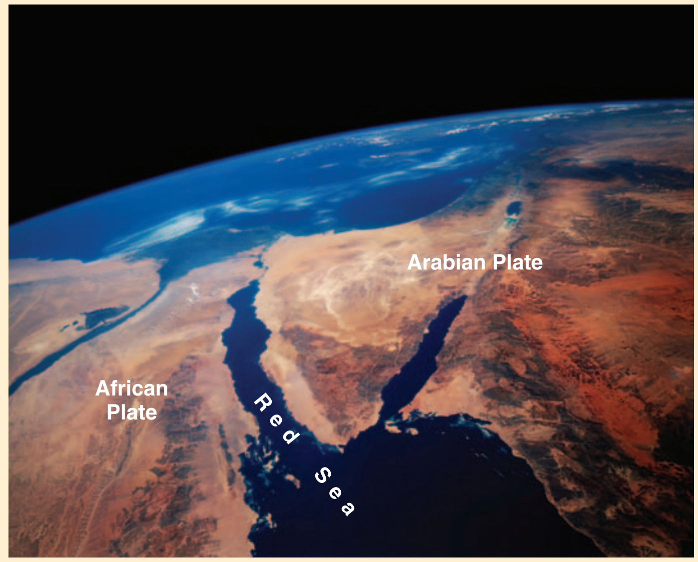
c Continued spreading further separates the continent until it splits apart and a narrow seaway develops. The Red Sea, which separates the Arabian Peninsula from Africa, is a good example of this stage of development.



d As spreading continues, an oceanic ridge system forms, and an ocean basin develops and grows. The Mid-Atlantic Ridge illustrates this stage in a divergent plate boundary’s history.

▶ **Figure 2.16 East African Rift Valley and the Red Sea—Present-Day Examples of Divergent Plate Boundaries** The East African Rift Valley and the Red Sea represent different stages in the history of a divergent plate boundary.

a The East African Rift Valley is being formed by the separation of eastern Africa from the rest of the continent along a divergent plate boundary.



b The Red Sea represents a more advanced stage of rifting, in which two continental blocks (Africa and the Arabian Peninsula) are separated by a narrow sea.

solidifies or flows out onto the surface as lava flows; the latter often covering the rift valley floor (▶ Figure 2.15b). The East African Rift Valley is an excellent example of continental breakup at this stage (▶ Figure 2.16a).

As spreading proceeds, some rift valleys continue to lengthen and deepen until the continental crust eventually breaks and a narrow linear sea is formed, separating two continental blocks (▶ Figure 2.15c). The Red Sea separating the Arabian Peninsula from Africa (▶ Figure 2.16b) and the Gulf of California, which separates Baja California from mainland Mexico, are good examples of this more advanced stage of rifting.

As a newly created narrow sea continues to enlarge, it may eventually become an expansive ocean basin such as the Atlantic Ocean basin is today, separating North and South America from Europe and Africa by thousands of kilometers (▶ Figure 2.15d). The Mid-Atlantic Ridge is the boundary between these diverging plates (▶ Figure 2.10); the American plates are moving westward, and the Eurasian and African plates are moving eastward.

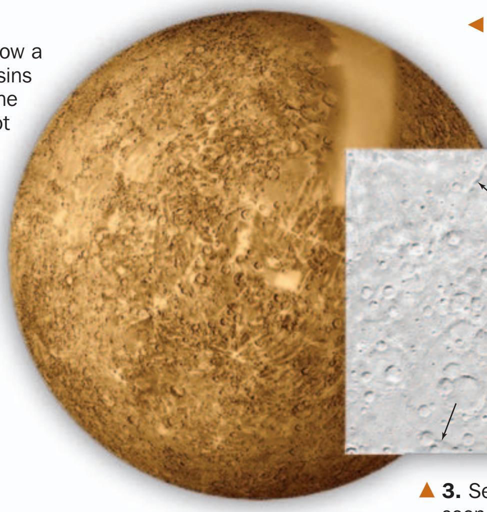
Tectonics of the Terrestrial Planets

The four inner, or terrestrial, planets—Mercury, Venus, Earth, and Mars—all had a similar early history involving accretion, differentiation into a metallic core and silicate mantle and crust, and formation of an early atmosphere by outgassing. Their early history was also marked by widespread volcanism and meteorite impacts, both of which helped modify their surfaces.

Whereas the other three terrestrial planets as well as some of the Jovian moons display internal activity, Earth appears to be unique in that its surface is broken into a series of plates.

▶ **1.** Images of **Mercury** sent back by *Mariner 10* show a heavily cratered surface with the largest impact basins filled with what appear to be lava flows similar to the lava plains on Earth's moon. The lava plains are not deformed, however, indicating that there has been little or no tectonic activity.

Another feature of Mercury's surface is a large number of scarps, a feature usually associated with earthquake activity. Yet some scientists think that these scarps formed when Mercury cooled and contracted.

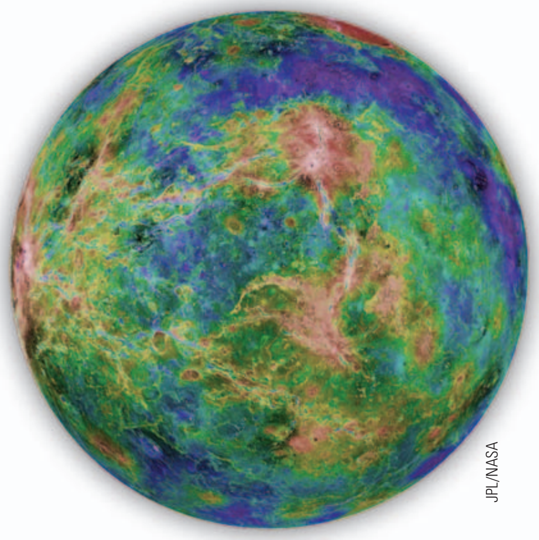


JPL/NASA

◀ **2.** A color-enhanced photomosaic of Mercury shows its heavily cratered surface, which has changed very little since its early history.

Courtesy of Victor Royer

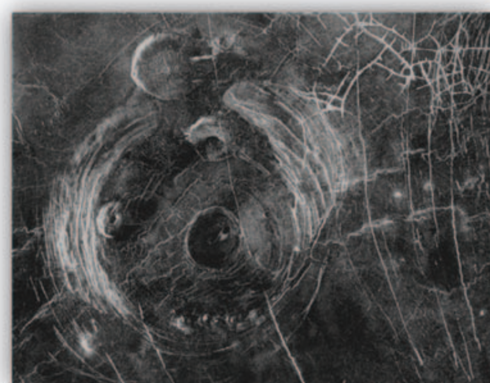
▲ **3.** Seven scarps (indicated by arrows) can clearly be seen in this image. These scarps might have formed when Mercury cooled and contracted early in its history.



JPL/NASA

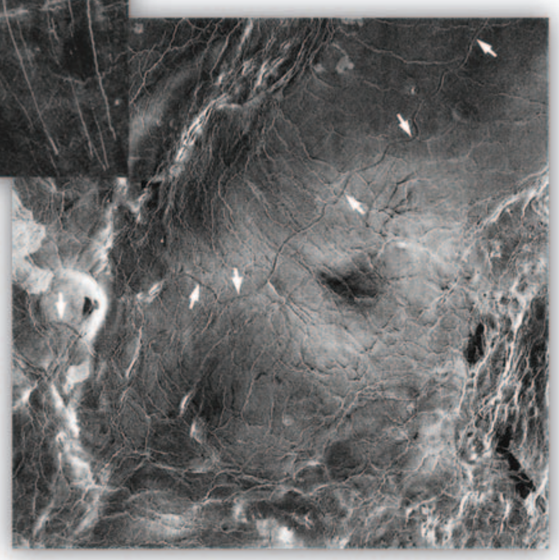
◀ **4.** Of all the planets, **Venus** is the most similar in size and mass to Earth, but it differs in most other respects. Whereas Earth is dominated by plate tectonics, volcanism seems to have been the dominant force in the evolution of the Venusian surface. Even though no active volcanism has been observed on Venus, the various-sized volcanic features and what appear to be folded mountains indicate a once-active planetary interior. All of these structures appear to be the products of rising convection currents of magma pushing up under the crust and then sinking back into the Venusian interior.

▲ **5.** A color-enhanced photomosaic of Venus based on radar images beamed back to Earth by the *Magellan* spacecraft. This image shows impact craters and volcanic features characteristic of the planet.



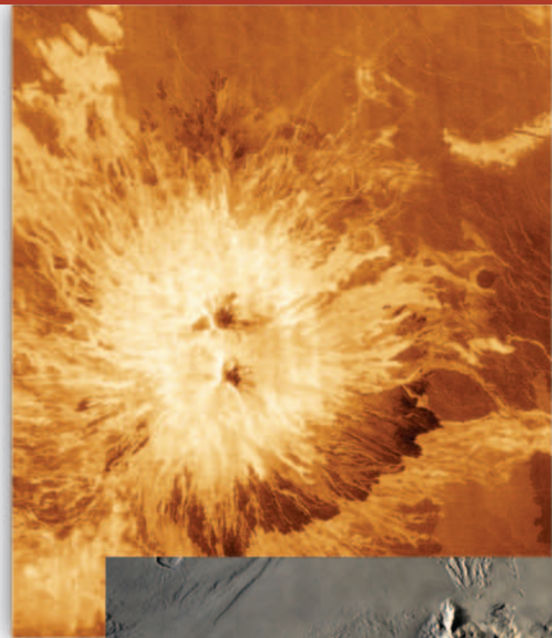
NASA

▶ **6.** Venus' Aine Corona, about 200 km in diameter, is ringed by concentric faults, suggesting that it was pushed up by rising magma. A network of fractures is visible in the upper right of this image, as well as a recent lava flow at the center of the corona, several volcanic domes in the lower portion of the image, and a large volcanic pancake dome in the upper left of the image.



JPL/NASA

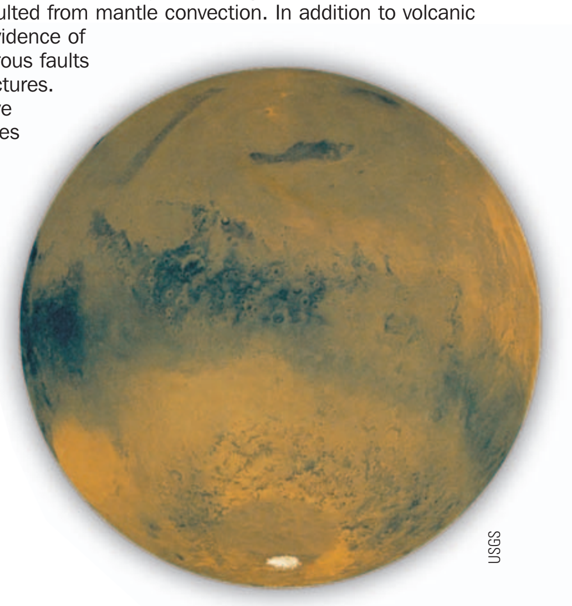
▼ **7.** Arrows point to a 600-km segment of Venus' 6800-km long Baltis Vallis, the longest known lava flow channel in our solar system.



JPL/NASA

◄ **8.** Volcano Sapas Mons contains two lava-filled calderas and is flanked by lava flows, attesting to the volcanic activity that was once common on Venus.

► **9. Mars,** the Red Planet, has numerous features that indicate an extensive early period of volcanism. These include Olympus Mons, the solar system's largest volcano, lava flows, and uplifted regions thought to have resulted from mantle convection. In addition to volcanic features, Mars displays abundant evidence of tensional tectonics, including numerous faults and large fault-produced valley structures. Although Mars was tectonically active during the past, no evidence indicates that plate tectonics comparable to those on Earth have ever occurred there.



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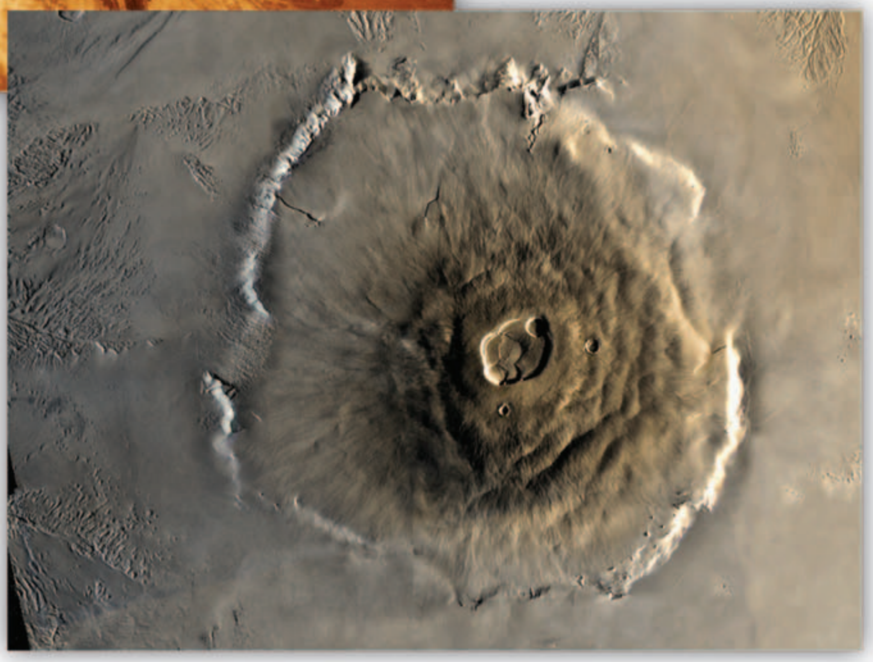
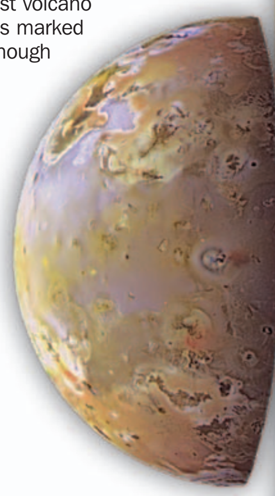
▲ **10.** A photomosaic of Mars shows a variety of geologic structures, including the southern polar ice cap.



JPL/NASA

▲ **11.** A vertical view of Olympus Mons, a shield volcano and the largest volcano known in our solar system. The edge of the Olympus Mons caldera is marked by a cliff several kilometers high. This huge summit crater is large enough to contain the greater New York City metropolitan area.



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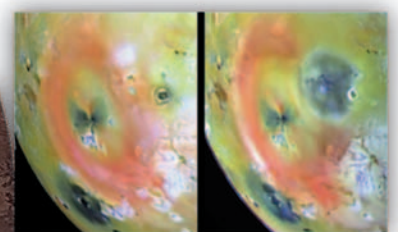
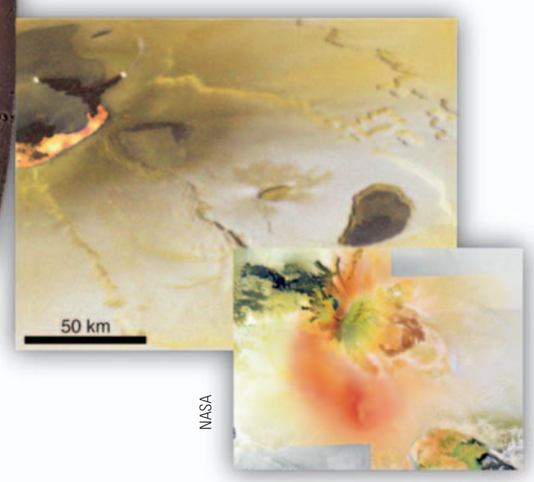


NASA

► **12.** Although not a terrestrial planet, **Io,** the innermost of Jupiter's Galilean moons, must be mentioned. Images from the *Voyager* and *Galileo* spacecrafts show that Io has no impact craters. In fact, more than a hundred active volcanoes are visible on the moon's surface, and the sulfurous gas and ash erupted by these volcanoes bury any newly formed meteorite impact craters. Because of its proximity to Jupiter, the heat source of Io is probably tidal heating, in which the resulting friction is enough to at least partially melt Io's interior and drive its volcanoes.



NASA

► **13.** Volcanic features of Io, the innermost moon of Jupiter. As shown in these digitally enhanced color images, Io is a very volcanically active moon.

■ *What features in the geologic record indicate ancient rifting?*

Associated with regions of continental rifting are faults, dikes (vertical intrusive igneous bodies), sills (horizontal intrusive igneous bodies), lava flows, and thick sedimentary sequences within rift valleys, all features that are preserved in the geologic record. The Triassic fault basins of the eastern United States are a good example of ancient continental rifting (▶ Figure 2.17a). These fault basins mark the zone of rifting that occurred when North America split apart from Africa. The basins contain thousands of meters of continental sediment and are riddled with dikes and sills.

Pillow lavas, in association with deep-sea sediment, are also evidence of ancient rifting. The presence of pillow lavas marks the formation of a spreading ridge in a narrow linear sea. A narrow linear sea forms when the continental crust in the rift valley finally breaks apart, and the area is flooded by seawater. Magma, intruding into the sea along this newly formed spreading ridge, solidifies as pillow lavas, which are preserved in the geologic record, along with the sediment being deposited on them.

■ *What are convergent boundaries?*

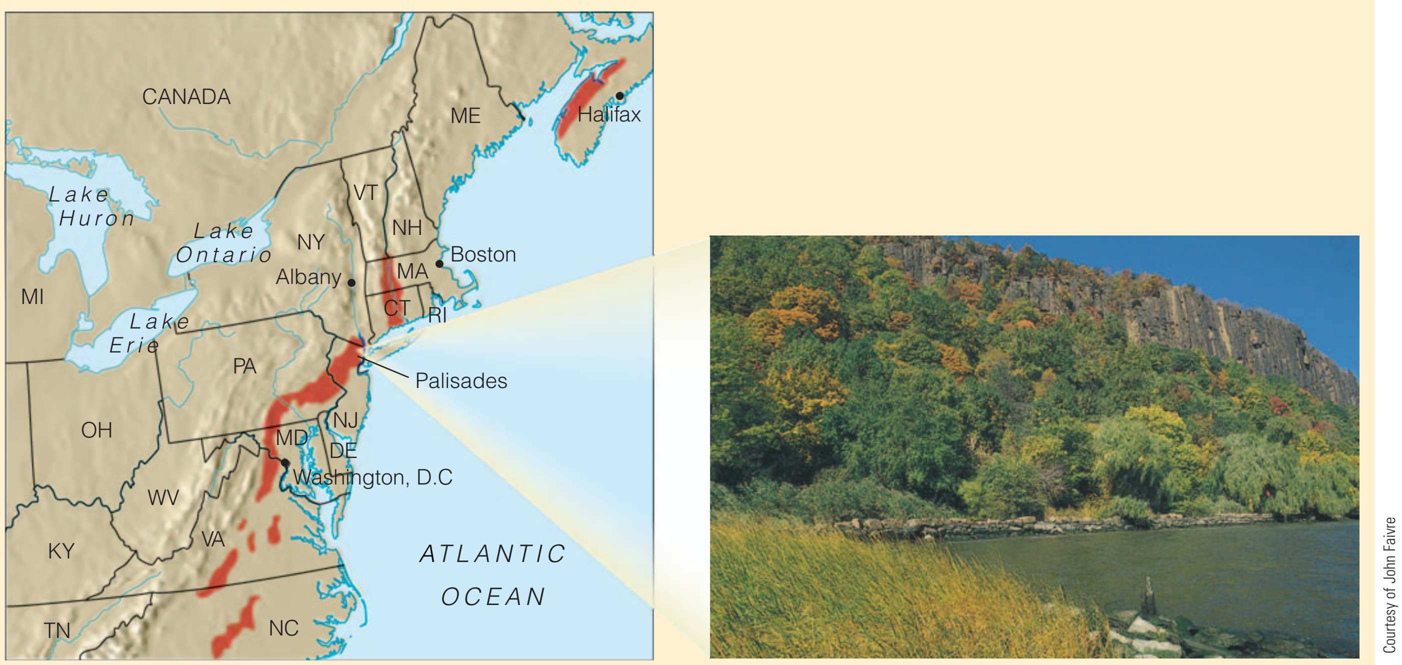
Whereas new crust forms at divergent plate boundaries, older crust must be destroyed and recycled in order for the entire surface area of Earth to remain the same. Otherwise, we would have an expanding Earth. Such plate destruction takes place at **convergent plate boundaries,** where two plates collide and the leading edge of one plate is subducted beneath the margin of the other plate and eventually is incorporated into the asthenosphere. A dipping plane of earthquake foci, called a *Benioff* (or sometimes *Benioff-Wadati*) *zone*, defines a subduction zone (see Figure 10.5). Most of these planes dip from oceanic trenches beneath adjacent island arcs or continents, marking the surface of slippage between the converging plates.

Deformation, volcanism, mountain building, metamorphism, earthquake activity, and deposits of valuable mineral ores characterize convergent boundaries. Three types of convergent plate boundaries are recognized: *oceanic–oceanic*, *oceanic–continental*, and *continental–continental*.

Oceanic–Oceanic Boundaries

When two oceanic plates converge, one is subducted beneath the other along an **oceanic–oceanic plate boundary** (▶ Figure 2.18a). The subducting plate bends downward to form the outer wall of an oceanic trench. A *subduction complex*, composed of wedge-shaped slices of highly folded and faulted marine sediments and oceanic lithosphere scraped off the descending plate, forms along the inner wall of the oceanic trench. As the subducting plate descends into the mantle, it is heated and partially melted, generating magma, commonly of andesitic composition (see Chapter 4). This

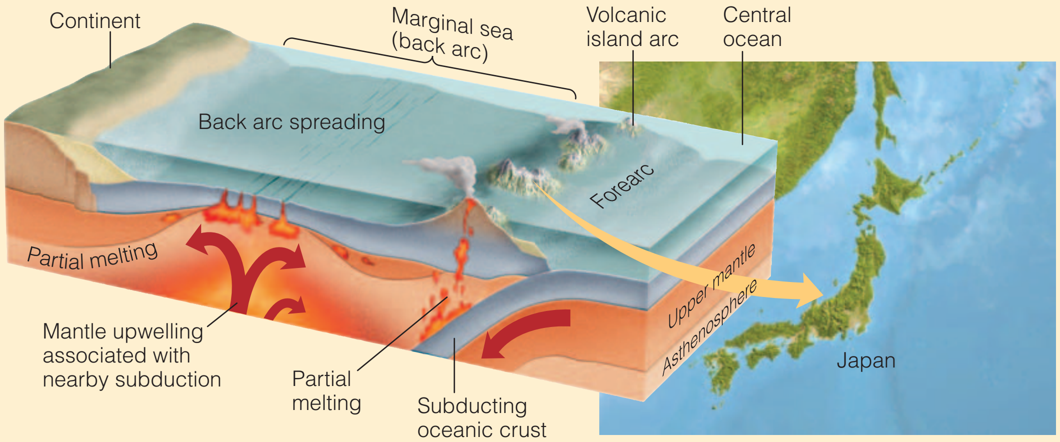
▶ Figure 2.17 Triassic Fault-Block Basins of Eastern North America—An Example of Ancient Rifting



a Triassic fault-block basin deposits appear in numerous locations throughout eastern North America. These fault-block basins are good examples of ancient continental rifting, and during the Triassic Period they looked like today's fault-block basins (rift valleys) of the East African Rift Valley.

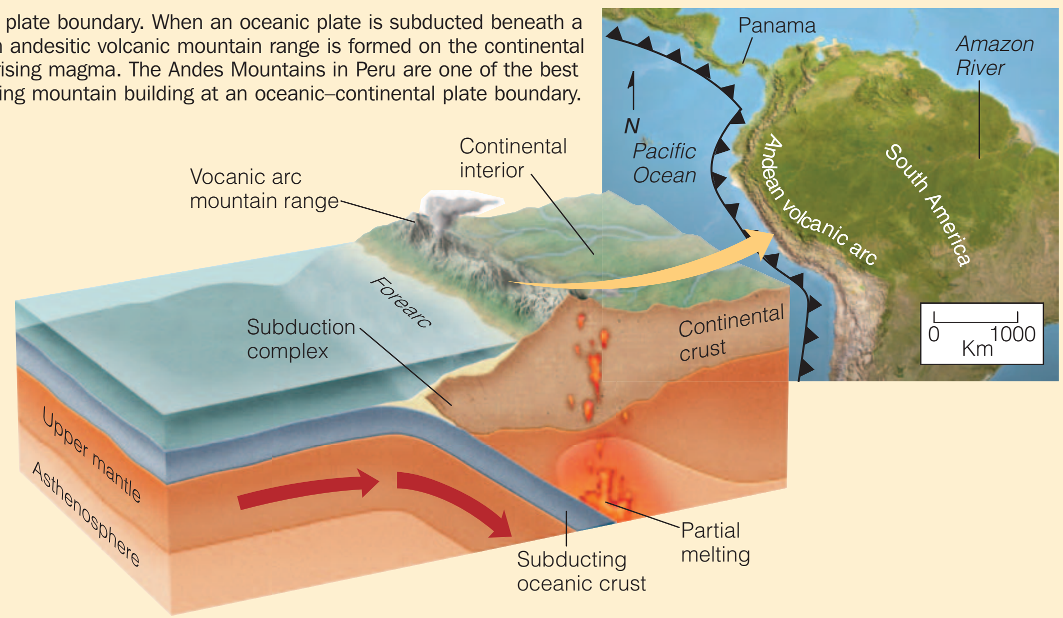
b Palisades of the Hudson River. This sill (tabular-shaped horizontal igneous intrusion) was one of many that were intruded into the fault-block basin sediments during the Late Triassic rifting that marked the initial separation of North America from Africa.

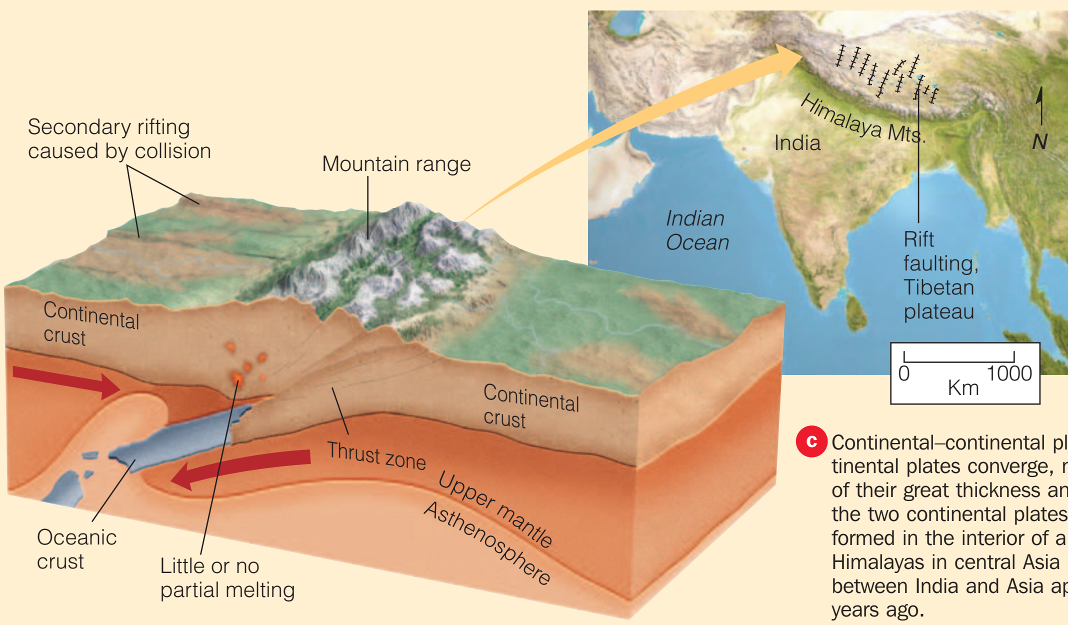
PHYSICAL Geology Now™ ▶ **Geo-focus/Active Figure 2.18 Three Types of Convergent Plate Boundaries**



a Oceanic–oceanic plate boundary. An oceanic trench forms where one oceanic plate is subducted beneath another. On the nonsubducted plate, a volcanic island arc forms from the rising magma generated from the subducting plate. The Japanese Islands are a volcanic island arc resulting from the subduction of one oceanic plate beneath another oceanic plate.

b Oceanic–continental plate boundary. When an oceanic plate is subducted beneath a continental plate, an andesitic volcanic mountain range is formed on the continental plate as a result of rising magma. The Andes Mountains in Peru are one of the best examples of continuing mountain building at an oceanic–continental plate boundary.





c Continental–continental plate boundary. When two continental plates converge, neither is subducted because of their great thickness and low and equal densities. As the two continental plates collide, a mountain range is formed in the interior of a new and larger continent. The Himalayas in central Asia resulted from the collision between India and Asia approximately 40 to 50 million years ago.

magma is less dense than the surrounding mantle rocks and rises to the surface of the nonsubducted plate to form a curved chain of volcanoes called a *volcanic island arc* (any plane intersecting a sphere makes an arc). This arc is nearly parallel to the oceanic trench and is separated from it by a distance of up to several hundred kilometers—the distance depending on the angle of dip of the subducting plate (▶ Figure 2.18a).

In those areas where the rate of subduction is faster than the forward movement of the overriding plate, the lithosphere on the landward side of the volcanic island arc may be subjected to tensional stress and stretched and thinned, resulting in the formation of a *back-arc basin*. This back-arc basin may grow by spreading if magma breaks through the thin crust and forms new oceanic crust (▶ Figure 2.18a). A good example of a back-arc basin associated with an oceanic–oceanic plate boundary is the Sea of Japan between the Asian continent and the islands of Japan.

Most present-day active volcanic island arcs are in the Pacific Ocean basin and include the Aleutian Islands, the Kermadec–Tonga arc, and the Japanese (▶ Figure 2.18a) and Philippine Islands. The Scotia and Antillean (Caribbean) island arcs are in the Atlantic Ocean basin.

Oceanic–Continental Boundaries

When an oceanic and a continental plate converge, the denser oceanic plate is subducted under the continental plate along an **oceanic–continental plate boundary** (▶ Figure 2.18b). Just as at oceanic–oceanic plate boundaries, the descending oceanic plate forms the outer wall of an oceanic trench.

The magma generated by subduction rises beneath the continent and either crystallizes as large intrusive igneous bodies (called *plutons*) before reaching the surface or erupts at the surface to produce a chain of andesitic volcanoes (also called a *volcanic arc*). An excellent example of an oceanic–continental plate boundary is the Pacific coast of South America, where the oceanic Nazca plate is currently being subducted beneath South America (▶ Figure 2.18b; see also Chapter 13). The Peru–Chile Trench marks the site of subduction, and the Andes Mountains are the resulting volcanic mountain chain on the nonsubducting plate.

Continental–Continental Boundaries

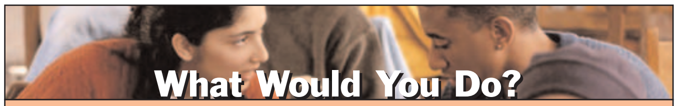
Two continents approaching each other are initially separated by an ocean floor that is being subducted under one continent. The edge of that continent displays the features characteristic of oceanic–continental convergence. As the ocean floor continues to be subducted, the two continents come closer together until they eventually collide. Because continental lithosphere, which consists of continental crust and the upper mantle, is less dense than oceanic lithosphere (oceanic crust and upper mantle), it cannot sink into the asthenosphere. Although one continent may partly slide under the other, it cannot be pulled or pushed down into a subduction zone (▶ Figure 2.18c).

When two continents collide, they are welded together along a zone marking the former site of subduction. At this **continental–continental plate boundary,** an interior mountain belt is formed consisting of deformed sediments and sedimentary rocks, igneous intrusions, metamorphic rocks, and fragments of oceanic crust. In addition, the entire region is subjected to numerous earthquakes. The Himalayas in central Asia, the world's youngest and highest mountain system, resulted from the collision between India and Asia that began 40 to 50 million years ago and is still continuing (▶ Figure 2.18c; see Chapter 13).

■ *How can ancient subduction zones be recognized in the geologic record?*

Igneous rocks provide one clue to ancient subduction zones. The magma erupted at the surface, forming island arc volcanoes and continental volcanoes, is of andesitic composition. Another clue is the zone of intensely deformed rocks between the deep-sea trench where subduction is taking place and the area of igneous activity. Here, sediments and submarine rocks are folded, faulted, and metamorphosed into a chaotic mixture of rocks called a *mélange*.

During subduction, pieces of oceanic lithosphere are sometimes incorporated into the mélange and accreted onto the edge of the continent. Such slices of oceanic crust and upper mantle are called *ophiolites* (▶ Figure 2.19). They consist of a layer of deep-sea sediments that include graywackes (poorly sorted sandstones containing abundant feldspar minerals and rock fragments, usually in a clay-rich matrix), black shales, and cherts (see Chapter 7). These deep-sea sediments are underlain by pillow lavas, a sheeted dike complex, massive gabbro (a dark intrusive igneous



You've been selected to be part of the first astronaut team to go to Mars. While your two fellow crewmembers descend to the Martian surface, you'll be staying in the command module and circling the Red Planet. As part of the geologic investigation of Mars, one of the crewmembers will be mapping the geology around the landing site and deciphering the geologic history of the area. Your job will be to observe and photograph the planet's surface and try to determine whether Mars had an active plate tectonic regime in the past and whether there is current plate movement. What features will you look for, and what evidence might reveal current or previous plate activity?

rock), and layered gabbro, all of which form the oceanic crust. Beneath the gabbro is peridotite, which probably represents the upper mantle. The presence of ophiolite in an outcrop or drilling core is a key indication of plate convergence along a subduction zone.

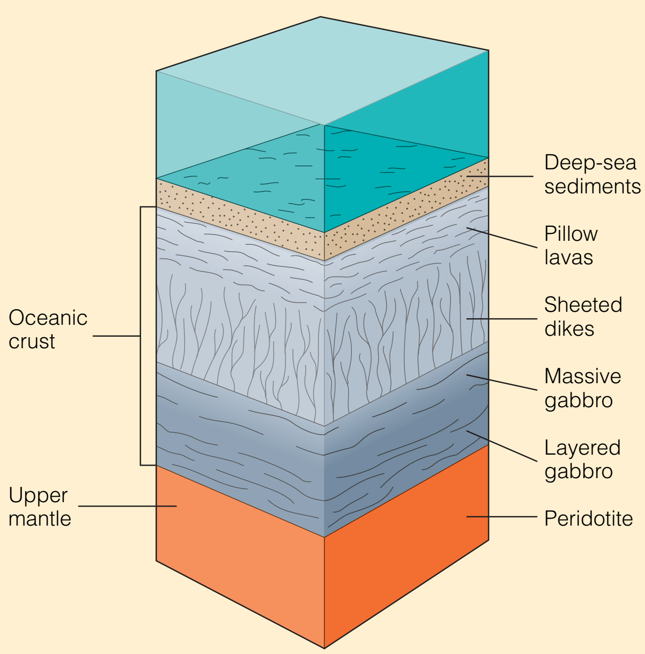
Elongate belts of folded and faulted marine sedimentary rocks, andesites, and ophiolites are found in the Appalachians, Alps, Himalayas, and Andes mountains. The combination of such features is good evidence that these mountain ranges resulted from deformation along convergent plate boundaries.

■ *What are transform boundaries?*

The third type of plate boundary is a **transform plate boundary.** These mostly occur along fractures in the seafloor, known as *transform faults*, where plates slide laterally past each other roughly parallel to the direction of plate movement. Although lithosphere is neither created nor destroyed along a transform boundary, the movement between plates results in a zone of intensely shattered rock and numerous shallow-depth earthquakes.

Transform faults "transform" or change one type of motion between plates into another type of motion. Most commonly, transform faults connect two oceanic ridge segments, but they can also connect ridges to trenches and trenches to trenches (▶ Figure 2.20). Although the majority of transform faults are in oceanic crust and are marked by distinct fracture zones, they may also extend into continents.

▶ **Figure 2.19 Ophiolites** Ophiolites are sequences of rock on land consisting of deep-sea sediments, oceanic crust, and upper mantle. Ophiolites are one feature used to recognize ancient convergent plate boundaries.



One of the best-known transform faults is the San Andreas fault in California. It separates the Pacific plate from the North American plate and connects spreading ridges in the Gulf of California with the Juan de Fuca and Pacific plates off the coast of northern California (▶ Figure 2.21). Many of the earthquakes affecting California are the result of movement along this fault (see Chapter 10).

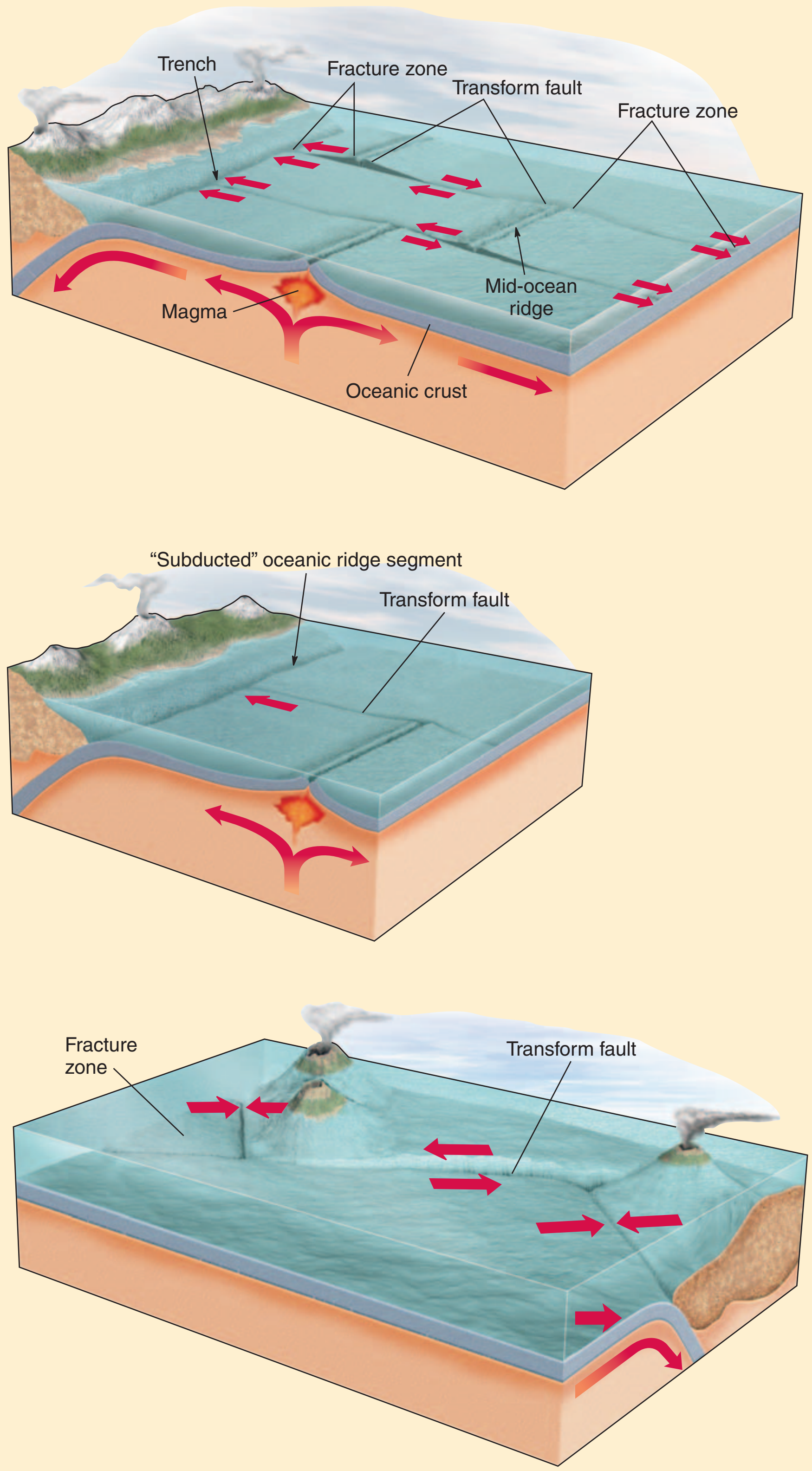
Unfortunately, transform faults generally do not leave any characteristic or diagnostic features except the obvious displacement of the rocks with which they are associated. This displacement is usually large, on the order of tens to hundreds of kilometers. Such large displacements in ancient rocks can sometimes be related to transform fault systems.

PHYSICAL Geology Now™ Log into GeologyNow and select this chapter to work through **Geology Interactive** activities on "Plate Boundaries" (click Plate Tectonics→Plate Boundaries) and "Triple Junctions and Seafloor Studies" (click Plate Tectonics→Triple Junctions and Seafloor Studies).

Section 2.7 Summary

- The three major types of plate boundaries are divergent, convergent, and transform.
- Divergent plate boundaries occur where plates are separating and new oceanic lithosphere is forming. They are characterized by thinning and fracturing of the crust, formation of rift valleys, intrusion of magma, and shallow-depth earthquakes.
- Zones of ancient continental rifting can be recognized by faults, dikes, sills, lava flows, and thick sedimentary sequences, whereas pillow lavas and associated deep-sea sediments are evidence of ancient spreading ridges.
- Convergent plate boundaries occur where two plates collide, and the leading edge of one plate is subducted beneath the margin of the other plate. They are characterized by metamorphism, mountain building, volcanic and earthquake activity, and the formation of various mineral deposits. Three types of convergent plate boundaries are recognized: oceanic–oceanic, where two oceanic plates converge, oceanic–continental, where an oceanic plate is subducted beneath the continental plate, and continental–continental, where an interior mountain belt is formed.
- Intensely deformed rocks, andesite lavas, and ophiolites are all evidence of ancient subduction zones, marking former convergent plate boundaries.
- Transform plate boundaries occur along fractures in the seafloor, called transform faults, where plates slide laterally past each other.

PHYSICAL Geology Now™ ▶ **Geo-focus Figure 2.20 Transform Plate Boundaries** Horizontal movement between plates occurs along transform faults. Extensions of transform faults on the seafloor form fracture zones.



a Most transform faults connect two oceanic ridge segments.

b A transform fault can connect a ridge and a trench.

c A transform fault can also link two trenches.

2.8 Hot Spots: An Intraplate Feature

■ *What are hot spots and what do they tell us about plate movement?*

Before leaving the topic of plate boundaries, we should mention an intraplate feature found beneath both oceanic and continental plates. A **hot spot** is the location on Earth's surface where a stationary column of magma, originating deep within the mantle (*mantle plume*), has slowly risen to the surface and formed a volcano (▶ Figure 2.22). Because mantle plumes apparently remain stationary (although some evidence suggests that they might not) within the mantle while plates move over them, the resulting hot spots leave a trail of extinct and progressively older volcanoes called *aseismic ridges* that record the movement of the plate.

One of the best examples of aseismic ridges and hot spots is the Emperor Seamount–Hawaiian Island chain (▶ Figure 2.22). This chain of islands and seamounts (structures of volcanic origin rising higher than 1 km above the seafloor) extends from the island of Hawaii to the Aleutian Trench off Alaska, a distance of some 6000 km, and consists of more than 80 volcanic structures.

Currently, the only active volcanoes in this island chain are on the islands of Hawaii and Maui and the Loihi Seamount. The rest of the islands are extinct volcanic structures that become progressively older toward the north and northwest. This means that the Emperor Seamount–Hawaiian Island chain records the direction that the Pacific plate traveled as it moved over an apparently stationary mantle plume. In this case, the Pacific plate first moved in a north-northwesterly direction and then, as indicated by the sharp bend in the chain, changed to a west-northwesterly direction about 43 million years ago. The reason the Pacific plate changed directions is not known, but the shift might be related to the collision of India with the Asian continent at around the same time (see Figure 13.22).

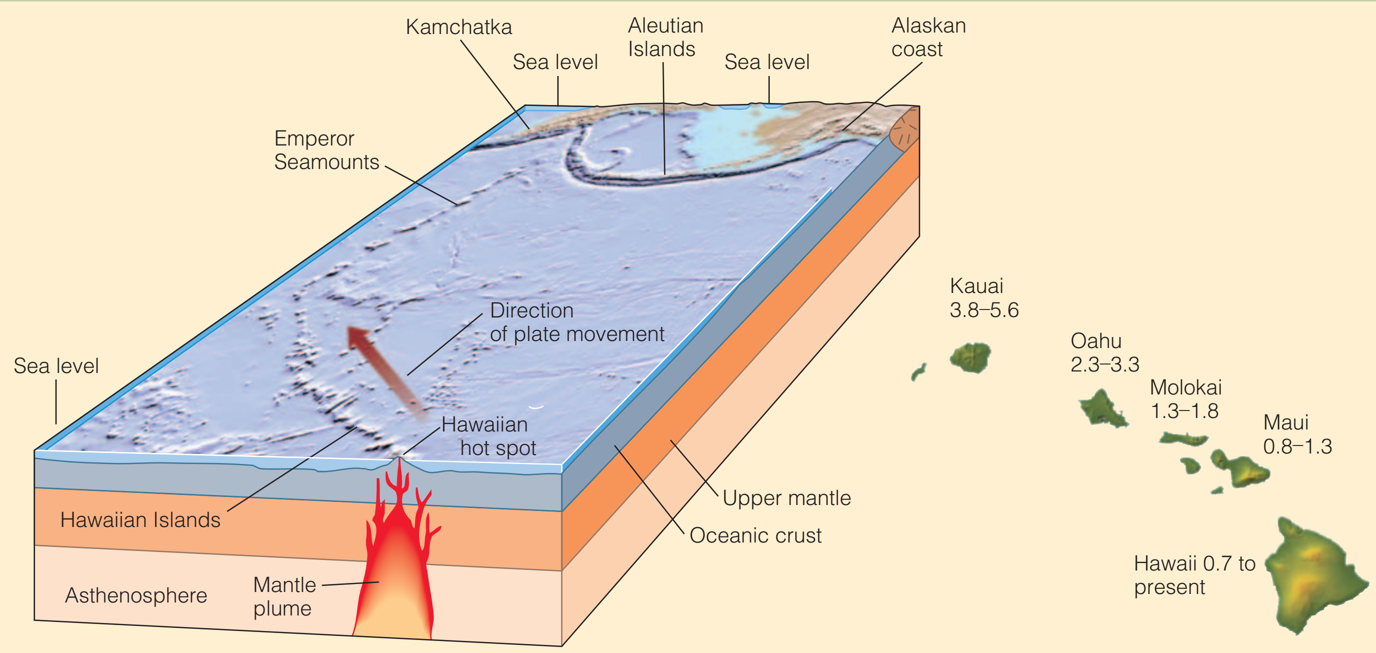
Mantle plumes and hot spots help geologists explain some of the geologic activity occurring within plates as opposed to activity occurring at or near plate boundaries. In addition, if mantle plumes are essentially fixed with respect to Earth's rotational axis, they can be used to determine not only the direction of plate movement but also the rate of movement. They can also provide reference points for determining paleolatitude, an important tool when reconstructing the location of continents in the geologic past.

Section 2.8 Summary

- Hot spots are locations where stationary columns of magma from the mantle (mantle plumes) have risen to the surface and formed volcanoes.

▶ **Figure 2.21 The San Andreas Fault—A Transform Plate Boundary** The San Andreas fault is a transform fault separating the Pacific plate from the North American plate. It connects the spreading ridges in the Gulf of California with the Juan de Fuca and Pacific plates off the coast of northern California. Movement along the San Andreas fault has caused numerous earthquakes. The insert photograph shows a segment of the San Andreas fault as it cuts through the Carrizo Plain, California.

PHYSICAL GeologyNow™ ▶ **Active Figure 2.22 Hot Spots** A hot spot is the location where a stationary mantle plume has risen to the surface and formed a volcano. The Emperor Seamount–Hawaiian Island chain formed as a result of the Pacific plate moving over a mantle plume, and the line of volcanic islands in this chain traces the direction of plate movement. The Hawaiian hot spot currently underlies the southern half of the island of Hawaii and adjoining offshore area. The numbers indicate the ages of the Hawaiian Islands in millions of years.



• Because the mantle plumes apparently remain stationary while plates move over them, the trail of hot spots, marked by extinct and progressively older volcanoes, records the direction and rate of plate movement.

2.9 Plate Movement and Motion

■ *How can the rate and direction of plate movement be determined?*

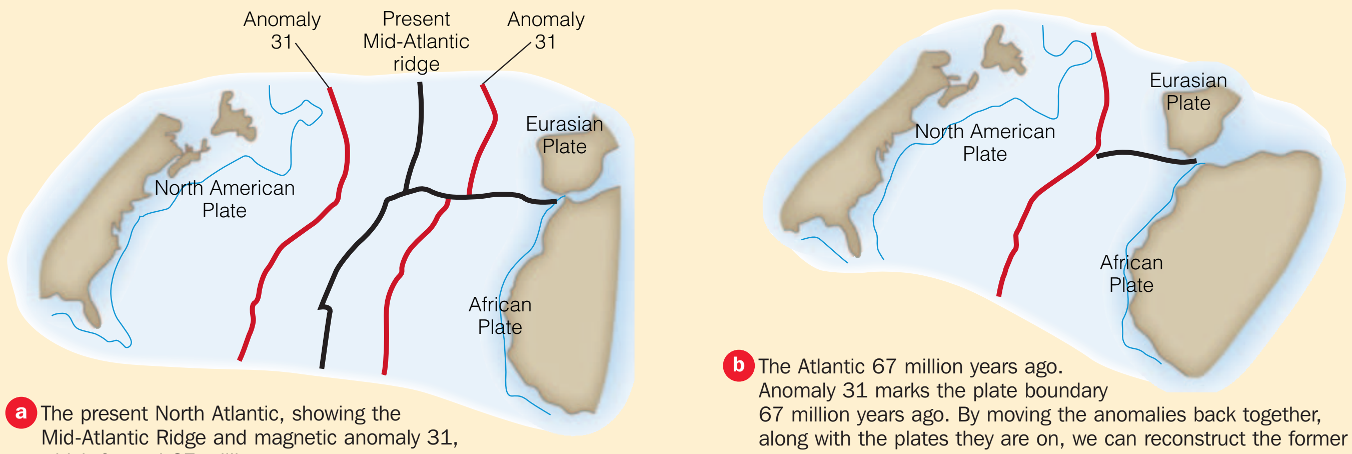
How fast and in what direction are Earth's plates moving? Do they all move at the same rate? Rates of plate movement can be calculated in several ways. The least accurate method is to determine the age of the sediments immediately above any portion of the oceanic crust and then divide the distance from the spreading ridge by that age. Such calculations give an average rate of movement.

A more accurate method of determining both the average rate of movement and the relative motion is by dating the magnetic anomalies in the crust of the seafloor. The distance from an oceanic ridge axis to any magnetic anomaly indicates the width of new seafloor that formed during that time interval. Thus, for a given interval of time, the wider the strip of seafloor, the faster the plate has moved. In this way, not only can the present average rate of movement and relative motion be determined (▶ Figure 2.14), but the average rate of movement during the past can also be calculated by dividing the distance between anomalies by the amount of time elapsed between anomalies.

Geologists use magnetic anomalies not only to calculate the average rate of plate movement but also to determine plate positions at various times in the past. Because magnetic anomalies are parallel and symmetric with respect to spreading ridges, all one must do to determine the positions of continents when particular anomalies formed is to move the anomalies back to the spreading ridge, which will also move the continents with them (▶ Figure 2.23). Unfortunately, subduction destroys oceanic crust and the magnetic record it carries. Thus we have an excellent record of plate movements since the breakup of Pangaea, but not as good an understanding of plate movement before that time.

The average rate of movement as well as the relative motion between any two plates can also be determined by satellite–laser ranging techniques. Laser beams from a station on one plate are bounced off a satellite (in geosynchronous orbit) and returned to a station on a different plate. As the plates move away from each other, the laser beam takes more time to go from the sending station to the stationary satellite and back to the receiving station. This difference in elapsed time is used to calculate the rate of movement and the relative motion between plates.

▶ Figure 2.23 Reconstructing Plate Positions Using Magnetic Anomalies



a The present North Atlantic, showing the Mid-Atlantic Ridge and magnetic anomaly 31, which formed 67 million years ago.

b The Atlantic 67 million years ago. Anomaly 31 marks the plate boundary 67 million years ago. By moving the anomalies back together, along with the plates they are on, we can reconstruct the former positions of the continents.

Plate motions derived from magnetic reversals and satellite–laser ranging techniques give only the relative motion of one plate with respect to another. Hot spots enable geologists to determine absolute motion because they provide an apparently fixed reference point from which the rate and direction of plate movement can be measured. The previously mentioned Emperor Seamount–Hawaiian Island chain formed as a result of movement over a hot spot. Thus the line of the volcanic islands traces the direction of plate movement, and dating the volcanoes enables geologists to determine the rate of movement.

Section 2.9 Summary

- One technique used to calculate the average rate of plate movement is to divide the distance from an oceanic ridge axis to any magnetic anomaly by the age of that anomaly. The average rate of movement during the past can also be calculated by dividing the distance between anomalies by the amount of time elapsed between anomalies.

- The relative motion of one plate with respect to another can be derived from magnetic reversals and satellite–laser ranging techniques. Hot spots are evidence for absolute motion because they provide an apparently fixed reference point from which the rate and direction of plate movement can be measured.

2.10 The Driving Mechanism of Plate Tectonics

■ *What drives plates?*

A major obstacle to the acceptance of the continental drift hypothesis was the lack of a driving mechanism to explain continental movement. When it was shown that continents and ocean floors moved together, not separately, and that new crust formed at spreading ridges by rising magma, most geologists accepted some type of convective heat system as the basic process responsible for plate motion. The question still remains, however: What exactly drives the plates?

■ *How do thermal convection cells move plates?*

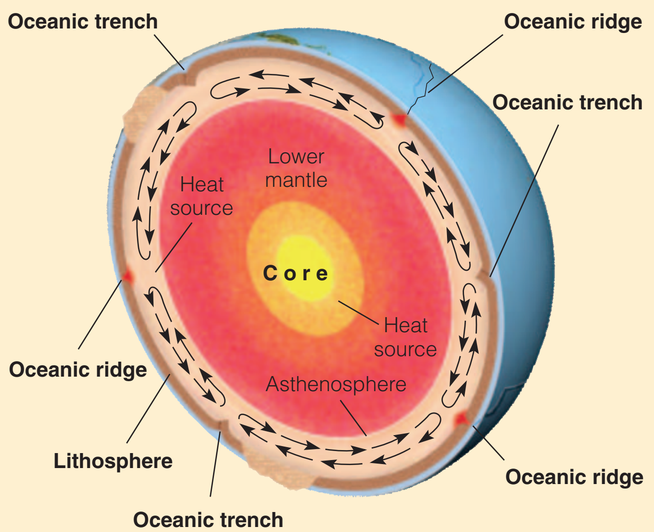
Two models involving thermal convection cells have been proposed to explain plate movement (▶ Figure 2.24). In one model, thermal convection cells are restricted to the asthenosphere; in the second model, the entire mantle is involved. In both models, spreading ridges mark the ascending limbs of adjacent convection cells, and trenches are present where convection cells descend back into Earth's interior. The convection cells therefore determine the location of spreading ridges and trenches, with the lithosphere lying above the thermal convection cells. Each plate thus corresponds to a single convection cell and moves as a result of the convective movement of the cell itself.

Although most geologists agree that Earth's internal heat plays an important role in plate movement, there are problems with both models. The major problem associated with the first model is the difficulty in explaining the source of heat for the convection cells and why they are restricted to the asthenosphere. In the second model, the heat comes from the outer core, but it is still not known how heat is transferred from the outer core to the mantle. Nor is it clear how convection can involve both the lower mantle and the asthenosphere.

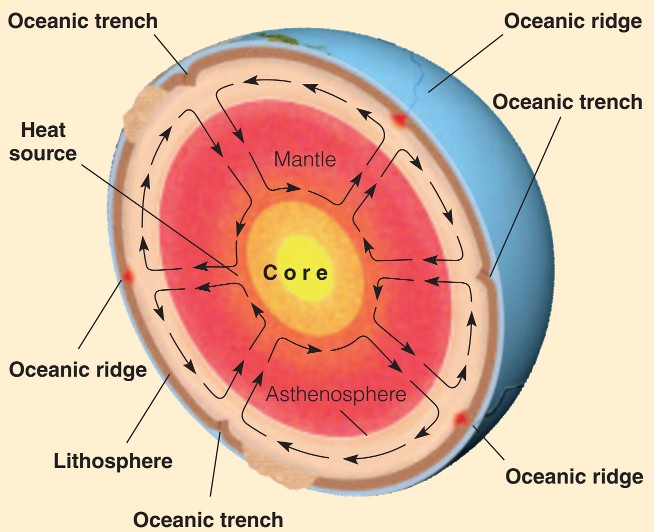
■ *Can plate movement be gravity driven?*

In addition to some type of thermal convection system driving plate movement, some geologists think plate movement occurs because of a mechanism involving

PHYSICAL Geology Now™ ▶ **Active Figure 2.24 Thermal Convection Cells as the Driving Force of Plate Movement** Two models involving thermal convection cells have been proposed to explain plate movement.



a In the first model, thermal convection cells are restricted to the asthenosphere.



b In the second model, thermal convection cells involve the entire mantle.

"slab-pull" or "ridge-push," both of which are gravity driven but still dependent on thermal differences within Earth (▶ Figure 2.25). In slab-pull, the subducting cold slab of lithosphere, being denser than the surrounding warmer asthenosphere, pulls the rest of the plate along as it descends into the asthenosphere. As the lithosphere moves downward, there is a corresponding upward flow back into the spreading ridge.

Operating in conjunction with slab-pull is the ridge-push mechanism. As a result of rising magma, the oceanic ridges are higher than the surrounding oceanic crust. It is thought that gravity pushes the oceanic lithosphere away from the higher spreading ridges and toward the trenches.

Currently, geologists are fairly certain that some type of convective system is involved in plate movement, but the extent to which other mechanisms such as slab-pull and ridge-push are involved is still unresolved. However, the fact that plates have moved in the past and are still moving today has been proven beyond a doubt. And although a comprehensive theory of plate movement has not yet been developed, more and more of the pieces are falling into place as geologists learn more about Earth's interior.

Section 2.10 Summary

- Plates are thought to move by some type of thermal convection system. In one model, thermal convection cells are restricted to the asthenosphere, and in the second model, the entire mantle is involved. Both models have problems associated with heat transfer and the source of heat.
- Some geologists think that, in addition to thermal convection, plate movement is primarily gravity driven, by either "slab-pull" or "ridge-push." In slab-pull, the subducting, cold, dense lithosphere pulls the rest of the plate along as it descends into Earth's interior. In ridge-push, gravity pushes the lithosphere away from the higher spreading ridges and toward the subduction trenches.

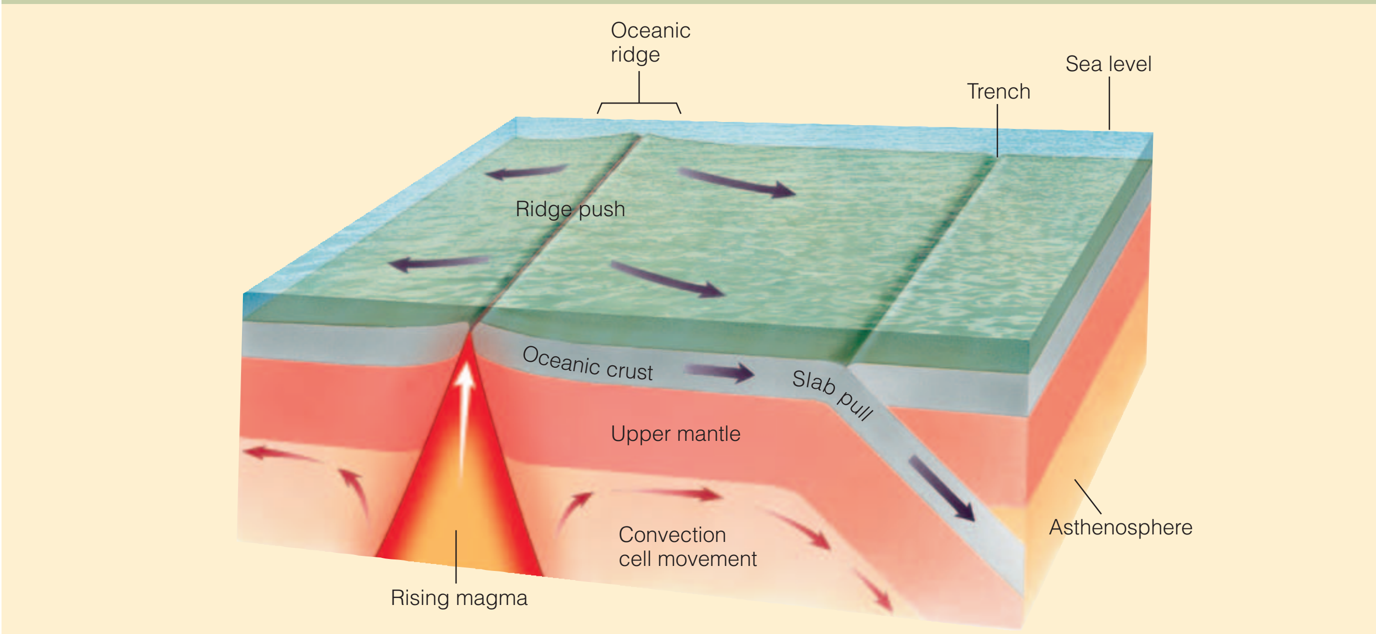
2.11 Plate Tectonics and the Distribution of Natural Resources

■ *How does plate tectonic theory relate to the origin and distribution of natural resources?*

Besides being responsible for the major features of Earth's crust and influencing the distribution and evolution of the world's biota, plate movements also affect the formation and distribution of some natural resources. The formation of many natural resources results from the interaction between plates, and economically valuable concentrations of such deposits are found associated with current and ancient plate boundaries. Consequently, geologists are using plate tectonic theory in their search for petroleum and mineral deposits and in explaining the occurrence of these natural resources.

It is becoming increasingly clear that if we are to keep up with the continuing demands of a global industrialized society, the application of plate tectonic theory to the origin and distribution of natural resources is essential.

PHYSICAL Geology Now™ ▶ **Geo-focus Figure 2.25 Plate Movement Resulting from Gravity-Driven Mechanisms** Plate movement is also thought to result, at least partially, from gravity-driven "slab-pull" or "ridge-push" mechanisms. In slab-pull, the edge of the subducting plate descends into the interior, and the rest of the plate is pulled downward. In ridge-push, rising magma pushes the oceanic ridges higher than the rest of the oceanic crust. Gravity thus pushes the oceanic lithosphere away from the ridges and toward the trenches.



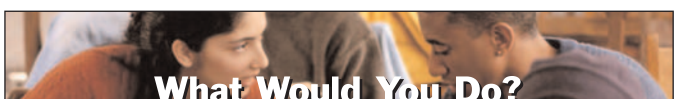
■ *What is the relationship between plate boundaries and various metallic mineral deposits?*

Many metallic mineral deposits such as copper, gold, lead, silver, tin, and zinc are related to igneous and associated hydrothermal (hot water) activity, so it is not surprising that a close relationship exists between plate boundaries and the occurrence of these valuable deposits.

The magma generated by partial melting of a subducting plate rises toward the surface, and as it cools, it precipitates and concentrates various metallic ores. Many of the world's major metallic ore deposits are associated with convergent plate boundaries, including those in the Andes of South America, the Coast Ranges and Rockies of North America, Japan, the Philippines, Russia, and a zone extending from the eastern Mediterranean region to Pakistan. In addition, the majority of the world's gold is associated with sulfide deposits located at ancient convergent plate boundaries in such areas as South Africa, Canada, California, Alaska, Venezuela, Brazil, southern India, Russia, and western Australia.

The copper deposits of western North and South America are an excellent example of the relationship between convergent plate boundaries and the distribution, concentration, and exploitation of valuable metallic ores (▶ Figure 2.26a). The world's largest copper deposits are found along this belt. The majority of the copper deposits in the Andes and the southwestern United States formed less than 60 million years ago when oceanic plates were subducted under the North and South American plates. The rising magma and associated hydrothermal fluids carried minute amounts of copper, which was originally widely disseminated but eventually became concentrated in the cracks and fractures of the surrounding andesites. These low-grade copper deposits contain from 0.2 to 2% copper and are extracted from large open-pit mines (▶ Figure 2.26b).

Divergent plate boundaries also yield valuable ore deposits. The island of Cyprus in the Mediterranean is rich in copper and has been supplying all or part of the world's needs for the last 3000 years. The concentration of copper on Cyprus formed as a result of precipitation adjacent to hydrothermal vents along a divergent plate boundary. This



You are part of a mining exploration team that is exploring a promising and remote area of central Asia. You know that former convergent and divergent plate boundaries are frequently sites of ore deposits. What evidence would you look for to determine whether the area you're exploring might be an ancient convergent or divergent plate boundary? Is there anything you can do before visiting the area that might help you to determine the geology of the area?

Figure 2.26 Copper Deposits and Convergent Plate Boundaries

a Valuable copper deposits are located along the west coasts of North and South America in association with convergent plate boundaries. The rising magma and associated hydrothermal activity resulting from subduction carried small amounts of copper, which became trapped and concentrated in the surrounding rocks through time.

Courtesy of R. V. Dietrich

b Bingham Mine in Utah is a huge open-pit copper mine with reserves estimated at 1.7 billion tons. More than 400,000 tons of rock are removed for processing each day.

deposit was brought to the surface when the copper-rich seafloor collided with the European plate, warping the seafloor and forming Cyprus.

Studies indicate that minerals of such metals as copper, gold, iron, lead, silver, and zinc are currently forming as sulfides in the Red Sea. The Red Sea is opening as a result of plate divergence and represents the earliest stage in the growth of an ocean basin (▶ Figures 2.15c and 2.16b).

Section 2.11 Summary

- The origin and distribution of many natural resources are related to the interaction between plates. Many metallic ores form as a result of igneous and hydrothermal activity related to the formation of magma along divergent and convergent plate boundaries.

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

2.1 Introduction

■ *Why should you know about plate tectonics?*

Plate tectonics affects all of us, whether in relation to the destruction caused by volcanic eruptions and earthquakes, or politically and economically due to the formation and distribution of valuable natural resources. Furthermore, plate tectonics is the unifying theory of geology, tying together many seemingly unrelated geologic phenomena and illustrating why Earth is a dynamic planet of interacting subsystems and cycles.

2.2 Continental Drift

■ *What were some early idea's about Earth's past geography?*

The idea that continents have moved in the past is not new and probably goes back to the first maps, in which one could see that the east coast of South America looks like it fits into the west coast of Africa.

■ *What is the continental drift hypothesis and who proposed it?*

Alfred Wegener originally proposed the continental drift hypothesis in 1912. He postulated that all landmasses were originally united into a supercontinent he named Pangaea. Pangaea consisted of a northern landmass called Laurasia and a southern landmass called Gondwana. As Pangaea broke up, the various continents moved to their present-day locations.

2.3 Evidence for Continental Drift

■ *What is the evidence for continental drift?*
Wegener and others amassed a large amount of evidence in support of continental drift. There is a close fit between continents off the coasts at a depth of about 2000 m. Marine, nonmarine, and glacial rock sequences of Pennsylvanian to Jurassic age are nearly identical on all the Gondwana continents, and the trend of several major mountain ranges produces a continuous mountain range when the continents are positioned next to each other as they were during the formation of Pangaea. Glacial tills and striations on the bedrock beneath the till provide evidence of glaciation at the same time on all the Gondwana continents, with South Africa located at the South Pole. Lastly, the distribution of fossil plants (*Glossopteris* flora) and animals (the nonmarine reptile *Mesosaurus* in particular) provides convincing evidence that the southern continents were united during the Late Paleozoic Era.

2.4 Paleomagnetism and Polar Wandering

■ *What is paleomagnetism?*
Paleomagnetism is the remanent magnetism in ancient rocks recording the direction and intensity of Earth's magnetic field at the time of the rock's formation.

■ *What is the Curie point and why is it important?*
The Curie point is the temperature at which iron-bearing minerals gain their magnetism. It is important because as long as the rock is not subsequently heated above the Curie point, it will preserve that remanent magnetism.

■ *How can the apparent wandering of the magnetic poles be best explained?*
The best explanation for polar wandering, which is the apparent movement of the magnetic poles through time, is that the magnetic poles have remained near their present locations at the geographic north and south poles and the continents have moved. When the continents are fitted together, the paleomagnetic data point to only one magnetic pole.

2.5 Magnetic Reversals and Seafloor Spreading

■ *What evidence is there that Earth's magnetic field has reversed in the past?*
Earth's present magnetic field is considered normal, that is, with the north and south magnetic poles located approximately at the north and south geographic poles. At various times in the geologic past, Earth's magnetic field has completely reversed. The existence of such magnetic reversals was discovered by dating and determining the orientation of the remanent magnetism in continental lava flows.

■ *What is the theory of seafloor spreading, and how does it validate continental drift?*
Harry Hess proposed the theory of seafloor spreading in 1962. He suggested that the seafloor separates at oceanic ridges, where new crust is formed by upwelling magma. As the magma cools, the newly formed oceanic crust moves laterally away from the ridge. Thus continents and oceanic crust move together, negating the need to explain how continents could plow through oceanic crust.

■ *How was the theory of seafloor spreading confirmed?*
Seafloor spreading was confirmed by the discovery of magnetic anomalies in the ocean crust that were both parallel to and symmetric around the ocean ridges. The pattern of oceanic magnetic anomalies matched the pattern of magnetic reversals already known from continental lava flows. Further evidence confirming seafloor spreading came from the Deep Sea Drilling Project and the age and thickness of the sediments overlying the oceanic crust.

2.6 Plate Tectonics: A Unifying Theory

■ *What are the main tenets of plate tectonic theory?*
According to plate tectonic theory, the rigid lithosphere, composed of oceanic and continental crust as well as the underlying upper mantle, is divided into different-sized plates. The lithosphere overlies the asthenosphere, and through some type of heat-transfer system within the asthenosphere, moves the plates. As the plates move over the asthenosphere, they separate mostly at oceanic ridges and collide and are subducted into Earth's interior at oceanic trenches.

■ *Why is plate tectonics a unifying theory of geology?*
The theory ties together many seemingly unrelated features and events and shows how they are interrelated. Furthermore, it illustrates the dynamic interactions between Earth's various subsystems and cycles.

■ *What is the supercontinent cycle?*
The hypothesis put forth by J. Tuzo Wilson in the early 1970s posits a large-scale global cycle in which a supercontinent fragments to form various ocean basins that widen and then close, thus reassembling another supercontinent.

2.7 The Three Types of Plate Boundaries

■ *What are the three types of plate boundaries?*
The three major types of plate boundaries are divergent, convergent, and transform.

■ *What are divergent boundaries?*
Divergent boundaries, also called spreading ridges, occur where plates are separating and new oceanic lithosphere is forming. Whereas most divergent boundaries occur along the crests of oceanic ridges, they are also present under continents during the early stages of continental breakup.

■ *What features in the geologic record indicate ancient rifting?*
Characteristic features of ancient continental rifting include faulting, dikes, sills, lava flows, and thick sedimentary sequences within rift valleys. Pillow lavas and associated deep-sea sediments are evidence of ancient spreading ridges.

■ *What are convergent boundaries?*
Convergent boundaries are places where two plates collide, and the leading edge of one plate is subducted beneath the margin of the other plate. There are three types of convergent boundaries. Oceanic–oceanic boundaries are where two oceanic plates collide, with one plate subducted beneath the other and a volcanic island arc forming on the nonsubducted plate, parallel to the oceanic trench where subduction is taking place. The volcanoes result from rising magma produced by the partial melting of the subducting plate. An oceanic–continental boundary is where an oceanic plate and a continental plate converge, with the denser oceanic plate being subducted under the continental plate. Just as with an oceanic–oceanic boundary, a chain of volcanoes forms

on the nonsubducted plate. A continental–continental boundary occurs when two continents approach each other and the ocean floor separating them is eventually subducted, resulting in a collision between the two continents. When the two continents collide, they are welded together to form an interior mountain chain along a zone marking the former site of subduction.

■ *How can ancient subduction zones be recognized in the geologic record?*
Intensely deformed rocks, andesite lavas, and ophiolites are all evidence of ancient subduction zones, marking former convergent plate boundaries.

■ *What are transform boundaries?*
These are boundaries along which plates slide laterally past each other along transform faults, which change one type of motion between plates into another type of motion.

2.8 Hot Spots: An Intraplate Feature

■ *What are hot spots and what do they tell us about plate movement?*
A hot spot is the location on Earth's surface where a stationary column of magma, originating deep within the mantle, has slowly risen to the surface and formed a volcano. Because mantle plumes apparently remain stationary within the mantle while plates move over them, the resulting hot spots leave a trail of extinct and progressively older volcanoes that record the movement of the plate.

2.9 Plate Movement and Motion

■ *How can the rate and direction of plate movement be determined?*
The average rate of plate movement is most commonly determined by dividing the distance from an oceanic ridge axis to any magnetic anomaly in the crust of the seafloor by the age of that anomaly. Because magnetic anomalies are parallel and symmetric with respect to spreading ridges, the relative direction of movement of a plate is perpendicular to the spreading ridge. Satellite–laser ranging techniques are also used to determine the rate of movement and relative motion of one plate with respect to another. Hot spots enable geologists to determine absolute motion because they provide an apparently fixed reference point from which the rate and direction of plate movement can be measured.

2.10 The Driving Mechanism of Plate Tectonics

■ *What drives plates?*
Most geologists agree that some type of convective heat system is the basic process responsible for plate motion.

■ *How do thermal convection cells move plates?*
Two models involving thermal convection cells have been proposed to explain plate movement. In one model, thermal cells are restricted to the asthenosphere, whereas in the second model, the entire mantle is involved. Problems with both models involve the source of heat for the convection cells and how heat is transferred from the outer core to the mantle.

■ *Can plate movement be gravity driven?*
Although they accept that some type of thermal convection system is involved in driving plate movement, some geologists think a gravity-driven mechanism such as "slab-pull" or "ridge-push" plays a major role. Both mechanisms still depend on thermal differences within Earth, but slab-pull involves pulling the plate behind a subducting cold slab of lithosphere, and ridge-push involves gravity pushing the oceanic lithosphere away from the higher spreading ridges and toward the subduction trenches.

2.11 Plate Tectonics and the Distribution of Natural Resources

■ *How does plate tectonic theory relate to the origin and distribution of natural resources?*
The formation of many natural resources results from the interaction between plates, and economically valuable concentrations of such deposits are found associated with current and ancient plate boundaries.

■ *What is the relationship between plate boundaries and various metallic mineral deposits?*
Many metallic mineral deposits are related to igneous and associated hydrothermal activity, so it is not surprising that a close relationship exists between plate boundaries and the occurrence of these valuable deposits. Many of the world's major metallic ore deposits are associated with convergent plate boundaries. Divergent plate boundaries also yield valuable ore deposits.

ESSENTIAL TERMS TO KNOW

continental–continental plate boundary (p. 54)
continental drift (p. 35)
convergent plate boundary (p. 52)
Curie point (p. 40)
divergent plate boundary (p. 47)
Glossopteris flora (p. 38)
Gondwana (p. 34)
hot spot (p. 57)
Laurasia (p. 36)
magnetic anomaly (p. 43)
magnetic reversal (p. 41)
oceanic–continental plate boundary (p. 54)
oceanic–oceanic plate boundary (p. 52)
paleomagnetism (p. 40)
Pangaea (p. 35)
plate (p. 46)
plate tectonic theory (p. 34)
seafloor spreading (p. 41)
thermal convection cell (p. 42)
transform fault (p. 55)
transform plate boundary (p. 55)

REVIEW QUESTIONS

1. What evidence convinced Wegener and others that continents must have moved in the past and at one time formed a supercontinent?
2. Why was the continental drift hypothesis proposed by Wegener rejected by so many geologists for so long?
3. How did the theory of seafloor spreading, proposed by Harry Hess in 1962, overcome the objections of those opposed to continental drift?
4. Explain how magnetic anomalies recorded in oceanic crust as well as the sediments deposited on oceanic crust confirm the seafloor spreading theory.
5. Plate tectonic theory builds on the continental drift hypothesis and the theory of seafloor spreading. As such, it is a unifying theory of geology. Explain why it is a unifying theory.
6. Explain why such natural disasters as volcanic eruptions and earthquakes are associated with divergent and convergent plate boundaries.
7. What is the supercontinent cycle? What elements of continental drift and seafloor spreading are embodied in the cycle?
8. Why is some type of thermal convection system thought to be the major force driving plate movement? How have “slab-pull” and “ridge-push,” both mainly gravity driven, modified a purely thermal convection model for plate movement?
9. What can hot spots tell us about the absolute direction of plate movement?
10. In addition to the volcanic eruptions and earthquakes associated with convergent and divergent plate boundaries, why are these boundaries also associated with the formation and accumulation of various metallic ore deposits?

APPLY YOUR KNOWLEDGE

1. Using the age for each of the Hawaiian Islands in Figure 2.22 and an atlas in which you can measure the distance between islands, calculate the average rate of movement per year for the Pacific plate since each island formed. Is the average rate of movement the same for each island? Would you expect it to be? Explain why it may not be.
2. Estimate the age of the seafloor crust and the age and thickness of the oldest sediment off the East Coast of North America (e.g., Virginia). In so doing, refer to Figure 2.12 for the ages and to the deep-sea sediment accumulation rate stated in this chapter.
3. If the movement along the San Andreas fault, which separates the Pacific plate from the North American plate, averages 5.5 cm per year, how long will it take before Los Angeles is opposite San Francisco?
4. Based on your knowledge of biology and the distribution of organisms throughout the world, how do you think plate tectonics has affected this distribution both on land and in the oceans?

GEOLOGY IN FOCUS Oil, Plate Tectonics, and Politics

It is certainly not surprising that oil and politics are closely linked. The Iran–Iraq War of 1980–1989 and the Gulf War of 1990–1991 were both fought over oil (▶ Figure 1). Indeed, many of the conflicts in the Middle East have had as their underlying cause control of the vast deposits of petroleum in the region. Most people, however, are not aware of why there is so much oil in this part of the world.

Although large concentrations of petroleum occur in many areas of the world, more than 50% of all proven reserves are in the Persian Gulf region. It is interesting, however, that this region did not become a significant petroleum-producing area until the economic recovery following World War II (1939–1945). After the war, Western Europe and Japan in particular became dependent on Persian Gulf oil, and they still rely heavily on this region for most of their supply. The United States is also dependent on imports from the Persian Gulf but receives significant quantities of petroleum from other sources such as Mexico and Venezuela.

Why is so much oil in the Persian Gulf region? The answer lies in the ancient geography and plate movements of this region during the Mesozoic and Cenozoic eras. During the Mesozoic Era, and particularly the Cretaceous Period when most of the petroleum formed, the Persian Gulf area was a broad marine shelf extending eastward from Africa. This continental margin lay near the equator where countless microorganisms lived in the surface waters. The remains of these organisms accumulated with the bottom sediments and were buried, beginning the complex process of petroleum generation and the formation of source beds in which the petroleum forms.

As a consequence of rifting in the Red Sea and Gulf of Aden during the Cenozoic Era, the Arabian plate is moving northeast away from Africa and subducting beneath Iran. As the sediments of the continental margin were initially subducted, during the early stages of collision between Arabia and Iran, the heating broke down the organic molecules and led to the formation of petroleum. The tilting of the Arabian block to the northeast allowed the newly formed petroleum to migrate upward into the interior of the Arabian plate. The continued subduction and collision with Iran folded the rocks, creating traps for petroleum to accumulate, such that the vast area south of the collision zone (know as the Zagros suture) is a major oil-producing region.

Figure 1
The Kuwaiti night skies were illuminated by 700 blazing oil wells set on fire by Iraqi troops during the 1991 Gulf War. The fires continued for nine months.

Reuters NewMedia Inc./Corbis

GEOLOGY IN UNEXPECTED PLACES

A Man's Home Is His Castle

Imagine visiting a castle in Devonshire, England, or Glasgow, Scotland, and noticing that the same rocks used in the construction of those castles can be seen in the Catskill Mountains of New York (▶ Figure 1). Whereas most people who visit castles in Great Britain and elsewhere in Europe are learning about the history of the castles—when they were built, why they were built, who lived in them, and other historical facts—geologists frequently are looking at the rocks that make up the walls of a castle and trying to determine what type of rock it is, how old it is, and anything else they can learn about it.

During the Devonian Period (416 to 359 million years ago), the North American continent and what is now Europe were moving toward each other along an oceanic–continental convergent plate boundary. As movement along this boundary continued, the ocean basin separating these landmasses shrunk until the two continents collided in what is known as the Acadian Orogeny. This mountain-building episode formed a large mountain range. Just as is happening today, those mountains began weathering and their eroded sediments were carried by streams and deposited as large deltas in the shallow seas adjacent to the mountains. The sediments deposited in what is now New York are referred to by geologists as the Catskill Delta. The counterpart in Great Britain is known as the Old Red Sandstone. These sediments were deposited in the same environment and reflect the conditions at the time of deposition.

Later during the Mesozoic Era (251 to 66 million years ago), as the supercontinent Pangaea broke apart along divergent plate boundaries, the Atlantic Ocean basin formed, separating North America from Europe. Even though the Devonian rocks of the present-day Catskill Mountains in New York are separated by several thousand kilometers from the Old Red Sandstone rocks of Great Britain, they were formed at the same time and deposited in the same environment hundreds of millions of years ago. That is why they have the same red color and composition and contain many of the same fossils.

So, the next time you see someone closely inspecting the rocks of a castle wall, there is a good chance that person is a geologist or someone, like yourself, who took a geology course.

Figure 1
Remains of Goodrich Castle in Herefordshire, England, dated to the period between 1160 and 1270. Goodrich Castle is one of many castles built from rocks quarried from the Old Red Sandstone, a Devonian-age formation. Identical red sandstone is found in the Catskill Mountains of New York. It too has been used as a building stone for many structures in the New York area.

Shayne McGuire/Myth and Legends Photography

Geology AND CULTURAL CONNECTIONS

The Struggle toward Scientific Progress

Progress in science isn't made easily. It would be nice if a scientist could come up with a good idea and then quickly convince other scientists of its merits, but in fact science is more like one long argument.

When Alfred Wegener proposed his idea of continental drift, it was met by derision from most geologists. They pointed out that Wegener had no convincing explanation for *how* continents moved across entire ocean basins. That was indeed a great weakness in his story, and Wegener's critics capitalized on it. But it wasn't the only issue that they focused on in their attack on Wegener's ideas.

As you read in this chapter, Edward Suess pointed to fossil evidence of similar ancient animals and plants apparently separated by great distances across oceans. Suess thought that land bridges had linked what are now different continents. Wegener, however, took the fossils of Suess and others and argued that the rocks in which the fossils were embedded must have been physically together in one ancient supercontinent (▶ Figure 1). Unfortunately, Wegener was a meteorologist by training, not a paleontologist, and he made mistakes about the details of the fossil evidence he relied on in his argument. Not surprisingly, fossil experts denounced his work because of those errors.

Wegener also thought that continental movement was quite rapid, much faster than anything we understand today in plate tectonic theory. Indeed, Wegener thought that Greenland was moving away from Europe at speeds up to meters per year—and he died while in Greenland trying to measure that amazing rate of movement. When news of Wegener's disappearance and presumed death in Greenland reached the civilized world, few geologists mourned his passing. The arguments Wegener had spawned had been vociferous even by the standards of scientific disputes.

Progress in science isn't easy, and the arguments that ultimately drive science forward are often unpleasant. In the case of Alfred Wegener, it is now clear that his insights outweighed his errors.

Figure 1
Mesosaurus, a Permian-aged freshwater reptile whose fossil remains are found in Brazil and South Africa, indicating these two continents were joined at the end of the Paleozoic Era.

Reed Wicander

Geology AT WORK

The Geologic Exploration of Mars

How would you like to have an extra 39 minutes to work or play each day? Well, you would if you lived on Mars, or were part of NASA's (National Aeronautics and Space Administration) Mars Exploration Rover project. With the successful landing on Mars of the two mobile robots *Spirit* and *Opportunity* in January 2004, members of the Mars Exploration Rover team started working on Mars time, or "sols," as the 24-hour, 39-minute Martian day-night cycle became known. They continued to do so for the first few months of the mission, as the two rovers explored the Martian surface. The downside of living on Martian time is that each day begins 39 minutes later than the previous day, which means that, after awhile, your Earth day will be starting in the evening instead of the morning. But most team members would probably agree that is a small price to pay for working on such an exciting voyage of discovery and exploration.

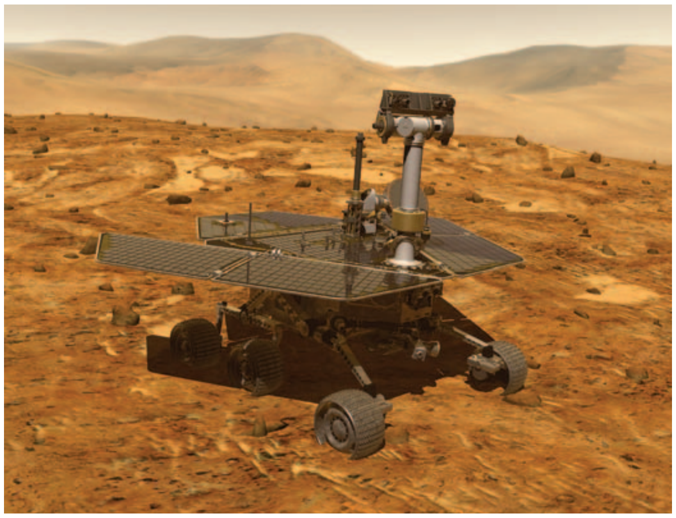
Launched on June 10 and July 7, 2003, respectively, the Mars Exploration Rovers *Spirit* and *Opportunity* successfully landed on opposite sides of Mars on January 3 and 24, 2004 (▶ Figures 1 and 2), and began their primary goal of searching for evidence that Mars once harbored an environment suitable for sustaining life. To achieve this goal, the rovers each carried panoramic cameras that provide 360-degree, stereoscopic, humanlike views of the terrain, as well as being able to focus up close on surface features of the local terrain; a miniature thermal emission spectrometer for identifying minerals at the site; a Moessbauer spectrometer for close-up investigations of the composition of iron-bearing rocks and soils; an alpha particle X-ray spectrometer for close-up analysis of the abundances of elements that make up the Martian rocks and soils; and a microscopic imager for looking at the fine-scale features of the rocks and soils encountered. In addition, they carried a rock abrasion tool for removing the weathered surfaces of rocks to expose the fresh interiors for examination, and magnetic targets for collecting magnetic dust particles.

Shortly after landing both rovers found strong and convincing evidence that Mars harbored abundant quantities of salty water during its early history, several billion years ago. How long this water persisted is still not known, but it does offer the tantalizing prospect that an ancient warmer and wetter Mars might possibly have harbored life. Evidence from *Opportunity* that Mars was awash in water, at least at the Meridiani Planum landing site, was soon forthcoming. Meridiani Planum, a broad, flat, equatorial plain, had been picked as *Opportunity*'s landing site because orbital surveys indicated the presence of gray hematite on the ground, a mineral that usually forms only in the presence of liquid water.

Shortly after landing, *Opportunity* transmitted images of what appeared to be outcrops of layered bedrock, which you would expect to have been deposited in an aqueous environment. However, the most exciting discovery was the presence of what soon came to be called "blueberries," grey BB-size spheres embedded in the rock layers or scattered across the surface as a result of having weathered out from the bedrock. Their resemblance to blueberries in a muffin is what gave them their popular name. These hematite-rich spheres were what the orbital surveys were picking up as the grey layers, making Meridiani Planum such a compelling site. In addition, the spectrometers on *Opportunity* indicated the outcrops were rich in water-deposited sulfate-salt minerals and iron-rich compounds. And lastly, a 0.3-m-long outcrop showed distinct cross-bedding, indicating the sediments were deposited in flowing water.

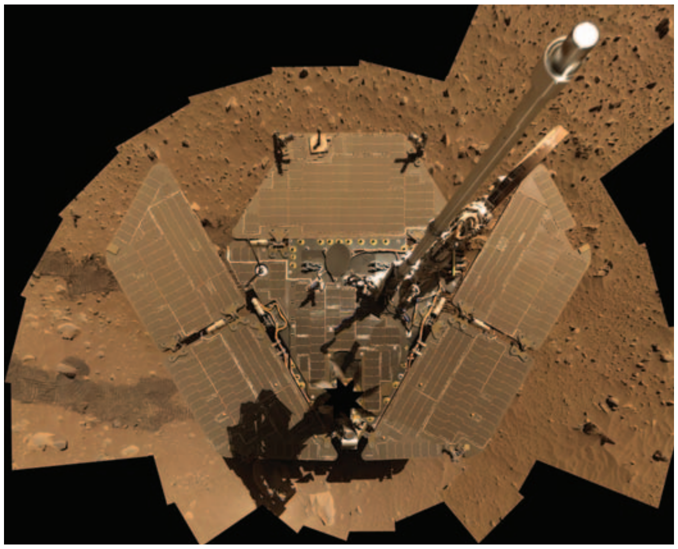
As exciting as these discoveries are, we still don't know how long water may have existed on Mars, how extensive its "seas" were, and why and how it disappeared so quickly. Nor do we know unequivocally whether Mars ever supported life. *Opportunity* and *Spirit* were not designed to answer such questions, and it will be up to the next generation of robotic rovers or even a manned landing to hopefully answer that question.

Figure 1
Artistic rendition of the Mars Exploration Rover *Opportunity* on the Martian surface at Meridiani Planum. Since landing in January 2004, *Opportunity* has transmitted images of what appear to be outcrops of layered sedimentary rocks, and it has analyzed hematite-rich spheres scattered across the surface that indicate the presence of water during their formation.



NASA/JPL/Cornell

Figure 2
Self-portrait of the Mars Exploration Rover *Spirit* taken by its panoramic camera during its 329th and 330th Martian days. The images combined into this mosaic show the Martian surface with numerous pebbles, some of which indicate evidence of wind erosion. Martian dust accumulations are also visible on *Spirit's* solar panel.



NASA/JPL/Cornell