CHAPTER

4

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Plate Tectonics

As you studied volcanoes, igneous, metamorphic and sedimentary rocks, and earthquakes, you learned how these topics are related to plate tectonics. In this chapter we take a closer look at plates and plate motion. We will pay particular attention to plate boundaries and the possible driving mechanisms for plate motion.

The history of the concept of plate tectonics is a good example of how scientists think and work and how a hypothesis can be proposed, discarded, modified, and then reborn. In the first part of this chapter we trace the evolution of an idea—how the earlier hypotheses of moving continents (continental drift) and a moving sea floor (sea-floor spreading) were combined to form the theory of plate tectonics.

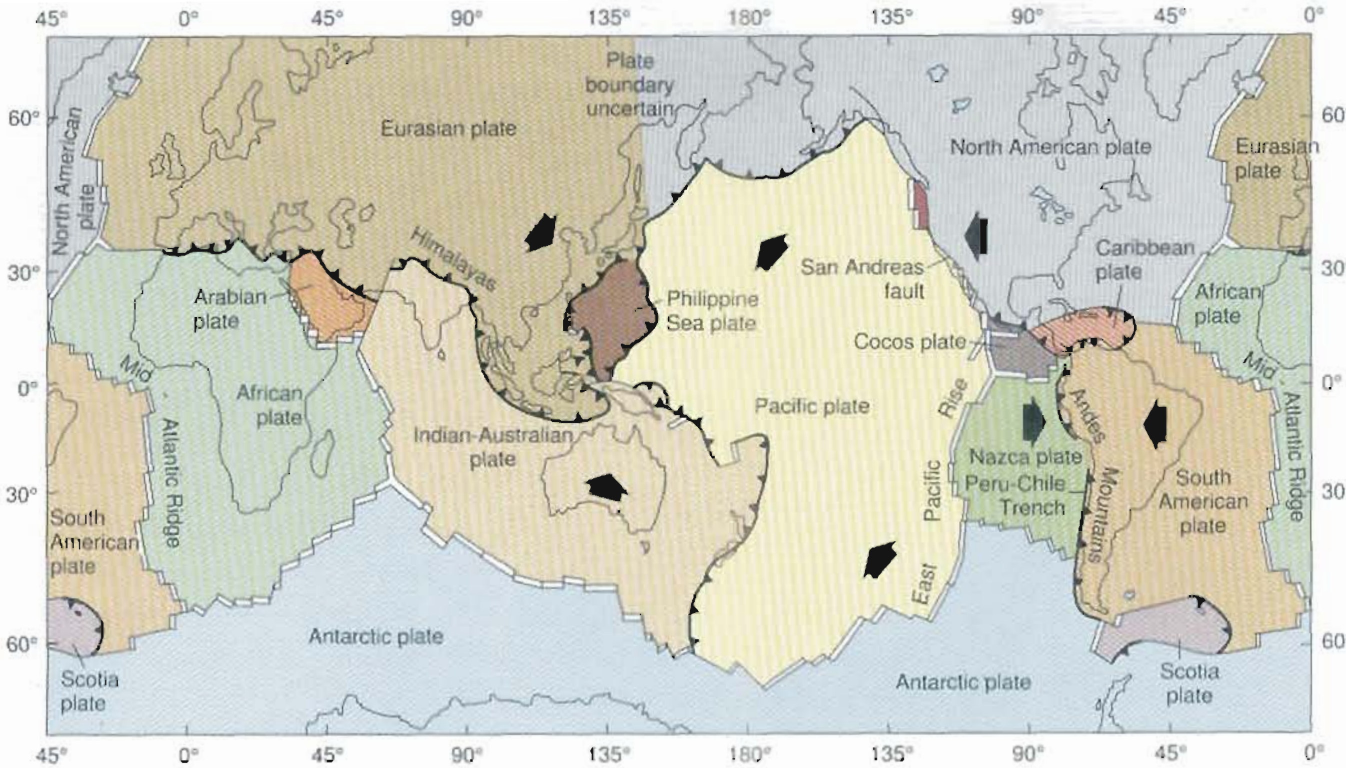


Figure 4.1

The major plates of the world. The western edge of the map repeats the eastern edge so that all plates can be shown unbroken. Double lines indicate spreading axes on divergent plate boundaries. Single lines show transform boundaries. Heavy lines with triangles show convergent boundaries, with triangles pointing down subduction zones.

Modified from W. Hamilton, U.S. Geological Survey.

Tectonics is the study of the origin and arrangement of the broad structural features of the earth's surface, including not only folds and faults, but also mountain belts, continents, and earthquake belts. Tectonic models such as an expanding earth or a contracting earth have been used in the past to explain *some* of the surface features of earth. Plate tectonics has come to dominate geologic thought today because it can explain so *many* features. The basic idea of **plate tectonics** is that the earth's surface is divided into a few large, thick plates that move slowly and change in size. Intense geologic activity occurs at *plate boundaries* where plates move away from one another, past one another, or toward one another. The eight large plates shown in figure 4.1, plus a few dozen smaller plates, make up the outer shell of the earth (the crust and upper part of the mantle).

The concept of plate tectonics was born in the late 1960s by combining two preexisting ideas—continental drift and sea-floor spreading. **Continental drift** is the idea that continents move freely over the earth's surface, changing their positions relative to one another. **Sea-floor spreading** is a hypothesis that the sea floor forms at the crest of the mid-oceanic ridge, then moves horizontally away from the ridge crest toward an oceanic trench. The two sides of the ridge are moving in opposite directions like slow conveyor belts.

Before we take a close look at plates, we will examine the earlier ideas of moving continents and a moving sea floor because these two ideas embody the theory of plate tectonics.

The Early Case for Continental Drift

Continents can be made to fit together like pieces of a picture puzzle. The similarity of the Atlantic coastlines of Africa and South America has long been recognized. The idea that continents were once joined together, and have split and moved apart from one another, has been around for more than 130 years (figure 4.2).

In the early 1900s Alfred Wegener, a German meteorologist, made a strong case for continental drift. He noted that South America, Africa, India, and Australia had almost identical late Paleozoic rocks and fossils (including the plant *Glossopteris*). He reassembled the continents to form a giant supercontinent *Pangaea* (also spelled Pangea today). Wegener thought that the similar rocks and fossils were easier to explain if the continents were joined together, rather than in their present, widely scattered positions.

Pangaea initially separated into two parts. *Laurasia* was the northern supercontinent, containing what is now North America and Eurasia (excluding India). *Gondwanaland* was the southern supercontinent, composed of all the present-day southern-hemisphere continents and India (which has drifted north).

The distribution of Late Paleozoic glaciation strongly supports the idea of Pangaea (figure 4.3). The Gondwanaland

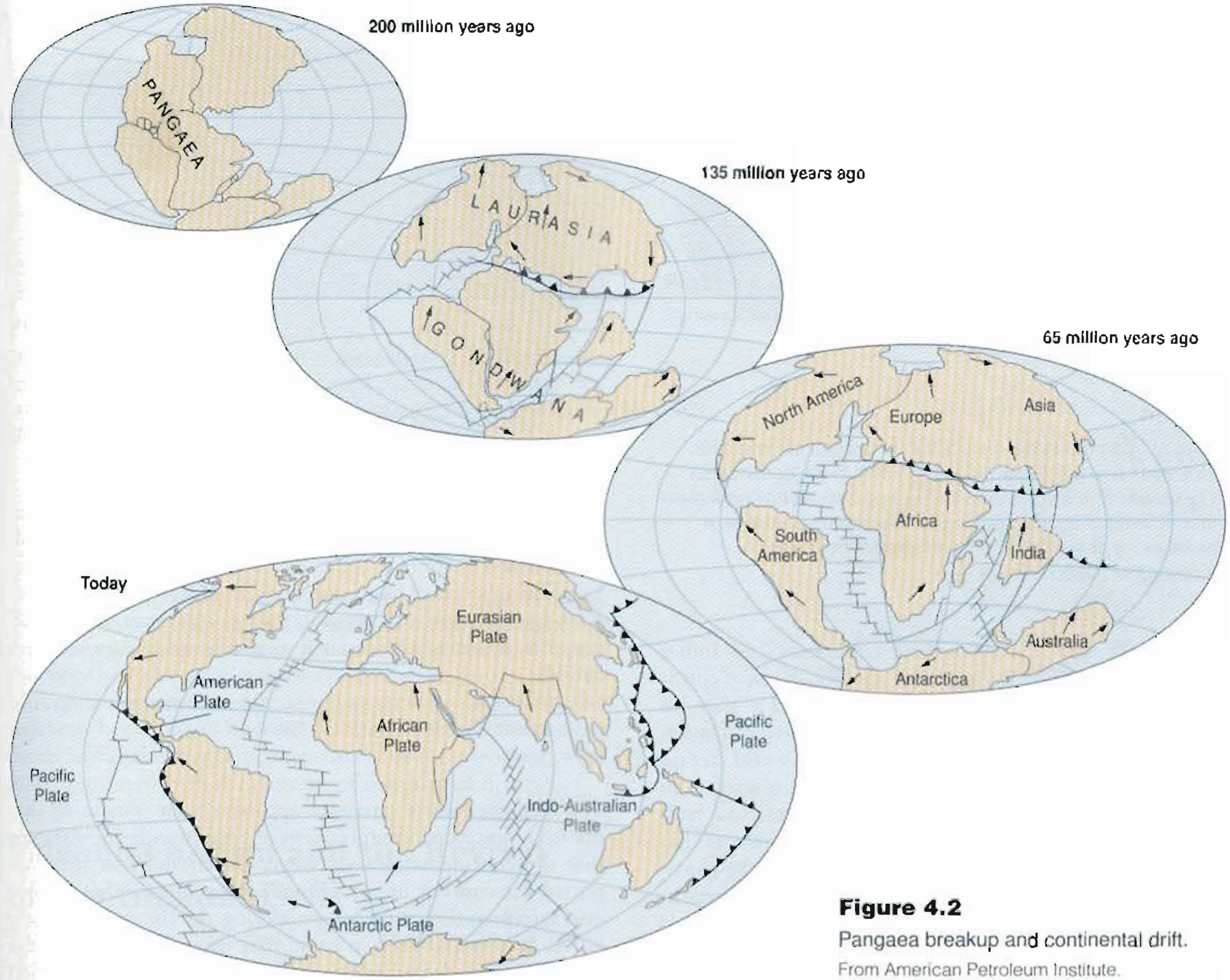


Figure 4.2

Pangaea breakup and continental drift.

From American Petroleum Institute.

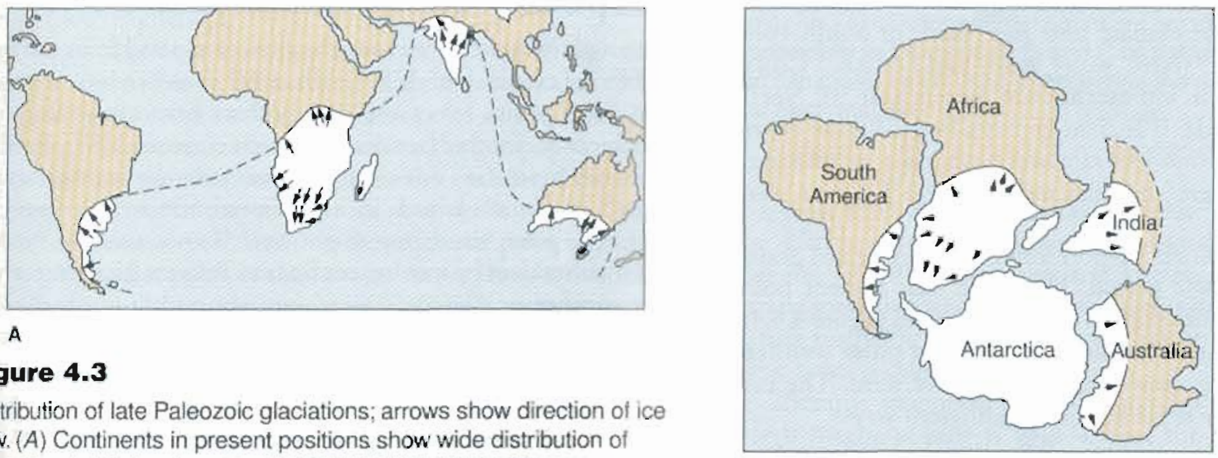


Figure 4.3

Distribution of late Paleozoic glaciations; arrows show direction of ice flow. (*A*) Continents in present positions show wide distribution of glaciation (white land areas with flow arrows). (*B*) Continents reassembled into Pangaea. Glaciated region becomes much smaller.

A from Arthur Holmes, 1965, *Principles of Physical Geology*, 2d ed., Ronald Press.

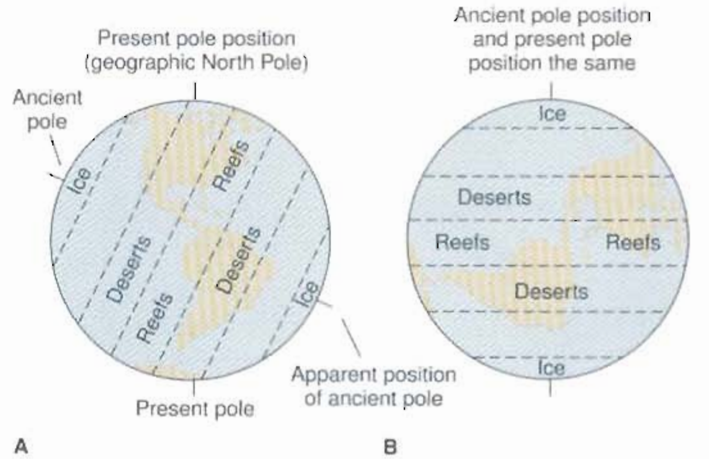


Figure 4.4

Two ways of interpreting the distribution of ancient climate belts. (*A*) Continents fixed, poles wander. (*B*) Poles fixed, continents drift. For simplicity, the continents in *B* are shown as having moved as a unit, without changing positions relative to one another. If continents move, they should change relative positions, complicating the pattern shown.

continents (the southern-hemisphere continents and India) all have glacial deposits of Late Paleozoic age. If these continents were spread over the earth in Paleozoic time as they are today, a climate cold enough to produce extensive glaciation would have had to prevail over almost the whole world. Yet no evidence has been found of widespread Paleozoic glaciation in the northern hemisphere. In fact, the late Paleozoic coal beds of North America and Europe were being laid down at that time in swampy, probably warm environments. If the continents are arranged according to Wegener's Pangaea reconstruction, then glaciation in the southern hemisphere is confined to a much smaller area (figure 4.3), and the absence of widespread glaciation in the northern hemisphere becomes easier to explain.

Wegener also reconstructed old climate zones (the study of ancient climates is called *paleoclimatology*). Glacial till and striations indicate a cold climate near the North or South Pole. Coral reefs indicate warm water near the Equator. Cross-bedded sandstones can indicate ancient deserts near 30° North and 30° South latitude. If ancient climates had the same distribution on earth that modern climates have, then sedimentary rocks can show where the ancient poles and Equator were located.

Wegener determined the positions of the North and South Poles for each geologic period. He found that ancient poles were in different positions than the present poles (figure 4.4*A*). This apparent movement of the poles he called **polar wandering.** Polar wandering, however, is a deceptive term. The evidence can actually be explained in two different ways:

1. The continents remained motionless and the poles actually *did* move—polar wandering (figure 4.4*A*).
2. The poles stood still and the continents moved—continental drift (figure 4.4*B*).

Figure 4.5

Apparent wandering of the South Pole since the Cretaceous Period as determined by Wegener from paleoclimate evidence. Wegener, of course, believed that *continents* rather than poles moved.

From A. Wegener, 1928, *The Origins of Continents and Oceans*, reprinted and copyrighted, 1968, Dover Publications.

Wegener plotted curves of apparent polar wandering (figure 4.5). Since one interpretation of polar wandering data was that the continents moved, Wegener believed that this supported his concept of continental drift. (Notice that in only one interpretation of polar wandering do the poles actually move. You should keep in mind that when geologists use the term *polar wandering* they are referring to an *apparent* motion of the poles, which may or may not have actually occurred.)

Skepticism about Continental Drift

Although Wegener presented the best case possible in the early 1900s for continental drift, much of his evidence was not clear-cut. Fossil plants, for example, could have been spread from one continent to another by winds or ocean currents. Their distribution over more than one continent does not *require* that the continents were all joined in the supercontinent, Pangaea. In addition, polar wandering might have been caused by moving poles rather than by moving continents. Because his evidence was not conclusive, Wegener's ideas were not widely accepted. This was particularly true in the United States, largely because of the mechanism Wegener proposed for continental drift.

Wegener proposed that continents plowed through the oceanic crust (figure 4.6), perhaps crumpling up mountain ranges on the leading edges of the continents where they pushed against the sea floor. Most geologists in the United States thought that this idea violated what was known about the strength of rocks at the time. The driving mechanism

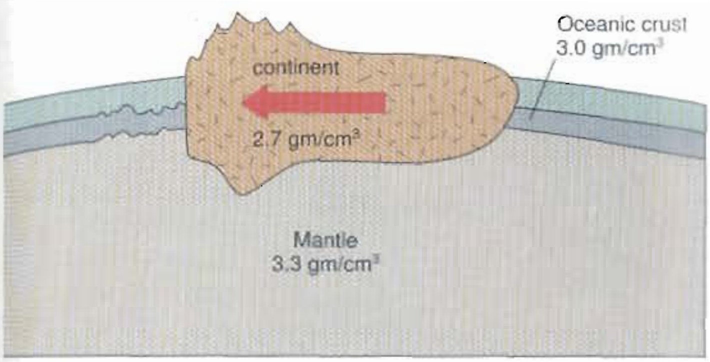


Figure 4.6

Wegener's concept of continental drift implied that the less dense continents drifted *through* oceanic crust, crumpling up mountain ranges on their leading edges as they pushed against oceanic crust.

proposed by Wegener for continental drift was a combination of centrifugal force from the earth's rotation and the gravitational forces that cause tides. Careful calculations of these forces showed them to be too small to move continents. Because of these objections, Wegener's ideas received little support in the United States or much of the northern hemisphere (where the great majority of geologists live) in the first half of the twentieth century. The few geologists in the southern hemisphere, however, where Wegener's matches of fossils and rocks between continents were more evident, were more impressed with the concept of continental drift.

Paleomagnetism and the Revival of Continental Drift

Much work in the 1940s and 1950s set the stage for the revival of the idea of continental drift and its later incorporation, along with sea-floor spreading, into the new concept of plate tectonics. The new investigations were in two areas: (1) study of the sea floor and (2) geophysical research, especially in relation to rock magnetism.

Convincing new evidence about polar wandering came from the study of rock magnetism. Wegener's work dealt with the wandering of the earth's *geographic* poles of rotation. The earth's *magnetic* poles are located close to the geographic poles, as you saw in the chapter on the earth's interior. Historical measurements show that the position of the magnetic poles moves from year to year, but that the magnetic poles stay close to the geographic poles as they move. As we discuss magnetic evidence for polar wandering, we are referring to an apparent motion of the magnetic poles. Because the magnetic and geographic poles are close together, our discussion will refer to apparent motion of the geographic poles as well.

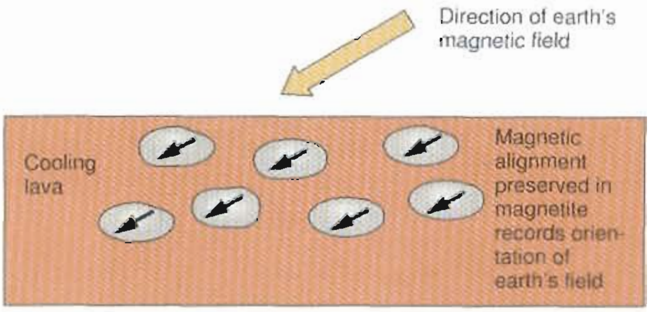
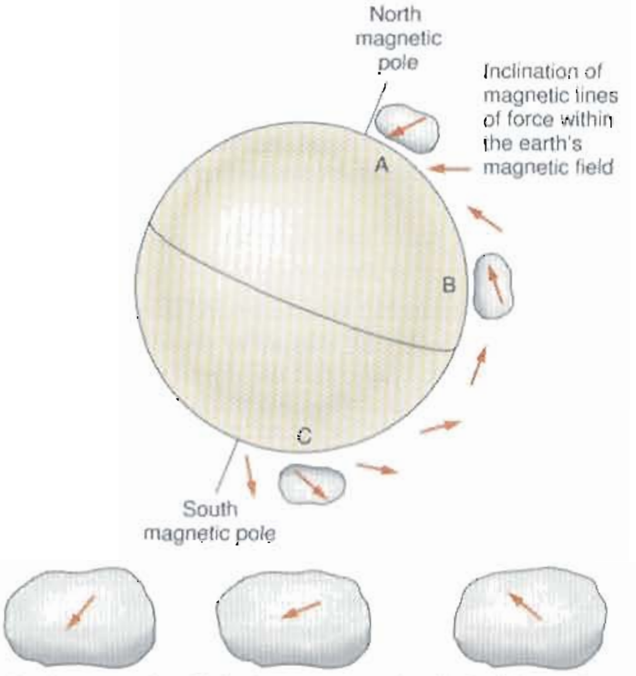


Figure 4.7

Some rocks preserve a record of the earth's magnetic field.



A Rock near north magnetic pole **B** Rock near equator in northern hemisphere **C** Rock in southern hemisphere

Figure 4.8

Magnetic dip (inclination) increases toward the north magnetic pole. Rocks in bottom part of figure are small samples viewed horizontally at locations A, B, and C on the globe. The magnetic dip can therefore be used to determine the distance from a rock to the north magnetic pole.

As we discussed in chapter 2, many rocks record the strength and direction of the earth's magnetic field at the time the rocks formed. Magnetite in a cooling basaltic lava flow acts like a tiny compass needle, preserving a record of the earth's magnetic field when the lava cools below the *Curie point* (figure 4.7). Iron-stained sedimentary rocks such as red sandstone can also record earth magnetism. The magnetism of old rocks can be measured to determine the direction and strength of the earth's magnetic field in the past. The study of ancient magnetic fields is called *paleomagnetism.*

Because magnetic lines of force dip more steeply as the north magnetic pole is approached, the inclination (dip) of the magnetic alignment preserved in the magnetite minerals in the lava flows can be used to determine the distance from a flow to the pole at the time that the flow formed (figure 4.8).

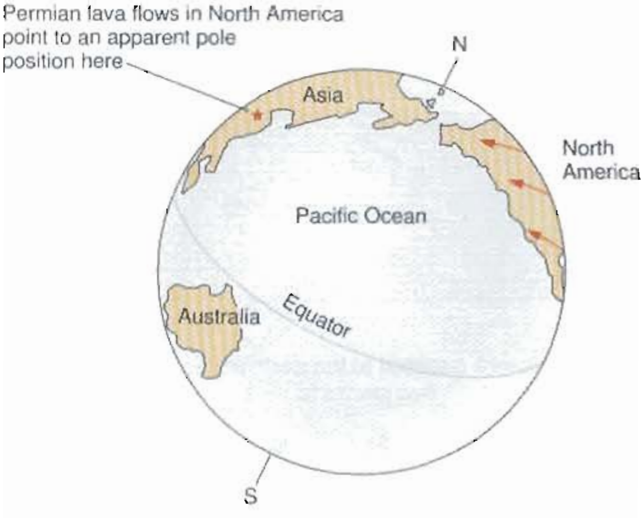


Figure 4.9

Paleomagnetic studies of Permian lava flows on North America indicate an apparent position for the north magnetic pole in eastern Asia.

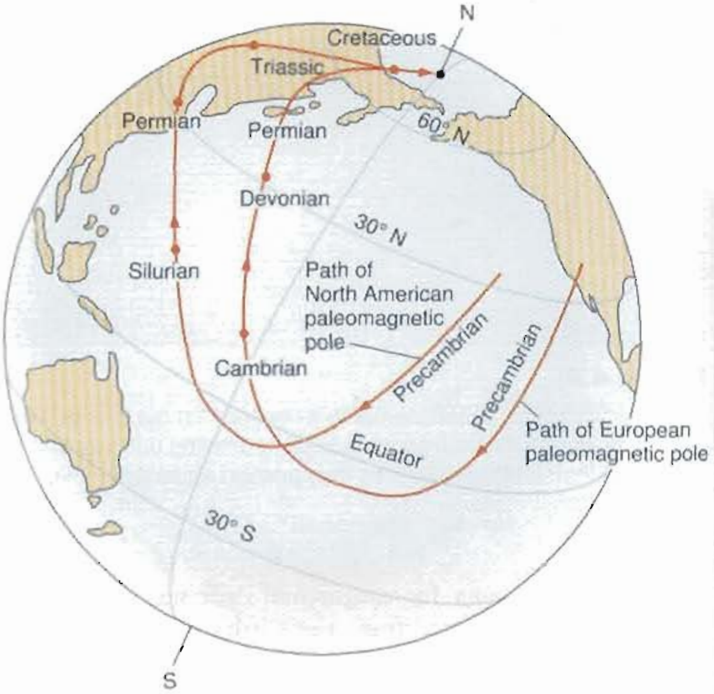


Figure 4.10

Polar wandering of the north magnetic pole as determined from measurements of rocks from North America and Europe.

From A. Cox and R. R. Doell, 1960, *Geological Society of America Bulletin*.

Old pole positions can be determined from the magnetism of old rocks. The magnetic alignment preserved in magnetite minerals points to the pole, and the dip of the alignment tells how far away the pole was. Figure 4.9 shows how Permian lava flows in North America indicate a Permian pole position in eastern Asia.

For each geologic period, North American rocks reveal a different magnetic pole position; this path of the *apparent* motion of the north magnetic pole through time is shown in figure 4.10. Paleomagnetic evidence thus verifies Wegener's idea of polar wandering (which he based on paleoclimatic evidence).

Like Wegener's paleoclimatic evidence, the paleomagnetic evidence from a *single* continent can be interpreted in two ways: either the continent stood still and the magnetic pole moved or the pole stood still and the continent moved. At first glance, paleomagnetic evidence does not seem to be a significant advance over paleoclimatic evidence. But when paleomagnetic evidence from *different* continents was compared, an important discovery was made.

Although Permian rocks in North America point to a pole position in eastern Asia, Permian rocks in *Europe* point to a different position (closer to Japan), as shown in figure 4.10. Does this mean there were *two* north magnetic poles in the Permian Period? In fact, every continent shows a different position for the Permian pole. A different magnetic pole for each continent seems highly unlikely. A better explanation is that a single pole stood still while continents split apart and rotated as they diverged.

Note the polar wandering paths for North America and Europe in figure 4.10. The paths are of similar shape, but the path for European poles is to the east of the North American path. If we mentally push North America back toward Europe, closing the Atlantic Ocean, and then consider the paths of polar wandering, we find that the path for North America lies exactly on the path for Europe. This strongly suggests that there was one north magnetic pole and that the continents were joined together. There appear to be two north magnetic poles because the rocks of North America moved west; their magnetic minerals now point to a different position than they did when the minerals first formed.

Recent Evidence for Continental Drift

As paleomagnetic evidence revived interest in continental drift, new work was done on fitting continents together. By defining

Figure 4.11

Jigsaw puzzle fit and matching rock types between South America and Africa. Light-blue areas around continents are continental shelves (part of continents). Colored areas within continents are broad belts of rock that correlate in type and age from one continent to another. Arrows show direction of glacier movement as determined from striations.

the edge of a continent as the middle of the continental slope, rather than the present (*constantly changing*) shoreline, a much more precise fit has been found between continents (figure 4.11).

The most convincing evidence for continental drift came from greatly refined rock matches between now-separated continents. If continents are fitted together like pieces of a jigsaw puzzle, the "picture" should match from piece to piece.

The matches between South America and Africa are particularly striking. Some distinctive rock contacts extend out to sea along the shore of Africa. If the two continents are fitted together, the identical contacts are found in precisely the right position on the shore of South America (figure 4.11). Isotopic ages of rocks also match between these continents.

Glacial striations show that during the late Paleozoic Era continental glaciers moved from Africa toward the present Atlantic Ocean, while similar glaciers seemingly moved *from* the Atlantic Ocean *onto* South America (figure 4.11). Continental glaciers, however, cannot move from sea onto land. If the two continents had been joined together, the ice that moved off Africa could have been the ice that moved onto South America. This hypothesis has now been confirmed; from their lithology, many of the boulders in South American tills have been traced to a source that is now in Africa.

Some of the most detailed matches have been made between rocks in Brazil and rocks in the African country of Gabon. These rocks are similar in type, structure, sequence, fossils, ages, and degree of metamorphism. Such detailed matches are convincing evidence that continental drift did, in fact, take place.

History of Continental Positions

Rock matches show when continents were together; once the continents split, the new rocks formed are dissimilar. Paleomagnetic evidence indicates the direction and rate of drift, allowing maps of old continental positions, such as figure 4.2, to be drawn.

Although Pangaea split up 200 million years ago to form our present continents, the continents were moving much earlier. Pangaea was formed by the collision of many small continents long before it split up. Recent work shows that continents have been in motion for the past 2 billion years (some geologists say 4 billion years), well back into Precambrian time. For half or more of earth's history, the continents appear to have collided, welded together, then split and drifted apart, only to collide again, over and over, in an endless, slow dance.

Sea-Floor Spreading

At the same time that many geologists were becoming interested again in the idea of moving *continents*, Harry Hess, a geologist at Princeton University, proposed that the *sea floor* might be moving, too. This proposal contrasted sharply with the earlier ideas of Wegener, who thought that the ocean floor remained stationary as the continents plowed through it (figure 4.6). Hess's 1962 proposal was quickly named sea-floor spreading, for it suggests that the sea floor moves away from the mid-oceanic ridge as a result of mantle convection (figure 4.12).

According to the concept of sea-floor spreading, the sea floor is moving like a conveyor belt away from the crest of the mid-oceanic ridge, down the flanks of the ridge, and across the deep-ocean basin, to disappear finally by plunging beneath a

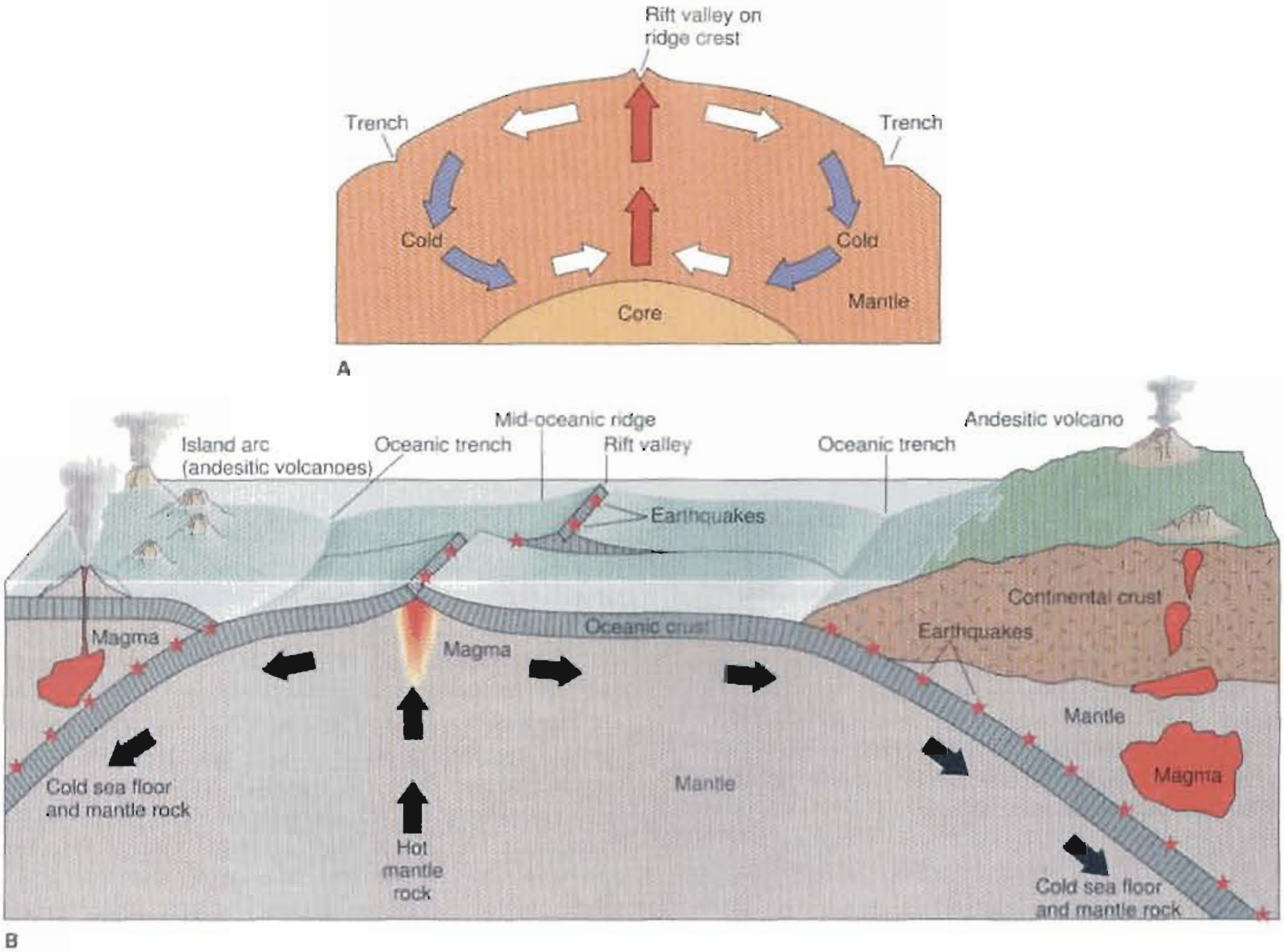


Figure 4.12

Sea-floor spreading. (*A*) Hess proposed that convection extended throughout the mantle. (Scale of ridge and trenches is exaggerated.) (*B*) Hot mantle rock rising beneath the mid-oceanic ridge (a spreading axis) causes basaltic volcanism and high heat flow. Divergence of sea floor splits open the rift valley and causes shallow-focus earthquakes (stars on ridge). Sinking of cold rock causes subduction of older sea floor at trenches, producing Benioff zones of earthquakes and andesitic magma.

continent or island arc (figure 4.12). The ridge crest, with sea floor moving away from it on either side, has been called a *spreading axis* (or *spreading center*). The sliding of the sea floor beneath a continent or island arc is termed **subduction.** The sea floor moves at a rate of 1 to 6 centimeters per year (your fingernail grows at about 1 cm/year). Although this may seem to be quite slow, it is rapid compared to most geologic processes.

Hess's Driving Force

Why does the sea floor move? Hess's original hypothesis was that sea-floor spreading is driven by deep mantle convection. **Convection** is a circulation pattern driven by the rising of hot material and/or the sinking of cold material. Hot material has a low density, so it rises; cold material has a high density and sinks. The circulation of water heating in a pan on a stove is an example of convection. Convection in the mantle was a controversial idea in 1962; for although convection can be easily demonstrated in a pan of water, it was hard to visualize the solid rock of the earth's mantle behaving as a liquid. Over very long periods of time, however, it is possible for the hot mantle rock to flow plastically. A slow convective circulation is set up by temperature differences in the rock, and convection can explain many sea-floor features as well as the young age of the sea-floor rocks. (The heat that flows outward through the earth to drive convection is both original heat from the earth's formation and heat from the decay of radioactive isotopes, as discussed in chapter 2.)

Explanations

The Mid-Oceanic Ridge

If convection drives sea-floor spreading, then hot mantle rock must be rising under the mid-oceanic ridge. Hess showed how the *existence of the ridge* and its *high heat flow* are caused by the rise of this hot mantle rock. The *basalt eruptions* on the ridge crest are also related to this rising rock, for here the mantle rock is hotter than normal and therefore close to its melting point.

As hot rock continues to rise beneath the ridge crest, the circulation pattern splits and diverges near the surface. Mantle rock moves horizontally away from the ridge crest on each side of the ridge. This movement creates tension at the ridge crest, cracking open the oceanic crust to form the *rift valley* and its associated *shallow-focus earthquakes*.

Oceanic Trenches

As the mantle rock moves horizontally away from the ridge crest, it carries the sea floor (the basaltic oceanic crust) piggyback along with it. As the hot rock moves sideways, it cools and becomes denser, sinking deeper beneath the ocean surface. Hess thought it would become cold and dense enough to sink back into the mantle. This downward plunge of cold rock accounts for the *existence of the oceanic trenches* as well as their *low heat flow* values. It also explains the large *negative gravity anomalies* associated with trenches, for the sinking of the cold rock provides a force that holds trenches out of isostatic equilibrium (see chapter 2).

As the sea floor moves downward into the mantle along a subduction zone, it interacts with the stationary rock above it. This interaction between the moving sea-floor rock and the stationary rock can cause the *Benioff zones of earthquakes* associated with trenches. It can also produce *andesitic volcanism*, which forms volcanoes either on the edge of a continent or in an island arc (figure 4.12).

Hess's ideas have stood up remarkably well over more than 30 years. We now think of plates moving instead of sea floor riding piggyback on convecting mantle, and we think that several mechanisms cause plate motion, but Hess's explanation of sea-floor topography, earthquakes, and age remain valid today.

Age of the Sea Floor

The *young age of sea-floor rocks* (see the previous chapter) is neatly explained by Hess's sea-floor spreading. New, young sea floor is continually being formed by basalt eruptions at the ridge crest. This basalt is then carried sideways by convection and is subducted into the mantle at an oceanic trench. Thus old sea floor is continually being destroyed at trenches, while new sea floor is being formed at the ridge crest. (This is also the reason for the puzzling lack of pelagic sediment at the ridge crest. Young sea floor at the ridge crest has little sediment because the basalt is newly formed. Older sea floor farther from the ridge crest has been moving under a constant rain of pelagic sediment, building up a progressively thicker layer as it goes.)

Note that sea-floor spreading implies that the youngest sea floor should be at the ridge crest, with the age of the sea floor becoming progressively older toward a trench. This increase in age away from the ridge crest was not known to exist at the time of Hess's proposal but was an important prediction of his hypothesis. This prediction has been successfully tested, as you shall see later in this chapter when we discuss marine magnetic anomalies.

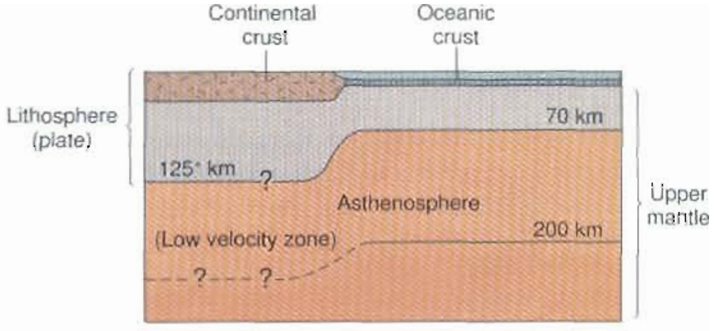


Figure 4.13

The rigid lithosphere includes the crust and uppermost mantle; it forms the plates. The plastic asthenosphere acts as a lubricating layer beneath the lithosphere. Oceanic lithosphere averages 70 kilometers thick; continental lithosphere varies from 125 to 250 kilometers thick. Asthenosphere may not be present under continents.

Plates and Plate Motion

By the mid-1960s the twin ideas of moving continents and a moving sea floor were causing great excitement and emotional debate among geologists. By the late 1960s, these ideas had been combined into a single theory that revolutionized geology by providing a unifying framework for earth science—the theory of plate tectonics.

As described earlier, a **plate** is a large, mobile slab of rock that is part of the earth's surface (figure 4.1). The surface of a plate may be made up entirely of sea floor (as is the Nazca plate), or it may be made up of both continental and oceanic rock (as is the North American plate). Some of the smaller plates are entirely continental, but all the large plates contain some sea floor.

Plate tectonics has added some new terms, based on rock behavior, to the zones of the earth's interior, as we have discussed in some previous chapters. The plates are part of a relatively rigid outer shell of the earth called the **lithosphere.** The lithosphere includes the rocks of the earth's crust and uppermost mantle (figure 4.13).

The lithosphere beneath oceans increases in both age and thickness with distance from the crest of the mid-oceanic ridge. Young lithosphere near the ridge crest may be only 10 kilometers thick, while very old lithosphere far from the ridge crest may be as much as 100 kilometers thick. An average thickness for oceanic lithosphere might be 70 kilometers, as shown in figure 4.13.

Continental lithosphere is thicker, varying from perhaps 125 kilometers thick to as much as 200 to 250 kilometers thick beneath the oldest, coldest, and most inactive parts of the continents.

Below the rigid lithosphere is the **asthenosphere,** a zone of low seismic-wave velocity that behaves plastically because of increased temperature and pressure. Some geologists think that the asthenosphere is partially molten; the melting of just a few percent of the asthenosphere's volume could account for its properties and behavior. The plastic asthenosphere acts as a lubricating layer under the lithosphere, allowing the plates to move. The asthenosphere, made up of upper mantle rock, is the low-velocity zone described in chapter 2. It may extend from a depth of 70 to 200 kilometers beneath oceans; its thickness, depth, and even existence under continents is vigorously debated. Below the asthenosphere is more rigid mantle rock.

The idea that plates move is widely accepted by geologists, although the reasons for this movement are debated. Plates move away from the mid-oceanic ridge crest or other spreading axes. Some plates move toward oceanic trenches. If the plate is made up mostly of sea floor (as are the Nazca and Pacific plates), the plate can be subducted down into the mantle, forming an oceanic trench and its associated features. If the leading edge of the plate is made up of continental rock (as is the South American plate), that plate will not subduct. Continental rock, being less dense (specific gravity 2.7) than oceanic rock (specific gravity 3.0), is too light to be subducted.

A plate is a rigid slab of rock that moves as a unit. As a result, the interior of a plate is relatively inactive tectonically. Plate interiors generally lack earthquakes, volcanoes, young mountain belts, and other signs of geologic activity. According to plate-tectonic theory, these features are caused by plate interactions at plate boundaries.

Earthquakes, volcanoes, and young mountains are distributed in narrow belts separated by broad regions of inactivity, as you have seen in previous chapters. This distribution puzzled geologists for a long time, and many hypotheses were advanced to explain it. The plate-tectonic concept is the latest explanation. Plate boundaries are defined and located by mapping narrow belts of earthquakes, volcanoes, and young mountains. The plates themselves are the broad, inactive regions outlined by these belts of geologic activity.

Plate tectonics has become a unifying theory of geology because it can explain so many diverse features of the earth. Earthquake distribution, the origin of mountain belts, the origin of sea-floor topography, the distribution and composition of volcanoes, and many other features can all be related to plate tectonics. It is a convenient framework that unifies geologic thought, associating features that were once studied separately and relating them to a single cause: plate interactions at plate boundaries.

Plate boundaries are of three general types, based on whether the plates move away from each other, move toward each other, or move past each other. A **divergent plate boundary** is a boundary between plates that are moving apart. A **convergent plate boundary** lies between plates that are moving toward each other. A **transform plate boundary** is one at which two plates move horizontally past each other.

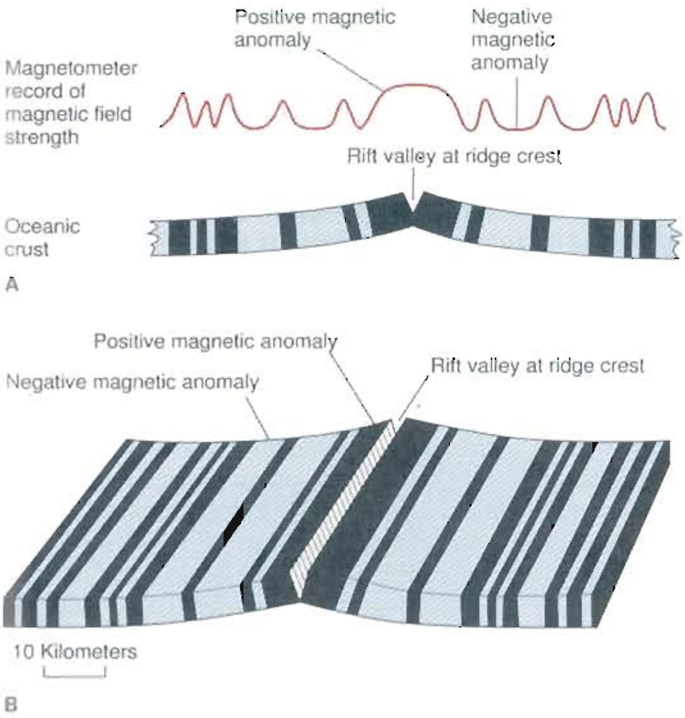


Figure 4.14

Marine magnetic anomalies. (*A*) The red line shows positive and negative magnetic anomalies as recorded by a magnetometer towed behind a ship. In the cross section of oceanic crust, positive anomalies are drawn as black bars and negative anomalies are drawn as blue bars. (*B*) Perspective view of magnetic anomalies shows that they are parallel to the rift valley and symmetric about the ridge crest.

How Do We Know That Plates Move?

The proposal that the earth's surface is divided into moving plates was an exciting, revolutionary hypothesis, but it required testing to win acceptance among geologists. You have seen how the study of paleomagnetism supports the idea of moving continents. In the 1960s two critical tests were made of the idea of a moving sea floor. These tests involved marine magnetic anomalies and the seismicity of fracture zones. These two, successful tests convinced most geologists that plates do indeed move.

Marine Magnetic Anomalies

In the mid-1960s, magnetometer surveys at sea disclosed some intriguing characteristics of marine magnetic anomalies. Most magnetic anomalies at sea are arranged in bands that lie parallel to the rift valley of the mid-oceanic ridge. Alternating positive and negative anomalies (chapter 2) form a stripelike pattern parallel to the ridge crest (figure 4.14).

The Vine-Matthews Hypothesis

Two British geologists, Fred Vine and Drummond Matthews, made several important observations about these anomalies.

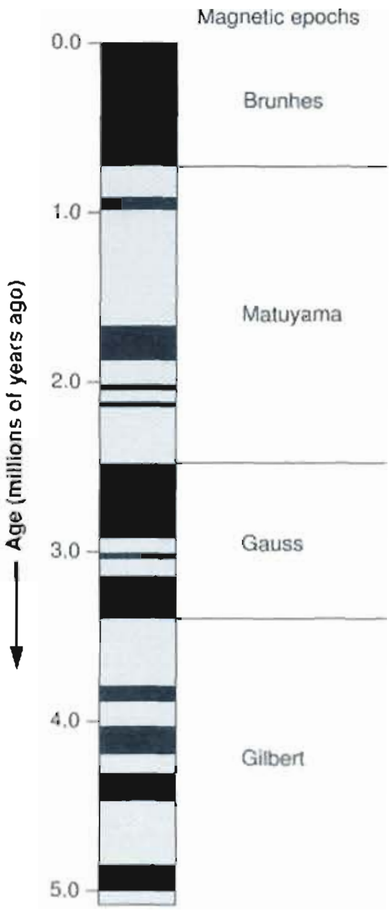


Figure 4.15

Magnetic reversals during the past 5 million years. Black represents normal magnetism; blue represents reverse magnetism.

From Robert Butler, 1992, *Paleomagnetism*, Blackwell Scientific Publications, p. 212.

They recognized that the pattern of magnetic anomalies was symmetrical about the ridge crest. That is, the pattern of magnetic anomalies on one side of the mid-oceanic ridge was a mirror image of the pattern on the other side (figure 4.14). Vine and Matthews also noticed that the same pattern of magnetic anomalies exists over different parts of the mid-oceanic ridge. The pattern of anomalies over the ridge in the northern Atlantic Ocean is the same as the pattern over the ridge in the southern Pacific Ocean.

The most important observation that Vine and Matthews made was that the pattern of magnetic *anomalies* at sea matches the pattern of magnetic *reversals* already known from studies of lava flows on the continents (figure 4.15 and chapter 2). This correlation can be seen by comparing the pattern of colored bands in figure 4.15 (reversals) with the pattern in figure 4.14 (anomalies).

Putting these observations together with Hess's concept of sea-floor spreading, which had just been published, Vine and Matthews proposed an explanation for magnetic anomalies.

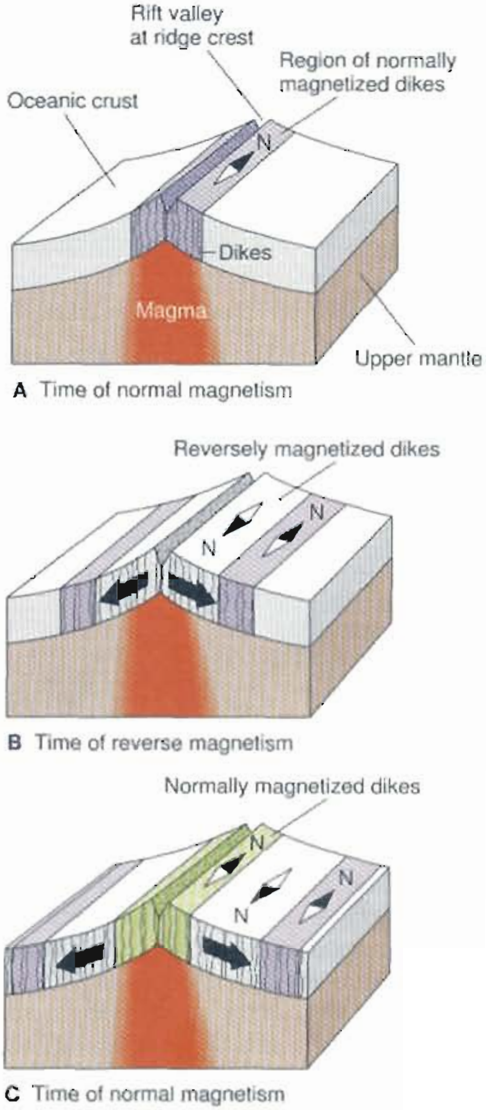


Figure 4.16

The origin of magnetic anomalies. (*A*) During a time of normal magnetism, a series of basaltic dikes intrudes the ridge crest, becoming normally magnetized. (*B*) The dike zone is torn in half and moved sideways, as a new group of reversely magnetized dikes forms at the ridge crest. (*C*) A new series of normally-magnetized dikes forms at the ridge crest. The dike pattern becomes symmetric about the ridge crest.

They suggested that there is continual opening of tensional cracks within the rift valley on the mid-oceanic ridge crest. These cracks on the ridge crest are filled by basaltic magma from below, which cools to form dikes. Cooling magma in the dikes records the earth's magnetism at the time the magnetic minerals crystallize. The process is shown in figure 4.16.

When the earth's magnetic field has a *normal polarity* (the present orientation), cooling dikes are normally magnetized. Dikes that cool when the earth's field is reversed (figure 4.16) are reversely magnetized. So each dike preserves a record of the polarity that prevailed during the time the magma cooled. Extension produced by the moving sea floor then cracks a dike in two, and

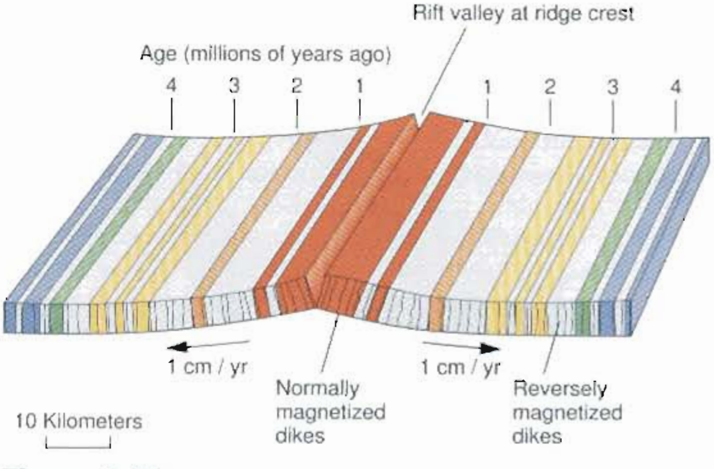


Figure 4.17

Correlation of magnetic anomalies with magnetic reversals allows anomalies to be dated. Magnetic anomalies can therefore be used to predict the age of the sea floor and to measure the rate of sea-floor spreading (plate motion).

the two halves are carried away in opposite directions down the flanks of the ridge. New magma eventually intrudes the newly opened fracture. It cools, is magnetized, and forms a new dike, which in turn is split by continued extension. In this way a system of reversely magnetized and normally magnetized dikes forms parallel to the rift valley. These dikes, in the Vine-Matthews hypothesis, are the cause of the anomalies.

The magnetism of normally magnetized dikes adds to the earth's magnetism, and so a magnetometer carried over such dikes registers a stronger magnetism than average—a *positive* magnetic anomaly. Dikes that are reversely magnetized subtract from the present magnetic field of the earth, and so a magnetometer towed over such dikes measures a weaker magnetic field—a *negative* magnetic anomaly. Since sea-floor motion separates these dikes into halves, the patterns on either side of the ridge are mirror images.

Measuring the Rate of Plate Motion

There are two important points about the Vine-Matthews hypothesis of magnetic anomaly origin. The first is that it allows us to measure the *rate of sea-floor motion* (which is the same as plate motion, since continents and the sea floor move together as plates).

Because magnetic reversals have already been dated from lava flows on land (figure 4.15), the anomalies caused by these reversals are also dated and can be used to discover how fast the sea floor has moved (figure 4.17). For instance, a piece of the sea floor representing the reversal that occurred 4.5 million years ago may be found 45 kilometers away from the rift valley of the ridge crest. The piece of sea floor, then, has traveled 45 kilometers since it formed 4.5 million years ago. Dividing the distance the sea floor has moved by its age gives 10 km/million years, or 1 cm/year for the rate of sea-floor motion here. In other words, on each side of the ridge, the sea floor is moving away from the ridge crest at a rate of 1 centimeter per year. Such measured rates generally range from 1 to 6 centimeters per year.

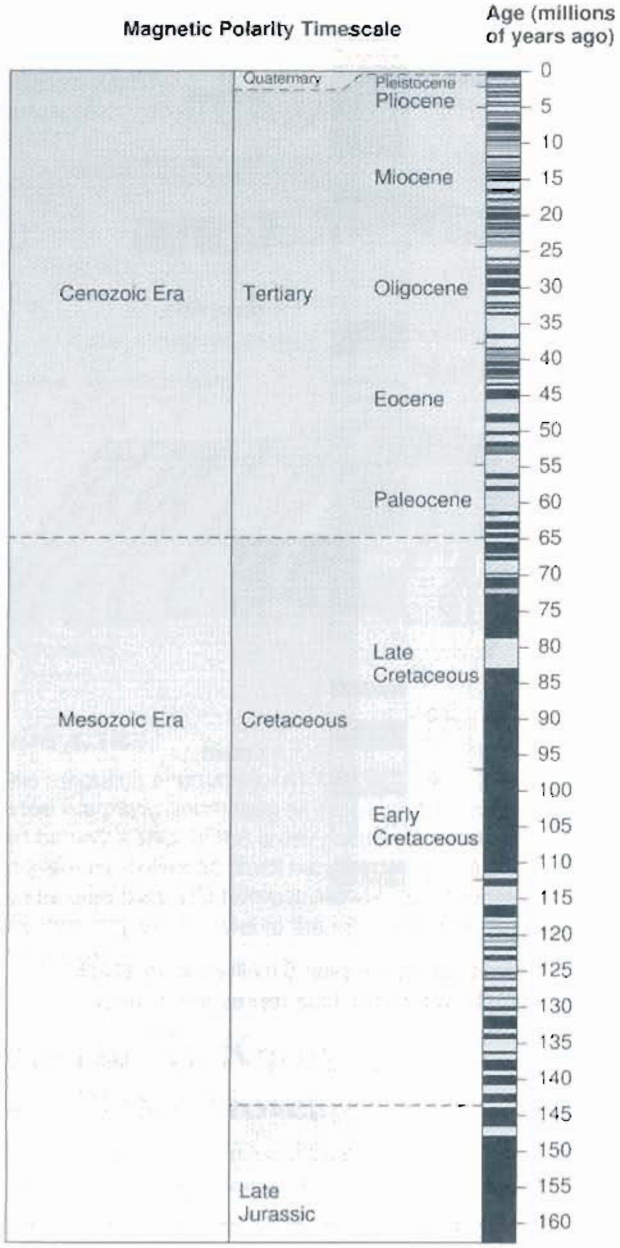


Figure 4.18

Marine magnetic anomaly pattern from the Cenozoic and Mesozoic Eras. Black indicates positive anomalies (and therefore normal polarity). Blue indicates negative anomalies (reverse polarity).

Modified from R. L. Larson and W. C. Pitman, III, 1972, *Geological Society of America Bulletin*.

Predicting Sea-Floor Age

The other important point of the Vine-Matthews hypothesis is that it *predicts the age of the sea floor* (figure 4.17). Magnetic reversals are now known to have occurred back into Precambrian time. Sea floor of *all* ages is therefore characterized by parallel bands of magnetic anomalies. Figure 4.18 shows the

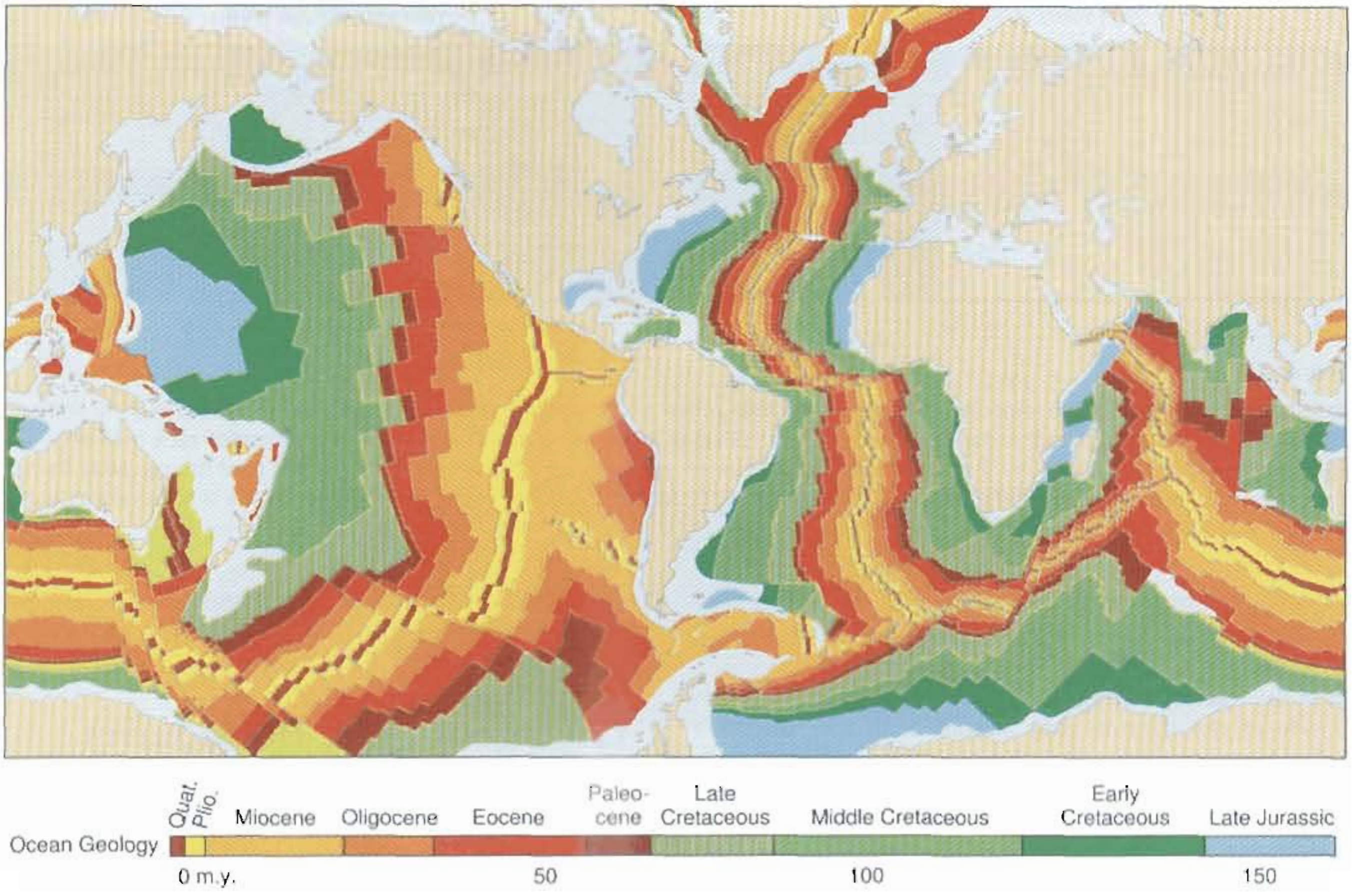


Figure 4.19

The age of the sea floor as determined from magnetic anomalies.

After *The Bedrock Geology of the World* by R. L. Larson, W. C. Pitman, III, et al. W. H. Freeman

pattern of marine magnetic anomalies (and the reversals that caused them) during the past 160 million years. The distinctive pattern of these anomalies through time allows them to be identified by age, a process similar to dating by tree rings.

Now, even before they sample the sea floor, marine geologists can predict the age of the igneous rock of the sea floor by measuring the magnetic anomalies at the sea surface. Most sections of the sea floor have magnetic anomalies. By matching the measured anomaly pattern with the known pattern that is shown in figure 4.18, the age of the sea floor in the region can be predicted, as shown on the map in figure 4.19.

This is a very powerful test of the hypothesis that the sea floor moves. Suppose, for example, that the sea floor in a particular spot is predicted to be 70 million years old from a study of its magnetic anomalies. If the hypothesis of sea-floor motion and the Vine-Matthews hypothesis of magnetic anomaly origin are correct, a sample of igneous rock from that spot *must* be 70 million years old. If the rock proves to be 10 million years old or 200 million years old or 1.2 billion years old, or any other age except 70 million years, then both these hypotheses are wrong. But if the rock proves to be 70 million years old, as predicted, then both hypotheses have been successfully tested.

Hundreds of rock and sediment cores recovered from holes drilled in the sea floor were used to test these hypotheses. Close correspondence has generally been found between the predicted age and the measured age of the sea floor. (The sea-floor age is usually measured by fossil dating of sediment in the cores rather than by isotopic dating of igneous rock.) This evidence from deep-sea drilling has been widely accepted by geologists as verification of the hypotheses of plate motion and magnetic anomaly origin. Most geologists now think that these concepts are no longer hypotheses but can now be called theories. (A *theory*, as discussed in Box 1.3 in connection with the scientific method, is a concept with a much higher degree of certainty than a hypothesis.)

Another Test: Fracture Zones and Transform Faults

Deep-sea drilling tested plate motion by allowing us to compare the actual age of the sea floor with the age predicted from magnetic anomalies. Another rigorous test of plate motion has been made by studying the seismicity of fracture zones.

The mid-oceanic ridge is offset along fracture zones (see figure 3.18). Conceivably, the mid-oceanic ridge was once continuous across a fracture zone but has been offset by strike-slip

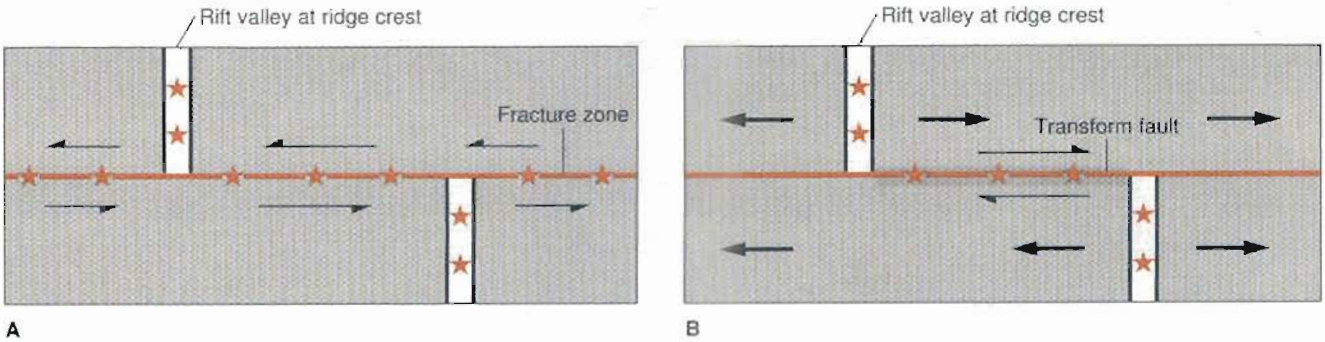


Figure 4.20

Two possible explanations for the relationship between fracture zones and the mid-oceanic ridge. (*A*) The expected rock motions and earthquake distribution assuming that the ridge was once continuous across the fracture zone. (*B*) The expected rock motions and earthquake distribution assuming that the two ridge segments were never joined together and that the sea floor moves away from the rift valley segments. Only explanation *B* fits the data. The portion of the fracture zone between the ridge segments is a transform fault.

motion along the fracture zone (figure 4.20*A*). If such motion is occurring along a fracture zone, we would expect to find two things: (1) earthquakes should be distributed along the entire length of the fracture zone, and (2) the motion of the rocks on either side of the fracture zone should be in the direction shown by the arrows in figure 4.20*A*.

In fact, these things are not true about fracture zones. Earthquakes do occur along fracture zones, but only in those segments between offset sections of ridge crest. In addition, first-motion studies of earthquakes (see chapter 7) along fracture zones show that the motion of the rocks on either side of the fracture zone during an earthquake is exactly opposite to the motion shown in figure 4.20*A*. The actual motion of the rocks as determined from first-motion studies is shown in figure 4.20*B*. The portion of a fracture zone between two offset portions of ridge crest is called a **transform fault.**

The motion of rocks on either side of a transform fault was predicted by the hypothesis of a moving sea floor. Note that sea floor moves away from the two segments of ridge crest (figure 4.20*B*). Looking along the length of the fracture zone, you can see that blocks of rock move in opposite directions only on that section of the fracture zone between the two segments of ridge crest. Earthquakes, therefore, occur only on this section of the fracture zone, the transform fault. The direction of motion of rock on either side of the transform fault is exactly predicted by the assumption that rock is moving away from the ridge crests. Verification by first-motion studies of this predicted motion along fracture zones was another successful test of plate motion.

Measuring Plate Motion Directly

In recent years the motion of plates has been directly measured using satellites, radar, lasers, and the Global Positioning System. These techniques can measure the distance between two widely separated points to within one centimeter. If two plates move toward each other at individual rates of 2 cm/year and 6 cm/year, the combined rate of convergence is 8 cm/year. The measurement techniques are sensitive enough to easily measure such a rate if measurements are repeated each year. Such measured rates match closely the predicted rates from magnetic anomalies.

Divergent Plate Boundaries

Divergent plate boundaries, where plates move away from each other, can occur in the middle of the ocean or in the middle of a continent. The result of divergent plate boundaries is to create, or open, new ocean basins. This dynamic process has occurred throughout the geologic past.

When a supercontinent such as Pangaea breaks up, a divergent boundary can be found in the middle of a continent. The divergent boundary is marked by rifting, basaltic volcanism, and uplift. During rifting, the continental crust is stretched and thinned. This extension produces shallow-focus earthquakes on normal faults, and a rift valley forms as a central *graben* (a down-dropped fault block). The faults act as pathways for basaltic magma, which rises from the mantle to erupt on the surface as cinder cones and basalt flows. Uplift at a divergent boundary is usually caused by the upwelling of hot mantle beneath the crust; the surface is elevated by the thermal expansion of the hot, rising rock and of the surface rock as it is warmed from below.

There is current debate on the sequence of events as continents split. Some geologists think that rifting comes first (figure 4.21). The thinning of cold crust would reduce pressure on

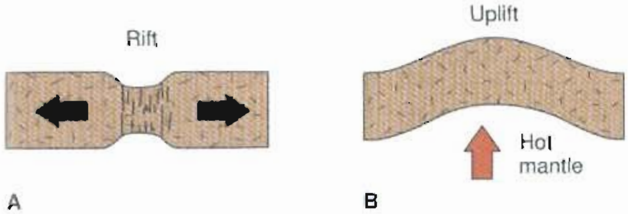
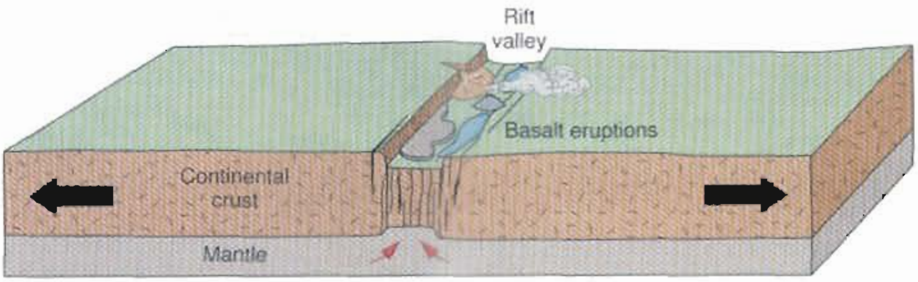
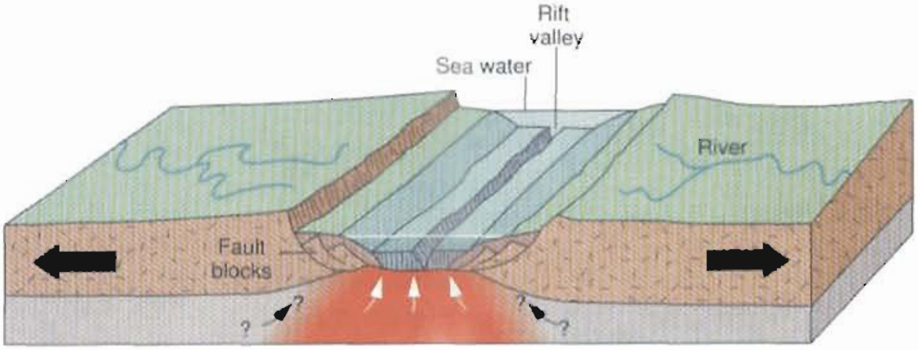


Figure 4.21

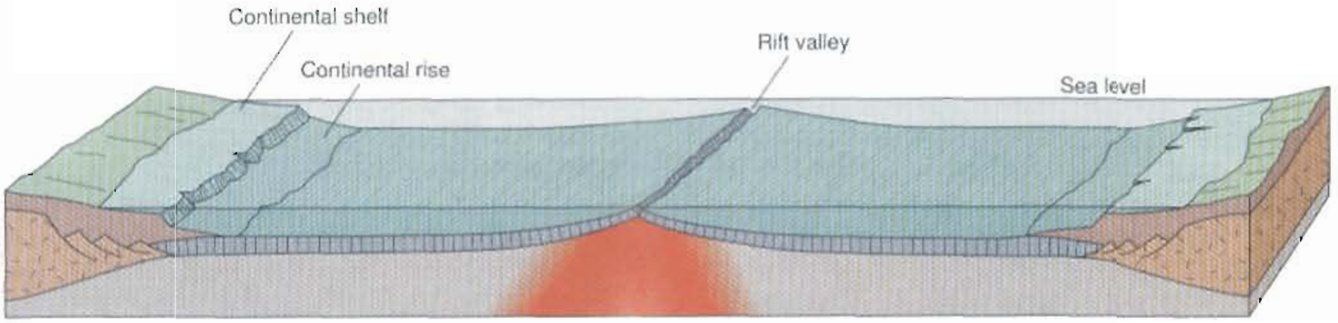
Two models of the beginning of continental divergence. (*A*) Rifting comes first; uplift may follow. (*B*) Uplift comes first; rifting may follow.



A Continent undergoes extension. The crust is thinned and a rift valley forms (East African Rift Valleys).



B Continent tears in two. Continent edges are faulted and uplifted. Basalt eruptions form oceanic crust (Red Sea).



C Continental sediments blanket the subsiding margins to form continental shelves and rises. The ocean widens and a mid-oceanic ridge develops (Atlantic Ocean).

Figure 4.22

A divergent plate boundary forming in the middle of a continent will eventually create a new ocean.

the underlying rock and allow hot mantle rock to rise passively, elevating the land by thermal expansion; in this case rifting *causes* uplift. Other geologists believe that thermal uplift comes first as hot mantle rock rises actively under uniformly thick crust. As the uplifted crust is stretched, rifting occurs; in this case rifting is the *result* of uplift.

Figure 4.22 shows how a continent might rift to form an ocean. The figure shows rifting before uplift, because recent work indicates that this was the sequence for the opening of the Red Sea. The crust is initially stretched and thinned. Numerous normal faults break the crust, and the surface subsides into a central graben (figure 4.22*A*). Shallow earthquakes and basalt eruptions occur in this rift valley, which also has high heat flow. An example of a boundary at this stage is the African Rift Valleys in eastern Africa (figure 4.23). The valleys are grabens that may mark the site of the future breakup of Africa.

As divergence continues, the continental crust on the upper part of the plate clearly separates, and seawater floods into the linear basin between the two divergent continents (figure 4.22*B*). A series of fault blocks have rotated along curved fault planes at the edges of the continents, thinning the continental crust. The rise of hot mantle rock beneath the thinned crust causes continued basalt eruptions that create true oceanic crust between the two continents. The center of the narrow ocean is marked by a rift valley with its typical high heat flow

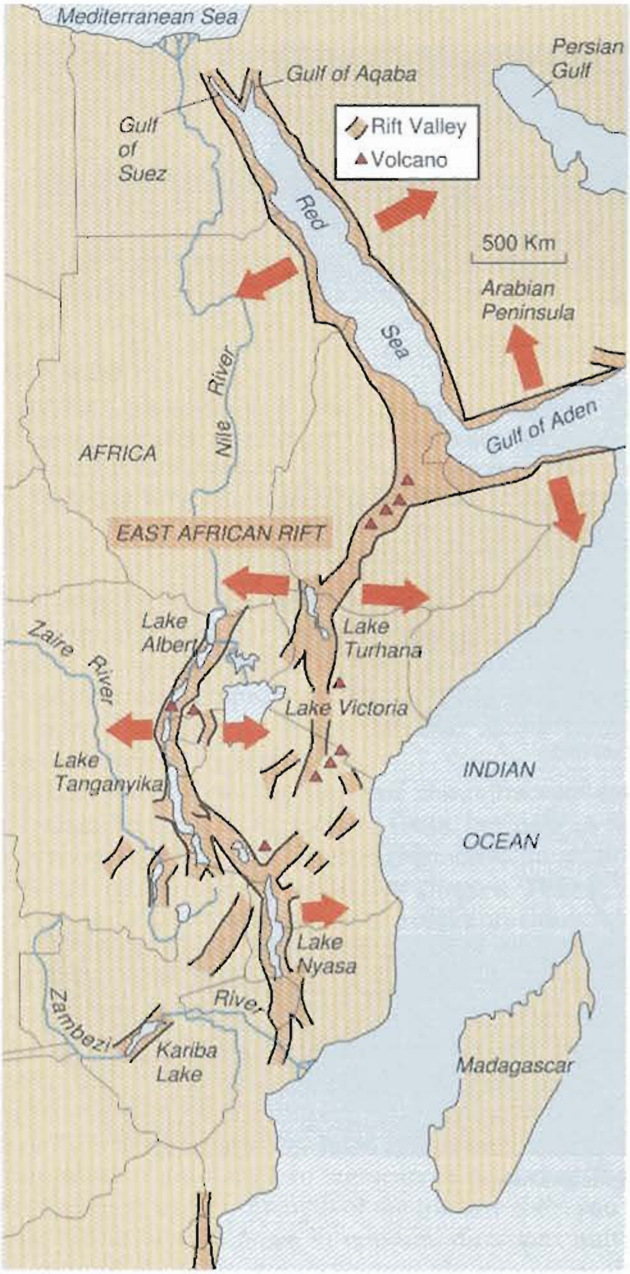


Figure 4.23

The East African Rift Valleys and the Red Sea.

and shallow earthquakes. The Red Sea is an example of a diverging margin at this stage (figures 4.23 and 4.24).

The upward rise of basaltic magma from the mantle to form oceanic crust between two diverging continents is analogous to the rise of water between two floating blocks of wood that are moved apart (figure 4.25).

After modest widening of the new ocean, uplift of the continental edges may occur. As continental crust thins by stretching and faulting, the surface originally subsides. At the same time, hot mantle rock wells up beneath the stretched

Figure 4.24

Spacecraft photograph looking south along the Red Sea. Gulf of Suez at bottom, Gulf of Aqaba at lower left. Note similarities in the shorelines of the Arabian peninsula (left) and Africa (right), suggesting that the Red Sea was formed by splitting of the continent.

Photo by NASA

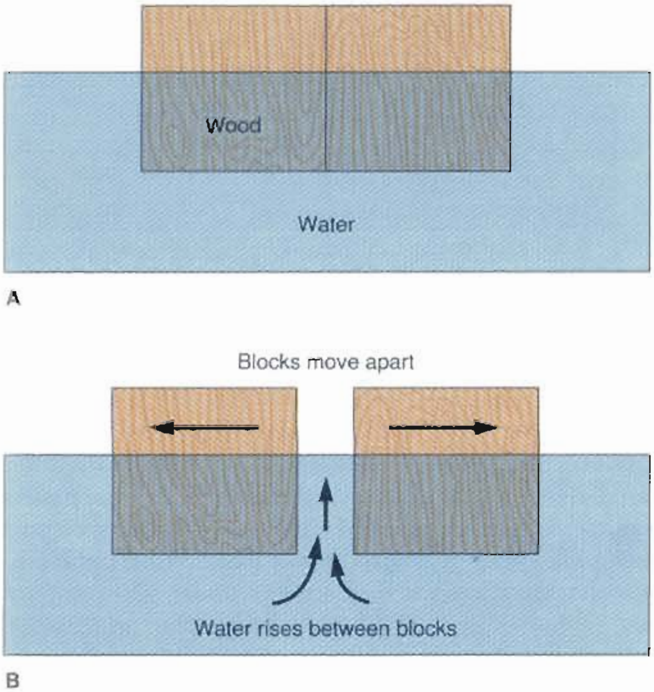


Figure 4.25

Water rises upward to fill the gap when (*A*) two floating blocks are (*B*) moved apart. The water moves as a result of the motion of the blocks.

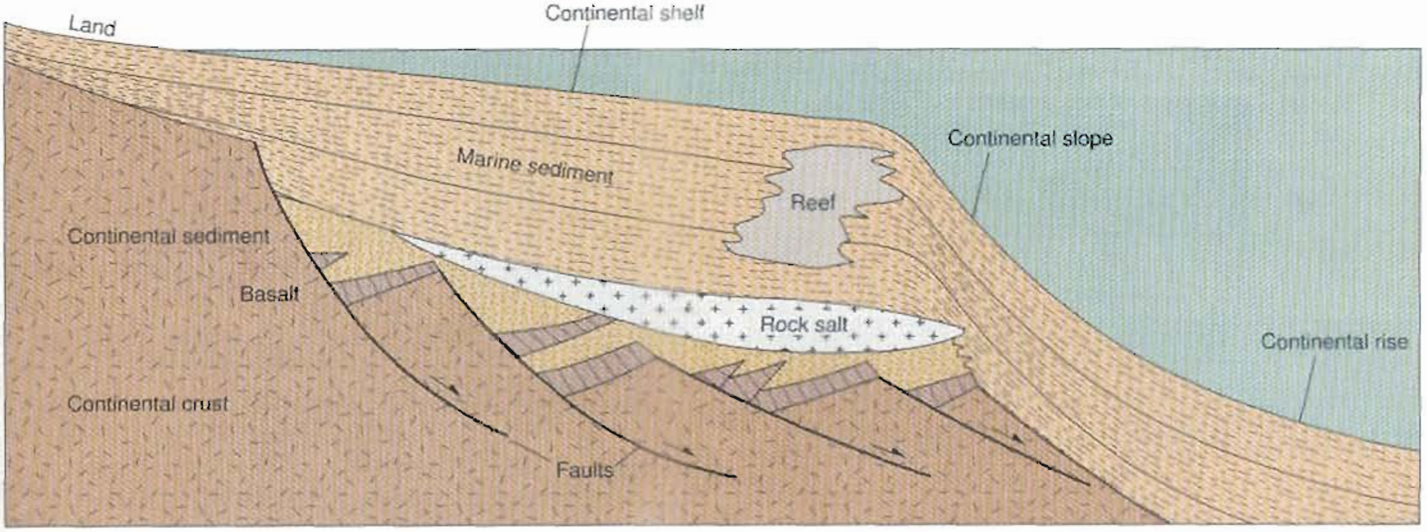


Figure 4.26

A passive continental margin formed by continental breakup and divergence. Downfaulted continental crust forms basins, which fill with basalt and sediment. A layer of rock salt may form if a narrow ocean evaporates. A thick sequence of marine sediments covers these rocks and forms the continental shelf, slope, and rise. A reef may form at the shelf edge if the water is warm; buried reefs occur on many parts of the Atlantic shelf of North America.

crust (figure 4.22*B*). The rising diapir of hot mantle rock would cause uplift by thermal expansion.

The new ocean is narrow, and the tilt of the adjacent land is away from the new sea, so rivers flow away from the sea (figure 4.22*B*). At this stage the seawater that has flooded into the rift may evaporate, leaving behind a thick layer of rock salt overlying the continental sediments. The likelihood of salt precipitation increases if the continent is in one of the desert belts or if one or both ends of the new ocean should become temporarily blocked, perhaps by volcanism. Not all divergent boundaries contain rock salt, however.

The plates continue to diverge, widening the sea. Thermal uplift creates a mid-oceanic ridge in the center of the sea (figure 4.22*C*). The flanks of the ridge subside as the sea-floor rock cools as it moves.

The trailing edges of the continents also subside as they are lowered by erosion and as the hot rock beneath them cools. Subsidence continues until the edges of the continents are under water. A thick sequence of marine sediment blankets the thinned continental rock, forming a *passive continental margin* (figures 4.22*C* and 4.26; see also previous chapter). The sediment forms a shallow continental shelf, which may contain a deeply buried salt layer. The deep continental rise is formed as sediment is carried down the continental slope by turbidity currents and other mechanisms. The Atlantic Ocean is currently at this stage of divergence (figure 3.16).

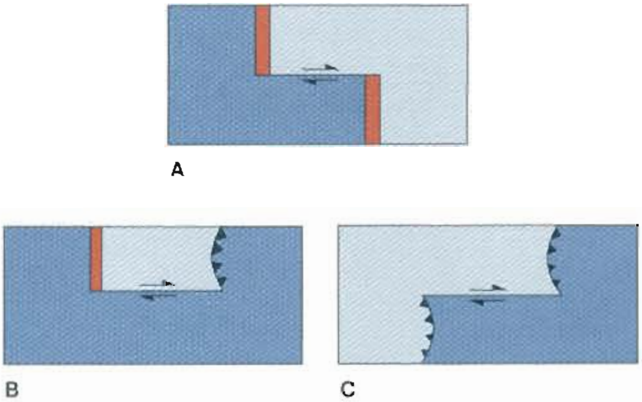
A divergent boundary on the sea floor is located on the crest of the mid-oceanic ridge. If the spreading rate is slow, as it is in the Atlantic Ocean (1 cm/year), the crest has a rift valley. Fast spreading, as in the Pacific Ocean (6 cm/year), prevents a rift from forming. A divergent boundary at sea is marked by the same features as a divergent boundary on land—tensional cracks, normal faults, shallow earthquakes, high heat flow, and basaltic eruptions. The basalt forms dikes within the cracks and pillow lavas on the sea floor, creating new oceanic crust on the trailing edge of plates.

Transform Boundaries

At transform boundaries, where one plate slides horizontally past another plate, the plate motion can be taken up on a single fault or on a group of parallel faults. Transform boundaries are marked by shallow-focus earthquakes in a narrow zone for a single fault, or in a broad zone for a group of parallel faults (see figure 7.30). First-motion studies of the quakes indicate strike-slip movement parallel to the faults.

The name *transform fault* comes from the fact that the displacement along the fault abruptly ends or transforms into another kind of displacement. The most common type of transform fault occurs along fracture zones and connects two divergent plate boundaries at the crest of the mid-oceanic ridge (figures 4.27 and 4.20*B*). The spreading motion at one ridge segment is transformed into the spreading motion at the other ridge segment by strike-slip movement along the transform fault.

Not all transform faults connect two ridge segments. As you can see in figures 7.28 and 4.27, a transform fault can connect a ridge to a trench (a divergent boundary to a convergent bound-



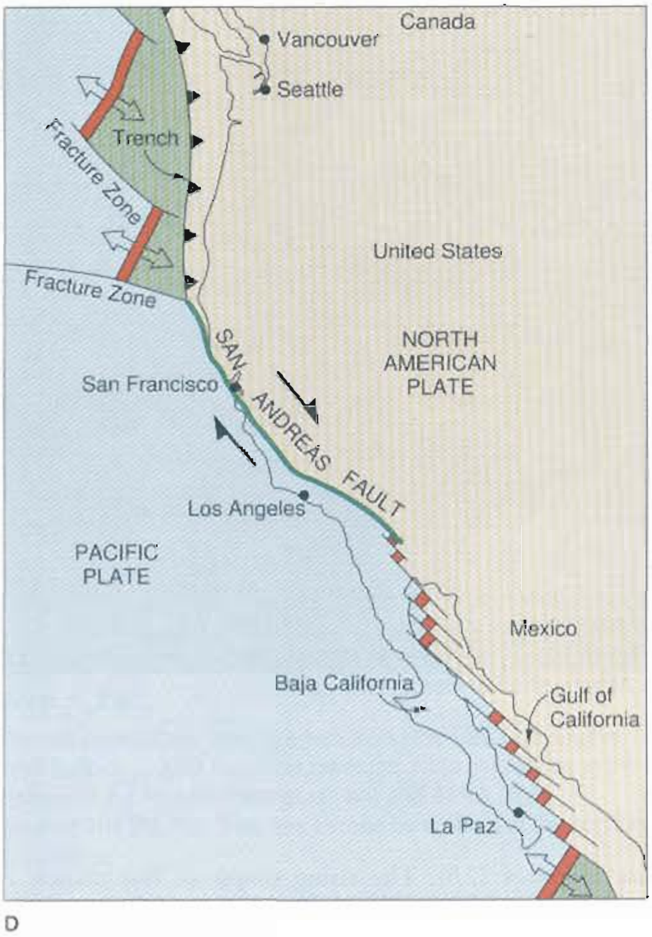


Figure 4.27

Transform boundaries (*A*) between two ridges; (*B*) between a ridge and a trench; and (*C*) between two trenches. Triangles on trenches point down subduction zones. Color tones show two plates in each case. (*D*) The San Andreas fault is a transform plate boundary between the North American plate and the Pacific plate. The south end of the San Andreas fault is a ridge segment (shown in red) near the U.S.-Mexico border. The north end of the fault is a "triple junction" where three plates meet at a point. The relative motion along the San Andreas fault is shown by the large black arrows, as the Pacific plate slides horizontally past the North American plate.

Modified from U.S. Geological Survey.

ary), or can connect two trenches (two convergent boundaries). The San Andreas fault in California is a transform fault with a complex history (figure 4.27*D*).

What is the origin of the offset in a ridge-ridge transform fault? The offsets appear to be the result of irregularly shaped divergent boundaries (figure 4.28). When two oceanic plates begin to diverge, the boundary may be curved on a sphere. Mechanical constraints prevent divergence along a curved boundary, so the original curves readjust into a series of right-angle bends. The ridge crests align perpendicular to the spreading direction, and the transform faults align parallel to the spreading direction. An old line of weakness in a continent may cause the initial divergent boundary to be oblique to the spreading direction when the continent splits. The boundary will then readjust into a series of transform faults parallel to the spreading direction.

Convergent Plate Boundaries

At convergent plate boundaries two plates move toward each other (often obliquely). The character of the boundary depends partly on the type of plates that converge. A plate

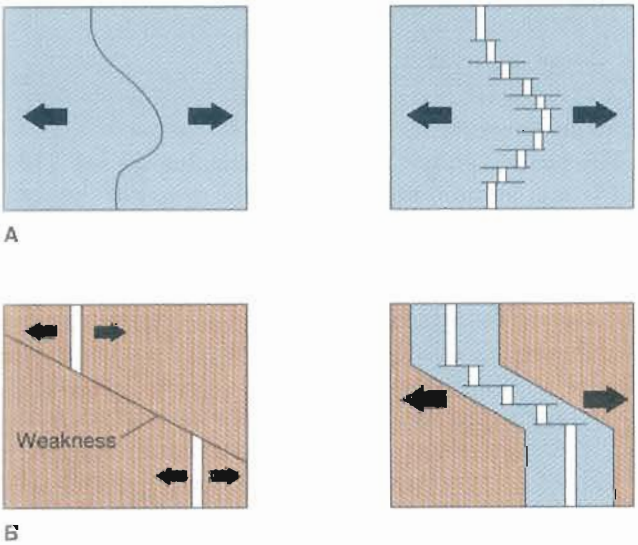


Figure 4.28

Divergent boundaries form ridge crests perpendicular to the spreading direction and transform faults parallel to the spreading direction. (*A*) Oceanic plates. (*B*) Continental plates.

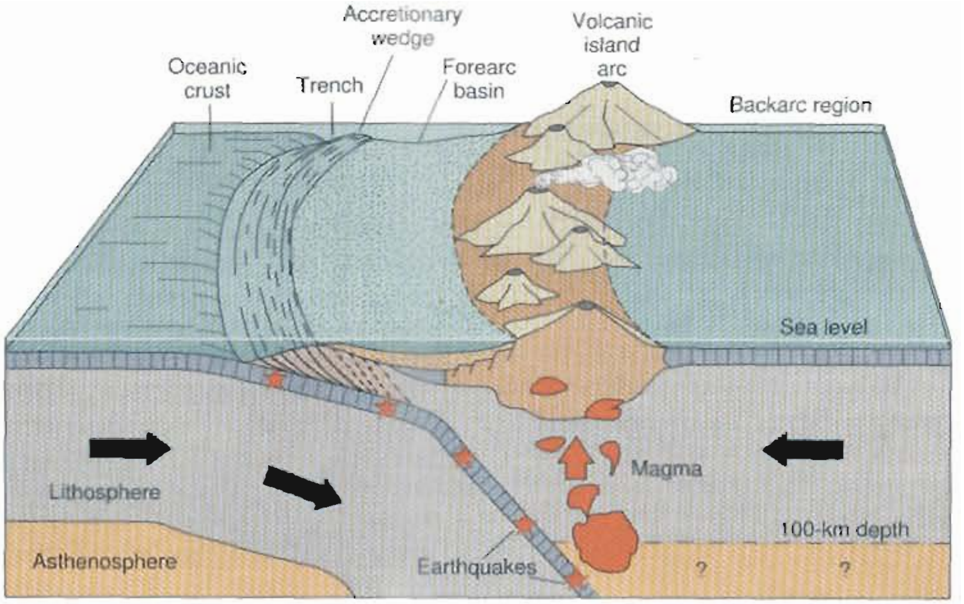


Figure 4.29

Ocean-ocean convergence forms a trench, a volcanic island arc, and a Benioff zone of earthquakes.

Modified from W. R. Dickinson, 1977, in *Island Arcs, Deep Sea Trenches and Back-Arc Basins* (pp. 33–40), copyrighted by American Geophysical Union.

capped by oceanic crust can move toward another plate capped by oceanic crust, in which case one plate dives (subducts) under the other. If an oceanic plate converges with a plate capped by a continent, the dense oceanic plate subducts under the continental plate. If the two approaching plates are both carrying continents, the continents collide and crumple but neither is subducted.

Ocean-Ocean Convergence

Where two plates capped by sea floor converge, one plate subducts under the other (the Pacific plate sliding under the western Aleutian Islands is an example). The subducting plate bends downward, forming the outer wall of an oceanic trench, which usually forms a broad curve convex to the subducting plate (figures 4.29 and 4.30).

As one plate subducts under another, a Benioff zone of shallow-, intermediate-, and deep-focus earthquakes is created within the upper portion of the downgoing lithosphere (figure 4.29). The reasons for these quakes are discussed in chapter 7. The existence of deep-focus earthquakes to a depth of 670 kilometers tells us that brittle plates continue to (at least) that depth. The pattern of quakes shows that the angle of subduction changes with depth, usually becoming steeper (figure 4.29). Some plates crumple or break into segments as they descend.

As the descending plate reaches depths of at least 100 kilometers, magma is generated in the overlying asthenosphere (figure 4.29). The magma probably forms by partial melting of the asthenosphere, perhaps triggered by dewatering of the downgoing oceanic crust as it is subducted, as described in chapter 11. Differentiation and assimilation may also play an important role in the generation of the magma, which is typically andesitic to basaltic in composition.

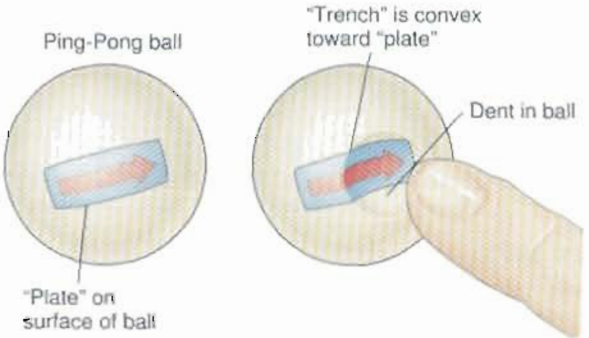


Figure 4.30

A dented Ping-Pong ball can show why trenches are curved on a sphere.

The magma works its way upward to erupt as an **island arc,** a curved line of volcanoes that form a string of islands parallel to the oceanic trench (figure 4.29). Beneath the volcanoes are large plutons in the thickened arc crust.

The distance between the island arc and the trench can vary, depending upon where the subducting plate reaches the 100-kilometer depth. If the subduction angle is steep, the plate reaches this magma-generating depth at a location close to the trench, so the horizontal distance between the arc and trench is short (figure 4.31). If the subduction angle is gentle, the arc-trench distance is greater. A thick, buoyant plate (such as a subducting aseismic ridge) may subduct at such a gentle angle that

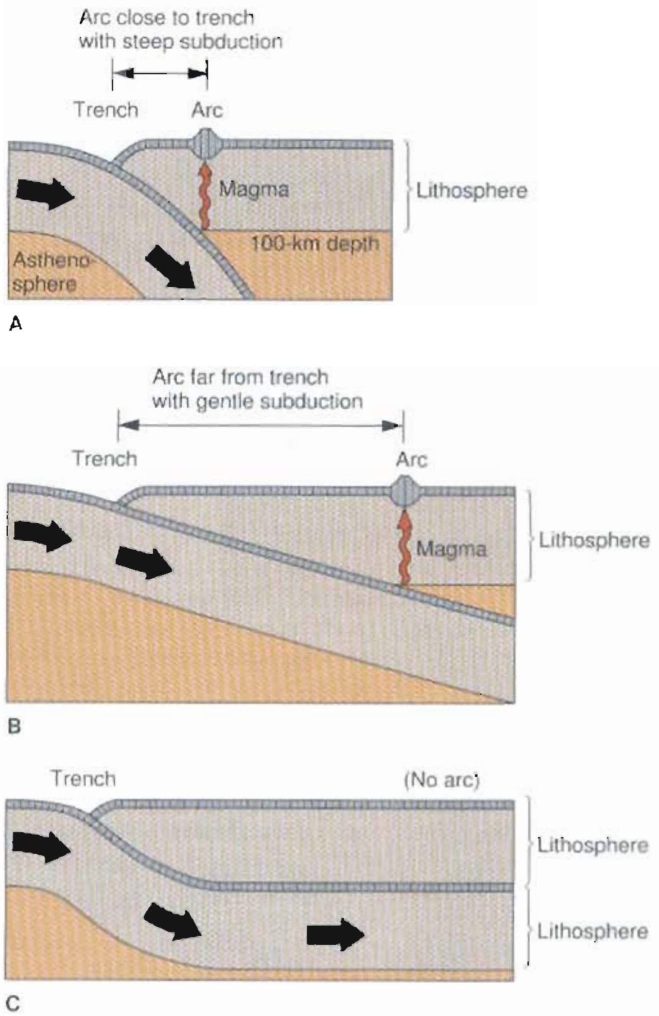


Figure 4.31

Andesitic magma is generated where the top of the subducting lithosphere reaches a depth of 100 kilometers, so the subduction angle determines the arc-trench spacing.

it merely slides horizontally along under another plate. Because the top of the subducting plate never reaches the 100-kilometer depth, such very shallow subduction zones lack volcanism.

When a plate subducts far from a mid-oceanic ridge, the plate is cold, with a low heat flow. Oceanic plates form at ridge crests, then cool and sink as they spread toward trenches. Eventually they become cold and dense enough to sink back into the mantle. Oceanic trenches are marked by strong negative gravity anomalies. These show that trenches are not currently in isostatic equilibrium, but are being actively pulled down. Hess thought that this pulling was caused by a down-turning convection current in the mantle. Today most geologists think that the pulling is caused by the sinking of cold, dense lithosphere.

The inner wall of a trench (toward the arc) consists of an *accretionary wedge* (or *subduction complex*) of thrust-faulted and folded marine sediment (figure 4.29). The sediment is snowplowed off the subducting plate by the overlying plate. New slices of sediment are continually added to the bottom of the accretionary wedge, pushing it upward to form a ridge on the sea floor. A relatively undeformed *forearc basin* lies between the accretionary wedge and the volcanic arc. (The trench side of an arc is the forearc; the other side of the arc is the backarc.)

Trench positions change with time (figure 4.32). As one plate subducts, the overlying plate may be moving toward it. The motion of the leading edge of the overlying plate will force the trench to migrate horizontally over the subducting plate (figure 4.32*A*). The Peru-Chile trench is moving over the Nazca plate in this manner as South America moves westward (figure 4.1). There is another reason that trenches move. It is now widely believed that a subducting plate does not sink in a direction parallel to the length of the plate, but falls through the mantle at an angle that is *steeper* than the dip of the down-going plate (figure 4.32*B*). This steep sinking pulls the subducting plate progressively away from the overlying plate, and causes the hinge line of bending and the oceanic trench to migrate seaward onto the subducting plate. The location at which the subducting plate contacts the 100-kilometer depth to generate andesite also migrates seaward toward the subducting plate, and may cause the position of the island arc to migrate toward the subducting plate as well.

Ocean-Continent Convergence

When a plate capped by oceanic crust is subducted under the *continental* lithosphere, an accretionary wedge and forearc basin form an *active continental margin* between the trench and the continent (figure 4.33). A Benioff zone of earthquakes dips under the edge of the continent, which is marked by andesitic volcanism and a young mountain belt. An example of this type of boundary is the subduction of the Nazca plate under western South America.

The magma that is created by ocean-continent convergence forms a **magmatic arc,** a broad term used both for island arcs at sea and for belts of igneous activity on the edges of continents. The surface expression of a magmatic arc is either a line of andesitic islands (such as the Aleutian Islands) or a line of andesitic continental volcanoes (such as the Cascade volcanoes of the Pacific Northwest). Beneath the volcanoes are large plutons in thickened crust. We see these plutons as batholiths on land when they are exposed by deep erosion. The igneous processes that form the granitic and intermediate magmas of batholiths are described in chapter 11.

The hot magma rising from the subduction zone thickens the continental crust and makes it weaker and more mobile than cold crust. Regional metamorphism takes place within this hot, mobile zone. Crustal thickening causes uplift, so a young mountain belt forms here as the thickened crust rises isostatically.

Another reason for the growth of the mountain belt is the stacking up of thrust sheets on the continental (backarc) side of the magmatic arc (figure 4.33). The thrust faults, associated with folds, move slivers of mountain-belt rocks landward over the continental interior (the *craton*). Underthrusting of the rigid craton beneath the hot, mobile core of the mountain belt may help form the fold-thrust belt.

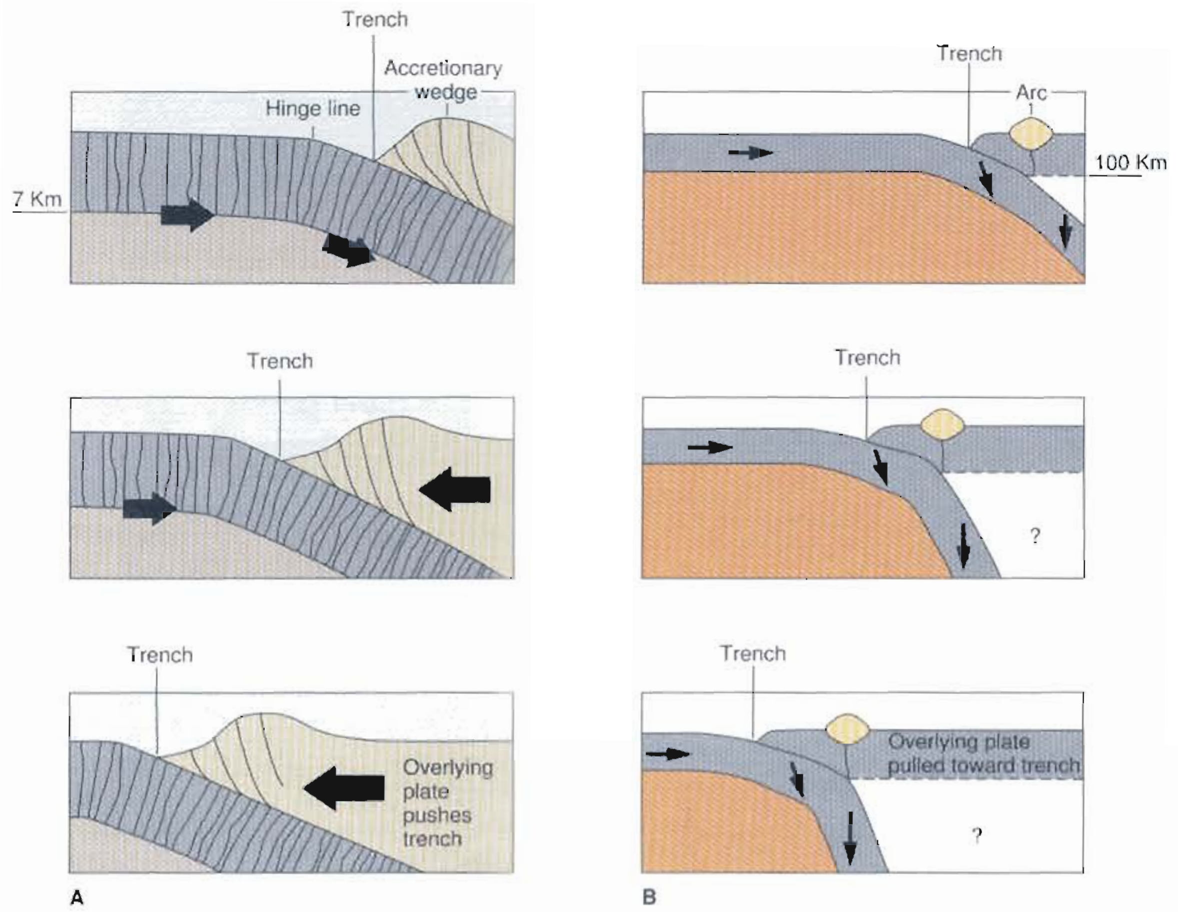


Figure 4.32

Migration of trench, hinge line, accretionary wedge, and volcanic arc. (*A*) The motion of the overlying plate can force this migration. (*B*) The cooling, subducting plate sinks at a steeper angle than its dip, pulling the overlying plate toward the subducting plate.

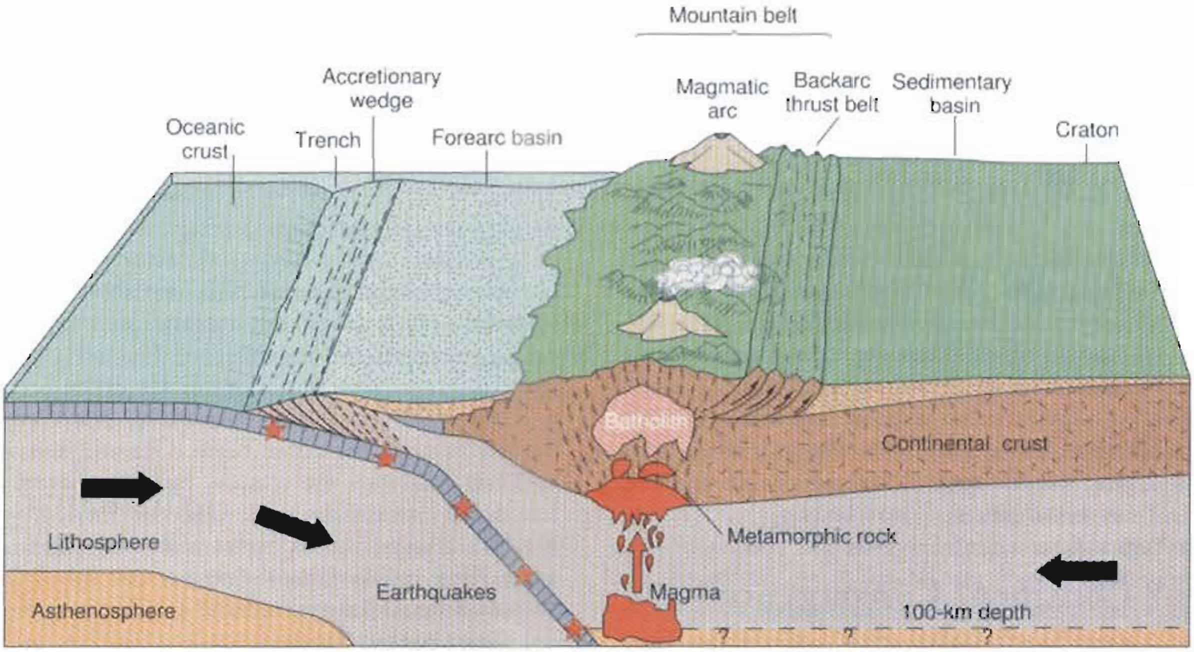
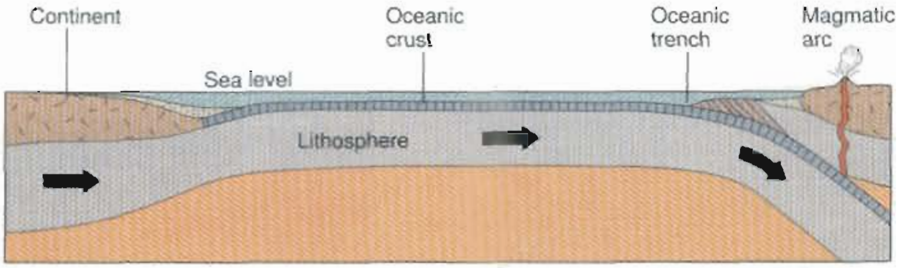
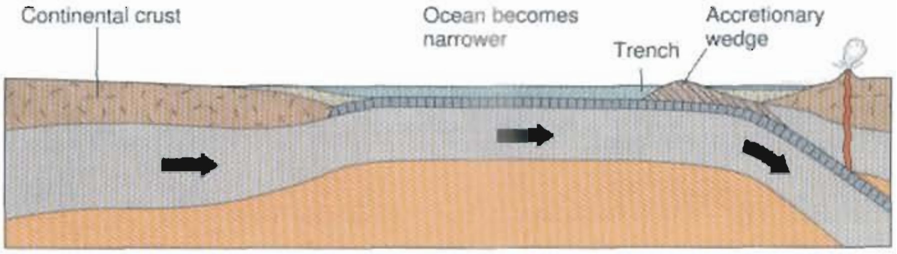


Figure 4.33

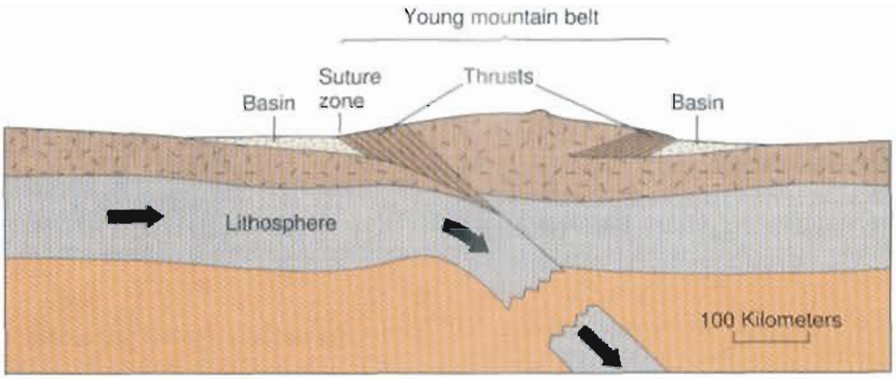
Ocean-continent convergence forms an active continental margin with a trench, a Benioff zone, a magmatic arc, and a young mountain belt on the edge of the continent.



A Ocean-continent convergence



B Ocean-continent convergence



C Continent-continent collision

Figure 4.34

Continent-continent collision forms a young mountain belt in the interior of a new, larger continent.

Modified from W. R. Dickinson, 1977, in *Island Arcs, Deep Sea Trenches and Back-Arc Basins* (pp. 33–40), copyrighted by American Geophysical Union.

Inland of the backarc fold-thrust belt, the craton subsides to form a sedimentary basin (sometimes called a *foreland basin*). The weight of the stacked thrust sheets depresses the craton isostatically. The basin receives sediment, some of which may be marine if the craton is forced below sea level. This basin extends the effect of subduction far inland. Subduction of the sea floor off California during the Mesozoic Era produced basin sedimentation as far east as the central Great Plains.

Continent-Continent Convergence

Two continents may approach each other and collide. They must be separated by an ocean floor that is being subducted under *one* continent and that lacks a spreading axis to create new oceanic crust (figure 4.34). The edge of one continent will initially have a magmatic arc and all the other features of ocean-continent convergence.

As the sea floor is subducted, the ocean becomes narrower and narrower until the continents eventually collide and destroy or close the ocean basin. Oceanic lithosphere is heavy and can sink into the mantle, but continental lithosphere is less dense and cannot sink. One continent may slide a short distance under another, but it will not go down a subduction zone. After collision the heavy oceanic lithosphere breaks off the continental lithosphere and continues to sink, leaving the continent behind (figure 4.34*C*).

The two continents are welded together along a dipping *suture zone* that marks the old site of subduction. Thrust belts

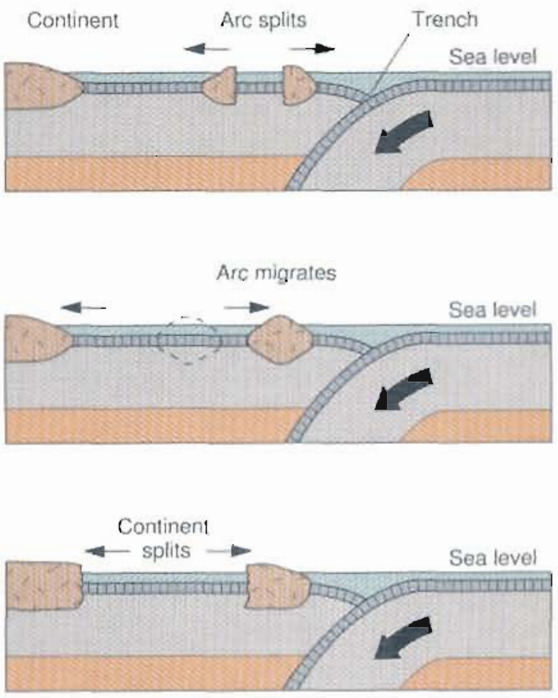


Figure 4.35

Backarc spreading. Regional extension in the overlying plate of a subduction zone can split an arc, move an arc offshore, or split a continent.

and subsiding basins occur on both sides of the original magmatic arc, which is now inactive. The presence of the original arc thickens the crust in the region of impact. The crust is thickened further by the shallow underthrusting of one continent beneath the other and also by the stacking of thrust sheets in the two thrust belts. The result is a mountain belt in the interior of a continent (a new large continent formed by the collision of the two smaller continents). The entire region of impact is marked by a broad belt of shallow-focus earthquakes along the numerous faults, as shown in figure 7.31*A*. A few deeper quakes may occur within the sinking oceanic lithosphere beneath the mountain range.

The Himalaya Mountains in central Asia are thought to have formed in this way, as India collided with and underthrust Asia to produce exceptionally thick crust and high elevations. Paleomagnetic studies show that India was once in the southern hemisphere and drifted north to its present position. The collision with Asia occurred after an intervening ocean was destroyed by subduction (figure 4.2).

Backarc Spreading

Regional extension occurs within or behind many arcs. This extension can tear an arc in two, moving the two halves in opposite directions (figure 4.35). If it occurs behind an arc, it can move the arc away from a continent. It can split the edge of a continent, moving a narrow strip of the continent seaward (this is apparently how Japan formed). In each case the spreading creates new oceanic crust that is similar, but not identical, to the oceanic crust formed at the crest of mid-oceanic ridges. This backarc oceanic crust is apparently the type of crust found in most ophiolites (chapter 3).

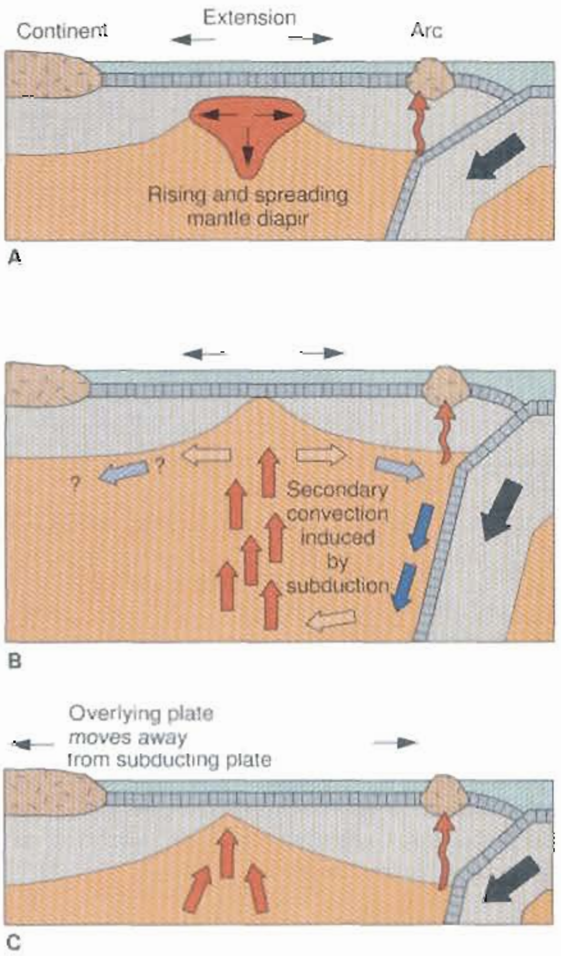


Figure 4.36

Causes of backarc spreading. Extension may be caused by a rising mantle diapir, by secondary convection, or by relative plate motions.

The reason for backarc extension is energetically debated. One suggestion is that extension is caused by a rising and spreading mantle diapir of hot rock or magma somehow generated by the downgoing plate (figure 4.36). The spreading diapir tears open the backarc basin, and the rising magma forms new oceanic crust. Another suggestion is that the subducting plate drags on the overlying asthenosphere, causing it to move in secondary convection cells that stretch and fracture the overlying oceanic crust. A third suggestion, which seems the best explanation for the most rapidly spreading backarc basins in the Pacific, is that the overlying plate is retreating away from the subducting plate. If the arc on the overlying plate stays fixed near the subducting plate, the retreat of the overlying plate will tear open the backarc basin.

The Motion of Plate Boundaries

Almost nothing is fixed in plate tectonics. Not only do plates move, but plate boundaries move as well. Plates may move away from each other at a divergent boundary on a ridge crest for tens of millions of years, but the ridge crest can be migrating across the earth's surface as this occurs. Ridge crests can also jump to new positions. The original ridge crest may suddenly become inactive; the divergence will jump quickly to a new position and create a new ridge crest (the evidence lies in the sea-floor magnetic anomaly pattern).

Convergent boundaries migrate, too, as shown in figure 4.32. As they migrate, trenches and magmatic arcs migrate along with the boundaries. Convergent boundaries can also jump; subduction can stop in one place and begin suddenly in a new place.

Transform boundaries change position, too. California's San Andreas fault has been in its present position about 5 million years. Prior to that, the plate motion was taken up on sea-floor faults parallel to the San Andreas (figure 4.37). In the future, the San Andreas may shift eastward again. The 1992 Landers earthquake, on a new fault in the Mojave Desert, and its pattern of aftershocks extending an astonishing 500 miles northward, suggest that the San Andreas may be trying to jump inland again. If it eventually does, most of California will be newly attached to the Pacific plate instead of the North American plate, and California will slide northwestward relative to the rest of North America.

Plate Size

Plates can change in size. For example, new sea floor is being added on the trailing edge of the North American plate at the spreading axis in the central Atlantic Ocean. Most of the North American plate is not being subducted along its leading edge because this edge is made up of lightweight continental rock. Thus the North American plate is growing in size as it moves slowly westward.

The Nazca plate probably is getting smaller. The spreading axis is adding new rock along the trailing edge of the Nazca plate, but the leading edge is being subducted down the Peru-Chile Trench. If South America were stationary, the Nazca plate might remain the same size, because the rate of subduction and the rate of spreading are equal. But South America is slowly moving westward, pushing the Peru-Chile Trench in front of it. This means that the site of subduction of the Nazca plate is gradually coming closer to its spreading axis to the west, and so the Nazca plate is getting smaller. The same thing is probably happening to the Pacific plate as the Eurasian plate moves eastward into the Pacific Ocean.

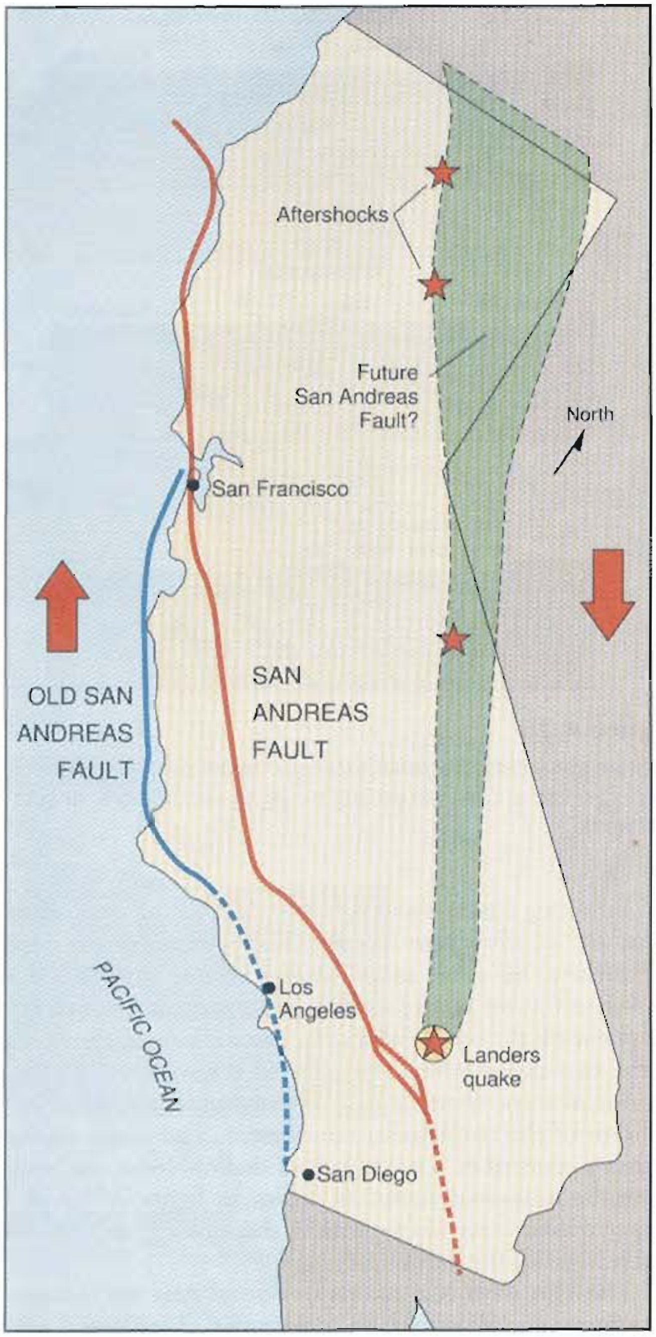


Figure 4.37

The San Andreas fault (a transform boundary) has changed position through time. Prior to 5 million years ago, the fault was offshore (blue line). In the future it may jump inland again (green zone).

The Attractiveness of Plate Tectonics

Most geologists accept the general concept of plate tectonics because it can explain in a general way the distribution and origin of many earth features. These features are discussed throughout this book, and we summarize them here.

The distribution and composition of the world's *volcanoes* can be explained by plate tectonics. *Basaltic* volcanoes and lava flows form at divergent plate boundaries when hot mantle rock rises at a spreading axis. *Andesitic* volcanoes, particularly those in the circum-Pacific belt, result from subduction of an oceanic

4.1

IN GREATER DEPTH

Plate Tectonics and Sea Level

Geologists have long known that at certain times in the geologic past the sea covered vast areas of the continents that are now dry land. Much of the interior of the United States, for example, is underlain by marine limestones deposited during parts of the Paleozoic Era. Were the continents lower at these times or was sea level higher?

As you have seen, the subsidence of the craton during subduction can allow vast regions of the continental interior to be flooded with seawater. Some marine deposits on the craton, however, are so extensive that they probably were caused by a rise in sea level.

Although several mechanisms, such as glaciation, can change sea level, the development of plate tectonics has led to a hypothesis that may explain some of the ancient sea-level fluctuations.

During an episode of rapid plate motion, an active spreading axis will be marked by a mid-oceanic ridge caused by the thermal expansion of rock on the rising limb of a convection current. When plate motion stops, convection also stops, and the rock at an old spreading axis cools off and contracts. This means that the mid-oceanic ridge subsides and eventually becomes level sea floor. That is, when plates move, a ridge is present; and when plates stop, the ridge is absent.

When a ridge is present, it displaces seawater, raising sea level and causing the sea to flood land areas. When the ridge is absent, the water returns to the ocean basin and the continents are dry once again.

The plates need not stop completely. A rapid spreading rate would cause a large ridge and a sea-level rise, and a slower spreading rate would cause a smaller ridge and a lower sea level. There is good evidence that some sea-level fluctuations can be correlated to changes in the rate of the sea-floor motion. Not all changes in sea level can be explained by this mechanism, however. Glaciation and other factors clearly affect sea level too.

plate beneath either a continental plate or another oceanic plate. Although most of the world's volcanoes occur at plate margins, some do not (Hawaii being an example). We will discuss some of these isolated volcanoes later in the chapter when we describe mantle plumes.

Earthquake distribution and first motion can largely be explained by plate tectonics. Shallow-focus earthquakes along normal faults are caused by extension at divergent plate boundaries. Shallow-focus earthquakes occur on transform faults when plates slide past one another. Broad zones of shallow-focus earthquakes are located where two continents collide. Dipping Benioff zones of shallow-, intermediate-, and deep-focus quakes are found along the giant thrust faults formed when an oceanic plate is subducted beneath another plate. Most of the world's earthquakes (like most volcanoes) occur along plate boundaries, although a few take place within plates and are difficult to explain in terms of plate tectonics.

Young mountain belts—with their associated igneous intrusions, metamorphism, and fold-thrust belts—form at convergent boundaries. "Subduction mountains" form at the edges of continents where sea floor is sliding under continents. "Continental-collision" mountains form in continental interiors when two continents collide to form a larger continent. Old mountain belts mark the position of old, now inactive, plate boundaries.

The major features of the sea floor can also be explained by plate tectonics. The *mid-oceanic ridge* with its rift valley forms at divergent boundaries. *Oceanic trenches* are found where oceanic plates are subducted at convergent boundaries. *Fracture zones* are created at transform boundaries.

Other hypotheses can explain some of these features, but not all of them. Belts of folded mountains have been attributed to compression caused by a contracting earth. Rift valleys, on the other hand, have been explained by extension caused by an *expanding* earth. The hypotheses are incompatible with each other and do not give a unifying view of the earth. Plate tectonics explains more features than any other hypothesis or theory, and it provides a unifying framework for the study of the earth. That is why so many geologists support the concept, at least as a working model of how the earth works.

What Causes Plate Motions?

There is currently a great deal of speculation about why plates move. There may be several reasons for plate motion. Any mechanism for plate motion has to explain why:

1. mid-oceanic ridge crests are hot and elevated, while trenches are cold and deep;
2. ridge crests have tensional cracks;

3. the leading edges of some plates are subducting sea floor, while the leading edges of other plates are continents (which cannot subduct).

Convection in the mantle, proposed as a mechanism for sea-floor spreading (figure 4.12), can account for these facts, as we have shown earlier in this chapter. Mantle convection is quite likely because heat loss from the earth's core should heat the overlying mantle, causing it to overturn. Debate about the size and shape of mantle convection cells led to several models (figure 4.38). The old seafloor-spreading model assumed mantle-deep convection. Proponents of a layered mantle think that the 670-kilometer boundary may be a compositional boundary that prevents mantle-deep convection, so two-layer convection models have been proposed. Rising hot rock in the lower mantle may heat the base of the upper mantle, causing the upper mantle to rise directly over the rising lower mantle (figure 4.38*B*). Alternatively, the horizontal motion of the lower mantle just below the boundary may drag the upper mantle rock along in the same direction (figure 4.38*C*). Note that this creates *sinking* upper mantle directly over rising lower mantle.

Many geologists now think that mantle convection is a *result* of plate motion rather than a cause of it. The sinking of a cold, subducting plate can create mantle convection (convection can be driven by either hot, rising material or by cold, sinking material). Hot mantle rock rises at divergent boundaries to take the place of the diverging plates (figure 4.25). Such plate-caused convection could be shallow, rather than mantle-deep.

The basic question in plate motion is why do plates diverge and sink? Two or three different mechanisms may be at work here.

One proposal is called "*ridge-push*." As a plate moves away from a divergent boundary, it cools and thickens. Cooling sea floor subsides as it moves, and this subsidence forms the broad side slopes of the mid-oceanic ridge. An even more important slope forms on the base of the lithosphere as new igneous rock is added to the base of the lithosphere by progressive cooling of the asthenosphere below (figure 4.39). The oceanic plate is thought to slide down this slope at the base of the lithosphere, which may have a relief of 80 to 100 kilometers.

Another mechanism is called "*slab-pull*" (figure 4.40). Cold lithosphere sinking at a steep angle through hot mantle should pull the surface part of the plate away from the ridge crest and then down into mantle as it cools. A subducting plate sinks because it is denser than the surrounding mantle. This density contrast is partly due to the fact that the sinking lithosphere is cold. The subducting plate may also increase its density while it sinks, as low-density materials such as water are lost, and as plate minerals collapse into denser forms during subduction. Slab-pull is thought to be at least twice as important as ridge-push in moving an oceanic plate away from a ridge crest. Slab-pull causes rapid plate motion.

If subducting plates fall into the mantle at angles steeper than their dip (figure 4.32), then trenches and the overlying

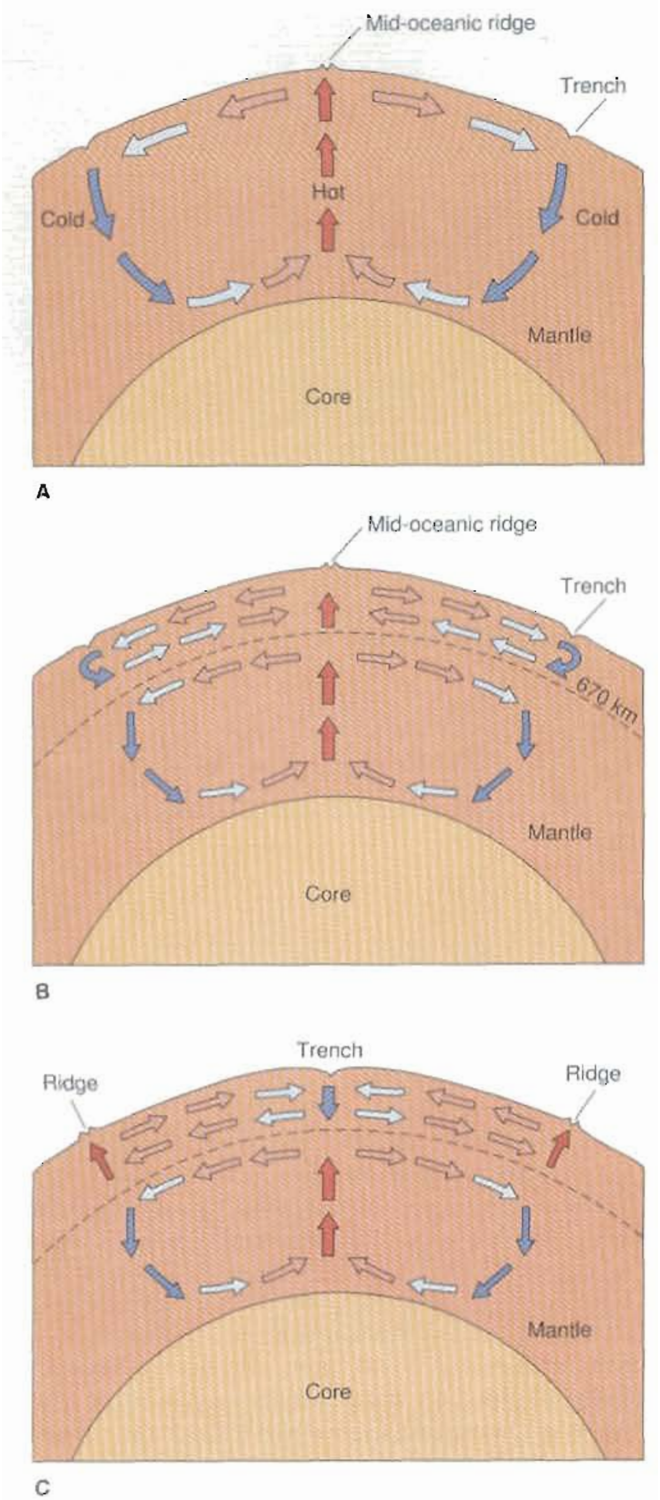


Figure 4.38

Models of mantle convection. (*A*) Mantle-deep convection. (*B*) Two-tiered convection separated at 670-kilometer boundary. The lower mantle delivers heat to the upper mantle. (*C*) Two-tiered convection. The lower mantle drags on the upper mantle.

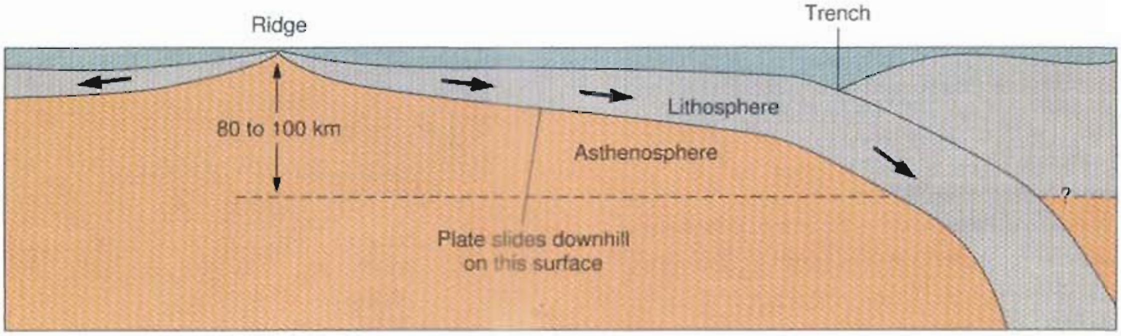


Figure 4.39

Ridge-push. A plate may slide downhill on the sloping boundary between the lithosphere and the asthenosphere at the base of the plate.

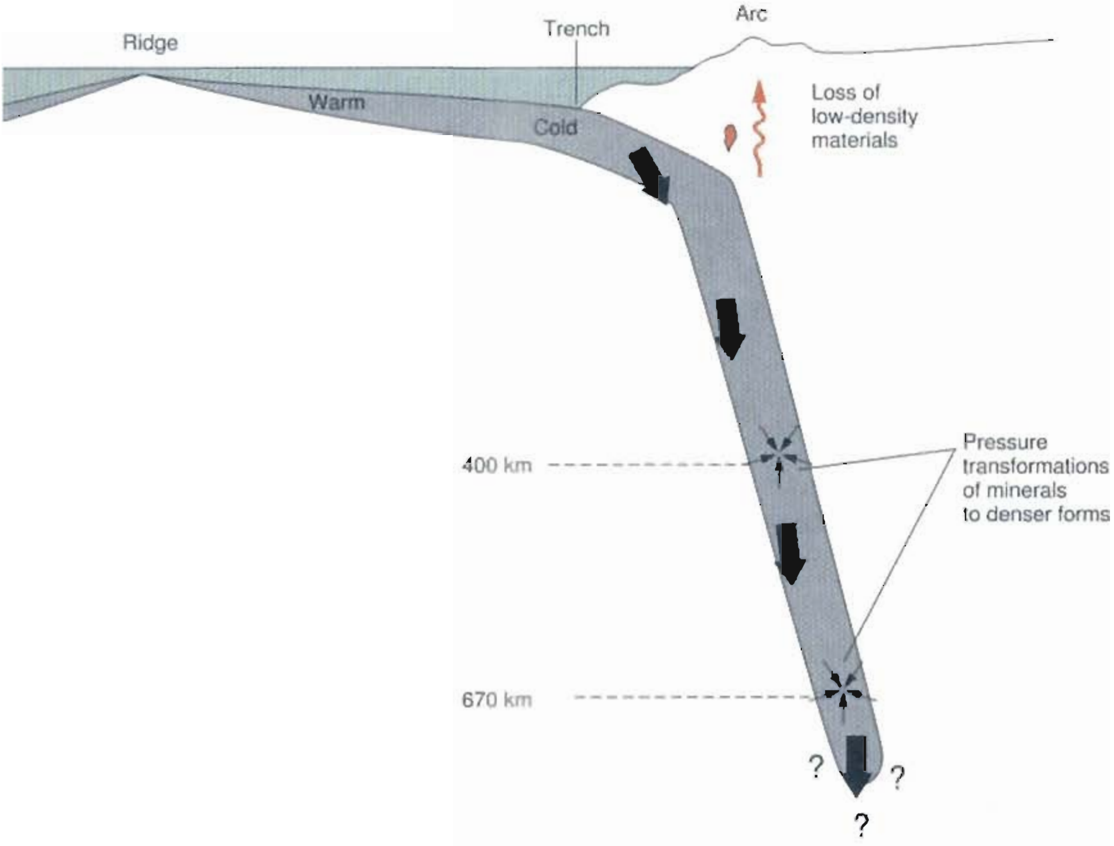


Figure 4.40

Slab-pull. The dense, leading edge of a subducting plate pulls the rest of the plate along. Plate density increases due to cooling, loss of low-density material, and pressure transformation of minerals to denser forms.

plates are pulled horizontally seaward toward the subducting plates. This mechanism has been termed "*trench-suction*." It is probably a minor force, but may be important in moving continents apart. Divergent continents at the leading edges of plates cannot be moved by slab-pull, because they are not on subducting plates. They might be moved by ridge-push from the rear, and/or trench-suction from the front (figure 4.41). They move much more slowly than subducting plates.

All three of these mechanisms (ridge-push, slab-pull, and trench-suction), particularly in combination, are compatible with high, hot ridges; cold, deep trenches; and tensional cracks at the ridge crest. They can account for the motion of both oceanic and

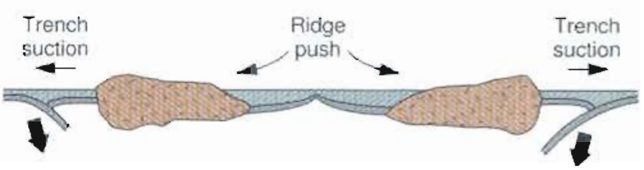


Figure 4.41

Divergent continents may be moved by ridge-push from the rear, or trench-suction (caused by steeply sinking plates) from the front.

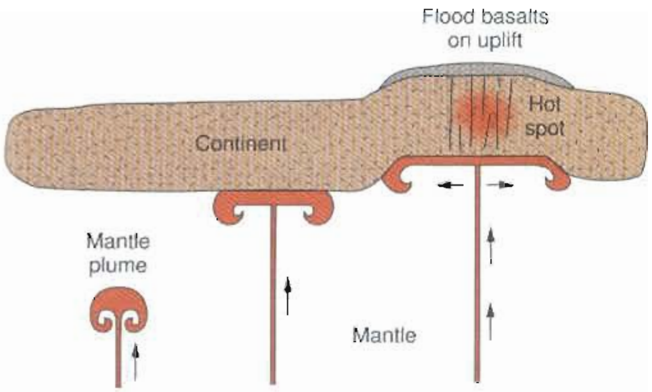


Figure 4.42

Mantle plumes rise upward through the mantle. When the large head contacts a continent, it causes uplift and the eruption of flood basalts.

continental plates. In this scheme, plate motions are controlled by variations in lithosphere density and thickness, which, in turn, are controlled largely by cooling. In other words, the reasons for plate motions are the properties of the plates themselves and the pull of gravity. This idea is in sharp contrast to most convection models, which assume that plates are dragged along by the movement of mantle rock beneath the plates.

Mantle Plumes and Hot Spots

A modification of the convection process has been suggested by W. Jason Morgan of Princeton University. Morgan believes that convection occurs in the form of **mantle plumes,** narrow columns of hot mantle rock that rise through the mantle, much like smoke rising from a chimney (figure 4.42). Mantle plumes are now thought to have large spherical or mushroom-shaped heads above a narrow rising tail. They are essentially stationary with respect to moving plates and to each other.

Plumes form "hot spots" of active volcanism at the earth's surface. Note in figure 4.43 that many plumes are located in

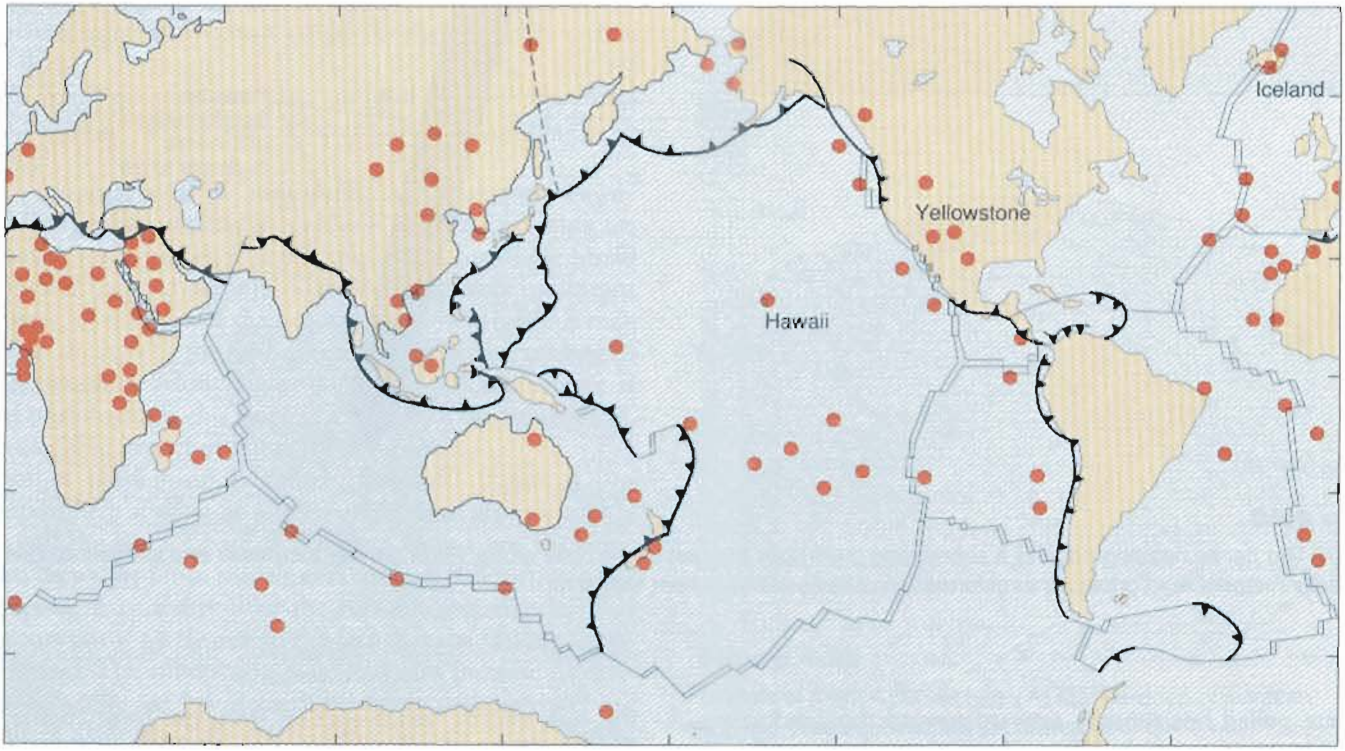


Figure 4.43

Distribution of hypothesized mantle plumes, identified by volcanic activity and structural uplift within the past few million years. The hot spots near the poles are not shown.

Compiled by W. S. F. Kidd and K. Burke, SUNY at Albany.

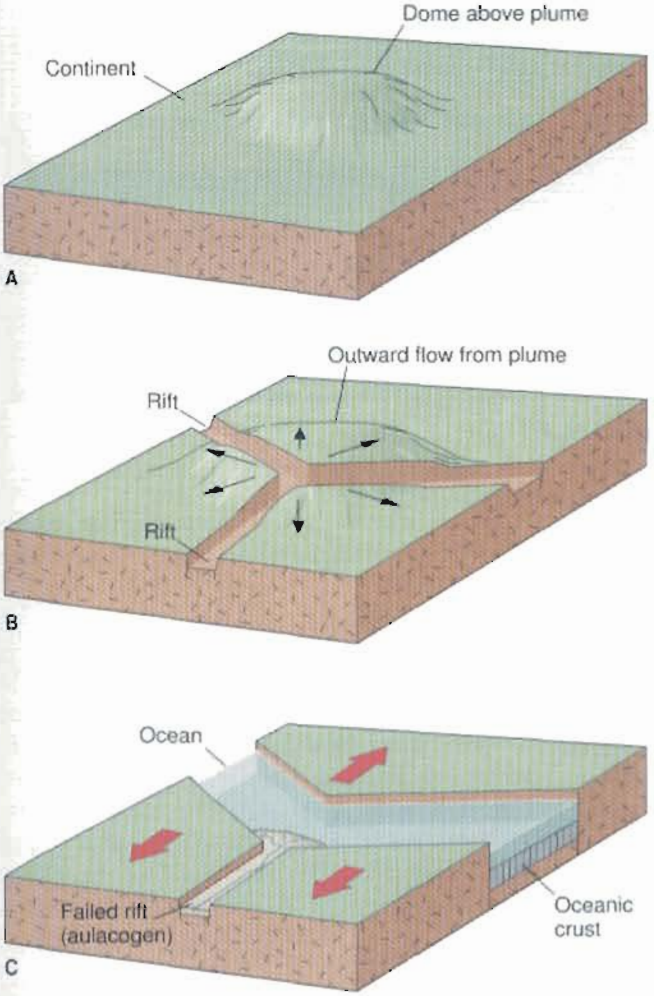


Figure 4.44

Continental breakup caused by a mantle plume. (*A*) A dome forms over a mantle plume rising beneath a continent. (*B*) Three radial rifts develop due to outward radial flow from the top of the mantle plume. (*C*) Continent separates into two pieces along two of the three rifts, with new ocean floor forming between the diverging continents. The third rift becomes an inactive "failed rift" (or aulacogen) filled with continental sediment.

volcanic regions such as Iceland, Yellowstone, and Hawaii. When the large head of the plume nears the surface, it causes uplift and the eruption of vast fields of flood basalts. As the head widens beneath the crust the flood-basalt area widens and the crust is stretched. The tail that follows the head produces a narrow spot of volcanic activity, much smaller than the head.

The outward, radial flow of the expanding head may be strong enough to break the lithosphere and start plates moving. In Morgan's view a few plumes, such as those on the mid-oceanic ridge in the Atlantic Ocean in figure 4.43, are enough to drive plates apart (in this case, to push the American plates westward).

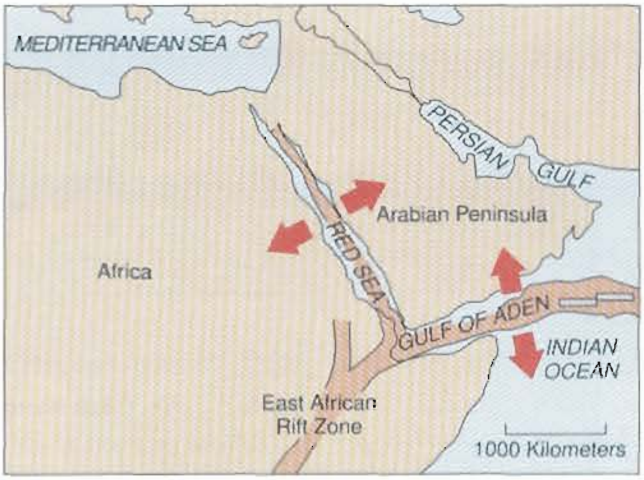


Figure 4.45

An example of radial rifts. The Red Sea and the Gulf of Aden are the active rifts, as the Arabian peninsula drifts away from Africa. The Gulf of Aden contains a mid-oceanic ridge and central rift valley. The inactive failed rift is the rift valley shown in Africa.

A mantle plume rising beneath a continent should heat the land and bulge it upward to form a dome marked by volcanic eruptions. As the dome forms, the stretched crust typically fractures in a three-pronged pattern (figure 4.44). Continued radial flow outward from the rising plume eventually separates the crust along two of the three fractures but leaves the third fracture inactive. In this model of continental breakup, the two active fractures become continental edges as new sea floor forms between the divergent continents. The third fracture is a *failed rift* (or *aulacogen*), an inactive rift that becomes filled with sediment.

An example of this type of fracturing may exist in the vicinity of the Red Sea (figure 4.45). The Red Sea and the Gulf of Aden are active diverging boundaries along which the Arabian Peninsula is being separated from northeastern Africa. The third, inactive, rift is the northernmost African Rift Valley, lying at an angle of about 120° to each of the narrow seaways.

Figure 4.46 shows how two plumes might split a continent and begin plate divergence. Local uplift *causes* rifting over each plume. The rifts lengthen with time until the land is torn in two. The two halves begin to diverge either from sliding down the uplifts or from being dragged along from below by the outward radial flow of the plume. Along the long rift segments between plumes, rifting occurs *before* uplift.

A place where a mantle plume might now be rising beneath a continent is in Yellowstone National Park in northwestern Wyoming. The area's volcanism, high elevation, high heat flow, and hot spring and geyser activity all may be due to this plume. Radial flow of mantle rock beneath the western United States may be tearing the continent apart and causing the earthquakes in the region, including the 1959 earthquake near Madison Canyon, Montana. Eventually an ocean may form here as North America is split apart by the plume.

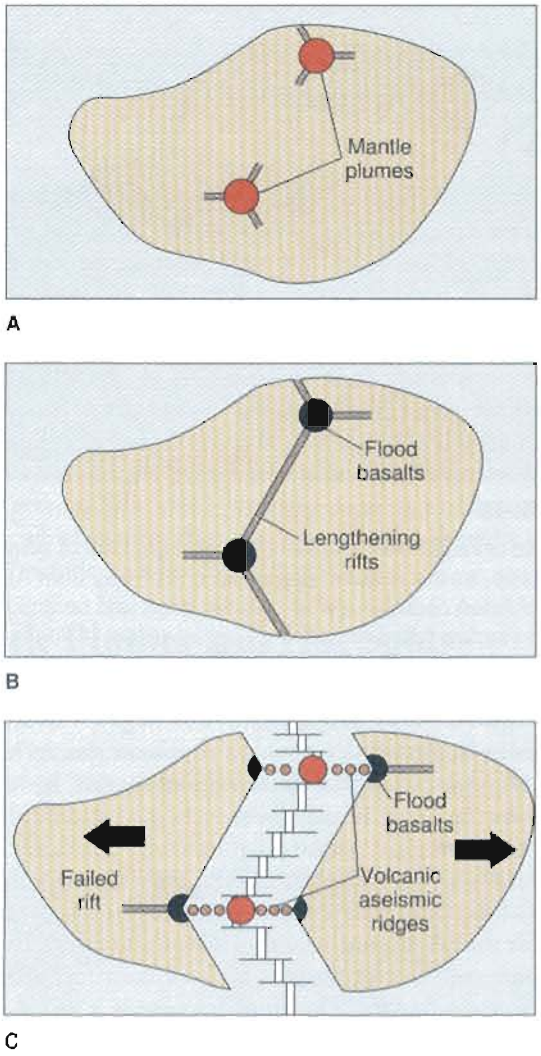


Figure 4.46

(*A*) Two mantle plumes beneath a continent. (*B*) The rifts lengthen and flood basalts erupt over the plumes. (*C*) The continent splits and failed rifts form. The new ocean is marked by ridge crests, fracture zones, and aseismic ridges (chains of volcanoes).

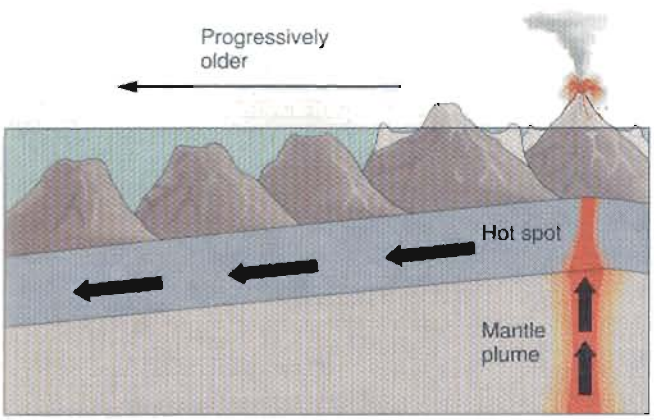


Figure 4.47

Sea floor moving over a hot spot forms an aseismic ridge as a chain of volcanoes and guyots.

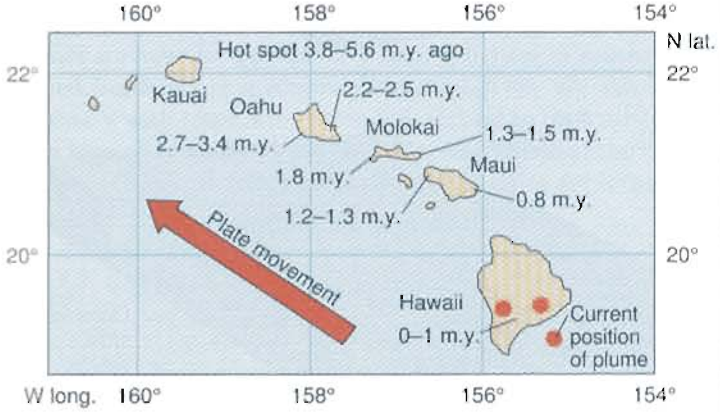


Figure 4.48

Ages of volcanic rock of the Hawaiian island group. Ages increase to northwest. Two active volcanoes on Hawaii shown by red dots. See also figure 3.22.

Some plumes rise beneath the centers of oceanic plates. A plume under Hawaii rises in the center of the Pacific plate. As the plate moves over the plume, a line of volcanoes forms, creating an aseismic ridge (figure 4.47 and chapter 3). The volcanoes are gradually carried away from the eruptive center, sinking as they go because of cooling. The result is a line of extinct volcanoes (seamounts and guyots) increasing in age away from an active volcano directly above the plume.

In the Hawaiian island group, the only two active volcanoes are in the extreme southeastern corner (figure 4.48). The isotopic ages of the Hawaiian basalts increase regularly to the northwest, and a long line of submerged volcanoes forms an aseismic ridge to the northwest of Kauai (figure 3.22). Most aseismic ridges on the sea floor appear to have active volcanoes at one end, with ages increasing away from the eruptive centers. Deep-sea drilling has shown, however, that not all aseismic ridges increase in age along their lengths. This evidence has led to alternate hypotheses for the origin of aseismic ridges. It may pose difficulties for the plume hypothesis itself.

Note in figure 3.22 that the three large aseismic ridges in the Pacific Ocean change direction abruptly. If these ridges formed from three separate stationary plumes, they suggest that the Pacific plate has moved in two directions in the past. Early movement approximately northward, followed by more westerly movement, could have produced the ridge patterns.

The Relationship Between Plate Tectonics and Ore Deposits

The plate tectonic theory provides an overall model for the origin of metallic ore deposits that has been used to explain the occurrence of known deposits and in exploration for new

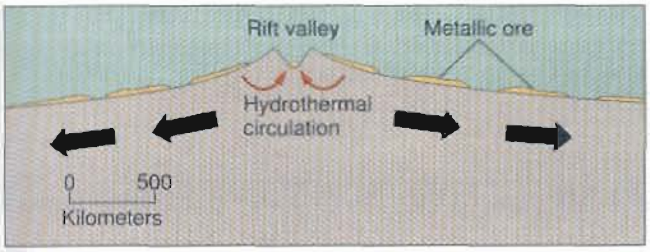


Figure 4.49

Divergent oceanic plates carry metallic ores away from rift valley. (Size of ore deposits exaggerated.)

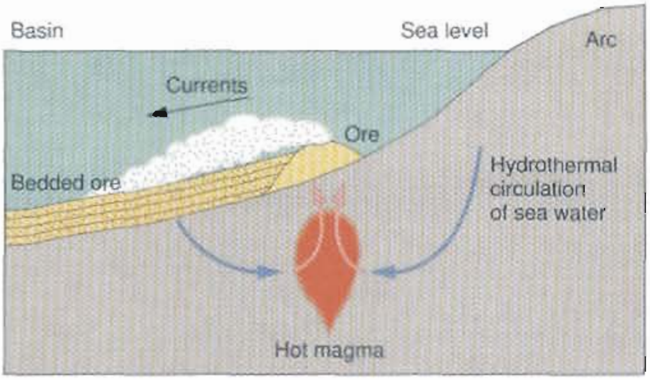


Figure 4.50

On island arcs metallic ores can form over hot springs and be redistributed into layers by currents in shallow basins.

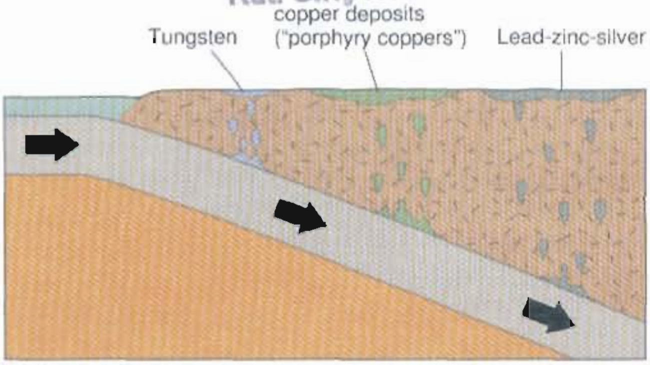


Figure 4.51

Possible relation of ore belts in the western United States to depth along the subduction zone. Different metallic ores (and different igneous rocks) are generated at different depths along a subducted plate.

deposits. Because many ore deposits are associated with igneous activity, there is a close relationship between plate boundaries and metallic ore deposits.

As discussed in chapter 3, *divergent plate boundaries* are often marked by lines of active hot springs in rift valleys that carry and precipitate metallic minerals in mounds around the hot springs. The metals in rift-valley hot springs are predominantly iron, copper, and zinc, with smaller amounts of manganese, gold, and silver. Although the mounds are nearly solid metal sulfide, they are small and widely scattered on the sea floor, so commercial mining of them may not be practical. Occasionally, the ore minerals may be concentrated in richer deposits. On the floor of the Red Sea metallic sediments have precipitated in basins filled with hot-spring solutions. Although the solutions are hot (up to 60°C or 140°F), they are very dense because of their high salt content (they are seven times saltier than sea water), so they collect in sea-floor depressions instead of mixing with the overlying sea water. Although not currently mined, the metallic sediments were estimated in 1983 to be worth $25 billion.

Hot metallic solutions are also found along some divergent continental boundaries. Near the Salton Sea in southern California, which lies along the extension of the mid-oceanic ridge inland, hot water very similar to the Red Sea brines has been discovered underground. The hot water is currently being used to run a geothermal power plant. The high salt and metal content is corrosive to equipment, but metals such as copper and silver may one day be recovered as valuable by-products.

Sea-floor spreading carries the metallic ores away from the ridge crest (figure 4.49), perhaps to be subducted beneath island arcs or continents at *convergent plate boundaries*. Slivers of *ophiolite* on land may contain these rich ore minerals in relatively intact form. A notable example of such ores occurs on the island of Cyprus in the Mediterranean Sea. Banded chromite ores may also be contained in the serpentinized ultramafic rock at the bottom of ophiolites.

Volcanism at *island arcs* can also produce hot-spring deposits on the flanks of the andesitic volcanoes. Pods of very rich ore collect above local bodies of magma, and the ore is sometimes distributed as sedimentary layers in shallow basins (figure 4.50). The circulation pattern and the ore-forming processes are quite similar to those of spreading centers, but the island arc ores usually contain more lead. Rich *massive sulfide deposits* overlying fractured volcanic rock in the Precambrian shield area of Canada may have formed in this way on ancient island arcs.

Subduction of the sea floor beneath a *continent* produces broad belts of metallic ore deposits on the edge of the continent. Figure 4.51 shows how the distribution of some metals in the western United States might be related to depth along a subduction zone (the figure shows only one of several competing models relating continental ore deposits to plate tectonics). The pattern of ore belts in the United States has probably been disturbed by changing subduction angles, strike-slip faulting, and backarc spreading. Similar patterns of ore belts occur in other subduction mountain ranges, notably the Andes.

The origin of the continental ores above a subduction zone is not clear. The hot-spring deposits from the ridge crest

4.2

IN GREATER DEPTH

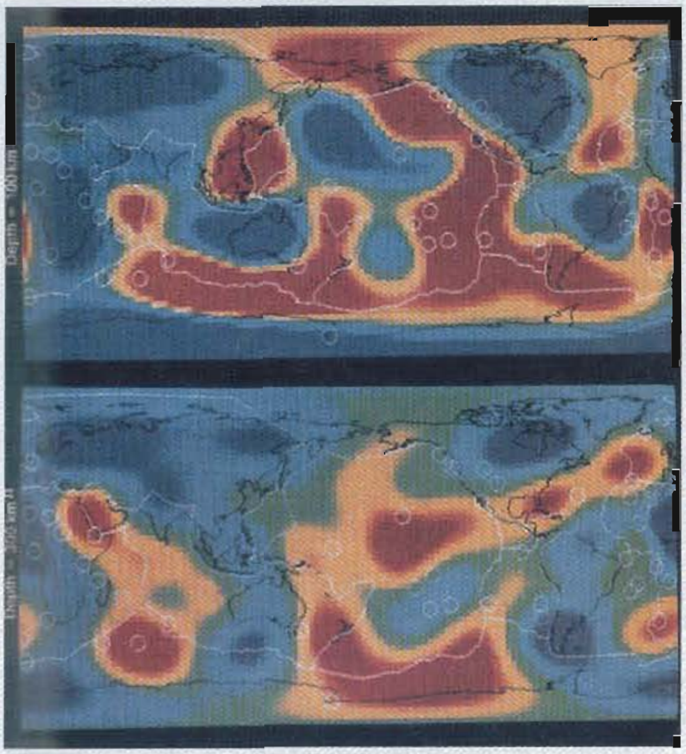
A CAT Scan of the Mantle

A new technique for looking at the mantle is similar to the medical technique of CAT scanning (CAT stands for computed axial tomography), which builds up a three-dimensional picture of soft body tissues such as the brain by taking a series of X-ray pictures along successive planes in the body.

Seismic tomography uses earthquake waves and powerful computers to study planar cross sections of the mantle following large earthquakes. Slight variations from expected arrival times at distant seismograph stations can be used to find temperature variations in the mantle. Hot rock slows down seismic waves, so a late arrival of a seismic wave shows that the wave went through hot rock. Cold rock is dense and strong, so it speeds up seismic waves, resulting in early arrivals. Sophisticated computer analysis of hundreds of sections through the mantle allows maps of seismic-wave velocity (and therefore mantle rock temperature) to be drawn for various depths.

Box figure 1, top shows mantle velocities at a depth of 100 kilometers. Red areas show low velocities (probably caused by hot rock) in generally expected positions—along the crest of the mid-oceanic ridge and beneath hot spots. Blue areas show high-velocity (probably cold) rock under continents and old sea floor such as the western Pacific. Box figure 1, bottom shows that these patterns are dramatically different at a depth of 300 kilometers. High-velocity rock extends to this depth below most continents, implying that continents have very deep roots. Some areas that appear hot at 100 kilometers are cold at 300 kilometers, such as the ridge crest just south of Australia. Areas such as the central Pacific and the Red Sea region appear cold at 100 kilometers and hot at 300 kilometers.

In box figure 2, vertical cross sections of seismic velocity are shown to a depth of 670 kilometers for two regions. Note in box figure 2*A* that high-velocity (cold) roots beneath North America, Asia, and Antarctica extend 400 to 600 kilometers downward. This finding casts doubt on our simple lithosphere-asthenosphere model of plate behavior—continental plates here seem to be hundreds of kilometers thick. Notice, too, how some low-velocity hot spots near Greenland (box figure 2, top) and in the south Atlantic and south Pacific (box figure 2, bottom) are underlain by apparently cold rock. This pattern suggests to some geologists that mantle plumes may be quite shallow and may not extend vertically throughout the mantle. On the other hand, plume tails may be too narrow to be detected by this technique.



Box 4.2 Figure 1

Map views of seismic-wave velocities in the mantle at depths of 100 and 300 kilometers, as determined by seismic tomography. Blue indicates high velocity (cold rock), red indicates low velocity (hot rock). White lines outline plates; white circles are major hot spots.

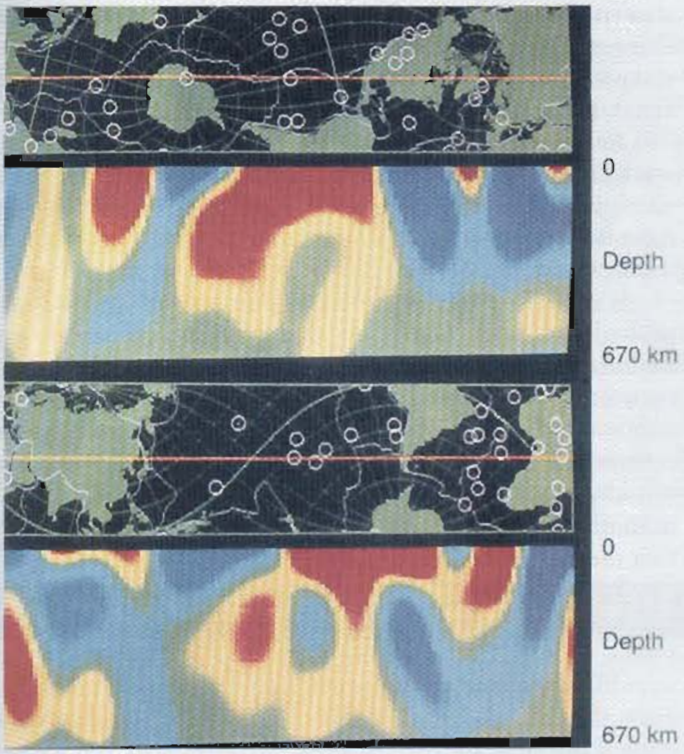
From Dziewonski and Anderson, *American Scientist*, 1984, 72:483–94.

More recent, deeper CAT scans of the mantle (box figure 3) seem to indicate that some mantle plumes emanate from the core-mantle boundary and are fed by heat loss from the core. It is likely that the hot plumes originate from various depths in the mantle.

The new tomographic images reveal high-velocity areas, which are interpreted as cold sinking slabs of subducted

are subducted with oceanic crust and could become remobilized to rise into the continent above. The ores may also "distill" off other parts of the descending oceanic crust or upper mantle. The metals may also derive from the continental crust itself or the mantle below it. The metals may be concentrated somehow by the heat of a rising blob of magma or the hydrothermal circulation associated with it.

The connection between some hydrothermal ore deposits and plate tectonics is tenuous at best. The "Mississippi Valley-type" lead-zinc deposits of the continental interior are very puz-



Box 4.2 Figure 2

Vertical cross sections of seismic-wave velocities to a depth of 670 kilometers in the mantle. The orange lines show the locations of the cross sections.

From Dziewonski and Anderson, *American Scientist*, 1984, 72:483-94.

plates, also extend all the way to the core-mantle boundary (box figures 3 and 4).

Other plates stop descending at the 670-kilometer boundary within the mantle. Perhaps the depth of sinking is controlled by plate density. The older the subducting rock is, the colder and denser it is. Old, dense plates may sink to the base of the mantle, while younger plates, being less dense, stop at a depth of 670 kilometers (box figure 4).

It is becoming increasingly apparent that the core-mantle boundary may play an important role in the overall mechanism of plate movement.

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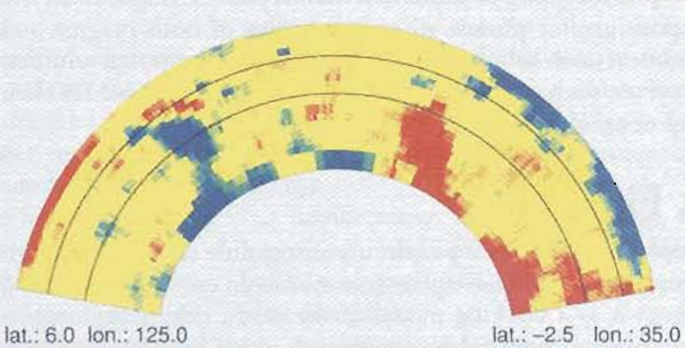
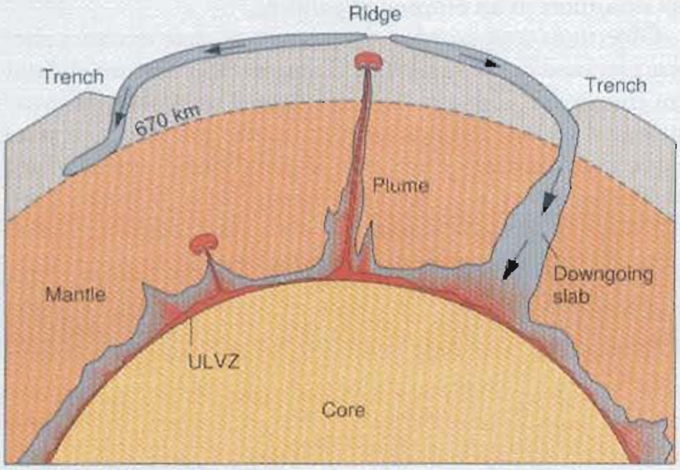


Box 4.2 Figure 3

Cross section of seismic-wave velocities from the earth's surface (upper curve) to core. Blue indicates fast seismic velocities (cold rock), and red indicates low velocities (hot rock). There is a presumed cold slab of rock, shown on the left side of the cross section, that is sinking into the lower mantle into other slabs that rest on the core-mantle boundary. Hot rocks, believed to represent mantle plumes, also emanate from the core-mantle boundary, on the right side of the cross section.

Photo courtesy of Stephen Grand, University of Texas at Austin



Box 4.2 Figure 4

Seismic data suggest some plates sink to the base of the mantle, whereas other plates are impeded by the increase in density of the mantle at 670 km. Deep mantle plumes emanating from the core-mantle boundary are thought to be underlain by an ultralow-velocity zone (ULVZ).

zling features. Over broad areas metal ore has been emplaced in limestone and dolomite, both by cavity filling and replacement (both are usually considered to be hydrothermal processes). There is no obvious connection between the ores and any igneous rocks, which may be absent in the ore regions. The presence of the ores in the thin sedimentary cover of a supposedly inactive interior of a plate is difficult to explain. The ores do group roughly around the New Madrid earthquakes of southeastern Missouri (figure 7.12); deep faults, perhaps on a failed rift, may have provided pathways for ore-bearing fluids.

It is tempting to think that *mantle plumes* might cause ore deposition, for plumes provide a source of both magma and hydrothermal solutions. The locations of supposed plumes, however, such as Yellowstone and Hawaii, are notable for their *lack* of ore deposits.

A Final Note

Geologists, like other people, are susceptible to fads. Although most geologists believe plate tectonics is an exciting theory and accept it as a working model of the earth, the theory may or may not be correct. Most geologists today believe that plates exist and move. But widespread belief in a theory does not make it true. Two hundred years ago geologists "knew" that basalt crystallized out of seawater. In the 1800s glacial deposits were thought to be deposited by Noah's flood. Both of these incorrect ideas were finally disproved by decades of exacting field work and often bitter debate.

Forty years ago continental drift rated only a footnote in most introductory textbooks. Now there are many believers in continental motion, and textbooks use it as a framework for the entire field of physical geology. Although the idea of continental stability provided the framework for many past textbooks, today the idea that continents are fixed in position rates only a footnote as an outmoded concept.

Objections were raised to the concept of plate tectonics after it was proposed in the late 1960s. Some sea-floor features did not seem compatible with a moving sea floor. The geology of many continental regions did not seem to fit into the theory of plate tectonics, in some cases not even slightly. But a revolutionary, new idea in science is always controversial. As it progresses from an "outrageous hypothesis" to a more widely accepted theory, after much discussion and testing, a new idea evolves and changes. The newness of the idea wears off, and successful tests and predictions convert skeptics to supporters (sometimes grudgingly). Perhaps equally importantly, dissenters die off.

As refinements were made to plate tectonics, and as more was learned about the puzzling sea-floor features and continental regions, they began to seem more compatible with plate tectonics. Objections died out, and plate tectonics became widely accepted.

It is wise to remember that at the time of Wegener most geologists vehemently disagreed with continental drift. Because Wegener proposed that continents plow through sea-floor rock, and because his proposed forces for moving continents proved inadequate, most geologists thought that continental drift was wrong. Although these geologists had sound reasons for their dissent, we now think that due to the mounting evidence, continental drift is more acceptable and that the early *geologists* were wrong.

Science should not depend on majority vote. The arguments of a dissenting minority, such as opponents of plate tectonics, should be carefully studied and rationally and scientifically answered, if possible. This is the very heart of science, the careful consideration of *all* possible explanations of natural phenomena.

The evidence for plate tectonics is very convincing. The theory has been rightly called a revolution in earth science, comparable to the development of the theory of evolution in the biological sciences. It is an exciting time to be a geologist. Our whole concept of earth dynamics has changed in the last forty years.

Summary

Plate tectonics is the idea that the earth's surface is divided into several large plates that change position and size. Intense geologic activity occurs at plate boundaries.

Plate tectonics combines the concepts of *sea-floor spreading* and *continental drift.*

Alfred Wegener proposed continental drift in the early 1900s. His evidence included coastline fit, similar fossils and rocks in now-separated continents, and paleoclimatic evidence for *apparent polar wandering.* Wegener proposed that all continents were once joined together in the supercontinent *Pangaea.*

Wegener's ideas were not widely accepted until the 1950s, when work in paleomagnetism revived interest in polar wandering.

Evidence for continental drift includes careful fits of continental edges and detailed rock matches between now-separated continents. The positions of continents during the past 200 million years have been mapped.

Hess's hypothesis of *sea-floor spreading* suggests that the sea floor moves away from the ridge crest and toward trenches as a result of mantle convection.

According to the concept of sea-floor spreading, the high heat flow and volcanism of the ridge crest are caused by hot mantle rock rising beneath the ridge. Divergent *convection* currents in the mantle cause the rift valley and earthquakes on the ridge crest, which is a *spreading axis* (or *center*). New sea floor near the rift valley has not yet accumulated pelagic sediment.

Sea-floor spreading explains trenches as sites of sea-floor *subduction,* which causes low heat flow and negative gravity anomalies. Benioff zones and andesitic volcanism are caused by interaction between the subducting sea floor and the rocks above.

Sea-floor spreading also explains the young age of the rock of the sea floor as caused by the loss of old sea floor through subduction into the mantle.

Plates are composed of blocks of *lithosphere* riding on a plastic *asthenosphere.* Plates move away from spreading axes, which add new sea floor to the trailing edges of the plates.

An apparent confirmation of plate motion came in the 1960s with the correlation of marine *magnetic anomalies* to *magnetic reversals* by Vine and Matthews. The origin of magnetic anomalies at sea apparently is due to the recording of normal and reverse magnetization by dikes that intrude the crest of the mid-oceanic ridge, then split

and move sideways to give anomaly patterns a mirror symmetry.

The Vine-Matthews hypothesis gives the rate of plate motion (generally 1 to 6 cm/year) and can predict the age of the sea floor before it is sampled.

Deep-sea drilling has apparently verified plate motions and the age predictions made from magnetic anomalies.

Earthquake distribution and first-motion studies on *transform faults* on fracture zones also verify plate motions.

Divergent plate boundaries are marked by rift valleys, shallow-focus earthquakes, high heat flow, and basaltic volcanism.

Transform boundaries between plates sliding past one another are marked by strike-slip (transform) faults and shallow-focus earthquakes.

Convergent plate boundaries can cause *subduction* or *continental collision.* Subducting plate boundaries are marked by trenches, low heat flow, Benioff zones, andesitic volcanism, and young mountain belts or island arcs. Continental-collision boundaries have shallow-focus earthquakes and form young mountain belts in continental interiors.

The distribution and origin of most volcanoes, earthquakes, young mountain belts, and major sea-floor features can be explained by plate tectonics.

Plate motion was once thought to be caused by *mantle convection* (either shallow or deep), but is now attributed to the cold, dense, leading edge of a subducting plate pulling the rest of the plate along with it (*slab-pull*). Plates near mid-oceanic ridges also slide down the sloping lithosphere-asthenosphere boundary at the ridge (*ridge-push*). *Trench-suction* may help continents diverge.

Mantle plumes are narrow columns of hot, rising mantle rock. They cause flood basalts and may split continents, causing plate divergence.

An aseismic ridge may form as an oceanic plate moves over a mantle plume acting as an eruptive center (hot spot).

Terms to Remember

asthenosphere 80
continental drift 72
convection 78
convergent plate boundary 80
divergent plate boundary 80
island arc 89
lithosphere 79
magmatic arc 90
mantle plume 98
plate 79
plate tectonics 72
polar wandering 74
sea-floor spreading 72
subduction 78
transform fault 84
transform plate boundary 80

Testing Your Knowledge

Use the questions below to prepare for exams based on this chapter.

1. What was Wegener's evidence for continental drift?
2. What is polar wandering? What is the paleoclimatic evidence for polar wandering? What is the magnetic evidence for polar wandering? Does polar wandering require the poles to move?
3. What is the evidence that South America and Africa were once joined?
4. In a series of sketches show how the South Atlantic Ocean might have formed by the movement of South America and Africa.
5. What is Pangaea?
6. In a single cross-sectional sketch, show the concept of sea-floor spreading and how it relates to the mid-oceanic ridge and oceanic trenches.
7. How does sea-floor spreading account for the age of the sea floor?
8. What is a plate in the concept of plate tectonics?
9. Define *lithosphere* and *asthenosphere*.
10. What is the origin of marine magnetic anomalies according to Vine and Matthews?
11. Why does the pattern of magnetic anomalies at sea match the pattern of magnetic reversals (recorded in lava flows on land)?
12. How has deep-sea drilling tested the concept of plate motion?
13. How has the study of fracture zones tested the concept of plate motion?
14. Explain how plate tectonics can account for the existence of the mid-oceanic ridge and its associated rift valley, earthquakes, high heat flow, and basaltic volcanism.
15. Explain how plate tectonics can account for the existence of oceanic trenches as well as their low heat flow, their negative gravity anomalies, the associated Benioff zones of earthquakes, and andesitic volcanism.

16. What is a transform fault?

17. Discuss possible driving mechanisms for plate tectonics.

18. Describe the various types of plate boundaries and the geologic features associated with them.

19. What is a mantle plume? What is the geologic significance of mantle plumes?

20. The southern supercontinent is called (a) Gondwanaland (b) Pangaea (c) Laurasia (d) Glossopteris

21. The sliding of the sea floor beneath a continent or island arc is called (a) rotation (b) tension (c) subduction (d) polar wandering

22. In cross section, the plates are part of a rigid outer shell of the earth called the (a) lithosphere (b) asthenosphere (c) crust (d) mantle

23. The Vine-Matthews hypothesis explains the origin of (a) polar wandering (b) sea floor magnetic anomalies (c) continental drift (d) mid-ocean ridges

24. The San Andreas fault in California is a (a) normal fault (b) reverse fault (c) transform fault (d) thrust fault

25. What would you most expect to find at ocean-ocean convergence? (a) suture zone (b) island arc (c) mid-ocean ridge

26. What would you most expect to find at ocean-continent convergence? (a) magmatic arc (b) suture zone (c) island arc (d) mid-ocean ridge

27. What would you most expect to find at continent-continent convergence? (a) magmatic arc (b) suture zone (c) island arc (d) mid-ocean ridge

28. Passive continental margins are created at (a) divergent plate boundaries (b) transform faults (c) convergent plate boundaries

29. The Hawaiian islands are thought to be the result of (a) subduction (b) mid-ocean ridge volcanics (c) mantle plumes (d) ocean-ocean convergence

30. Metallic ores are created at diverging plate boundaries (a) through hydrothermal processes (b) in lava flows (c) in sedimentary deposits (d) through metamorphism

Expanding Your Knowledge

1. Plate tectonics helps cool the earth as hot mantle rock rises near the surface at ridge crests and mantle plumes. What can we assume about the internal temperature of other planets that do not seem to have plate tectonics? What would happen to earth's internal temperature if the plates stopped moving?
2. Are ridge offsets along fracture zones easier to explain with mantle-deep convection *causing* plate motion or with shallow convection occurring as a *result* of plate motion?
3. Why are mantle plumes narrow? What conditions at the core-mantle boundary could cause the formation and rise of a mushroom-shaped plume?
4. The slab-pull and ridge-push mechanisms of plate motion may operate only after a plate starts to move. What starts plate motion?
5. If subducting plates can penetrate the 670-kilometer mantle boundary, and perhaps sink all the way to the base of the mantle, why are there no earthquakes deeper than 670 kilometers?

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This Dynamic Earth: The Story of Plate Tectonics U.S. Geological Survey on-line book by W. J. Kious and R. Tilling provides general information about plate tectonics.

http://cddisa.gsfc.nasa.gov/926/slrtecto.html

Tectonic Plate Motion (explains how plate motion is calculated).

http://vishnu.glg.nau.edu/rcb/globaltext.html

View images of plate tectonic reconstructions by R. Blakely at Northern Arizona University.

Continental Drift and Plate Tectonics (UC Santa Barbara)

The Birth of a Theory (Annenburg/CPB Project)

Plate Dynamics (Annenburg/CPB Project)

Interacting with Journey Through Geology CD-ROM

Expand your knowledge of the concepts presented in this chapter by using the CD-ROM to answer the following questions.

1. Use the *Hot Spots* module. Go to "Hawaiian Islands" and then to "Watch Hot Spots Animation." Why do the Hawaiian islands become older to the northwest? Why is the Hawaiian Island chain bent?
2. Use the *Hot Spots* module: Go to "Hawaiian Islands" and click on "Next Volcano." Predict where the next Hawaiian island will emerge. Justify your answer.
3. Go to the *Convergent Margins* module. After the introduction, click on "Alaska," then on "Earthquakes Through Time." Describe the pattern of earthquakes near Cook Inlet in terms of their depth of focus and geographic distribution. What plate tectonic process creates this pattern? Draw a cross-section through this plate boundary, showing where earthquakes of different depths occur.
4. Go to the *Transform Faults* module. After the introduction, click on "Watch Transform Faults Animation." Transform faults usually run between offset segments of a mid-ocean ridge, yet motion along the fault does not further offset the ridge segments. Why not?
5. Use the *Transform Faults* module and click on "Watch the Fault Evolve." How was the San Andreas Fault created?