ocean water—dust from the atmosphere, organic material from marine plants and animals—begin to accumulate as seafloor *sediments* as soon as new oceanic crust forms. Therefore, the age of the oldest sediments in the core, those immediately on top of the crust, tells the geologist how old the ocean floor is at that spot. The age of sediments is obtained primarily from the fossil skeletons of tiny, single-celled animals that live in the ocean and sink to the bottom when they die (see Chapter 10). It was found that the sediments in the cores become older with increasing distance from mid-ocean ridges and that the age of the seafloor at any one place agrees almost perfectly with the age determined from magnetic reversal data. This agreement validated magnetic dating of the seafloor and clinched the concept of seafloor spreading.

Measurements of Plate Motions by Geodesy

In his publications advocating continental drift, Alfred Wegener made a big mistake: he proposed that North America and Europe were drifting apart at a rate of nearly 30 m/year—a thousand times faster than the Atlantic seafloor is actually spreading! This unbelievably high speed was one of the reasons that many scientists roundly rejected his notions of continental drift. Wegener made this estimate by incorrectly assuming that the continents were joined together as Pangaea as recently as the last ice age (which occurred only about 20,000 years ago). His belief in a rapid rate also involved some wishful thinking. In particular, he hoped that the drift hypothesis could be confirmed by repeated, accurate measurements of the distance across the Atlantic Ocean using astronomical positioning.

Figure 2.12 One of the 250 GPS stations in a network that collects satellite observations along faults in southern California. These instruments use signals from GPS satellites orbiting Earth to detect small displacements of the surface, from which plate motions and plate-boundary deformations can be computed. Observations of these motions may help scientists to evaluate future occurrences of earthquakes. [Southern California Earthquake Center.]

Astronomical Positioning Astronomical positioning—measuring the positions of stars in the night sky to determine where you are—is a technique of *geodesy,* the ancient science of measuring the shape of the Earth and locating points on its surface. Surveyors have used astronomical positioning for centuries to determine geographic boundaries on land, and sailors have used it to locate their ships at sea. Four thousand years ago, Egyptian builders used astronomical positioning to aim the Great Pyramid due north.

Wegener imagined that geodesy could be used to measure continental drift in the following way. Two observers, one in Europe and the other in North America, would simultaneously determine their positions relative to the fixed stars. From these positions, they would calculate the distance between their two observing posts at that instant. They would then repeat this distance measurement from the same observing posts sometime later, say, after 1 year. If the continents are drifting apart, then the distance should have increased, and the value of the increase would determine the speed of the drift.

For this technique to work, however, one must determine the relative positions of the observing posts accurately enough to measure the motion. In Wegener's day, the accuracy of astronomical positioning was poor; uncertainties in fixing intercontinental distances exceeded 100 m. Therefore, even at the high rates of motion he was proposing, it would take a number of years to observe drift. He claimed that two astronomical surveys of the distance between Europe and Greenland (where he worked as a meteorologist), taken 6 years apart, supported his high rate, but he was wrong again. We now know that the spreading of the Mid-Atlantic Ridge from one survey to the next was only about a tenth of a meter—a thousand times too small to be observed by the techniques that were then available.

Owing to the high accuracy required to observe plate motions directly, geodetic techniques did not play a significant role in the discovery of plate tectonics. Geologists had to rely on the evidence for seafloor spreading from the geologic record—the magnetic stripes and ages from fossils described earlier. Beginning in the late 1970s, however, an astronomical positioning method was developed that used signals from distant "quasi-stellar radio sources" (quasars) recorded by huge dish antennas. This method can measure intercontinental distances to an amazing accuracy of 1 mm. In 1986, a team of scientists published a set of measurements based on this technique that showed the distance between antennas in Europe (Sweden) and North America (Massachusetts) had increased 19 mm/yr over a period of 5 years, very close to the amount predicted by geologic models of plate tectonics. Wegener's dream of directly measuring continental drift by astronomical positioning was realized at last!

Postscript: Today, the Great Pyramid of Egypt is not aimed directly north, as stated previously, but slightly east of north. Did the ancient Egyptian astronomers make a mistake in orienting the pyramid 40 centuries ago? Archaeologists think probably not. Over this period, Africa drifted enough to rotate the pyramid out of alignment with true north.

Global Positioning System Doing geodesy with big radio telescopes is an expensive operation and is not a practical tool for detailed investigations of plate tectonic motions in remote areas of the world. Since the mid-1980s, geologists have been able to take advantage of a new constellation of 24 Earth-orbiting satellites, called the Global Positioning System (GPS), to make the same types of measurements with the same astounding accuracy using inexpensive, portable radio receivers not much bigger than this book (**Figure 2.12**). GPS receivers record high-frequency radio waves keyed to precise atomic clocks aboard the satellites. The satellite constellation serves as an outside frame of reference, just as the fixed stars and quasars do in astronomical positioning.

The changes in distance between land-based GPS receivers placed on different plates, recorded over several years, agree in both magnitude and direction with those found from magnetic anomalies on the seafloor. These experiments indicate that plate motions are remarkably steady over periods of time ranging from a few years to millions of years. Geologists are now using GPS to measure plate motions on a yearly basis at many locations around the globe (**Figure 2.13**).

Besides determining plate velocities, GPS observations have shown that the convergence between the Nazca and

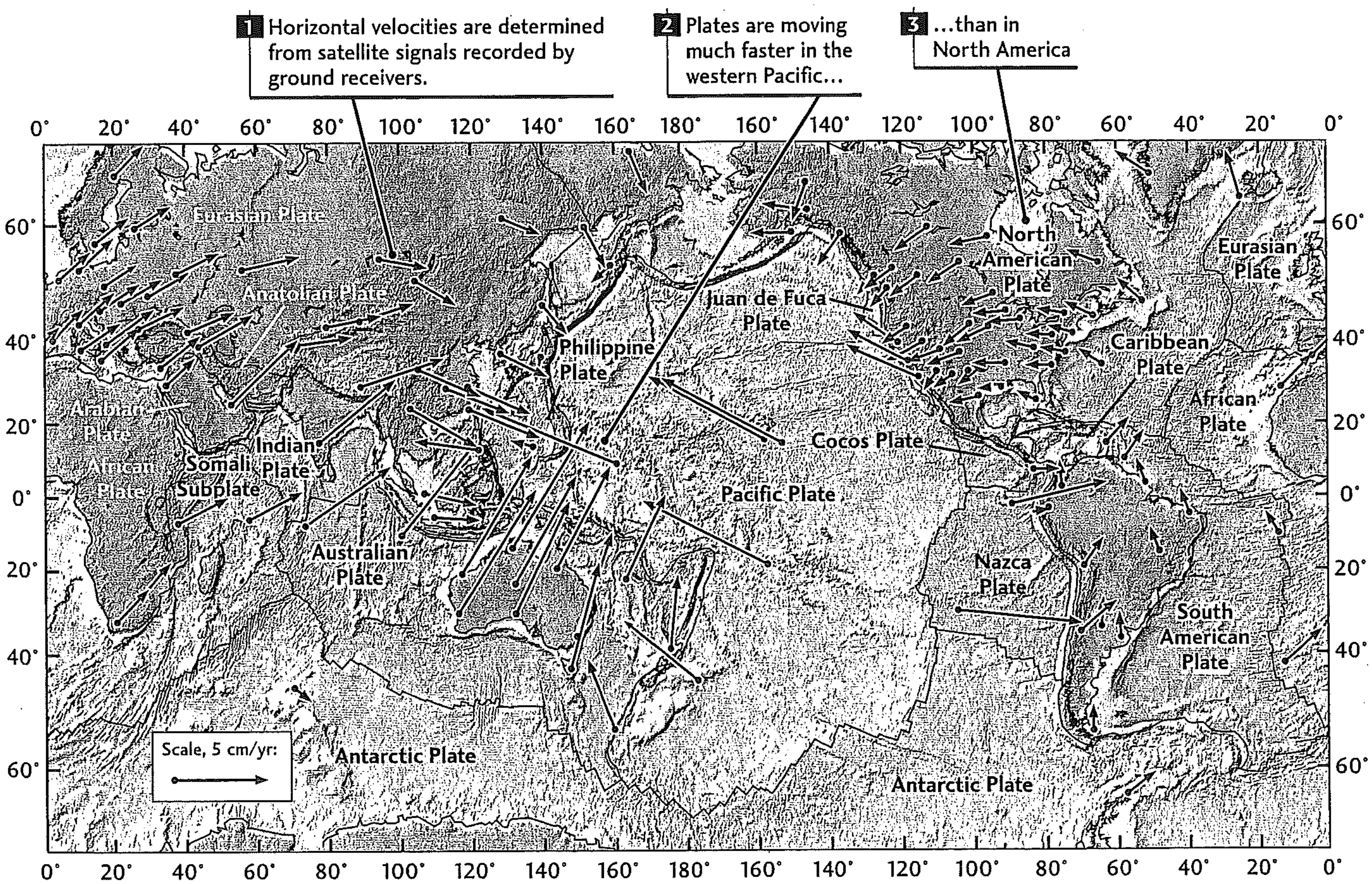


Figure 2.13 The Global Positioning System (GPS) is used to measure plate motions at many locations on Earth. The velocities shown here are determined for stations that continuously record GPS data. [Michael Heflin, JPL/CalTech.]

South American plates can be divided into three parts. About 40 percent is smooth, continuous slip between the two plates. Some 20 percent occurs as deformation at this plate boundary, which causes the uplift of the Andes Mountains. About 40 percent occurs in great earthquakes when the interface between the two plates ruptures and slips suddenly. By definition, a rigid plate should not deform. What is happening here? We will learn more about the process of plate deformation when we study earthquakes in Chapter 19.

Postscript: GPS receivers are now used in automobiles, as part of a navigating system that will lead the driver to a specific street address. It is interesting that the scientists who developed the atomic clocks used in GPS did so for research in fundamental physics and had no idea that they would be creating a multibillion-dollar industry. Along with the transistor, laser, and many other technologies, GPS demonstrates the serendipitous manner in which basic research repays the society that supports it.

The Grand Reconstruction

The supercontinent of Pangaea was the only major landmass that existed 250 million years ago. One of the great triumphs of modern geology is the reconstruction of events that led to the assembly of Pangaea and to its later fragmentation into the continents that we know today. Let's use what we have learned about plate tectonics to see how this feat was accomplished.

Seafloor Isochrons

The colorful map in **Figure 2.14** shows the ages of the world's ocean floors as determined by magnetic reversal data and fossils from deep-sea drilling. Each colored band represents a span of time corresponding to the age of the crust within that band. The boundaries between bands, called **isochrons,** are contours that connect rocks of equal age. Isochrons tell us the time that has elapsed since the

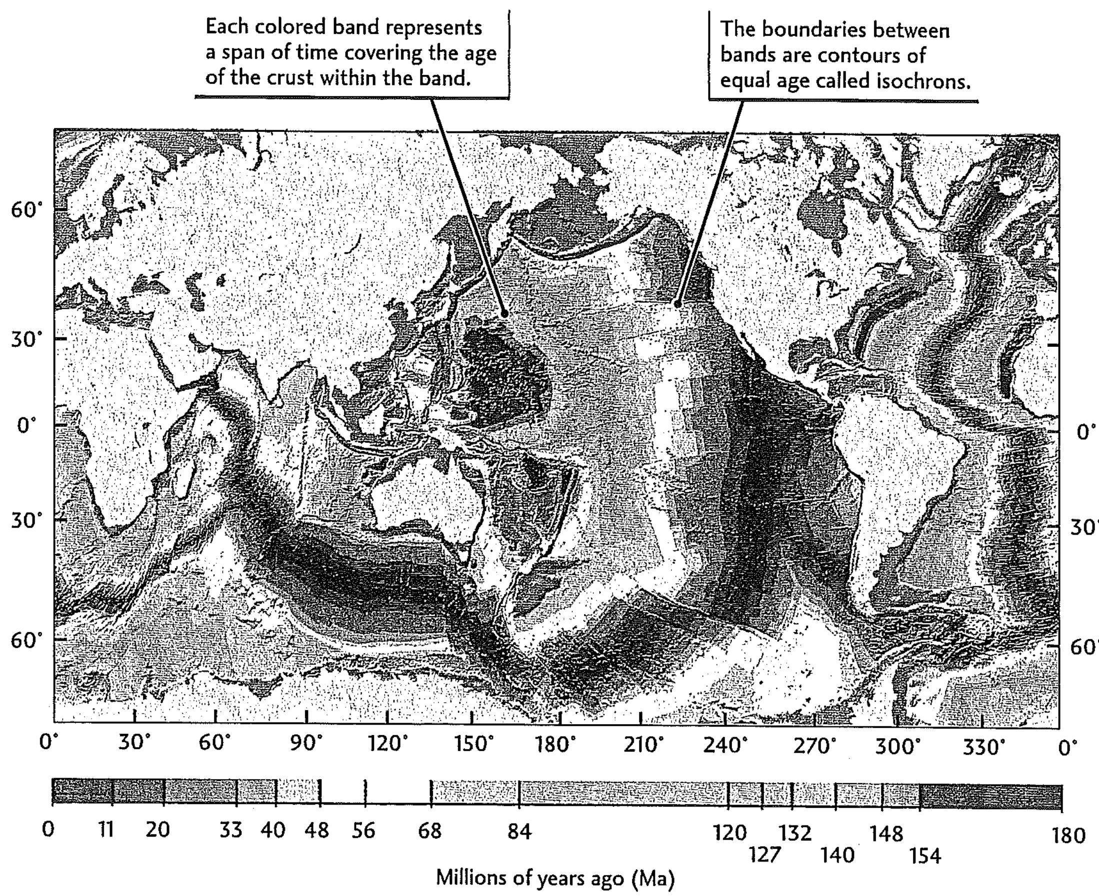


Figure 2.14 Age of seafloor crust. Each colored band represents a span of time covering the age of the crust within the band. The boundaries between bands are contours of equal age called isochrons. Isochrons give the age of the seafloor in millions of years since its creation at mid-ocean ridges. Light gray indicates land. Dark gray indicates shallow water over continental shelves. Mid-ocean ridges, along which new seafloor is extruded, coincide with the youngest seafloor (red). [*Journal of Geophysical Research* 102 (1997): 3211–3214. Courtesy of R. Dietmar Müller.]

crustal rocks were injected as magma into a mid-ocean rift and, therefore, the amount of spreading that has occurred since they formed. Notice how the seafloor becomes progressively older on both sides of the mid-ocean rifts. For example, the distance from a ridge axis to a 140-million-year isochron (boundary between green and blue bands) indicates the extent of new ocean floor created over that time span. The more widely spaced isochrons (the wider colored bands) of the eastern Pacific signify faster spreading rates than those in the Atlantic.

In 1990, after a 20-year search, geologists found the oldest oceanic rocks by drilling into the seafloor of the western Pacific. These rocks turned out to be about 200 million years old, only about 4 percent of Earth's age. This date indicates how geologically young the seafloor is compared with the continents. Over a period of 100 million to 200 million years in some places and only tens of millions of years in others, the ocean lithosphere forms, spreads, cools, and subducts back into the underlying mantle. In contrast, the oldest continental rocks are about 4 billion years old.

Reconstructing the History of Plate Motions

Earth's plates behave as rigid bodies. That is, the distances between three points on the same rigid plate—say, New York, Miami, and Bermuda on the North American Plate—do not change very much, no matter how far the plate moves. But the distance between, say, New York and Lisbon increases because the two cities are on different plates that are being separated along a narrow zone of spreading on the Mid-Atlantic Ridge. The direction of the movement of one plate in relation to another depends on geometric principles that govern the behavior of rigid plates on a sphere. Two primary principles are

1. *Transform boundaries indicate the directions of relative plate movement.* With few exceptions, no overlap, buckling, or separation occurs along typical transform boundaries in the oceans. The two plates merely slide past each other without creating or destroying plate material. Look for a transform boundary if you want to deduce the direction of relative plate motion, because the orientation of the fault is the direction in which one plate slides with respect to the other, as Figure 2.10 shows.

2. *Seafloor isochrons reveal the positions of divergent boundaries in earlier times.* Isochrons on the seafloor are roughly parallel and symmetrical with the ridge axis along which they were created. Figure 2.14 illustrates this observation. Because each isochron was at the boundary of plate separation at an earlier time, isochrons that are of the same age but on opposite sides of an ocean ridge can be brought together to show the positions of the plates and the configuration of the continents embedded in them as they were in that earlier time.

The Breakup of Pangaea

Using these principles, geologists have reconstructed the opening of the Atlantic Ocean and the breakup of Pangaea. The supercontinent of Pangaea is shown as it existed 240 million years ago in **Figure 2.15**a. It began to break apart with the rifting of North America away from Europe about 200 million years ago (Figure 2.15b). The opening of the North Atlantic was accompanied by the separation of the northern continents (Laurasia) from the southern continents (Gondwanaland, or Gondwana) and the rifting of Gondwanaland along what is now the eastern coast of Africa (Figure 2.15c). The breakup of Gondwanaland separated South America, Africa, India, and Antarctica, creating the South Atlantic and Southern oceans and narrowing the Tethys Ocean (Figure 2.15d). The separation of Australia from Antarctica and the ramming of India into Eurasia closed the Tethys Ocean, giving us the world we see today (Figure 2.15e).

The plate motions have not ceased, of course, so the configuration of the continents will continue to evolve. A plausible scenario for the distribution of continents and plate boundaries 50 million years into the future is displayed in Figure 2.15f.

The Assembly of Pangaea by Continental Drift

The isochron map in Figure 2.14 tells us that all of the seafloor extant on Earth's surface has been created since the breakup of Pangaea. We know from the geologic record in older continental mountain belts, however, that plate tectonics was operating for billions of years before this breakup. Evidently, seafloor spreading took place as it does today, and there were previous episodes of continental drift and collision. The seafloor created in these earlier times has been destroyed by subduction back into the mantle, so we must rely on the older evidence preserved on continents to identify and chart the movements of these "paleocontinents."

Old mountain belts such as the Appalachians of North America and the Urals, which separate Europe from Asia, help us locate ancient collisions of the paleocontinents. In many places, the rocks reveal ancient episodes of rifting and subduction. Rock types and fossils also indicate the distribution of ancient seas, glaciers, lowlands, mountains, and climates. The knowledge of ancient climates enables geologists to locate the latitudes at which the continental rocks formed, which in turn helps them to assemble the jigsaw puzzle of ancient continents. When volcanism or mountain building produces new continental rocks, they also record the direction of Earth's magnetic field, just as oceanic rocks do when they are created by seafloor spreading. Like a compass frozen in time, the fossil magnetism of a continental fragment records its ancient orientation and position.

Figure 2.15 shows one of the latest efforts to depict the pre-Pangaean configuration of continents. It is truly

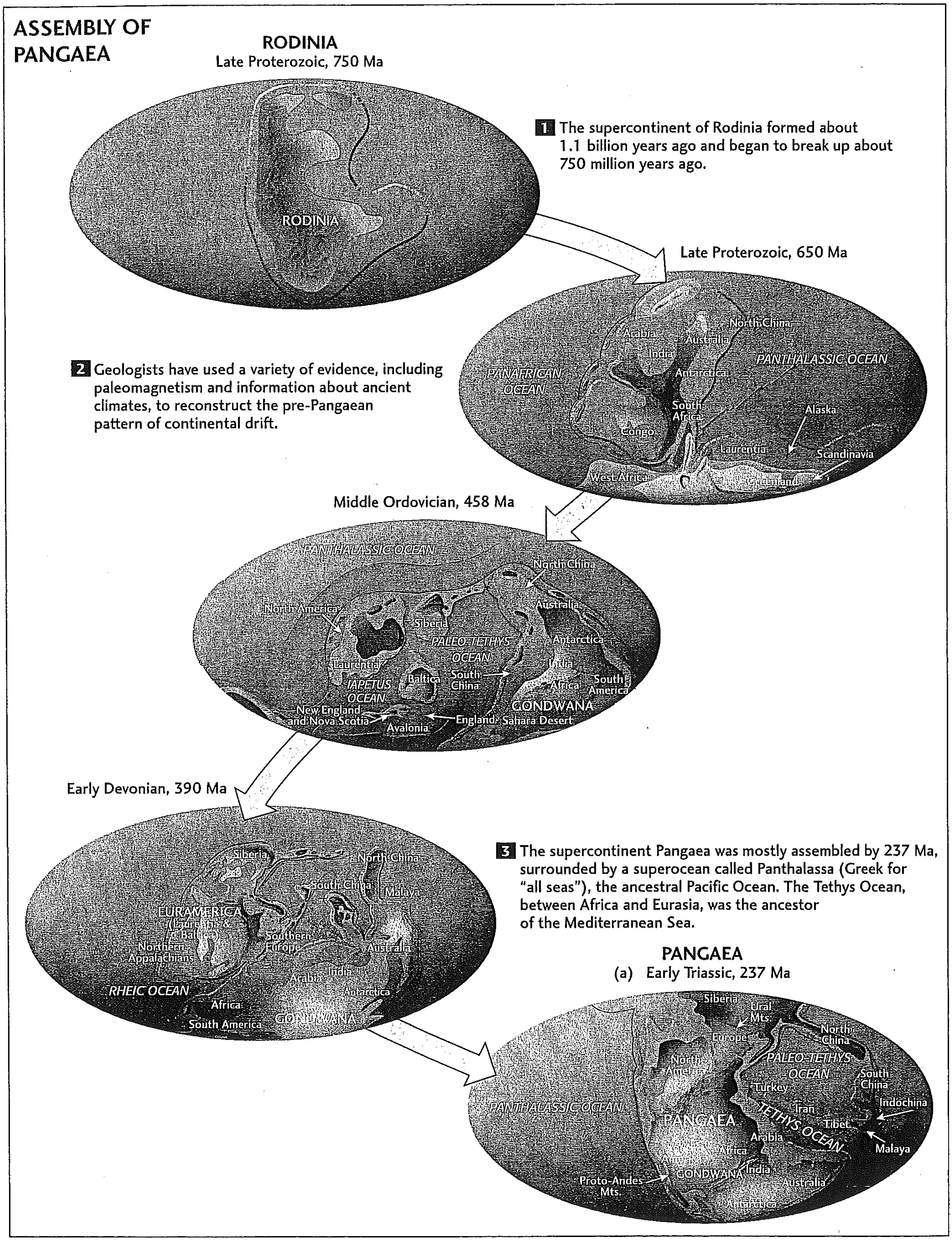
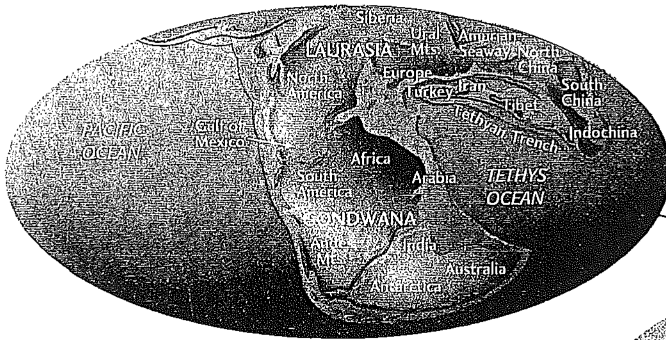


Figure 2.15 The assembly and breakup of Pangaea, from 750 million years ago to 50 million years into the future. [Paleogeographic maps by Christopher R. Scotese, 2003 PALEOMAP Project (www.scotese.com).]

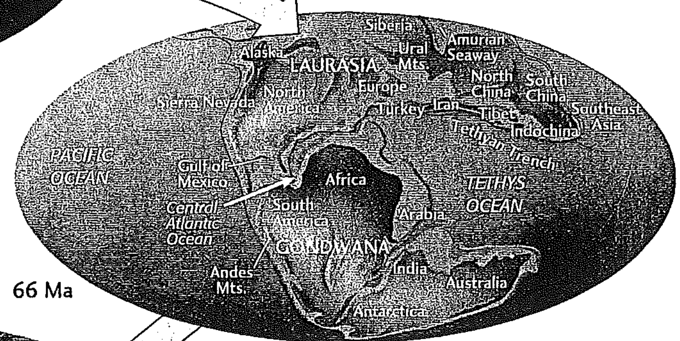
BREAKUP OF PANGAEA

(b) Early Jurassic, 195 Ma



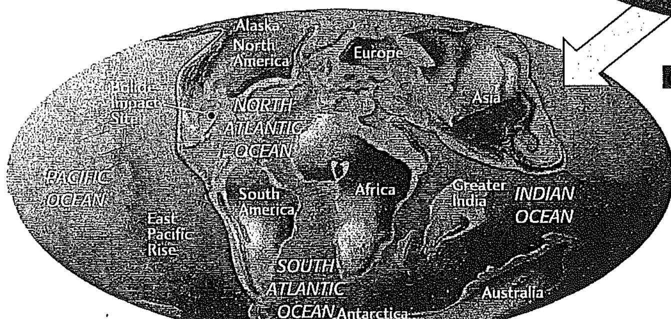
4 The breakup of Pangaea was signaled by the opening of rifts from which lava poured. Rock assemblages that are relics of this great event can be found today in 200-million-year-old volcanic rocks from Nova Scotia to North Carolina and in the great Palisades bluffs along the Hudson River. These rocks tell us that the breakup and the beginning of drift occurred about 200 million years ago.

(c) Late Jurassic, 152 Ma



5 By about 150 million years ago, Pangaea was in the early stages of breakup. The Atlantic Ocean had partially opened, the Tethys Ocean had contracted, and the northern continents (Laurasia) had all but split away from the southern continents. Gondwana (India, Antarctica, and Australia) began to split away from Africa.

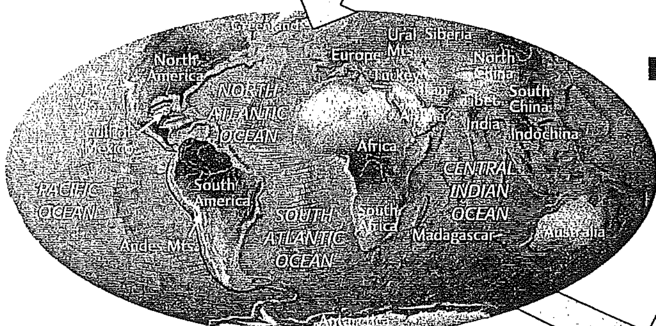
(d) Late Cretaceous, Early Tertiary, 66 Ma



6 By 66 million years ago, the South Atlantic had opened and widened, Madagascar had split from Africa, India was well on its way northward toward Asia, and the Tethys was closing on its way to form an inland sea, the Mediterranean. After about 135 million years of drift, the modern configuration of continents became discernible. The red dot marks the location of the bolide impact that caused the extinction of the dinosaurs and many other forms of life.

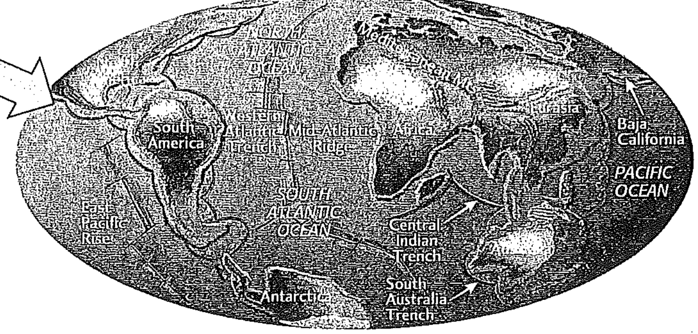
THE MODERN WORLD AND FUTURE

(e) MODERN WORLD



7 The modern world has been produced over the past 65 million years. India collided with Asia, ending its trip across the ocean, and is still pushing northward into Asia. Australia has separated from Antarctica.

(f) 50 million years in the future



impressive that modern science can recover the geography of this strange world of hundreds of millions of years ago. The evidence from rock types, fossils, climate, and paleomagnetism has allowed scientists to reconstruct an earlier supercontinent, called *Rodinia,* that formed about 1.1 billion years ago and began to break up about 750 million years ago. They have been able to chart its fragments over the subsequent 500 million years as these fragments drifted and reassembled into the supercontinent of Pangaea. Geologists are continuing to sort out more details of this complex jigsaw puzzle, whose individual pieces change shape over geologic time.

Implications of the Grand Reconstruction

Hardly any branch of geology remains untouched by this grand reconstruction of the continents. Economic geologists have used the fit of the continents to find mineral and oil deposits by correlating the rock formations in which they exist on one continent with their predrift continuations on another continent. Paleontologists have rethought some aspects of evolution in the light of continental drift. Geologists have broadened their focus from the geology of a particular region to a world-encompassing picture, because the concept of plate tectonics provides a way to interpret, in global terms, such geologic processes as rock formation, mountain building, and climate change.

Oceanographers are reconstructing currents as they might have existed in the ancestral oceans to understand the modern circulation better and to account for the variations in deep-sea sediments that are affected by such currents. Scientists are "forecasting" backward in time to describe temperatures, winds, the extent of continental glaciers, and the level of the sea as they were in predrift times. They hope to learn from the past so that they can predict the future better—a matter of great urgency because of the possibility of greenhouse warming triggered by human activity. What better testimony to the triumph of this once outrageous hypothesis than its ability to revitalize and shed light on so many diverse topics?

Mantle Convection: The Engine of Plate Tectonics

Everything discussed so far might be called descriptive plate tectonics. But a description is hardly an explanation. We will not fully understand plate tectonics until we have a more comprehensive theory that can explain why plates move. Finding such a theory remains one of the outstanding challenges confronting scientists who study the Earth system. In this section, we will discuss several aspects of the problem that have been central to the recent research by these scientists.

As Arthur Holmes and other early advocates of continental drift realized, mantle convection is the "engine" that drives the large-scale tectonic processes operating on Earth's surface. In Chapter 1, we described the mantle as a hot solid capable of flowing like a sticky fluid (warm wax or cold syrup, for example). Heat escaping from Earth's deep interior causes this material to convect (circulate upward and downward) at speeds of a few tens of millimeters per year.

Almost all scientists now accept that the lithospheric plates somehow participate in the flow of this mantle convection system. As is often the case, however, "the devil is in the details." Many different hypotheses have been advanced on the basis of one piece of evidence or another, but no one has yet come up with a satisfactory, comprehensive theory that ties everything together. In what follows, we will pose three questions that get at the heart of the matter and give you our opinions regarding their answers. But you should be careful not to accept these tentative answers as facts. Our understanding of the mantle convection system remains a work in progress, which we may have to alter as new evidence becomes available. Future editions of this book may contain different answers!

Where Do the Plate-Driving Forces Originate?

Here's an experiment you can do in your kitchen: heat up a pan of water until it is about to boil and sprinkle some dry tea leaves into the center of the pan. You will notice that the tea leaves move across the surface of the water, dragged along by the convection currents in the pan. Is this the way plates move about, passively dragged to and fro on the backs of convection currents rising up from the mantle?

The answer appears to be no. The main evidence comes from the rates of plate motion we discussed earlier in this chapter. From Figure 2.5, we see that the faster-moving plates (the Pacific, Nazca, Cocos, and Indian plates) are being subducted along a large fraction of their boundaries. In contrast, the slower-moving plates (the North American, South American, African, Eurasian, and Antarctic plates) do not have significant attachments of downgoing slabs. These observations suggest that rapid plate motions are caused by the gravitational pull exerted by the cold (and thus heavy) slabs of old lithosphere. In other words, the plates are not dragged along by convection currents from the deep mantle but rather "fall back" into the mantle under their own weight. According to this hypothesis, seafloor spreading is the passive upwelling of mantle material where the plates have been pulled apart by subduction forces.

But wait—if the only important force in plate tectonics is the gravitational pull of subducting slabs, why did Pangaea break apart and the Atlantic Ocean open up? The only subducting slabs of lithosphere currently attached to the North and South American plates are found in the small island arcs that bound the Caribbean and Scotia seas, which are thought to be too wimpy to drag the Atlantic apart. One possibility is that the overriding plates, as well as the sub-

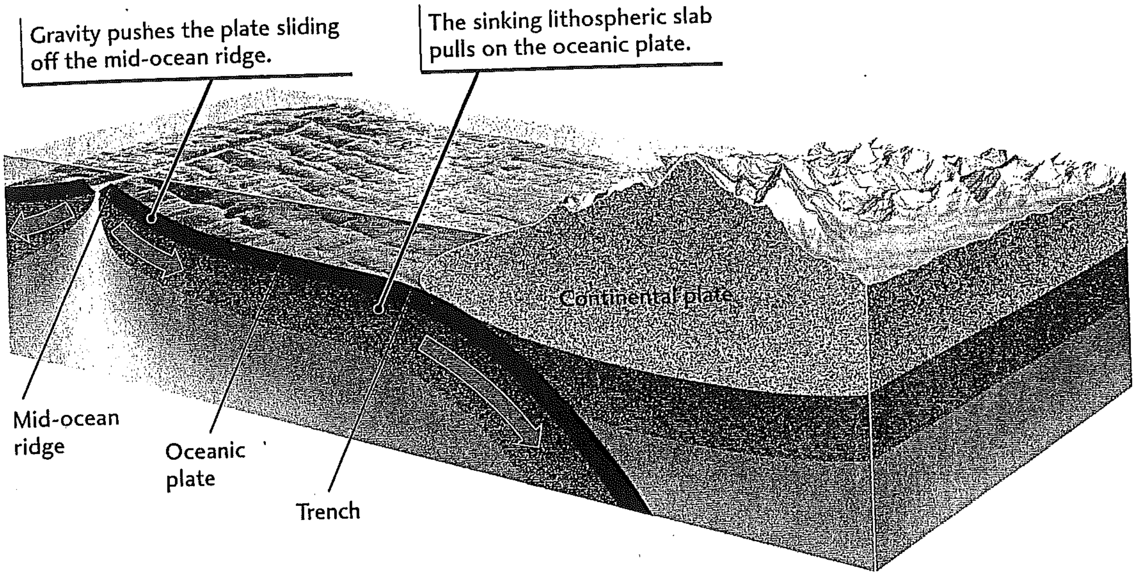


Figure 2.16 A schematic cross section through the outer part of Earth, illustrating two of the forces thought to be important in driving plate tectonics: the pulling force of a sinking lithospheric slab and the pushing force of plates sliding off a mid-ocean ridge. [Adapted from Figure 1 in an article by D. Forsyth and S. Uyeda, *Geophys. J. Roy. Astr. Soc.* 43 (1975): 163–200.]

ducting plates, are pulled toward their convergent boundaries. For example, as the Nazca Plate subducts beneath South America, it may cause the plate boundary at the Peru-Chile Trench to retreat toward the Pacific, "sucking" the South American Plate to the west.

Another possibility is that Pangaea acted like an insulating blanket, preventing heat from getting out of Earth's mantle (as it usually does through the process of seafloor spreading). This heat presumably built up over time, causing hot bulges to form in the mantle beneath the supercontinent. These bulges raised Pangaea (slightly) and caused it to rift apart in a kind of "landslide" off the top of the bulges. These gravitational forces continued to drive subsequent seafloor spreading as the plates "slid downhill" off the crest of the Mid-Atlantic Ridge. Earthquakes that sometimes occur in plate interiors show direct evidence of the compression of plates by these "ridge push" forces.

As you can tell from this brief discussion, the driving forces of plate tectonics probably involve several types of interactions. All of them are manifestations of convection in the mantle, in the sense that they involve hot matter rising in one place and cold matter sinking in another (**Figure 2.16**). Although many questions remain, we can be reasonably sure that (1) the plates themselves play an active role in this system, and (2) the forces associated with the sinking slabs and elevated ridges are probably the most important in governing the rates of plate motion. Scientists are attempting to resolve other issues raised in this discussion by comparing observations with detailed computer models of the mantle convection system. Some results will be discussed in Chapter 21.

How Deep Does Plate Recycling Occur?

For plate tectonics to work, the lithospheric material that goes down in subduction zones must be recycled through the mantle and eventually come back up as new lithosphere created along the spreading centers of the mid-ocean ridges. How deep into the mantle does this recycling process extend? That is, where is the lower boundary of the mantle convection system?

The deepest it can reach is about 2900 km below Earth's outer surface, where a sharp boundary separates the mantle from the core. The iron-rich liquid below this *core-mantle boundary* is much denser than the solid rocks of the mantle, preventing any significant interchange of material between the two layers. We can thus imagine a system of "whole-mantle" convection in which the material from the plates circulates all the way through the mantle, down as far as the core-mantle boundary (**Figure 2.17**a).

In the early days of plate tectonics theory, however, many scientists were convinced that plate recycling takes place at much shallower depths in the mantle. The evidence came from deep earthquakes that mark the descent of lithospheric slabs in subduction zones. The greatest depth of these earthquakes varies among subduction zones, depending on how cold the descending slabs are, but geologists found that no earthquakes were occurring below about 700 km. Moreover,

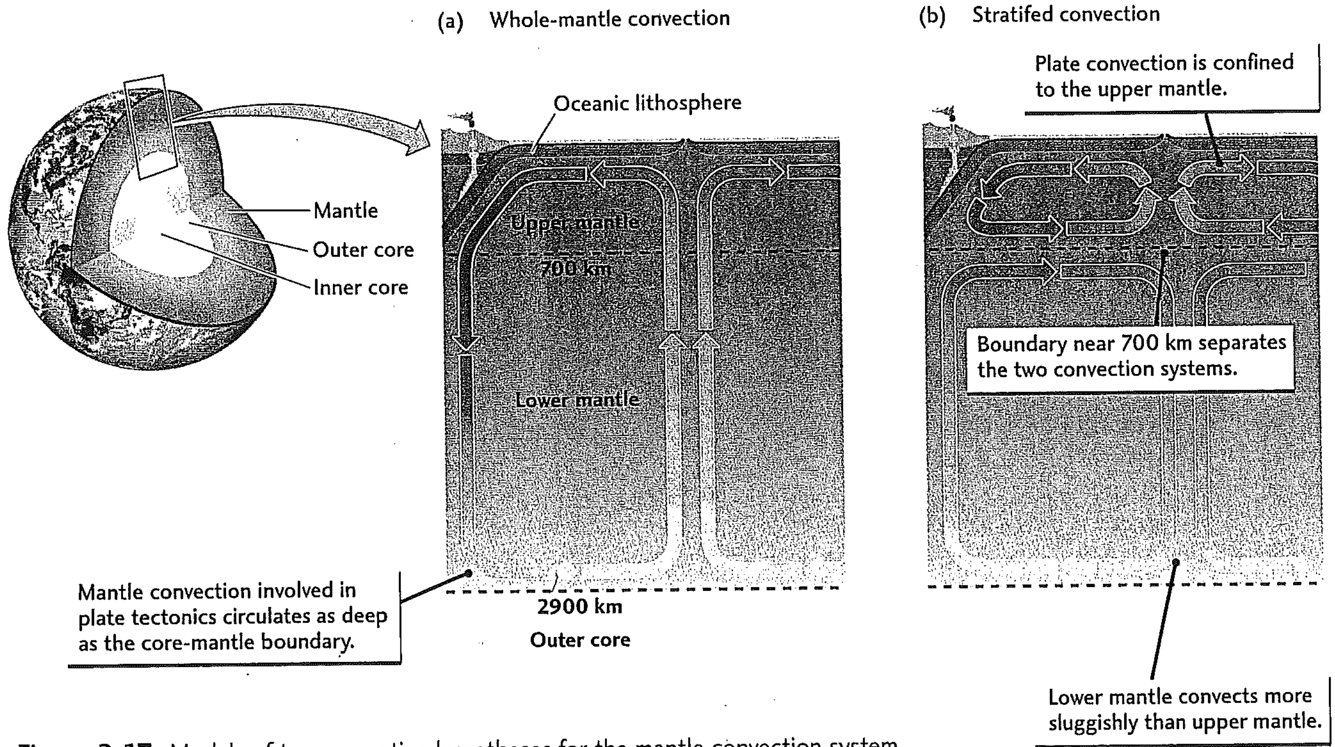


Figure 2.17 Models of two competing hypotheses for the mantle convection system.

the properties of earthquakes at these great depths indicated that the slabs were encountering more rigid material that slowed and perhaps blocked their downward progress.

Based on this and other evidence, scientists concluded that the mantle might be divided into two layers: an upper mantle system in the outer 700 km, where the recycling of lithosphere takes place, and a lower mantle system, from 700 km deep to the core-mantle boundary, where convection is much more sluggish. According to this hypothesis, called "stratified convection," the separation of the two systems is maintained because the upper system consists of lighter rocks than the lower system and thus floats on top, in the same way the mantle floats on the core (Figure 2.17b).

The way to test these two competing hypotheses is to look for "lithospheric graveyards" below the convergent zones where old plates have been subducted. Old subducted lithosphere is colder than the surrounding mantle and can therefore be "seen" using earthquake waves (much as doctors use ultrasound waves to look into your body). Moreover, there should be lots of it down there. From our knowledge of past plate motions, we can estimate that, just since the breakup of Pangaea, lithosphere equivalent to the surface area of Earth has been recycled back into the mantle. Sure enough, scientists have found regions of colder material in the deep mantle under North and South America, eastern Asia, and other sites adjacent to plate collision boundaries. These zones occur as extensions of descending lithospheric slabs, and some appear to go down as far as the core-mantle boundary. From this evidence, most scientists have concluded that plate recycling takes place through whole-mantle convection rather than stratified convection.

What Is the Nature of Rising Convection Currents?

Mantle convection implies that what goes down must come up. Scientists have learned a lot about downgoing convection currents because they are marked by narrow zones of cold subducted lithosphere that can be detected by earthquake waves. What about the rising currents of mantle material needed to balance subduction? Are there concentrated, sheetlike upwellings directly beneath the mid-ocean ridges? Most scientists who study the problem think not. Instead, they believe that the rising currents are slower and spread out over broader regions. This view is consistent with the idea, discussed above, that seafloor spreading is a rather passive process: pull the plates apart almost anywhere, and you will generate a spreading center.

There is one big exception, however: a type of narrow, jetlike upwelling called a *mantle plume* (**Figure 2.18**). The best evidence for mantle plumes comes from regions of intense, localized volcanism (called *hot spots*), such as Hawaii, where huge volcanoes are being formed in the middle of plates, far away from any spreading center. The plumes are thought to be slender cylinders of fast-rising material, less than 100 km across, that come from the deep mantle, perhaps forming in very hot regions near the core-mantle boundary. Mantle plumes are so intense that they

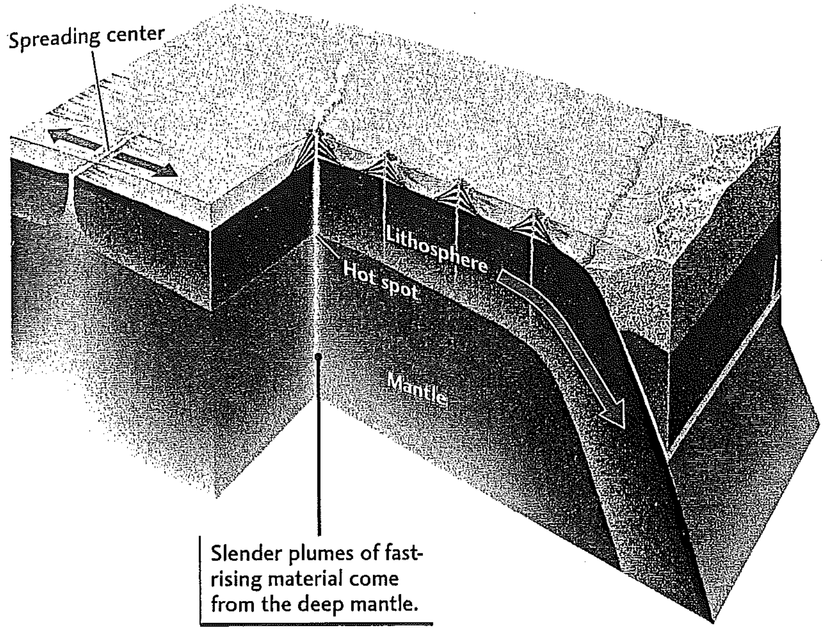


Figure 2.18 A model of the mantle plume hypothesis.

can literally burn holes in the plates and erupt tremendous volumes of lava. Plumes may be responsible for the massive outpourings of lava—millions of cubic kilometers—found in such places as Siberia and the Columbia Plateau of eastern Washington and Oregon. Some of these lava "floods" were so large and occurred so quickly that they may have changed Earth's climate and killed off many life-forms in mass extinction events (see Chapter 1). We will describe plume volcanism in more detail in Chapter 6.

The plume hypothesis was first put forward by one of the founders of plate tectonics, W. Jason Morgan of Princeton University, in 1970, soon after the plate theory had been established. Like other aspects of the mantle convection system, however, the observations that bear on rising convection currents are indirect, and the plume hypothesis remains very controversial.

The Theory of Plate Tectonics and the Scientific Method

Earlier, we considered the scientific method and the ways in which it guides the work of geologists. In the context of the scientific method, plate tectonics is not a dogma but a confirmed theory whose strength lies in its simplicity, its generality, and its consistency with many types of observations. Theories can always be overturned or modified. As we have seen, competing hypotheses have been advanced about how convection generates plate tectonics. But the theory of plate tectonics—like the theories of the age of Earth, the evolution of life, and genetics—explains so much so well and has survived so many efforts to prove it false that geologists treat it as fact.

The question remains, why wasn't plate tectonics discovered earlier? Why did it take the scientific establishment so long to move from skepticism about continental drift to acceptance of plate tectonics? Scientists work in different styles. Scientists with particularly inquiring, uninhibited, and synthesizing minds are often the first to perceive great truths. Although their perceptions frequently turn out to be false (think of the mistakes Wegener made in proposing continental drift), these visionary people are often the first to see the great generalizations of science. Deservedly, they are the ones that history remembers.

Most scientists, however, proceed more cautiously and wait out the slow process of gathering supporting evidence. Continental drift and seafloor spreading were slow to be accepted largely because the audacious ideas came far ahead of the firm evidence. The oceans had to be explored, new instruments had to be developed and used, and the deep sea had to be drilled to see what was there before the majority could be convinced. Today, many scientists are still waiting to be convinced of ideas about how the mantle convection system really works.

SUMMARY

What is the theory of plate tectonics? According to the theory of plate tectonics, the lithosphere is broken into about a dozen rigid, moving plates. Three types of plate boundaries are defined by the relative motion between plates: divergent, convergent, and transform fault.

What are some of the geologic characteristics of plate boundaries? In addition to earthquake belts, many