3

The Origin of Ocean Basins

There rolls the deep where grew the tree
O earth, what changes hast thou seen!
There where the long street roars hath been
The stillness of the central sea.
The hills are shadows, and they flow
From form to form, and nothing stands;
They melt like mist, the solid lands,
Like clouds they shape themselves and go.
—*Alfred Lord Tennyson,*
In Memoriam, *1850*

web navigator

critical thinking on the web

math tutor on the web

PREVIEW

ONCE YOU HAVE COMPLETED this chapter, you will understand Tennyson's meaning: that the Earth's surface—its rocks and topography—is not dormant, but is actively changing and evolving. The Earth is a pulsating planetary body, engaging in grand geologic cycles as its immense ocean basins expand and contract, and its towering mountains are raised upward and beveled downward. At first, it's quite difficult to understand that mountains and ocean basins grow; they seem so solid and inert over our lifetimes. But change they do, as we will discover. According to current theories, the oceans and continents are continually created and recreated. "All that is solid melts into air" when viewed across dumfounding intervals of geologic time. This colossal geologic drama is the central topic of this chapter.

The chapter begins with an examination of the drift patterns of continents (continental drift) and ocean basins (seafloor spreading). Then, we'll inspect the details of a remarkable scientific idea—global plate tectonics—that accounts for the geologic and geophysical properties of the ocean floor and the land's mountain ranges.

One of the main concerns of marine geologists is tracing the development of the ocean basins since their formation on the Earth. Geologists use the term **ocean basin** to refer to the large portion of the oceans' floor that lies deeper than 2,000 meters (~6,600 feet) below sea level. In other words, ocean basins are huge topographic depressions, literally gigantic holes in the Earth's surface. Despite the fact that these basins are composed of rigid rock, their shape and size change slowly but surely with time. How is this possible? Aren't rocks as solid and unchangeable a natural material as exist anywhere? Indeed they are—from year to year, and even from generation to generation. But when viewed across enormous time spans, over millions of years, they no longer appear rigid, but flow ever so slowly (somewhat like a syrupy fluid) in reaction to the high temperatures and pressures that exist in the Earth's interior. Even the continents are not anchored lastingly to one spot on the Earth's surface as we portray them on maps, but are wandering across the globe with the passage of geologic time. As you read this, the building where you are is drifting slowly, but relentlessly, with the continent on which it is located. Our maps represent merely still photographs of continents in motion over geologic time; the geography we see as so permanent is not.

3-1

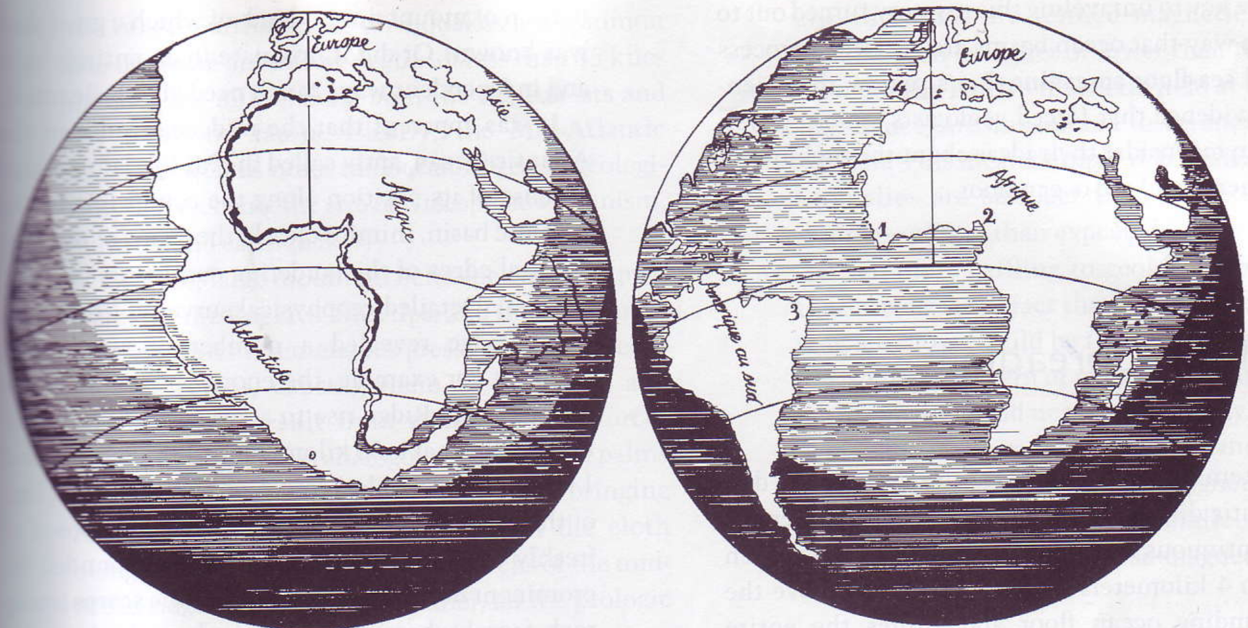
Continental Drift

A look at any world map shows the striking jigsaw-puzzle fit of the coastlines on either side of the Atlantic Ocean. Prominent bulges of land are matched across the sea by equally imposing embayments with similar geometries. This parallelism is most noticeable in the opposing edges of Africa and South America (**Figure 3–1**). In fact, careful matching of the edges of all the continents shows that they can be reassembled into a single large landmass of immense size. This implies that the continents have moved vast distances relative to one another, making the present geography of the Earth quite different from what it was in the geologic past.

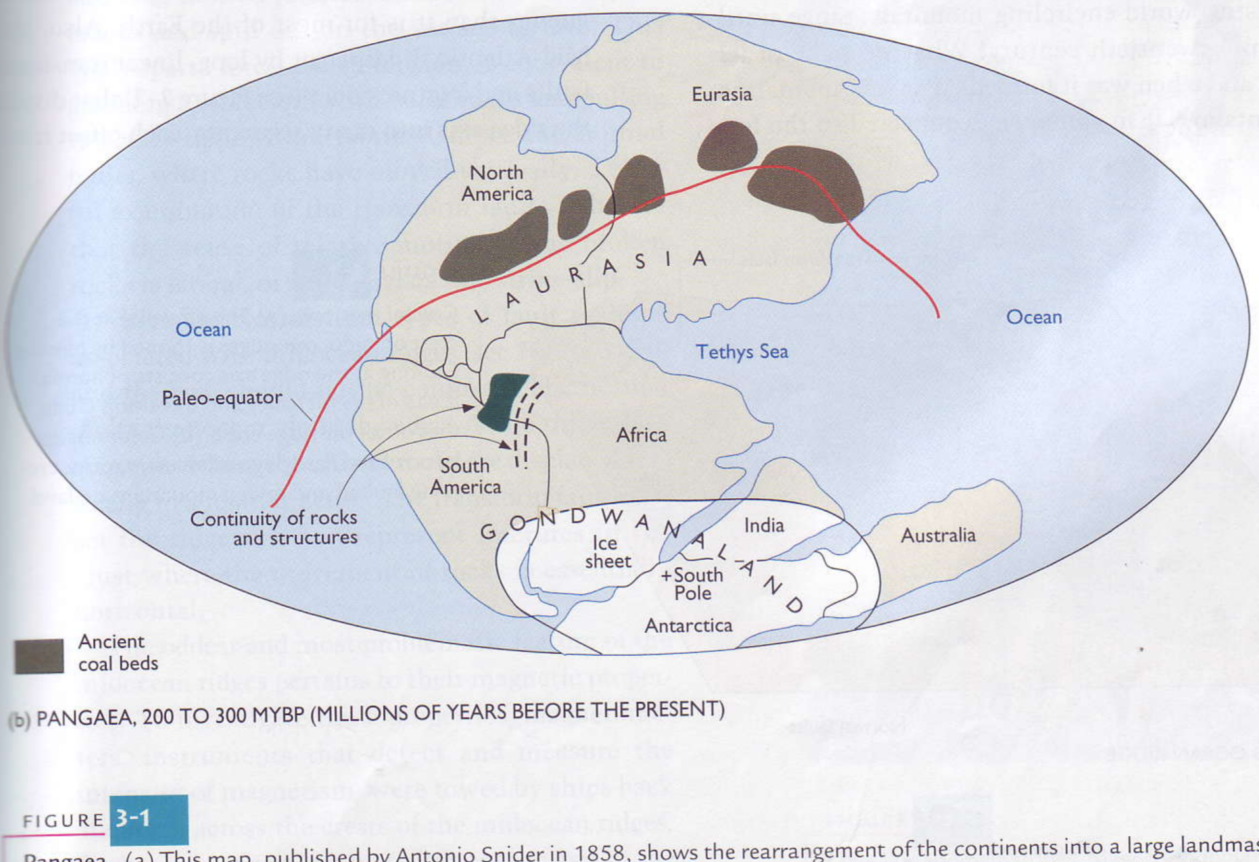
In 1915 Alfred Wegener (1880–1930), a German meteorologist, published a book in which he proposed a bold new hypothesis for understanding the Earth's history—**continental drift**. According to Wegener, geologic and **paleontological** (fossil) information indicated that the present continents had been parts of a much larger landmass more than 200 million years ago. He surmised that some 100 million to 150 million years before the present, this large landmass, which he called **Pangaea** (Figure 3–1), splintered apart, and the fragments (the present-day continents) slowly drifted away from one another, opening new ocean basins between them.

Relying on detailed geographic and geologic reconstructions and abundant fossil and paleoclimatological (ancient climates) evidence, Wegener proposed that Pangaea broke apart along a global system of fractures, or geologic faults, that shattered the granitic crust of the land. The granite of the resulting continental fragments, Wegener surmised, "plowed" through the basalt crust of the oceans. Concurrently, fresh basalt was injected into the widening gap between the Americas and Africa-Europe, creating a juvenile Atlantic Ocean. During this drifting episode, the leading, western edges of North and South America were buckled into the Rocky and Andes mountains when the dense basalt crust of the Pacific Ocean resisted the drift. Just what caused the continents to drift was not apparent to Wegener.

The notion that these huge continental masses of granite were adrift struck many scientists of the time as being a bit far-fetched, more like science fiction than natural science. They particularly objected to Wegener's assertion that the light granitic crust of the continents could "plow" its way through the denser, and therefore stronger, basalt crust of the oceans. Besides, the geophysicists showed that the driving mechanism for continental drift proposed by Wegener was not possible according to their calculations. Though some reactions among geologists to such a new, bold concept bordered more on fascination than outrage, geologic orthodoxy prevailed, and Wegener's theory of continental drift was ignored for more than half a century. Later work by geological oceanographers confirmed the mobility of the continents, elevating the continental-drift idea from the realm of the impossible to a status as certain as any theory in science can hold.



(a) FITTING THE CONTINENTS TOGETHER



(b) PANGAEA, 200 TO 300 MYBP (MILLIONS OF YEARS BEFORE THE PRESENT)

FIGURE 3-1

Pangaea. (a) This map, published by Antonio Snider in 1858, shows the rearrangement of the continents into a large landmass. (b) If the continents are arranged into the megacontinent Pangaea (Laurasia to the north and Gondwanaland to the south), coal beds and glacial deposits that are 200 to 300 million years old fall into latitudinal belts instead of being scattered about everywhere.

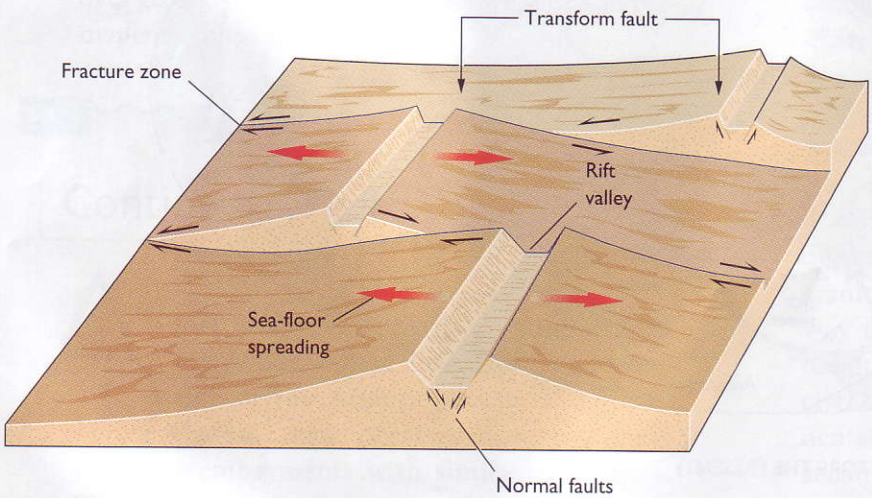
The key to unraveling this mystery turned out to be the way that ocean basins are created, a process called **sea-floor spreading**. Let's review the scientific evidence that forced geologists and geophysicists to reconsider their ideas about the mobility of continents and the ocean floor.

3-2

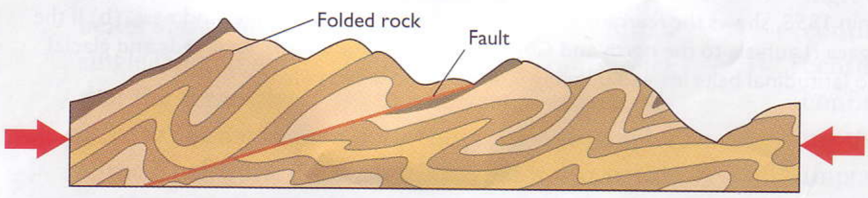
Sea-Floor Spreading

Systematic soundings of the deep sea led to a dramatic discovery—the presence of a submerged, continuous mountain range that rises as much as 3 to 4 kilometers (~1.9 to 2.5 miles) above the surrounding ocean floor and girdles the entire Earth. Its total length of over 60,000 kilometers (~36,365 miles) dwarfs the more familiar mountain belts on land; yet, humans were unaware of this majestic, world-encircling mountain range until the mid-twentieth century! What to make of it? How and when was it formed? Was this submarine mountain belt in some way connected to the formation of mountains on land, of which a great deal was known? Or did it originate in an entirely new and independent way? Much needed to be learned.

It was apparent that the midocean ridge in the Atlantic Ocean, aptly called the Mid-Atlantic Ridge because of its position along the center line of the Atlantic basin, mimics clearly the shape of the continental edges of the bordering continents (see Figure 2–2). Detailed geophysical surveys of this midocean ridge revealed a number of remarkable features. For example, the enormous flanks of the Mid-Atlantic Ridge rise to a sharp crest. A prominent valley that is 50 kilometers (31 miles) wide and 1 kilometer (0.6 miles) deep runs along the crest line of the ridge. The floor of this valley is composed of freshly crystallized young basalt and bounded by prominent **normal faults**—topographic **scarps** (steep rock faces) where crustal rocks have broken and dropped past one another creating the valley (**Figure 3–2a**). The amount of heat escaping from the Earth's interior at the ridge's crest is as much as ten times greater than it is for most of the Earth. Also, the Mid-Atlantic Ridge is cut by long, linear transform faults and fracture zones (see Figure 2–2) that divide the ridge axis into many segments, each offset from



(a) SEGMENTED OCEAN RIDGE



(b) SEDIMENTARY ROCKS SQUEEZED BY COMPRESSION

FIGURE 3-2

Crustal motions. (a) The rift valley at the crest of midocean ridges is formed by tension. Faulting at the ridge axis consists of normal faults of the rift valley and transform faults that offset the ridge crest. (b) Compression has crushed flat-lying sedimentary rocks, creating faulted and folded mountains on land.

the other. Furthermore, earthquakes are common and originate at shallow depths of less than 35 kilometers (~22 miles) along both the ridge crests and the transform faults. Clearly, the Mid-Atlantic Ridge, as well as other midocean ridges, is geologically active, being the site of widespread volcanism, faulting, and earthquakes.

On land, large mountain belts such as the Appalachians, the Rockies, the Alps, and the Himalayas are the result of tremendous pressures that squeeze rocks together, causing them to be folded and faulted. Folds result from **compressional** forces (**Figure 3–2b**). This is analogous to laying the palms of your hands flat on a tablecloth and bringing them together. This action results in the cloth being folded by compression. The rocks of the midocean ridges are not folded. Rather, all the geologic evidence indicates that these mountains have been stretched and pulled apart, creating the normal faults at the shoulders of the crestal rift valley and allowing molten (melted) basalt to rise along the cracks and spill out on the surface as lava. This "pull-apart" force, called **tension**, is equivalent to grabbing a tablecloth with both hands and pulling it apart, ripping the fabric. Unlike the normal faults, where rocks have moved vertically, a careful examination of the transform faults indicates that the sense of relative motion of the broken rocks is lateral, or as geologists say, **strike-slip**.

There are two distinct types of fault systems associated with midocean ridges (see Figure 3–2a), and the two should not be confused. The normal faults that occur along the edges of the rift valleys are zones where the crustal rocks are displaced vertically in a relative sense. The transform faults offset the ridge axis and represent fractures in the crust where the movement of rocks is essentially horizontal.

The oddest and most problematic feature of the midocean ridges pertains to their magnetic properties. To investigate these properties, **magnetometers**, instruments that detect and measure the intensity of magnetism, were towed by ships back and forth across the crests of the midocean ridges. Such a survey was conducted across the axis of the Reykjanes Ridge , part of the Mid-Atlantic Ridge just southwest of Iceland (**Figure 3-3**). Each magnetic profile across this ridge showed alternating high magnetic readings (positive peaks) and low magnetic readings (negative peaks). These high and low variations are termed **magnetic anomalies**, because each is higher or lower than the predicted value for the Earth's magnetic field at that locality and, hence, are considered to be anomalous (not normal). This means simply that positive magnetic anomalies are stronger than expected, negative readings weaker than expected.

Even more baffling to geologists investigating this issue was the fact that the magnetic highs and magnetic lows could be traced from profile to profile, so that a pattern of magnetic "stripes" of alternating positive and negative intensity became evident. This is the case for the Reykjanes Ridge (see Figure 3–3). Here distinct magnetic anomaly stripes are evident, running parallel to the ridge line. More surprisingly, these magnetic bands are

FIGURE 3-3

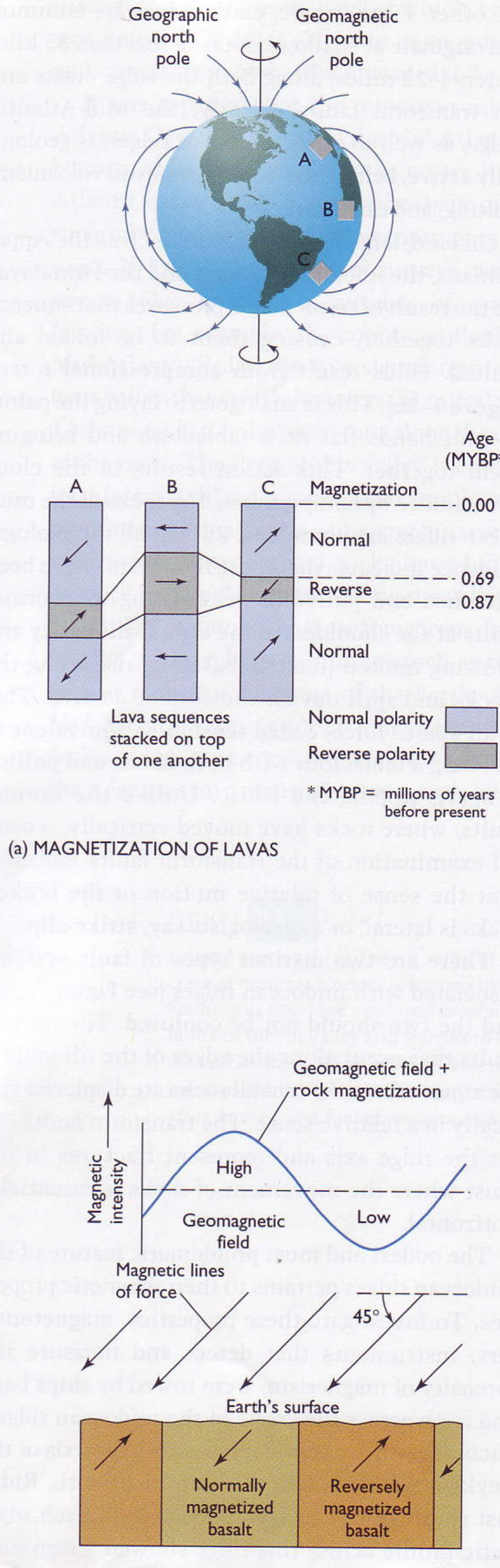
Magnetic anomaly stripes. Magnetic anomaly stripes run parallel and are symmetrically arranged on both sides of the midocean ridge axis. For example, anomalies B and C on the eastern ridge flank have counterparts B' and C' on the western flank that are the same distance from the crestal anomaly A. [Adapted from J. R. Heirtzler, X. LePichon, and J. C. Bason, *Deep Sea Research* 13 (1966): 427–33.]

symmetrically distributed about the ridge axis. That is, each magnetic anomaly on one flank of the ridge has a counterpart on the opposite flank at the same distance from the ridge crest. In Figure 3–3 note that the central anomaly A, located over the ridge crest, is flanked by anomalies B and B', C and C', each pair being equidistant from the ridge line. This regular, symmetric pattern of magnetic anomaly stripes has been found along most of the midocean-ridge system, and is seen as one of its fundamental properties. What created such regularity, and what could possibly be its significance? Answers to these questions awaited the study of the magnetic properties of rocks on land.

THE GEOMAGNETIC FIELD

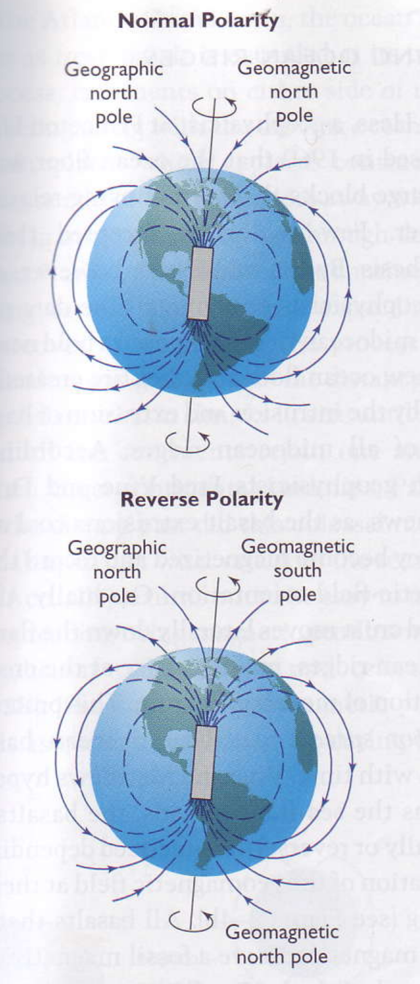
The Earth's magnetic (geomagnetic) field can be compared to a large, powerful bar magnet, a dipole (having two poles) placed at the center of the Earth and oriented nearly parallel to its rotational axis (**Figure 3–4a**). This dipole creates a magnetic field, invisible lines of magnetic force that surround the Earth and are capable of attracting or deflecting magnetized material. This magnetic field is what "pulls" the magnetized needle of a compass, allowing you to navigate by determining the direction of the north magnetic pole. The intensity of the geomagnetic field is strongest at the magnetic poles, where magnetic lines of force are vertically oriented. They point out of the Earth's surface near the south pole and into the Earth's surface near the north pole (**Figure 3–4b**). The magnetic field lines (which, remember, are invisible) intersect the Earth's surface at angles that vary directly with latitude (see Figure 3–4b). At 45° N latitude, for example, your compass needle would point toward the north magnetic pole and would be tilted into the ground at an angle of about 45 degrees. At 45° S latitude, the needle would point toward magnetic north and be tilted into the air at about 45 degrees (see top lava layer in column C of Figure 3–4a). Near the equator, the magnetic lines of force lie parallel to the Earth's surface; so the needle has no tilt and merely points to the north magnetic pole.

When lava extrudes and cools, minerals crystallize systematically out of solution as the lava solidifies into a rock, in the same way that solid ice

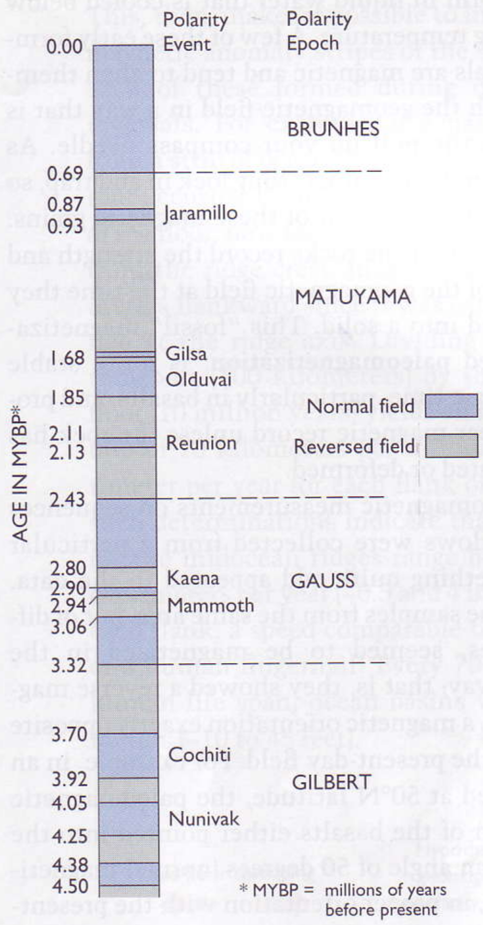


(a) MAGNETIZATION OF LAVAS

(d) MAGNETIC ANOMALIES



(b) GEOMAGNETIC POLARITY REVERSALS



(c) GEOMAGNETIC POLARITY TIME SCALE

FIGURE 3-4

Paleomagnetism. (a) The lava sequence in areas A, B, and C have alternating directions of rock magnetization. The lavas at each site are stacked on top of one another, with the oldest lava on the bottom and the youngest on top of the sequence. Note that the volcanic rocks of the same age in all areas are either all normally or all reversely magnetized. This effect results from the geomagnetic dipole flipping its polarity back and forth over geologic time. (b) During normal polarity, the geomagnetic north pole lies near the geographic north pole. During a reversal, the geomagnetic north pole flips with the geomagnetic south pole so that it lies adjacent to the geographic south pole. (c) Based on numerous analyses of lava flows on land, the pattern of polarity reversals of the Earth's magnetic field has been accurately established. [Adapted from A. Cox, *Science* 163 (1969): 237–45.] (d) A magnetometer measures simultaneously both the Earth's magnetic field and the fossil magnetization in the rocks. A magnetic high results from the rock magnetization reinforcing the Earth's magnetic field, so that the reading is higher than expected. A magnetic low results from rock magnetization opposing the earth's magnetic field, so that the reading is lower than expected.

crystals form in liquid water that is cooled below its freezing temperature. A few of these early forming minerals are magnetic and tend to align themselves with the geomagnetic field in a way that is similar to the pull on your compass needle. As other minerals crystallize, they lock in and trap, so to speak, the alignment of these magnetic grains. This means that the rocks record the strength and direction of the geomagnetic field at the time they crystallized into a solid. This "fossil" magnetization, called **paleomagnetization**, is quite stable over geologic time, particularly in basalts, and provides a clear magnetic record unless the rock has been reheated or deformed.

As paleomagnetic measurements on sequences of basalt flows were collected from a particular area, something quite odd appeared in the data. Many of the samples from the same area, but of different ages, seemed to be magnetized in the "wrong" way; that is, they showed a reverse magnetization, a magnetic orientation exactly opposite to that of the present-day field. For example, in an area located at 50°N latitude, the paleomagnetic orientation of the basalts either pointed into the ground at an angle of 50 degrees (normal magnetization, i.e., in proper orientation with the present-day magnetic lines of force) or out of the ground at an angle of 50 degrees (reverse magnetization, i.e., in direct opposition to the present-day magnetic force field). What could this possibly mean? Furthermore, paleomagnetic studies in many volcanic terrains showed that basalts of a particular age are either all normally or all reversely magnetized, regardless of where they erupted on the Earth's surface (see Figure 3–4a). All these data taken together could mean only one thing—the geomagnetic field had flipped repeatedly back and forth over time (see Figure 3–4b), sometimes oriented as it is at present (**normal polarity**) and sometimes oriented in the opposite direction (**reverse polarity**). This information led to the development of a paleomagnetic polarity time scale that simply depicts the times when the geomagnetic field had a normal or reverse polarity (**Figure 3–4c**). During any reverse polarity, the north-seeking compass needle would point to the south rather than to the north magnetic pole. As we shall see, this knowledge of magnetic field reversals finally helped geologists understand the significance of magnetic anomaly stripes on the sea floor.

SPREADING OCEAN RIDGES

Harry Hess, a geophysicist at Princeton University, proposed in 1960 that the ocean floor was broken into large blocks that were moving relative to one another. Few geologists accepted this radical hypothesis. By the mid-1960s, however, geologists and geophysicists studying all the data pertaining to the midocean ridges proposed a bold new hypothesis: new ocean floor and crust are created continuously by the intrusion and extrusion of basalt at the crest of all midocean ridges. According to the British geophysicists Fred Vine and Drummond Matthews, as the basalt extrusions cool and solidify, they become magnetized and record the Earth's magnetic-field orientation. Gradually, the newly formed crust moves laterally down the flanks of the midocean ridges, making space at the crest for the formation of more basalt crust. This process, called *sea-floor spreading,* leads to ocean basins that widen with time. Vine and Matthews hypothesized that, as the sea floor spreads, the basalts become normally or reversely magnetized depending on the orientation of the geomagnetic field at their time of cooling (see Figure 3–4b). All basalts that are normally magnetized have a fossil magnetization that is aligned with the Earth's present-day magnetic field. This magnetic parallelism causes a reinforcement, so that a magnetometer measures a higher than normal reading, resulting in a strong or positive magnetic anomaly (**Figure 3–4d**). In contrast, all rocks that formed during a period of reverse polarity have a fossil magnetic orientation opposite to that of the present-day geomagnetic field. This contrary alignment reduces the magnetic reading over reversely magnetized basalt, producing a low or negative magnetic anomaly. Because sea-floor spreading is symmetrical, the basalt crust is split at the crest into halves, creating pairs of magnetic anomaly stripes of about equal width that are symmetrically disposed about the ridge axis (**Figure 3-5a**). In other words, the magnetic profiles on either flank of the midocean ridges are mirror images of each other. In effect, the pattern of magnetic anomaly stripes is equivalent to a tape recording of the Earth's magnetic-field reversals of the past.

In the vicinity of the Mid-Atlantic Ridge, sea-floor spreading is causing symmetrical expansion of the Atlantic Ocean basin; the ocean is growing in size as fresh basalt is extruded at its center. In the process, continents on either side of the basin are traveling along with the moving ocean floor as part of the plate—which explains continental drift as Wegener described it, but does away with the idea of light granitic crust plowing through denser oceanic crust. Rather, the granite of the continents is simply being carried along by the expanding sea floor. Moreover, if we reverse the process of sea-floor spreading and go back into the distant geologic past, the Atlantic basin shrinks in size until it disappears, and all the continents rejoin one another into a much larger continental landmass, Pangaea. When in the distant past did this colossal megacontinent break apart? At what rate does the sea floor spread?

Actually, it turns out to be easy to measure rates of spreading using magnetic profiles measured perpendicular to the crests of midocean ridges (**Figure 3–5b**). The timing of geomagnetic polarity reversals is easily established by dating basalt flows. This, then, makes it possible to infer the age of the magnetic anomaly stripes of the sea floor, because each of these formed during unique magnetic reversals. For example, if a particular anomaly from a strip of ocean floor formed during a reversal that occurred 10 million years ago, then that piece of sea floor, now located 100 kilometers (~62 miles) from the ridge crest, must have moved 100 kilometers flankward since it was extruded and solidified at the ridge axis. Dividing that distance of transport (100 kilometers) by the age of the sea floor (10 million years) yields an average spreading rate of 10 kilometers per million years or 1 centimeter per year for each flank of the ridge. Many such determinations indicate that spreading rates for the midocean ridges range between 1 and 10 centimeters per year (~0.5 and 4 inches per year) for each flank, a speed comparable to the growth rate of a human fingernail! Every 70 years, roughly a human life span, ocean basins widen by 3 to 14 meters (~10 to 45 feet).

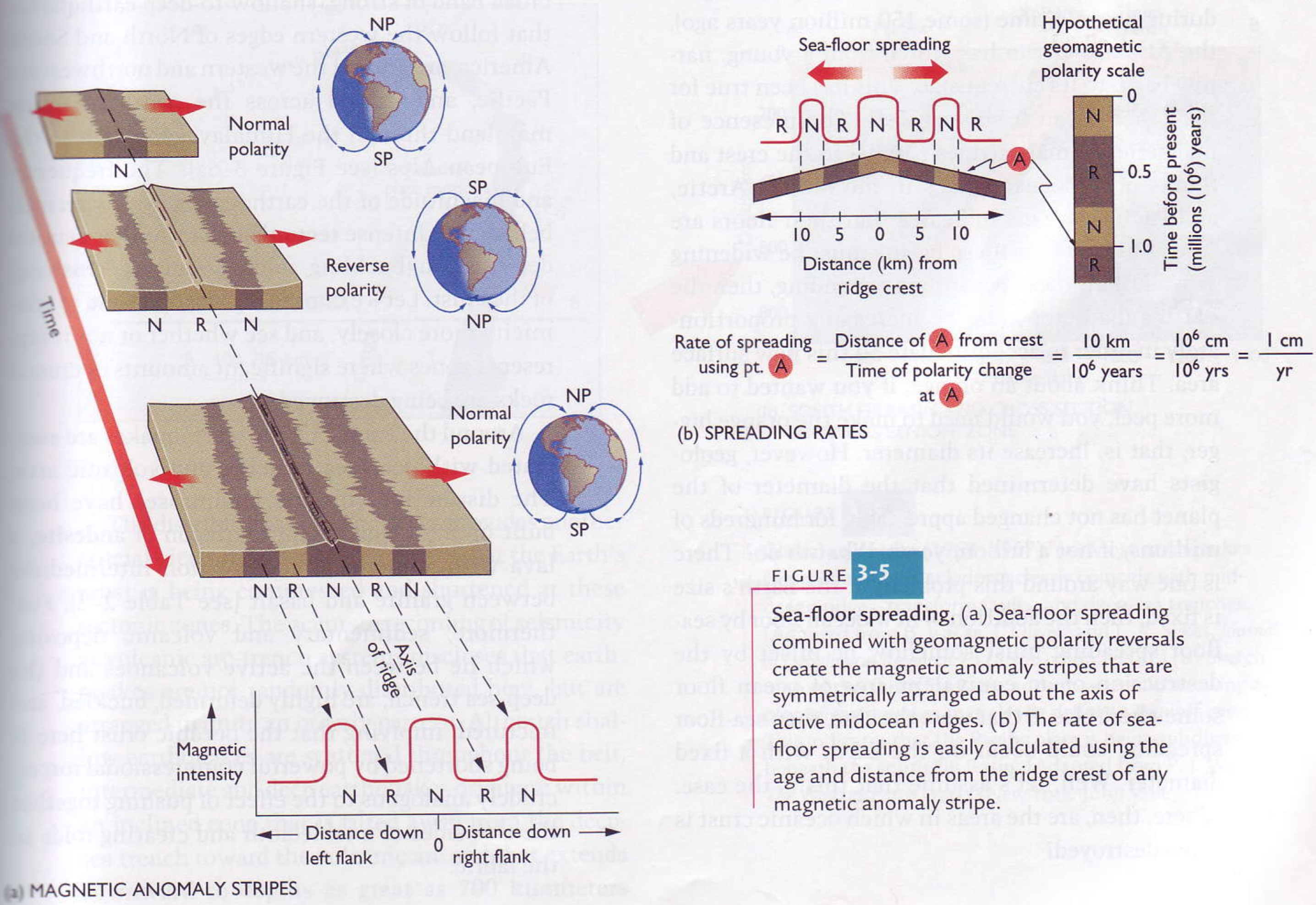


FIGURE 3-5

Sea-floor spreading. (a) Sea-floor spreading combined with geomagnetic polarity reversals create the magnetic anomaly stripes that are symmetrically arranged about the axis of active midocean ridges. (b) The rate of sea-floor spreading is easily calculated using the age and distance from the ridge crest of any magnetic anomaly stripe.

Several important findings are explained by the sea-floor spreading model. For instance, sea-floor spreading means that the oceanic crust that lies to either side of the ridge moves apart. This separation produces tensional forces that create normal faults and rift valleys at ridge crests. Also, spreading of the ocean floor implies that the basaltic crust becomes increasingly older with distance from the ridge line. Eventually, as the basaltic crust is transported down the ridge flank, it becomes covered with sediment. This sedimentary cover gets steadily thicker with distance from the ridge axis.

3-3

Global Plate Tectonics

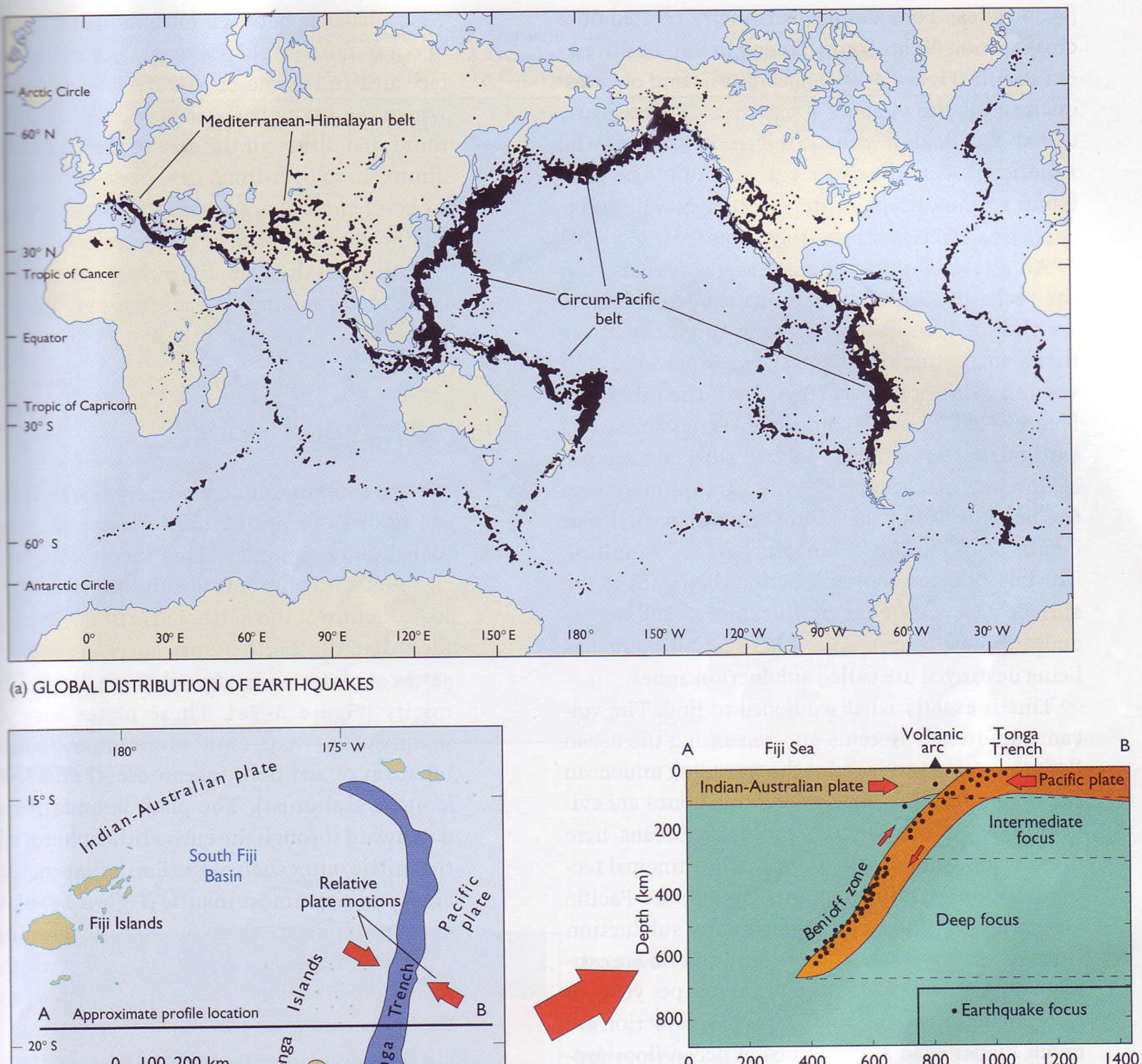
The axis of midocean ridges is a narrow, linear zone where basaltic crust forms and then moves away from the ridge crest at a rate of several centimeters per year. Since the breakup of Pangaea during Jurassic time (some 150 million years ago), the Atlantic Ocean has grown from a young, narrow basin to its current size. This has been true for the other ocean basins as well. The presence of magnetic anomaly stripes parallel to the crest and flanks of midocean ridges in the Indian, Arctic, and Pacific Oceans indicates that their floors are spreading and that these basins must be widening as well. If all these oceans are expanding, then the Earth's diameter must be increasing proportionately in order to accommodate all this new surface area. Think about an orange. If you wanted to add more peel, you would need to make the orange bigger, that is, increase its diameter. However, geologists have determined that the diameter of the planet has not changed appreciably for hundreds of millions, if not a billion, years. What to do? There is one way around this problem. If the Earth's size is fixed, then the addition of new ocean floor by sea-floor spreading must somehow be offset by the destruction of an equivalent area of ocean floor somewhere else. If that were the case, then sea-floor spreading could occur on the Earth with a fixed diameter. Well, let's assume that this is the case. Where, then, are the areas in which oceanic crust is being destroyed?

SUBDUCTION ZONES

It stands to reason that if crustal rocks are being crushed and destroyed at a rate comparable to their formation at midocean ridges, this activity should generate earthquakes, a shaking of the ground caused by the deformation of rocks. An examination of world **seismicity**—the frequency (number), magnitude (strength), and distribution of earthquakes—reveals two distinct groupings of earthquakes on the Earth (**Figure 3–6a**). One grouping consists of a narrow clustering of shallow, relatively weak disturbances that closely follow the crest line of the spreading midocean ridges and their transform faults. The earthquakes along the ridge axis result from volcanism and normal faulting along the crestal rift valley; those along the transform faults are generated by the strike-slip motion of the crust to either side of the fault.

But, what is the significance of the second grouping of seismic events, which appears as a broad band of strong, shallow-to-deep earthquakes that follow the western edges of North and South America, arc around the western and northwestern Pacific, and extend across the southern Asian mainland through the Himalayas and across the European Alps (see Figure 3–6a)? The frequency and magnitude of the earthquakes in this seismic belt signify intense **tectonism**, a term that denotes deformation (buckling, folding, faulting, crushing) of the crust. Let's examine this second band of seismicity more closely, and see whether or not it represents zones where significant amounts of crustal rocks are being destroyed.

Around the Pacific Ocean, earthquakes are associated with deep-sea trenches and volcanic arcs. The distinctive volcanic landmasses have been built up by the abundant extrusion of **andesite**, a lava with a chemical composition intermediate between granite and basalt (see Table 2–2). Furthermore, sedimentary and volcanic deposits, which lie between the active volcanoes and the deep-sea trench, are highly deformed, buckled, and fractured, implying that the oceanic crust here is being shortened by powerful compressional forces, crudely analogous to the effect of pushing together the two sides of a tablecloth and creating folds in the fabric.



(a) GLOBAL DISTRIBUTION OF EARTHQUAKES

(b) SOUTH FIJI BASIN AND CROSS SECTION SHOWING BENIOFF ZONE

FIGURE 3-6

Global seismicity (1961–1967). (a) Most earthquakes (represented by black dots) clearly coincide with mid-ocean ridges, transform faults, and deep-sea trenches. [Adapted from B. Isacks, J. Oliver, and L. R. Sykes, *Journal of Geophysical Research* 73 (1968): 5855–900.] (b) Sketch map of the south Fiji Basin and cross section showing a plot of earthquakes that clearly defines a Benioff zone. This indicates that the Pacific plate is being subducted beneath the south Fiji Basin. [Adapted from P. J. Wyllie, *The Way the Earth Works* (New York: John Wiley, 1976).]

The distribution of earthquakes provides another crucial piece of evidence to indicate that the Earth's crust is being compressed and shortened at these tectonic zones. The accurate recording of seismicity at volcanic arc-trench systems discloses that earthquakes are not randomly distributed here, but are arranged in quite an orderly pattern. Although shallow earthquakes are scattered throughout the belt, intermediate and deep earthquakes originate within an inclined zone that is tilted away from the deep-sea trench toward the volcanic arc and that extends downward to depths as great as 700 kilometers

(~434 miles). For example, seismicity plotted on a cross section of the Tonga Trench in the southwestern Pacific (**Figure 3–6b**) appears as a band of earthquakes dipping at about 45 degrees. This feature, called the **Benioff zone** after its discoverer, the American seismologist Hugo Benioff, has been found at other deep-sea trench sites as well. What could this odd pattern possibly mean?

An analysis of earthquake waves reveals that the rocks immediately beneath the Benioff zone are sliding downward relative to the rocks above them, suggesting that large slabs of rocks are converging, with one mass riding over the other (see Figure 3–6b). The slab going down generates strong earthquakes as its upper surface slips and scrapes against the rocks above it. Also, as it plunges into the hot interior of the Earth, it melts partially at depths of 100 to 200 kilometers (~62 to 124 miles). The hot, buoyant molten fraction then rises to the surface and spews out of volcanic island arcs as andesite lava. These sites where basaltic crust is being destroyed are called **subduction zones**.

This is exactly what we hoped to find. The volcanic arc-trench systems are consuming the ocean floor that is being created at the spreading midocean ridges. Interestingly, few subduction zones are evident in the Atlantic, Indian, and Arctic oceans; here the spreading midocean ridges are the principal tectonic features. Only along the edges of the Pacific Ocean do we find nearly continuous subduction zones, where rates of sea-floor consumption are estimated to be about 15 to 45 centimeters per year (~6 to 18 inches per year). These rates of subduction are much higher than are the rates of ocean-floor production at midocean ridges, because there are more spreading sites than subduction zones on the Earth's surface. Calculations indicate that the rates of production and destruction of ocean floor for the entire planet are about equal, indicating that the Earth's diameter and surface area have been constant over geologic time.

One additional conclusion should be obvious to you as well. The absence of subduction zones in the Atlantic, Indian, and Arctic oceans indicates that these basins are expanding with time, occupying more and more of the Earth's surface as they grow progressively larger. This, in turn, implies that the Pacific Ocean is shrinking rapidly in a geologic sense at a pace equal to the combined production rates of the entire midocean ridge system. Otherwise a balance between formation and destruction of ocean crust could not exist, and the Earth's surface area and diameter would have had to increase, which we know has not happened. Also, bear in mind that although the size of the Pacific basin is diminishing over time, new ocean floor continues to be created along its midocean ridge, the East Pacific Rise, as clearly indicated by earthquakes and fresh basalt at the ridge crest and the presence of magnetic anomaly stripes that run parallel to the ridge axis.

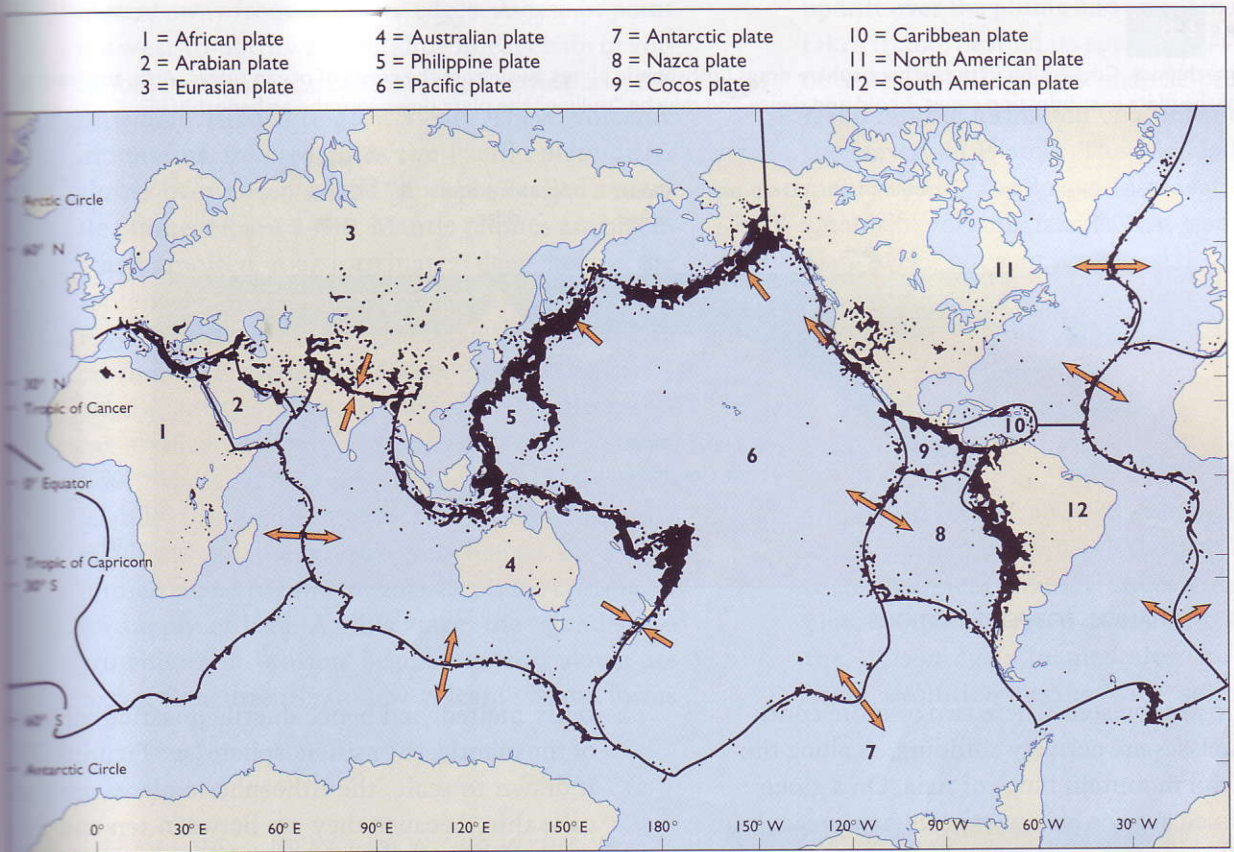
PLATE-TECTONIC MODEL

We can combine all that we have learned about the sea floor so far into a unified concept known as **global plate tectonics**. This theory formulated in the 1960s revolutionized thinking about the geologic history of the Earth. Basic to the theory is the idea that the Earth's surface is divisible into a series of **plates** with edges that are defined by seismicity (**Figure 3–7a**). These plates may consist mainly of sea floor, or more commonly some combination of sea floor (ocean crust) and landmass (continental crust). The plate boundaries extend downward through the entire lithosphere, which is the brittle outer shell of the Earth that includes the crust and uppermost mantle (**Figure 3–7b**). Geologists refer to them, therefore, as **lithospheric plates**.

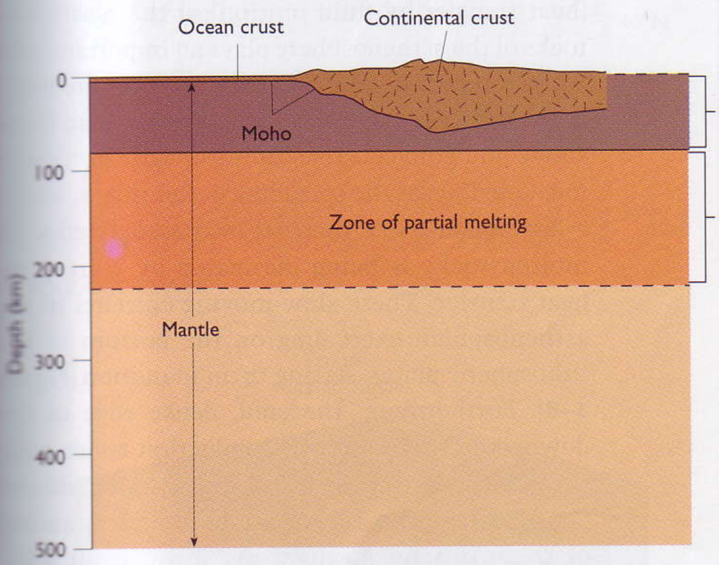
Seismicity and volcanism are not randomly distributed over the Earth's surface; rather, they are largely confined to the edges of the plates. There are three fundamental types of plate boundaries:

1. *Midocean ridges* are boundaries where two plates under tension move apart from one another. Each plate grows by the process of sea-floor spreading, which adds new lithosphere (crust plus upper mantle) to the trailing edges of the two diverging plates.

2. *Subduction zones* are plate boundaries where compression is dominant, as two plates converge, one overriding and destroying the other. The ocean floor can be thrust downward beneath another ocean plate, common in the western Pacific, or beneath a continent, as along western South America, where the andesite volcanoes, rather than being submarine landforms, appear as volcanic peaks in the high Andes. Subduction



(a) LITHOSPHERIC PLATES



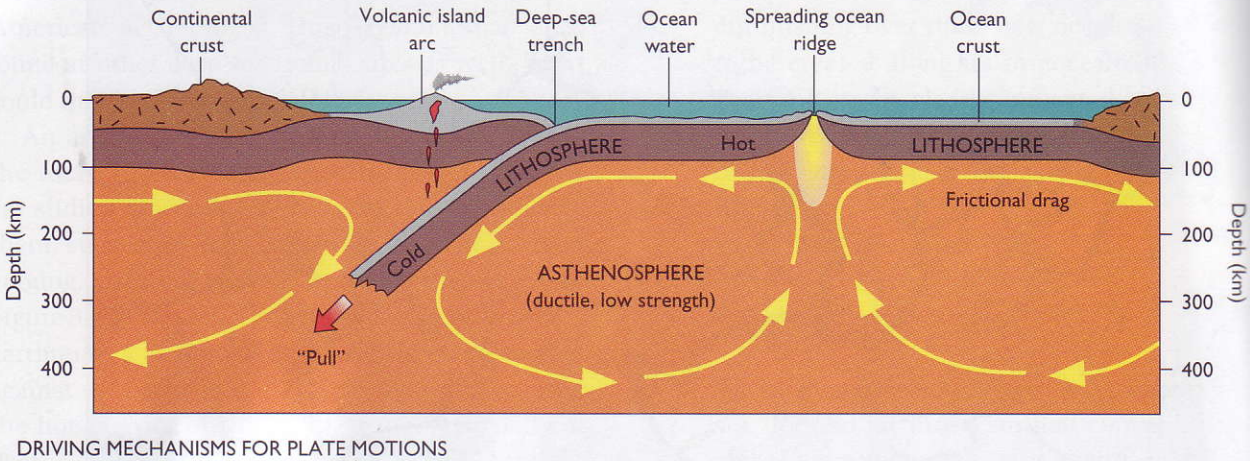
(b) THE LITHOSPHERE AND THE ASTHENOSPHERE

FIGURE **3-7**

Lithospheric plates. (a) The edges of large lithospheric plates are indicated by bands of seismicity. The arrows indicate relative plate motions. [Adapted from K. S. Stowe, *Ocean Science* (New York: John Wiley, 1983).] (b) A brittle lithospheric plate, which includes the crust and the upper mantle, overlies and moves relative to the plasticlike asthenoshpere. [Adapted from J. F. Dewey, *Scientific American* 266 (1972): 56–58.]

FIGURE 3-8

Plate mechanics. Convection in the asthenosphere drags lithospheric plates away from the crests of ocean ridges. Also, the leading edge of the plate in subduction zones is cold and dense and may be "pulling" the plate down into the asthenoshpere.



zones are also present where two or more continental masses are actively colliding, as along the Himalayan mountain range of Asia. On a globe with a fixed surface area over geologic time, subduction (plate destruction) at convergent boundaries is balanced by sea-floor spreading (plate growth) at divergent edges.

3. *Transform faults* are plate boundaries where ocean floor is neither created nor destroyed. Rather, the lithosphere along transform faults is conserved as plates slide laterally (strike-slip motion) past one another. Although there are various transform boundaries, the most common type is the one that connects two midocean ridge segments such that they are offset from each other. An example of such a transform boundary slices across southern California (see boxed feature, "The San Andreas Fault").

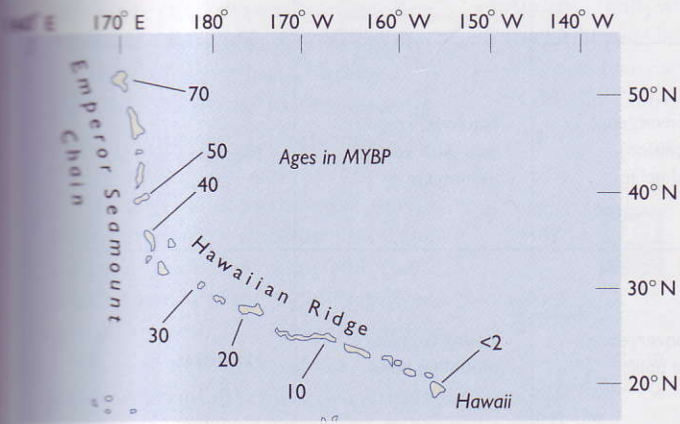
Thus, the distribution of seismicity indicates clearly that the Earth's outer shell is fragmented into a mosaic of plates (see Figure 3-7a) that diverge (spreading ridges), converge (subduction zones), or slide past one another (transform faults). The plate edges are, however, not merely surface ruptures. They extend downward through the entire lithosphere, which includes the crust and the uppermost mantle. The lithosphere, which is 100 to 150 kilometers (~62 to 93 miles) thick, has appreciable strength and rigidity and it overlies a hotter, partially melted, and hence ductile (plasticlike) layer of the mantle, the asthenosphere (see Figure 3–7b). If drawn to scale, the lithospheric plates are pancake thin, because they are between ten and fifty times wider than they are thick.

Although the actual driving mechanism that causes the plates to move is still being investigated, there is little doubt that **thermal convection** (heat transfer by fluid motion) of the plasticlike rocks of the asthenosphere plays an important role. As heat builds up in the Earth's interior, the rocks in the asthenosphere become less dense than those above and convect (rise) upward. This process is most obvious at the spreading ocean ridges, where a large quantity of internal heat associated with molten rocks is being dissipated by convective heat transfer. These slow-moving currents in the asthenosphere exert drag on the bottom of the lithospheric plates, setting them in motion (**Figure 3–8**). Furthermore, the cold, dense edge of the downgoing lithosphere at subduction zones pulls the plate downward as it sinks into hotter and less dense asthenosphere. An accurate understanding of these driving mechanisms must await additional theoretical and experimental studies.

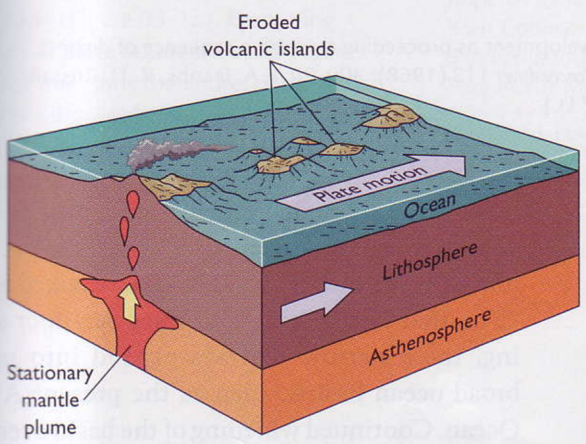
Most of the volcanic outpourings on the Earth's surface occur at the plate boundaries. Basalt lava spews out of the spreading ocean ridges, and andesite lava is produced at subduction zones. Less common, but impressive, outpourings of lava also occur in the interior of plates, thousands of kilometers away from the plate edges. A case in point is a west-to-northwest-trending linear chain of volcanoes located in the center of the Pacific plate, the Hawaiian Islands (**Figure 3–9a**). These volcanic mountains are created as the Pacific plate drifts slowly over a deep-seated "hot spot" called a **mantle plume** (**Figure 3–9b**). Mantle plumes are places where molten rock originates deep below the asthenosphere. This molten rock rises and melts its way through the lithosphere, spilling out as lava on the top of the plate (**Figure 3–9c**). With time, large quantities of lava are added to the pile, creating a volcanic cone that towers above the ocean floor. Many such cones rise out of the water as islands. Eventually, the motion of the plate, as a result of sea-floor spreading, transports the newly formed island beyond the mantle plume cutting off its supply of lava. At this stage, the island stops growing, and erosion begins to wear down its rocks. Concurrently, a new volcanic island forms updrift over the plume and grows in size until drift takes it, too, beyond its source of lava. The growth of volcanic islands by mantle-plume injection results in the formation of a linear chain, such as the Hawaiian Islands. The islands become older, more eroded, and lower in elevation downdrift. Chains of volcanic islands that trace the path of a plate over a hot spot have been discovered all over the world.

THE OPENING AND CLOSING OF OCEAN BASINS

During the course of several hundred million years, ocean basins have evolved through distinct stages of development that are directly linked to global plate tectonics (**Figure 3–10**). The initial stage in the *Wilson cycle* (named after its originator) of basin evolution begins with splintering of the



(a) VOLCANIC CHAINS

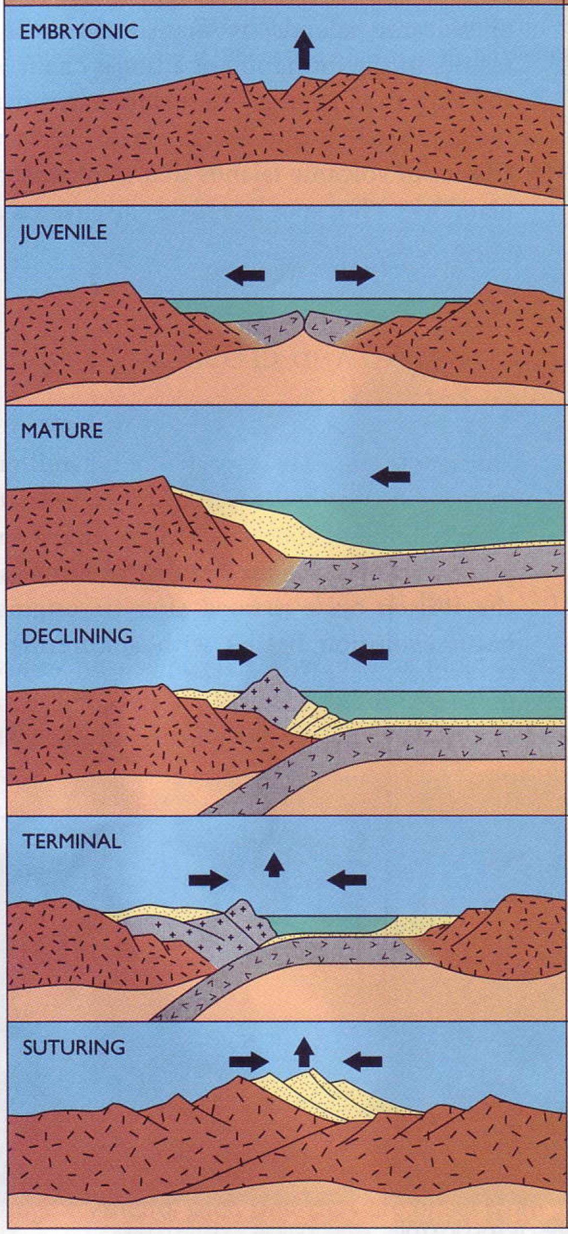


(b) MANTLE PLUME

(c) KILAUEA, HAWAII

FIGURE 3-9

Volcanic chains and mantle plumes. (a) Some volcanoes are not associated with the edges of plates. They form long, linear chains with the age of the volcanoes increasing systematically from one end to the other, as illustrated here for the Hawaiian Islands and their submarine continuation, the Emperor Seamount Chain. [Adapted from G. B. Dalrymple, E. A. Silver, and E. D. Jack, *American Scientist* 6 (1973): 294–308; D. A. Claque and R. D. Jarrard, *Geological Society of America Bulletin* 84 (1975): 1135–54.] (b) The linear volcanic chains trace the drift path of a plate over a mantle plume. The volcanoes on each island become extinct and erode once they are transported away from the mantle plume. (c) Kilauea, an active volcano spewing out lava and ash, is located at the southeastern end of the island of Hawaii. The very hot lava is igniting all vegetation in its path.



STAGE	MOTION	PHYSIOGRAPHY	EXAMPLE
EMBRYONIC	Uplift	Complex system of linear rift valleys on continent	East African rift valleys
JUVENILE	Divergence (spreading)	Narrow seas with matching coasts	Red Sea
MATURE	Divergence (spreading)	Ocean basin with continental margins	Atlantic, Indian, and Arctic oceans
DECLINING	Convergence (subduction)	Island arcs and trenches around basin edge	Pacific Ocean
TERMINAL	Convergence (collision) and uplift	Narrow, irregular seas with young mountains	Mediterranean Sea
SUTURING	Convergence and uplift	Young to mature mountain belts	Himalayas

FIGURE 3-10

Ocean-basin evolution. The Wilson cycle depicts ocean-basin development as proceeding through a sequence of distinct stages. [Adapted from J. T. Wilson, *American Philosophical Society Proceedings* 112 (1968): 309–20; J: A. Jacobs, R. D. Russell, and J. T. Wilson, *Physics and Geology* (New York: McGraw-Hill, 1974).]

granitic crusts of continents. This results in the formation of long, linear rift valleys, a process that is now occurring in East Africa. The basin at this time is *embryonic*. The continent is fractured by a system of normal faults, and basalt escapes to the surface and spills out onto the floor of the rift valley. The next stage, a *juvenile* ocean basin, occurs once the continents are separated into two independent masses. Basaltic crust forms between them along a young, spreading ocean ridge. This stage is exemplified at present by the Red Sea (see boxed feature, "The Red Sea"). With continued sea-floor spreading, these narrow seaways expand into *mature*, broad ocean basins, such as the present Atlantic Ocean. Continued widening of the basin eventually leads to instability, and the broad plate ruptures

The San Andreas Fault

The edges of most plates are underwater and are therefore studied by indirect methods of observation and sampling such as those described in the feature, "Probing the Sea Floor." An exception is a spectacular exposure of a complex fault system known as the San Andreas fault, which slices through the countryside of western and southern California (**Figure B3–1a**). Aerial views of the landscape that borders the San Andreas fault show a linear topography (**Figure B3–2a**) underlain by fractured crustal rocks that have been forced upward into craggy mountains or downward into splintered valleys. Earthquakes in this region (**Table B3–1**) are frequent and powerful, as rocks on either side of the fault alternately grab and slip past one another, often with dire consequences for people and their structures (**Figure B3–2b**). The reason for this tectonic activity is now well understood, because this 1,300 kilometer-long (~806 miles) fault system represents a plate boundary, a transform fault that separates the Pacific plate from the North America plate. Remarkably, it runs right through southern California.

The San Andreas fault is a long transform fault that joins two spreading ridges, one located in the Gulf of California, the other off the northwestern United States and southwestern Canada (Figure B3-1a). Examining maps of plate boundaries (see Figure 3-7a) one gains the impression that the breaks are clean, the sort that one could perhaps straddle, each foot placed firmly on a different plate. These maps, in a sense, are cartoons, meant to suggest, rather than precisely delineate, the edges of the plates. The San Andreas fault is not a single fracture, but a complex system of intertwined breaks that have splintered the rocks that outcrop on either side of the boundary. In fact, both ends of the transform boundary on land splay out, or bifurcate, into a branching network of faults (**Figure B3–1b**). As along any transform boundary, the dominant motion is strike-slip, meaning that the crust is being sheared horizontally, that is, parallel to the fault trace. Irregularities in the trace of the transform fault can, however, lead to localized compression (pushing together) or tension (pulling apart). This happens at a number of spots along the San Andreas fault, where the geometry of the fault trace leads either to compression and transverse topography, such as the San Gabriel Mountains near Los Angeles, or to tension and "pull-apart" basins (**Figure B3–1c**), such as Death Valley in east central California.

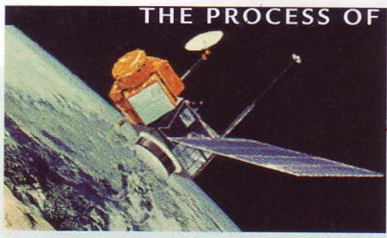
In an effort to gauge the probability of earthquakes in the region, new instruments have been developed that measure seismicity and small changes in the ground's elevation and in its horizontal displacement. The slippage rate, which is not uniform along the fault's length, is estimated to be between 1 and 10 centimeters (~0.5 and 4 inches) per year. This rate and the direction of crustal displacement imply that southern California and Baja are moving to the northwest relative to North America and, eventually (some 15 million years into the future), will become detached and form a large island off California (Figure B3-1a).

Visit www.jbpub.com/oceanlink for more information.

TABLE **B3-1**
Major Earthquakes along the San Andreas Fault

Location	Year	Magnitude
Santa Barbara	1812	7
San Francisco area	1838	7
Fort Tejon	1857	8.3
Hayward	1868	7
San Francisco	1906	8.3
Imperial Valley	1940	7.1
Kern County	1952	7.7
San Fernando Valley	1971	6.5
Santa Cruz Mountains	1989	7.1

Source: Adapted from E. J. Tarbuck and F. K. Lutgens, *The Earth* (New York: Macmillan,1993).



THE PROCESS OF SCIENCE

The Scientific Process: Sea-Floor Spreading

An essential part of the scientific method is the falsification of hypotheses. This means that one should be able to test any valid scientific hypothesis in such a way that it can be disproved by the test results. Let's examine an actual test of a hypothesis. In 1963 the British geologists Fred Vine and Drummond Matthews proposed that the symmetrical magnetic anomaly stripes that lie parallel to midocean ridges in all the oceans were the result of sea-floor spreading (see Figure 3–5). If correct, the hypothesis of sea-floor spreading had revolutionary implications for interpreting the geological development of ocean basins. But how exactly to test this radical idea? Actually, this turned out to be quite easy. Marine geologists reasoned that, if all of the sea floor were created along the crests of spreading ocean ridges, as proposed by Vine and Matthews, then it stands to reason that the age of the ocean crust should increase with the distance from the ridge axis. Also, the older the basaltic crust of the sea floor, the thicker must be its sediment cover. In other words, the Vine-Matthews model of sea-floor spreading predicts clearly that the crust should get older and be buried by a thicker blanket of sediment with increasing distance from the ridge crest. These were testable predictions.

To make these observations, geologists on the drilling ship *Glomar Challenger* (see Figure 1–10a) could, for the first time, drill anywhere in the ocean in thousands of meters of water. It was relatively simple to drill through the sediment layers to the underlying basaltic crust on the flanks of the ocean ridges. The total thickness of the sediment cover at the drilling site could thus be determined and paleontologists could obtain samples of the remains of microfossils embedded in the sediment that was deposited directly on the basalt. At any particular site the fossils could then be used to establish the age of the oldest layer of sediment, which would be very close to the age of the basalt directly beneath it. The data obtained from numerous drill sites indicated that both the age of the oldest sediment and the total thickness of the sediment cover

where the lithosphere is old and is supporting a heavy load of sediment. This tends to occur at continental margins because of the tremendous pile of sediment that accumulates there. The process of subduction begins where one side of the now-fragmented plate overrides the other. The ocean basin then enters a *declining* stage as the ocean lithosphere, and ultimately the spreading ocean ridge itself, are subducted and disappear from the face of the Earth, a situation that is currently happening to the East Pacific Rise in the Pacific Ocean (see boxed feature, "The San Andreas Fault"). As the basin continues to close up, the *terminal* stage is reached. Continents and subduction zones on either side of the basin collide, crushing and uplifting the sedimentary deposits of the basin into a young mountain belt of folded and faulted marine sedimentary rocks. Finally, the two colliding continental masses become *sutured* (fused) tightly together, and the sedimentary deposits and the ocean crust are buckled in a viselike grip and forced upward into a majestic, towering mountain range. A fine example of this suturing stage is the Himalayan range, where sedimentary rocks with marine fossils attest to a time when they were submerged in seawater in an ocean basin that once existed between India and mainland Asia (**Figure 3–11**). Remarkably, the top of the world, Mount Everest, was once an ocean basin at the very bottom of the world.

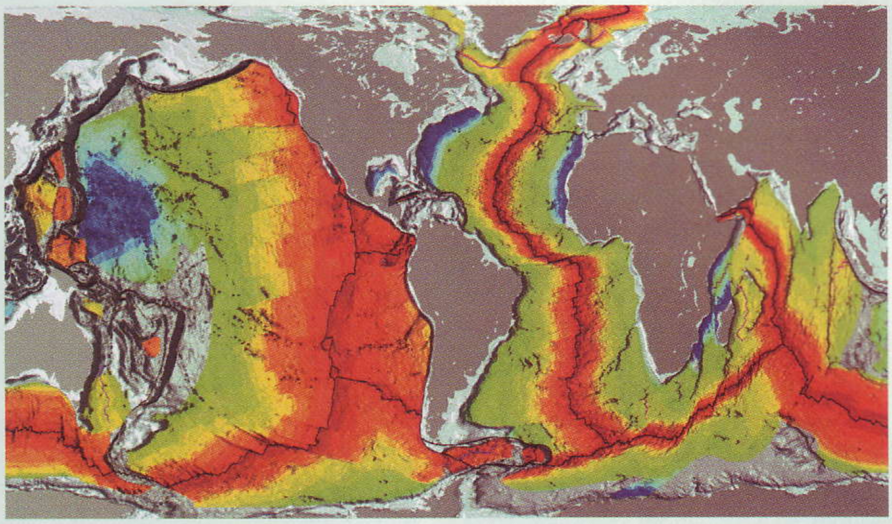
A SUMMARY OF GLOBAL PLATE TECTONICS

We've covered a lot of ground, so to speak, in this chapter. Let's take a moment to reflect about the chapter's main points; these may have become lost among the details that were needed to flesh out the concept of global plate tectonics. The main idea is that many features of the Earth's surface—its volcanoes, earthquakes, ocean ridges, deep-sea trenches, mountain belts, magnetic anomaly stripes—can be understood as the result of the interactions between lithospheric plates. Some of these plates are moving apart at midocean ridges. This process, called sea-floor spreading, is occurring in all the ocean basins increased systematically with the increasing distance from the ridge axis. The conclusion was inescapable: the hypothesis of sea-floor spreading that Vine and Matthews proposed was not falsified by the test. This meant that sea-floor spreading offered a legitimate new model for interpreting the geologic history of the Earth's ocean basins.

The map in **Figure B3–3** shows the global age pattern of the oceanic crust determined from a synthesis of all the latest research findings. The youngest oceanic crust is associated everywhere with the crest of the spreading ridges. The age of the basalt increases systematically with increasing distance from the ridge crest, with the oldest crust located everywhere far down the flanks of the spreading ridges.

FIGURE B3-3

Age of the ocean crust. Age determination indicates that the basaltic crust gets older with increasing distance from the crest of spreading ocean ridges.



and results in the formation of new sea floor and the drift of continents. Other pairs of lithospheric plates are actively colliding. One overriding plate forces another downward into the asthenosphere, where it melts to produce andesite lava. This lava feeds volcanoes on the surface. The process, called subduction, occurs principally around the edges of the Pacific Ocean. Over geologic time, the quantity of new lithosphere produced at spreading ridges has equaled the quantity that has been consumed at subduction zones. Plate boundaries where the lithosphere is conserved (neither created nor destroyed) are called transform faults. These immense fractures separate two plates that are sliding laterally past each other.

The granite of the continents is imbedded in the lithospheric plates and is swept passively across the Earth's surface as the ocean floors spread and grow in size. When continents on two separate plates meet at a subduction zone, they collide and squeeze the intervening marine sediments tightly, lifting them skyward to create a high, folded mountain belt. This very process is presently uplifting the Himalayas, as India collides with the Asian mainland (see Figure 3–11).

This is the basic theory of global plate tectonics, a magnificent and unexpected discovery of modern oceanography. With this background, we can move ahead to the study of marine sediments, examining the origin of these materials that collect on the sea bottom and their history of transport by the moving lithospheric plates.

3-4

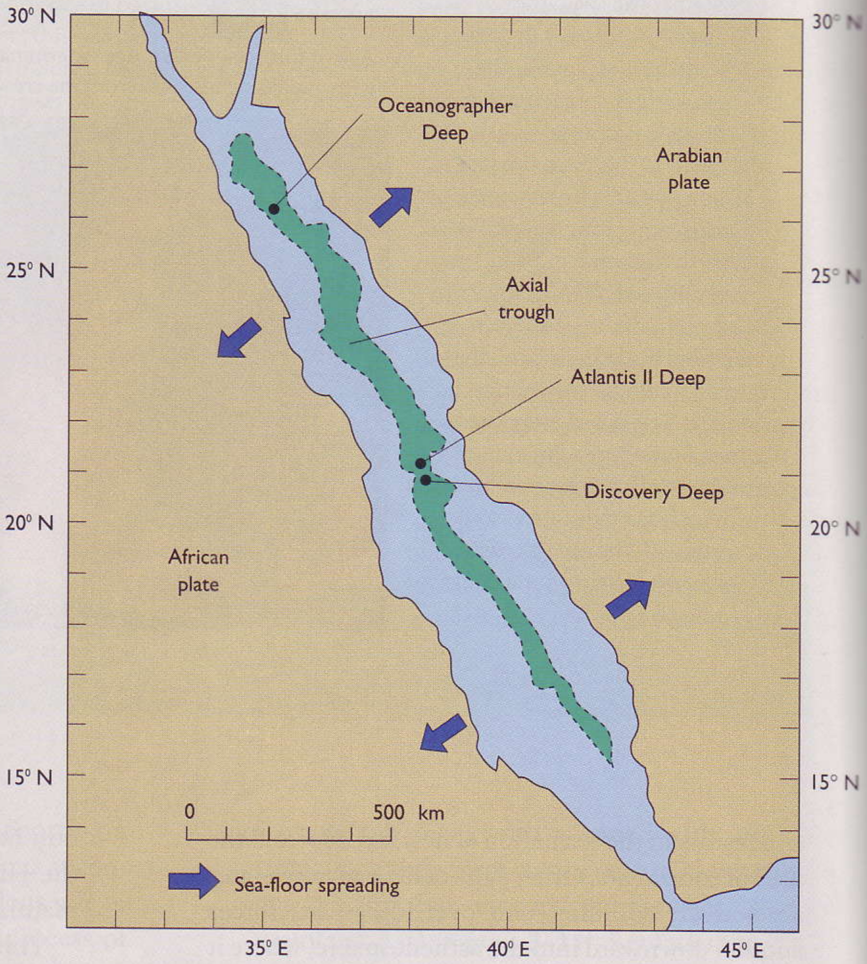
Future Discoveries

A great deal of effort is being directed at understanding how undersea eruptions have affected ocean processes and marine life. Mantle plumes like the one that created the Hawaiian Islands may generate megaplumes,

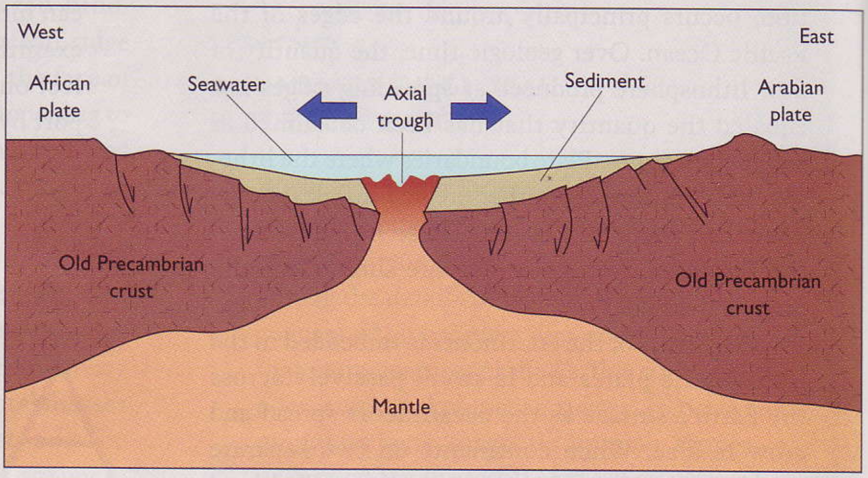
The Red Sea

The Red Sea (**Figure B3–4a**) is a roughly rectangular basin about 1,900 kilometers (~1,178 miles) long and about 300 kilometers (~186 miles) wide (**Figure B3–4b**). Much of the sea bottom is quite shallow, with an average water depth of 490 meters (~1,617 feet) and a maximum water depth of 2,850 meters (~9,405 feet). Running along the center of the Red Sea is a narrow trough with an average depth of about 1,000 meters (3,300 feet). Basalt—new ocean crust—is being injected into this deep axial trough as Arabia drifts away from Africa. In effect, the Red Sea is a miniature ocean (**Figure B3–4c**), a classic juvenile ocean basin that is slowly widening as a result of

(a) SATELLITE IMAGE OF THE RED SEA REGION



(b) THE RED SEA SPREADING CENTER



(c) GEOLOGIC (WEST–EAST) CROSS SECTION

FIGURE **B3-4**

The Red Sea. (a) This satellite image shows the terrain of the Red Sea region. (b) The Red Sea is a juvenile ocean basin that has just recently opened up as the Arabian plate separates from the African plate. (c) New oceanic crust is forming in the axial trough of the Red Sea by the process of sea-floor spreading. [Adapted from D. A. Ross, *Mineral Resources Bulletin* 22 (1977): 1–14.]

sea-floor spreading. This process was responsible for the opening of the Atlantic Ocean, and this is what the Atlantic basin must have looked like in its early development as Africa and Europe moved away from North and South America.

It appears as if the Red Sea basin began to develop some 20 million to 30 million years ago as the granitic crust of East Africa and Arabia was stretched until it broke apart along a system of normal faults. These large faults have splintered the thick granitic crust into large blocks (see Figure B3–4c). The sediments that blanket the sea bottom include salt deposits up to 7 kilometers (~4.3 miles) thick. Their presence indicates that much of the ocean dried up periodically as its water was evaporated and salt deposits were laid down on its bottom. To imagine what this was like, fill a glass with seawater and leave it in the sun for a few days. What will happen, of course, is that the water will disappear because of evaporation, and the bottom of the glass will be encrusted with salt.

Not only is there salt on the sea floor, but the water itself, which fills the deeps of the axial trough—such as the Atlantis II deep (**Figure B3–5**), the Discovery deep, and the Oceanographer deep—is unusually salty. It is so much saltier than normal seawater that it is referred to as **brine.** This brine is hot (50 to 60°C) and filled with dissolved metals. The source of the unusual salt and metal content of the water in these deeps is the flow of groundwater (subterranean water) through fractures in the underlying rocks. This briny groundwater is heated as it flows through the hot crust, becoming corrosive and leaching metals from the basalt rocks. The heated, high-salinity, metalliferous water is discharged along fractures and faults on the bottom of the deeps, where it is trapped because of its high density. As the levels of dissolved metals (iron, manganese, copper, silver, lead, and zinc) build up, many of them are precipitated as sulfide deposits that impart bright colors to the sediment.

Geochemical surveys indicate that the metal deposits of the Atlantis II deep are sufficiently concentrated to be exploited commercially. Several field tests indicate that it is feasible to mine this resource. High-pressure water jets (large, powerful hoses in effect) lowered from a vessel could convert the bottom sediment into a mud slurry, which would then be pumped to the surface at a rate estimated to be about 200,000 tons each day! This enormous volume of slurry would have to be processed aboard the mining vessel while at sea, because it would be too expensive to transport it to land. Unfortunately, once processed, the residue would become a major waste-disposal problem, because it contains highly toxic heavy metals. Engineers have developed a processing technique whereby only 1 percent of the metal concentrate would be transported to a smelter on land. The remaining 99 percent of the slurry would be diluted with seawater and treated with chemicals before being discharged into water deeper than 1,000 meters (~3,300 feet). Marine life is sparse at those depths in the Red Sea so the engineers reason that the effect of the metal toxins on the ecosystem of the area would be minimized.

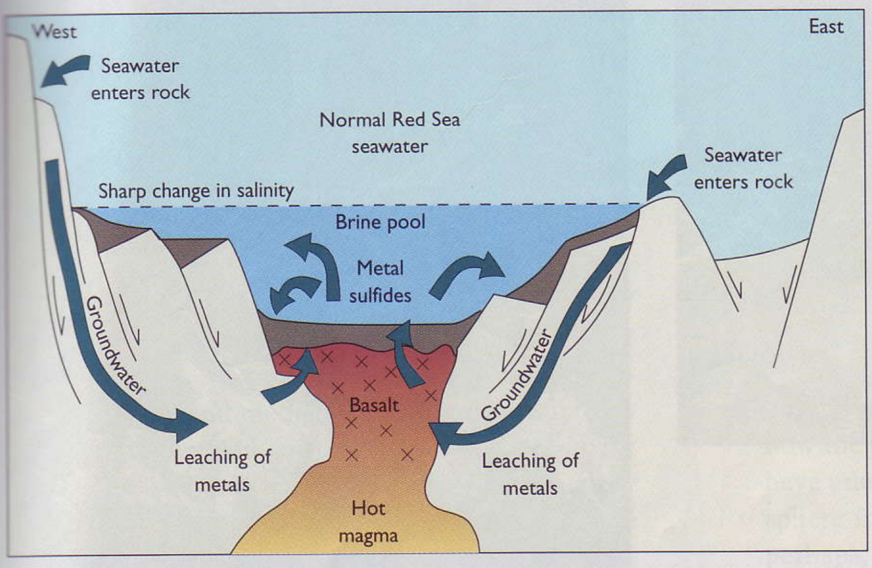
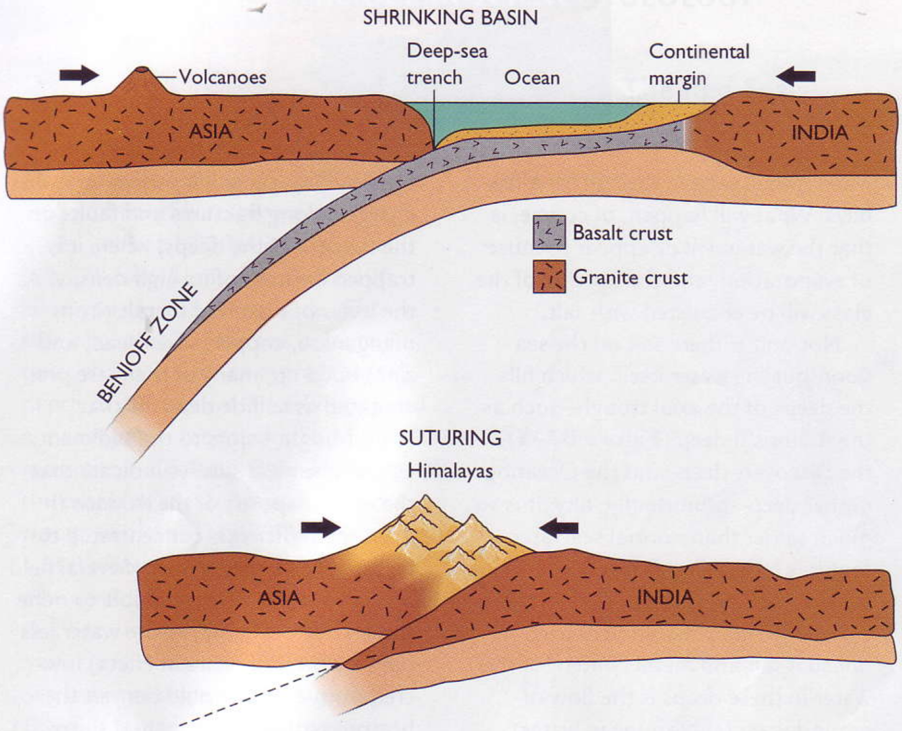


FIGURE **B3-5**

The Atlantis II deep. Groundwater flowing through fractures in the basaltic crust is acidic and corrosive. These hot salty fluids leach out metals from the rocks. When they seep out of fractures, the very dense water is trapped in the deeps. [Adapted from H. Backer, *Erzmetall* 26 (1973): 544–55.]

Visit www.jbpub.com/oceanlink for more information.



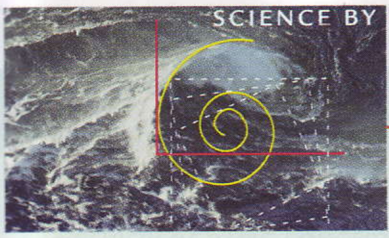
(a) PLATE TECTONIC MODEL

(b) SATELLITE IMAGE OF HIMALAYAS

(c) PROMINENT HIMALAYAN PEAKS

FIGURE 3-11

Collision of continents and mountain building. (a) These diagrams depict the collision and suturing of the India and Asia plates. The Himalayas were raised when the ocean sedimentary layers were crushed between the two continental masses. (b) Space shuttle image of the Himalayas showing the zone where the two plates are colliding. The view is southeasterward across Tibet. (c) These Himalayan peaks with their great relief and high elevations are the result of compression associated with the collision of Asia and India.



SCIENCE BY NUMBERS

Sea-Floor Spreading Rates

Lithospheric plates are moving apart at midocean ridges because of sea-floor spreading. Oceanic crust, once created, will slowly move away from the axis of the ridge. This means that the sea floor will have a speed. Speed is distance (d) traveled per unit of time (t), or

$$\text{speed} = d/t.$$

The sea floor is moving slowly, such that its speed cannot be measured directly with a stopwatch. Yet we can easily determine its speed (its spreading rate) by noting the age of the sea floor at any distance from the ridge. The older the sea floor is, the farther it will be from the ridge axis. Also, the faster the rate of sea-floor spreading, the farther the sea floor of a particular age will be from the ridge axis. Let's calculate a sea-floor spreading rate.

First, assume that we obtain a piece of basalt 400 kilometers from the ridge axis and determine its age to be 10 million years old. This implies that this rock took 10 million years to travel a distance of 400 kilometers. The number 400 can be expressed as 4×10^2 (i.e., 4 times 100). The number 10 million can be expressed as 10^7 (i.e., 10 times itself seven times). If this notation is unclear, review the Math Box called, "Powers of 10" in Chapter 2. The rate of the sea-floor spreading is

$$\text{speed} = \text{spreading rate} = d/t = 4 \times 10^2 \text{ km}/10^7 \text{ yr}.$$

When you divide powers of 10, you merely subtract the exponents. So,

$$4 \times 10^2 \text{ km}/10^7 \text{ years} = 4 \times 10^{(2-7)} \text{ km/yr} = 4 \times 10^{-5} \text{ km/yr}$$

is the rate of sea-floor spreading for this ridge.

Let's now convert this rate to centimeters per year (cm/yr), which would make more intuitive sense to us. The trick, as discussed in the Chapter 1 Math Box "Conversions," is to keep tab of the units.

$$(4 \times 10^{-5} \cancel{\text{km}}/\text{yr})\ (10^3 \cancel{\text{m}}/\cancel{\text{km}})\ (10^2 \text{ cm}/\cancel{\text{m}}) = (4 \times 10^{-5})\ (10^3)\ (10^2) \text{ cm/yr}.$$

When you multiply powers of ten, you merely add their exponents. So,

$$(4 \times 10^{-5})\ (10^3)\ (10^2) \text{ cm/yr} = 4 \times 10^{(-5+3+2)} \text{ cm/yr} = 4 \times 10^0 \text{ cm/yr}.$$

Because any number raised to a power of zero is 1,

$$4 \times 10^0 \text{ cm/yr} = 4 \text{ cm/yr}.$$

This is the spreading rate for that side or flank of the midocean ridge.

immense twisting, swirling "mushroom clouds" of very hot water that are tens of kilometers (>6.2 miles) broad. Megaplumes carry gases such as carbon dioxide and methane and countless microbes as they spin and drift about in the ocean for months, moving hundreds of kilometers away from their site of origin. Some biologists believe that life itself may have begun at the bottom of the sea in sea-floor geysers located at spreading ridge crests. These hydrothermal vents may have been sites where raw inorganic materials were miraculously shaped by chemical reactions into simple organic compounds that ultimately led to the origin of life some four billion years ago. So the study of megaplumes and hydrothermal systems may lead to new theories about the origin of life and its dispersal throughout the world's oceans.

Other exciting new research in marine geology involves probing the Earth's interior to determine how the planet works. For example, geophysicists have uncovered old, cold slabs of subducted lithosphere in the Earth's upper mantle; others may, perhaps, be deep in the lower mantle as well. These "fossil" slabs are surviving remnants of plate tectonic events that occurred during the Earth's ancient geologic past. Understanding how they got there and what happens to them over time will give geologists a clearer and more complete view of the Earth's history and geochemical evolution.

STUDY GUIDE

KEY CONCEPTS

1. Geologic and paleontological evidence supports the existence in the geologic past of an immense landmass known as *Pangaea*. Beginning about 150 million years ago, Pangaea broke apart, and the pieces drifted across the Earth's surface to form today's continents. This process is called *continental drift*.

2. Studies of the magnetic properties of the sea floor reveal that the crests of the midocean ridges are sites where new oceanic crust is forming. The divergence of the basaltic crust away from the crestline of the ridge—a process called *sea-floor spreading*—leads to the expansion of ocean basins and to the drift of the continents. The repeated flipping back and forth of the geomagnetic poles causes basalts ejected at spreading ocean ridge crests to be normally and reversely magnetized, giving rise to a symmetric pattern of *magnetic anomaly stripes* that run parallel to the ridge axis. These magnetic anomaly stripes can be used to calculate the rate of sea-floor spreading.

3. Basaltic crust is being destroyed at *subduction zones,* which are associated with volcanic arcs and deep-sea trenches. Here, large slabs of rock are being compressed as they converge and override one another, producing an inclined plane of earthquakes called the *Benioff zone*.

4. The global distribution of earthquakes indicates the Earth's surface is broken into a mosaic of irregularly shaped plates. Each plate, which is 100 to 150 kilometers (~62 to 93 miles) thick, consists of the entire crust and the uppermost mantle, which combined constitute the *lithosphere*. The lithospheric plates are cold, rigid, and brittle, and overlie a hot, ductile (plasticlike) layer of the mantle, the *asthenosphere*.

5. Lithospheric plates have three kinds of boundaries: *spreading ridges* that are under tension, where new lithosphere is formed; *subduction zones* that are under compression, where lithosphere is destroyed; and *transform faults*, where lithosphere is preserved as plates slip laterally (strike-slip motion) past one another.

6. The vast majority of volcanoes are formed at plate boundaries. Many lie along subduction boundaries where the lithosphere has melted as it was forced downward into the Earth's hot interior by an overriding lithospheric plate. Other volcanoes form along the crests of spreading ocean ridges as well, as lithospheric plates diverge and lava spills out of fractures onto the sea floor. In contrast, some linear chains of volcanoes form on the plate interior, far from its edges, as the lithosphere drifts slowly over a *mantle plume*, or "hot spot," in the underlying asthenosphere. The mantle plume feeds lava to the plate's surface and creates a long, linear chain of volcanoes that mark the track of the plate over the mantle plume.

7. Ocean basins undergo a regular evolutionary history related to plate tectonics. A narrow, embryonic basin forms between the splintered pieces of a continent; expands into a broad, mature ocean basin by the mechanism of sea-floor spreading; declines into old age as the basin is consumed by subduction; and disappears as colliding continental masses become tightly sutured together and form an immense mountain belt on land.

QUESTIONS

REVIEW OF BASIC CONCEPTS

1. Explain the concepts of continental drift, sea-floor spreading, and global plate tectonics.

2. What exactly is a magnetic anomaly, and why does it appear as a stripe on the sea floor?

3. How do plate motions differ among a spreading ridge, a transform fault, and a subduction zone? Which of the three is characterized by the strongest earthquakes, the deepest earthquakes? Why?

4. Draw a detailed cross section of the Earth's outer layers, showing the relationships among deep-sea trenches, island arcs, Benioff zones, andesite volcanism, the lithosphere, the ocean crust, the asthenosphere, and the Moho. (You may have to refer back to Chapter 2.)

CRITICAL-THINKING ESSAYS

1. Why do magnetic anomaly stripes of similar age have the same magnetic polarity, regardless of where they are discovered in the ocean?

2. It is unlikely that magnetic anomaly stripes older than about 200 million years will be found anywhere in the oceans. Why?

3. In which ocean is the oldest oceanic crust likely to be found? Why?

4. Assume that you discover a series of large submarine volcanoes on the deep-ocean floor of the Pacific. How would you determine whether or not these volcanoes had been created by a mantle plume?

5. Cite a variety of evidence that supports the notion of (a) continental drift, (b) sea-floor spreading, (c) subduction.

DISCOVERING WITH NUMBERS:

1. Convert 33 kilometers into centimeters: 4.1×10^6 cm into kilometers (see Appendix II).

2. Assume that magnetic anomaly C in Figure 3–3 is 650,000 years old. Calculate a spreading rate for the sea floor. Now, using the calculated sea-floor spreading rate, estimate the age of magnetic anomaly B in Figure 3–3.

3. Assume that you are conducting geophysical work on the flank of a spreading ocean ridge that trends directly north-south. As the captain steers the vessel to the east, your magnetometer measures a series of magnetic highs and lows. A strong, broad magnetic high is positioned directly over the ridge crest. It is followed to the east by a magnetic low of modest width and, at 45 kilometers from the ridge crest, a narrow but prominent magnetic high. Determine the age of this latter magnetic high by consulting Figure 3–4c, and then determine the spreading rate in centimeters per year for this midocean ridge.

4. In Problem 3 above, how many kilometers from the ridge crest would you have to sail to the west in order to be positioned over ocean crust that is 15 million years old?

5. Consult Figure 3–9a. Given that 10 degrees of latitude equals about 1,110 kilometers, calculate an approximate rate of sea-floor spreading in centimeters per year for the North Pacific plate, assuming that mantle plumes do not drift over time. Does the rate of spreading change over time?

KEY WORDS

andesite
asthenosphere
Benioff zone
compression
continental drift
lithospheric plate
lithosphere
magnetic anomaly stripe
mantle plume
normal fault
normal polarity
paleomagnetism
paleontology
Pangaea
plate tectonics
reverse polarity
rift valley
sea-floor spreading
seismicity
strike-slip fault
subduction zone
tension
thermal convection
transform fault

SELECTED READINGS

Anderson, R. N. 1986. *Marine Geology: A Planet Earth Perspective.* New York: John Wiley.

Ballard, R. D. 1975. Dive into the great rift. *National Geographic.* 147 (5): 604–15.

———, 1983. *Exploring Our Living Planet.* Washington, D.C.: National Geographic Society.

Bonatti, E. 1987. The rifting of continents. *Scientific American* 256 (3): 96–103.

———, 1994. The Earth's mantle below the ocean. *Scientific American* 270 (3): 44–51.

Bonatti, E., and Crane, K. 1984. Oceanic fracture zones. *Scientific American* 250 (5): 40–51.

Courtillot, V., and Vink, G. E. 1983. How continents break up. *Scientific American* 249 (1): 42–49.

Dalgiel, I. W. D. 1995. Earth before Pangaea, *Scientific American* 271 (1): 58–63.

Dewey, J. R. 1972. Plate tectonics. *Scientific American* 226 (5): 56–68.

Dietz, R. S. 1971. Those shifting continents. *Sea Frontiers* 17 (4): 204–12.

Dietz, R. S., and Holden, J. C. 1970. The breakup of Pangaea. *Scientific American* 223 (4): 30–41.

Francheteau, J. 1983. The oceanic crust. *Scientific American* 249 (3): 114–29.

Frohlich, C. 1989. Deep earthquakes. *Scientific American* 260 (1): 48–55.

Fryer, P. 1992. Mud volcanoes of the Marianas. *Scientific American* 266 (2): 46–52.

Hallam, A. 1975. Alfred Wegener and the hypothesis of continental drift. *Scientific American* 232 (2): 88–97.

Heirtzler, J. R. 1968. Sea-floor spreading. *Scientific American* 219 (6) 60–70.

Heirtzler, J. R., and Bryan, W. B. 1975. The floor of the Mid-Atlantic Rift. *Scientific American* 233 (2): 78–91.

Hekinian, R. 1984. Undersea volcanoes. *Scientific American* 251 (1): 46–55.

Hoffman, K. A. 1988. Ancient magnetic reversals: clues to the geodynamo. *Scientific American* 258 (5): 76–83.

Hyndman, R.D. 1995. Great earthquakes of the Pacific Northwest. *Scientific American* 276 (6): 68–75.

Larson, R. I. 1995. The mid-Cretaceous superplume episode. *Scientific American* 272 (2): 82–89,

Lonsdale, P., and Small, C. 1991–92. Ridges and rises: a global view. *Oceanus* 34 (4): 26–35.

Macdonald, J. B., and Fox, P. J. 1990. The mid-ocean ridge. *Scientific American* 262 (6): 72–79.

Macdonal, K. C., and Lyendyk, B. P. 1981. The crest of the East Pacific Rise. *Scientific American* 244 (5): 100–16.

Molnar, P. 1986. The structure of mountain ranges. *Scientific American* 255 (1): 70–79.

Molnar, P. and Tapponnier. P. 1977. The collision between India and Eurasia. *Scientific American* 236 (4): 30–41.

Morgan, W. J., and Vogt, P. R. 1986. The earth's hot spots. *Scientific American* 252 (4): 50–57.

Murphy, J. B., and Nance, R. D. 1992. Mountain belts and the supercontinent cycle. *Scientific American* 266 (4): 84–91.

Nance, R. D., Worsley, T. R., Moody, J. B. 1988. The supercontinent cycle. *Scientific American* 259 (1): 72–79.

Oceanus. 1991–1992. Midocean ridges. Special issue 34 (4).

———. 1993–1994. 25 years of ocean drilling. Special issue 36 (4).

———. 1998. The Mid-Ocean Ridge: Part I. Special issue 41 (1): 1–37.

Powell, C. C. 1991. Peering inward. *Scientific American* 264 (6): 100-11.

Sclater, J. G., and Tapscott, C. 1979. The history of the Atlantic. *Scientific American* 240 (6): 156–74.

Siever, R. 1983. The dynamic earth. *Scientific American* 249 (3): 46–55.

Tokosoz, M. N. 1975. The subduction of the lithosphere. *Scientific American* 233 (5): 88–98.

Toomey, D. R., 1991–92. Tomographic imaging of spreading centers. *Oceanus* 34 (4): 92–99.

TOOLS FOR LEARNING

Tools for Learning is an on-line review area located at this book's web site OceanLink (**www.jbpub.com/oceanlink**). The review area provides a variety of activities designed to help you study for your class. You will find chapter outlines, review questions, hints for some of the book's math questions (identified by the math icon), web research tips for selected Critical Thinking Essay questions, key term reviews, and figure labeling exercises.

A printed study guide, containing additional study questions and exercises, can also be ordered directly from the publisher through OceanLink.