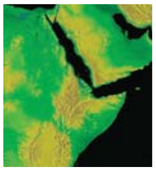
CHAPTER 3

Plate Tectonics and Earthquakes



Many geologists have maintained that movements of the Earth's crust are concentrated in mobile belts, which may take the form of mountains, mid-ocean ridges or major faults . . . This article suggests that these features are not isolated, that few come to dead ends, but that they are connected into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates.

—*John Tuzo Wilson,* Nature, *1965*

Outline

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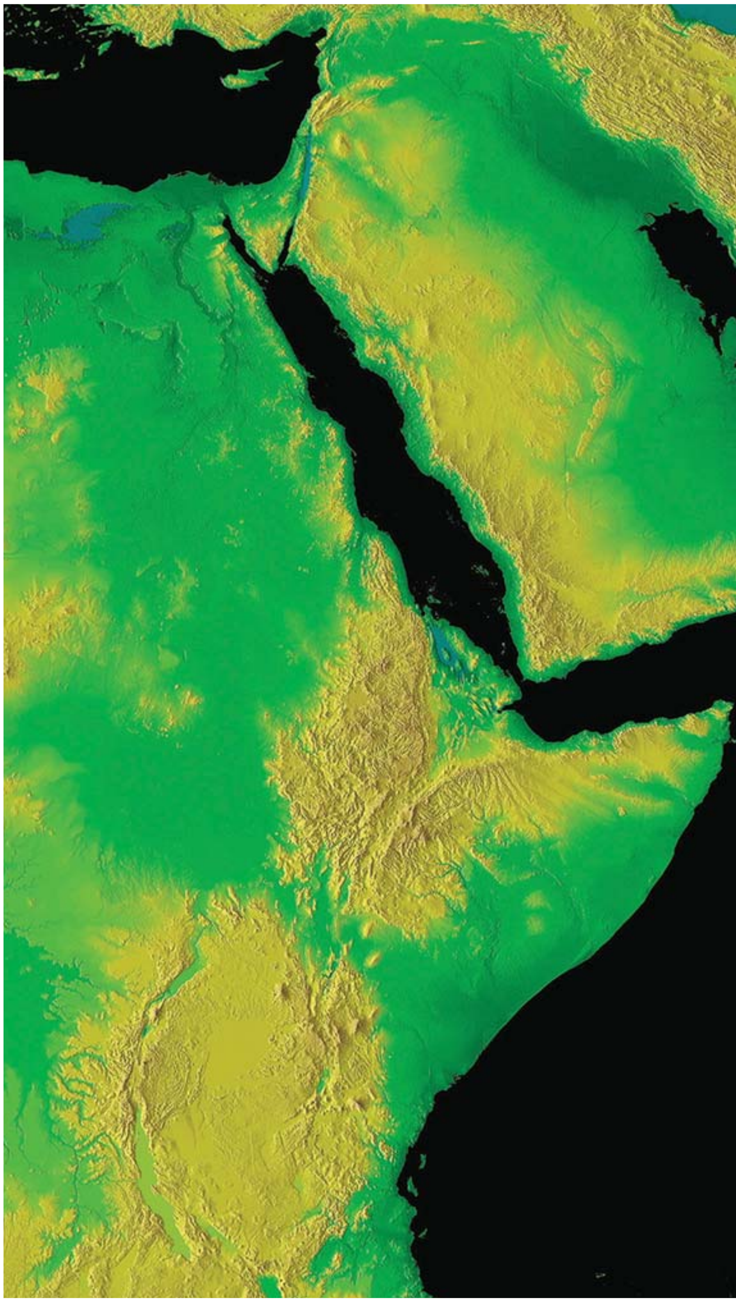


Satellite view of Arabia moving away from Africa.
Photo: © NOAA.

On Friday morning, 26 January 2001, Hidendre Barot was at home with his wife in their apartment on the top floor of a ten-storey building in Ahmedabad in the state of Gujarat in west-central India. At 8:46 a.m. the apartment building began shaking, and Barot and his wife fled onto the roof, held hands, and waited for the violent motions to stop. But the building failed, and Barot fell ten stories with the collapsing structure, ending up surrounded by debris but with no serious injuries. For days afterward, he helped search the building wreckage looking for his wife, but she was one of the 20,103 people killed by this major earthquake, the deadliest natural disaster of 2001.

Our planet is mobile and active; its uppermost rocky layers move horizontally in the process of plate tectonics. These movements are directly responsible for most of the earthquakes, volcanic eruptions, and mountains on Earth.

Plate Tectonics

The lithosphere of Earth is broken into pieces called **plates** (Figure 3.1). These gigantic pieces pull apart during seafloor spreading at **divergence zones**, slide past at **transform faults**, or collide at **convergence zones**. The study of the movements and interactions of the plates is known as **plate tectonics**. The Greek word *tekton* comes from architecture and means "to build"; it has been adapted by geologists as the term **tectonics**, which describes the deformation and movement within Earth's outer layers, and the building of **topography**. The topographic and bathymetic map of the world reveals several prominent features created by tectonic forces—on continents, the Himalaya and the Tibetan Plateau, and the cordillera of the west coast of the Americas; on the ocean floor, mid-oceanic **ridges**, deep trenches, and chains of volcanic islands and seamounts (Figure 3.2).

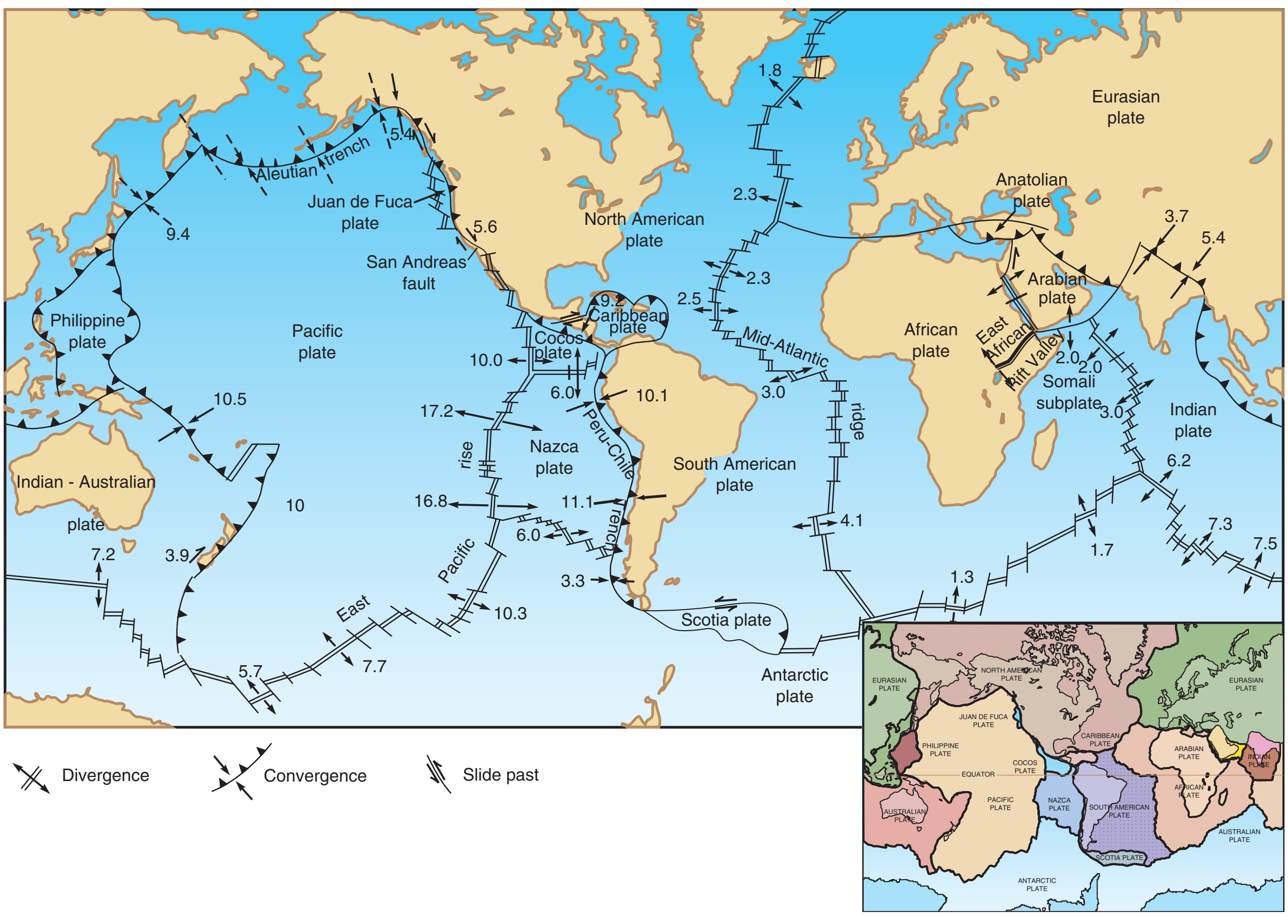


Figure 3.1
A tectonic view of the world. In the context of natural disasters, the boundaries between the different plates are more important than the familiar continental coastlines. Arrows indicate the direction of plate movement. Rates of movements are shown in centimetres per year.

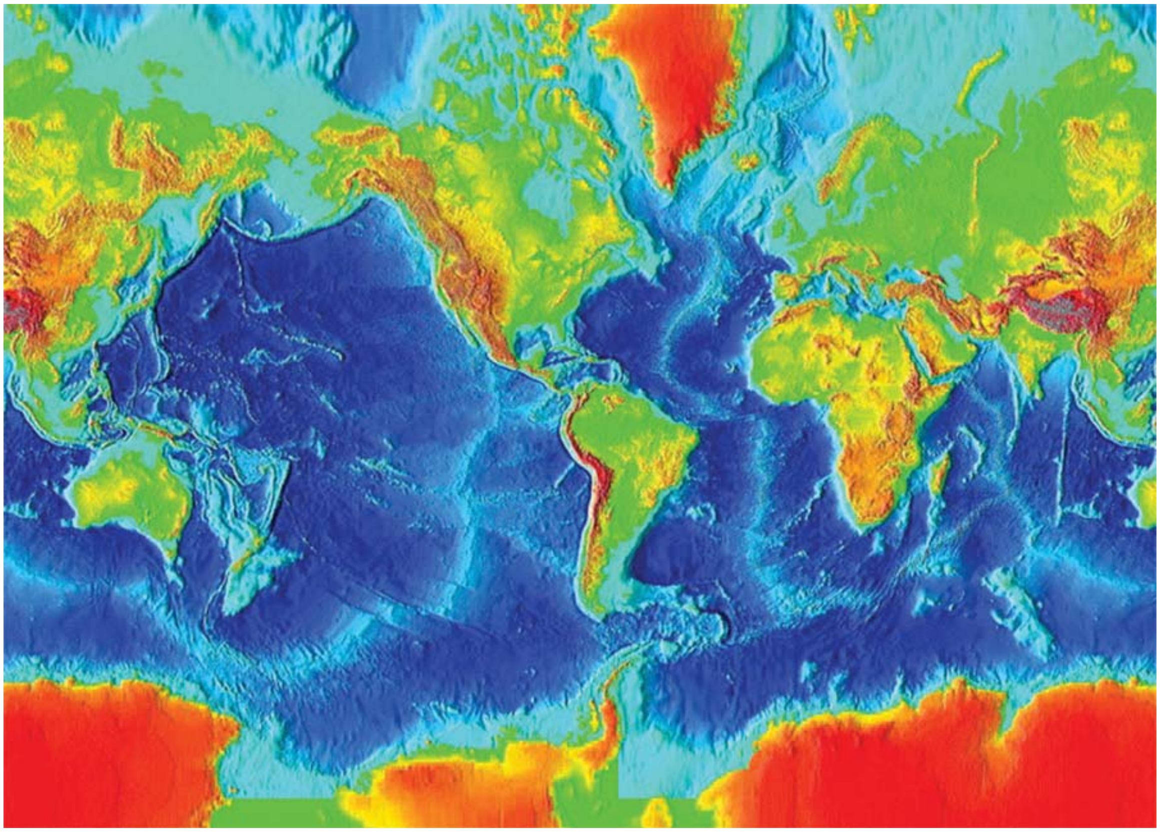


Figure 3.2
Topographic and bathymetric map of the world. Red and dark blue correspond to the most elevated and depressed regions, respectively.
Source: NOAA http://whale.wheelock.edu/whalenet-stuff/MAPSindex.

To grasp the concepts of plate tectonics, we must adopt a new perspective when looking at the world's map. We must move our focus away from the continental coastlines and concentrate on plate boundaries. Several of these boundaries are underwater, which explains why the initial development of the plate tectonics concept was closely linked to the exploration of the oceans.

We saw in the previous chapter that Earth's surface is subjected to vertical forces. Adding the horizontal components of movements on Earth allows us to understand the **tectonic cycle**, which can be simplified as follows (Figure 3.3). First, melted asthenosphere flows upward as magma and cools to form new lithosphere on the ocean floor. Second, the new lithosphere slowly moves laterally away from the zones of oceanic crust formation on top of the underlying asthenosphere (**seafloor spreading**). Third, when the leading edge of a moving slab of oceanic lithosphere collides with another slab, the denser slab turns downward and is pulled by gravity back into the asthenosphere (**subduction**), while the less-dense, more buoyant slab overrides it. Last, the slab pulled into the asthenosphere is reabsorbed. The time needed to complete this cycle is long, commonly in excess of 250 million years.

Another way that plate tectonics can be visualized is by using a hard-boiled egg as a metaphor for Earth. Consider the hard-boiled egg with its brittle shell as the lithosphere, the slippery inner lining of the shell as the asthenosphere, the egg white (albumen) as the rest of the mantle, and the yolk as the core. Before eating a hardboiled egg, we break its brittle shell into pieces that slip around as we try to pluck them off. This handheld model of brittle pieces being moved atop a softer layer below is a small-scale analogue to the interactions between Earth's lithosphere and asthenosphere.

Development of the Plate Tectonics Concept

Human thought about Earth has long been limited by the smallness of our bodies and the restricted range of our travels in relation to Earth's gigantic size; it also has been

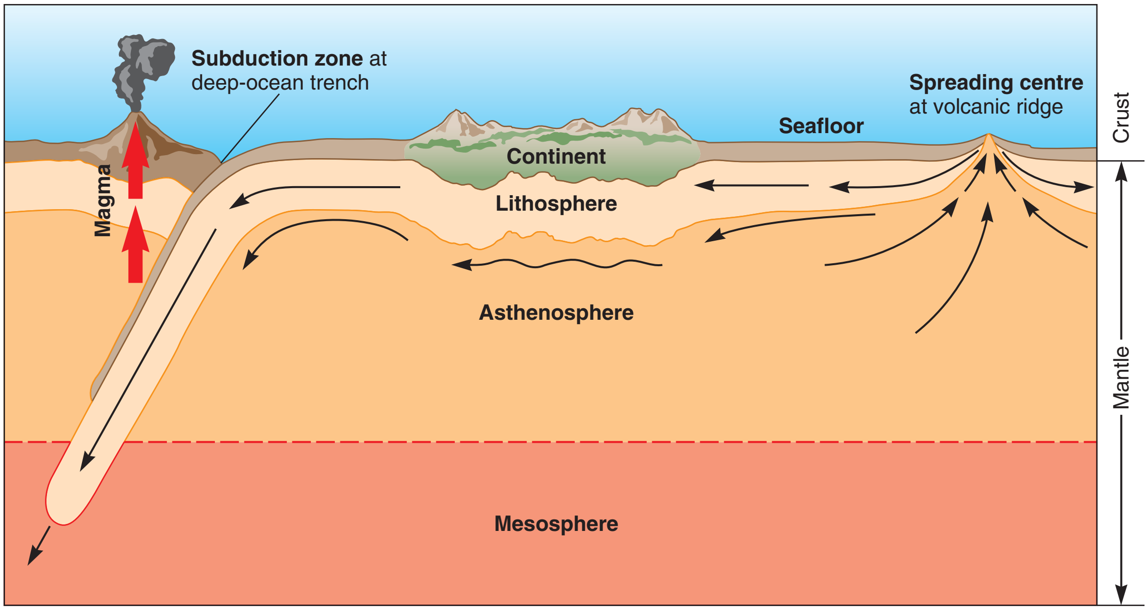


Figure 3.3

Schematic cross-section of the tectonic cycle. First, magma rises from the asthenosphere to the surface at the oceanic volcanic ridges where it solidifies and adds to the plate edges. Second, as the igneous rock cools, the plate moves laterally away. Third, the plate continues to cool, grows thicker at its base, becomes denser, collides with a less-dense plate, and subducts. Finally, it is ultimately reassimilated in the asthenosphere.

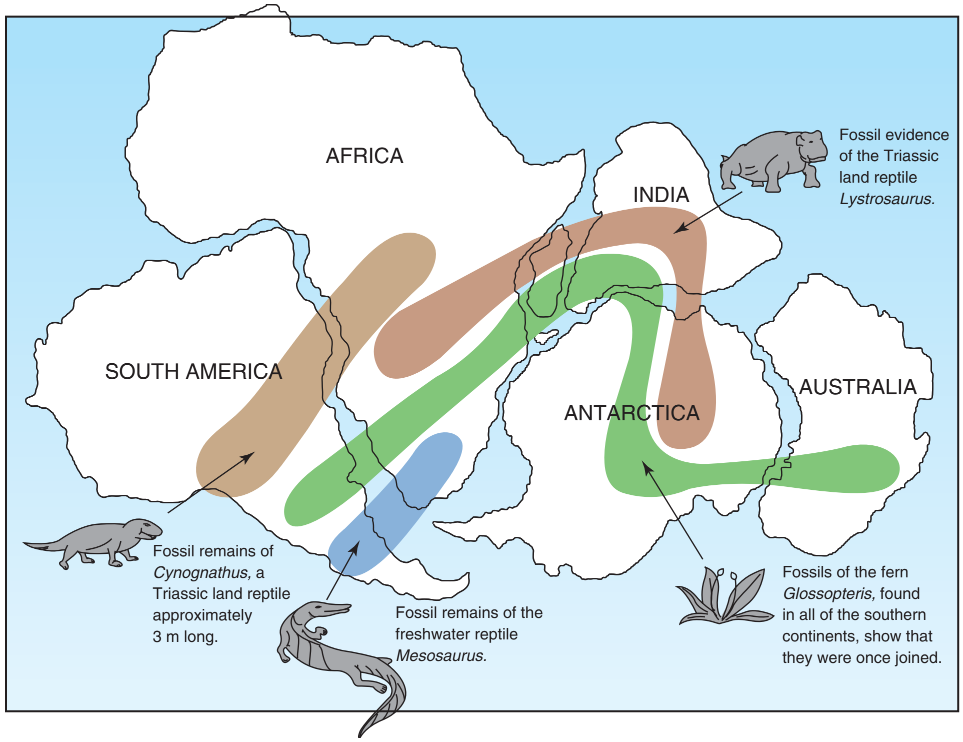
Adapted from A. Cox and R. B. Hart, *Plate Tectonics: How It Works.*

limited by the shortness of our life spans compared to the age of Earth. Our planet is so large and so old that the combined efforts of many geologists and philosophers over the last few hundred years have been required to amass enough observations to begin understanding how and why Earth changes as it does. The first glimpse of our modern understanding began after the European explorers of the late 1400s and 1500s made maps of the shapes and locations of the known continents and oceans. These early world maps raised intriguing possibilities. For example, in 1620, Francis Bacon of England noted the parallelism of the Atlantic coastlines of South America and Africa and suggested that these continents had once been joined. During the late 1800s, Austrian geologist Eduard Suess presented abundant evidence in support of Gondwanaland, an ancient southern supercontinent composed of a united South America, Africa, Antarctica, Australia, India, and New Zealand, which later split apart. The most famous and outspoken of the early proponents of **continental drift** was the German meteorologist Alfred Wegener. In his 1915 book, *The Origin of Continents and Oceans,* he collected powerful evidence, such as the continuity of geological structures and fossils, on opposite sides of the Atlantic Ocean (Figure 3.4). Wegener suggested that all the continents had once been united in a supercontinent called **Pangaea**.

Much is made of the fact that during his lifetime, Wegener's hypothesis of continental drift gathered more ridicule than acceptance. But why were his ideas not widely accepted? Wegener presented an intriguing hypothesis well supported with observations and logic, but failed to provide a plausible mechanism for the movements of the continents. When Wegener presented his evidence for continental drift, geologists and geophysicists were faced with trying to visualize how a continent could break loose from the underlying rock and plow a path over it. It seemed physically impossible then. When it became known that the rigid lithosphere decouples from the plastic asthenosphere and moves laterally, then the relatively small, low-density continents, set within the oceanic crust, were seen to be carried along as incidental passengers (Figure 3.3).

By the mid-1960s, the plate tectonics theory was developed and widely accepted. Tuzo Wilson, a professor of geophysics at the University of Toronto, was instrumental in formulating several of the key concepts of plate tectonics (see In Greater Depth box: John Tuzo Wilson (1908–1993)). It is rare in science to find widespread agreement on a broadly encompassing theory such as plate tectonics. But when data from Earth's magnetic field locked inside seafloor rock were widely understood, skeptics around the world became convinced that seafloor spreading occurs and that the concept of plate tectonics is valid.

Figure 3.4
The distribution of several fossils is continuous when the continents are restored to the position they occupied when these life forms existed.
Source: United States Geological Survey.



Evidence of Plate Tectonics from Seafloor Surveys

MAGNETIZATION PATTERNS ON THE SEAFLOORS

As the **lava** erupted from a volcano cools at the surface of Earth, minerals begin to grow as crystals. Some of the earliest formed crystals incorporate iron into their structures. After the lava cools below the **Curie point**, at about 550°C, atoms in iron-bearing minerals become magnetized in the direction of Earth's **magnetic field** (see In Greater Depth box: Earth's Magnetic Field in Chapter 16) at that time and place. The lined-up atoms in the iron-rich crystals behave like compass needles, pointing toward the **magnetic pole** of their time: the north magnetic pole (normal polarity) or the south magnetic pole (reverse polarity). Lava flows pile up as sequences of stratified rock, and the magnetic polarity of each rock layer can be measured (Figure 3.6). Many of the volcanic rocks also contain minerals with radioactive elements that allow determination of their age. When this information is plotted together in a vertical column, a timescale of magnetic polarities emerges (Figure 3.7).

Since the late 1940s, oceanographic research vessels criss-crossing the Atlantic Ocean have towed magnetometers to measure the magnetization of the seafloor. As the number of voyages grew and more data were obtained, a striking pattern began to emerge (Figure 3.8). The floor of the Atlantic Ocean is striped by parallel bands of magnetized rock that show alternating polarities. The pattern is symmetrical and parallel with the mid-ocean volcanic ridge. That is, each striped piece of seafloor has its twin on the other side of the oceanic mountain range.

A remarkable relationship exists between the time of reversals of magnetic polarity, as dated radiometrically from a sequence of solidified lava flows (Figure 3.7), and the widths of alternately polarized seafloor (Figure 3.8): they are comparable. How stunning it is that the widths of magnetized seafloor strips have the same ratios as the lengths of time between successive reversals of Earth's magnetic field. This means that distance in kilometres is proportional to time in millions of years. Magma is injected into the ocean ridges where it is imprinted by Earth's magnetic field as it cools to form new rock. Then the seafloor is physically pulled away from the oceanic ridges as if they were parts of two large conveyor belts going in opposite directions (Figure 3.9).

AGES FROM THE OCEAN BASINS

Another stunning fact discovered during the exploration of the oceans is the youthfulness of the ocean basins.

In Greater Depth

John Tuzo Wilson (1908–1993) The Father of Plate Tectonics

John Tuzo Wilson was born in Ottawa in 1908, the first child of Henrietta Tuzo and John Armistead Wilson (Figure 3.5). His mother was an accomplished mountaineer and his father an engineer. This heritage was reflected by Tuzo Wilson's choice of studies: he graduated from the University of Toronto in 1930 with a double major in physics and in geology, and earned a second undergraduate degree from the University of Cambridge in England, taking a collection of lectures in the same topics. After a brief period of employment at the Geological Survey of Canada, Tuzo Wilson went on to do a Ph.D. at Princeton where he met Harry Hesse and Maurice Ewing, leading scientists studying geological processes in ocean basins. Like many young men of his generation, Tuzo Wilson's career was interrupted by World War II, during which he served overseas as an engineer in the Canadian Army. After the war, Tuzo Wilson returned to Canada to become professor of geophysics at the University of Toronto.

Initially opposed to continental drift, Tuzo Wilson developed his vision of a dynamic Earth through several years of study of the different geological domains that have amalgamated to form the Canadian Precambrian Shield. The word "vision" is particularly fitting here since Tuzo-Wilson's problem-solving approach was largely visual and stemmed from field observations and the detailed examination of maps. He is reported to have reflected on the formation of the Hawaiian islands using the bucolic image of someone lying on his back in a stream and blowing bubbles to the surface through a straw.

Between 1963 and 1966, Tuzo Wilson presented his views on hot spots and transform faults in three papers that would cause a revolution in the earth sciences. His first paper, entitled "A Possible Origin of the Hawaiian Islands," was first rejected by the leading American geophysical journal before being published in the *Canadian Journal of Physics,* not exactly a widely read journal in earth science circles! Nevertheless, Tuzo Wilson went on to make an outstanding contribution in providing an integrated framework for understanding geology at a planetary scale.

Tuzo Wilson was not only a towering figure in the earth science community, but also a gifted communicator. After retiring from the University of Toronto, he became director-general of the Ontario Science Centre, a pioneering interactive science museum, and shared with a large public his passion for science.

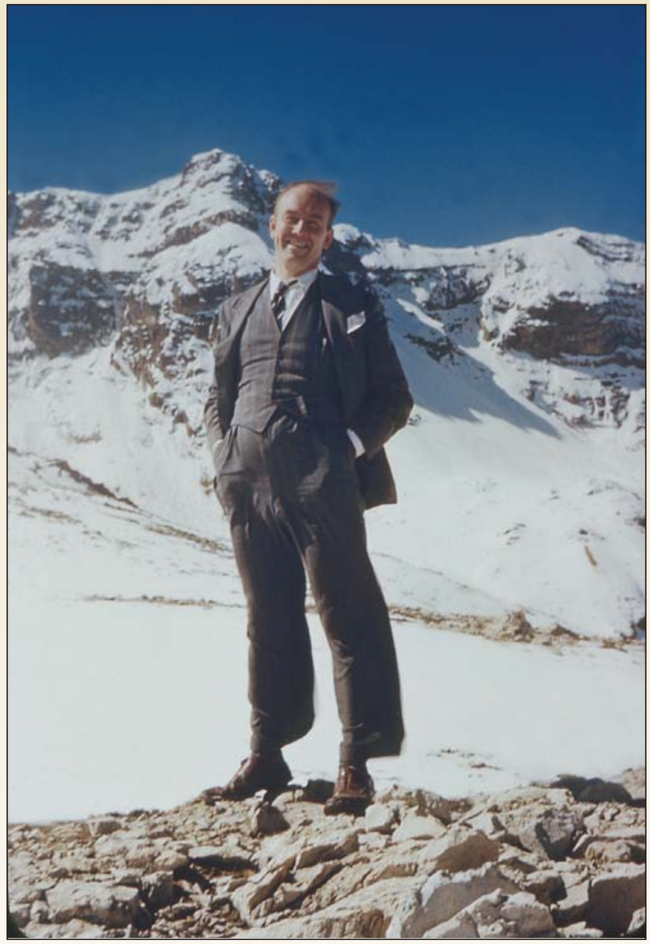


Figure 3.5 Prof. Tuzo Wilson in the Andes (Chile) in 1960. A few years later, Tuzo Wilson would put forward ideas bringing a new understanding of the process of mountain building.
Photo courtesy of Susan Wilson.

Two seamounts, located 200 km west of Vancouver Island, have been named in Tuzo Wilson's honour, a very appropriate gesture to acknowledge the contribution of the scientist who provided insight into their formation. The tectonic cycle is also often referred to as the Wilson cycle.

The oldest rocks on the ocean floors are about 200 million years in age; this is less than 5% of the age of Earth. Why? Because the ocean basins are young features that are continuously being formed and destroyed. Along the oceanic ridges, volcanism is active, and new seafloor is forming (Figure 3.9). Moving away from the ridges, the seafloor volcanic rocks and islands become progressively older. The oldest seafloor rocks are found at the edges of the ocean basins (Figure 3.10).

OCEANIC HOT SPOTS

At certain locations, deep-seated **hot spots** produce more heat, causing hotter rock with lower density; these **plumes** of buoyant hot rock rise through the mesophere, begin to melt near the top of the overlying asthenosphere, and pass up through the lithosphere as magma. Hot spots have active volcanoes above them on Earth's surface. The volcanoes rest on moving plates that carry them away from their hot-spot source. This process forms lines of extinct volcanoes on the ocean floor, from youngest to oldest, pointing in the direction of plate movement (Figure 3.11). In other words, the ages of the former volcanoes increase with their distance from the hot spot.

BATHYMETRY

Bathymetry provides additional supporting evidence for plate tectonics (Figure 3.2). The greatest mountain ranges

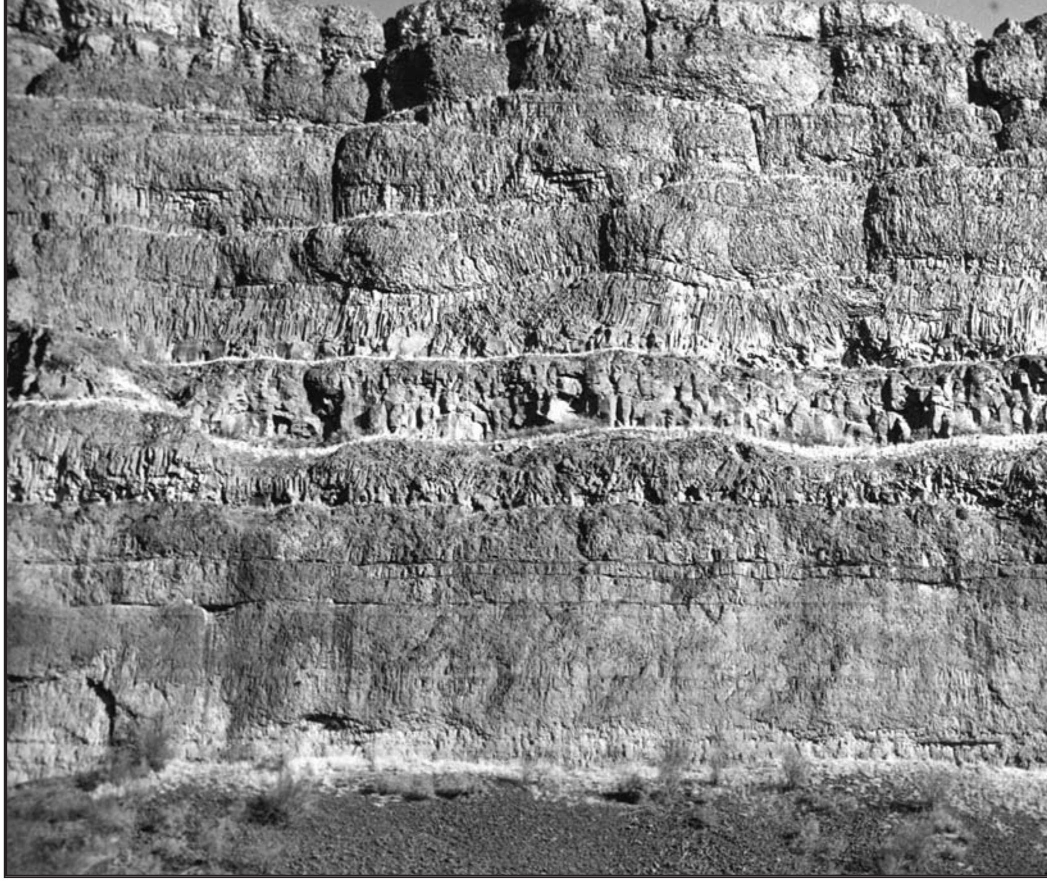


Figure 3.6
A stratified pile of former lava flows of the Columbia River flood basalt exposed in the east wall of Grand Coulee, Washington State. The oldest flow is on the bottom and is
overlain by progressively younger flows.
Photo by John S. Shelton.

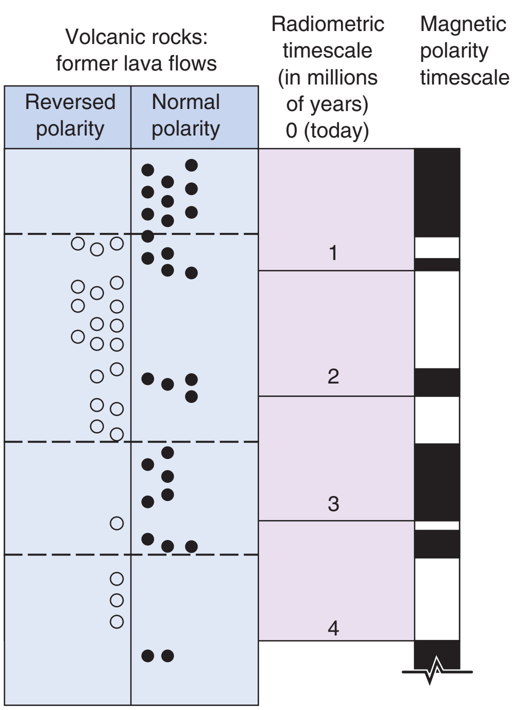


Figure 3.7
A portion of the magnetic polarity timescale. Magnetic polarity measurements in volcanic rocks combined with radiometric ages determined from the same rocks allow formation of a timescale based on magnetic polarity reversals. Notice the unique and nonrepetitive pattern of the polarity reversals.
Source: © John Wiley & Sons, Inc.

on Earth, the oceanic ridges, lie on the seafloor and extend more than 65,000 km. These long and continuous volcanic ridges are forming at **spreading centres** where plates pull apart and magma rises to fill the gaps. Above the oceanic ridges, the water depth is relatively shallow. However, moving progressively away from the ridges, the water depth increases systematically with seafloor age (Figure 3.12). This is due to the cooling and contraction of the oceanic crust with a resultant increase in density. Also, there is some down-warping due to the weight of sediments deposited on the seafloor. The older the seafloor, the more time it has had to accumulate a thick cover of silt, clay, and fossils.

The ocean floor has an average depth of 3.7 km, yet depths greater than 11 km exist in elongate, narrow **trenches**. These long and deep trenches were known since the *Challenger* oceanographic expedition in the 1870s, but they were not understood until the 1960s, when it was recognized that they are the tops of the subducting plates turning downward to re-enter the asthenosphere.

Evidence of Plate Tectonics from Earthquakes and Volcanoes

The **epicentre** of an earthquake is the projection on Earth's surface of the **hypocentre**, the location at depth of initial energy release during an earthquake (Figure 4.2). Because most earthquakes are caused by a release of stress

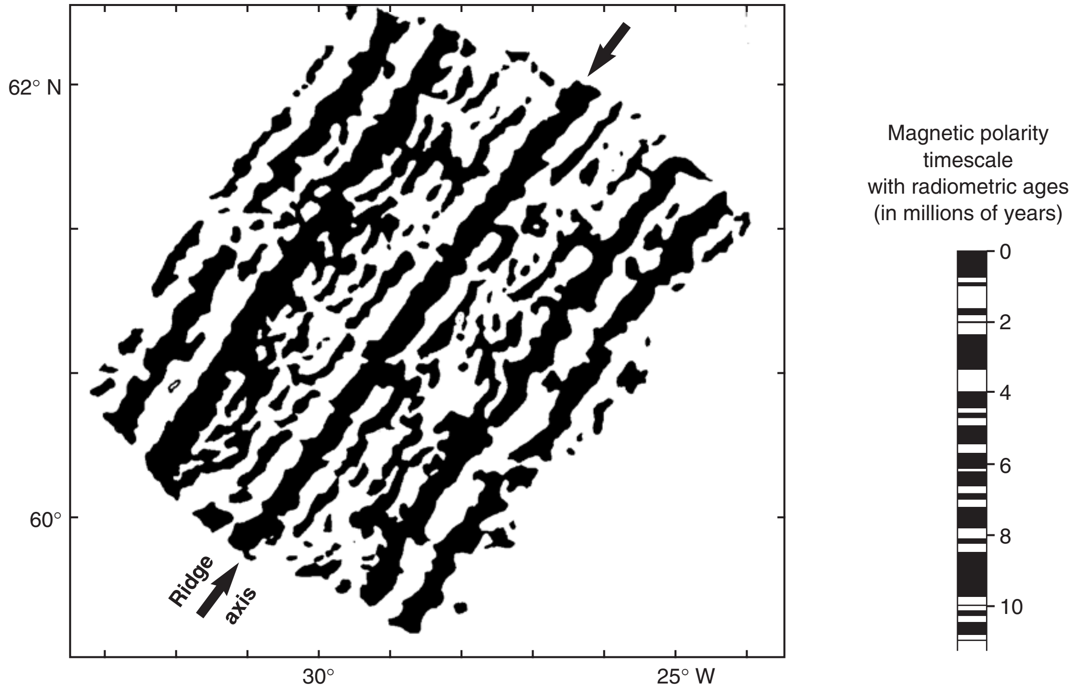


Figure 3.8

Map of the magnetically striped Atlantic Ocean floor southwest of Iceland. Black areas are magnetized pointing to a north pole and white areas to a south pole. Notice the near mirror images of the patterns on each side of the volcanic ridge (spreading centre).

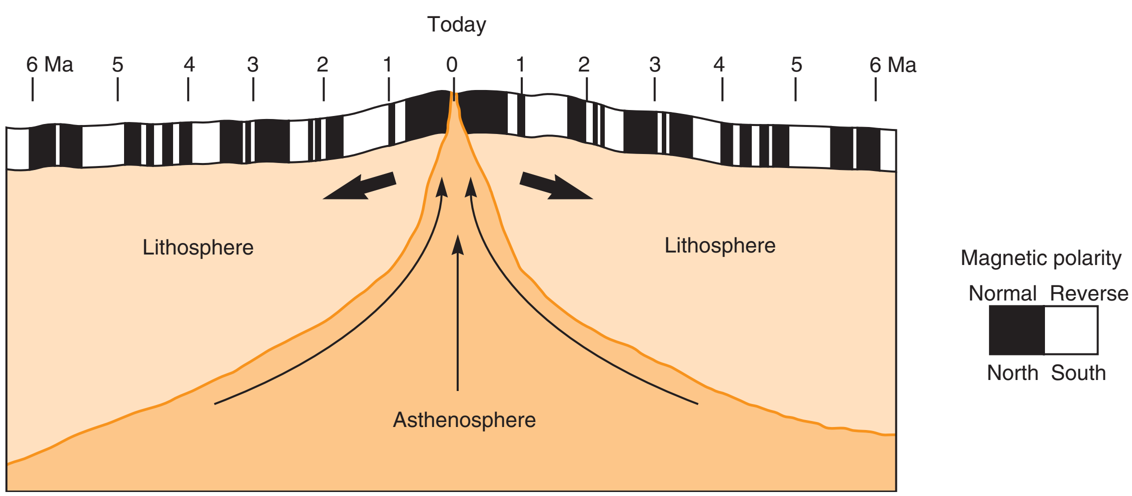


Figure 3.9

Cross-section of magnetically striped seafloor. Numbers above the seafloor are radiometrically determined ages in millions of years. The near mirror-image magnetic pattern is like a tape recorder that documents "conveyor belt" movements away from volcanic ridges.

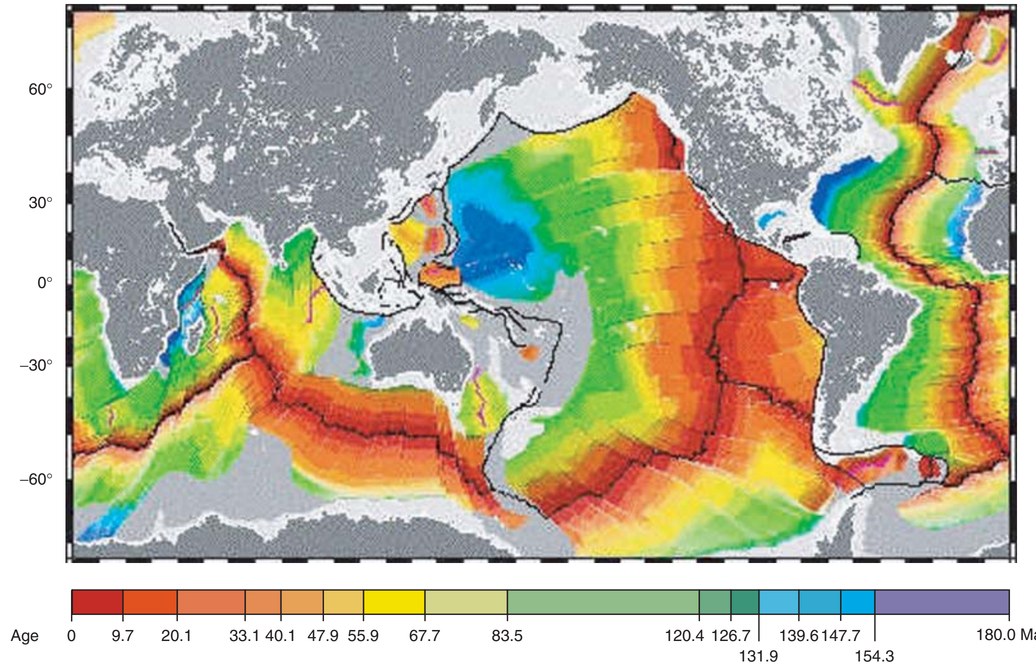
accumulated at plate boundaries, it is no surprise that there is a close relationship between earthquake epicentre and hypocentre locations, and plate tectonics.

1. Earthquake epicentres outline tectonic plates. The map of earthquake epicentres (Figure 1.11) can be viewed as a connect-the-dots puzzle. Each epicentre represents a place where one major section of rock has moved past another section. Take your pen or pencil, connect the epicentres, and you will outline and define the edges of the tectonic plates, the separately moving pieces of lithosphere (compare Figures 1.11 and 3.1). Remember that these plates are about 100 km thick and thousands of kilometres across.

Figure 3.10

Age of the ocean basins.

Source: Mueller, R.D., Roest, W.R., Royer, J-Y., Gahagan, L.M., and Sclater, J.G., 1997. Digital isochrons of the World's ocean floor. *Journal of Geophysical Research* Volume 102, No. B2, p. 3211–3214. 10 February 1997. Plate 1(a) on page 3212. Copyright 1997 by the American Geophysical Union.



A popular way of forecasting the locations of future earthquakes uses the **seismic-gap method**. If segments of one fault have moved recently, then it seems reasonable to expect that the unmoved portions will move next and thus fill the gaps. It is easy to see the gaps in earthquake locations on a map of earthquake epicentres (Figures 3.30 and 4.42). Although seismic-gap analysis is logical, however, it yields only expectations, not guarantees. One segment of a fault can move two or more times before an adjoining segment moves once.

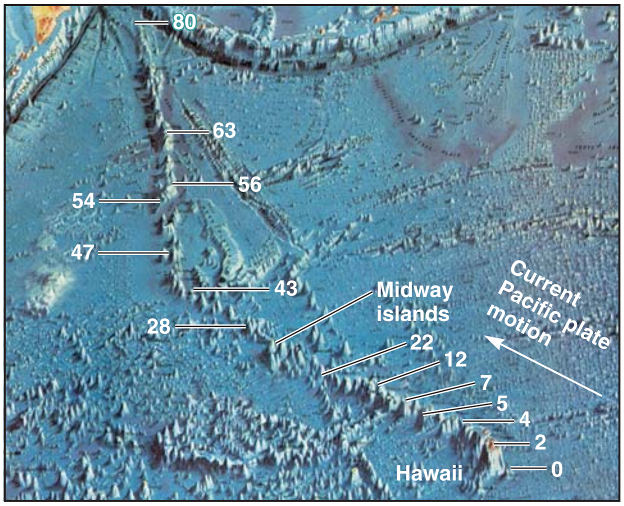
2. Earthquake hypocentres follow subducting plates. Hypocentres are classified as shallow (depth less than 100 km), intermediate (depth ranging from 100 to 300 km) or deep (depth ranging from 300 to 700 km). Intermediate and deep hypocentres are found along inclined planes adjacent to ocean trenches (Figure 3.13). These hypocentres define the subducting plates being pulled forcefully back into the asthenosphere.
3. A majority of active volcanoes are found on the edges of tectonic plates (Figure 1.11). The creation of new lithosphere and the destruction of old lithosphere is generally accompanied by volcanic activity.

Recycling Earth's Outer Layers

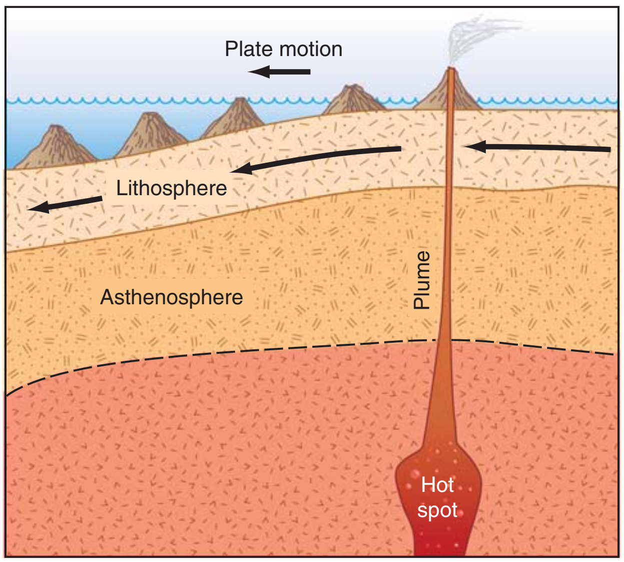
The upper few hundred kilometres of Earth are constantly being recycled according to the tectonic cycle. Figure 3.14 shows how Earth's outer layers are operating today in plate-tectonic action and introduces the four tectonic environments: (1) divergent, (2) convergent, and (3) transform plate boundaries, and (4) hot spots.

1. Divergent plate boundaries

Plates are pulled apart under tension at divergent boundaries. Hot rock flowing in rising convection cells reaches the asthenosphere and begins to melt. The buildup of magma and heat causes expansion and topographic elevation of the overlying lithosphere, which then fractures and begins to be pulled apart sideways by gravity. This downward and outward movement of the lithosphere is aided by convection cells moving laterally in the asthenosphere. It occurs because the rigid lithosphere decouples from the soft plastic asthenosphere and provides a sliding surface over which plates can be dragged. Convection in the asthenosphere is the main driving mechanism of plate movement, the crucial element missing in Wegener's continental drift hypothesis. In an ocean basin, the pulling apart of oceanic lithosphere causes a reduction in pressure on the superheated asthenosphere rock, which liquefies even more and rises upward to fill the fractures and create new oceanic lithosphere via seafloor spreading. The same pull-apart movement can also split a continent, forming a rift zone, a young divergent plate boundary such as the East African Rift Valley. Earth's surface may bulge upward into a dome, causing the elevated rock to fracture into a pattern radiating out from a **triple junction**, a point where three plate edges touch (Figure 3.15). Gravity can then pull the dome apart, allowing magma to swell up and fill three major fracture zones, and the spreading process is initiated.



(a) Map



(b) Cross-section

Figure 3.11

A hot spot and its path. (a) Map shows the Hawaiian Islands-Emperor Seamount chain of hotspot-fed volcanoes with plots of their radiometric ages in millions of years. The map pattern of volcano ages testifies to movement of the Pacific plate through time. (b) Cross-section shows a hot spot at a depth where hot mantle rock rises up through the asthenosphere and passes through the lithosphere as a plume of magma supplying a volcano. Because the lithospheric plate keeps moving, new volcanoes are formed.

2. Convergent plate boundaries

Plates deform under compression at convergent boundaries. When oceanic lithosphere collides with another plate, the denser plate goes beneath the less-dense plate in the process of subduction. If an oceanic plate goes beneath another oceanic plate at a convergent plate boundary, an **island arc** of volcanoes next to a trench can form, such as Japan and the Aleutian Islands of Alaska (Figure 3.16a). If the subducting oceanic plate is pulled beneath a continent-carrying plate, the top of the downbending oceanic plate forms a trench, and a line of active volcanoes builds on the continent edge, such as the Cascade Range of British Columbia and northwestern United States (Figure 3.16b). As the leading edge of the subducting plate turns downward, gravity exerts an even stronger pull on it, which helps tear the trailing edge of the plate away from the spreading centre.

3. Transform plate boundaries

Oceanic spreading ridges are subjected to shear stress at transform plate boundaries. Figure 3.17 shows this process. Spreading plates are rigid slabs of oceanic rock, tens of kilometres thick, that are being wrapped around a near-spherical Earth. To accommodate the Earth's curvature, the plates must fracture, and these fractures are transform faults, first recognized by Tuzo Wilson in 1965. In the region between two spreading centres, the relative motions of the two plates are in opposite directions. However, passing both to the right and left of the spreading centres, the two slabs are moving in the same direction. In the first case, the plates are separated by a transform fault; in the second case, by a fracture zone.

4. Hot spots

Originating deep in the mesosphere, hot spots send up hot, buoyant rock that turns into magma near the surface, building shield volcanoes on the seafloor, such as in Hawaii, or explosive mega-volcanoes on continents, such as in Yellowstone National Park in the northwestern United States.

In summary, the combination of convection in the asthenosphere and gravity pulling on elevated spreading-centre mountains and on down-going plates at subduction zones keeps the lithospheric plates moving. Thus, an ongoing tectonic cycle operates where each moving part stimulates and maintains motions of the others in a large-scale, long-term recycling operation. Subducted plates are reassimilated into the asthenosphere as physical slabs that remain solid enough to be recognized by their effects on propagation velocities of seismic waves. Plate movements are now so well understood due to the magnetic record of seafloor rock that not only are the plates outlined, but also their rates of movement are measured using the global positioning system (GPS) (Figure 3.1).

Plate tectonics provides us with new perspectives about Earth that are quite different from those encountered in our life or historical experiences. Because Earth is so much older and so much larger than a human being, we must set aside our personal time and size scales. If we change our time perspective to millions and billions

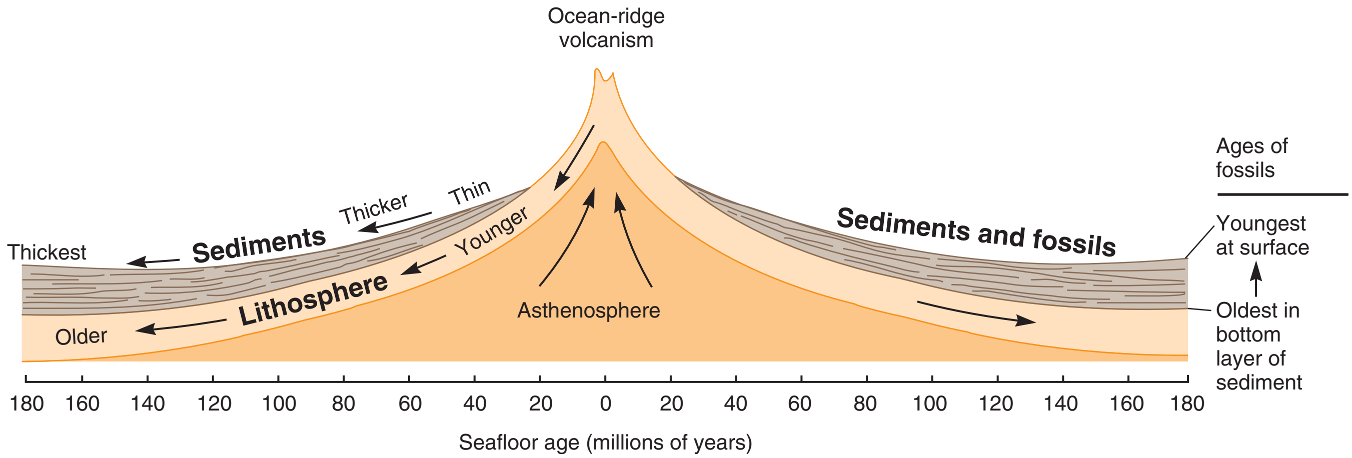


Figure 3.12
Schematic cross-section perpendicular to a volcanic ridge. Moving away from the ridge: (1) radiometric ages of seafloor increase, (2) thicknesses of accumulated sediments increase, and (3) ages of fossils in the sediments increase, and (4) water depths increase. The systematic increases in water depth are due to cooling, shrinking, and increase in density of the aging seafloor rocks.

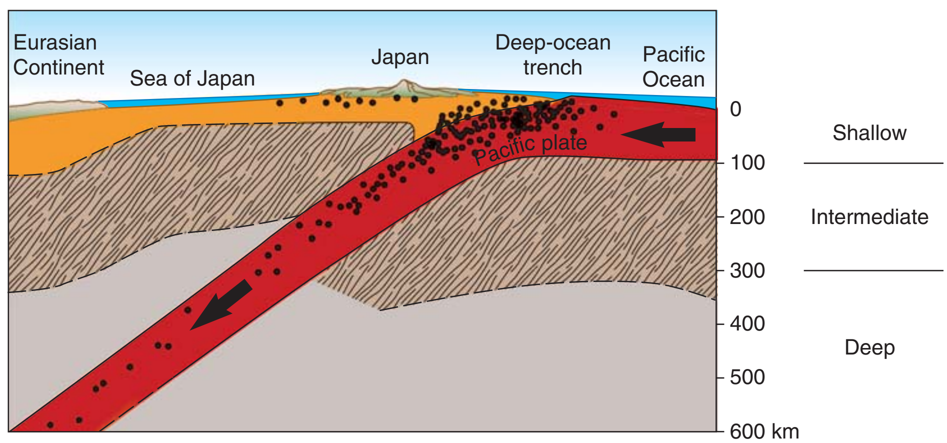


Figure 3.13
Cross-section showing earthquake hypocentre locations at depth; notice the inclined plane defined by the earthquake hypocentres. The earthquake locations define the subducting plate beneath Japan. At shallow depths, earthquakes are generated in brittle rocks in both subducting and overriding plates. At greater depths, only the interior of the subducting Pacific plate is cold enough to maintain the rigidity necessary to produce earthquakes. Striped areas are hot rocks defined by relatively lower-velocity seismic waves.

of years and our size scales to continents and plates, then, and only then, can we begin to understand Earth. The rates of plate movement are comparable to those of human fingernail growth. An active plate may move 1 cm in a year—only 75 cm in a human lifetime. But when we consider Earth over its own time span of 4.5 billion years, there is plenty of time for small events to add up to big results. The plate moving 1 cm/yr travels 10 km in just 1 million years; therefore, the 1 cm/yr process is fast enough to uplift a mountain in a small amount of geological time. Uniformitarianism is key to understanding how Earth behaves; we must think of repeated small changes occurring for great lengths of time to create large features such as mountains.

So far, plate tectonics has been recognized only on Earth. Mars is a one-plate planet where several hot spots have been identified although none are feeding active volcanoes at present. The Martian lithosphere being static, lava outpours at the same location over tens of millions of years, creating gigantic volcanoes. Venus seems to have experienced a dramatic resurfacing event 750 million years ago and its surface has not significantly evolved since then, other than bearing the scars from numerous impacts with space bodies.

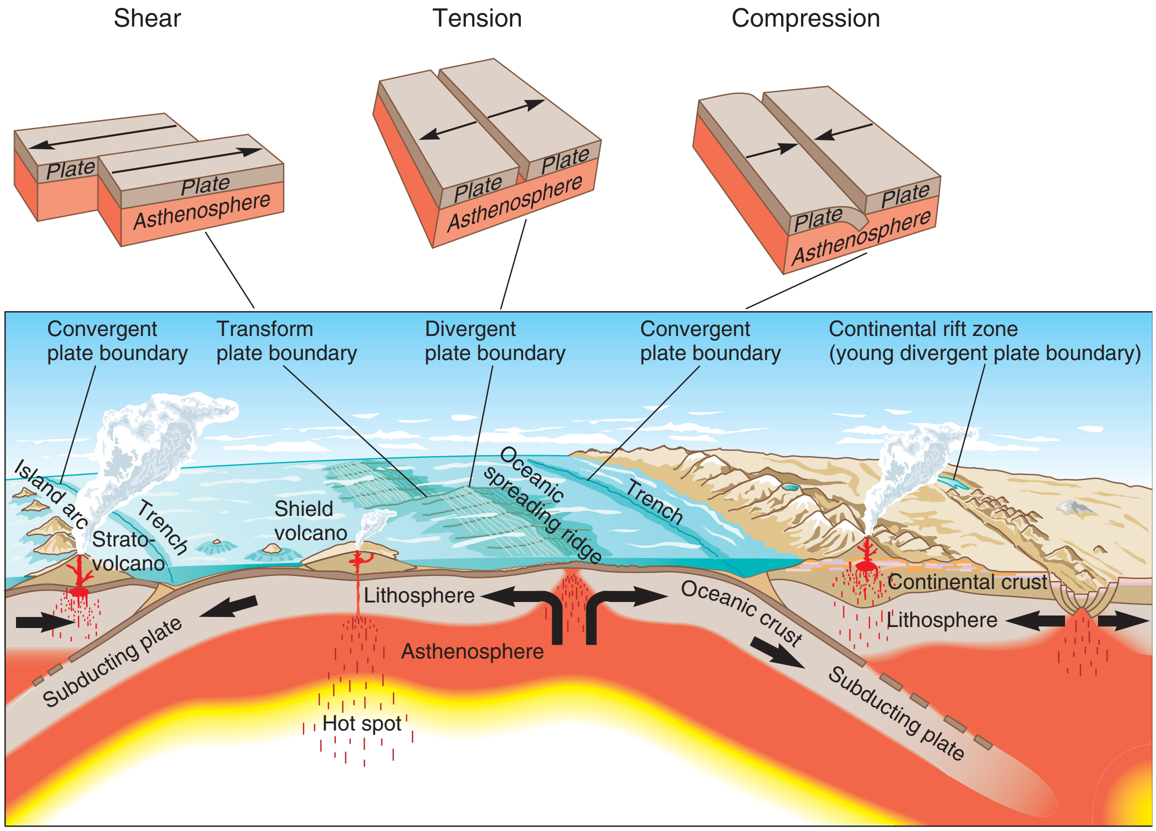


Figure 3.14
Three-dimensional view of tectonic plates with divergent, convergent, and transform boundaries plus volcanoes above subducting plates and a hot spot.
From Kious and Tilling, *US Geological Survey.*

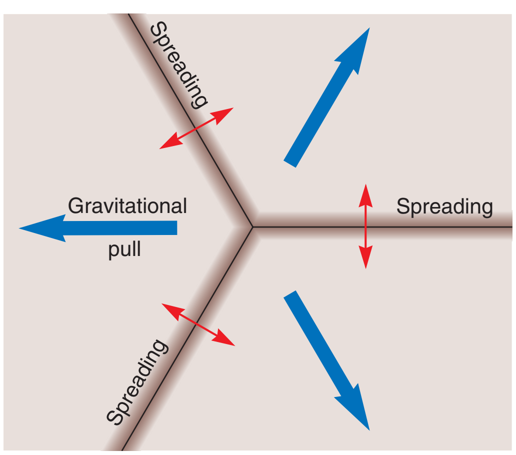


Figure 3.15
Schematic map of a triple junction formed by three young spreading centres. Heat may concentrate in the mantle and rise in a magma plume, doming the overlying lithosphere and causing fracturing into a radial set with three rifts. Gravity may then pull the dome apart, initiating spreading in each rift.

The Dance of the Continents

Undoing the seafloor spreading of the last 220 million years restores the continents of today into the supercontinent Pangaea (*pan* meaning "all" and *gaea* meaning "earth"), which covered 40% of Earth. Although the present continents had yet to form, Figure 3.18 shows their relative positions within Pangaea before its breakup. The remaining 60% of Earth's surface was a massive ocean called **Panthalassa** (meaning "all oceans").

Figure 3.19(a) shows the breakup of Pangaea at 180 million years before present. An equatorial spreading centre separated the northern supercontinent **Laurasia** from the southern supercontinent **Gondwanaland**. Much of the sediment deposited in the Tethys Sea at that time has since been uplifted to form mountain ranges from the Himalaya to the Alps. Another spreading centre began opening the Indian Ocean and separating Africa–South America from Antarctica–Australia.

At 135 million years ago, seafloor spreading had begun opening the North Atlantic Ocean, India was moving toward Asia, and the South Atlantic Ocean was a narrow sea similar to the Red Sea today (Figure 3.19b).

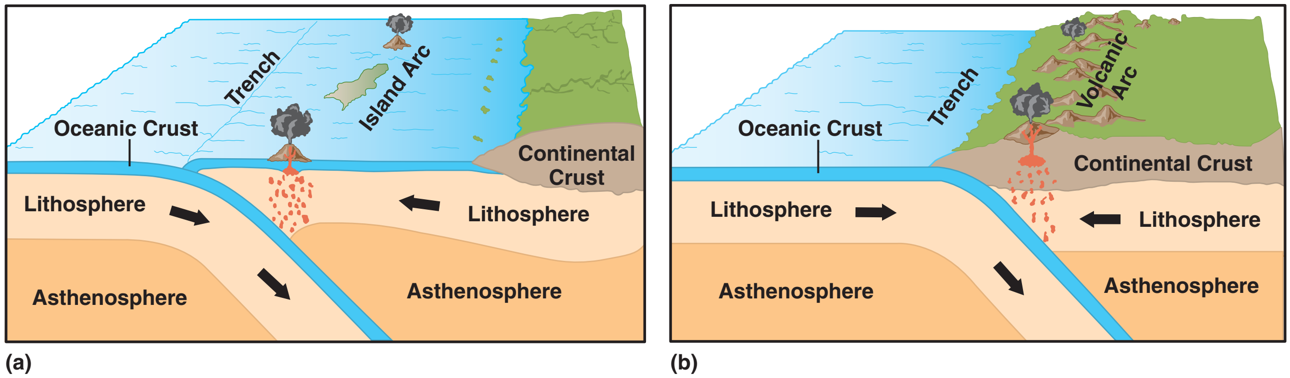


Figure 3.16
(a) Oceanic–oceanic convergence results in the formation of a deep offshore trench and volcanoes on the seafloor. Over time, the erupted lava and volcanic debris pile up until submarine volcanoes rise above sea level to form an island arc. (b) Oceanic–continental convergence creates a coastal trench and a chain of continental volcanoes.
Source: United States Geological Survey.

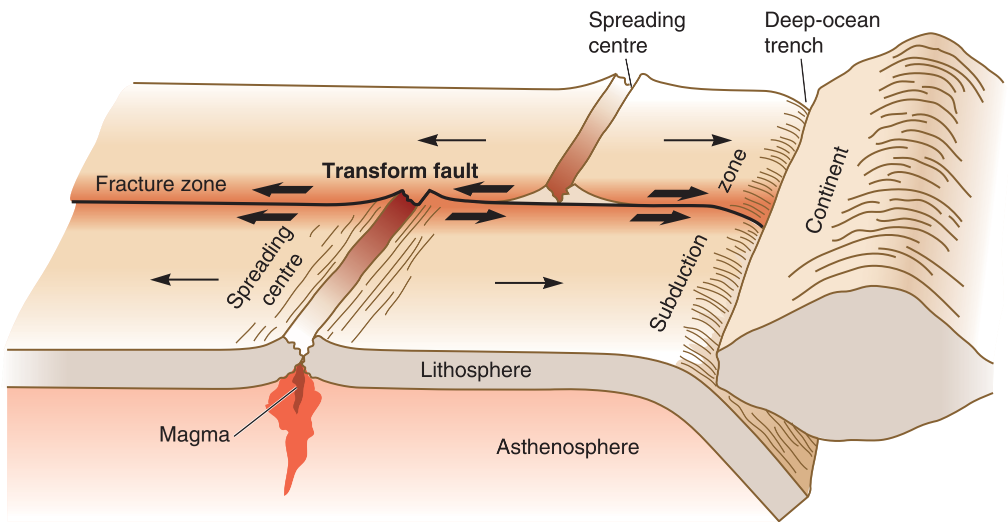


Figure 3.17
Plate-tectonics model of transform faults. Notice that the transform fault connects the two separated spreading centres; seafloor moves in opposite directions here. Beyond the spreading centres, the two plates move in the same direction and are separated by a fracture zone; there is no transform fault here.

By 65 million years ago, seafloor spreading had opened the South Atlantic Ocean and connected it with the North Atlantic, and Africa came into contact with Europe, cutting off the western end of the Tethys Sea to begin the Mediterranean Sea (Figure 3.19c). Although the modern world had become recognizable, note that North America and Eurasia were still connected and that Australia had not yet left Antarctica.

Nearly half of the present ocean floor was created during the last 65 million years (Figure 3.10). India has rammed into Asia, continued opening of the North Atlantic has split Eurasia from North America, and Australia has moved a long way from Antarctica.

Throughout Earth's history, there have been several cycles of supercontinent amalgamation and breakup. Reconstructing the dance of the continents becomes more and more difficult as scientists try to unravel the geological record further back in time. Figure 3.20 shows Rodinia, the supercontinent predating Pangaea. Pieces came together to form Rodinia about 1 billion years ago, including Greenland and large portions of the Canadian Precambrian Shield, which were located in its central core. Rodinia existed as a unified landmass until 750 million years ago.

Plate Tectonics and Earthquakes

Most earthquakes are explainable based on plate tectonics theory. The lithosphere is broken into rigid plates that move away from, past, and into other rigid plates. These

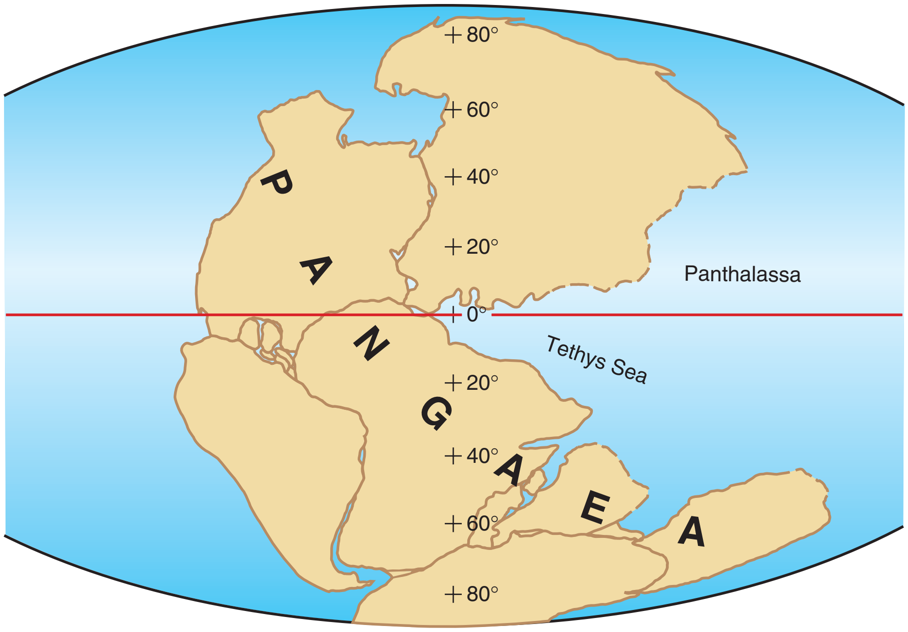


Figure 3.18
Pangaea, the supercontinent, 220 million years before present. The modern continents are drawn to be recognizable in this restoration. The superocean of the time (Panthalassa) exists today in shrunken form as the Pacific Ocean.
Source: © 1970 American Geophysical Union.

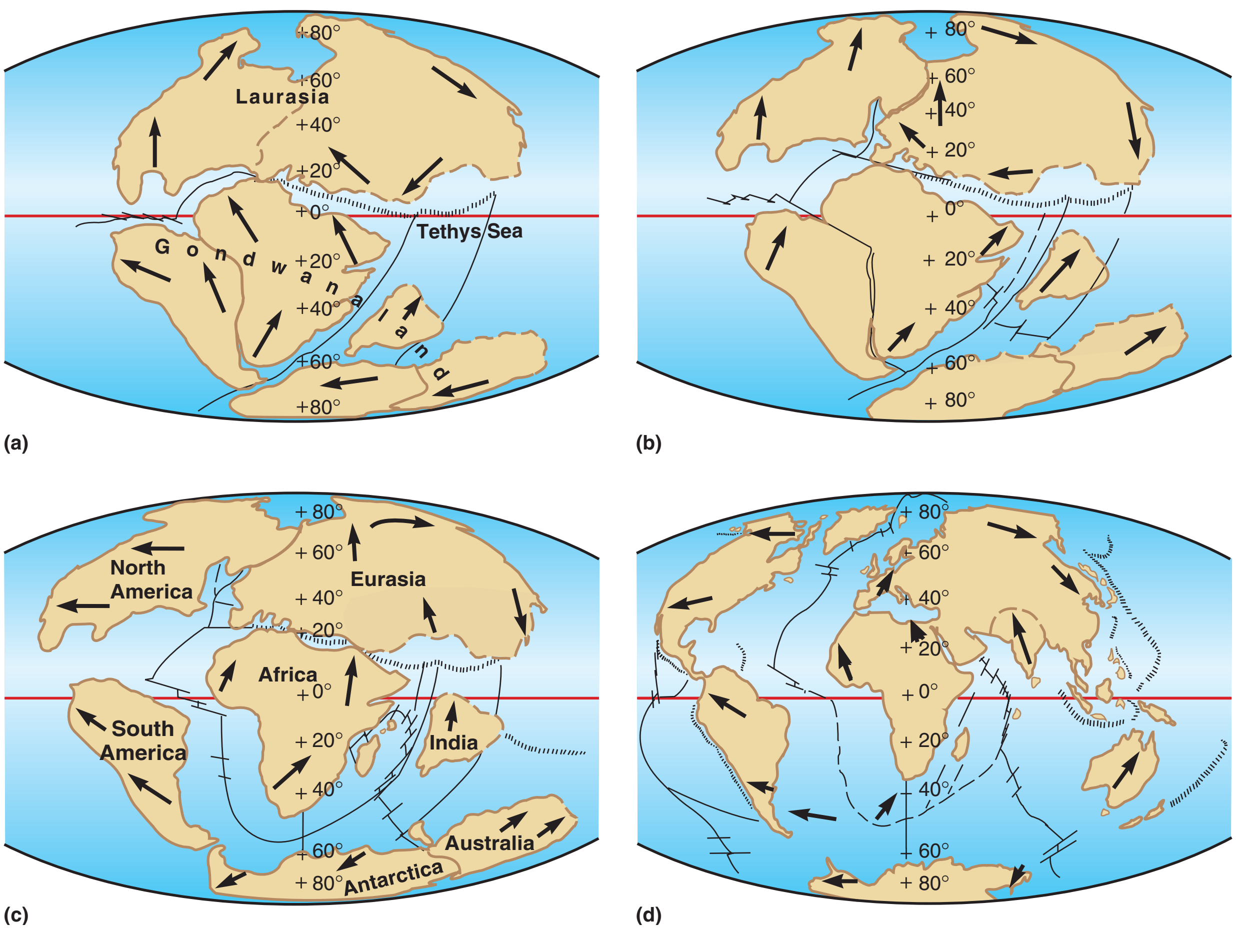
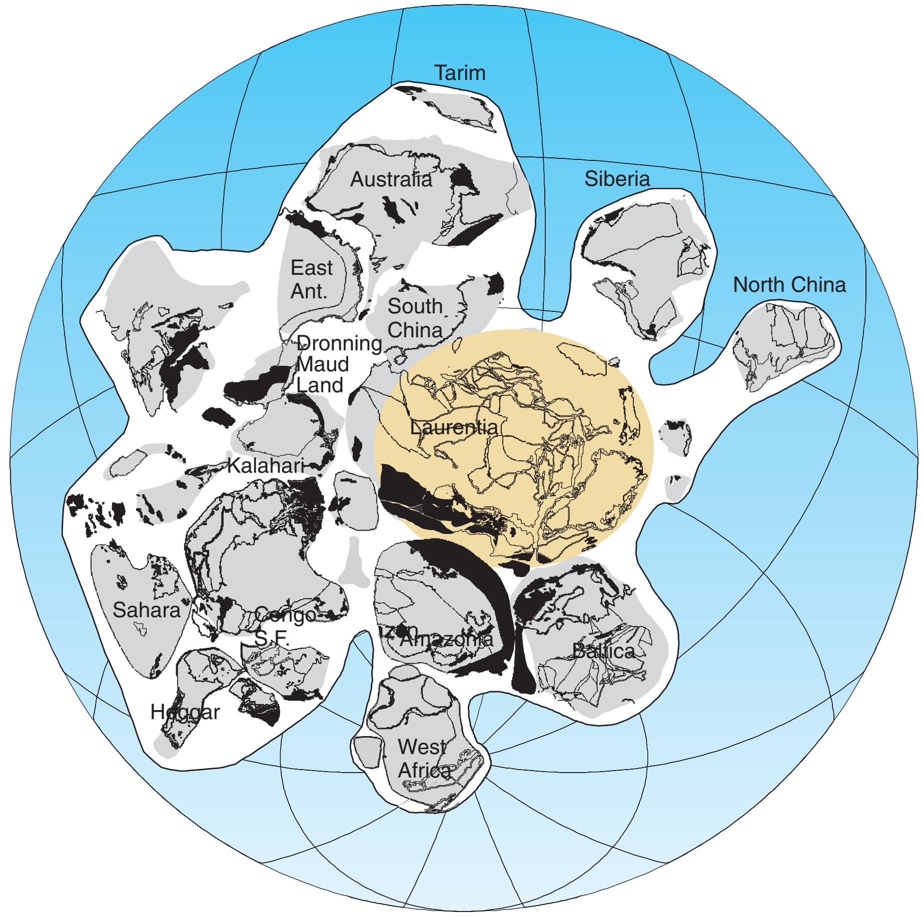


Figure 3.19
Changing positions of the continents. (a) 180 million years ago. (b) 135 million years ago. (c) 65 million years ago. (d) Today.

Figure 3.20

The supercontinent Rodinia, which existed between 1,000 and 750 million years ago. The coloured area corresponds to the Canadian Precambrian Shield and Greenland.

Source Li et al., (2008) *Precambrian Research* (Vol. 160, 179–210).



global-scale processes are seen on the ground as individual **faults** where Earth ruptures and the two sides move past each other in earthquake-generating events.

Figure 3.24 shows an idealized tectonic plate and assesses the varying earthquake hazards that are concentrated at plate edges:

1. The divergent or pull-apart motion at spreading centres causes rock to fail in tension. Rock ruptures relatively easily when subjected to tension. Also, much of the rock here is at a high temperature, causing early failures. Thus, the spreading process yields mainly smaller earthquakes that do not pose an especially great threat to humans.
2. The slide-past motion occurs as the rigid plates fracture and move around the curved Earth. The plates slide past each other in the dominantly horizontal movements of transform faults and are subjected to shear stress. This process creates large earthquakes as the plate boundaries retard movement because of irregularities along the faults. It takes a lot of stored energy to overcome the rough surfaces, non-slippery rock, and bends in faults. When these impediments are finally overcome, a large amount of seismic energy is released.
3. At subduction zones and in continent–continent collisions, rock deforms mainly under compression. The convergent motions pulling a 70 to 100 km thick oceanic plate back into the asthenosphere at a subduction zone or pushing continents together—such as India slamming into Asia to uplift the Himalaya—involve incredible amounts of energy. This results in Earth's greatest earthquakes.

Moving from an idealized plate, let's examine an actual plate—the Pacific plate. Figure 3.25 shows the same type of plate-edge processes and expected earthquakes as described in Figure 3.24. The Pacific plate is created at the spreading centres along its eastern and southern edges. The action there produces smaller earthquakes that also happen to be located away from major human populations. The slide-past motions of long transform faults occur (1) along the Queen Charlotte fault, located in northern British Columbia; (2) along the San Andreas fault in California; and (3) at the southwestern edge of the Pacific Ocean where the Alpine fault cuts across the South Island of New Zealand. The Pacific plate subducts along its northern and western edges and creates enormous earthquakes, such as the 1923 Tokyo seism and the 1964 Alaska event.

In Greater Depth

The Tectonic History of Canada

Canada grew gradually over the whole of geological time from a core of very old rock (Figure 3.21). This large area, the Canadian Precambrian Shield, includes the oldest rock so far discovered on our planet, the Acasta gneiss (Figure 2.11). The older portions of the Canadian Shield have been described as a "sea of granite" after their most abundant rock type. The geology of these older parts, which constitute the Archean **cratons**, is radically different than that of younger areas. It attests of vigorous processes, fuelled by the abundant heat of the early Earth, in which the fragile primitive crust was continuously recycled at a fast pace. The Archean cratons consist, therefore, of relatively small subunits, organized in alternating bands of primitive continental and oceanic crust.

Earth progressively cooled, and large rafts of low-density crust floating on top of turbulent oceans of magma slowly consolidated into continents. Modern plate tectonics probably started 2.5 billion years ago when the Rae, Slave, and Hearne cratons in Canada, as well as the Wyoming and North Atlantic cratons in the United States and Greenland respectively, amalgamated together through plate convergence and collision. The Superior craton was added to this landmass 1.8 billion years ago with the first recorded large-scale continent–continent collision in Earth history. Finally, 1.2 to 1.0 billion years ago, another massive continent–continent collision brought the Grenville province to complete the formation of the Canadian Precambrian Shield, which was subsequently incorporated into the supercontinent Rodinia 750 million years ago (Figure 3.20).

To the east, the next addition to the Canadian territory occurred much later when the Appalachians were created in association with closing of the Iapetus ocean (a precursor to the present Atlantic ocean) and the formation of the supercontinent Pangaea 250 million years ago. The present-day St. Lawrence River follows the contact between the Canadian Precambrian Shield and the Appalachians in Quebec and eastern Ontario. Appalachian rocks can also be found outcropping in Scotland and Norway. These rocks now lie thousands of kilometres away from each other, having been pushed away by the Atlantic seafloor that formed between them during the breakup of Pangaea.

Over the last 185 million years, Canada grew to the west. Small pieces of continental crust transported along the Pacific coast accreted to Canada as plates subducted underneath North America. This process led to the formation of the cordillera, which includes five major bands of added material roughly oriented parallel to the coastline. It is still active today with the subduction of the Explorer and Juan de Fuca plates beneath Vancouver Island and southern British Columbia.

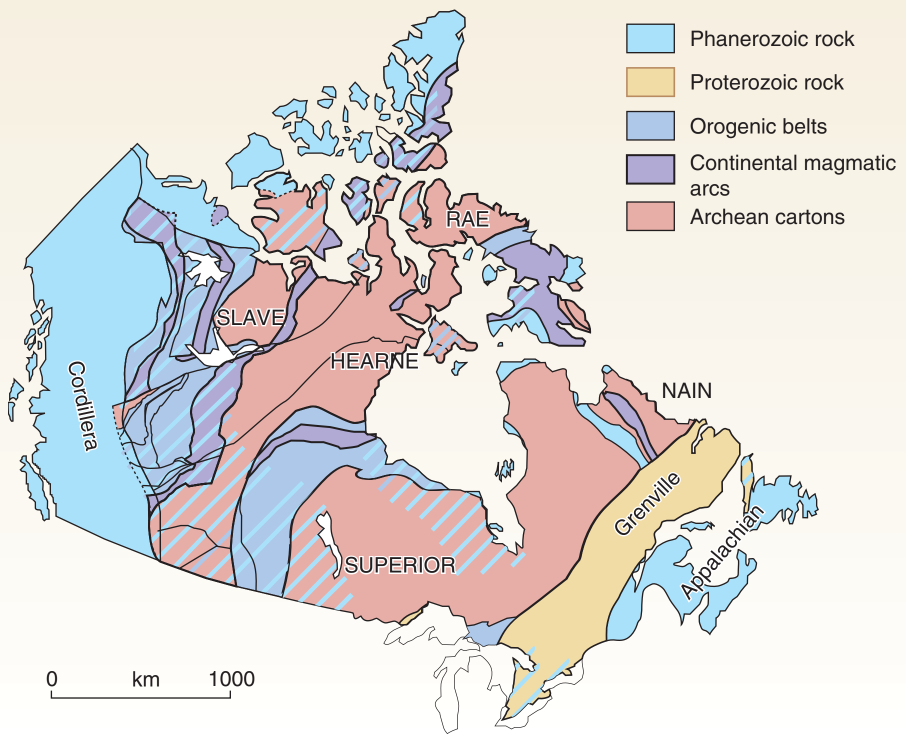


Figure 3.21 Tectonic map of Canada.
After Lucas et al. *Geology of the Precambrian Superior and Grenville Provinces and Precambrian Fossils in North America,* 1998.

Our main emphasis here is to understand plate-edge effects as a means of forecasting where earthquakes are likely to occur and what their frequencies and sizes may be. Qualitative relationships between tectonic environments and earthquake characteristics are summarized in Table 3.1. Worldwide, there is on average one great earthquake (magnitude 8 or higher) and 20 major earthquakes (magnitude between 7 and 8) annually (Table 4.4). Strong (magnitude between 6 and 7) earthquakes are more frequent, with about 250 occurrences per year.

In Greater Depth

Active Tectonic Zones of Western North America

The lives of the inhabitants of the west coast of North America are affected by the fate of an ancient tectonic plate, the Farallon plate. Most of the Farallon plate has now been consumed beneath North America but its effects remain today as earthquakes and volcanoes.

Until 30 million years ago, the eastern edge of the Farallon plate was destroyed by subduction underneath the North American plate, itself moving westward to accommodate the widening of the North Atlantic Ocean (Figures 3.1 and 3.19). Approximately 28 million years ago, the Pacific Ocean spreading centre collided with North America near the site of the city of Los Angeles today (Figure 3.22). The collision segmented the Farallon plate into smaller plates, the Juan de Fuca plate to the north and the precursor of the Rivera and Cocos plates to the south. The spreading

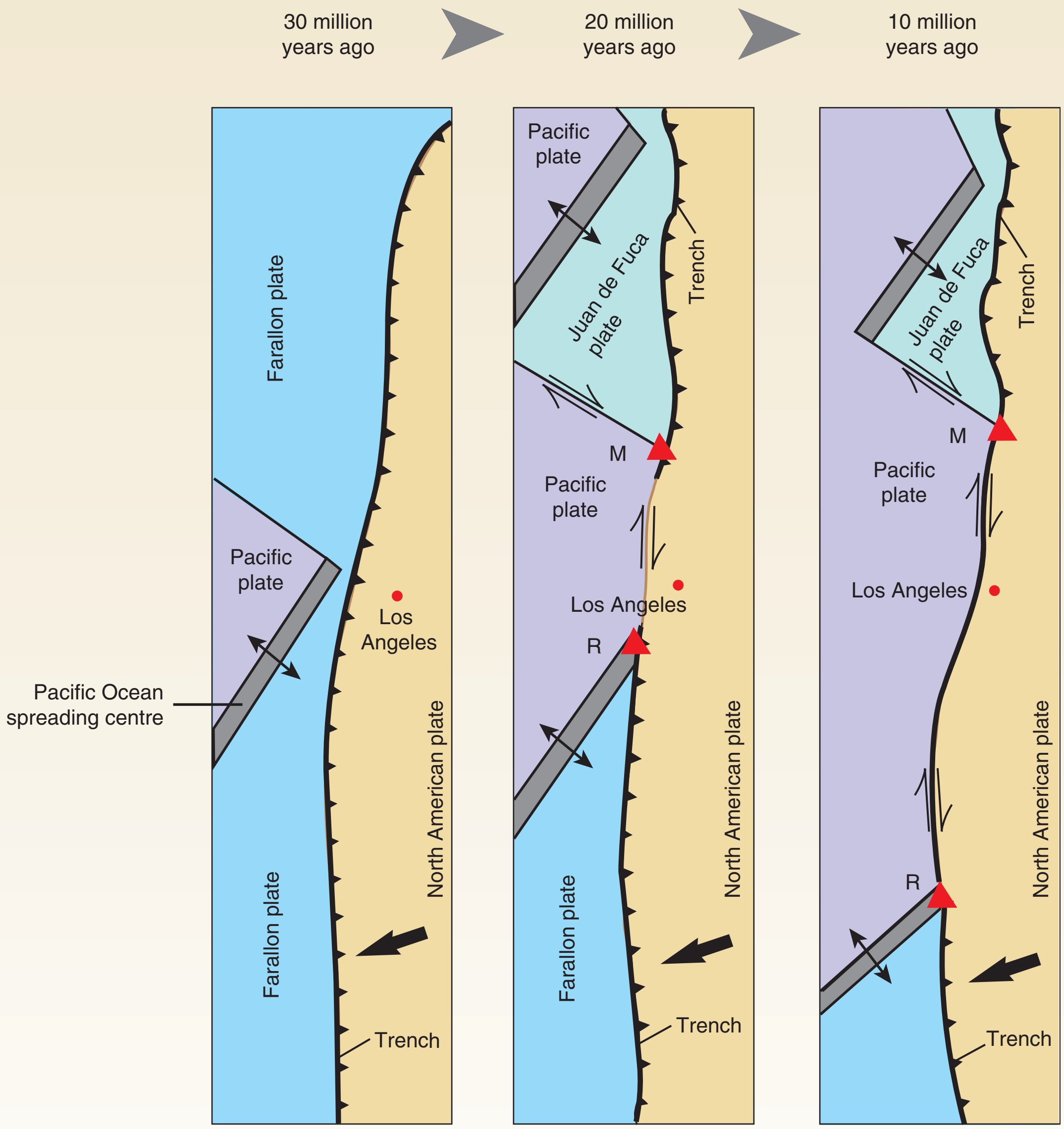


Figure 3.22 Collision of the Pacific Ocean spreading centre with the North American plate: (a) 30 million years ago—first spreading-centre segment nears Southern California, (b) 20 million years ago—growing transform fault connects remaining spreading centres, (c) 10 million years ago—the Mendocino (M) and Rivera (R) triple junctions continue to migrate north and south respectively. The long transform fault between the two triple junctions is the ancestor of the San Andreas fault. Interpretations based on work of Tanya Atwater.

Source: Kious, W. J., and Tilling, R. I., *This Dynamic Earth*. US Geological Survey, p. 77.

Continued

centres to the north and south continued to operate. What connected them? A transform fault, specifically the ancestor of the San Andreas fault. In the ensuing few millions of years, the fault grew, and the Mendocino and Rivera triple junctions migrated further north and south, respectively.

Figure 3.23 shows the present-day tectonic setting along the western edge of the North American plate. In the last 5.5 million years, continued seafloor spreading to the south of the San Andreas fault has opened the Gulf of California by approximately 300 km. This rifting action has torn Baja California and the Los Angeles areas from the North American plate and piggybacked them onto the Pacific plate. This example illustrates the fact that tectonic boundaries do not necessarily follow coastlines: the contact between the Pacific and North American plates in California is not along its famous beaches, but along the Gulf of California spreading centre and the San Andreas fault. Los Angeles, located west of the fault, is on the Pacific plate, whereas San Francisco, located east of the fault, is on the North American plate.

North of the Mendocino triple junction, the Gulf of California spreading centre is still active, but is now broken into four small segments. The northern fragment of the ancient Farallon plate is now composed of three plates. The larger Juan de Fuca plate is located in between the Explorer plate to the north and the Gorda plate to the south. These three plates are currently subducting underneath Vancouver Island and the northwestern United States along the Cascadia Subduction Zone at a rate of approximately 4 cm per year. Over the last tens of millions of years, this sustained subduction has produced outpourings of vast quantities of very fluid lavas, built the Cascade Range volcanoes (Figures 8.7, 8.8, and 8.9) and triggered major earthquakes. North of the Cascadia Subduction Zone, the Queen Charlotte fault accommodates the alongside movement of the Pacific and North American plates in a fashion similar to its southern cousin, the San Andreas fault, and has been the site of large earthquakes. Finally, the Queen Charlotte fault moves inland in the Alaska Panhandle and connects to the Aleutian Subduction Zone.

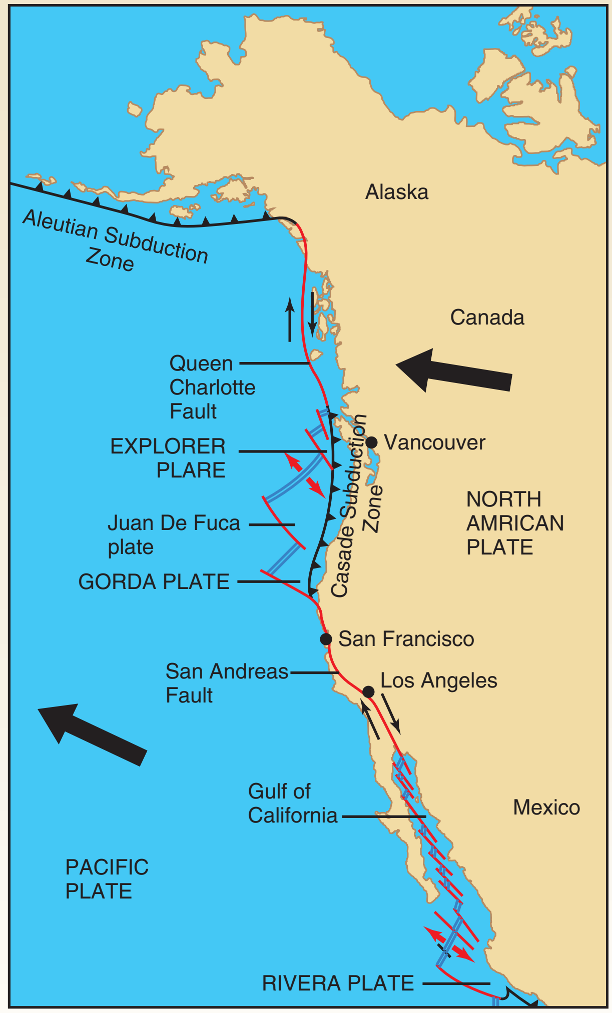


Figure 3.23 Present-day tectonic setting of Western North America.

Source: Claire Samson.

Spreading Centres and Earthquakes

Earthquakes at spreading centres are typically too small to destroy buildings and kill people. The expanded volumes of warm rock in the oceanic ridge systems have a higher heat content and a resultant decrease in rigidity. This heat-weakened rock does not build up and store the huge stresses necessary to create large earthquakes.

ICELAND

The style of spreading-centre earthquakes can be appreciated by looking at the earthquake history of Iceland, a nation that exists solely on a hot spot–fed volcanic island portion of the mid-Atlantic ridge (Figures 3.26 and 3.27). In the portions of the country underlain by north-south-oriented spreading centres, small to moderate-size earthquakes tend to occur in swarms, as is typical of volcanic areas where magma is on the move. Iceland does have large earthquakes, but they are associated with east-west-oriented transform faults between the spreading-centre segments.

RED SEA AND GULF OF ADEN

Iceland formed on a mature spreading centre that is related to the opening of the North Atlantic Ocean, which began some 135 million years ago. The specific ridge

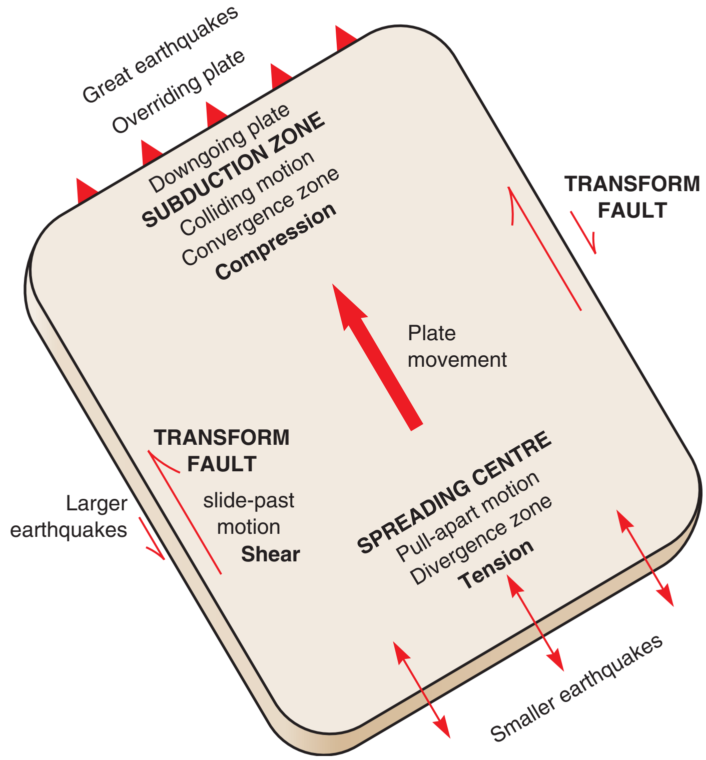


Figure 3.24
Map view of an idealized plate and the earthquake potential along its edges.

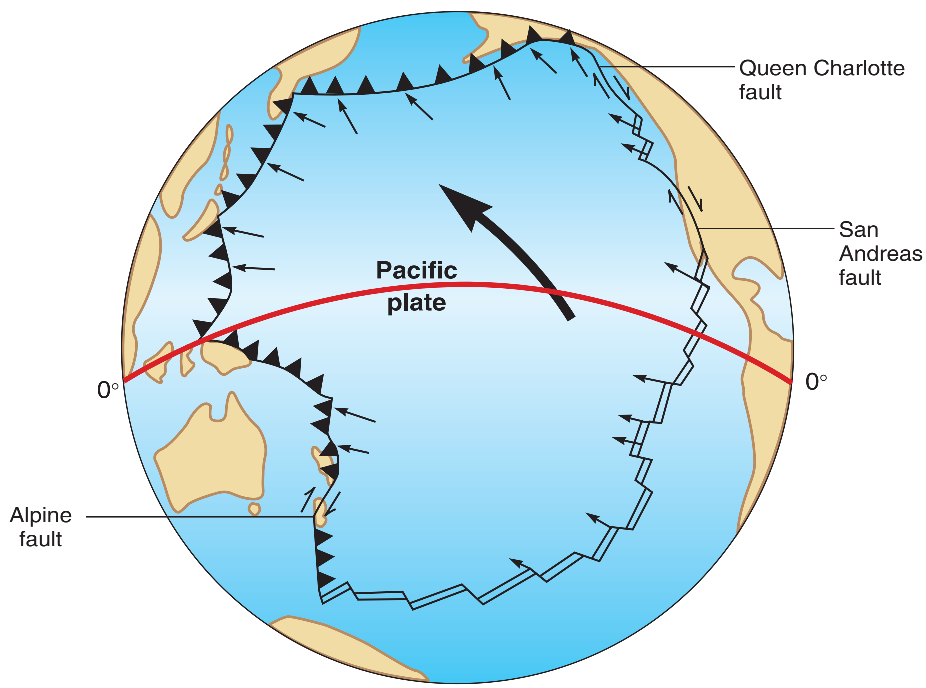


Figure 3.25
The Pacific plate is the largest in the world; it underlies part of the Pacific Ocean. Its eastern and southern edges are mostly spreading centers characterized by small- to intermediate-size earthquakes. Three long transform faults exist along its sides in Canada (Queen Charlotte), California (San Andreas), and New Zealand (Alpine); all are marked by large earthquakes. Subduction zones (shown by black triangles) lie along the northern and western edges, from Alaska to Russia to Japan to the Philippines to Indonesia to New Zealand; all are characterized by gigantic earthquakes.

Source: © 1976 John Wiley & Sons, Inc.

Table 3.1

Tectonic Environments and Earthquake Characteristics

Tectonic Environment	Deformation Force	Earthquake Characteristics		
		Frequency	Maximum Size	Maximum Hypocenter Depth
Divergent zone	Tension	Frequent	Strong	Shallow
Convergent zone	Compression	Infrequent	Great	Deep
Transform fault	Shear	Infrequent	Major	Shallow
Hot spot	Tension Compression	Frequent	Strong	Shallow

Source: Claire Samson.

segment on which Iceland is built started to open 60 million years ago. What would a much younger spreading centre and new ocean basin look like? Long and narrow. In today's world, long and narrow ocean basins exist in northeast Africa as the Red Sea and the Gulf of Aden (Figure 3.28). Following is a model explaining how spreading began: The northeastern portion of Africa sits above an extra-hot area in the upper mantle. The heat contained within this mantle hot zone is partially trapped by the blanketing effect of the overlying African plate and its embedded continent (Figure 3.29a). The hot rock expands in volume and some liquefies to magma. This volume expansion causes doming of the overlying rock, with resultant uplift of the surface to form topography (Figure 3.29b). The doming uplift sets the stage for gravity to pull the raised landmasses downward and apart, thus creating pull-apart faults with centrally located, down-dropped **rift** valleys, also described as pull-apart basins (Figure 3.29c). As the faulting progresses, magma rises up through the cracks to build volcanoes. As rifting and volcanism continue, seafloor spreading processes take over, the down-dropped linear rift valley becomes filled by the ocean, and a new sea is born (Figure 3.29d).

Figure 3.28 reveals another interesting geometric feature. Three linear pull-apart basins meet at the south end of the Red Sea at a triple junction. This triple junction is geologically young, having begun about 25 million years ago. To date, spreading in the Red Sea and Gulf of Aden has been enough to split off northeast Africa and create an Arabian plate and to allow seawater to flood between them. But the East African Rift Valley has not yet been pulled far enough apart for the sea to fill it. The East African Rift Valley is a truly impressive physiographic feature. It is 5,600 km long and has steep escarpments and dramatic valleys. Beginning at the Afar triangle at its northern end and moving southwest are the domed and stretched highlands of Ethiopia, beyond which the rift valley divides into two major branches. The western rift is markedly curved and has many deep lakes, including the world's second deepest lake, Lake Tanganyika. The eastern rift is straighter and holds shallow, alkaline lakes and volcanic peaks, such as Mount Kilimanjaro, Africa's highest mountain. The rift valley holds the oldest humanoid fossils found to date and is the probable homeland of the first human beings. Will the spreading continue far enough to split a Somali plate from Africa? It is simply too early to tell.

How severe are the earthquakes in the geologically youthful Red Sea and Gulf of Aden? Significant, but spreading-centre earthquakes are not as large as the earthquakes on the other types of plate edges.

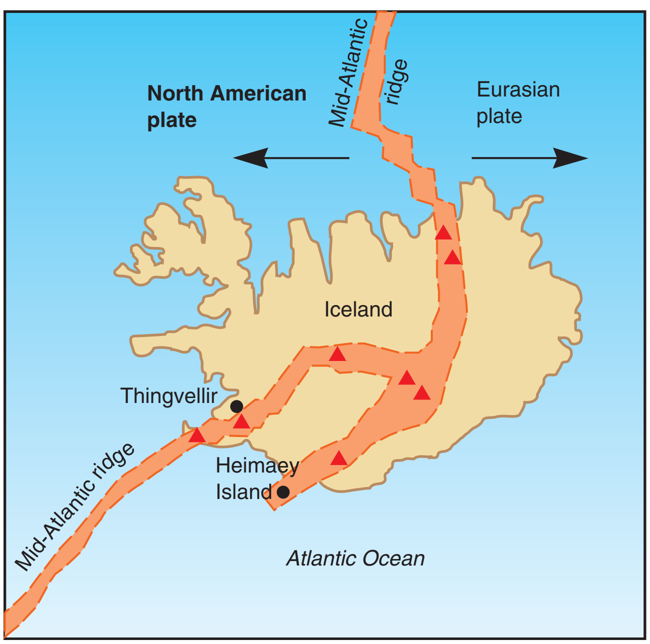


Figure 3.26
Iceland sits on top of a hot spot and is being pulled apart by the spreading centre in the Atlantic Ocean. Triangles mark sites of some active volcanoes.

Figure 3.27
Looking south along the fissure at Thingvellir, Iceland. This is the rift valley being pulled apart in an east-west direction by the continuing spreading of the Atlantic Ocean.
Photo © John S. Shelton.

Convergent Zones and Earthquakes

The greatest earthquakes in the world occur where plates collide (Table 3.2). The three basic classes of collisions are (1) oceanic plate versus oceanic plate, (2) oceanic plate versus continent, and (3) continent versus continent. These collisions result in either subduction or continental upheaval. If oceanic plates are involved, subduction will occur. The younger, warmer, less-dense plate will override the older, colder, denser plate, which will then bend downward and be pulled back into the mantle. If two continents are involved, they will not subduct because their huge volume of low-density, high-buoyancy rock simply cannot sink to great depth and cannot be pulled into the denser asthenosphere rock below. The fate of oceanic plates is destruction via subduction and reassimilation within the mantle, whereas continents float about on the asthenosphere in perpetuity. Continents are ripped asunder and then reassembled into new configurations via collisions, but they are not destroyed by subduction.

SUBDUCTION ZONES

Subduction zones are the sites of great earthquakes. Imagine pulling a 100 km thick rigid plate into the weaker, deformable rock of the mantle that resist the plate's intrusion. This process creates tremendous stores of energy, which are released periodically as great earthquakes.

Although subduction zones are characterized by a dominantly compressional stress regime, earthquakes from these regions result from different types of fault movements in shallow versus deeper realms. At shallow depths (less than 100 km), the two rigid lithospheric plates are pushing against each other. Earthquakes result from compressive movements where the overriding plate moves upward and the subducting plate moves downward. Pull-apart fault movements also occur near the surface within the subducting plate as it is bent downward and snaps in tensional failure and within the overriding plate as it is lifted up from below. Notice in Figure 3.13 that the shallow earthquakes occur (1) in the upper portion of the down-going plate, (2) at the bend in the subducting plate, and (3) in the overriding plate.

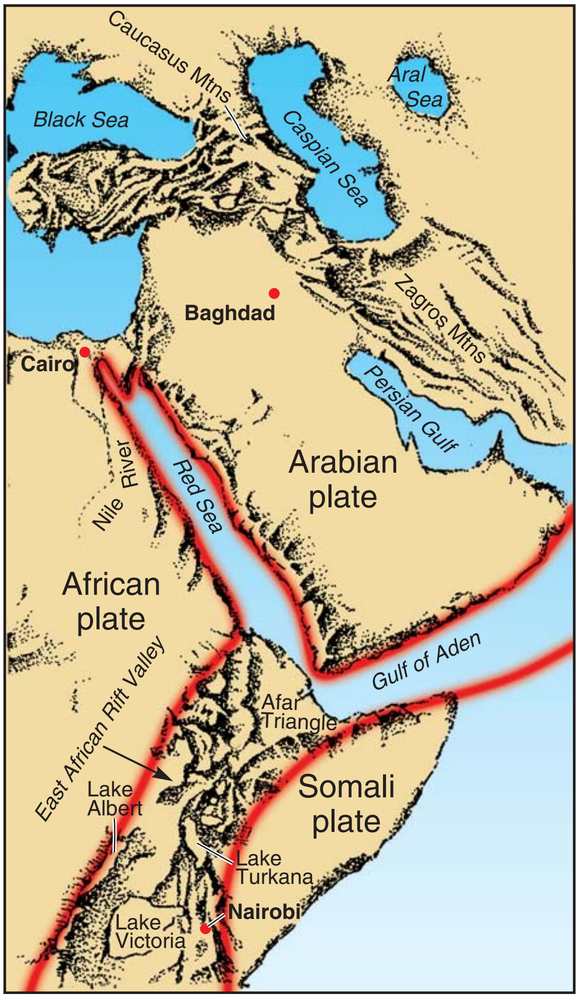


Figure 3.28

Topography in northeastern Africa and Arabia. Northeastern Africa is being torn apart by three spreading centres: Red Sea, Gulf of Aden, and East African Rift Valley. The spreading centres meet at the triple junction in the Afar Triangle.

Compare the locations of the shallow earthquakes to those of intermediate and deep earthquakes (Figure 3.13). At depths below 100 km, the upper and lower surfaces of the subducting slabs are too warm to generate large earthquakes. Thus, the earthquakes occur in the cooler interior area of rigid rock, where stress stored as gravity pulls against the asthenosphere resistance to slab penetration. Note, however, that a great earthquake that occurs deep below the surface has much of its seismic energy dissipated while travelling to the surface and is generally less destructive than a shallow earthquake.

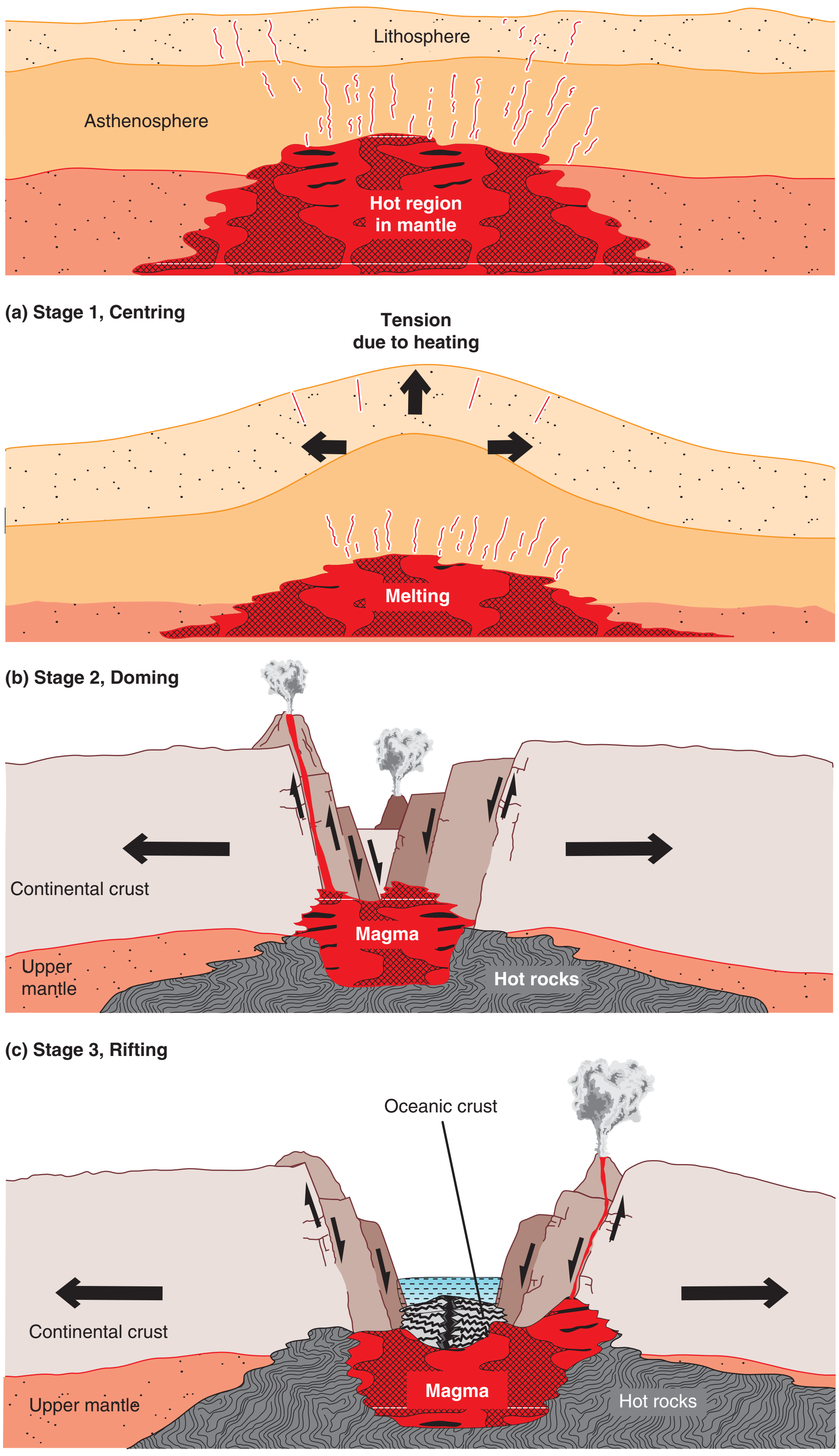
Tokyo, Japan, 1923

Early on Saturday morning, 1 September 1923, the cities of Tokyo and Yokohama were drenched by the last squalls of a waning storm. Later that morning, the skies cleared and the Sun beamed down as the residents prepared their midday meal. Moments later, this tranquil scene was shattered by a deadly series of earthquakes. The principal shock was powerful; Earth averages less than one earthquake a year that releases this much energy. It occurred beneath Sagami Bay southwest of the big cities. The floor of Sagami Bay dropped markedly and sent a 11 m high tsunami crashing against the shore. The waves washed away hundreds of homes. Yet fishermen spending their day out on the open ocean were unaware of the monster waves. At day's end, as they sailed toward home through Sagami Bay, they were sickened to find the floating wreckage of their houses and the bodies of their families. Devastation on land was great. Houses were destroyed, bridges fell, tunnels collapsed, and landslides destroyed both forested slopes and terraced hillsides created for agriculture. The wreckage of Tokyo and Yokohama buildings begun by the shaking Earth was completed by the ensuing fires. The shaking caused the collapse of flammable house materials onto cooking fires, and the flames, once liberated, quickly raced out of control throughout both cities. Little could be done to stem their spread because the earthquake had broken the water mains. Shifting winds advanced the fires through Tokyo for two and a half days, destroying 71% of the city's houses. Infernos in Yokohama gutted the city, a 100% loss.

Possibly the most tragic event in this disaster occurred when 40,000 people, clutching their personal belongings, attempted to escape the flames by crowding into a 100-hectare garden owned by a wealthy banker on the edge of the Sumida River. People packed themselves into this open space so densely that they were barely able to move. At about 4 p.m., several hours after the earthquake, the roaring fires approached on all three landward sides of the crowd. Suddenly the fire-heated winds spawned a tornado that carried flames onto the huddled masses and their combustible belongings. After the flames had died, 38,000 people lay dead, either burned or asphyxiated. The usual instinct to seek open ground during a disaster was shockingly wrong this time.

The combined forces of earthquakes, tsunami, and fires killed 99,331 people and left another 43,476 missing and presumed dead. In Tokyo, irreplaceable records were lost, and 2,000 years of art treasures were destroyed. Yet, despite this immense catastrophe, the morale of the Japanese people remained high. They learned from the disaster. They have rebuilt their cities with wider streets, more open space, and less use of combustible construction materials.

The historical record of earthquakes in the region is thought provoking. The region 80 km southwest of Tokyo has been rocked by five very strong earthquakes in the last 400 years (Figure 3.30). The seisms have occurred roughly every 73 years, the most recent in 1923.



(a) Stage 1, Centring

(b) Stage 2, Doming

(c) Stage 3, Rifting

(d) Stage 4, Spreading

Figure 3.29
A model of the stages in the formation of an ocean basin. (a) Stage 1, Centring: Moving lithosphere centres over an especially hot region of the mantle. (b) Stage 2, Doming: Mantle heat causes melting and the overlying lithosphere/ continent extends. The increase in heat causes surface doming through uplifting, stretching, and fracturing. (c) Stage 3, Rifting: Volume expansion causes gravity to pull the uplifted area apart; fractures fail and form faults. Fractures/faults provide escape for magma; volcanism is common. Then, the dome's central area sags downward, forming a valley such as the present East African Rift Valley. (d) Stage 4, Spreading: Pulling apart has advanced, forming a new seafloor. Most magmatic activity is seafloor spreading, as in the Red Sea and Gulf of Aden.

Table 3.2

Earth's Largest Earthquakes, 1904–2005

Rank	Location	Year	Magnitude (M_w)	Cause
1.	Chile	1960	9.5	Subduction—Nazca plate
2.	Indonesia	2004	9.2	Subduction—Indian plate
3.	Alaska	1964	9.2	Subduction—Pacific plate
4.	Kamchatka	1952	9.0	Subduction—Pacific plate
5.	Ecuador	1906	8.8	Subduction—Nazca plate
6.	Indonesia	2005	8.7	Subduction—Indian plate
7.	Alaska	1965	8.7	Subduction—Pacific plate
8.	Assam	1950	8.6	Collision—India into Asia
9.	Alaska	1957	8.6	Subduction—Pacific plate
10.	Banda Sea	1938	8.5	Subduction—Pacific/Indian plate
11.	Chile	1922	8.5	Subduction—Nazca plate
12.	Kuril Island	1963	8.5	Subduction—Pacific plate

CONTINENT–CONTINENT COLLISIONS

The grandest continental pushing match in the modern world is the ongoing ramming of Asia by India. When Gondwanaland began its breakup, India moved northward toward Asia. The 5,000 km of seafloor (oceanic plate) that lay in front of India's northward path had all subducted beneath Asia by about 40 million years ago. Then, with no seafloor left to separate them, India punched into the exposed underbelly of Asia (Figure 3.31). Since the initial contact, the assault has remained continuous. India has moved another 2,000 km farther north, causing complex accommodations within the two plates as they shove into, under, and through each other accompanied by folding, overriding, and stacking of the two continents into the huge mass of the Himalaya and the Tibetan Plateau. The precollision crusts of India and Asia were each about 35 km thick. Now, after the collision, the combined crust has been thickened to 70 km to create the highest-standing continental area on Earth. The Tibetan Plateau dwarfs all other high landmasses. In an area the size of France, the average elevation exceeds 5,000 m. But what does all of this have to do with earthquakes? Each year, India continues to move about 5 cm into Asia along a 2,000 km front. This ongoing collision jars a gigantic area with great earthquakes. The affected area includes India, Pakistan, Afghanistan, the Tibetan Plateau, much of eastern Russia, Mongolia, and most of China.

A relatively simple experiment shows how earthquake-generating faults may be caused by continental collision (Figure 3.32). The experiment uses a horizontal jack to push into a pile of plasticine, deforming it under the force. The experimental deformation is similar to the tectonic map of the India–Asia region (Figure 3.33). The northward wedging of India seems to be forcing Indochina to escape to the southeast and is driving a large block of China to the east.

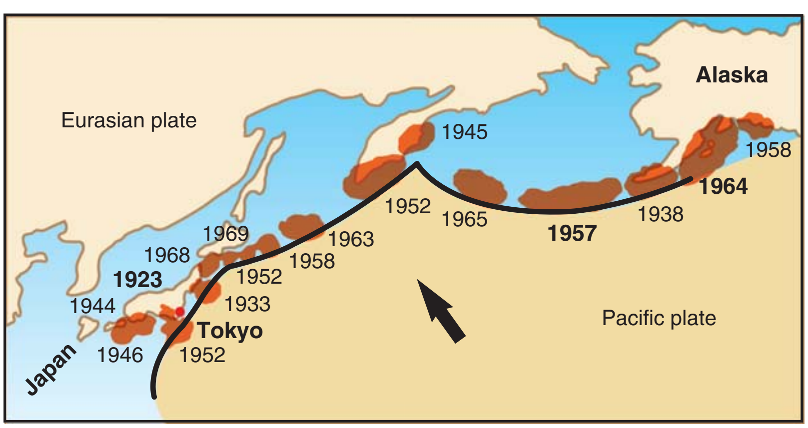


Figure 3.30
Brown patterns show severely shaken areas, with dates, from recent earthquakes caused by Pacific plate subduction. The 1957 and 1964 Alaska earthquakes are two of the largest in the 20th century. Using the seismic-gap method, where are the next earthquakes most likely to occur?

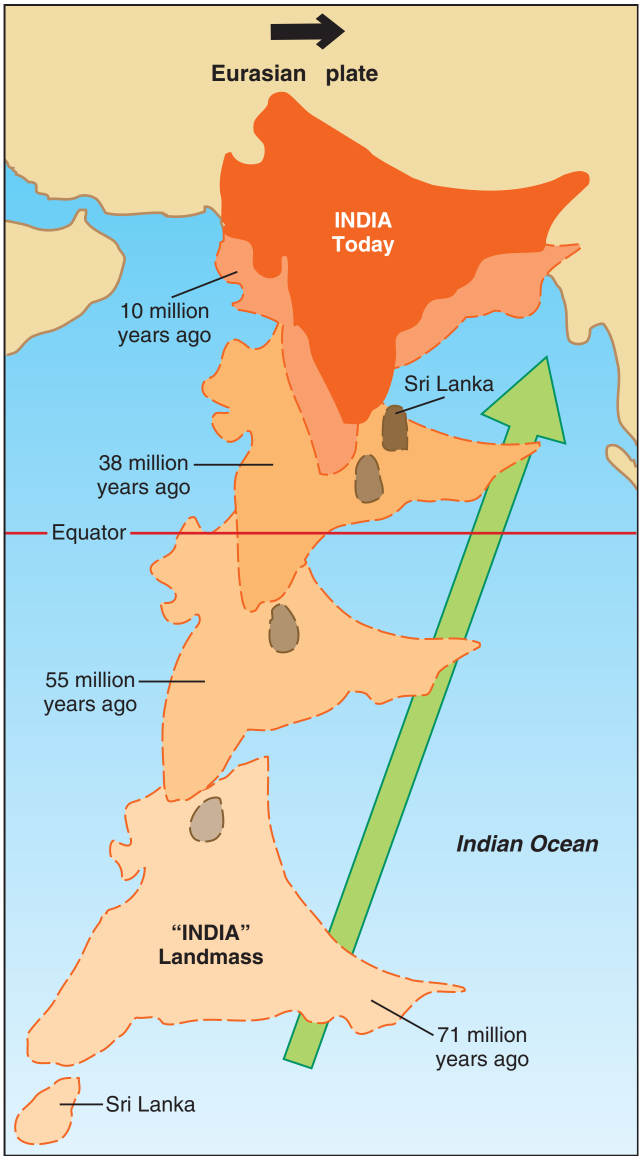


Figure 3.31
Map showing the movement of India during the last 71 million years. India continues to shove into Eurasia, creating great earthquakes all the way through China.

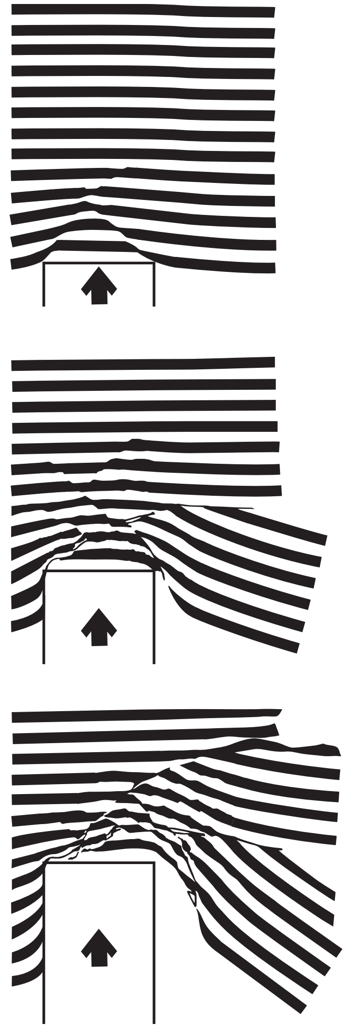


Figure 3.32
Simulated collision of India into Asia. A wedge is slowly jacked into layered plasticine confined on its left side but free to move to the right. From top to bottom of figure, notice the major faults that form and the masses that are compelled to move to the right. Compare this pattern to the tectonic map of India and Asia in Figure 3.33.
Source: © P. Tapponier, et al. (1982). *Geology*, 10, 611–16.

Shaanxi Province, China, 1556

The deadliest earthquake in history occurred in 1556 when about 830,000 Chinese were killed in and near Xi'an on the banks of the mighty Huang River (once known as the Yellow River). The region has numerous hills composed of deposits of windblown silt and fine sand that have very little **cohesion** (ability to stick together). Because of the ease of digging in these loose sediments, a tremendous number of the homes in the region were caves dug by the inhabitants. Most of the residents were in their cave homes at 5 a.m. on the wintry morning of 23 January, when the seismic waves rolled in from the great earthquake. The severe shaking caused much of the soft silt and sand sediments of the region to vibrate apart and literally behave like fluids. Most of the cave-home dwellers were entombed when the once-solid walls of their homes liquefied and collapsed.

Tangshan, China, 1976

The deadliest earthquake in recent times occurred directly beneath the city of Tangshan. A fault ruptured at a depth of 11 km in a local response to the regional stress created by the ongoing collision of India with Asia. The earthquake was much larger than local officials expected. Building codes were lenient—fatally so. This poor decision was instrumental in the deaths of over 240,000 people.

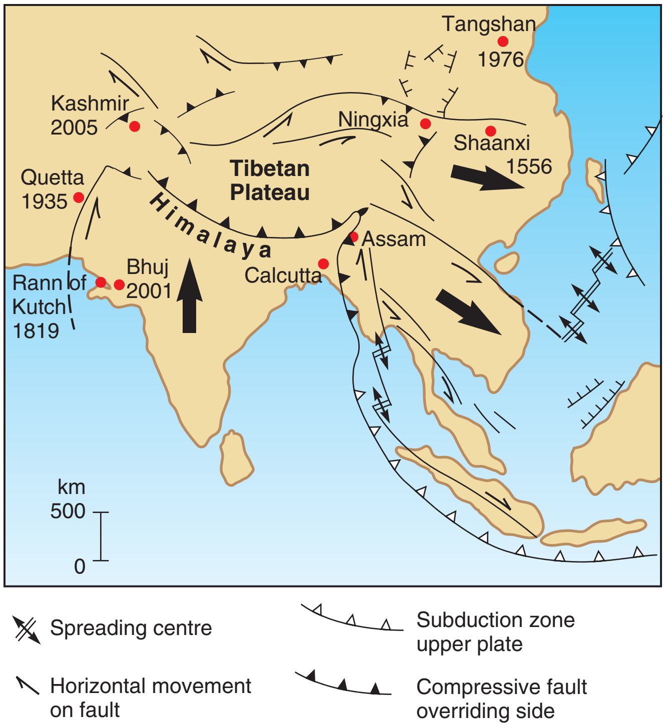


Figure 3.33
Tectonic map showing India pushing into Asia. The ongoing collision causes devastating earthquakes, each killing tens or hundreds of thousands of people. The list includes two in the Indian state of Gujarat in 1819 at Rann of Kutch and in 2001 near Bhuj, two in China in 1556 at Shaanxi and in 1976 at Tangshan, and two in Pakistan in Quetta in 1935, and in Kashmir in 2005.

In 1976, Tangshan was an industrial and mining city with two million residents. It contained the largest coal mines in China, so heavy industry found a home there also. Its coal, steel, electricity, and diesel- and locomotive-engine industries combined to create about 1% of China's gross national product. For Tangshan residents, the night of 27 July was unusually warm with rain and wind. Most unusual that night were the fireballs and lightning of all colours that rolled through the sky. At 3:42 a.m. on 28 July, the ground began the rumbling that reduced the city to almost total rubble. Most residents were at home in densely packed houses made of mud bricks held together by poor-quality mortar and covered with mud-and-lime roofs that had grown heavier through the years as new layers were added. Home was not a good place to be that day, as 93% of residential buildings collapsed. Industrial buildings fared somewhat better; still, 78% of them collapsed. Overall, older buildings performed better than newer ones. Some of the "luckier" individuals were the nightshift coal miners hard at work thousands of metres below the surface during the earthquake. Although 13 of these 15,000 miners died, as a whole, they fared far better than their day-shift comrades. Collapsing homes killed 6,500 of 85,000 off-duty miners. Through it all, the human spirit remained. Tangshan was rebuilt and is again home to more than a million residents, but now they live and work in better-designed buildings.

Transform Faults and Earthquakes

The transform faults forming the sides of some tectonic plates have dominantly horizontal movements that cause major earthquakes. Examples include the Alpine fault of New Zealand, the San Andreas fault in California, and the North Anatolian fault in Turkey.

TURKEY, 1999

A warm and humid evening made sleep difficult, so many people were still up at 3:01 a.m. on 17 August 1999 near the Sea of Marmara in the industrial heartland of Turkey. They were startled by a ball of flame rising out of the sea, a loud explosion, sinking land along the shoreline, and a big wave of water. Another big rupture moved along the North Anatolian fault as a magnitude 7.4 earthquake. This time the fault ruptured the ground surface for 120 km, with the south side of the fault moving westward up to 5 m (Figure 3.34). Several weeks later, after evening prayers for Muslims, a segment of the North Anatolian fault to the east ruptured in a 7.1 magnitude earthquake. The two devastating events combined to kill over 19,000 people and cause an estimated $20 billion in damages.

Why were so many people killed? Bad buildings collapsed (Figure 3.35). Industrial growth in the region attracted hordes of new residents who, in turn, caused a boom in housing construction. Unfortunately, many residential buildings were built on top of soft, shaky ground, and some building contractors cut costs by increasing the percentage of sand in their concrete, causing it to crumble as the ground shook.

The North Anatolian fault is a 1,400 km long fault zone made of numerous subparallel faults that split and combine, bend and straighten. It is not located on the Arabian plate, but it is caused by it (Figure 3.36). As the Arabian plate pushes farther into Eurasia, Turkey is forced to move westward and slowly rotate counterclockwise. Bounded by the North Anatolian fault in the north and the east Anatolian fault in the southeast, Turkey is squeezed westward like a watermelon seed from between your fingers.

A remarkable series of earthquakes began in 1939 near the eastern end of the North Anatolian fault with the magnitude 7.9 Erzincan earthquake, which killed 30,000 people. Since 1939, 11 earthquakes with magnitudes greater than 6.7 have occurred as the fault ruptures westward in a semiregular pattern that is unique in the world (Figure 3.34). At intervals ranging from 3 months

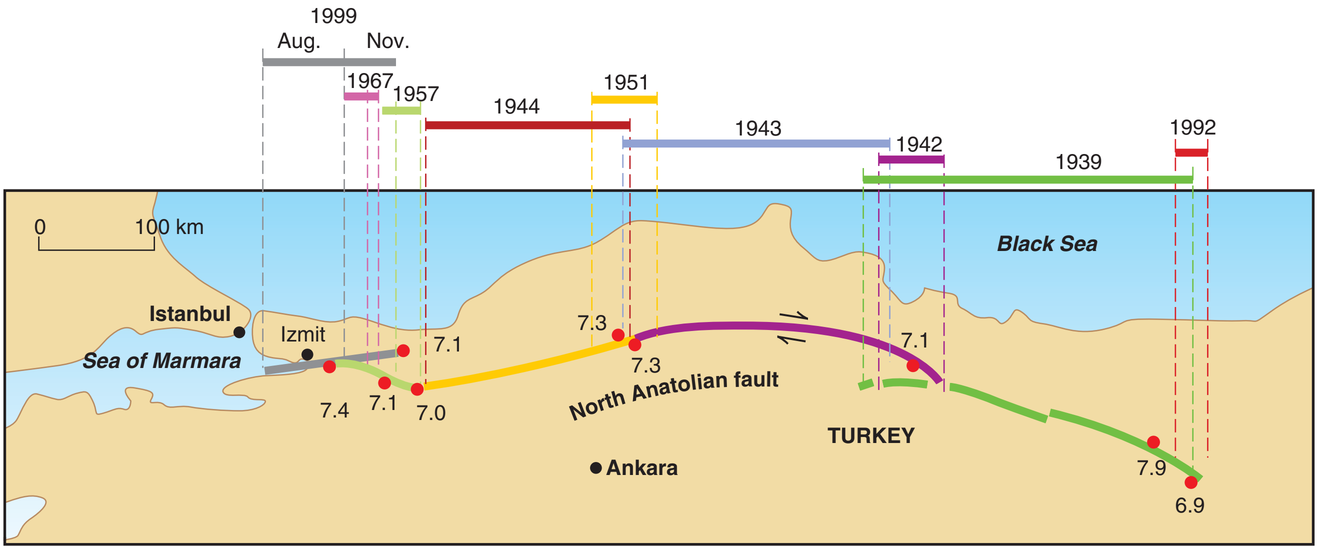


Figure 3.34
The North Anatolian fault accommodates the movement of Turkey westward into the Mediterranean basin (Figure 3.36). Note the time sequence of the fault ruptures from east to west. What does the near future hold for Istanbul?

Figure 3.35
A six-storey building pancaked in Duzce, Turkey, on 12 November 1999 when its supporting columns failed.
Photo © Roger Bilham, courtesy of NOAA.

to 32 years, over 1,000 km of the active portion of the fault has moved in big jumps.

What is likely to happen next? There is every reason to expect the fault rupture to keep moving to the west. The next big earthquake will likely occur near Istanbul, a city of 13 million people and growing rapidly. In the last 15 centuries, Istanbul has been heavily damaged by 12 earthquakes. Calculations indicate the next big earthquake affecting Istanbul has a 62(+/−15)% probability of occurring within the next 30 years.

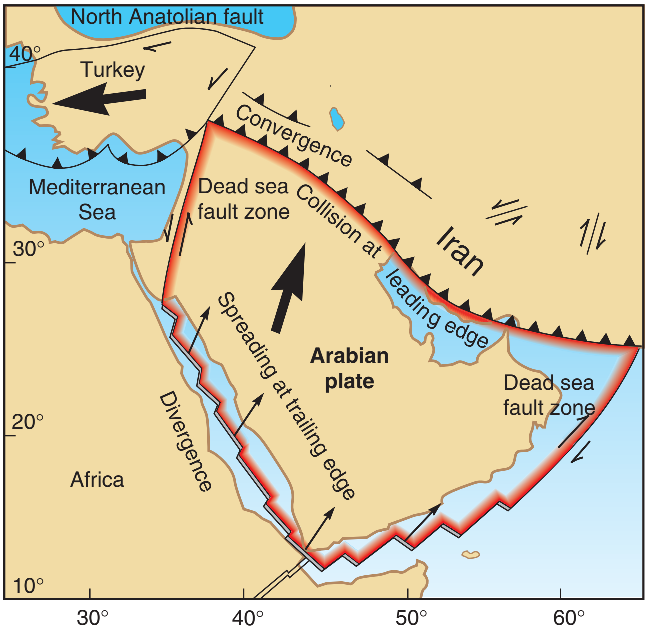


Figure 3.36
The Arabian plate pulls away from Africa, pushes into Eurasia, slices through the Middle East with a transform fault, and squeezes Turkey westward.

Hot Spots and Earthquakes

When one thinks about natural hazards in Hawaii, it is volcanism that comes to mind. But the movement of magma at hot spots can cause earthquakes, including large ones. In fact, several active volcanoes around the world, including Kilauea, are under surveillance to detect signs of increased earthquake activity leading to an eruption. When rock liquefies, its volume expands, and neighbouring brittle rock must fracture and move out of the way. The sudden breaks and **slips** of brittle rock are fault movements that produce earthquakes.

When magma is on the move at shallow depths, it commonly generates a nearly continuous swarm of relatively small earthquakes referred to as **harmonic tremors**. Figure 3.37 shows that the earthquakes below Kilauea volcano are dominantly near-surface events.

Magma movements also cause larger-scale topographic features and larger earthquakes. The land surface is commonly uplifted due to the injection of magma below the ground surface. But the land surface is also commonly down-dropped due to withdrawal of magma. Figure 3.38 shows some down-dropped valleys on Kilauea. Kilauea is "supported" on the northwest by the gigantic Mauna Loa volcano and the mass of the Big Island of Hawaii. However, on its southeastern side, there is less support; Kilauea drops off into the Pacific Ocean. The effects of subsurface magma movement, both compressive during injection and extensional during removal, combine with gravitational pull to cause large movements along faults.

On 29 November 1975, one of the seaward-inclined faults moved suddenly in a 7.2 magnitude seism. It happened at 4:48 a.m., when a large mass slipped for 14 seconds with a movement of about 6 m seaward and 3.5 m downward. The movement of this mass into the sea caused a tsunami up to 12 m high. Campers sleeping on the beach were rudely awakened by shaking ground; those who didn't immediately hustle to higher ground were subjected to crashing waves. Two people drowned. This fault movement had an effect on subsurface magma analogous to shaking a bottle of soda pop—gases escaping from magma unleashed an 18-hour eruption featuring magma fountains up to 50 m high.

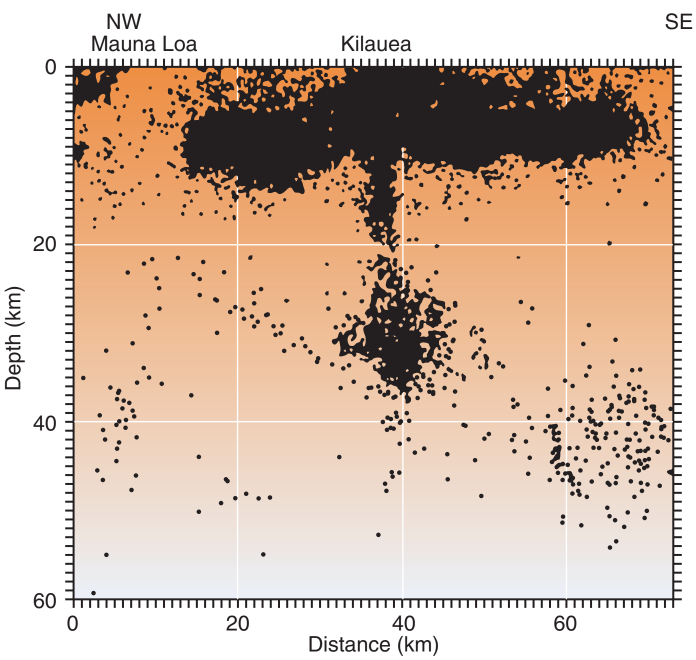


Figure 3.37
Cross-section showing hypocentres beneath Kilauea volcano on the flank of the larger Mauna Loa volcano, southeastern Hawaii, 1970–1983.

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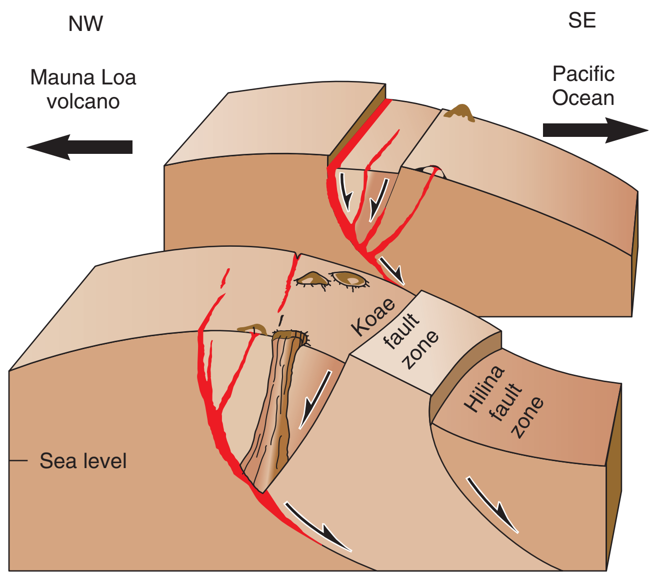
Figure 3.38
Schematic block diagrams of the southeastern flank of Kilauea volcano. Intruding magma (red) forces brittle rock to break and move, generating earthquakes. Gravity-aided sliding down normal faults causes more earthquakes as rock masses slide southeastward into the ocean and cause rare mega-tsunami.
Source: © Geological Society of America, *Decade of North American Geology*, Vol N.



Summary

- Earth's outer layer, the lithosphere, is broken into a dozen large tectonic plates, and several smaller ones. Plates are approximately 100 km thick. The larger plates are several thousands of kilometres across.
- The boundary between the rigid lithosphere and the underlying plastic asthenosphere provides a sliding surface for plates to move. Convection in the asthenosphere and gravity are the driving mechanisms of plate movement.
- The tectonic cycle describes the recycling of Earth's outer layers over a time period of approximately 250 million years. Different processes take place in the four different tectonic environments: (1) divergent, (2) convergent, (3) and transform plate boundaries, and (4) hot spots. New lithosphere is created by seafloor spreading when plates are pulled apart at divergent zones. Old lithosphere is being reabsorbed into the asthenosphere by subduction where two plates of differing densities collide. Transform faults accommodate the along-side movements of plates without creation or destruction of lithosphere. Hot spots originate deep in Earth and are the source of isolated plumes of partially molten rock rising through the asthenosphere and lithosphere.
- Ocean studies have contributed solid evidence attesting to the movement of tectonic plates. Magnetization patterns on the seafloor delineate the newly formed lithosphere in space and time. Bathymetric surveys have mapped deep subduction trenches and relatively shallow volcanic ridges.
- Oceans and continents are fundamentally different. Ocean floors are relatively young features on the surface of Earth, being constantly recycled by seafloor spreading and subduction. Continents comprise older lower-density rock that rides on top of the denser rock of the moving plates.
- Plate tectonics has been operating on Earth for over half the planet's history. The Canadian territory has grown from a core of very old rock through successive episodes of seafloor spreading, subduction, and continental collisions.
- Most earthquakes are caused by fault movements and occur preferentially along the edges of tectonic plates. Magma movement in the shallow subsurface at spreading centres and hot spots tends to induce swarms of small earthquakes. The dominantly horizontal movements at transform faults produce large earthquakes. The compressional movements at subduction zones and continent–continent collisions generate the largest tectonic earthquakes, and they affect the widest areas.
- The west coast of Canada is tectonically active and prone to large earthquakes. The Explorer plate is currently subducting offshore Vancouver Island. To the north, the Pacific and North American plates rub uneasily against one another along the Queen Charlotte transform fault.

Terms to Remember

bathymetry 54
cohesion 73
continental drift 52
convergence zone 50
craton 64
Curie point 53
divergence zone 50
epicentre 55
fault 63
Gondwanaland 60
harmonic tremors 76
hot spot 54
hypocentre 55
island arc 58
Laurasia 60
lava 53
magnetic field 53
magnetic pole 53
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spreading centre 55
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tectonics 50
topography 50
transform fault 50
trench 55
triple junction 57

Questions for Review

1. Explain several lines of evidence indicating that the continents move about Earth.
2. Provide evidence indicating that seafloors spread.
3. What are the ages of the oldest (a) rocks on the continents, and (b) rocks making up the ocean floor?
4. Explain the seismic-gap method of forecasting earthquakes.
5. Why did the plate tectonics theory supersede the continental drift hypothesis and gain wide acceptance?
6. Draw and label a cross-section that explains the tectonic cycle.
7. Sketch a sequence of cross-sections that shows how a continent is separated to accommodate an ocean basin.
8. Describe a deep-ocean trench. How does one form?
9. Why do deep earthquakes tend to occur within inclined bands?
10. Why are the Himalaya the world's largest mountain range?
11. Explain why earthquakes at subduction zones are many times more powerful than spreading-centre earthquakes.
12. How do hot spots help determine the directions of plate motions?
13. Why is British Columbia vulnerable to large earthquakes?
14. What are the similarities between the Queen Charlotte fault of British Columbia and the San Andreas fault of California?

Questions for Further Thought

1. Why did the realization that Earth's surface is broken into large plates come about only a few decades ago?
2. How can the rate of motion of a plate be measured?
3. Is East Africa likely to pull away from the rest of Africa to form a Somali plate?
4. If a space body with active Earth-style plate tectonics is found, what would this discovery reveal about the internal structure of this body?