CHAPTER 4

Global Tectonics and Geohazards

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CHAPTER OUTLINE

INTRODUCTION

In this chapter, we introduce material that you must learn if you are to understand, among other important concepts, why and where earthquakes and volcanoes occur, and, therefore, the origin of the many geological hazards they generate. First, we will discuss the concept of the geological *model.* Then we will review the *scientific method* and continue with a brief look at the history of recent scientific thought on the nature of the Earth's interior. Finally, we present a *model* of the Earth's interior to set the stage for our discussion of global tectonics, the great unifying theory of geology.

THE CONCEPT OF THE MODEL

If scientists want to know the Earth's composition and structure at any depth, the easiest way to find out would be to drill a hole and collect a sample (FIGURE 4-1).

In the United States alone, over 250,000 holes have been drilled exploring for oil and gas!

How deep into the interior do you think we have succeeded in drilling (the radius of the Earth is about 6600 km, or 4100 mi)? Science-fiction writers to the contrary, scientists have succeeded in drilling less that ¼ of *one percent* of the way to the Earth's center, or only about 14 km (8.7 mi)!

The reason we have not drilled deeply into the Earth is that temperatures and pressures increase as depth increases, and the conditions eventually become too extreme for drilling material to hold its strength. Solid steel drill pipe starts to act like angel-hair pasta. The cost becomes prohibitive as well. This illustrates a very important point about our knowledge of the Earth's interior: *almost all our knowledge is indirect.*

Concept Check 4-1. Recall that knowledge is not scientific if it is not observable. Discuss whether our knowledge of the Earth's interior is scientific, given that we have drilled only ¼ of one percent into the planet.

Because we don't have direct samples from boreholes into the Earth's center, we must content ourselves with making **models** of the interior based on indirect evidence. And we must constantly test the validity of these models, which is the scientific standard of "suspended judgment."

An Analogy: A Model of an Aircraft

Models in geology are *abstract representations of a general concept.* As kids, many of us put together model airplanes. To make those models, we bought kits

(A) THE *GLOMAR CHALLENGER*

(B) THE *JOIDES RESOLUTION*

(C) THE *CHIKYU*

FIGURE 4-1 Ships designed for deep-sea drilling. (A) The *Glomar Challenger,* a unique drilling vessel 122 meters long, could manage about 7.6 kilometers of drill pipe. Courtesy of Integrated Drilling Program. (B) The *Joides Resolution,* about 300 meters long,can handle over 9.1 kilometers of drill pipe and operate safely in heavier seas and winds than the Glomar Challenger could. Courtesy of Ocean Drilling Program, Texas A&M University. (C)The 210-meter-long *Chikyu* can drill in water depths up to 2.5 kilometers and carries enough drill pipe to continue 7.5 kilometers below the sea floor. © Kyodo/Landov.

consisting of the exterior parts of the plane all reduced by the same amount to the original airplane: in other words, a *scale model.* But what if you had to design a *general model* for an aircraft—something that immediately would be recognized by everybody as an aircraft, without being an actual model of any real aircraft? Obviously you would first have to decide *what characteristics are common to all aircraft.* Perhaps you'd conclude that all aircraft have wings, a body (fuselage), one or more engines, and a tail of some sort. So, you might make a general model of an aircraft with these four characteristics. However, they may be of different sizes and shapes. For example, some planes have straight wings and some have wings that are swept back at an angle. Some have propellers for engines and others have jets. But these specific variants do not mean that you couldn't make a general model of a plane that everyone could recognize *as a plane*; they would only have to know something about the variations in plane types.

This is the basis for the geological use of the model: we try to boil down the *system* we are trying to model to the basic and essential characteristics that all variants share. Models are essential to a geologist: in sedimentary geology we make models of sedimentary environments, like rivers, in order to be able to recognize river sediment from ancient sedimentary rocks.

Concept Check 4-2. Find photographs of at least three different deltas. Design a model of a delta (in other words, determine common features of these deltas that would characterize all deltas). Describe your model.

A VERY BRIEF REVIEW OF THE SCIENTIFIC METHOD

Let's review the scientific method, because we use it to make our model of the Earth's interior. Being scientists, geologists use **hypotheses** to explain some natural phenomenon, and then gather evidence to test their hypotheses. They also may design experiments to test them. After this, the hypothesis has either been supported or rejected and, if supported, geologists may elevate it to a **theory** (a widely accepted explanation for a phenomenon); if rejected, it's back to the drawing board.

MODELING THE EARTH'S INTERIOR

A model of the Earth's interior shows the general structure such as: interior layers drawn to *scale,* where interior boundaries are, what the **states of matter** are (whether solid, liquid or gas, for example), and the composition of the interior, in as much detail as necessary. We may not know the exact composition of each zone, or the layers may vary in composition, so our model might try to show an "average" composition; or our model might try to show how compositions vary with depth, or laterally.

To make our model, we use all available evidence that will allow us to put *constraints* on what our model looks like. For example, we know (from its gravitational interactions with other bodies in the Solar System) the Earth's overall **density** (an indicator of the mass of a substance relative to its volume, in other words, how heavy it is) is 5.52 g/cm^3, so our interior material must *average* 5.52 in density, even though the density of each zone or layer may be higher or lower.

The Importance of Earthquake Waves

The energy stored in a stick when bent is released quickly when the stick breaks. Some of the energy is released as *sound*: a sharp crack is heard. Sound is a form of energy and breaking the stick generates sound waves. In the same way, breaking rocks along *faults,* which are fractures in the Earth along which movement takes place, also releases energy. Several types of energy waves are generated (discussed elsewhere in this text; **FIGURE 4-2**).

Seismic *wave paths* and velocities inside the Earth depend on the property of the material through which the waves pass. If we can track the wave path, we can tell a lot about the nature of the material along its path (**FIGURE 4-3**).

Summary of Evidence Used to Model the Earth's Interior

We use evidence from the following sources to make our model of the Earth's interior.

- The composition and distribution of surface rocks. There are three categories of rocks: **igneous**, which form from a molten mass called **magma**; **sedimentary**, which form by erosion of pre-existing rocks or by organisms, like corals; and **metamorphic**, a "hybrid" rock formed when a pre-existing rock is subjected to heat and pressure, causing the original minerals to align themselves, recrystallize, or both. Besides outcrops, we have hundreds of

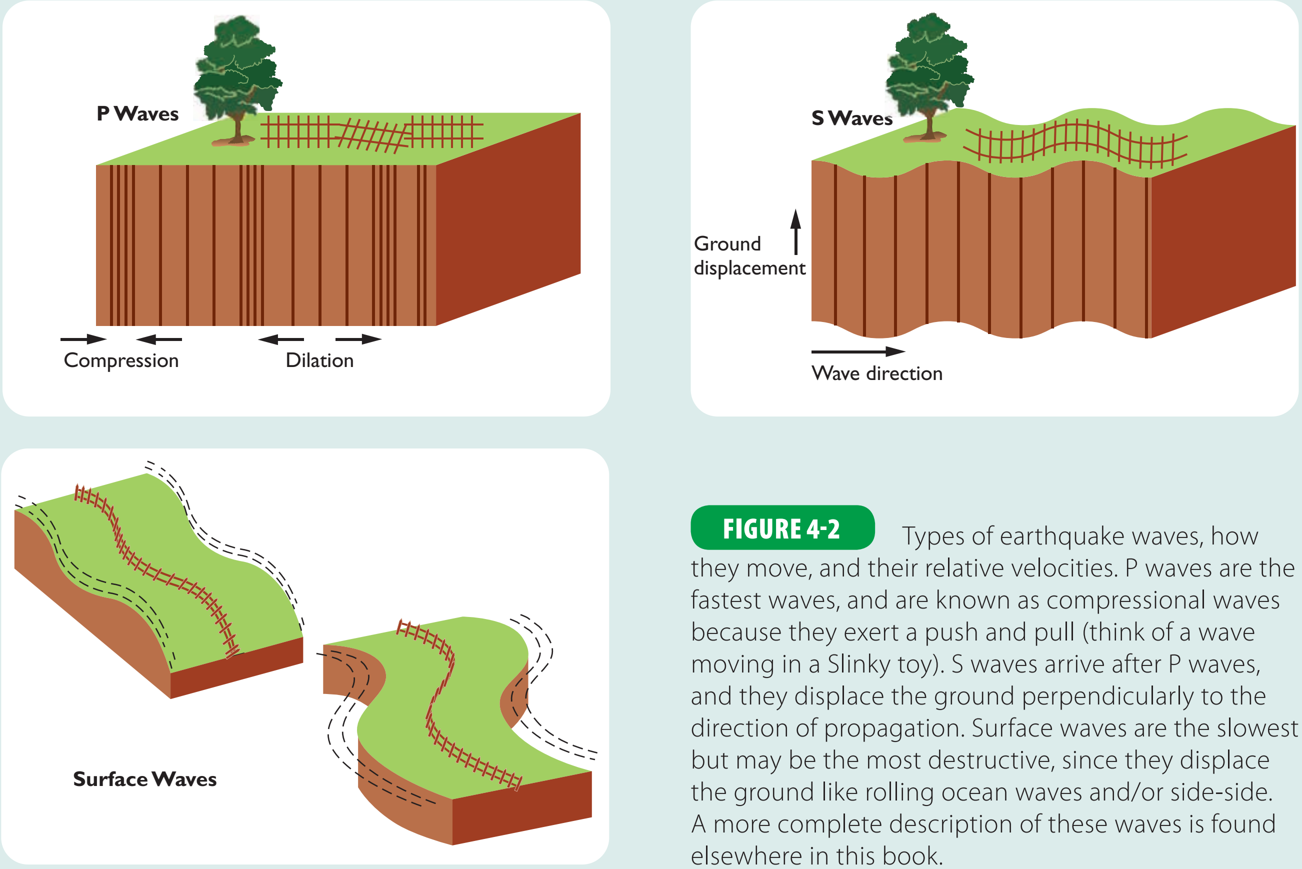


FIGURE 4-2 Types of earthquake waves, how they move, and their relative velocities. P waves are the fastest waves, and are known as compressional waves because they exert a push and pull (think of a wave moving in a Slinky toy). S waves arrive after P waves, and they displace the ground perpendicularly to the direction of propagation. Surface waves are the slowest but may be the most destructive, since they displace the ground like rolling ocean waves and/or side-side. A more complete description of these waves is found elsewhere in this book.

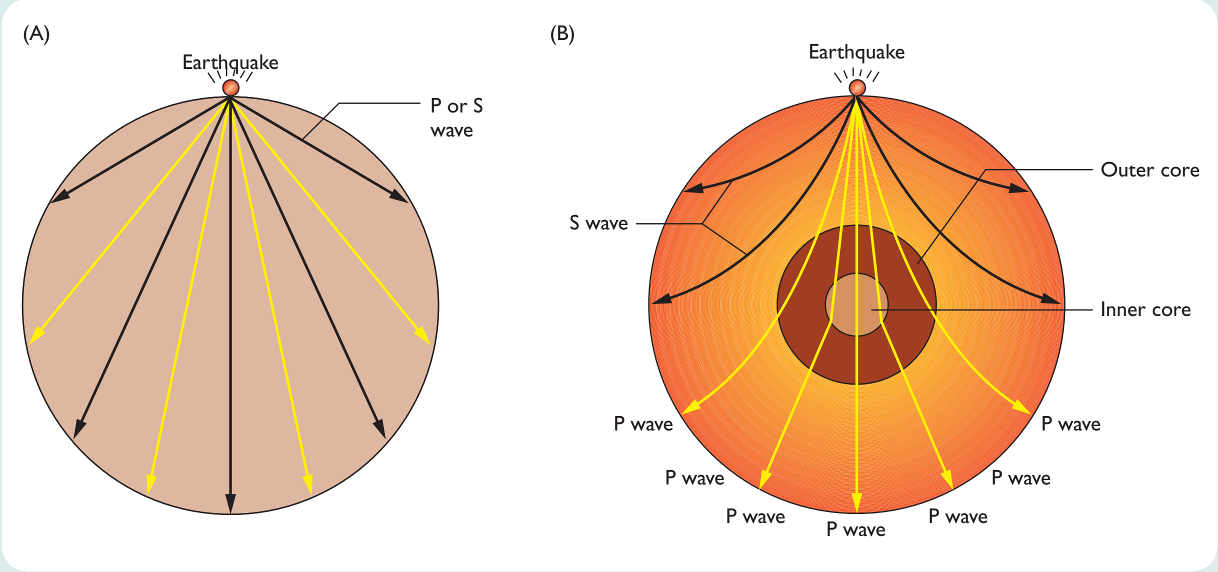


FIGURE 4-3 Changes in seismic wave velocities with depth. P waves penetrate through liquid, while S waves are reflected. Internal zones where waves abruptly change velocity are known as discontinuities. They are important internal boundaries and indicate a change of state, of composition, or both. (A) How waves would travel through an Earth with a homogeneous interior. (B) Actual wave paths, which demonstrate the increase in density with depth and the existence of the core.

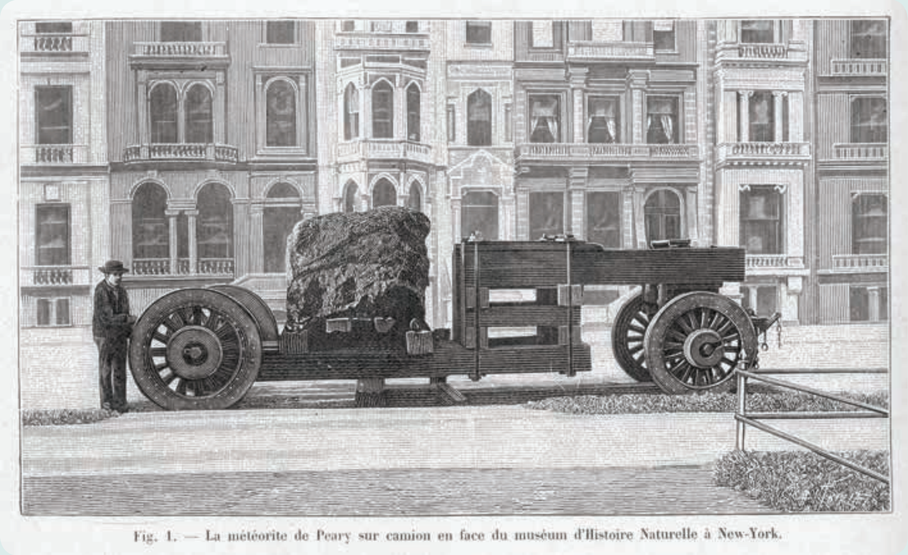


FIGURE 4-4 A meteorite recovered from Greenland. The snow cover helped researchers spot the dark meteorites. © Mary Evans Picture Library/Alamy Images.

thousands of samples of the shallow continental crust from boreholes, so we can estimate the average composition of the Earth's continents.

- Meteorites, the "raw material" of the original Earth. Meteorites, objects from space that have survived impact on Earth, commonly are either an iron-nickel alloy (about 6%), or composed of silicate minerals containing the elements silicon and oxygen (about 93%; **FIGURE 4-4**).
- Thousands of drill holes and dredge samples of oceanic sediment and underlying bedrock. We also have seismic data that show where boundaries exist in the oceanic crust. We can confidently infer the composition of these layers.
- We know the Earth's average density is 5.52 g/cm^3, which puts strong limits on the kinds of substances that can possibly make up the interior. **TABLE 4-1** shows densities of some common substances, which should give you an idea of what a density of 5.52 means.

TABLE 4-1 ***Some Common Substances and Their Densities***

Diamond	3.5
Pyrite	5.2
Gold (22 carat)	17.5
Cement	1.6
Concrete	2.4
Cast iron	7.7
Marble	2.7

- The physics of the Earth's rotation dictates that the densest material must be at the Earth's center and densities must decrease outward (and of course we know the average density of the outer layer from direct samples).
- When an earthquake occurs, **seismic waves** are generated, which travel through the Earth, making it "ring like a bell." Like light off a mirror, seismic waves can bounce off surfaces inside the Earth where densities abruptly change. We therefore know from the behavior of seismic waves as they travel through the Earth where the major boundaries are located between subsurface materials, and we know something about their properties, because rock properties determine seismic wave velocity. For example, other things being equal, the higher the density of rock, the faster seismic waves travel through it. Figure 4-3 shows how waves, in this case sound waves, are reflected and bent (refracted) by the various layers inside the Earth. Internal zones where waves abruptly change velocity are known as **discontinuities**. They are important internal boundaries and indicate a change of state, composition, or both.
- The Earth's powerful magnetic field puts limits on the possible composition and state of the planet's interior (**FIGURE 4-5**).

Using such information, we could hypothesize that the Earth is made of material that *gradually* increases in density from that at the surface to a denser mass at the center, so that the overall average density is 5.52. Crustal rocks, that is, rocks near the Earth's surface, have densities in the range of 2.5 to 3.1, but no common natural rock has a density approaching 5.52.

Applying data from seismic waves, we find that this model won't work, because seismic wave velocities (which tell us the density of Earth materials) change abruptly at several *discontinuities* within the Earth. So we have to modify our model by hypothesizing separate *layers* inside the Earth, rather than material that gradually increases from surface to center.

Concept Check 4-3. Explain why not altering our hypothesis given the existence of the seismic data would have violated the "rules" of science.

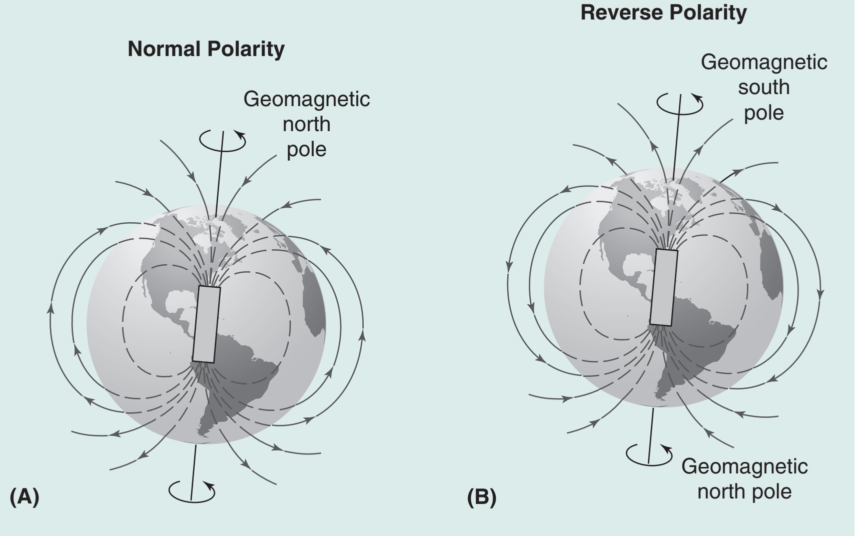


FIGURE 4-5 A diagram showing the lines of force of the Earth's magnetic field. The field is generated by convection in the Earth's core. Data from A. Cox, *Science*. 163 (1969): 237–245.

Concept Check 4-4. Explain the concept of a geological model. Based on the information in the preceding sections, explain the model of the Earth's interior.

THE INTERIOR: LITHOSPHERE, ASTHENOSPHERE, CRUST, MANTLE, AND CORE

One of the most fundamental discoveries about the Earth was that the interior was composed of *layers* with recognizable boundaries. Geologists at first divided the Earth into three layers: the **crust** (outermost material), an underlying **mantle**, and a **core** at the center, based on hypothesized differences in rock *composition.* **FIGURE 4-6A** shows the major zones within the Earth. Material may vary in composition, and properties such as strength (which measures how it responds to deforming force), or state (whether solid, liquid, or gas). Strength and state in turn depend on the temperature and pressure to which the material is subjected.

Later study of seismic waves and the Earth's magnetic field, coupled with laboratory research, allowed detail to be added to this model. The *core* was hypothesized to consist of an inner solid portion and an outer liquid portion. Two types of crust were found: **oceanic**, comprising **basaltic** (*basalt* is a dark-colored, fine-grained, igneous rock) rocks below sediment, and **continental**, composed of all three rock types, but on average having a composition near that of granite. The lower mantle was denser than the upper mantle. The upper mantle was found to contain a zone near its top where seismic wave velocities were lower than above and below: This zone became known as the *low-velocity zone,* or **asthenosphere**. The

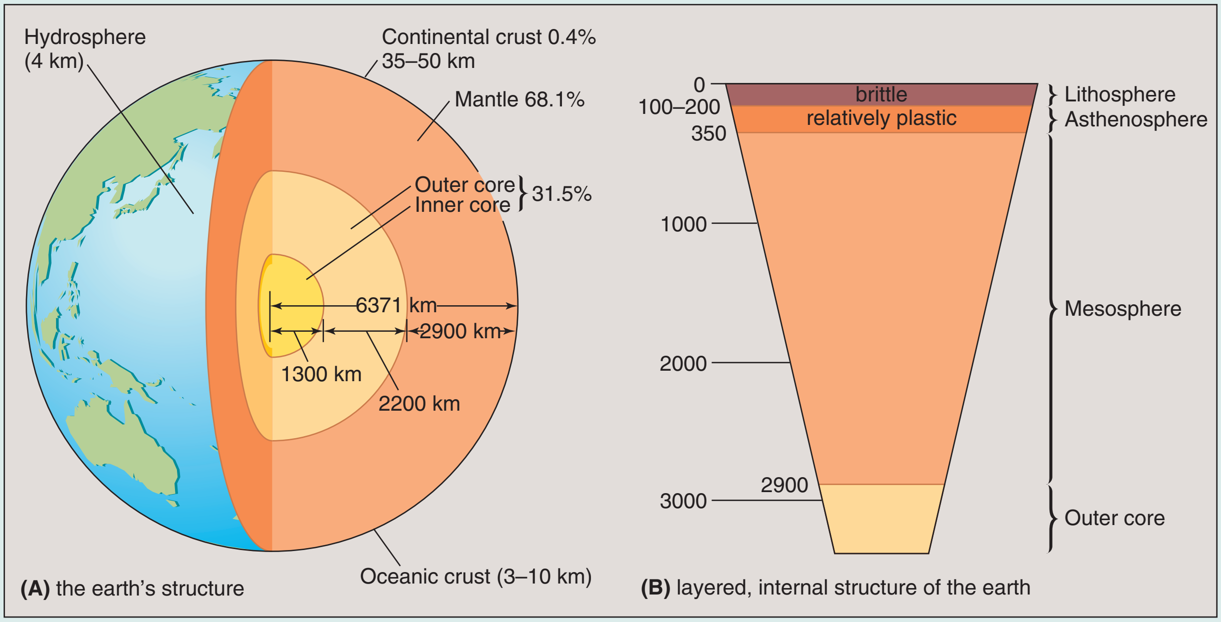


FIGURE 4-6 Earth's internal structure. Percentages indicate the relative masses of the core, mantle, and continental crust. Where is most of the Earth's mass concentrated? (A) Layering based on chemical composition and physical state. (B) Layering based on response to a deforming force. The lithosphere was defined to include the crust (both continental and oceanic: see arrows) and the rigid uppermost portion of the mantle. The asthenosphere lies entirely within the upper mantle.

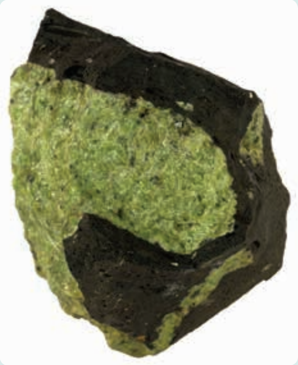


FIGURE 4-7 A peridotite sample, brought up by lava known to have originated in the mantle. Peridotite takes its name from the gem-quality form of the mineral olivine—peridot—which is a magnesium-rich silicate mineral. Silicon is the second most abundant element in the Earth after oxygen. It thus should be no surprise then that minerals made mainly of silicon and oxygen should be so common. © Slim Sepp/ShutterStock, Inc.

term is derived from the Greek *asthenos* (meaning weakness or loss of strength), which means a weak, plastic (that is, deformable), partially molten zone, to distinguish it from the **lithosphere** (Greek, *lithos* = rock), a strong, rigid zone, above it (**FIGURE 4-6B**). The lithosphere sits atop the asthenosphere and includes the crust (both continental and oceanic) and the rigid uppermost portion of the mantle.

The upper mantle's composition is best described as **peridotite**, a magnesium-rich rock containing abundant olivine, based on several lines of evidence (**FIGURE 4-7**). First, peridotite is a rock, which on being partially melted, yields a *basaltic* magma, and basalt is the universal bedrock of the ocean basins (below a veneer of sediment), so it is likely that the ocean basin bedrock formed from partially melted peridotite. Furthermore, the density and properties of peridotite are consistent with the behavior of seismic waves traveling through the upper mantle. Finally, it is possible to derive peridotite from the composition of stony meteorites, the probable raw material from which the planet was built more than 4 billion years ago.

SUMMARY OF THE EARTH'S INTERIOR

Our model at present is like this: The Earth is a layered body that has discrete boundaries separating the layers. These layers, based on compositional differences from the surface inward are, crust, mantle, and core. The uppermost few hundred km of the Earth are divided into a lithosphere (containing the crust and uppermost mantle) and an asthenosphere, or low-velocity zone; a partially molten zone entirely within the mantle. The crust is of two types: oceanic, consisting mainly of basaltic rocks below a variable layer of sediment, and continental, composed of all three rock types, but on average having a composition near that of granite. The outer core is molten and the inner core solid. The composition of the core is mainly iron, with some nickel and minor elements such as sulfur, silicon, and/or potassium. The upper mantle is of peridotitic composition (a material which, if partially melted, yields a basaltic magma) and the lower mantle is probably made up of densely packed oxide minerals, with a similar composition to the upper mantle but made up of denser crystal structures.

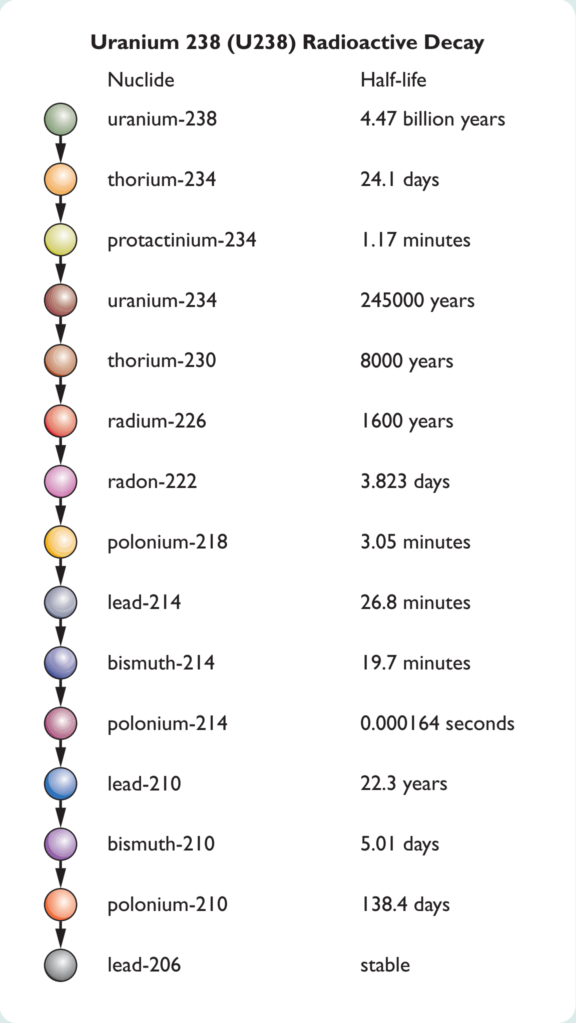
RADIOACTIVE DECAY AND INTERIOR HEAT

One additional factor affects the nature and behavior of the Earth's interior and surface: radioactive decay (**FIGURE 4-8**). **Radioactivity** refers to the "decay" of unstable atomic nuclei. (Decay here means the radioactive atom changes to a non-radioactive element by emitting particles and energy.) We discuss radioactive decay further elsewhere.

The reason we introduce radioactivity here is that it produces a great deal of *heat* in the Earth's interior, and radioactive heat powers the global process we call plate tectonics, which is introduced below. The fact that radioactive decay is irreversible that is, once an atom has decayed it no longer produces heat, helps us understand how the planet's crust has evolved over the past 4+ billion years. Thus, heat available to power plate tectonics, including volcanic activity, has declined over geologic time.

HEAT TRANSFER

Heat produced by radioactive decay moves from high concentrations to areas where there is less heat, forming a heat *gradient*. The same thing happens when you put a pot on a hot burner on the stove. The pot warms by heat that migrates from high heat (the burner) toward low heat regions (the pot's contents). In general the Earth's



Uranium 238 (U238) Radioactive Decay

Nuclide	Half-life
uranium-238	4.47 billion years
thorium-234	24.1 days
protactinium-234	1.17 minutes
uranium-234	245000 years
thorium-230	8000 years
radium-226	1600 years
radon-222	3.823 days
polonium-218	3.05 minutes
lead-214	26.8 minutes
bismuth-214	19.7 minutes
polonium-214	0.000164 seconds
lead-210	22.3 years
bismuth-210	5.01 days
polonium-210	138.4 days
lead-206	stable

FIGURE 4-8

Radioactive decay. The U238/Pb206 decay series. Heat produced by radioactive decay has decreased over the Earth's history. If the Earth's heat engine is based on radioactive decay, and the rate at which plates move is related to heat produced, how do you think plate motion rates have changed over planetary history? How do you think plate motion rates will change going into the future? Will they stay the same, increase, or decrease? On what do you base your answer?

interior is hot and the surface is cold, so heat tends to move from the interior toward the surface. Three ways that heat can move are: by *conduction,* by *convection,* and by **radiation** (**FIGURE 4-9**).

Conduction

In the solid parts of the Earth's interior, **heat transfer** is accomplished by molecular motion, like sticking a cold iron bar in a hot fire (Figure 4-9). This is also called **conduction**, and it is a relatively slow process.

Convection

If there is any liquid or gas present in a system, heating can make it behave like a pot of soup on the stove: *convection cells* or plumes will form, carrying hot soup at the pot's bottom to the surface, and displacing colder soup at the top of the pot to the bottom, where it is heated. **Convection** will continue as long as the pot is being heated and at least part of it is liquid or gas, and this is apparently the process by which much of the heat in the mantle is transferred towards the surface. Computer simulations of models of the mantle show that concentrations of heat will form such convection cells, as shown in Figure 4-9.

Convection cells and plumes powered by radioactive decay are the means by which new oceanic bedrock is made, and new oceans may be formed in the process. The oceanic bedrock is composed of basalt and basaltic rock.

The great *mass* of material being moved by convection, as well as the material's high viscosity (resistance to flow) limits the speed of the convection currents to a few

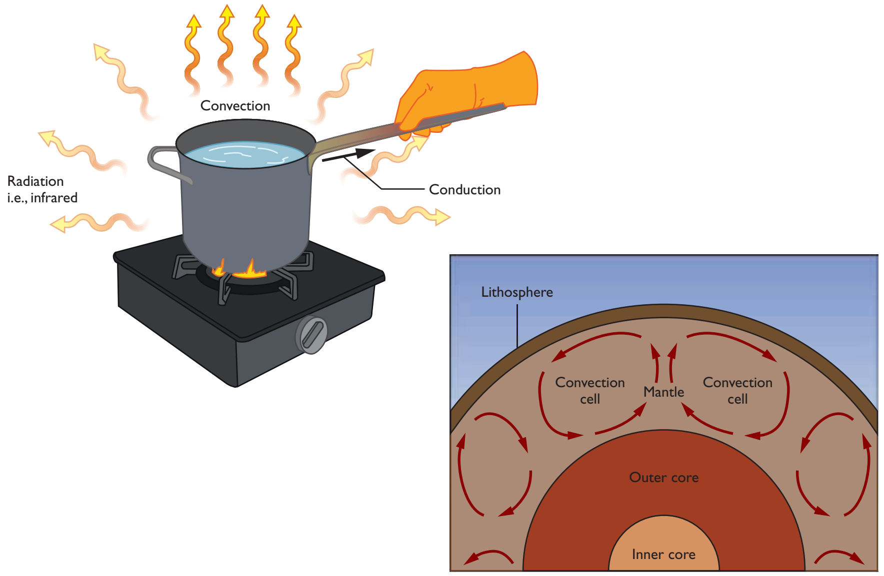


FIGURE 4-9 (A) Three modes of heat transfer: conduction, convection, and radiation. Radiation here does not mean radioactivity; radiation means transferring heat by electromagnetic radiation (e.g. by microwaves). (B) Formation of a convection cell in the Earth's interior. Heat may be transferred rapidly by convection, and the material need not be entirely liquid for convection to occur.

centimeters a year and this is not coincidentally the rate at which the lithospheric plates, which we'll discuss below, are moving at the present time. Because continents are imbedded in these plates, they are passively carried over the Earth's surface like rafts.

GLOBAL TECTONICS AND THE DYNAMIC EARTH MODEL

Plate Tectonics as a Unifying Theory of Geology

Now, we're ready to introduce the concept of **plate tectonics**. The word *tectonics* has Latin/Greek origins and means *of or relating to building,* in this case, of the structures on the Earth's surface. Plate tectonic theory states that the surface of the Earth is covered by seven major rigid lithospheric plates and a number of smaller plates (**FIGURE 4-10**), all of which are in motion, and not all in the same direction or at the same speed. Plate tectonics explains the majority of the Earth's large-scale geologic structures and processes, from island arcs like the Aleutians to events like earthquakes and, as one might expect for a concept of such overarching significance, has been called a **unifying principle** of geology.

Continental Drift and Seafloor Spreading

The theory of plate tectonics evolved from two older ideas, **continental drift** and **seafloor spreading**. The concept of continental drift is credited to German meteorologist Alfred Wegener who, during the early twentieth century, postulated that the location of the Earth's continents in the distant past was different from their current location, in other words, the continents had "drifted" over geological time. Based in part on the jigsaw puzzle fit of the current continents that was evident on maps at the time, for example, the east coast of South America meshing almost seamlessly with the west coast of Africa, and using evidence from earlier researchers, Wegener proposed the existence of a supercontinent known as

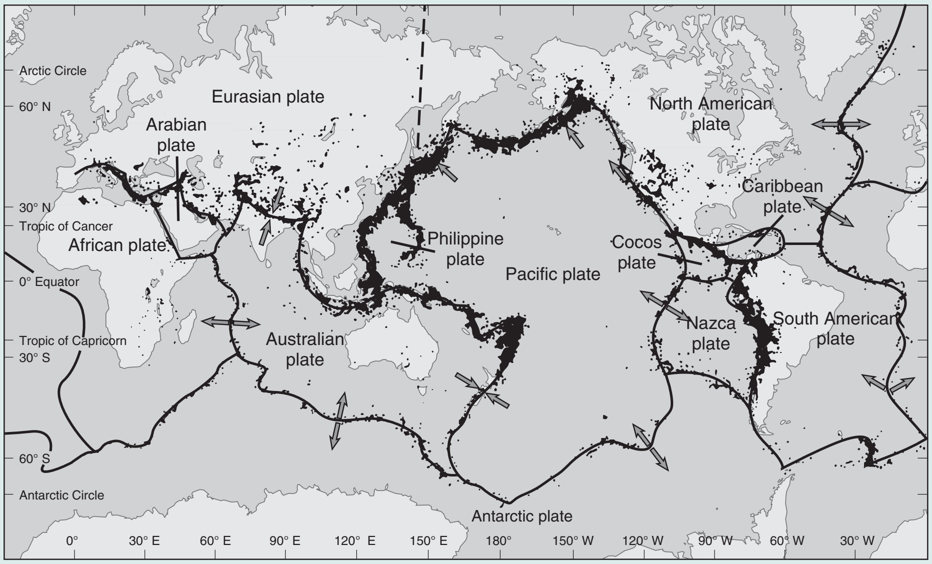


FIGURE 4-10 Earth's lithospheric plates. Clusters of black dots indicate earthquake activity. Arrows show relative plate motion. Plates are generally very thin (tens of kilometers is typical) relative to their other dimensions. Therefore, they are rather like the fractured shell of an egg in scale. Data from Stowe, K.S. *Ocean Science*. John Wiley & Sons, Ltd., 1983.

Pangaea (from the Greek meaning "all land") surrounded by single large ocean, **Panthalassa** ("all sea"), about 200 million years ago. Wegener marshaled additional supporting evidence, including the presence of the late Paleozoic fossil plant *Glossopteris* on India, Australia, South Africa, and South America, areas dissimilar in their current climate and thus unlikely to support these plants unless under a similar climate regime in the past when these areas were all connected. Other evidence included the contiguous distributions of fossil reptiles across ocean basins, an event unlikely unless the basins were closed and the continents had been connected. Geological structures like coal veins and mountains of the same age showed similar distributions across ocean basins. There was evidence of ancient glaciation in tropical parts of South America, India, Africa, and Australia, a phenomenon best explained by these locations once having existed as part of an Antarctic supercontinent (**FIGURE 4-11**). Despite a seeming abundance of geologic, paleontologic, and climatologic substantiation for his idea, Wegener's concept of continental drift was not widely accepted by the scientific community because a sound explanation for the mechanism by which the continents moved could not be made. How could granitic continents plow through the denser basaltic oceanic crust, scientists wondered?

In the late 1950s–early 1960s, the advent of post-World War II technology, namely SONAR (SOund Navigation And Ranging), allowed for more extensive mapping of the sea floor. The most extraordinary finding was the existence of 65,000 km (40,400 mi) ridge system—an underwater mountain chain—on the sea floor and deep-ocean trenches (**FIGURE 4-12**).

Other evidence came from new discoveries of magnetism of fossil rocks, **paleomagnetism**. This new arena of study revealed that information on the direction and intensity of the Earth's magnetic fields at a particular time was locked into the iron in magma when it solidified into rock at the ridges. It was

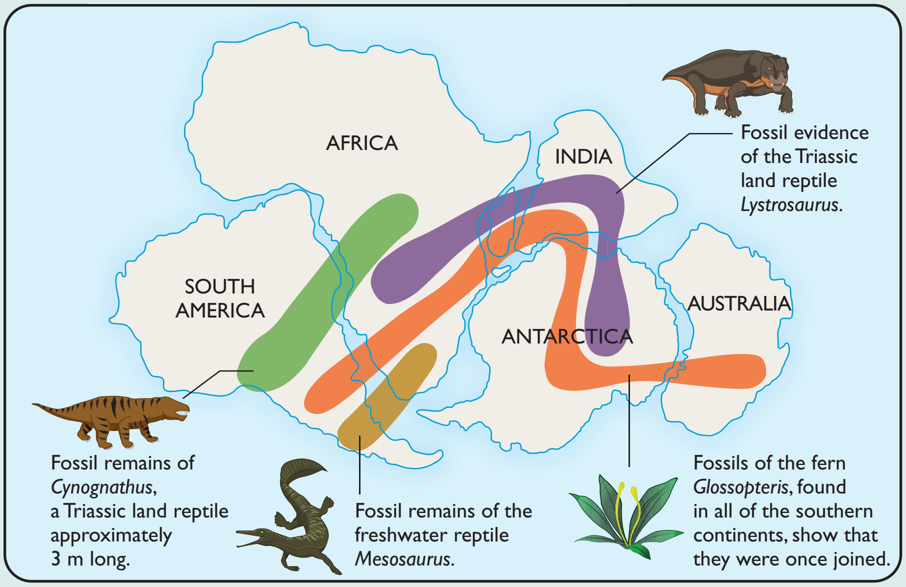


FIGURE 4-11 The continuous distributions of certain fossil plants and animals on present-day, widely separated continents demonstrates a pattern if the continents are rejoined. Modified from This Dynamic Earth, USGS.

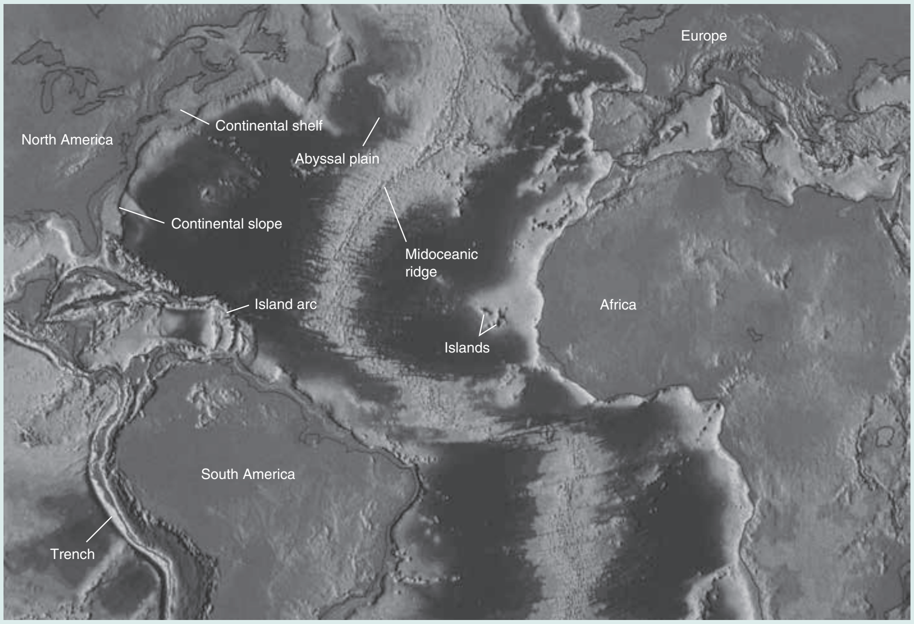


FIGURE 4-12 The mid-oceanic ridge (MOR) system, shown here in the Atlantic Ocean. Courtesy National Geophysical Data Center/NOAA.

thus learned that the current Earth's magnetic field has undergone complete reversals in the past, 170 during last 76 million years (**FIGURE 4-13**). When a **magnetometer**, a device developed at the Scripps Institution of Oceanography (**FIGURE 4-14**) to measure magnetic properties of the sea floor, was deployed, it revealed a pattern of magnetic "stripes" parallel to the ridge and symmetrically distributed around it (**FIGURE 4-15**).

This information was synthesized by Harry Hess of Princeton University in 1962. Hess proposed the theory of seafloor spreading. According to this theory, new seafloor is produced at the ocean ridges from magma, which solidifies and moves very slowly bilaterally away from the ridge, preserving information on the current direction and intensity of the Earth's magnetic field. When the field reversed, evidence of this reversal was similarly locked into the new sea floor. The striped pattern of alternating magnetic orientations symmetrical to the ridge revealed by the magnetometer thus was explained (Figure 4-15).

In addition to the paleomagnetic evidence, further validation of seafloor spreading came from radiometric dating of the ocean crust, which revealed (1) that oceanic crust is geologically young, much younger than continental crust (180 million years for the oldest oceanic crust compared to nearly 4 *billion* years for the oldest continental crust) and (2) the farther away from the ridge, the older the oceanic crust was, and there was a symmetrical distribution of ages around the ridge. New seafloor therefore was produced at the ridges and subducted ("destroyed") at the trenches. Moreover, this idea did not rely on the continents plowing through the ocean (recall that this was a major objection to Wegener's theory of continental drift), but rather both continents and oceans move.

Concept Check 4-5. Explain the concept of paleomagnetism and discuss its role in understanding seafloor spreading.

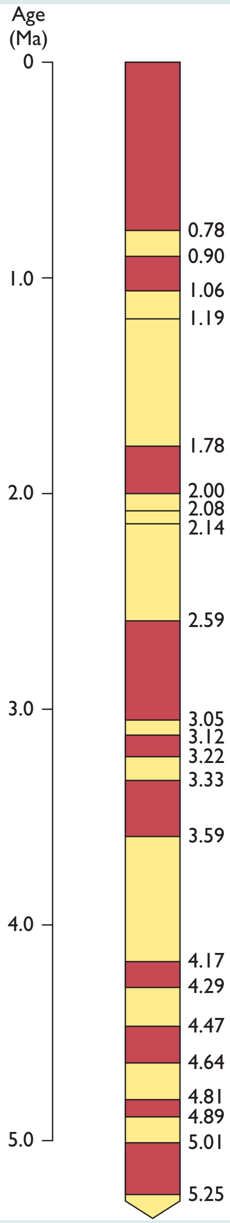


FIGURE 4-13 Reversals of the Earth's magnetic fields over the last 5 million years. Red represents periods of normal polarity. Yellow represents reversals.

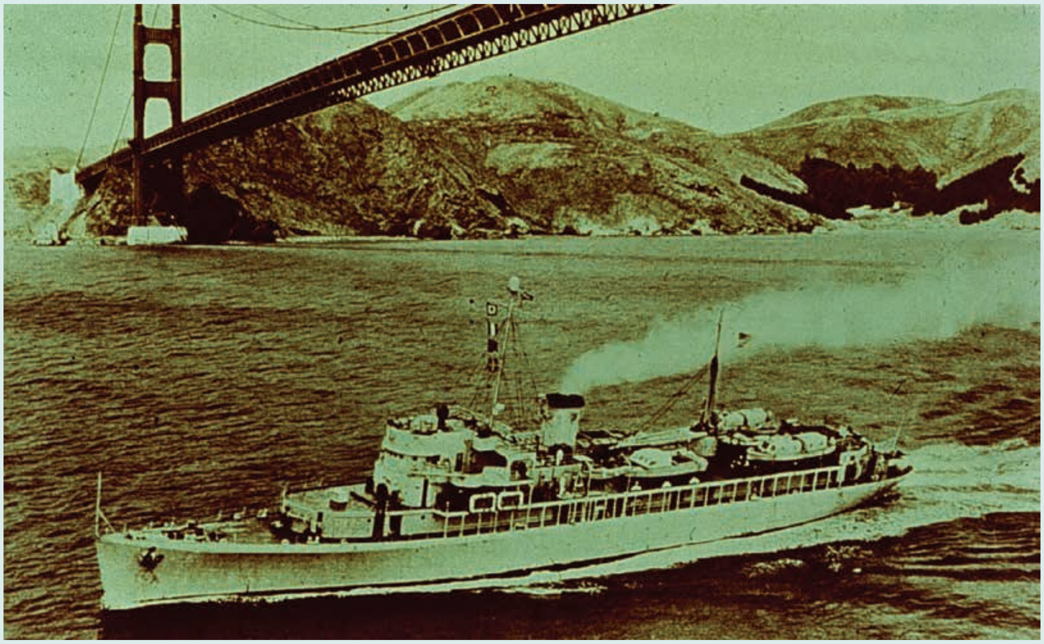


FIGURE 4-14 The survey ship *Pioneer*, which first deployed the magnetometer, steaming under the Golden Gate Bridge in the late 1950's. The discovery of magnetic striping on the seafloor contributed to our understanding of the theory of seafloor spreading. Renowned marine geologist, H. W. Menard called the discovery of the magnetic stripes, "among most significant geophysical surveys ever made." Courtesy of NOAA.

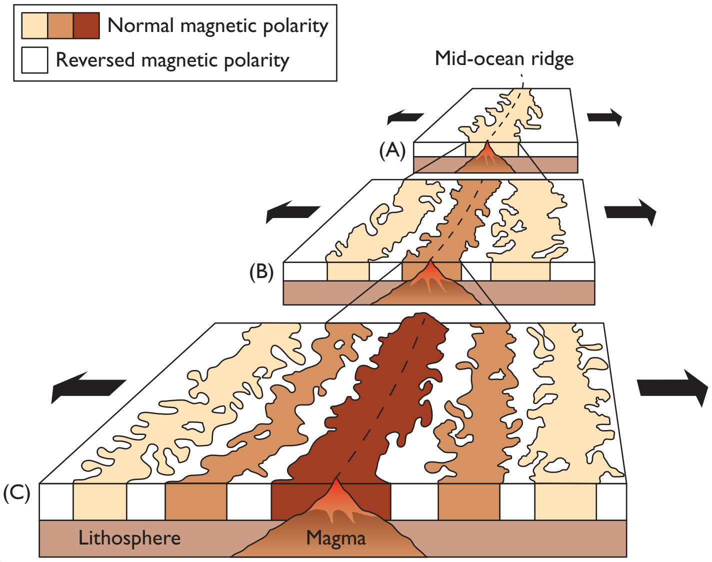


FIGURE 4-15 The pattern of magnetic stripes parallel to the ridge and symmetrically distributed around it. The oldest are shown by the pale brown color, the youngest are shown by the darkest brown color. What was the significance of these stripes? Modified from The Dynamic Earth, USGS.

Plates and Plate Boundaries

Plates are segments of the lithosphere (see Figure 4-10). The geological "action"—mountain-building, earthquakes, volcanoes—is mainly concentrated at **plate boundaries**, because here is where plates are jostling against one another, relieving great stresses.

The three types of plate boundaries are: *divergent, convergent, and transform.*

Divergent Boundaries

If the plates move away from each other, a **divergent boundary** is formed. Rift zones, like the East African Rift, form where continents are ripped apart. Here, ascending convection cells reach the surface and spread out at the base of the lithosphere, tugging at it, heating it, and thereby weakening it. With enough time, the spreading convection cell may fracture the thinned and weakened overlying lithosphere, allowing molten basaltic magma to rise from the asthenosphere and fill the cracks between the spreading plates (Figure 4-12).

Oceans grow and contract as ocean floor rock forms and is in turn consumed, and thus modern oceans exhibit various stages of development. **FIGURE 4-16** illustrates the

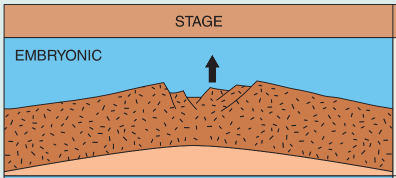
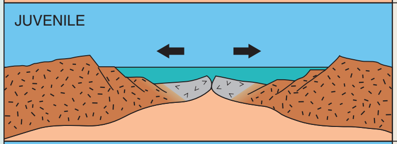
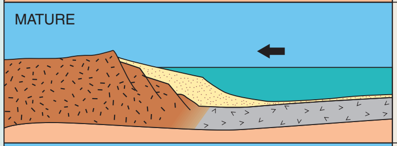
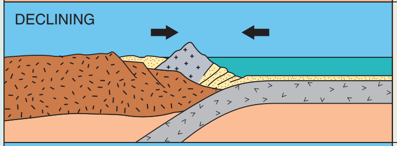
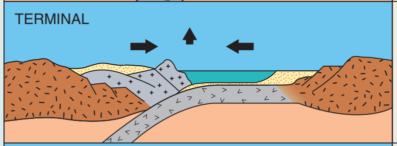
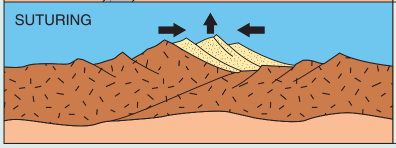
STAGE	MOTION	PHYSIOGRAPHY	EXAMPLE
EMBRYONIC 	Uplift	Complex system of linear rift valleys on continent	East African rift valleys
JUVENILE 	Divergence (spreading)	Narrow seas with matching coasts	Red Sea
MATURE 	Divergence (spreading)	Ocean basin with continental margins	Atlantic, Indian, and Arctic oceans
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 4-16 The Wilson Cycle, which shows the evolution of ocean basin development. Data from Wilson, J.T. *American Philosophical Society Proceedings* 112 (1968): 309–320; Jacobs, J.A., et al. *Physics and Geology*. McGraw-Hill, 1974.

Wilson Cycle, which shows the evolution of ocean basin development. Representative examples could be the Rift Valley of East Africa, the Gulf of California, the Gulf of Aden, and the North Atlantic.

Convergent Boundaries and Subduction Zones

Where plates move together a **convergent boundary** results. At convergent boundaries old oceanic lithosphere is recycled back into the mantle. A place where this happens is called a **subduction zone** (**FIGURE 4-17**).

Convergent boundaries may be of three types: if two masses of continental crust are brought together at a subduction zone, a *continent–continent convergent boundary* is formed. If oceanic lithosphere is subducted beneath continental lithosphere, an *ocean–continent convergent boundary* is formed. And if two oceanic lithosphere segments converge, an *ocean–ocean convergent boundary* is formed (**FIGURE 4-18**).

Modern subduction zones are usually found with **trenches**. Trenches are arcuate (that is, curved) topographic lows that form by the incessant downward tugging on the oceanic lithosphere. Earthquakes are distributed along subduction zones from near the surface (shallow-focus), through intermediate depths (intermediate-focus), to depths where the subducting material gets too weak to store stress (about 700 km). Deepest earthquakes are called deep-focus earthquakes. **Island arcs**, arcs of volcanic islands formed by subduction at ocean–ocean boundaries, are one of the planets most distinctive features. They also are the site of some of the world's highest concentrations of human populations and some of the most severe zones of geohazards. Japan and Indonesia are examples.

Concept Check 4-6. Name and distinguish between the types of plate boundaries.

Transform Boundaries

When plates slide laterally past one another, *transform or shear* boundaries result. **Transform boundaries** on continents are recognized by the presence of strike-slip faults (vertical fractures where the blocks slide horizontally past each other) like the San Andreas in California (**FIGURE 4-19**), the Alpine Fault in New Zealand, and the Dead Sea Fault Zone in the Middle East Strike-slip faults pose enormous hazards to growing human populations and infrastructure. We discuss earthquake hazards elsewhere in this text.

Continent-Continent Collisions

If two masses of continental lithosphere are brought together by plate motion at a subduction zone, a continent–continent collision eventually occurs (Figure 4-18). Collisions build great mountain ranges, with continental crust greatly thickened and usually intensely deformed. Continental crust thickens because it is too low in density to be subducted, so it piles up at the surface. Isostatic (Greek *isos* = equal, *stasis* = standstill) forces push the light rock ever higher. To understand **isostasy** (**FIGURE 4-20**), imagine blocks of slightly differing densities floating in a pail of water.

The Himalayas formed when India collided with Asia, nearly doubling the thickness of the continental crust there. The resulting uplift and subsequent erosion of the light crustal rocks generates huge volumes of sediment, which are presently being deposited in the floodplains of the great rivers draining the Himalayas. Some

Text continues on page 91.

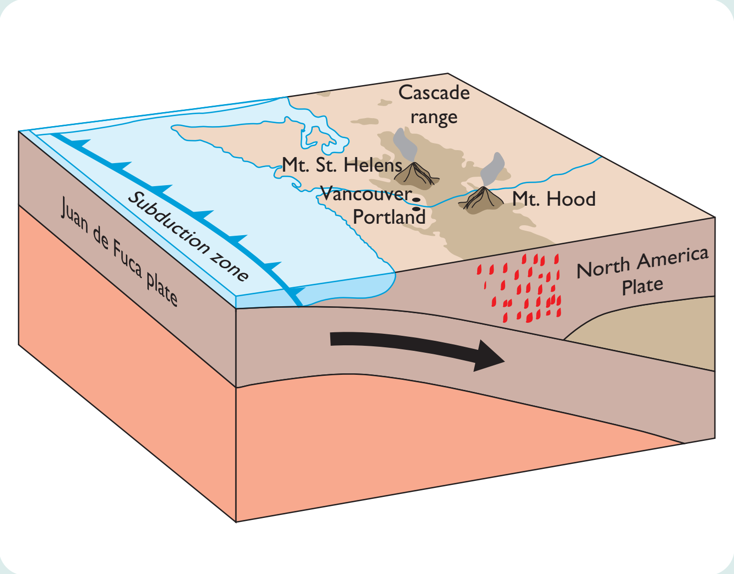
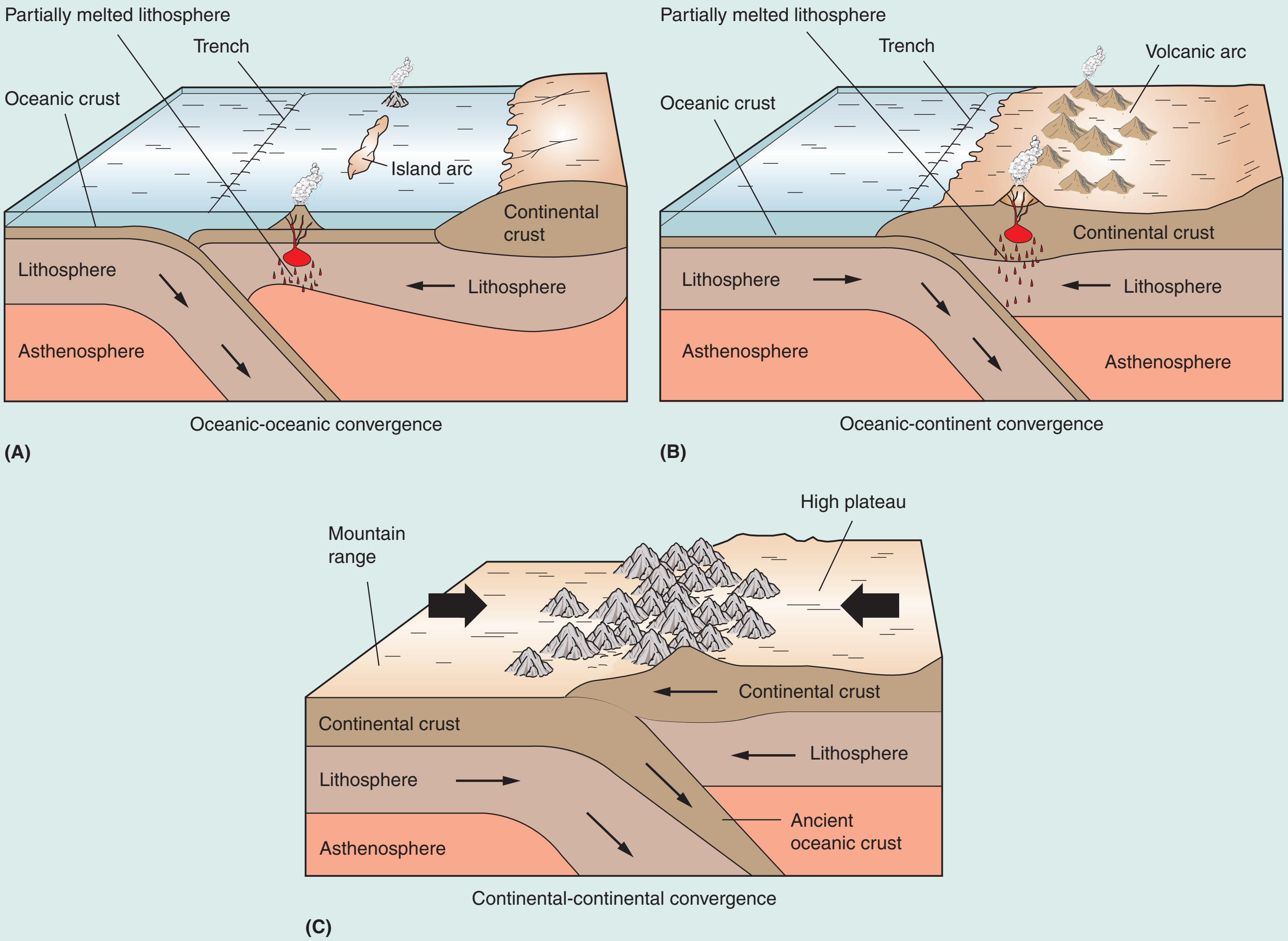


FIGURE 4-17 A model of a subduction zone. The Cascadia subduction zone and associated centers of volcanic activity. Modified from USGS.



Oceanic-oceanic convergence

Oceanic-continent convergence

Continental-continental convergence

FIGURE 4-18 Types of convergent plate boundaries. (A) and (C) Data from Tarbuck, E.J. and Lutgens, F.K. 2000. *Earth Science* 9th ed, Upper Saddle River, NJ: Prentice-Hall. Figure 7.13 (p. 194). (B) Courtesy of USGS/NPS..

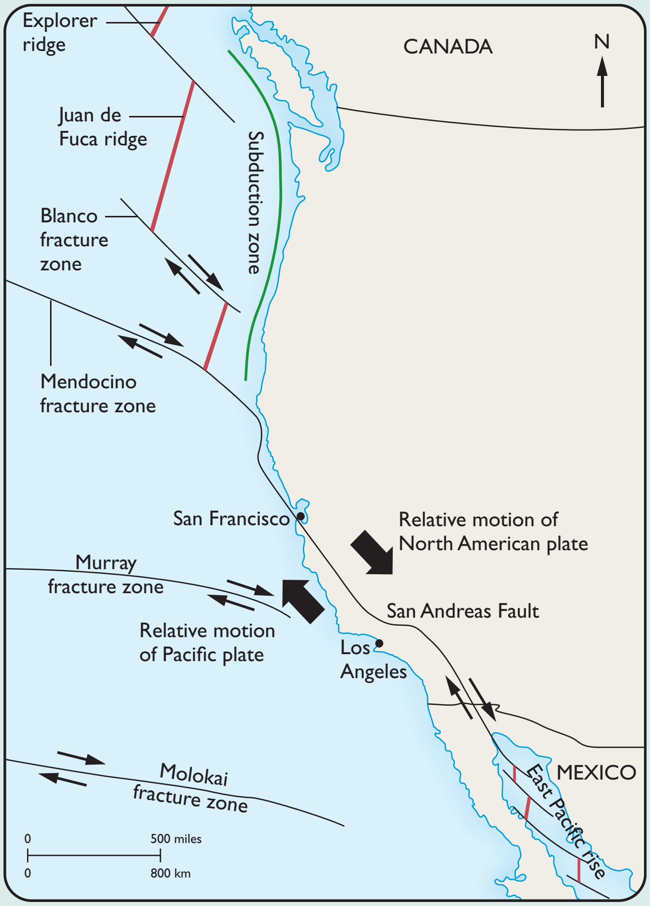


FIGURE 4-19 The San Andreas Fault system, a transform-fault boundary between the North American and Pacific Plates.

FIGURE 4-20 Two barges on the Saigon River in Vietnam, one with cargo, one without, float at different levels due isostatic equilibrium. © Pluff Mud Photography.

CASE STUDY

An Island Arc, a Subduction Zone, and a Great Tragedy: The 2004 Sumatra-Andaman Earthquake and Its Aftermath

Background © Hemera Technologies/AbleStock.com/Thinkstock. Title © iStockphoto/Thinkstock.

An online travel guide[1] describes Sumatra thusly:

> *"Anchored tenuously in the deep Indian Ocean, this giant island is still as wild and unpredictable as the Victorian-era jungle-seekers dreamed. Millennia of chaos erupting from the earth's toxic core or from the fierce ocean waves create and destroy in equal measure. When the earth and sea remain still, the past's death and destruction fertilise a verdant future."*

Located in western Indonesia, Sumatra is the sixth largest island in the world. Despite the "millennia of chaos erupting from the Earth's toxic core or from the fierce ocean waves," 50 million people call Sumatra home.

From a geological perspective, Sumatra lies near a convergent plate boundary. The Indian (also known as the Indo-Australian) Plate lies to the south and east. To the north and west is the Eurasian Plate (**Figure CS 1-1**). The Indian Plate moves northerly at a rate of about 40–50 mm/year (1.6–2 in/year). It subducts beneath a portion of the Eurasian plate (technically, the Burma microplate, on which also sit the Andaman and Nicobar Islands in the Bay of Bengal) creating the **Sunda Trench** as well as a large fault called an *interplate thrust*. This Sunda fault runs for approximately 5,500 km (3,300 mi).

These plates creep past each other until large portions of the plates lock or "get stuck" in some locations, building up tremendous forces. When these plates rupture, the stored force is released, resulting in an earthquake (detailed elsewhere in this text).

Although earthquakes along the Sunda fault and within both the subducting Indian and overriding Eurasian Plates are not uncommon, the massive earthquake that struck 60 km off the west coast of northern Sumatra on December 26, 2004 surprised geologists. The event, known as the **Sumatra-Andaman Earthquake**, and the resulting **tsunami**, enormous water waves generated when the seismic energy

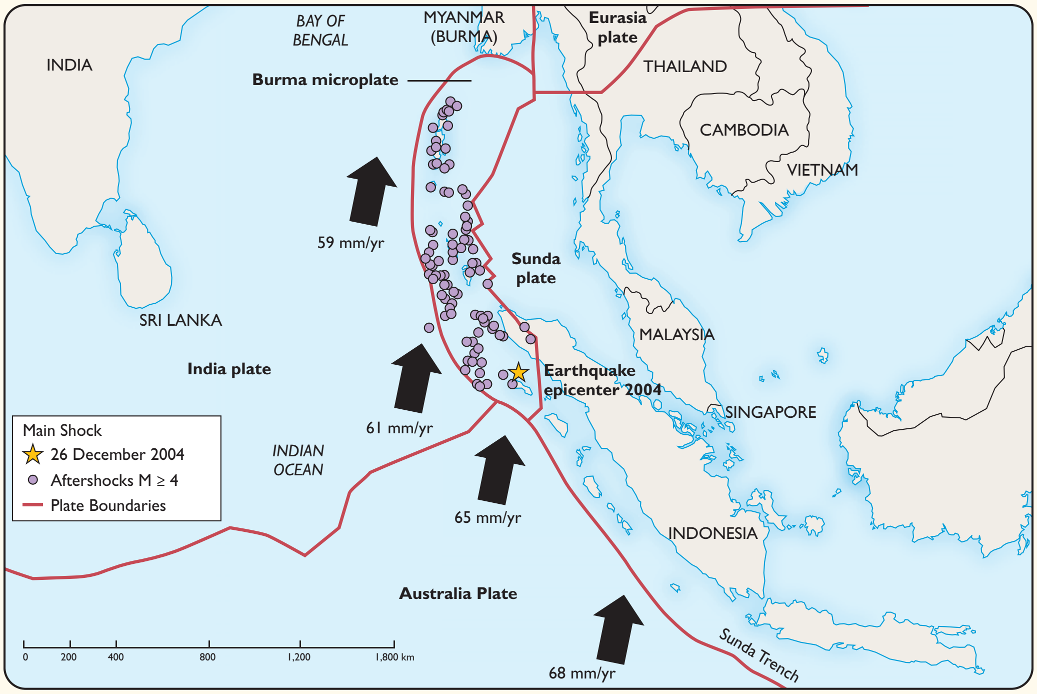


FIGURE CS 1-1 Tectonic setting for the 2004 Sumatra-Andaman Earthquake.

Continued ▸

released by the earthquake entered the ocean, killed 250,000 people in Indonesia, Thailand, India, Sri Lanka, and elsewhere around the Indian Ocean. It was one of the largest earthquakes ever recorded as well as one of the greatest natural disasters in human history.

The earthquake registered > 9.0 on the Richter scale, releasing energy said to be equivalent to that of 10,000 atomic bombs. The overriding Burma microplate was vertically displaced, elevating the seafloor by several meters and setting in motion the monstrous tsunami. Two "N-waves" traveling in opposite directions were generated, a local tsunami and a distant tsunami (**Figure CS 1-2**). The local wave traveled toward Indonesia, Thailand, and nearby islands, while the distant tsunami moved across the Bay of Bengal in the direction of India, and Sri Lanka, and was even detected by tide gauges along the Atlantic coast of North America from Nova Scotia to Florida. The height of the wave varied from 2 to 3 m along the African coast to 10 to 15 m at Sumatra.

Concept Check 4-7. If you could use one adjective to describe the geological setting of Sumatra, in light of this case study, what word would you choose? Explain your choice.

At locations of the tsunami's maximum impact, the force of the waves was so powerful that structures and people stood little chance (**Figure CS 1-3**). Along Sumatra's coastline, waves may have reached heights of 15 to 30 m over a distance of 100 km.

Further away, however, according to a report in *Science* magazine,[2] "areas with coastal [forest] were markedly less damaged than areas without." The trees referred to were mangroves, and they absorbed much of the energy of the waves, protecting the area landward of the mangrove forest. According to the report, mangrove area had been reduced before the tsunami (between 1980 and 2000) by 26% in the five countries most affected by the tsunami, from 5.7 to 4.2 million hectares (14.1–10.4 million acres) because of human activities that included aquaculture and development of resorts. Neil Burgess, a co-author of the study, stated,

> *"Just as the degradation of wetlands in Louisiana almost certainly increased Hurricane Katrina's destructive powers, the degradation of mangroves in India magnified the tsunami's destruction. Mangroves provide a valuable ecological service to the communities they protect."*

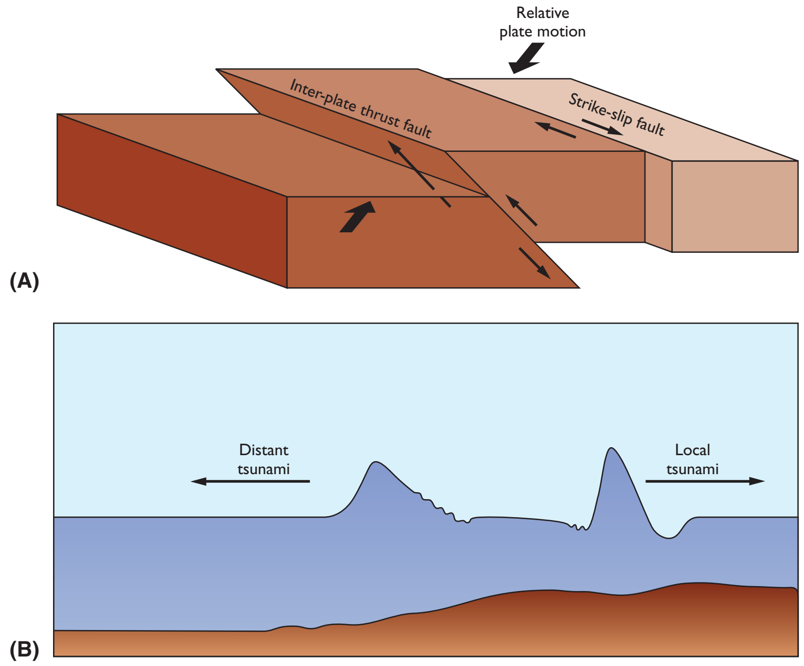


FIGURE CS 1-2 (A) Diagram of the type of vertical displacement of the Burma microplate that elevated the seafloor by several meters and set in motion the disastrous tsunami. (B) The resulting N-waves of the tsunami.

FIGURE CS 1-3 A view of the destruction caused by the 2004 Indonesian earthquake and tsunami. © Claudio Gallone/agefotostock.

Concept Check 4-8. Summarize the major points of this case study.

Value-added Question 4-1. The displacement of the fault occurred along a 1,200-km long segment. If the earthquake moved at a rate of 2.5 km/sec, how long (in minutes and seconds) did it take for the fault to propagate from its hypocenter (origin) to its extreme 1,200 km away?

Value-added Question 4-2. The initial velocity of the tsunami was 700 km/hr. Assuming that the tsunami maintained that speed (even though it slows in shallow water), how long would it take for it to reach: (A) India (approximate distance 2,000 km); (B) Sri Lanka (1,570 km); (C) Thailand (500 km); (D) Sumatra (60 km); (E) Myanmar (1,800 km); (F) Somalia (5,000 km); (G) Maldives (2,500 km)?

of the sediment is finding its way into the Indian Ocean, where it is building massive *submarine fans* (FIGURE 4-21).

The deformation of the continental crust north of the Himalaya extends at least 2,000 kilometers from the collision zone. Some of the planet's most destructive earthquakes have occurred along faults here.

Mantle Plumes and Hot Spots

FIGURE 4-22 shows the Hawaiian **island chain**. Island *chains* like Hawaii form as a result of movement of oceanic plates over **mantle plumes**. Plumes are believed to form due to abnormally high concentrations of heat that produce vertical, candle-flame shaped masses containing magma of basaltic composition. As they reach the surface they form *hot spots*. Magma rises to the surface mainly by convection, forms hot spots, and may punch holes in the overlying lithosphere, forming volcanic islands if the overlying lithosphere is oceanic.

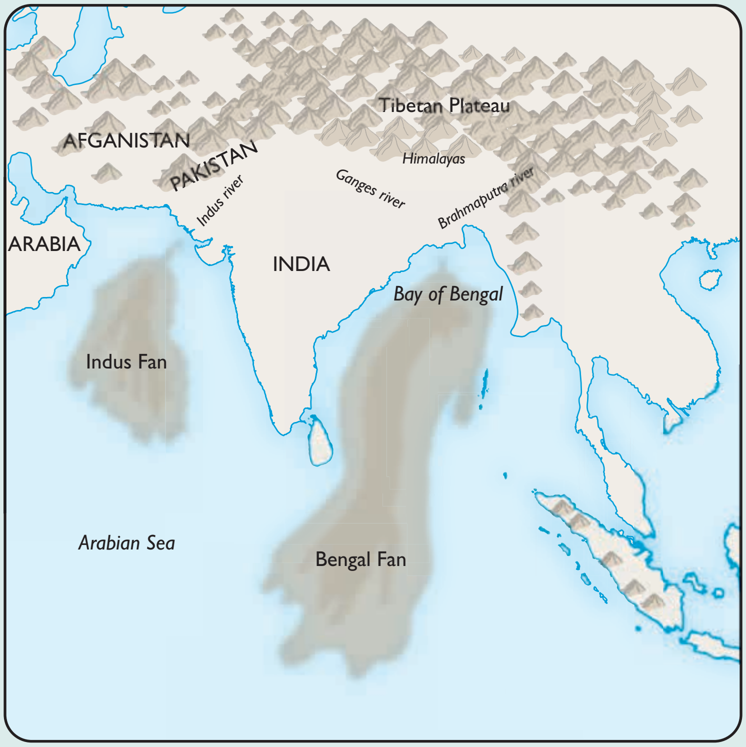


FIGURE 4-21 The Indus and Bengal submarine fans, formed of thousands of meters of sediment eroded at the Himalayan collision zone. The weight of the sediment depresses the oceanic crust in another example of isostatic adjustment.

Hot spots may also form along divergent boundaries. Iceland is formed by hot spot volcanism at the **Mid-Atlantic Ridge**. Hot spots under oceanic lithosphere produce volcanoes emitting mainly basalt lava and tephra (**tephra**, from the Greek for ash, describes volcanic rock fragments and lava of varying sizes that are explosively blasted into the air or lifted by hot gases). A good example of such a volcano is Hawaii's Mauna Loa, the world's largest volcano.

In an ocean, a *line* of volcanic islands formed as the oceanic plate passes over the hot spot, as contrasted with the *arc* of islands at a subduction zone (Figure 4-18). The orientation of the island chain traces the direction of plate movement. The Hawaiian Plume is presently situated immediately southeast of the Big Island of Hawaii, and, in addition to the active volcanoes on Hawaii, the plume is forming a new island called Loihi, presently entirely underwater (Figure 4-22).

Plumes may persist for tens of millions of years, and apparently stay near the same place in the mantle.

Volcanoes and Plate Tectonics

Volcanoes will be discussed in more detail elsewhere in this text. Geologists recognize *plate boundary volcanoes* and *hot-spot volcanoes*. The **plate tectonic setting** strongly influences magma type produced, which in turn determines viscosity (*viscosity* refers to internal resistance to flow and can thought of as a liquid's thickness) and ultimately risk, as we discuss elsewhere in this text.

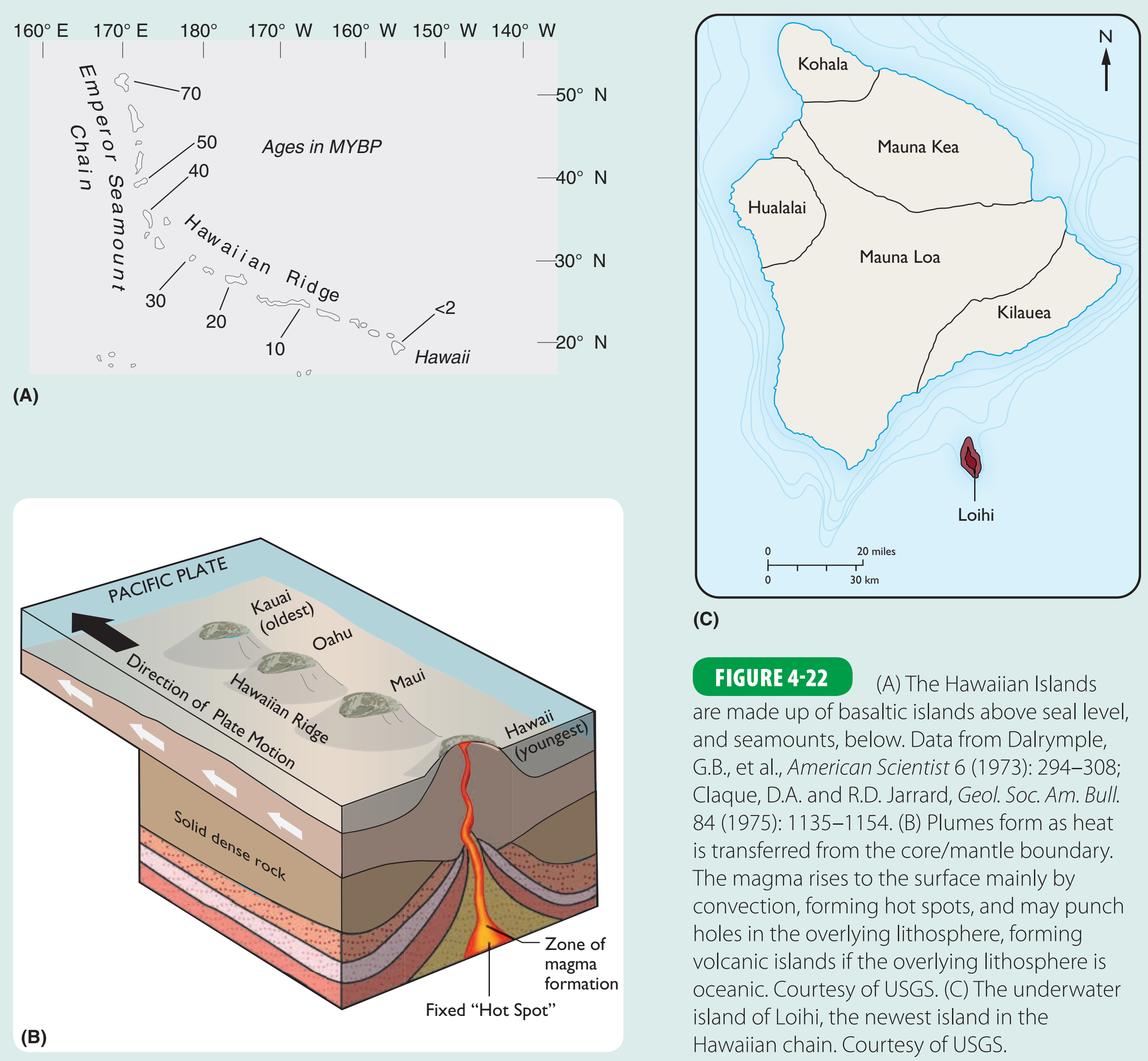


FIGURE 4-22 (A) The Hawaiian Islands are made up of basaltic islands above seal level, and seamounts, below. Data from Dalrymple, G.B., et al., *American Scientist* 6 (1973): 294–308; Claque, D.A. and R.D. Jarrard, *Geol. Soc. Am. Bull.* 84 (1975): 1135–1154. (B) Plumes form as heat is transferred from the core/mantle boundary. The magma rises to the surface mainly by convection, forming hot spots, and may punch holes in the overlying lithosphere, forming volcanic islands if the overlying lithosphere is oceanic. Courtesy of USGS. (C) The underwater island of Loihi, the newest island in the Hawaiian chain. Courtesy of USGS.

Plate Boundary Volcanoes

Plate boundary volcanoes can form at divergent and convergent boundaries.

Much volcanic activity occurs at divergent boundaries and at rift zones. Recall that partial melting of mantle peridotite produces basaltic magma. Because there is no continental (granitic) crust to contaminate this magma at mid-ocean ridges, basalt lava is overwhelmingly produced. Volcanoes of Iceland (**FIGURE 4-23**) are the most visible examples of these types, and they are mainly basalt.

Volcanoes of convergent boundaries form either at *ocean–ocean boundaries* or *ocean–continent boundaries.*

FIGURE 4-24 shows the Indonesian arc. These islands are made up largely of volcanic rocks. Island arc volcanoes derive their name from the broad curve of their volcanic islands. Indonesia, Japan, and the Aleutians are examples.

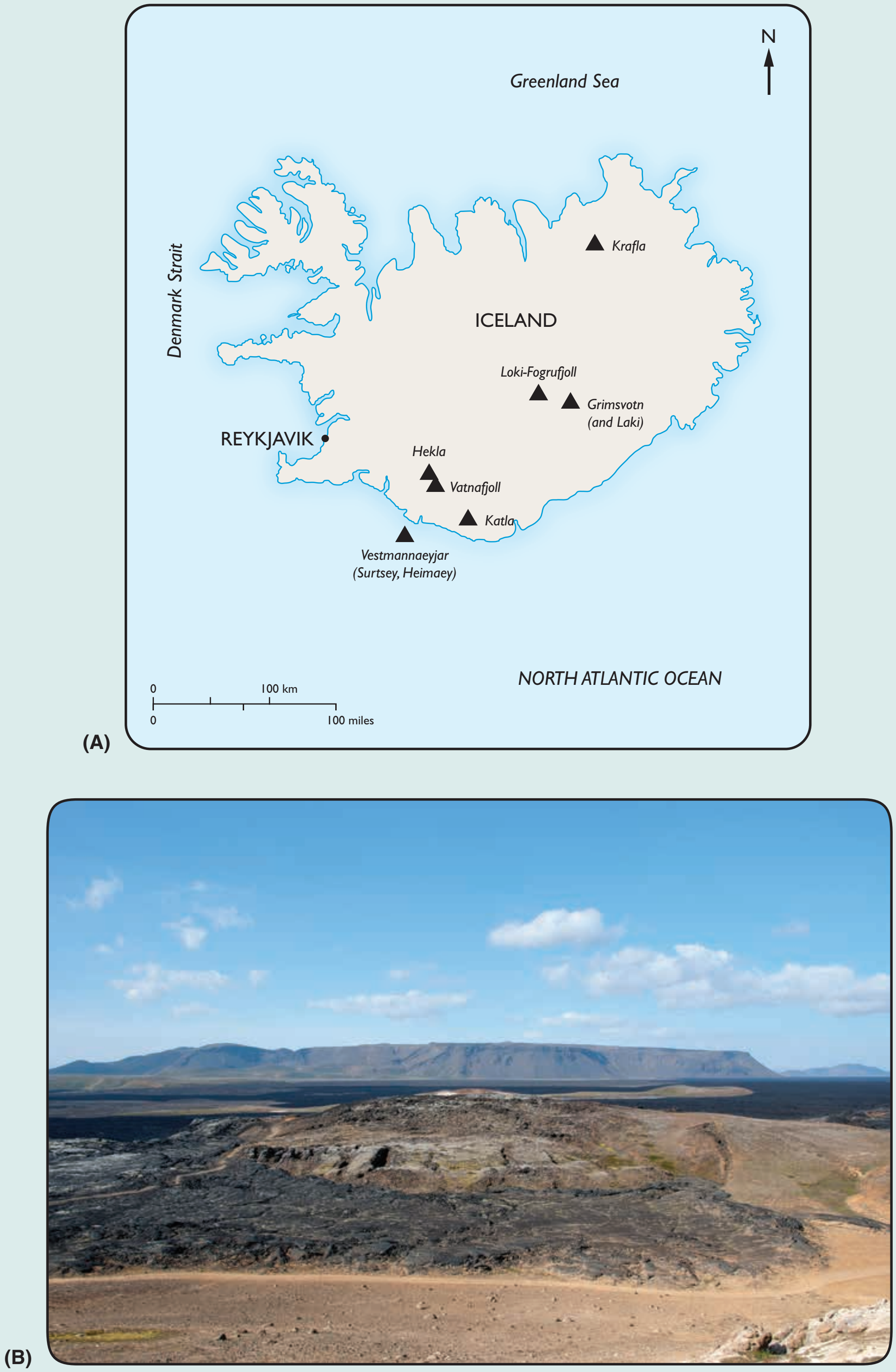


FIGURE 4-23 (A) Location of volcanoes of Iceland. Courtesy of USGS. (B) Photo of the volcano Krafla. © iStockphoto/Thinkstock.

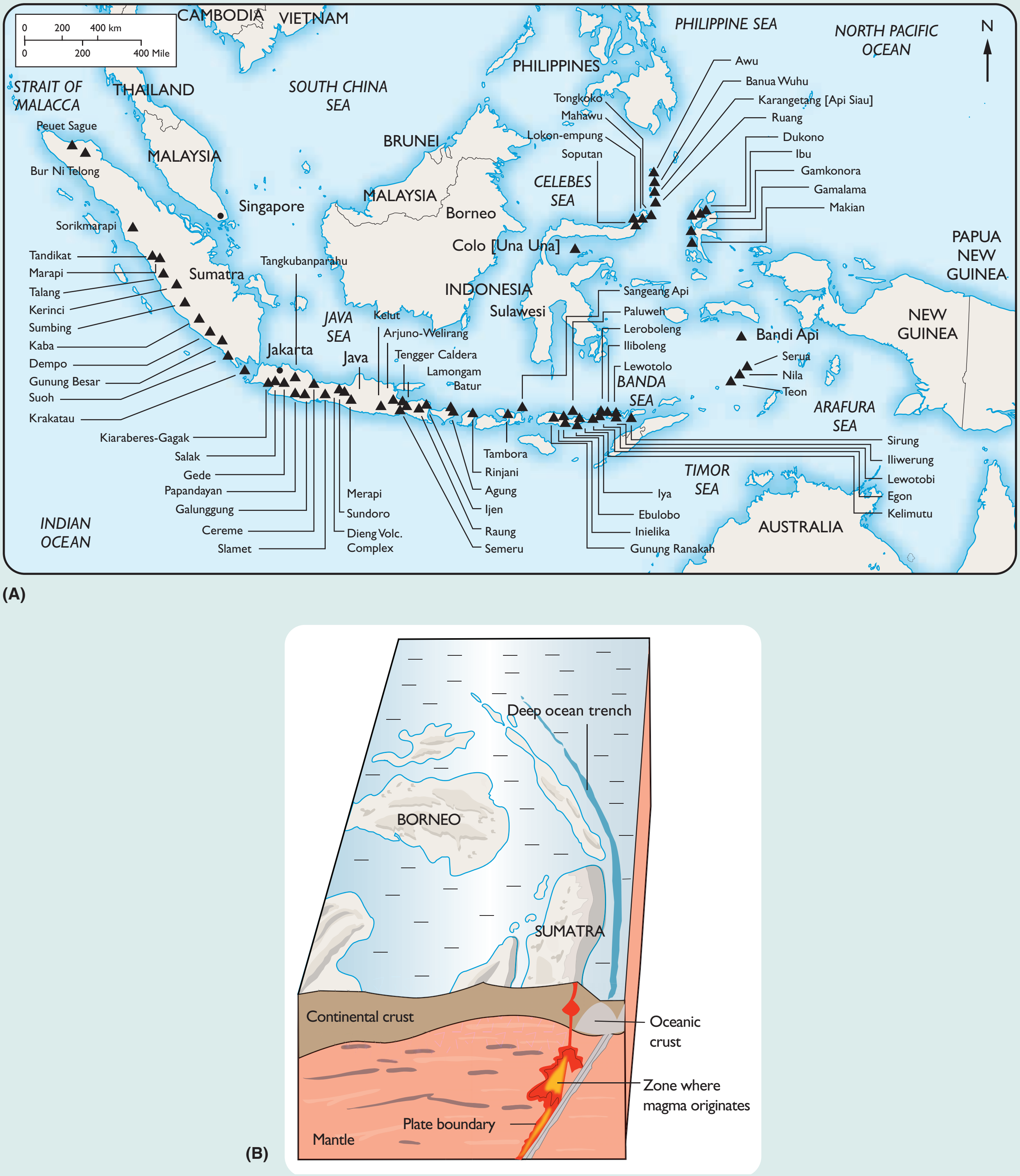


FIGURE 4-24 (A) The Indonesian Arc, showing some of the sites of active volcanoes. (B) Diagram depicting how these islands arc formed.

Island arc volcanoes are produced by the subduction of oceanic lithosphere as shown above. A wide variety of eruptive material (e.g., basalt, andesite, rhyolite, and compositions in between) can result from the partial melting of oceanic lithosphere as it is carried into the mantle.

Recent research has discovered that, counterintuitively, the pressure in some boreholes into the oceanic crust is higher at the sea *floor* than in the hole hundreds of meters below. This pressure differential can push seawater down into cooling basaltic rocks, hydrating them and altering their composition. This altered basalt can then undergo "dewatering" as it is subducted (**FIGURE 4-25**). The water driven off at high temperatures and pressures can melt overlying rocks. Eruptive products can be lava flows, pyroclastic flows (fast-moving mixtures of hot gas and rock fragments), and tephra eruptions. Compared to oceanic volcanoes, island arc volcanoes are much more dangerous, owing to their higher silica content.

The Cascades of the Northwestern United States, is an ocean–continent plate boundary. Volcanoes commonly form at ocean–continent plate boundaries, on the edges of continents. Ascending magma may be contaminated by assimilation of granitic continental crust through which it passes. This can result in a wide variety of lava and pyroclastic eruptions.

Concept Check 4-9. Write a few key terms that contrast divergent and convergent volcano types and processes. Which are most dangerous to humans? Why?

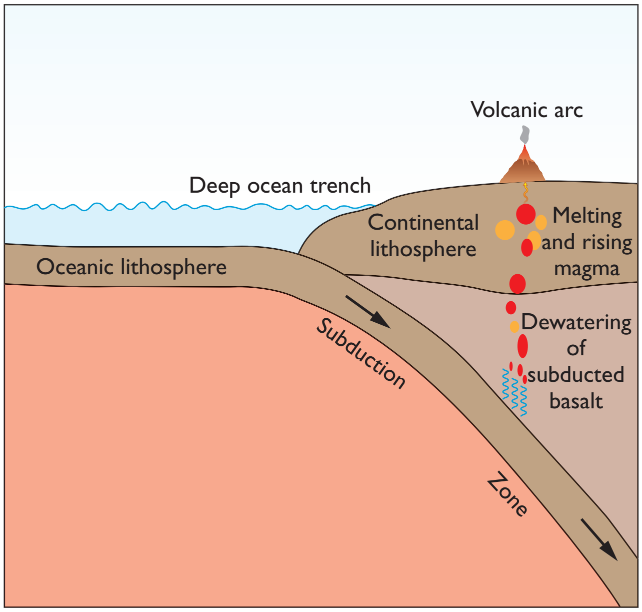


FIGURE 4-25 The dewatering of subducted basalt could induce melting in overlying rocks. Magmas of intermediate to silicic composition could result.

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CHAPTER SUMMARY

1. Because we don't have direct samples from boreholes into the Earth's center, we must content ourselves with making models of the interior based on our indirect evidence.
2. Geologists use hypotheses to explain some natural phenomenon, and then gather all evidence to test their hypotheses.
3. If the hypothesis is supported by evidence, geologists may elevate it to a theory.
4. A model of the Earth's interior shows the general internal structure, where interior boundaries are, what the states of matter are, and the composition of the interior, in as much detail as necessary.
5. We use evidence from the following sources to make a model of the Earth's interior. Seismic wave paths and velocities inside the Earth depend on the property of the material through which the waves pass. If we can track the wave path, we can put constraints on the nature of the material along its path. We have excellent knowledge of the composition and distribution of surface rocks. We also use evidence from meteorites. We have hundreds of drill holes and dredge samples of oceanic bedrock, and so we know its near-surface composition very well. We know the earth's average density is 5.52 g/cm^3. The physics of the Earth's rotation dictates that the densest material must be at the Earth's center. The existence and nature of the magnetic field puts limits on the possible composition and state of the planet's interior.
6. One of the most fundamental discoveries about the Earth was that the interior was composed of layers with recognizable boundaries.
7. Geologists divide the Earth into three layers: the crust (outermost material), an underlying mantle, and a core at the center. The core was found to consist of an inner solid portion and an outer liquid portion. The upper mantle was found to contain a zone near its top where seismic wave velocities were lower than above and below; this zone became known as the low-velocity zone, or asthenosphere, and is partially molten. The upper mantle is of peridotitic composition and the lower mantle is probably made up of densely packed oxide minerals.
8. Radioactivity refers to the decay of unstable atomic nuclei. Radioactive heat powers the global process we call plate tectonics. Three ways that heat can be transferred are: by conduction, by convection, and by radiation. Convection cells and plumes powered by radioactive decay are the means by which new oceanic bedrock is made, and new oceans may be formed in the process.
9. Plate tectonic theory holds that the Earth is covered by seven major rigid lithospheric plates and a number of smaller plates.
10. Plate tectonics explains the majority of the Earth's large-scale geologic structures and processes and has been called a Unifying Principle of Geology.
11. The theory of plate tectonics evolved from two older ideas, continental drift and seafloor spreading.
12. Plates move at a few centimeters a year.
13. The three types of plate boundaries are: divergent, convergent, and transform.
14. At convergent boundaries old oceanic lithosphere is recycled back into the mantle. A place where this happens is called a subduction zone.
15. In 2004 one of the Earth's most powerful earthquakes occurred at the subduction zone of the convergent Indian and Eurasian Plates. The quake and resulting tsunami killed 250,000 people in Indonesia, Thailand, India, Sri Lanka, and elsewhere around the Indian Ocean.

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16. Transform boundaries on continents are recognized by the presence of strike-slip faults like the San Andreas in California.
17. If two masses of continental lithosphere are brought together by plate motion at a subduction zone, a continent–continent collision eventually occurs.
18. Island chains like Hawaii are hypothesized to form as a result of movement of oceanic plates over mantle plumes.
19. Volcanoes can be classified as plate boundary volcanoes and hot-spot volcanoes. Island arc volcanoes are produced by the subduction of oceanic lithosphere. Continental volcanoes, like island arc volcanoes, are more dangerous than oceanic volcanoes, and may occasionally erupt with explosive and even cataclysmic force.

KEY TERMS

asthenosphere
basaltic
conduction
continental crust
continental drift
convection
convergent boundary
core
crust
density
discontinuity
divergent boundary
fault
heat transfer
hypothesis
igneous
island arc
island chain
isostasy
lithosphere
magma
magnetometer
mantle
mantle plume
metamorphic
Mid-Atlantic ridge
model
ocean trench
oceanic crust
paleomagnetism
Pangaea
Panthalassa
peridotite
plate
plate boundaries
plate tectonics
plate-tectonic setting of volcanoes
pyroclastic
radiation
radioactivity
seafloor spreading
sedimentary
seismic wave
states of matter
subduction zone
Sumatra-Andaman Earthquake
Sunda Trench
tephra
theory
transform boundary
trench
tsunami

REVIEW QUESTIONS

1. A hypothesis supported by experiments and observation can be elevated to a
   a. paradigm.
   b. fact.
   c. proof.
   d. theory.

2. The Earth's average density is closest to
   a. 5.5.
   b. 1.
   c. 55.
   d. 10.

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3. The two commonest kinds of meteorites are made of
    - **a.** uranium-lead and iron-nickel.
    - **b.** uranium-lead and silicate minerals.
    - **c.** silicate minerals and potassium-sulfur.
    - **d.** silicate minerals and iron-nickel.

4. Which is true about our knowledge of the Earth's interior?
    - **a.** We have direct drill samples through the mantle.
    - **b.** We have direct drill samples of the outer core.
    - **c.** We have direct drill samples of the outer few km only.
    - **d.** We have no direct drill samples of oceanic sediments, only the continents.

5. Zones within the Earth where seismic waves abruptly change velocity are called
    - **a.** discontinuities.
    - **b.** attenuated zones.
    - **c.** continuities.
    - **d.** batholiths.

6. Which is the most accepted model of the Earth's core?
    - **a.** The inner core is liquid and the outer core solid.
    - **b.** The inner core is liquid and the outer core gaseous.
    - **c.** The inner core is solid and the outer core is liquid.
    - **d.** The entire core is solid, according to magnetic field data.

7. Another name for the low-velocity zone in the upper mantle is
    - **a.** the discontinuity.
    - **b.** the lithosphere.
    - **c.** the ophiolite sequence.
    - **d.** the asthenosphere.

8. The composition of the upper mantle is most nearly which of the following?
    - **a.** peridotite
    - **b.** basalt
    - **c.** granite
    - **d.** iron-nickel alloy

9. Heat transfer occurs in three ways:
    - **a.** conduction, induction, and radioactivity.
    - **b.** conduction, convection, and radiation.
    - **c.** subduction, attenuation, and shear.
    - **d.** shear, transform, and divergence.

10. Plate motion, powered by radioactive decay, occurs at an average rate of
    - **a.** a few km/year.
    - **b.** a few meters/year.
    - **c.** a few centimeters/year.
    - **d.** a few nanometers/year.

11. Which of the following is considered a unifying principle of geology?
    - **a.** evolution
    - **b.** continental drift
    - **c.** seafloor spreading
    - **d.** basalt
    - **e.** the principle of radiometric dating

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12. Evidence for continental drift includes all of the following except
    - **a.** the jigsaw puzzle nature of continents.
    - **b.** the presence of the remains of early humans on Africa and South America.
    - **c.** the presence of the late Paleozoic fossil plant *Glossopteris* on India, Australia, South Africa, and South America.
    - **d.** the contiguous distributions of fossil reptiles across ocean basins.
13. In the late 1950s-early 1970s, paleomagnetism showed
    - **a.** that the Earth's poles periodically reversed.
    - **b.** that all rocks are magnetic.
    - **c.** that seafloor is produced at deep sea trenches and consumed at mid-ocean ridges.
    - **d.** none of the above.
14. The theory of seafloor spreading was confirmed in the 1960s by
    - **a.** magnetic striping parallel to and symmetrical around the ocean ridges.
    - **b.** current weather patterns across the planet.
    - **c.** advances in molecular biology.
    - **d.** all of the above.
15. Plates are
    - **a.** segments of the asthenosphere.
    - **b.** segments of the lithosphere.
    - **c.** segments of the biosphere.
    - **d.** formed at subduction zones.
16. New oceans form at a __________ type of plate boundary.
    - **a.** divergent
    - **b.** subduction/convergent
    - **c.** aseismic
    - **d.** discontinuous
17. At convergent boundaries, older lithosphere is
    - **a.** recycled back into the mantle.
    - **b.** converted to core.
    - **c.** converted to peridotite.
    - **d.** all of the above.
18. When plates slide laterally past each other,
    - **a.** transform or shear boundaries result.
    - **b.** no earthquakes occur.
    - **c.** earthquakes are all deep (>500 km) focus.
    - **d.** earthquakes occur, but none has to date caused damage.
19. Island *chains* like Hawaii are hypothesized to form as a result of movement of oceanic plates
    - **a.** over mid-ocean ridges.
    - **b.** over old continents.
    - **c.** over mantle plumes.
    - **d.** away from each other at a divergent boundary.
20. Island arc volcanoes are produced by
    - **a.** the subduction of oceanic lithosphere.
    - **b.** movement of plates over hot spots.
    - **c.** continent–continent collisions.
    - **d.** any of the above.

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21. Which is/are accurate contrasts between continental and oceanic volcanoes?
    - **a.** Continental volcanoes are more explosive and dangerous than oceanic volcanoes.
    - **b.** Oceanic volcanoes tend to be basalt, while continental volcanoes can vary in composition.
    - **c.** Ascending basaltic magma under continents can melt continental crust and change composition.
    - **d.** All of the above are correct.
    - **e.** None of the above is correct.

22. Doubling the thickness of the continental crust by formation of the Himalayas causes them to rise, and piling sediment derived from weathering of the Himalayas on the north Indian Ocean causes it to sink. These are examples of the Principle of
    - **a.** Uniformity.
    - **b.** Plate Activity.
    - **c.** Isostasy.
    - **d.** Discontinuity.

FOOTNOTES

[1] Introducing Sumatra. Retrieved August 19, 2012 from http://www.lonelyplanet.com/indonesia/sumatra

[2] Danielsen, F., et al. 2005. The Asian tsunami: A protective role for coastal vegetation. *Science* 310: 643.