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Plate Tectonics: A Revolution in Geology

This we know. The Earth does not belong to us; we belong to the Earth.

—attributed to Chief Seattle

It is my opinion that the Earth is very noble and admirable . . . and if it had continued an immense globe of crystal, wherein nothing had ever changed, I should have esteemed it a wretched lump of no benefit to the Universe.

—Galileo Galilei

OBJECTIVES

In this chapter you will learn

- what physical and historical geology are and the differences between them;
- how the theory of plate tectonics revolutionized geology;
- how scientists gathered evidence to support the theory of plate tectonics;
- how internal processes shape the surface of the Earth and make it a dynamic place to live.

1 UNDERSTANDING THE EARTH

Geology is the scientific study of the Earth. Geology is a young science; it has existed as a modern scientific discipline for just over 200 years. The study of the Earth is traditionally divided into two broad subject areas: physical geology and historical geology. **Physical geology** concerns the processes that operate at or beneath the surface of the Earth and the materials on which those processes operate. Some examples of geologic processes are mountain building, volcanic eruptions, river flooding, earthquakes, and the formation of ore deposits. Some examples of geologic materials are minerals, rocks, soils, lava, and water.

Historical geology concerns geologic events that occurred in the past. These events can be read from the rock record. Historical geologists try to answer questions such as when the oceans formed, why the dinosaurs died out, when the Rocky Mountains rose, and when the first trees appeared. Historical geology helps us establish a chronology of events in Earth history and gives us a context for understanding our present-day environment.

There are many more specialized areas of study within the traditional domains of physical and historical geology. For example, volcanologists study volcanoes and eruptions; seismologists study earthquakes; mineralogists study minerals and crystals; paleontologists study fossils and the history of life on the Earth; structural geologists study how rocks break and bend; economic geologists study the formation and occurrence of valuable ore deposits. This specialization is needed because geology encompasses such a broad range of topics.

Geologists are scientists who make a career out of the scientific study of the Earth. Yet to a certain extent we are all geologists. Everyone living on this planet relies on resources from the Earth: water, soil, building stones, metals, fossil fuels, gems, plastics (made from petroleum), ceramics (made from clay minerals), salt (the mineral halite), and many others. We are affected by geologic processes every single day we spend on the surface of this dynamic planet. By learning as much as we can about these processes, we can become better-informed, more responsible caretakers of our home planet.

Name three examples of geologic processes. Try to think of at least one example that was not mentioned in the text.

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Answer: Examples in the text are mountain building, volcanic eruptions, river flooding, earthquakes, and the formation of ore deposits. Some other examples are groundwater movement, oil and coal formation, evaporation, and erosion. Can you think of any more?

Name three examples of geologic materials. Try to think of at least one example that was not mentioned in the text.

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Answer: Examples in the text are minerals, rocks, lava, and water. Some other examples are soil, magma, glacial ice, and natural gas. Can you think of any more?

2 GEOLOGY THEN AND NOW: A SCIENTIFIC REVOLUTION

Even a science as young as geology can have a revolution, and that is what happened in the 1960s. At that time, a brand-new theory emerged and completely changed our understanding of geologic processes. The tools, the methods, and even the language of geology changed as a result of that scientific revolution. If you studied geology prior to the 1960s, you may remember some terms that are no longer in use today. Terms such as "eugeosyncline" and "miogeosyncline" were used to describe topographic features of the Earth's surface that geologists observed but could not explain. With the advent of the theory of plate tectonics, these features took on new meaning. Consequently, geologists began using new terms to describe them. This book will help you learn the vocabulary we use to describe our current understanding of the Earth.

This first chapter—and, indeed, much of the rest of this book—concerns the plate tectonic revolution and how it has informed and transformed our understanding of the Earth. But geology is currently undergoing another, more subtle revolution. This revolution is driven by the ability of scientists to observe and collect information about the Earth as a whole planet, using instruments mounted on satellites. This ability is quite new; remember that no one had ever seen a picture of the whole Earth until the 1960s, when the first photograph was taken of Earth from space.

Satellite images and data collected from outer space provide a scientific foundation for our study of the Earth as an integrated system. **Earth system science,** as this approach is called, is not new in philosophy, but its tools and techniques are very new. These tools are used in a wide range of applications, from weather forecasting to the monitoring of changes in sedimentation rates, measuring the flow of polar ice, locating mineral resources, documenting the extent of oil spills, tracking depletion of stratospheric ozone, and many others. Through Earth system science, geologists are contributing to our understanding of the Earth as a whole, how the Earth changes over time, and the impacts of human actions on the Earth system.

Name at least three applications of Earth system science.

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Answer: Examples in the text are weather forecasting, monitoring changes in sedimentation rates, measuring the flow of polar ice, locating mineral resources, documenting the extent of oil spills, and tracking the depletion of stratospheric ozone. Can you think of any more?

3 GEOLOGY BEFORE PLATE TECTONICS

During the 1800s, people favored the idea that the Earth, originally a molten mass, had been cooling and contracting for centuries. Scientists argued that mountain ranges full of folded rocks were expressions of the contraction and shrinkage of the Earth's interior (if the crust didn't contract as much as the interior, it would fold and crumple like the wrinkled skin of a dried prune). Contraction did appear to explain some features of the Earth's surface, but it could not explain the shapes and positions of the continents. Nor did it explain features like great rift valleys, clearly caused by stretching rather than by contraction.

At the beginning of the twentieth century, scientists discovered that the Earth's interior is heated by the decay of naturally occurring radioactive elements. This suggested that the Earth might not be cooling but rather heating up, and therefore expanding. A smaller Earth might once have been covered mostly by continents. As the Earth expanded, the continents would crack into fragments, and eventually the cracks would grow into oceans. The expanding Earth hypothesis did explain the apparent fit between the coastlines of Africa and South America, which look as if they have been ripped apart from each other. But there are other features that this hypothesis did not easily account for, such as folded mountain ranges formed by compression.

To get around the flaws in the expansion and contraction hypotheses, geologists began to search for other ways of explaining the shapes and positions of the continents, oceans, and mountain chains. By the middle of this century, all reasonable suggestions seemed to have been exhausted; the time was ripe for a totally new approach. This approach turned out to be **plate tectonics**—the theory that the continents are carried along on huge slabs, or **plates,** of the Earth's outermost layer. In some places the plates are slowly colliding, forming compressional features like huge mountain ranges. In other places the plates are moving apart, forming expansional features like great rift valleys. The theory of plate tectonics provided, for the first time, a coherent, unified explanation for *all* of these features of the Earth's surface.

What was wrong with the "contracting Earth" hypothesis?

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Answer: It did not adequately explain the shapes and positions of the continents, nor did it explain features like great rift valleys, which appear to have been caused by stretching.

What was wrong with the "expanding Earth" hypothesis?

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Answer: It did not adequately explain features such as folded mountain ranges formed by compression.

4 CONTINENTAL DRIFT AND THE STORY OF WEGENER

This chapter tells the story of how the theory of plate tectonics was conceived and developed and eventually came to be accepted. The modern part of the story began in the early 1900s with a German meteorologist named Alfred Wegener, who had some controversial ideas about the shapes and positions of the continents.

In 1910, Wegener began lecturing and writing scientific papers about continental drift. His **continental drift** hypothesis suggested that the continents have not always been in their present locations but instead have "drifted" and changed positions. Wegener's idea was that the continents had once been joined together in a single "supercontinent," which he called **Pangaea** (pronounced "pan-JEE-ah"), from Greek words meaning "all lands." He suggested that Pangaea had split into fragments like pieces of ice floating on a pond and that the continental fragments had slowly drifted to their present locations.

Wegener presented a great deal of evidence in support of the continental drift hypothesis. Nevertheless, his proposal created a storm of protest in the international scientific community. Part of the problem was that geologists simply could not envision how the continents could move around. Another part of the problem was that geologists had to be convinced that the evidence that the continents had once been joined was truly conclusive. Let's look at some of the evidence for continental drift, so you can judge for yourself. Notice that no single piece of evidence is conclusive on its own. It took several decades and the weight of all this evidence (and more) to finally convince geologists that continental drift really happens.

What was the name of the "supercontinent" proposed by Alfred Wegener?

Answer: Pangaea.

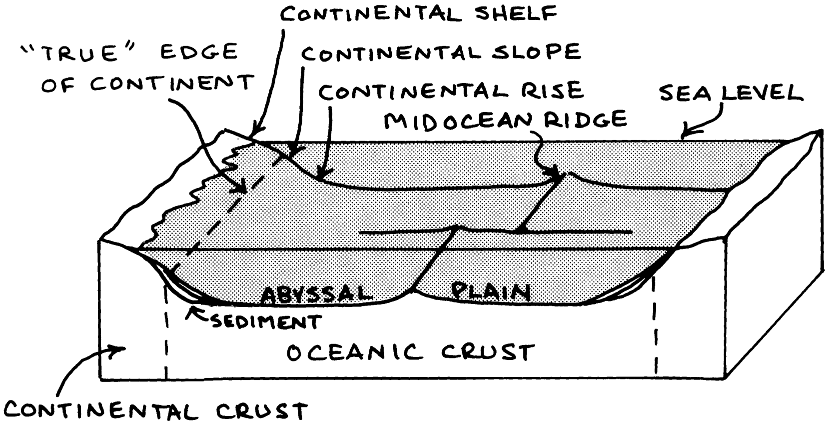
5 EVIDENCE FROM COASTLINES

Look at a map of the world. The Atlantic coastlines of Africa and South America seem to match, almost like puzzle pieces. The southern coast of Australia similarly seems to match part of the coast of Antarctica, and the same is true of some other continental coastlines. Is this apparent fit an accident, or does it support the hypothesis that the continents were once joined together?

To answer the question of whether continents were once joined, we must first recognize that the edge of the land—that is, the shoreline—usually isn't the true edge of the continent. To find the true edge of a continent, we need to locate the place where the rocks of the continent—mostly made of granite—meet the rocks of the ocean floor—mostly made of basalt. (You will learn more about these two important rock types in chapter 5.)

Along a noncliffed shoreline, such as the Atlantic coasts of North America, South America, and Africa, the land usually slopes very gently toward the sea (Figure 1.1). This gently sloping land is called the **continental shelf.** At the edge of the continental shelf there is a sharp drop-off to the steeper **continental slope.** At the bottom of the steep continental slope, the land begins to level off again; this is the **continental rise,** which marks the transition to the flat ocean floor, the **abyssal plain.** The actual place where the granitic rocks of the continent meet the basaltic rocks of the ocean floor is usually covered by sand, mud, and other loose rock particles. The actual shape of the shoreline depends on sea level, the presence or absence of cliffs, and the details of the topography of the continental shelf in any particular locality. Thus, the actual transition from continent to ocean may (or may not) be underwater.

So, how do we identify the true edge of a continent? Usually the edge of a continent is defined as being halfway down the steep continental slope. When we try to fit the continents together, we fit them along this line rather than along the present-day coastline. When we fit Africa and South America together in this way, the result is remarkable (Figure 1.2). In the "best-fit" position, the average gap or overlap between the two continents is only 90 kilometers (km) (about 56 miles



THE EDGE OF THE CONTINENT

Figure 1.1

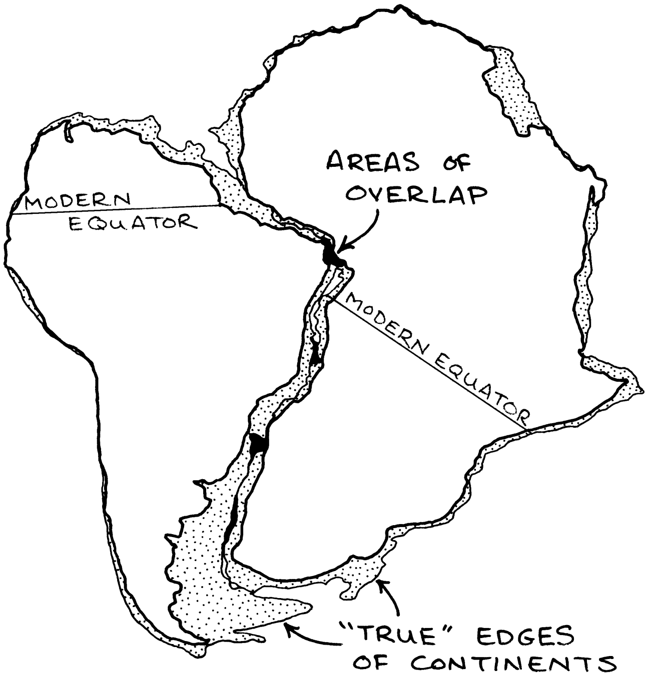


Figure 1.2

[mi]). (Note that 1 kilometer ≈ 0.62 miles; see Appendix 1 for more about units, conversions, and abbreviations.) Furthermore, the most significant overlapping areas consist of rocks that were formed *after* the time when the continents are thought to have split apart. This strongly suggests that Africa and South America were once joined.

Sketch and neatly label a diagram showing the transition from continent to ocean. Show how the slope of the land changes, and label all of the topographic features. On your diagram, indicate the "true" edge of the continent.

Answer: Refer to Figure 1.1.

6 EVIDENCE FROM ROCKS

If Africa and South America were once joined, one would expect to find similar geologic features on both sides of the join. Such correlations provided some of the most compelling evidence presented by Wegener in support of the continental drift hypothesis. However, matching the geology of rocks on opposite sides of an ocean is more difficult than you might imagine. Rock-forming processes never cease. Some rocks formed before the continents were joined, some while they were joined, others during the splitting of the continents, and still others after they separated. How can we tell which rocks are significant in trying to find a match between the continents?

A logical starting point is to see if the ages and orientations of similar rock types match up across the ocean. In Wegener's time, geologists did not have sophisticated tools for determining the exact age of a rock. But now we do have such tools, and we know that there are strong similarities in the ages of rocks across the oceans. The match is particularly good between rocks about 550 million years old and older in northeast Brazil and West Africa, but there is not a good match for younger rocks. This suggests that the two continents were joined together for some period of time prior to 550 million years ago, and they subsequently split apart.

We can also look for continuity of geologic features such as mountain chains. If we rejoin the continents as they would have been in the supercontinent Pangaea, mountain belts of similar ages seem to line up. For example, the oldest portions of the Appalachian Mountains, extending from the northeastern part of the United States through eastern Canada, match up with the Caledonides of Ireland, Britain, Greenland, and Scandinavia. A younger part of the Appalachians lines up with a mountain belt of similar age in Africa and Europe. These and other bedrock features that match up across the oceans are strong evidence that the continents were once joined together.

Another geologic feature that matches across continental joins is the deposits left by ancient ice sheets. These are similar to deposits left by recent glaciers in

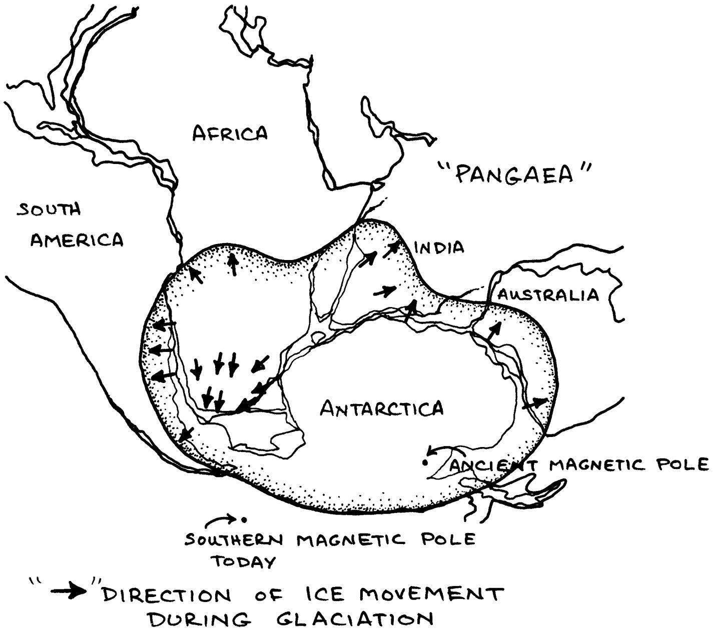


Figure 1.3

Canada, Scandinavia, and the northern United States. In South America and Africa there are very thick glacial deposits. The deposits are the same age, and they match almost exactly when the continents are "moved back together." As glacial ice moves, it cuts grooves and scratches in underlying rocks and produces folds and wrinkles in soft sediments. Such features provide evidence of the direction the ice was moving during the glaciation. When Africa and South America are moved back together, the grooves and scratches show that the ice was radiating outward from the center of a former ice sheet (Figure 1.3). It's hard to imagine how such similar glacial features could have been created if the continents had not once been joined together. Africa and South America must also have had similar climates during this period, colder than their present-day climates. This suggests that they were not in their present equatorial locations. In fact, the southern portion of Pangaea was most likely close to what was then the South Pole.

How can the ages of rocks provide evidence that two continents—now separated from each other by an ocean—were once joined?

Answer: If the continents were once joined, we would expect to find rocks of similar type and age on either side of the ocean. There are strong similarities in rocks about 550 million years old and older in northeast Brazil and West Africa. This suggests that the two continents were joined together for some period of time prior to 550 million years ago.

7 EVIDENCE FROM FOSSILS

If Africa and South America were joined at one time, with the same climate and matching geologic features, then they also should have hosted similar plants and animals. To check this, Wegener turned to the fossil record. This revealed that there were communities of plants and animals that appear to have evolved together until the time of the splitting apart of Pangaea, after which they evolved separately.

Wegener pointed to specific fossils found in matching areas across the oceans. One example he used was an ancient fern, *Glossopteris,* whose fossilized remains have been found in southern Africa, South America, Australia, India, and Antarctica. Could the seeds of this plant have been carried from one location to another across the oceans? Probably not. The seeds of *Glossopteris* were large and heavy, and could not have been carried very far by wind or water currents. This fern flourished in a cold climate; it would not have thrived in the warm present-day climates of the continents where its fossil remains are found. This, too, suggests that the continents once had similar, colder climates.

There are other examples as well. The fossilized remains of *Mesosaurus,* a small reptile, are found both in southern Brazil and in South Africa. The types of rocks in which the fossils are found are very similar. *Mesosaurus* did swim, but was probably too small to swim all the way across the ocean. Fossilized remains of specific types of earthworms also occur in areas that are now widely separated. How could they possibly have migrated across the oceans? The landmasses in which they lived must once have been connected.

How did Wegener use *Glossopteris* to support the hypothesis of continental drift?

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Answer: Fossils of *Glossopteris,* an ancient fern, have been found in similar rocks in southern Africa, South America, Australia, India, and Antarctica—locations that are now widely separated by oceans. Its seeds were large and heavy and could not have been transported very far by wind or water. This suggests that the areas where *Glossopteris* fossils are now found must once have been joined together.

8 THE MISSING CLUE: PALEOMAGNETISM

Wegener and his supporters gathered more and more evidence in support of continental drift, but many scientists remained unconvinced. Wegener died in 1930 without seeing the end of the debate, which continued after his death. A turning point occurred in the 1950s through the study of **paleomagnetism,** ancient magnetism preserved in rocks. When lava cools and solidifies into rock, it becomes magnetized and takes on the **polarity**—the north-south directionality—of the Earth's magnetic field at that time. Just as a free-swinging magnet today will point toward today's magnetic north pole, so too, does a rock's paleomagnetism act as a pointer toward the location of the Earth's magnetic north pole at the time of rock formation.

In the 1950s, geologists studying the paleomagnetism of rocks from different localities found evidence suggesting that the Earth's magnetic poles had wandered all over the globe for at least the past several hundred million years. They plotted the pathways of the poles on maps, and referred to the phenomenon as **apparent polar wandering** (Figure 1.4). Geologists were puzzled by this evidence. They knew that it was extremely unlikely that the magnetic poles themselves had moved. Instead they concluded, somewhat reluctantly, that it must have been the continents themselves that had moved, carrying their magnetic rocks with them.

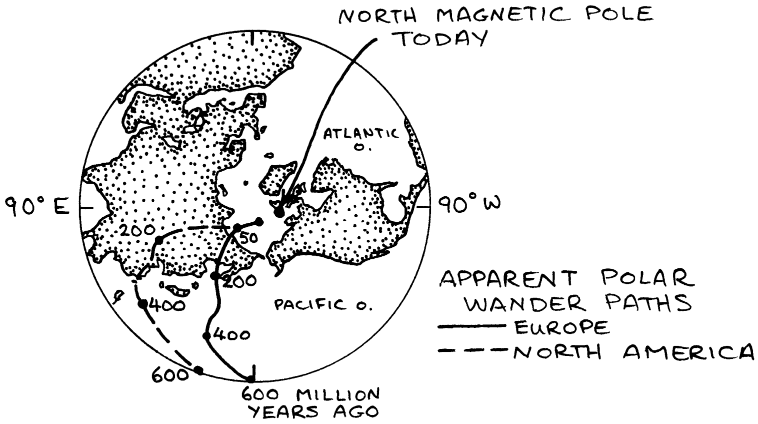

Figure 1.4

What is polarity?

Answer: The north-south directionality of the Earth's magnetic field.

9 SEAFLOOR SPREADING

The new evidence from paleomagnetism helped revive the hypothesis of continental drift. But many scientists were still holding out for a final piece of evidence that would demonstrate conclusively that a supercontinent had actually split apart and seas had flowed into the widening rift. They were trying to envision a mechanism whereby the seafloor could actually split open. This evidence finally appeared, but not until the early 1960s—three decades after Wegener's death.

Oceanographers measuring the paleomagnetic properties of rocks of the Atlantic Ocean floor were astonished to find a repeating series of rocks with alternating magnetic polarities: one stripe of rock with the same polarity (same magnetic north pole) as the Earth's present-day magnetic field, and the next stripe with the opposite polarity (north and south magnetic poles reversed). Scientists call these **normal** and **reversed magnetic polarities.** The stripes are hundreds of kilometers long, and they are exactly symmetrical on either side of the midocean ridge that runs down the middle of the Atlantic Ocean. In other words, if you could fold the seafloor in half along the midocean ridge, the pattern of alternating paleomagnetic stripes on either side would match exactly.

What could this possibly mean? At first, scientists were mystified by these symmetrical patterns of magnetic stripes in seafloor rocks. Then two groups of geologists, working independently, came up with the same explanation. They proposed that the seafloor had split apart along the midocean ridge and that the rocks on either side were moving away from the ridge (Figure 1.5). As the rocks spread apart, lava from below welled up into the crack, solidifying into new volcanic rock on the seafloor. When the molten lava solidified, it took on the magnetic polarity of the Earth at that time. Over time, the spreading seafloor acted like a conveyor belt, carrying the newly magnetized rock away from the centerline of the ridge in either direction. This process came to be known as **seafloor spreading.** The discovery of seafloor spreading was probably the single most powerful piece of evidence in support of the hypothesis of continental drift.

Geologists have shown that the ages of seafloor rocks increase with distance from the midocean ridge. The youngest rocks are located along the centerline of the ridge, where new lava rises through the crack to the seafloor. The farther the rocks have moved from the ridge, the older they are. Every half-million years or so, for reasons that are not entirely understood, the Earth's magnetic field reverses itself—north becomes south, and south becomes north. (This is discussed in further detail in chapter 3.) As magnetic reversals occurred in the past, the changing polarities were recorded in newly forming rocks along the midocean ridge. The result was symmetrical stripes of rock with alternating polarities—normal,

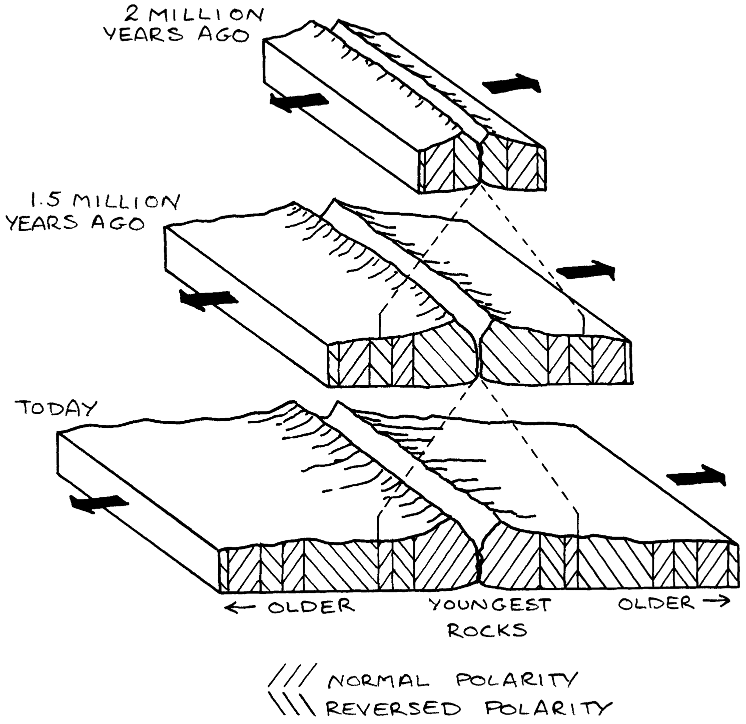

Figure 1.5

reversed, normal, reversed. This final piece of evidence convinced the great majority of geologists that seafloor spreading had indeed occurred and that the continents had drifted from their original locations.

What is the difference between a rock with normal paleomagnetic polarity and one with reversed paleomagnetic polarity?

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Answer: A rock with normal polarity has a magnetic north pole in essentially the same orientation as the present-day North Pole. A rock with reversed polarity has magnetic north and south poles reversed from their present-day orientations.

10 PLATE TECTONICS IN A NUTSHELL

By the 1960s most scientists had become convinced that continental drift had really occurred. However, it remained to put all of this together into a coherent model. This model became the theory of plate tectonics. (It's called a theory now, instead of a hypothesis. A **hypothesis** is an educated guess; a **theory** is supported by extensive scientific evidence and testing.) Here is a brief summary of the theory of plate tectonics.

The outermost, rocky part of the Earth is the **crust.** As mentioned above, there are two types of crust: **continental crust,** which is relatively thick (average thickness 45 km, or 30 mi) and mostly made of granite, and **oceanic crust,** which is relatively thin (average thickness 8 km, or about 5 mi) and mostly made of basalt. Beneath the crust is the **mantle,** also made of rocks, but different from the rocks of the crust. At the center of the Earth is the **core,** made of iron-nickel metal, not rock. (You will learn more about the internal structure of the Earth in chapter 4.) Together, the crust and the outermost part of the mantle make up the **lithosphere,** a thin, cold, brittle, rocky layer (about 100 km, or 60 mi, thick, on average). The mantle below the lithosphere is very hot, so it is relatively malleable, like putty, even though it is made of solid rock. The part of the mantle immediately beneath the lithosphere is called the **asthenosphere;** it is especially weak because it is close to the temperature at which rocks begin to melt.

If you were to do an experiment in which you placed a very thin, cool, brittle shell (like the lithosphere) on top of hot, weak material that is rather squishy (like the asthenosphere), what would happen? You might predict that the thin shell would break into pieces. That is precisely the state of the Earth's lithosphere; it has broken into many large fragments, or plates. Today there are six large lithospheric plates, each extending for several thousands of kilometers, and a large number of smaller plates. The plates are in a condition called **isostasy,** which means that they are essentially "floating" on the weak asthenosphere, like blocks of wood floating on water.

You can experiment with plate motion by carefully heating wax in a pan and then letting it cool until it forms a thin skin or crust. Be careful—molten wax is very hot.

Think again about thin, brittle fragments floating on top of hot, squishy material. You might expect that movement in the underlying material would cause the brittle fragments to shift about. Again, that is exactly what happens to the Earth's lithospheric plates. As movement occurs in the hot mantle, the plates shift and interact with one another. Such movements involve complicated events that are collectively described by the term "tectonics" (from the Greek word *tekton,* meaning "carpenter" or "builder"). "Plate tectonics" thus refers to the study of the movement and interactions of lithospheric plates.

What is the lithosphere?

Answer: The outer 100 km (60 mi) of the Earth; the crust and the upper part of the mantle, above the asthenosphere.

11 PLATE MARGINS AND INTERACTIONS

Lithospheric plates interact with one another mainly along their edges, or margins. Plates can interact in three basic ways: they can move away from each other (diverge); they can move toward each other (converge); or they can slide past each other. Consequently, there are three kinds of plate margins: divergent, convergent, and transform fault margins.

Divergent margins are huge fractures in the lithosphere where plates move apart from one another (Figure 1.6A). When oceanic crust splits apart, seafloor spreading occurs and a **midocean ridge** is formed, like the one in the middle of the Atlantic Ocean. When continental crust splits apart, a great **rift valley** forms, as in East Africa where the African Plate is being stretched and torn apart. Eventually, a new ocean may form in the widening continental rift valley; a modern example of this is the Red Sea. In both continents and oceans, divergent margins are characterized by earthquakes (caused by the splitting and cracking of the rocks) and volcanism (caused by melted rock from the mantle welling up into the fractures).

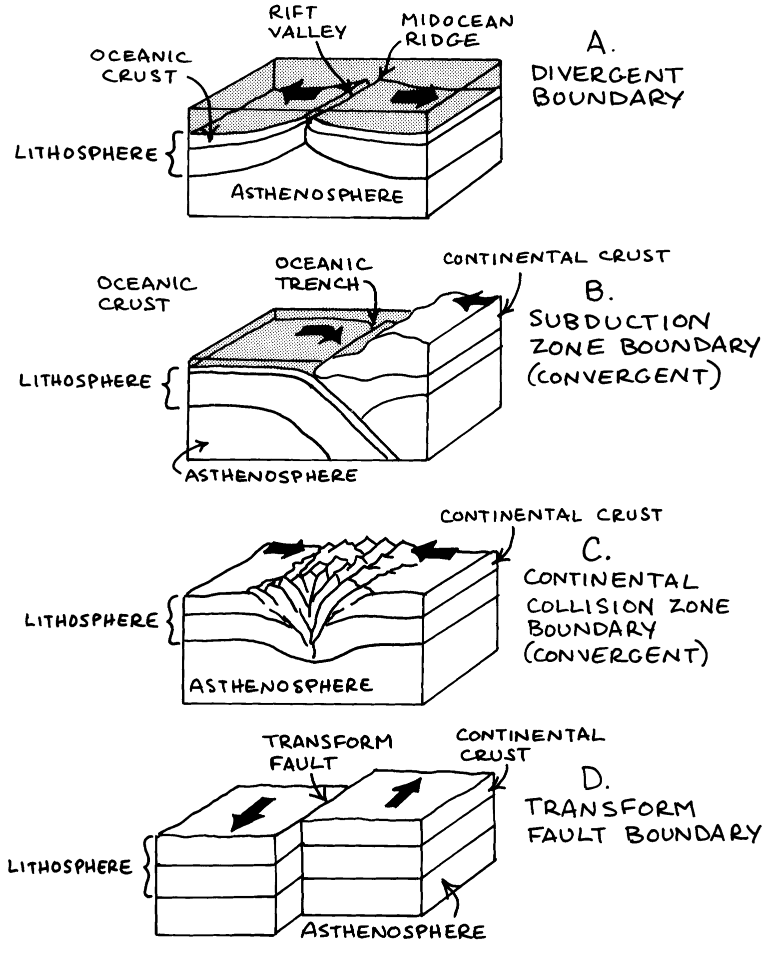

PLATE BOUNDARIES

Figure 1.6

Convergent margins occur where two plates move toward each other. There are three basic types of convergent margins: ocean-ocean, ocean-continent, and continent-continent. Oceanic crust is made of basalt, which is denser (heavier) than the granitic rocks that make up the continental crust. Whenever oceanic crust is involved in a convergent margin, the dense oceanic crust sinks beneath the other plate (Figure 1.6B). This process is called **subduction,** and places where it occurs are called **subduction zones.** Subduction zones are marked by deep oceanic trenches and lines of volcanoes, as in Indonesia (an ocean-ocean subduction zone) or the Andes (an ocean-continent subduction zone).

When one continent meets another continent at a convergent margin, no oceanic crust is available to form a subduction zone. Instead, the continents collide and crumple up, forming huge, uplifted mountain ranges like the Himalayas; this is a **collision zone** (Figure 1.6C). Collision zones and subduction zones have lots of earthquake activity, caused by rocks colliding and grinding past one another.

Transform fault margins are huge fractures in the lithosphere where two plates slide past each other, grinding along their edges and causing earthquakes as they go (Figure 1.6D). A famous modern example is the San Andreas Fault in California, where the Pacific Plate is moving north-northwest relative to the North American Plate.

All these types of plate interactions are occurring today, as they have occurred throughout most of Earth's history. We don't often notice plate motion because lithospheric plates move very slowly—usually between 1 and 10 centimeters (cm) (0.4 to 4.0 inches [in]) per year. But we often feel the earthquakes and observe the volcanic activity that happens along active plate margins. The scars

CONTINENTAL RIFT. This is the Great Rift Valley, part of the East African Rift System in Kenya. The view is looking west across the Kerio River Valley from the top of the Tugen Hills to the Elgeyo Escarpment, which is about 1,220 meters (m) (4,000 feet [ft]) high. The Great Rift Valley was formed by tensional forces that stretched, thinned, and fractured the Earth's crust. (Courtesy Brian Skinner) and remnants of ancient plate interactions are also preserved in the rock record for us to study.

What is the difference between a collision zone and a subduction zone?

Answer: A collision zone occurs where two continents converge. A subduction zone occurs along ocean-continent or ocean-ocean convergent margins.

12 CONVECTION: THE DRIVING FORCE

The theory of plate tectonics has been accepted by almost all geologists, but some questions remain. What causes plate motion? How does the mantle interact with the crust? What makes subduction occur? Scientists have a basic understanding of these processes, but the details have not been completely worked out. We know that thermal movement in the mantle is at least partly responsible for the movement of lithospheric plates. We also know that movement in the mantle is caused by the release of heat from inside the Earth. Let's examine the Earth's heat-releasing processes and consider how they cause plate motion.

The temperature inside the Earth is high—about 5,000° Celsius (C) (more than 9,000° Fahrenheit [F]) in the core. Some of this heat is left over from the Earth's beginnings, but some of it is constantly being generated by the decay of radioactive elements inside the Earth. This heat must be released; if it was not, the Earth would eventually become so hot that its entire interior would melt.

Some of the Earth's internal heat makes its way slowly to the surface through **conduction,** in which heat energy passes from one atom to the next. However, conduction is a slow way to transfer heat. It is faster and more efficient for a packet of hot material to be physically transported to the surface. This is similar to what happens when a fluid boils on a stovetop, as in the wax experiment described above. If you watch a fluid such as wax or spaghetti sauce as it boils, you will see that it turns over and over. Packets of hot material rise from the bottom of the pot to the top. As it reaches the surface, the hot fluid cools and then sinks back down to the bottom of the pot, where it is reheated. The continuous motion of material from bottom to top and down again is called a convection "cell," and this type of heat transfer is called **convection.**

Even though the Earth's mantle is mostly solid rock, it is so hot that it releases heat by convection (Figure 1.7). Rock deep in the mantle heats up and expands, making it buoyant. As a result, the rock moves toward the surface—very, very slowly—in huge convection cells of solid rock. Near the surface, the hot rock

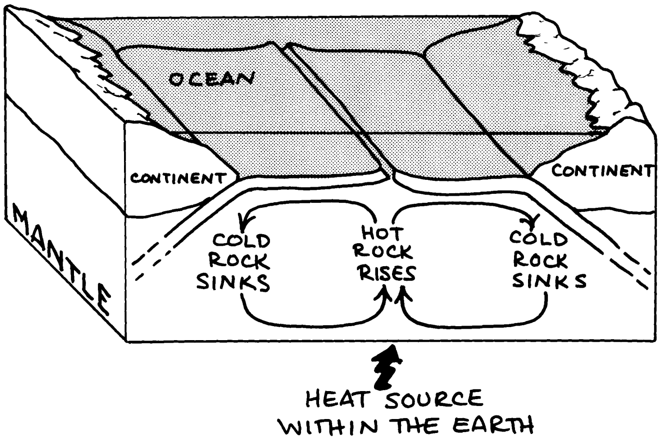

Figure 1.7

moves along the surface while losing heat, like the spaghetti sauce. The movement of hot rock in the asthenosphere is thought to be the main cause of plate motion. As the rock cools, it becomes denser (cool rock is denser, or heavier, than hot rock) and sinks back into the deeper parts of the mantle. This convection cycle provides an efficient way for the Earth to rid itself of some of its internal heat. Convection and the movement of plates near the surface create some of the most distinctive geologic and topographic features of the Earth's surface: the deep trenches where oceanic plates are subducted into the mantle; the midocean ridges and continental rift valleys where plates split apart; and the high, folded-and-crumpled mountain chains where continents collide.

Convection in the mantle is not nearly as simple as convection in a pot on a stovetop. Some of the most challenging unanswered questions about plate tectonics have to do with the exact nature of this process. Does the whole mantle convect as a unit, or is the top part of the mantle convecting separately from the bottom? In subduction zones, are the plates dragged down into the mantle, or do they sink under their own weight? What is the exact shape of convection cells in the mantle? Scientists are still seeking the answers to these and other questions about plate tectonics.

What is the temperature in the Earth's core?

Answer: About 5,000°C (9,000°F).

You have covered an enormous amount of material in this chapter—an entire scientific revolution in a few pages! Many of the concepts presented in this chapter may seem difficult and unfamiliar to you now, but don't worry. Plate tectonics

CONTINENTAL COLLISION. Mount Everest (center) is flanked by Lhotse (right) and Nuptse (left). They are the giants of the Himalaya Mountains, crowning the world's highest and most dramatic mountain range. The Himalayas were formed by compressive forces that folded, squashed, and thickened the Earth's crust. (Courtesy Brian Skinner)

is the foundation for our understanding of the Earth and its processes and materials, so many of these ideas will be revisited in the chapters to follow. Now test your knowledge of this material by trying out the Self-Test.

SELF-TEST

These questions are designed to help you assess how well you have learned the concepts presented in chapter 1. The answers are given at the end.

1. The ages of seafloor rocks generally ___________ with distance from a mid-ocean ridge, on either side of the ridge.
   a. increase
   b. decrease
   c. stay the same
   d. vary irregularly

2. The San Andreas Fault in California is a modern-day example of a ____________ plate margin.
   a. collisional
   b. subduction zone
   c. divergent
   d. transform fault

3. The “plates” in plate tectonics are made of fragments of ____________.
   a. continents
   b. oceanic crust
   c. the lithosphere
   d. the mantle

4. The weak layer of the mantle, immediately underlying the lithosphere, is called the ____________.

5. The Earth has two fundamentally different types of crust: ____________ crust is made mainly of basaltic rocks, and ____________ crust is made mainly of granitic rocks.

6. Along a noncliffed shoreline, the land usually slopes very gently toward the sea; this gently sloping land is called the abyssal plain. (T or F)

7. Wherever there is a convergent plate margin, a subduction zone will develop. (T or F)

8. Convection is faster and more efficient than conduction as a mechanism of heat transfer. (T or F)

9. Is the coastline, where the land meets the water, the true edge of a continent? Why, or why not?

10. What is the difference between a hypothesis and a theory?

11. Why is it tricky to match rock types and other geologic features across a continental split, such as where South America and Africa were once joined?

12. How does the distribution of glacial deposits support the idea that the continents were once joined together in the supercontinent Pangaea?

13. Summarize the main types of plate margins.

ANSWERS

1. a
2. d
3. c
4. asthenosphere
5. oceanic; continental
6. F
7. F
8. T
9. No. The true edge of a continent is where continental crust meets oceanic crust, but this is usually covered by mud (and sometimes by water). We define the edge of a continent to be halfway down the continental slope.
10. A theory is supported by extensive scientific evidence and testing; a hypothesis is an educated guess.
11. Rock-forming processes never cease. Some rocks were formed before the continents were joined, some while they were joined, others during the splitting of the continents, and still others after they became separated.
12. When the continents are rotated back into the "joined" position (Pangaea), the geology and ages of glacial deposits match remarkably well across the joins. Glacial grooves and scratches show that the ice was moving outward in all directions from what was then the South Pole.

13. The main types of plate margins are divergent (oceanic or continental); convergent subduction zone (ocean-ocean or ocean-continent); convergent collision zone (continent-continent); transform fault.

KEY WORDS

abyssal plain
apparent polar wandering
asthenosphere
collision zone
conduction
continental crust
continental drift
continental rise
continental shelf
continental slope
convection
convergent margin
core
crust
divergent margin
Earth system science
geology
historical geology
hypothesis
isostasy
lithosphere
mantle
midocean ridge
normal magnetic polarity
oceanic crust
paleomagnetism
Pangaea
physical geology
plates
plate tectonics
polarity
reversed magnetic polarity
rift valley
seafloor spreading
subduction
subduction zone
theory
transform fault margin