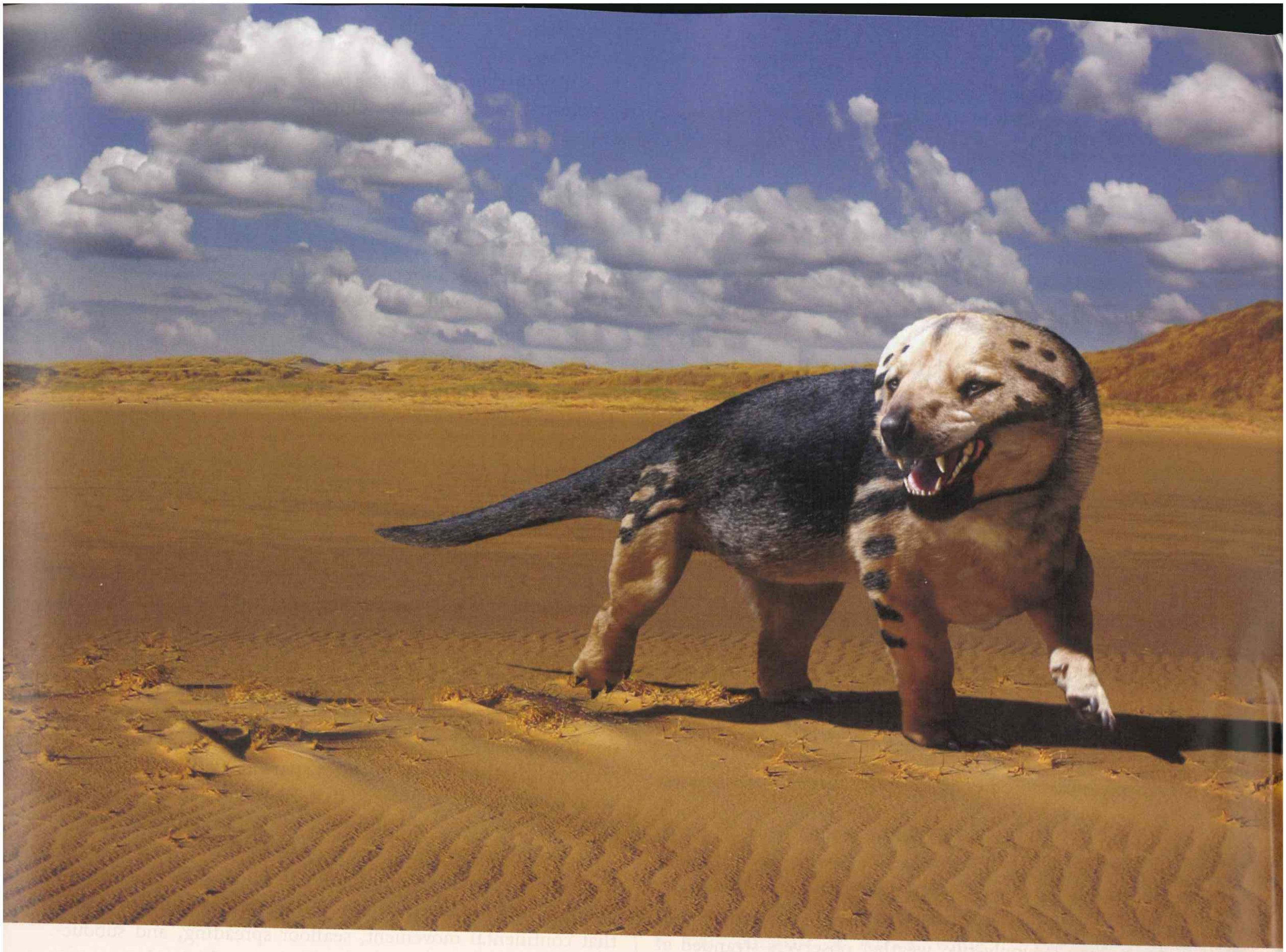


Fossilized remains of *Cynognathus*, an ancestor of mammals, occur on continents now separated by oceans. The organism couldn't swim across an ocean, so how could it have traveled so far? Mysteries such as this led Alfred Wegener to propose that the continents were once together and only later drifted apart.

CHAPTER 3

Drifting Continents and Spreading Seas

It is only by combing the information furnished by all the earth sciences that we can hope to determine "truth" here.

—*Alfred Wegener (1880–1930)*

LEARNING OBJECTIVES

By the end of this chapter, you should understand . . .

- the premise of the continental-drift hypothesis proposed by Alfred Wegener.
- the observations that Wegener used to justify continental drift.
- how studies of paleomagnetism later proved that continents move.
- the key observations, from study of the seafloor, that led Hess to propose seafloor spreading.
- some observations that can be used to prove that seafloor spreading happens.

3.1 Introduction

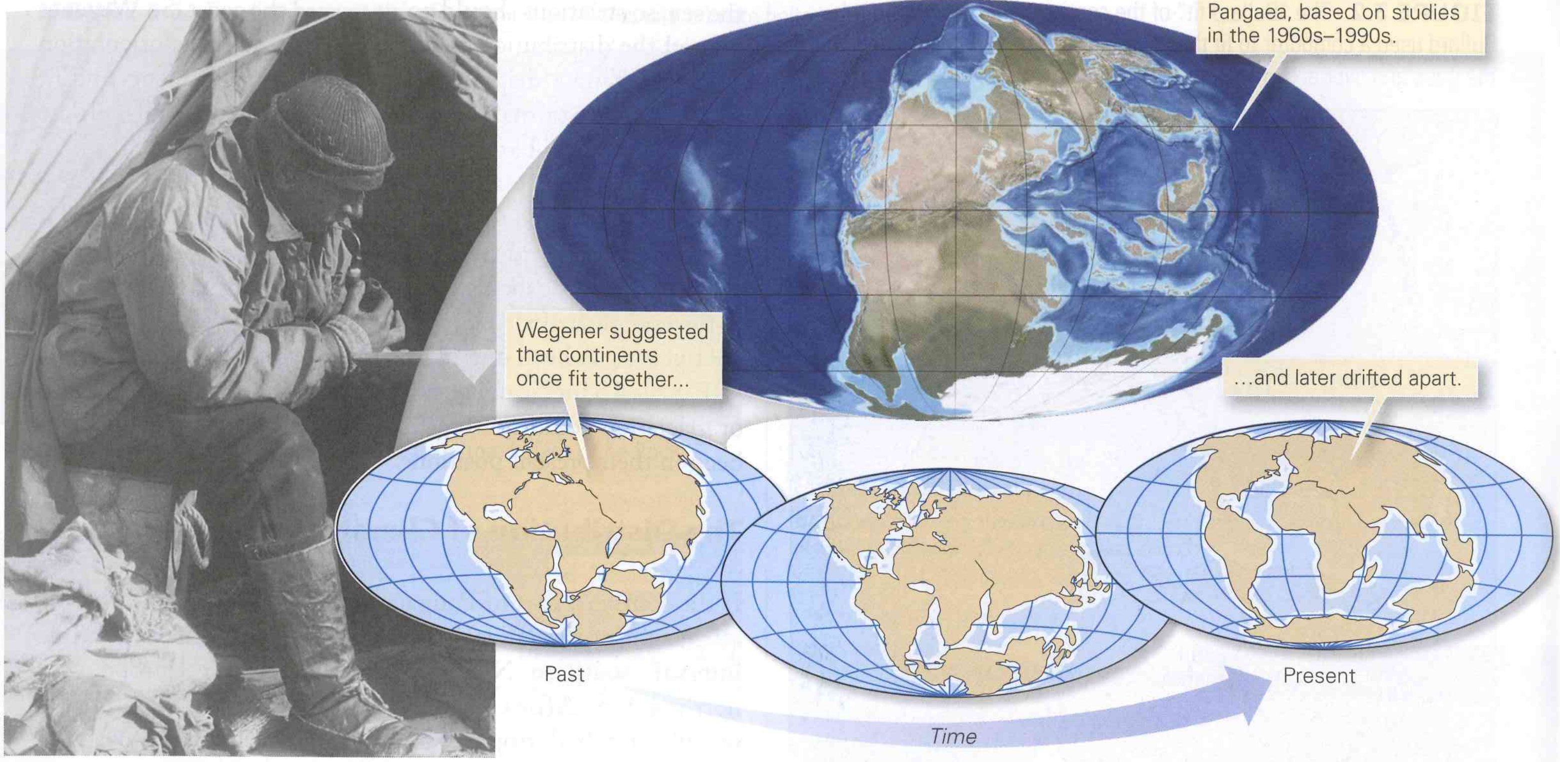
In September 1930, 15 explorers led by a German meteorologist, Alfred Wegener, set out across the endless snowfields of Greenland to resupply two weather observers stranded at a remote camp. The observers were planning to spend the long polar night recording wind speeds and temperatures on Greenland's polar plateau. Wegener was a scientist well known not only to researchers studying climate but also to geologists. Some 15 years earlier, he had published a small book, *The Origin of the Continents and Oceans*, in which he had dared to challenge geologists' long-held assumption that the continents had remained fixed in position through all of Earth history. Wegener proposed instead that the continents had once fit together like pieces of a giant jigsaw puzzle, making one vast **supercontinent**. This supercontinent, which he named **Pangaea** (pronounced pan-jee-ah) from the Greek *pan* (all) plus *gaia* (earth), later fragmented into separate continents that drifted apart, moving slowly to their present positions (**Fig. 3.1**). The phenomenon that Wegener proposed came to be known as *continental drift*.

Wegener presented many observations that he believed proved that continental drift had occurred, but he met strong resistance from his peers. At a widely publicized 1926 geology conference in New York City, a crowd of celebrated American professors challenged, "What force could possibly be great enough to move the immense mass of a continent?" Wegener's writings didn't provide a good answer, so most of the meeting's participants rejected continental drift. Four years later, Wegener faced an even greater challenge—survival itself. Sadly, he lost. On October 30, 1930, Wegener and a companion reached the observers, dropped off enough supplies to last the winter, and set out on the return trip the next day, but they never made it home.

Had Wegener survived to old age, he would have seen his hypothesis become the foundation of a scientific revolution. Today geologists accept Wegener's basic conclusion and take for granted the concept that the map of the Earth changes as continents seemingly waltz around this planet's surface, variously combining and breaking apart, through geologic time. In fact, Pangaea wasn't the only supercontinent in Earth history—others formed and broke into pieces that later combined again several times in the past few billion years. The scientific revolution began in 1960, when an American geologist, Harry Hess proposed that as continents move apart new ocean floor forms between them by a process that his contemporary, Robert Dietz, named *seafloor spreading*. Hess suggested that continents can move toward each other when the old ocean floor between them sinks back down into the Earth's interior, a process now called *subduction*. During the 1960s, geologists came to realize that continental movement, seafloor spreading, and subduction, along with a wide range of other geologic phenomena, were manifestations of the fact that the Earth's outer, relatively rigid shell is not a continuum but rather consists of about 20 distinct pieces—now called *plates*—that slowly move relative to each other. Because we can empirically confirm this idea, it has gained the status of a theory, which we now call the theory of *plate tectonics*, from the Greek word *tekton*, which means builder—plate movements effectively "build" regional geologic features. Geologists view plate tectonics as the grand unifying theory of geology, because it so successfully explains a great many geologic processes and features, as we will see.

In this chapter, we introduce the observations that led Wegener to propose his continental-drift hypothesis. Then we look at paleomagnetism, the record of Earth's magnetic field in the past, which provides a key proof of continental drift. Next we learn how observations about the seafloor, made by geologists during the mid-20th century, led to the proposal of seafloor spreading and how the idea was tested and shown to be correct. In Chapter 4 we will build on these concepts and describe the many facets of modern plate tectonics theory.

FIGURE 3.1 Alfred Wegener and his model of continental drift.



(a) Wegener in Greenland.

(b) Wegener's maps illustrating continental drift.

3.2 Wegener's Evidence for Continental Drift

Before Wegener, geologists viewed the continents and oceans as "immobile"—fixed in position throughout geologic time. According to Wegener, however, the positions of continents change through time. Specifically, Wegener suggested that a vast supercontinent, Pangaea, existed until the end of the Paleozoic Era and that it broke apart during the Mesozoic (see Fig. P.7 for a simplified geologic time scale). The resulting smaller continents, the ones that exist today, then moved away from each other. Let's look at some of Wegener's arguments and see what led him to formulate this hypothesis of **continental drift**.

The Fit of the Continents

Almost as soon as maps of the Atlantic coastlines became available in the 1500s, scholars noticed the fit of the continents. Specifically, the northwestern coast of Africa looks like it could tuck in against the eastern coast of North America, and the bulge of eastern South America could nestle cozily into the indentation of southwestern Africa. Australia, Antarctica, and India could all connect to the southeast of Africa, while Greenland, Europe, and Asia could pack against the northeastern margin of North America (Fig. 3.2). In fact, all the continents could be joined, with remarkably few overlaps or gaps, to form a single supercontinent, Pangaea. Wegener concluded that the fit was too good to be coincidence and thus that the continents once did fit together.

Did you ever wonder . . .

why coasts of the Atlantic look like they fit together?

Locations of Past Glaciations

Glaciers are rivers or sheets of ice that flow across the land surface. As a glacier flows, it carries sediment grains of all sizes (clay, silt, sand, pebbles, and boulders; see Chapter 2 for a definition of *sediment*). Grains protruding from the base of the moving

SEE FOR YOURSELF . . .

The Fit of Continents

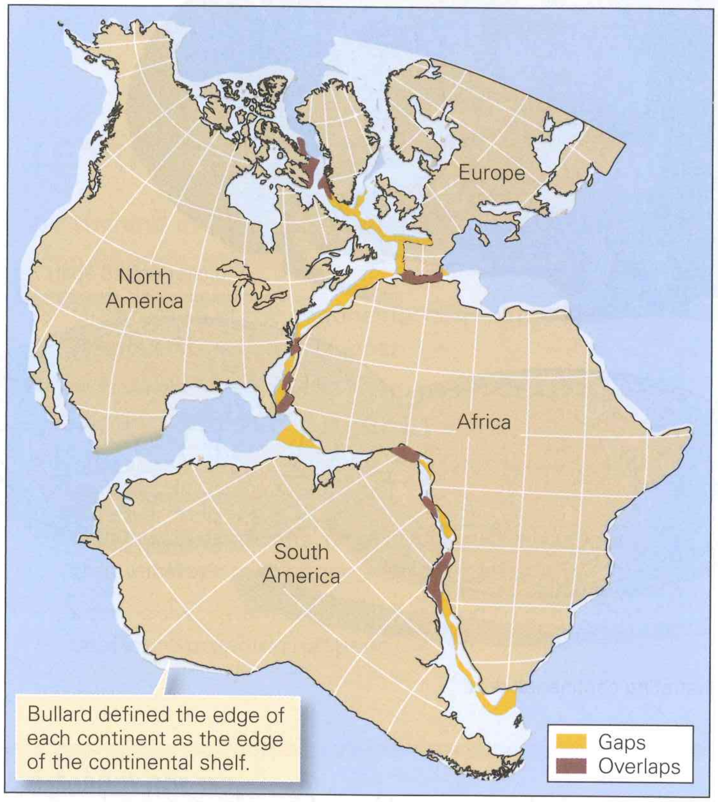
LATITUDE
33°31'25.77"N

LONGITUDE
39°26'23.32"W

Zoom to an elevation of 14,800 km (9,200 mi) and look straight down.

Note how northwest Africa could fit snuggly along eastern North America. Wegner used this fit as evidence for Pangaea.

FIGURE 3.2 The "Bullard fit" of the continents. In 1965, Edward Bullard used a computer to fit the continents and demonstrate how minor the gaps and overlaps are, although the match still isn't perfect.



ice carve scratches, called striations, into the substrate. In some cases, it's possible to tell the direction of slip from striations. When the ice melts, it leaves the sediment in a deposit called till, which may bury the striations. Thus, the occurrence of till and striations at a location serve as evidence that the location was covered by a glacier in the past. By studying the age of glacial till deposits, geologists have determined that large areas of land were covered by glaciers during discrete time intervals of Earth history called *ice ages*. One of these ice ages occurred from 280 to 260 Ma (million years ago), near the end of the Paleozoic Era.

Wegener was a climate scientist by training, and he studied the Arctic, so it's no surprise that he had a strong interest in glaciers. He knew that glaciers form at high (polar) latitudes today, so he was bothered by the observation that sediments indicative of late Paleozoic glaciation occurred in southern South America, southern Africa, southern India, Antarctica, and southern Australia. With the exception of Antarctica, these continents do not currently lie in high latitudes (**Fig. 3.3a–c**). Wegener also noted that most striations associated with these deposits seemed to point from the sea into the continents—this was puzzling because glaciers today form on land and flow to the sea, so striations should point toward the coast. So Wegener plotted the distribution of glacial deposits and the orientation of striations on a map and then cut out the continents and fit them together to make Pangaea. To his amazement, all late Paleozoic glaciated areas lie adjacent to each other on his map of Pangaea, forming a single coherent ice sheet. Furthermore, when he determined the diretion of movement, he found that it was roughly outward from the center of this ice sheet. In other words, Wegener concluded that the distribution of glaciations at the end of the Paleozoic Era could easily be explained if the continents had been united in Pangaea, with the southern part of Pangaea lying at polar latitudes. The observed distribution of glaciation could not be explained if continents had always been in their present positions.

The Distribution of Climatic Belts

If the southern part of Pangaea had straddled the South Pole at the end of the Paleozoic Era, then during this same time interval, southern North America, southern Europe, and northwestern Africa would have straddled the equator and would have had tropical or subtropical climates. Wegener searched for evidence that this was so by studying characteristics of late Paleozoic sedimentary rocks from these regions, for the material making up sedimentary rocks can reveal clues to the climate at the time the sediment formed. For example, in the swamps and jungles of tropical regions, thick deposits of plant material accumulate, and when deeply buried, this material transforms into coal. And, in the clear, shallow seas of tropical regions, large reefs made from the shells of marine organisms develop. Finally, in subtropical regions, on either side of the tropical belt, where desert climates exist, salt deposits (from evaporating seawater or salt lakes) accumulate, and sand dunes grow. Wegener speculated that the distribution of late Paleozoic coal, reef, sand-dune, and salt deposits could define climate belts on Pangaea.

Sure enough, in the belt of Pangaea that Wegener expected to be equatorial, late Paleozoic sedimentary rock layers include abundant coal and the relicts of reefs. And in the belts of Pangaea that Wegener predicted

SEE FOR YOURSELF . . .

Climate Belts

LATITUDE
0°10′24.19″S

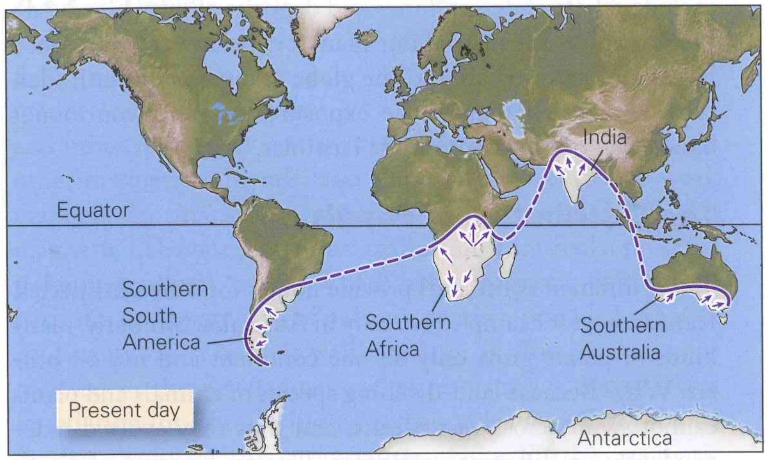
LONGITUDE
93° 7′7.22″W

Zoom to 15,000 km (9,200 mi) add the grid, and look straight down. Click "grid."

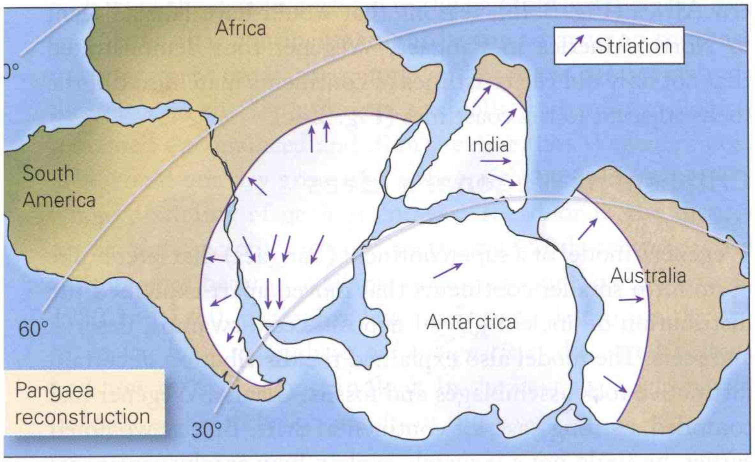
North America is now at temperate to arctic latitudes. Wegener noted that in the Late Paleozoic, it was tropical, as if near the equator.

FIGURE 3.3 The distribution of Late Paleozoic glacial deposits, climate belts, and fossils.

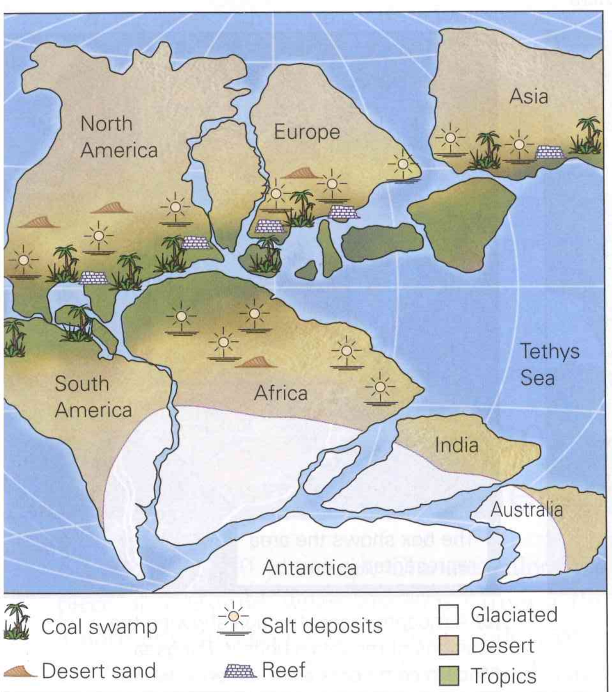
(a) Glacial striations of Late Paleozoic age on the surface of bedrock along the south coast of Australia.



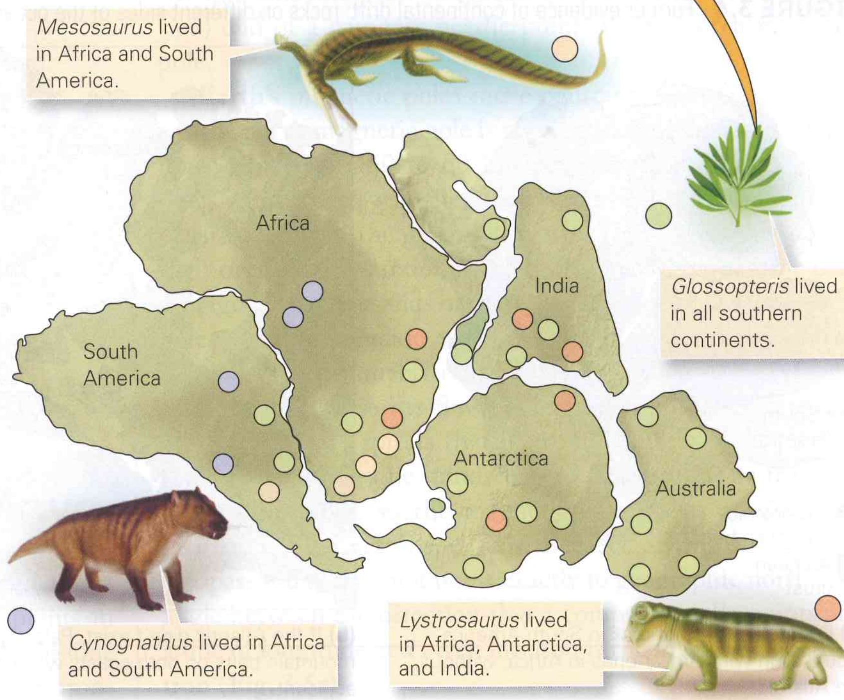
(b) A map showing the distribution of Late Paleozoic glacial deposits and the orientation of associated striations.



(c) On Wegener's reconstruction of Pangaea, the glaciated areas connect to outline a region of Late Paleozoic south polar ice caps.



(d) Climate belts, as indicated by distinct rock types, make sense on a map of Pangaea.



(e) Fossil localities shows that Mesozoic land-dwelling organisms occur on more than one continent. This would be hard to explain if oceans lay between these continents.

would be subtropical, late Paleozoic sedimentary rock layers include relicts of desert dunes and deposits of salt (**Fig. 3.3d**). On a present-day map of our planet, exposures of these rock layers are scattered around the globe at a variety of latitudes. On Wegener's Pangaea, the exposures align in continuous bands that occupy appropriate latitudes.

The Distribution of Fossils

Today different continents provide homes for different species. Kangaroos, for example, live only in Australia. Similarly, many kinds of plants grow only on one continent and not on others. Why? Because land-dwelling species of animals and plants cannot swim across vast oceans, and thus they evolved independently on different continents. During a period of Earth history when all continents were in contact, however, land animals and plants could have migrated relatively easily among many continents.

Did you ever wonder . . .

if you could have once walked from New York to Paris?

With this concept in mind, Wegener plotted fossil occurrences of land-dwelling species that existed during the late Paleozoic and early Mesozoic Eras (between 300 and 210 Ma) and found that these species had indeed existed on several continents (**Fig. 3.3e**). Wegener argued that the distribution of these fossils required the continents to have been adjacent to one another in the late Paleozoic and early Mesozoic Eras.

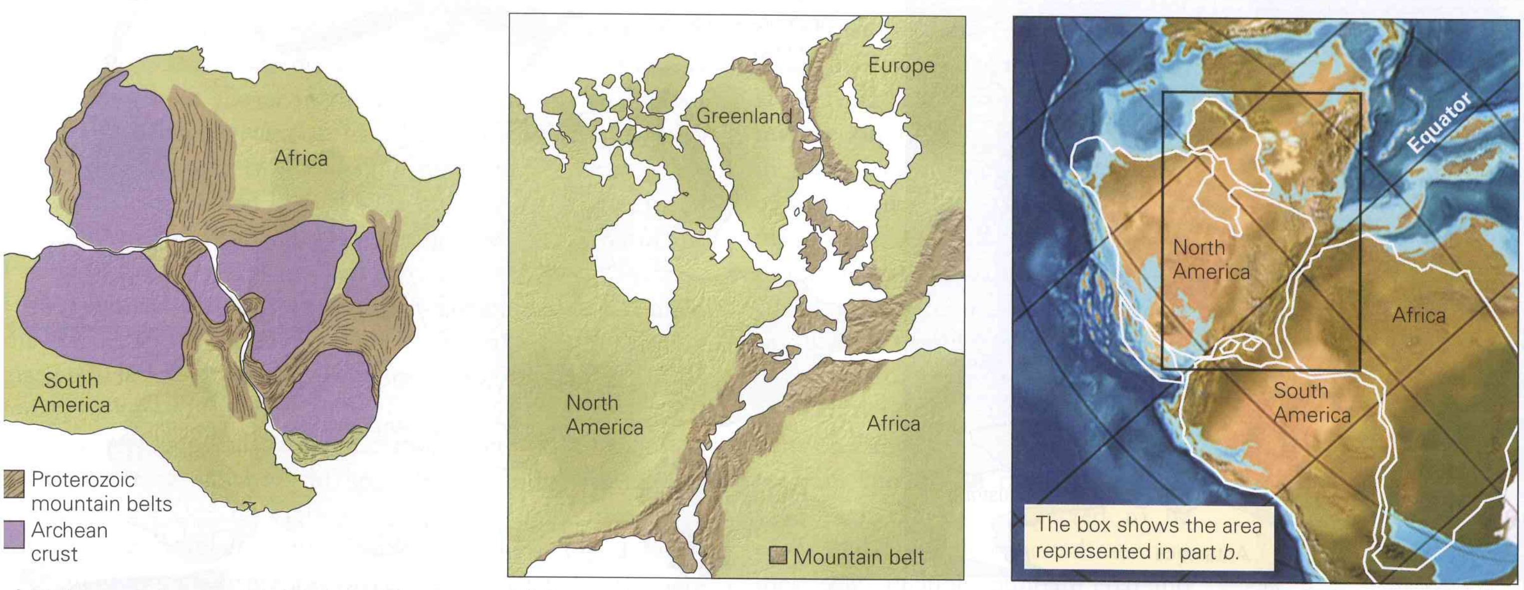
Matching Geologic Units

Art historians can recognize a Picasso painting, and architects know what makes a building's style Victorian. Similarly, geologists can identify distinctive assemblages of rocks. Wegener found that the same distinctive Precambrian (before 541 Ma) rock assemblages occurred on the eastern coast of South America and the western coast of Africa, regions now separated by an ocean (**Fig. 3.4a**). If the continents had been joined to create Pangaea in the past, then these matching rock groups would have been adjacent to each other and thus could have composed continuous blocks or belts. Wegener also noted that features of the Appalachian mountain belt of the United States and Canada closely resemble those of mountain belts in southern Greenland, Great Britain, Scandinavia, and northwestern Africa (**Fig. 3.4b**), regions that would have lain adjacent to North America in Pangaea. Wegener thus demonstrated that not only did the coastlines of continents match, so did the rocks adjacent to the coastlines (**Fig. 3.4c**).

Criticism of Wegener's Ideas

Wegener's model of a supercontinent (Pangaea) that later broke up to form smaller continents that moved apart explained the distribution of ancient glacial deposits, coal swamps, deserts, and reefs. The model also explained the distribution of certain distinctive rock assemblages and fossils. Clearly, Wegener had compiled a strong case for continental drift. But, as we noted earlier, he could not adequately explain how or why continents

FIGURE 3.4 Further evidence of continental drift: rocks on different sides of the ocean match.



(a) Distinctive belts of rock in South America would align with similar ones in Africa, without the Atlantic.

(b) If the Atlantic didn't exist, Paleozoic mountain belts on both coasts would be adjacent.

(c) A modern reconstruction showing the positions of mountain belts in Pangaea. Modern continents are outlined in white.

moved. Wegener's writings gave the impression that continents somehow "plowed" through the ocean floor like the keel of a ship plows through water, but that's not possible because ocean floor rock is too strong. Wegener also suggested that centrifugal force, due to the Earth's spin, drove continental movement, but that's not possible because the force isn't strong enough. He left on his final expedition to Greenland having failed to convince his peers, and he died without knowing that his ideas, after lying dormant for decades, would be reborn as the basis of the broader theory of plate tectonics.

In effect, Wegener was ahead of his time. In the three decades that followed his death, a handful of iconoclasts continued to champion his notions. Among them was Arthur Holmes, a British geophysicist who argued that huge convection cells existed inside the Earth, slowly transporting hot rock from the deep mantle up to the base of the crust. Holmes speculated that continents might be forced apart in response to convective flow in the mantle and that the continents rode like rafts on the top of convective cells. But most geologists remained unconvinced and didn't realize that Wegener's bold idea would one day grow into a theory that would change the whole discipline of geology forever. The door to the discovery of plate tectonics opened in the mid-20th century, when technologies became available to provide such data. Between 1930 and 1960, geologists learned how to determine the age of rocks, how to analyze *paleomagnetism* (discussed below), and how to "see" the ocean floor. In the next two sections, we describe some of the key results of this work.

Take-Home Message

In the early 20th century, Alfred Wegener argued that the continents had once been connected in a supercontinent, Pangaea, that later broke up to produce smaller continents that "drifted" apart. He showed that the matching shapes of coastlines, as well as the distribution of ancient glaciers, climate belts, fossils, and rock units, make better sense if Pangaea existed. But Wegener couldn't convince his peers.

QUICK QUESTION: Why were Wegener's peers skeptical of continental drift?

3.3 Paleomagnetism—Proving Continents Move

More than 1,500 years ago, Chinese sailors discovered that a piece of lodestone, when suspended from a thread, points in a northerly direction and can help guide a voyage. Lodestone exhibits this behavior because it consists of magnetite, an iron-rich mineral that, like a compass needle, aligns with Earth's magnetic field lines. While not as magnetic as lodestone, several other rock types contain trace amounts of magnetite, or other magnetic minerals, and thus behave overall like weak magnets. In this section, we explain how the study of such magnetic behavior led to the realization that rocks preserve **paleomagnetism**, a record of Earth's magnetic field in the past. An understanding of paleomagnetism provided proof of continental drift and, as we'll see later in this chapter, contributed to the development of plate tectonics theory. As a foundation for introducing paleomagnetism, we first provide further detail on the basic nature of the Earth's magnetic field.

Did you ever wonder . . .

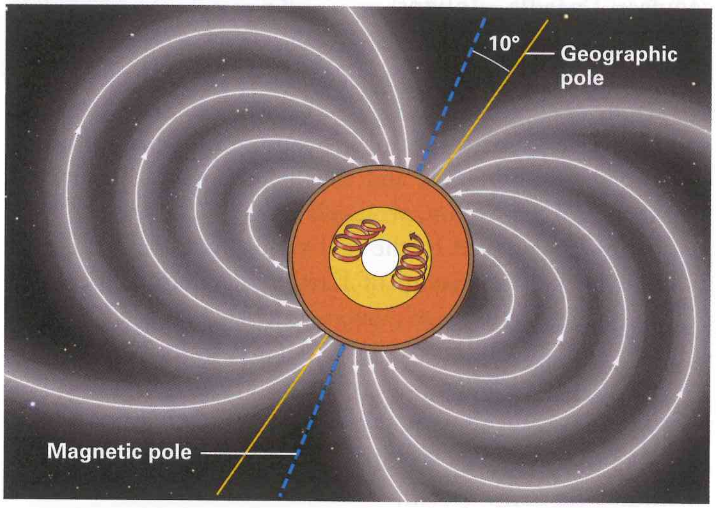
why compasses always point to the north?

Earth's Magnetic Field

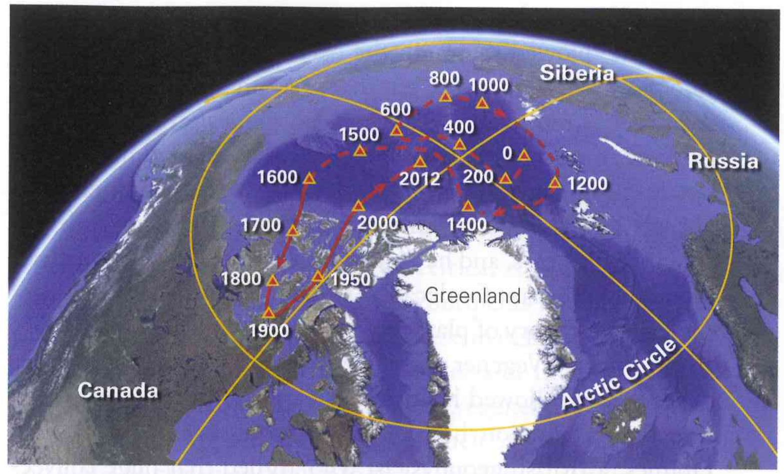
Circulation of liquid iron alloy in the outer core of the Earth generates a magnetic field. (A similar phenomenon happens in an electrical dynamo—we'll discuss this concept further in Interlude D.) Earth's magnetic field resembles the field produced by a bar magnet in that it has two ends of opposite polarity, as introduced in Chapter 2. Thus, we can represent Earth's field by a **magnetic dipole**, an imaginary arrow (**Fig. 3.5a**). Earth's dipole intersects the surface of the planet at two points, known as the **magnetic poles**. By convention, the north magnetic pole lies at the end of the Earth nearest the north geographic pole (the point where the northern end of the spin axis intersects the surface), so that the north-seeking (red) end of a compass needle points to the north magnetic pole.

Earth's magnetic poles move constantly—in fact, at present the north magnetic pole is moving across the Arctic Ocean toward Russia at 50 to 60 km per year. Significantly, poles don't seem to stray farther than about 2,000 km (about 20° of latitude) from the geographic poles (**Fig. 3.5b**). Because of their overall fairly random movements, geologists assume that, averaged over thousands of years, the locations of the magnetic poles roughly coincide with Earth's geographic poles. This relationship presumably reflects the rotation of the Earth, for the spin may cause the flow to organize into patterns resembling spring-like spirals that align with the axis. At present, the magnetic poles lie hundreds of kilometers away from the geographic poles, so the magnetic dipole tilts at about 10° relative to the Earth's spin axis. Because of this difference, a compass today does not point exactly to geographic north. The angle between the direction that a compass needle points and a line of longitude at a given location is the **magnetic declination** (**Fig. 3.5c**).

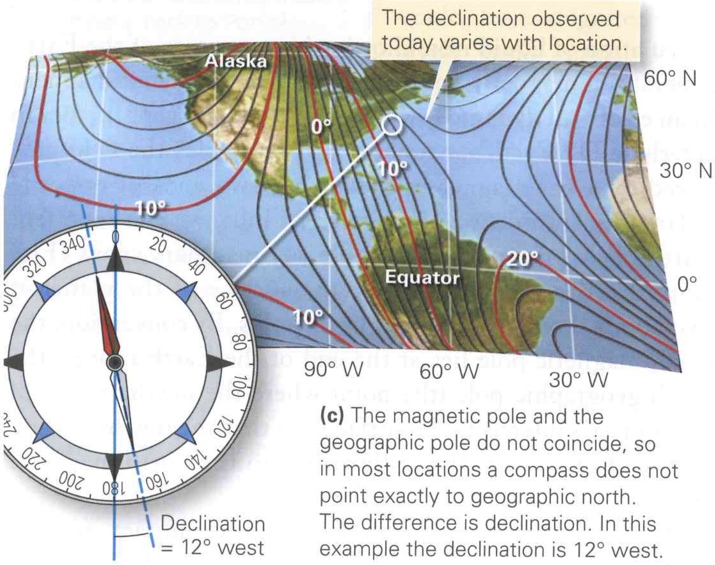
FIGURE 3.5 Features of Earth's magnetic field.



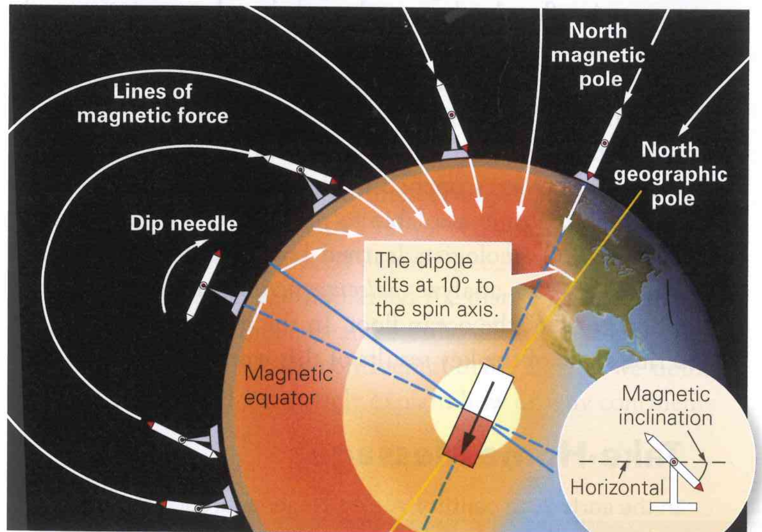
(a) The magnetic axis is not parallel to the spin axis. The field is due to flow in the outer core.



(b) A simplified map showing the changing position of the north magnetic pole over the past 2000 years. Before about 1600, the position was not as well constrained, so the path is dashed.



(c) The magnetic pole and the geographic pole do not coincide, so in most locations a compass does not point exactly to geographic north. The difference is declination. In this example the declination is 12° west.



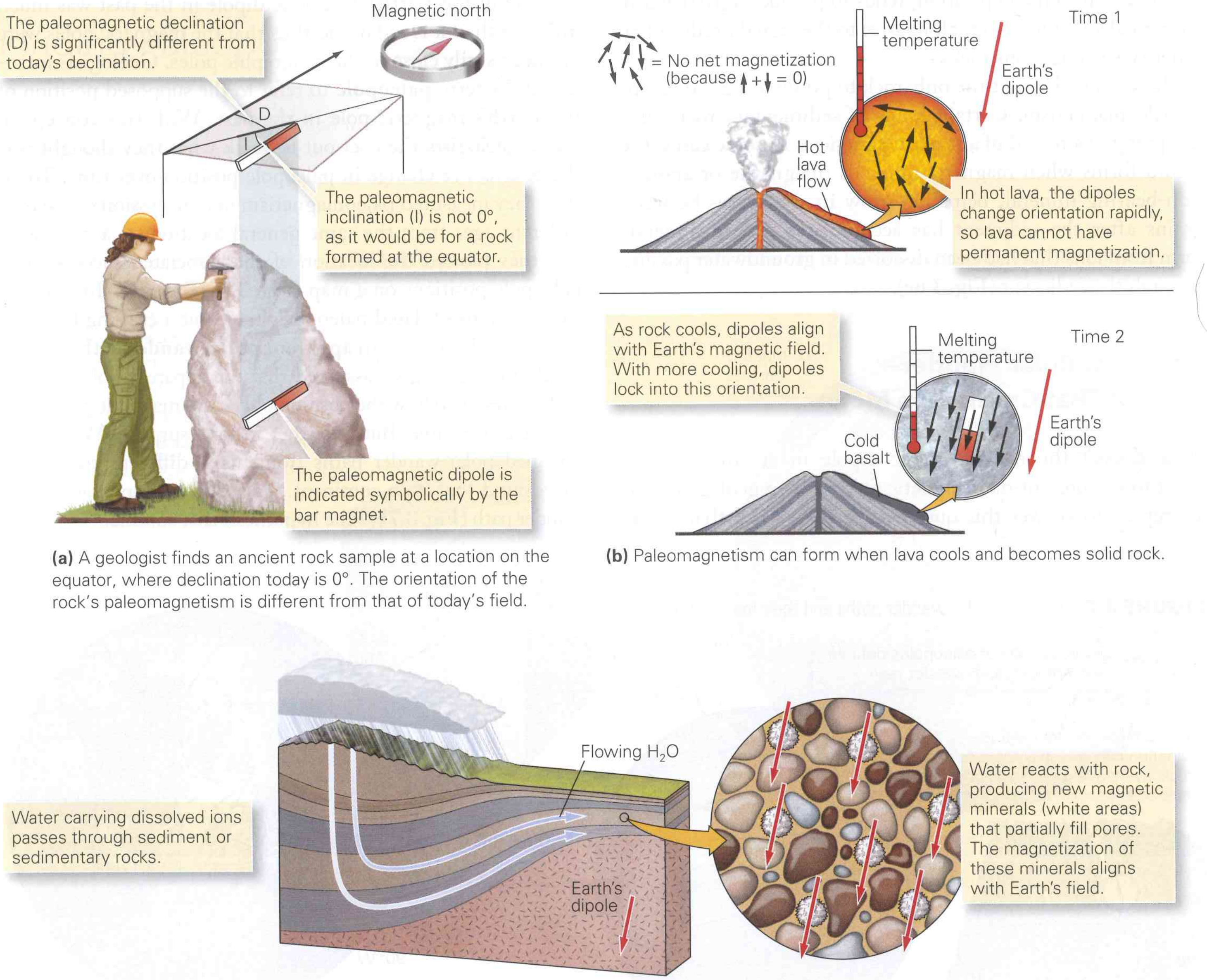
(d) Earth's field lines curve, so the tilt of a magnetic needle changes with latitude. This tilt is the magnetic inclination.

Invisible field lines curve through space between the magnetic poles (Fig. 3.5d). In a cross-sectional view, these lines lie parallel to the surface of the Earth (i.e., are horizontal) at the equator, tilt at an angle to the surface in midlatitudes, and plunge perpendicular to the surface (i.e., are vertical) at the magnetic poles. The angle between a magnetic field line and the surface of the Earth, at a given location, is called the **magnetic inclination**. If you place a magnetic needle on a horizontal axis so it can pivot up and down and then carry it from the magnetic equator to the magnetic pole, you'll see that the inclination varies with latitude—it is 0° at the magnetic equator and 90° at the magnetic poles. (Note that the compass you may carry with you on a hike does not show inclination because it has been balanced to remain horizontal and pivots on a vertical axis.)

What Is Paleomagnetism?

In the early 20th century, researchers developed instruments that could measure the very weak magnetic field produced by rocks and made a surprising discovery. In a rock that formed millions of years ago, the orientation of the dipole representing the magnetic field of the rock is not the same as that of present-day Earth (Fig. 3.6a). To understand this statement, imagine that you go to a locality and measure the very weak magnetic field emanating from a 90-million-year-old rock. (In reality, the signal is so weak that you would have to take a sample of the rock back to a laboratory and measure it with specialized instruments.) If you represent the rock's magnetic field by a bar magnet, you'll likely find that this magnet's declination differs from the declination that a compass at the location would

FIGURE 3.6 Paleomagnetism and how it can form.



(a) A geologist finds an ancient rock sample at a location on the equator, where declination today is 0°. The orientation of the rock's paleomagnetism is different from that of today's field.

(b) Paleomagnetism can form when lava cools and becomes solid rock.

(c) Paleomagnetism can can also form when iron-bearing minerals precipitate out of groundwater passing through sediment.

display today. Also, you would likely find that this magnet's inclination is not the same as the inclination appropriate for the latitude of your sample. These differences arise because the rock is preserving a record of the orientation of the location of the magnetic pole, relative to the rock, at the time the rock formed. In geologic jargon, the rock is preserving paleomagnetism.

Paleomagnetism can develop in many ways. For example, the paleomagnetism of basalt forms when the rock cools from a melt (**Fig. 3.6b**). Let's follow the stages of this process. Imagine a flow of lava so hot that it contains no solid crystals. As the lava starts to cool and solidify into rock, tiny magnetite crystals begin to grow along with several other types of minerals. Each magnetite crystal produces a tiny magnetic dipole. At first, thermal energy causes the magnetic dipole associated with each crystal to wobble and tumble chaotically. Thus, at any given instant, the dipoles of the crystals are randomly oriented and the magnetic forces they produce cancel each other out. As the rock cools, however, thermal energy decreases so the dipoles slow down and, like tiny compass needles, align with the Earth's magnetic field. Eventually, the rock cools down so much, that the dipoles can no longer move and lock into permanent parallelism with the Earth's magnetic field at the time this cooling takes place. Since the magnetic dipoles of all the grains point in the same direction, they can add together and produce a measurable field. Basalt, because of its small grain-size and iron-rich composition, tends to produce a particularly strong paleomagnetic signal, relative to the signal produced by other types of igneous rocks.

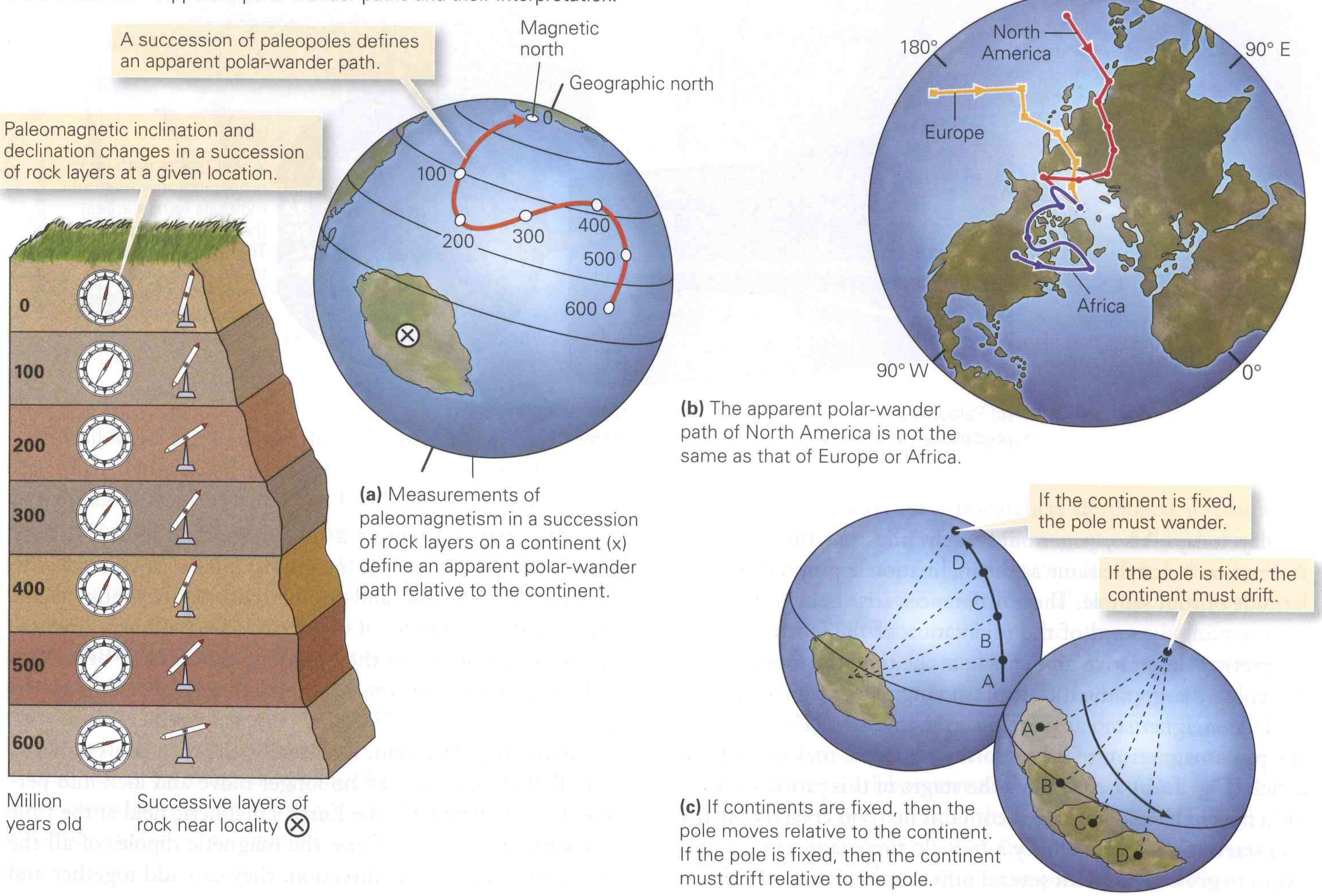
Igneous rock is not the only rock to preserve a good record of paleomagnetism. Certain kinds of sedimentary rocks also can preserve a record of ancient magnetism. In some cases, the record forms when magnetic minerals (magnetite or another iron-bearing mineral, hematite) grow in the spaces between grains after the sediment has accumulated. These minerals form from ions that had been dissolved in groundwater passing through the sediment (Fig. 3.6c).

Apparent Polar Wander–A Proof That Continents Move

Why doesn't the paleomagnetic dipole in an ancient rock point to the present-day magnetic field? When geologists first attempted to answer this question, they assumed that continents were fixed in position; so they concluded that the orientation of the Earth's magnetic dipole in the past was much different than it is today and thus that the magnetic poles were not necessarily close to the geographic poles. Geologists introduced the term **paleopole** to refer to the supposed position of the Earth's magnetic pole in the past. With this concept in mind, geologists then set out to track what they thought was the progressive change in paleopole position over time. To do this, they measured paleomagnetism in a succession of rocks of different ages from the same general location on a continent, and they plotted the location of the associated succession of paleopole positions on a map (Fig. 3.7a; Box 3.1). The successive positions of dated paleopoles trace out a curving line that came to be known as an **apparent polar-wander path**.

At first, geologists assumed that the apparent polar-wander path represented how the position of Earth's magnetic pole really migrated over time. But were they in for a surprise! When they obtained polar-wander paths from many different continents, they found that each continent has a different apparent polar-wander path (Fig. 3.7b). The hypothesis that continents are fixed

FIGURE 3.7 Apparent polar-wander paths and their interpretation.



(a) Measurements of paleomagnetism in a succession of rock layers on a continent (x) define an apparent polar-wander path relative to the continent.

(b) The apparent polar-wander path of North America is not the same as that of Europe or Africa.

(c) If continents are fixed, then the pole moves relative to the continent. If the pole is fixed, then the continent must drift relative to the pole.

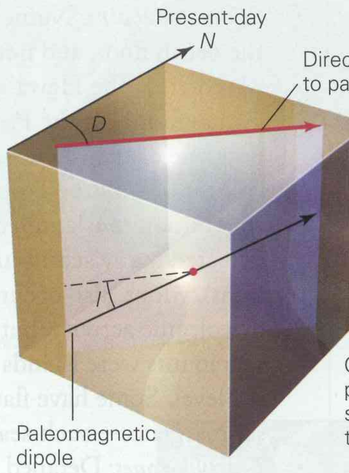
BOX 3.1 CONSIDER THIS . . .

Finding Paleopoles

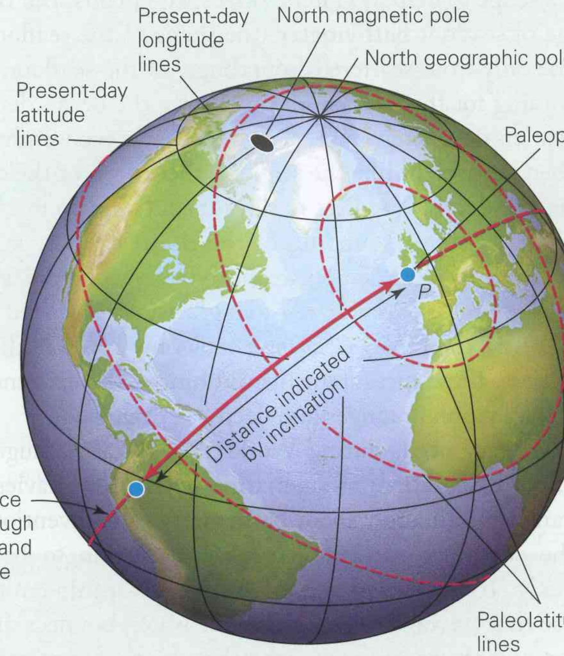
How do you find a paleopole position from the orientation of a paleomagnetic dipole in a rock sample? The horizontal projection of the dipole arrow on the Earth's surface (picture the projection as the shadow cast on the Earth's surface by the arrow if the Sun were directly overhead) is like a compass needle that points to the paleopole; that is, the projection defines an imaginary great circle around the Earth that passes through the paleopole and the sample (**Fig. Bx3.1**). This great circle is like an imaginary "paleolongitude" line. Note that when drawing the circle, we assume that the declination at the time the sample was magnetized equals 0, because we assume that, averaged over time, the magnetic pole coincides with the geographic pole.

To find the specific position of the paleopole on this great circle, we must look at the inclination of the paleomagnetic dipole in the rock. Recall that inclination depends on latitude (see Fig. 3.5d). Thus, the inclination of the paleomagnetic dipole defines the paleolatitude of the sample with respect to the paleopole, and paleolatitude simply represents the distance (measured in degrees) from the pole along the great circle to where the sample formed.

FIGURE Bx3.1 The basic concept of how to find a paleopole from a paleomagnetic measurement.



(a) In a sample of rock (represented by the cube), the paleomagnetic arrow has a declination, *D*, in the horizontal plane, and an inclination, *I*, in the vertical plane.



(b) The *D* of the sample points to the paleopole, *P*. Thus, the location of the rock outcrop and *P* lie on a circumference that represents a line of paleolongitude. The inclination indicates the paleolatitude of the sample and thus is a distance measured along the paleolongitude.

in position cannot explain this observation, for if the magnetic pole moved while all the continents stayed fixed, measurements from all continents should produce the same apparent polar-wander paths. Geologists suddenly realized that they were looking at apparent polar-wander paths in the wrong way. It's not the pole that moves relative to fixed continents but rather the continents that move relative to a fixed pole (**Fig. 3.7c**). And since each continent has its own unique polar-wander path, the continents must also be moving relative to one another. In effect, the interpretation of apparent polar-wander paths proved that Wegener was right all along—continents do move! Even so, much of the geologic community remained skeptical of continental movement because no one had yet been able to describe the mechanism that caused continents to move. But that was soon to come.

Take-Home Message

A rock can contain a record of the position of the Earth's magnetic poles, relative to the rock, at the time the rock formed. Study of such paleomagnetism indicates that the continents have moved relative to the Earth's magnetic poles. Each continent has a different apparent polar-wander path, which is possible only if the continents move relative to one another.

QUICK QUESTION: How does comparison of apparent polar-wander paths for different continents prove that continents move relative to each other?

3.4 The Discovery of Seafloor Spreading

New Images of Seafloor Bathymetry

Before World War II, we knew less about the shape of the ocean floor than we did about the shape of the Moon's surface. After all, we could at least see the surface of the Moon and could use a telescope to map its craters, ridges, and plains. But our knowledge of seafloor **bathymetry** (the shape of the seafloor surface) came only from scattered "soundings" of the seafloor. To take a sounding for the purpose of measuring the ocean depth, a surveyor lets out a length of cable with a heavy lead weight attached. When the weight hits the seafloor, the length of the cable indicates the depth. Needless to say, it could take up to a few hours to make a single sounding of the deep seafloor, so measurements were few and far between. In fact, during the world's first dedicated oceanographic research cruise, which lasted four years (1872–76), the HMS *Challenger* took only 360 soundings. Nevertheless, these measurements did hint at the existence of submarine mountain ranges and deep-sea troughs.

Military needs during World War II gave a huge boost to seafloor exploration; as submarine fleets grew, navies required detailed information about bathymetry. The invention of *sonar* (echo sounding) permitted such information to be gathered quickly. To make a sounding using sonar, a ship emits a sound pulse that travels down through the water, bounces off the seafloor, and returns up as an echo through the water to a receiver. Since sound waves travel at a known velocity, the time between the sound's emission and the echo's detection indicates the distance between the ship and the seafloor (Velocity = Distance ÷ Time; therefore: Distance = Velocity × Time). Because sound waves travel much faster than ships—a ship moves only about 2 m in the time it takes for a sound wave to travel to the deep seafloor and back—observers can obtain a continuous record of the depth to the seafloor and can produce a *bathymetric profile*, a graph showing how depth varies with location along a line. By cruising back and forth across the ocean many times at different locations, investigators eventually obtained enough bathymetric profiles to construct a *bathymetric map* of the seafloor. (Researchers now produce such maps much more rapidly and accurately using satellite data; **Fig. 3.8a**). Bathymetric maps reveal several important features (see Fig. 2.6).

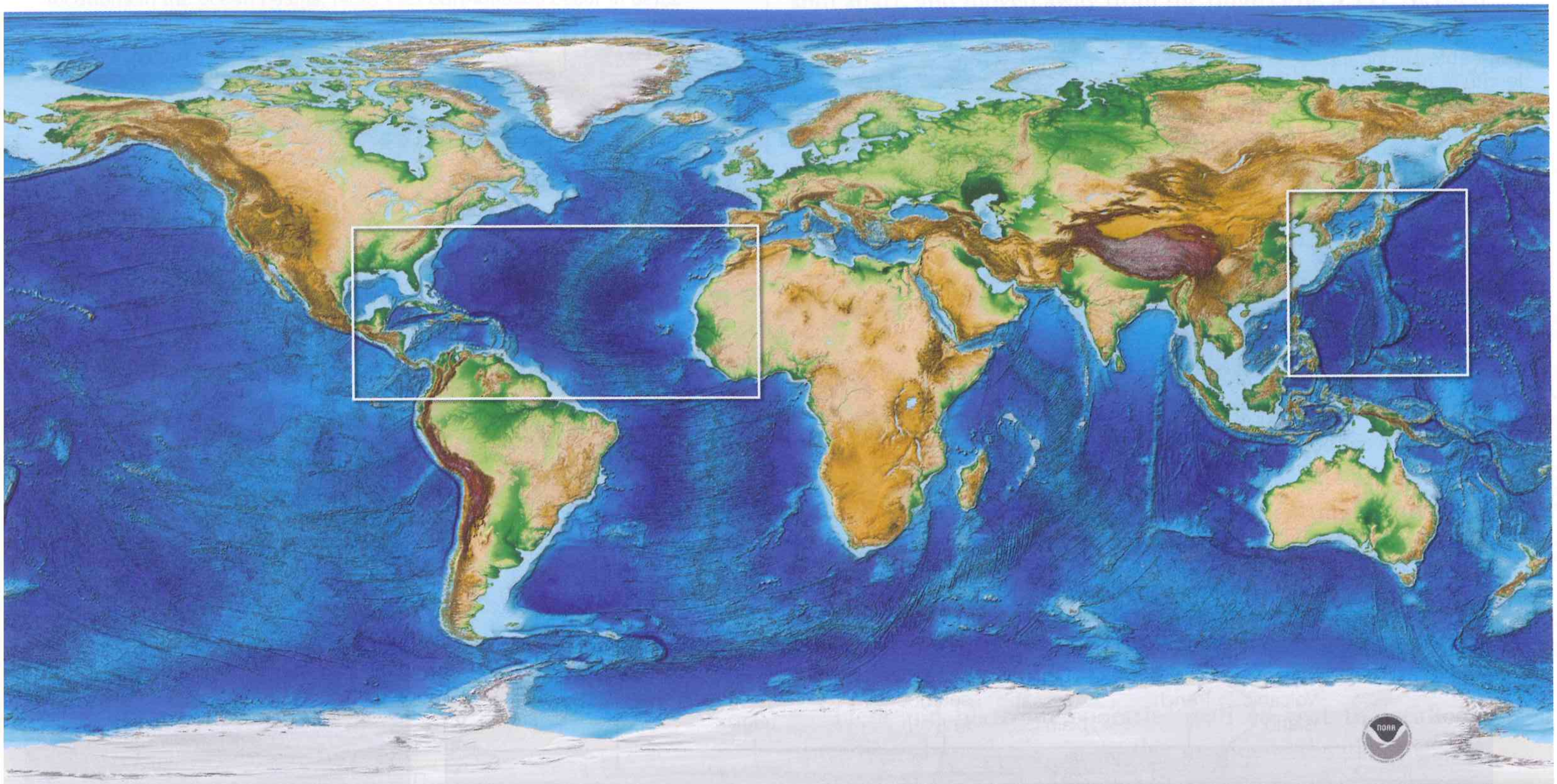
- *Mid-ocean ridges:* The floor beneath oceans includes **abyssal plains**, broad flat regions of the ocean that lie at a depth of 4 to 5 km below sea level, and **mid-ocean ridges**, elongate submarine mountain ranges whose peaks lie about 2 to 2.5 km below sea level (**Fig. 3.8b, c**). Geologists call the crest of the mid-ocean ridge the **ridge axis**. Mid-ocean ridges are roughly symmetrical, in that the bathymetry on one side of the ridge axis is more or less a mirror image of bathymetry on the other side.
- *Deep-ocean trenches:* Along much of the perimeter of the Pacific Ocean, and at several other localities as well, the ocean floor reaches depths greater than 5 km. These deep areas define elongate troughs that are now referred to as **trenches** (**Fig. 3.9**). Some trenches have depths in the range of 8 to 10 km, more than twice the depth of the abyssal plains. In fact, the deepest trench, the Mariana Trench of the western Pacific, reaches a depth of 10.9 km, deep enough to swallow Mt. Everest without a trace. All trenches border **volcanic arcs**, curving chains of active volcanoes (see Fig. 3.9b inset). Some volcanic arcs form a chain of islands, whereas others fringe the edge of continents.
- *Seamount chains:* Numerous volcanic islands poke up from the ocean floor, and not all of these are along volcanic island arcs. The Hawaiian Island chain, for example, lies in the middle of the Pacific. In contrast to an island arc, only one of the islands of the chain has active (erupting) volcanoes—all the other islands ceased erupting long ago. In addition to islands that rise above sea level, sonar has detected many **seamounts** (isolated submarine mountains), which also occur in chains. Seamounts originated by volcanic activity, but most are no longer active. Many seamounts were islands at one time but later sank beneath sea level. Some have flat tops due to reef growth before submergence—such seamounts are called *guyots.*
- *Fracture zones:* Detailed bathymetric surveys reveal that narrow bands of vertical cracks and broken-up rock locally dice up the seafloor of mid-ocean ridges. Notably, these bands, or **fracture zones**, trend at a high angle to the associated ridge axis and separate the ridge into small segments that do not align with one another (see Fig. 3.9a inset). Fracture zones become less distinct away from the ridge axis and are not visible on the surface of abyssal plains.

New Observations on the Nature of Oceanic Crust

By the mid-20th century, geologists had discovered many important characteristics of the seafloor crust and filled in huge blanks on the map of the Earth. These discoveries led them to realize that oceanic crust is quite different from continental crust and, further, that bathymetric features of the ocean floor provide clues to the origin of the crust. Of particular note:

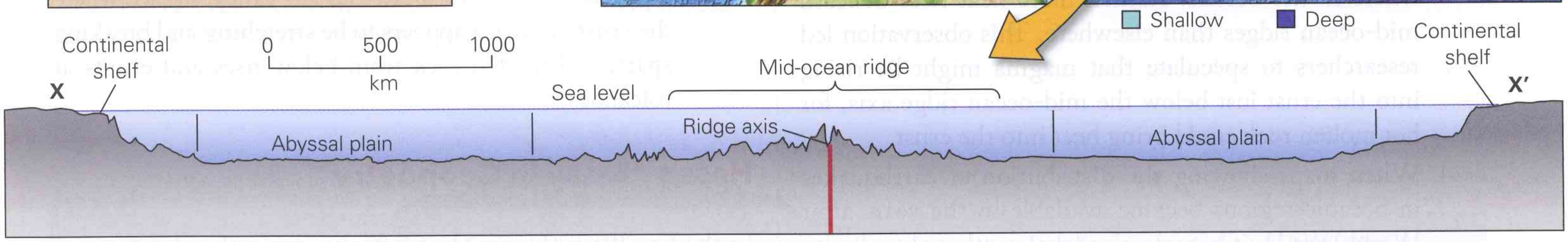
1. Researchers found that a layer of sediment, composed of clay and the tiny shells of dead plankton, covers much of the ocean floor, but even at its thickest, given observed rates of sediment accumulation, the sediment layer is far too thin to have been accumulating for the

FIGURE 3.8 Bathymetry of the whole ocean, and of mid-ocean ridges in particular.



(a) A modern bathymetric map of the ocean floor. The squares indicate the locations of the seafloor in Figure 3.8b and the inset of Figure 3.9a.

(b) Sonar allows a ship to map seafloor bathymetry easily. Sonar determines water depth using sound waves.

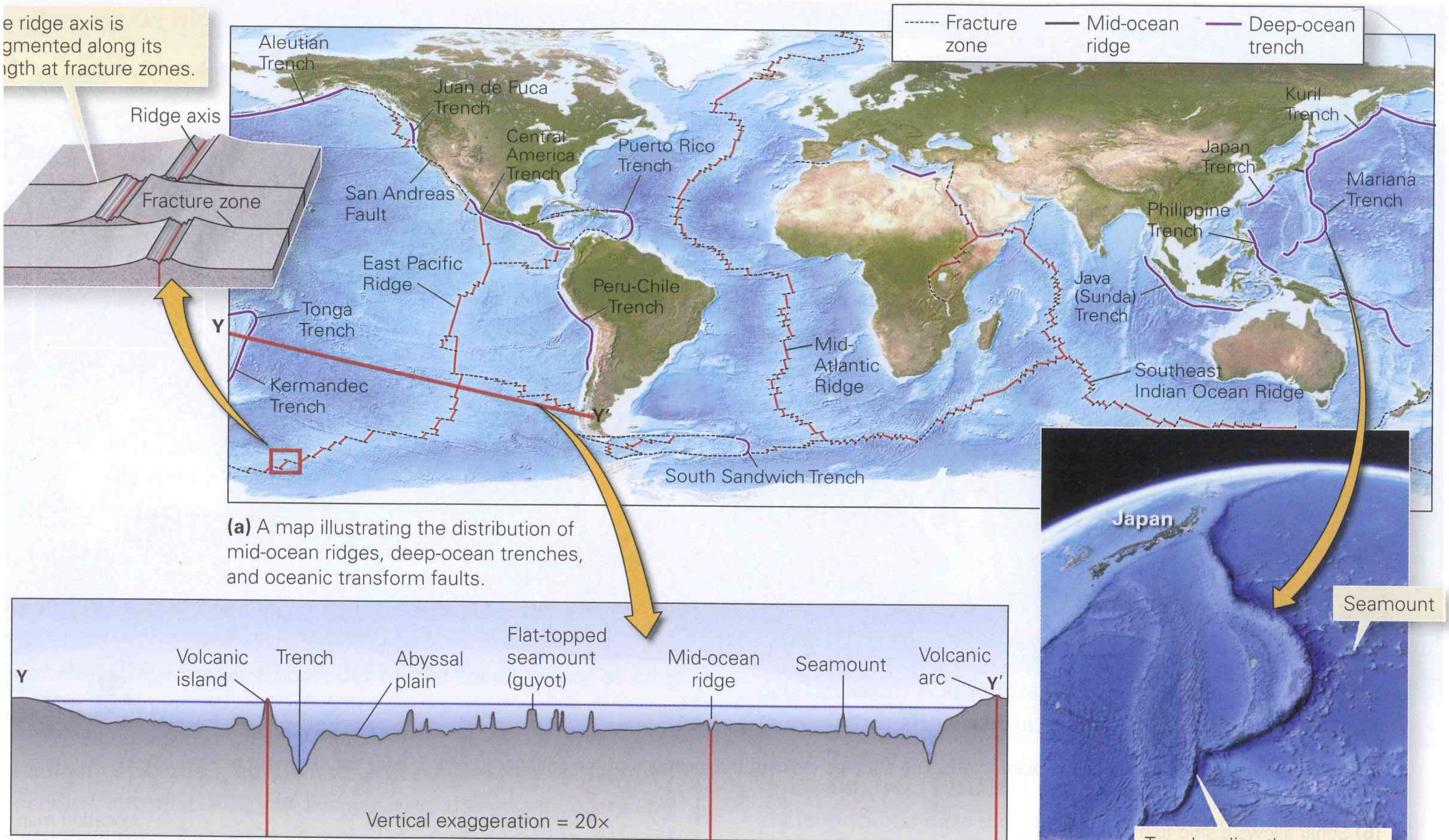


(c) A bathymetric profile along line X–X′ illustrates how mid-ocean ridges rise above abyssal plains. Both are deeper than continental shelves.

entirety of Earth history. Also of note, the sediment layer becomes progressively thicker away from the mid-ocean ridge axis—in fact, there's almost no sediment at all near the ridge axis.

2. By dredging up samples from the seafloor, geologists learned that oceanic crust is fundamentally different in composition from continental crust. Beneath its sediment cover, oceanic crust bedrock consists primarily

FIGURE 3.9 Other bathymetric features of the ocean floor.



(a) A map illustrating the distribution of mid-ocean ridges, deep-ocean trenches, and oceanic transform faults.

(b) In addition to mid-ocean ridges, the sea floor displays other bathymetric features such as deep-sea trenches, oceanic islands, guyots, and seamounts, as shown in this vertically exaggerated profile.

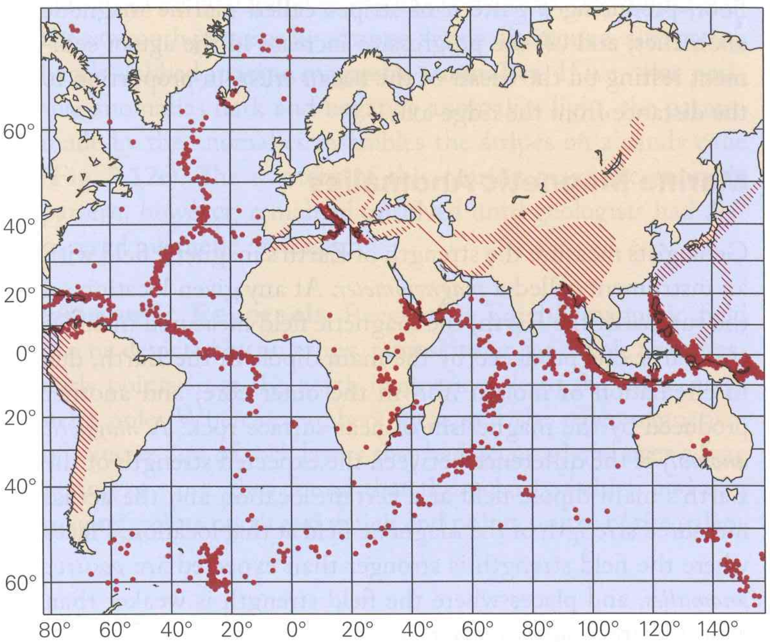
of basalt—it does not display the great variety of rock types found on continents.

3. **Heat flow**, the rate at which heat rises from the Earth's interior up through the crust, is not the same everywhere in the oceans. Rather, more heat rises beneath mid-ocean ridges than elsewhere. This observation led researchers to speculate that magma might be rising into the crust just below the mid-ocean ridge axis, for hot molten rock could bring heat into the crust.
4. When maps showing the distribution of earthquakes in oceanic regions became available in the years after World War II, it became clear that earthquakes do not occur randomly but rather occur in distinct zones called **seismic belts** (Fig. 3.10). Some belts follow trenches, some follow mid-ocean ridge axes, and others lie along portions of fracture zones. Since earthquakes define locations where rocks break and move, geologists concluded that these bathymetric features are places where movements of the crust are taking place.
5. The *ridge axis* of some mid-ocean ridges is marked by a narrow (a few kilometers wide), elongate trough hundreds of meters deeper than its borders. In this regard, the bathymetry of a mid-ocean ridge resembles the topography of the East African rift valley, a place where the crust of Africa appears to be stretching and breaking apart, and molten rock from below rises and erupts at volcanoes.

Hess's "Essay in Geopoetry"

In the late 1950s, Harry Hess, after studying the observations described above, concluded that because the sediment layer on the ocean floor was so thin overall, the ocean floor must be much younger than the continents, and because the sediment thickened progressively away from mid-ocean ridges, the ridges themselves likely were younger than the deeper parts of the ocean floor. If this was so, then somehow new ocean floor must be forming at the ridges, and thus an ocean could be get-

FIGURE 3.10 A 1953 map showing the distribution of earthquake locations in the ocean basins. Note that earthquakes occur in belts.



ting wider with time. But how? The association of earthquakes with mid-ocean ridges suggested to him that the seafloor was breaking at the ridge. Furthermore, the discovery of high heat flow along mid-ocean ridge axes and the similarity of ridges to the East African rift indicated that molten rock was rising up beneath ridges and that the seafloor crust was stretching. In 1960, Hess finally saw how these observations fit together and wrote a manuscript in which he proposed that this material from the mantle rose beneath mid-ocean ridges; that at the ridge axis melt derived from the mantle solidified to form oceanic crust; and that, once formed, the new crust cracked, split apart, and moved away from the ridge (**Fig. 3.11**). As each increment of seafloor formed and moved away from the ridge axis, more melt rose from the mantle, filled the space, and became the next increment of seafloor. Robert Dietz, as we've noted, named the process **seafloor spreading**.

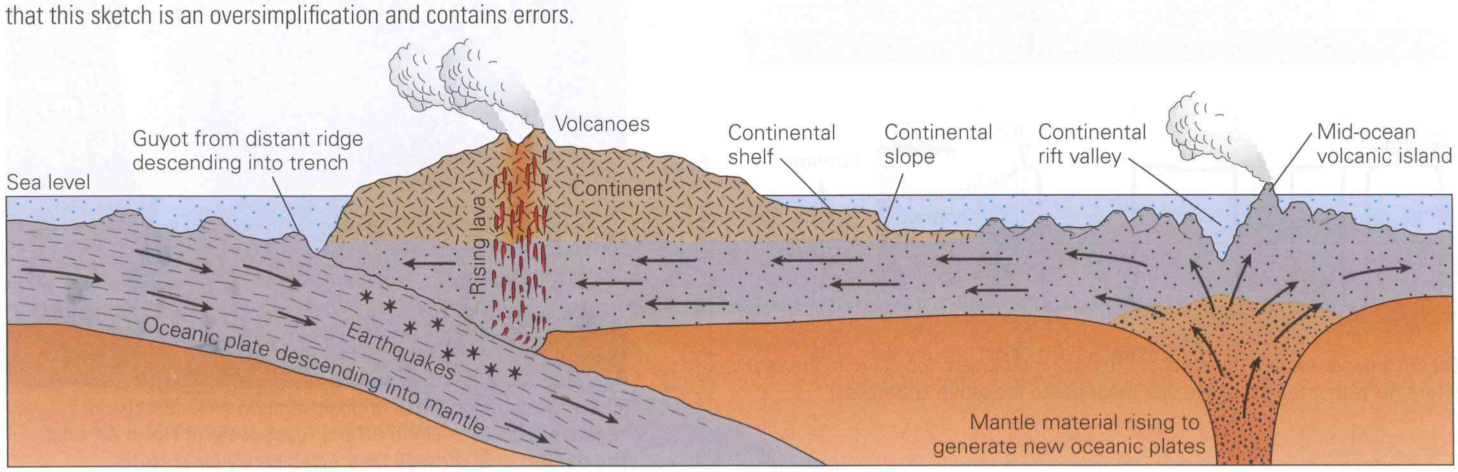
The concept that seafloor spreading takes place, allowing ocean basins to grow wider with time, led to a dilemma. Geologists realized that if new ocean floor formed, old ocean floor must be consumed or destroyed somewhere, or the Earth's circumference would have to increase, meaning the Earth would have to be expanding significantly, which the vast majority of studies had concluded wasn't possible. Hess suggested that deep-ocean trenches might be the places where the seafloor sank back into the mantle and that the earthquakes occurring at trenches were evidence of this movement. Part of the inspiration for this idea came from Hess's earlier study of guyots—he had found that guyots on the margins of trenches had tilted over, as if the seafloor that they had grown on was being bent and pulled into the trench. Geologists now refer to the process by which ocean floor bends and sinks back into the Earth's interior at trenches as **subduction**.

Hess and his contemporaries realized that the seafloor-spreading hypothesis instantly provided the long-sought explanation of how continental "drift" occurs. Continents passively move apart as the seafloor between them spreads at mid-ocean ridges, and they passively move together as the seafloor between them sinks back into the mantle at trenches. Researchers soon realized that the entity that was moving did not consist of crust alone but rather of the whole lithosphere (the crust plus the underlying cooler, and rigid,

Did you ever wonder . . .

if the distance between New York and Paris changes?

FIGURE 3.11 Harry Hess's basic concept of seafloor spreading (1962). Hess implied, incorrectly, that only the crust moved. We will see that this sketch is an oversimplification and contains errors.



portion of the upper mantle). The idea that the outer shell of the earth was in motion, with ocean floor formed at ridges and consumed at trenches, seemed to be so good that Hess referred to his description of it as "an essay in geopoetry."

Take-Home Message

New observations about seafloor bathymetry, sediment cover, heat flow, and seismicity led to Hess's proposal of seafloor spreading–new seafloor forms at mid-ocean ridges and then moves away from the ridge axis, so ocean basins can get wider with time. As this happens, old ocean floor sinks back into the mantle by subduction.

QUICK QUESTION: How does seafloor spreading and subduction provide an explanation for how continents move?

3.5 Evidence for Seafloor Spreading

For a hypothesis to become a theory (see Box P.1), it must be tested—scientists must demonstrate that the idea really works. During the 1960s, geologists found that the seafloor-spreading hypothesis successfully explained several previously baffling observations. Here we discuss two: (1) the existence of orderly variations in the strength of the magnetic field over the seafloor, producing a pattern of stripes called marine magnetic anomalies, and (2) the progressive increase in the age of sediment resting on the basalt of the ocean crust, in proportion to the distance from the ridge axis.

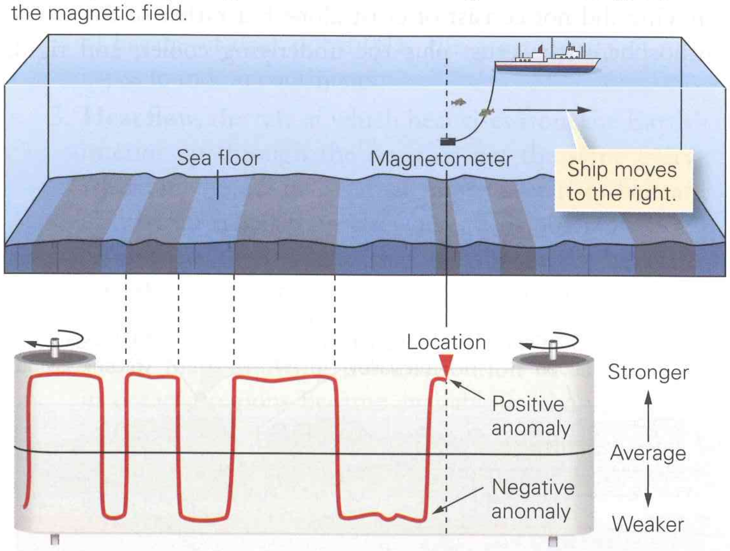
Marine Magnetic Anomalies

Geologists measure the strength of Earth's magnetic field with an instrument called a *magnetometer*. At any given location on the surface of the Earth, the magnetic field measured includes two parts: one produced by the main dipole of the Earth, due to circulation of molten iron in the outer core, and another produced by the magnetism of near-surface rock. A *magnetic anomaly* is the difference between the expected strength of the Earth's main dipole field at a certain location and the actual measured strength of the magnetic field at that location. Places where the field strength is stronger than expected are *positive anomalies*, and places where the field strength is weaker than expected are *negative anomalies*.

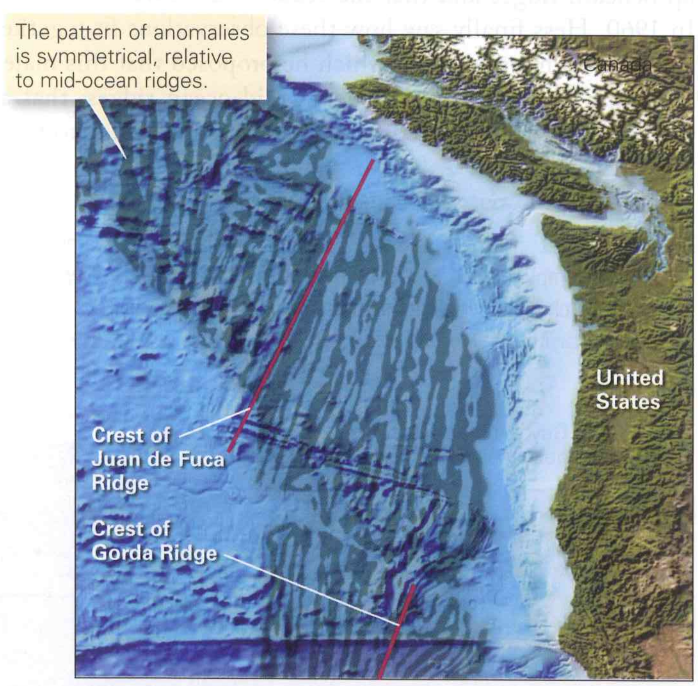
Year after year, in the course of doing other oceanographic and/or seafloor studies, researchers towed magnetometers back and forth across the ocean to map variations in magnetic field strength (**Fig. 3.12a**). As a ship cruised along its course, they found that the magnetometer's gauge would first detect an interval of strong signal (a positive anomaly) and then suddenly an interval of weak signal (a negative anomaly). A graph

FIGURE 3.12 The discovery of marine magnetic anomalies.

(a) A ship towing a magnetometer detects changes in the strength of the magnetic field.



(b) On a paper record, intervals of stronger magnetism (positive anomalies) alternate with intervals of weaker magnetism (negative anomalies).



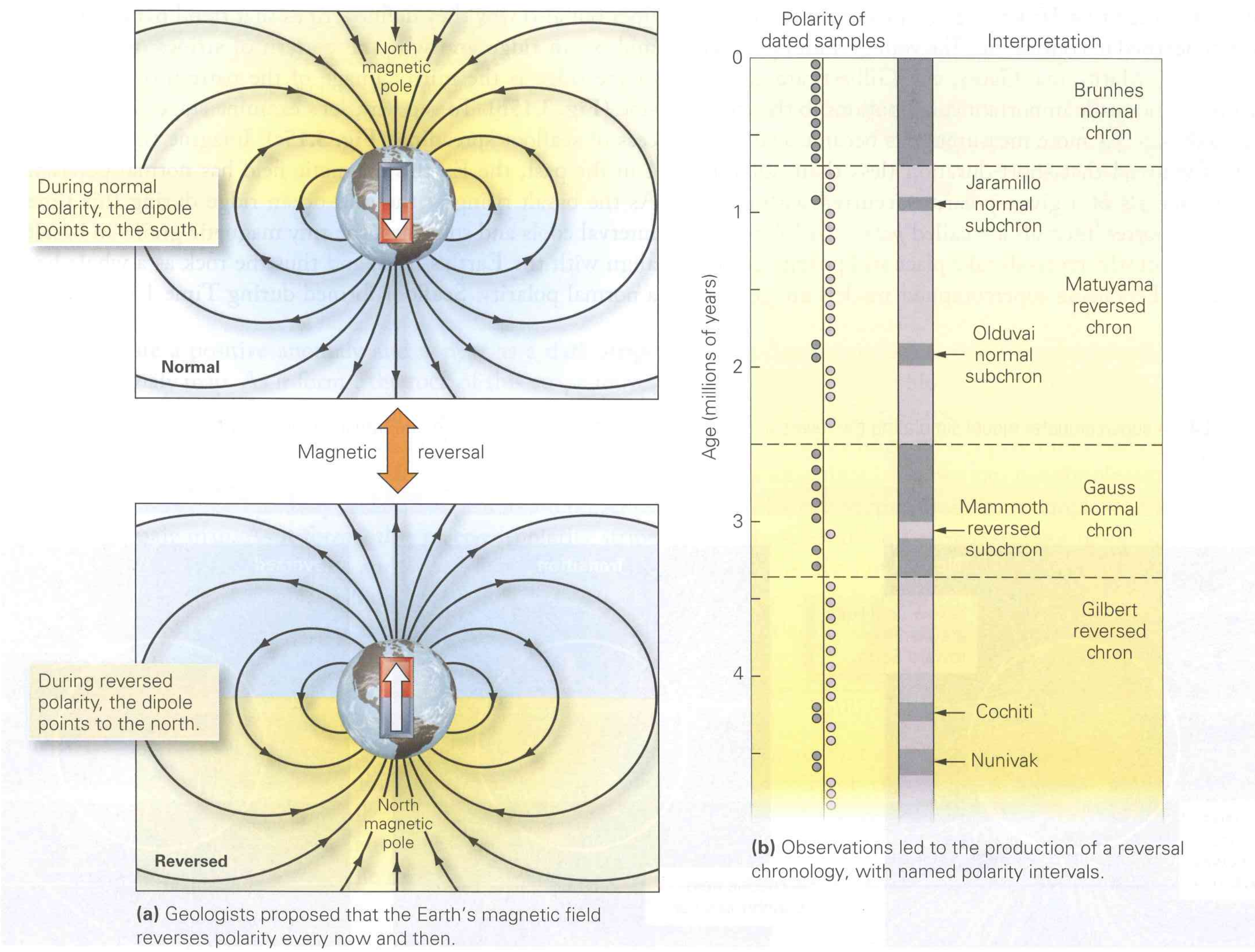
(c) A map showing areas of positive anomalies (dark) and negative anomalies (light) off the west coast of North America. The pattern of anomalies resembles candy-cane strips.

of signal strength versus distance along the traverse, therefore, has a sawtooth shape (**Fig. 3.12b**). When researchers compiled data from many parallel cruise lines on a map, they found that the sawtooth patterns lined up to define distinctive, alternating bands dubbed **marine magnetic anomalies**. If we color positive anomalies dark and negative anomalies light, the pattern made by the anomalies resembles the stripes on a candy cane (**Fig. 3.12c**). The mystery of this marine magnetic anomaly pattern, however, remained unsolved until geologists had discovered magnetic reversals.

Magnetic Reversals Recall that Earth's magnetic field can be depicted by an arrow, representing the dipole that presently points from the north magnetic pole to the south magnetic pole. When researchers measured the paleomagnetism of a succession of rock layers that had accumulated over a long period of time, they found that the polarity (which end of a magnet points north and which end points south) of the paleomagnetic field preserved in some layers was the same as that of Earth's present magnetic field, whereas in other layers it was the opposite.

At first, reversed polarity was thought to be the result of lightning strikes or of local chemical reactions between rock and water. But when repeated measurements from around the world revealed a systematic pattern of alternating normal and reversed polarity in rock layers, geologists realized that reversals were a worldwide, not a local, phenomenon. They reached the unavoidable conclusion that at various times during Earth history the polarity of Earth's magnetic field has suddenly flipped! In other words, sometimes the Earth has *normal polarity*, as it does today, and sometimes it has *reversed polarity* (**Fig. 3.13a**). When the Earth has reversed polarity, the south magnetic pole lies near the north geographic pole, and the north magnetic pole lies near the south geographic pole. Thus, if you were to use a compass during periods when the Earth's magnetic field was reversed, the north-seeking end of the needle would point

FIGURE 3.13 Magnetic polarity reversals and the chronology of reversals.



(a) Geologists proposed that the Earth's magnetic field reverses polarity every now and then.

(b) Observations led to the production of a reversal chronology, with named polarity intervals.

to the south geographic pole. A time when the Earth's field flips from normal to reversed polarity, or vice versa, is called a **magnetic reversal**. Note that the Earth itself doesn't turn upside down—it is just the magnetic field that reverses.

In the 1950s, about the same time that polarity reversals were discovered, researchers developed a technique that permitted them to define the *numerical age* of a rock, meaning the age of the rock in years. (The technique, called isotopic dating, will be discussed in detail in Chapter 12.) Geologists applied the technique to determine the ages of the rock layers for which they obtained their paleomagnetic measurements and thus determined when the magnetic field of the Earth reversed. With this information, they constructed a history of magnetic reversals for the past 4.5 million years; this history is now called a **magnetic-reversal chronology**.

A diagram representing the Earth's magnetic-reversal chronology (**Fig. 3.13b**) shows that reversals do not occur periodically, so the lengths of different **polarity chrons**, the time intervals between reversals, are different. A polarity reversal from reverse (before) to normal (after) happened about 700,000 years ago. Thus, we are living in a normal polarity chron, which began about the time that *Homo erectus*, a precursor of modern humans, first learned to control fire. The youngest four polarity chrons (Brunhes, Matuyama, Gauss, and Gilbert) are named after scientists who made important contributions to the study of rock magnetism. As more measurements became available, investigators realized that short-duration (less than 200,000 years long) intervals of a given polarity occurred within the chrons—these shorter intervals are called *polarity subchrons*.

The question of why reversals take place still puzzles geologists, but researchers using supercomputer models are getting closer to an answer. The models show that changes in the fluid motion of the outer core can trigger reversals and that during reversals the magnetic field first weakens and becomes complicated (chaotic) before reconfiguring with a different polarity (**Fig. 3.14**).

Interpreting Marine Magnetic Anomalies Why do marine magnetic anomalies exist? In 1963, researchers in Britain and Canada proposed a solution to this riddle. Simply put, a positive anomaly occurs over areas of the seafloor where underlying basalt has normal polarity. In these areas, the weak magnetic force produced by the magnetite grains in basalt adds to the force produced by the Earth's dipole—the sum of these forces yields a stronger magnetic signal than expected due to the dipole alone (**Fig. 3.15a**). A negative anomaly occurs over regions of the seafloor where the underlying basalt has a reversed polarity. In these regions, the magnetic force of the basalt subtracts from the force produced by the Earth's dipole, so the measured magnetic signal is weaker than expected.

The seafloor-spreading model easily explains not only why positive and negative magnetic anomalies exist over the seafloor but also why they define stripes that trend parallel to the mid-ocean ridge and why the pattern of stripes on one side of the ridge is the mirror image of the pattern on the other side (**Fig. 3.15b**). To see why, let's examine stages in the process of seafloor spreading (**Fig. 3.15c**). Imagine that at Time 1 in the past, the Earth's magnetic field has normal polarity. As the basalt rising at the mid-ocean ridge during this time interval cools and solidifies, the tiny magnetic grains in basalt align with the Earth's field, and thus the rock as a whole has a normal polarity. Seafloor formed during Time 1 will there-

FIGURE 3.14 A supercomputer model simulating the reversal of the Earth's magnetic field. In nature, the transition probably takes thousands of years.

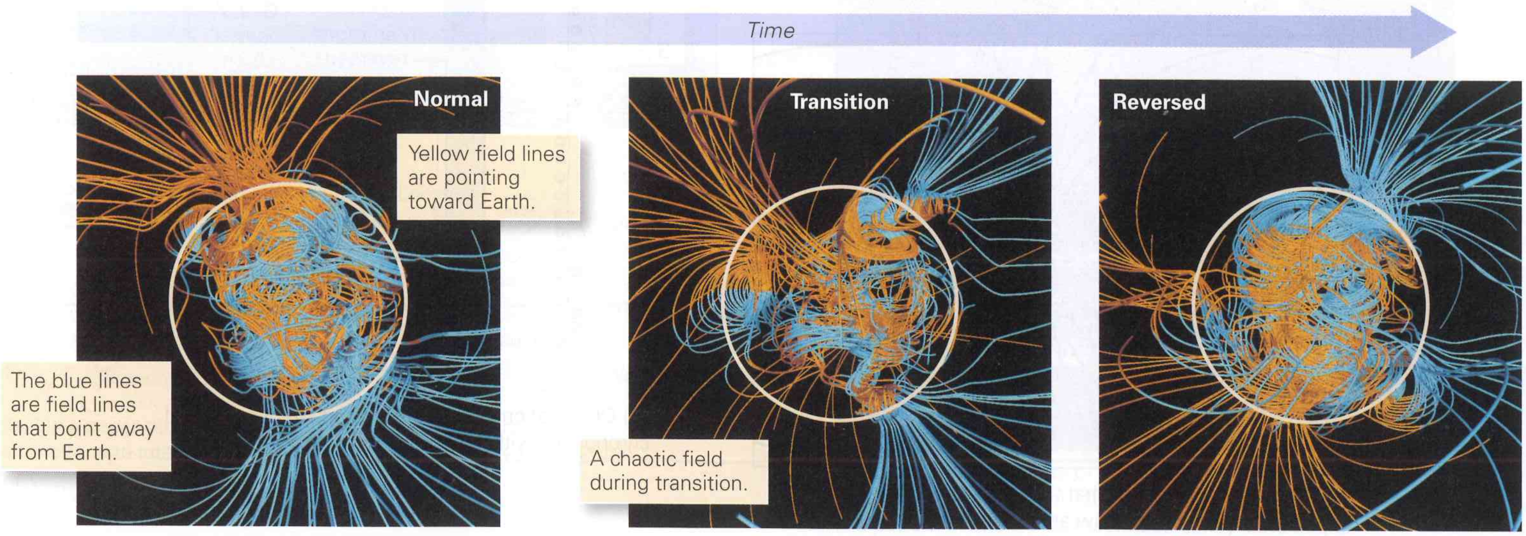
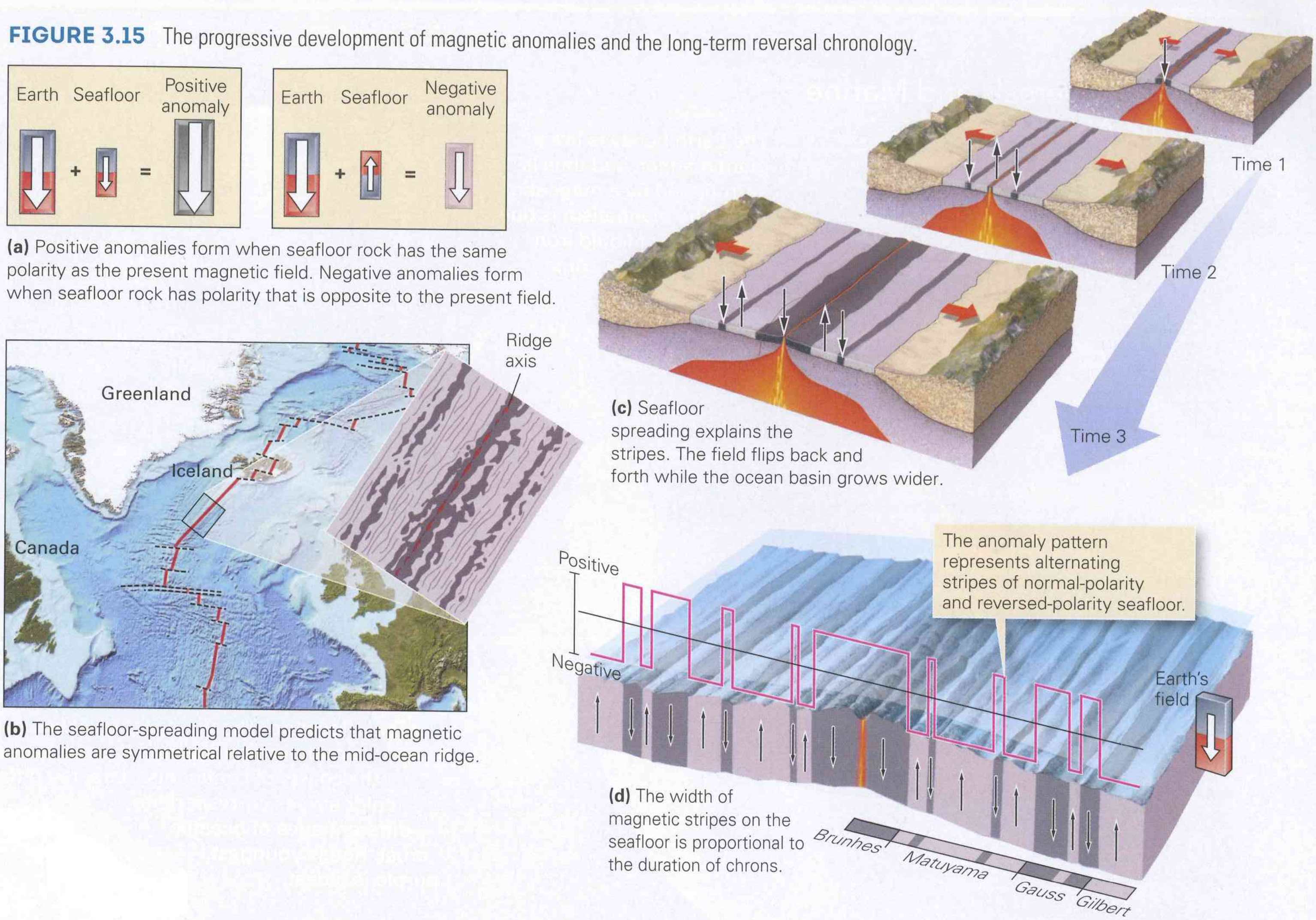


FIGURE 3.15 The progressive development of magnetic anomalies and the long-term reversal chronology.



(a) Positive anomalies form when seafloor rock has the same polarity as the present magnetic field. Negative anomalies form when seafloor rock has polarity that is opposite to the present field.

(b) The seafloor-spreading model predicts that magnetic anomalies are symmetrical relative to the mid-ocean ridge.

(c) Seafloor spreading explains the stripes. The field flips back and forth while the ocean basin grows wider.

(d) The width of magnetic stripes on the seafloor is proportional to the duration of chrons.

fore generate a positive anomaly and appear as a dark stripe on an anomaly map. As it forms, the rock of this stripe moves away from the ridge axis, so half goes to the right and half to the left. Now imagine that later, at Time 2, Earth's field has reversed polarity. Seafloor basalt formed during Time 2 therefore has reversed polarity and will appear as a light stripe on an anomaly map. As it forms, this reversed-polarity stripe moves away from the ridge axis, and even younger crust forms along the axis. The basalt in each new stripe of crust preserves the polarity that was present at the time it formed, so as the Earth's magnetic field flips back and forth, alternating positive and negative anomaly stripes form. A positive anomaly exists over the ridge axis today because seafloor is forming during the present chron of normal polarity.

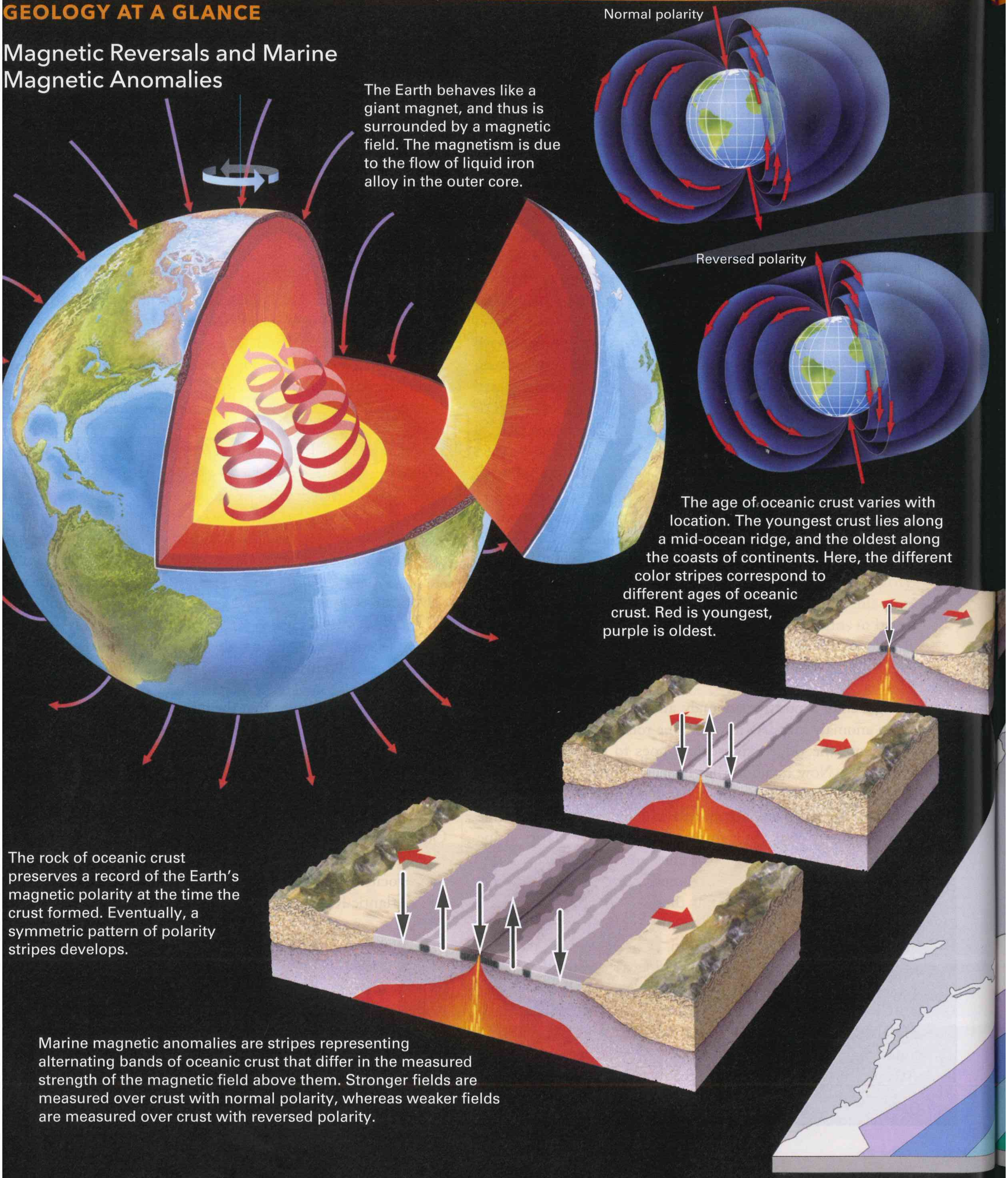
Closer examination of a seafloor magnetic anomaly map reveals that anomalies are not all the same width. Geologists found that the relative widths of anomaly stripes near the Mid-Atlantic Ridge are the same as the relative durations of paleomagnetic chrons (Fig. 3.15d; Geology at a Glance, pp. 80–81). This relationship between anomaly-stripe width and polarity-chron duration indicates that the rate of seafloor spreading has been fairly constant along the Mid-Atlantic Ridge for at least the last 4.5 million years.

If the spreading rate at a given mid-ocean ridge is constant over a long time, then we can use simple arithmetic to determine the rate of spreading. For example, in the North Atlantic Ocean, 4.5-million-year-old seafloor lies 45 km away from the ridge axis. Keeping in mind that Velocity = Distance/Time, the velocity (v) at which the seafloor moves away from the Mid-Atlantic Ridge axis can be calculated as follows:

$$v = \frac{45 \text{ km}}{4{,}500{,}000 \text{ years}} = \frac{4{,}500{,}000 \text{ cm}}{4{,}500{,}000 \text{ years}} = 1 \text{ cm/y}$$

This means that a point on one side of the ridge moves away from a point on the other side by 2 cm per year. We call this number the **spreading rate**. In the Pacific Ocean, seafloor spreading occurs at the East Pacific Rise. (Geographers named this a "rise" because it is not as rough and jagged as the Mid-Atlantic Ridge.) The anomaly stripes bordering the East Pacific Rise are much wider, and 4.5-million-year-old

Magnetic Reversals and Marine Magnetic Anomalies



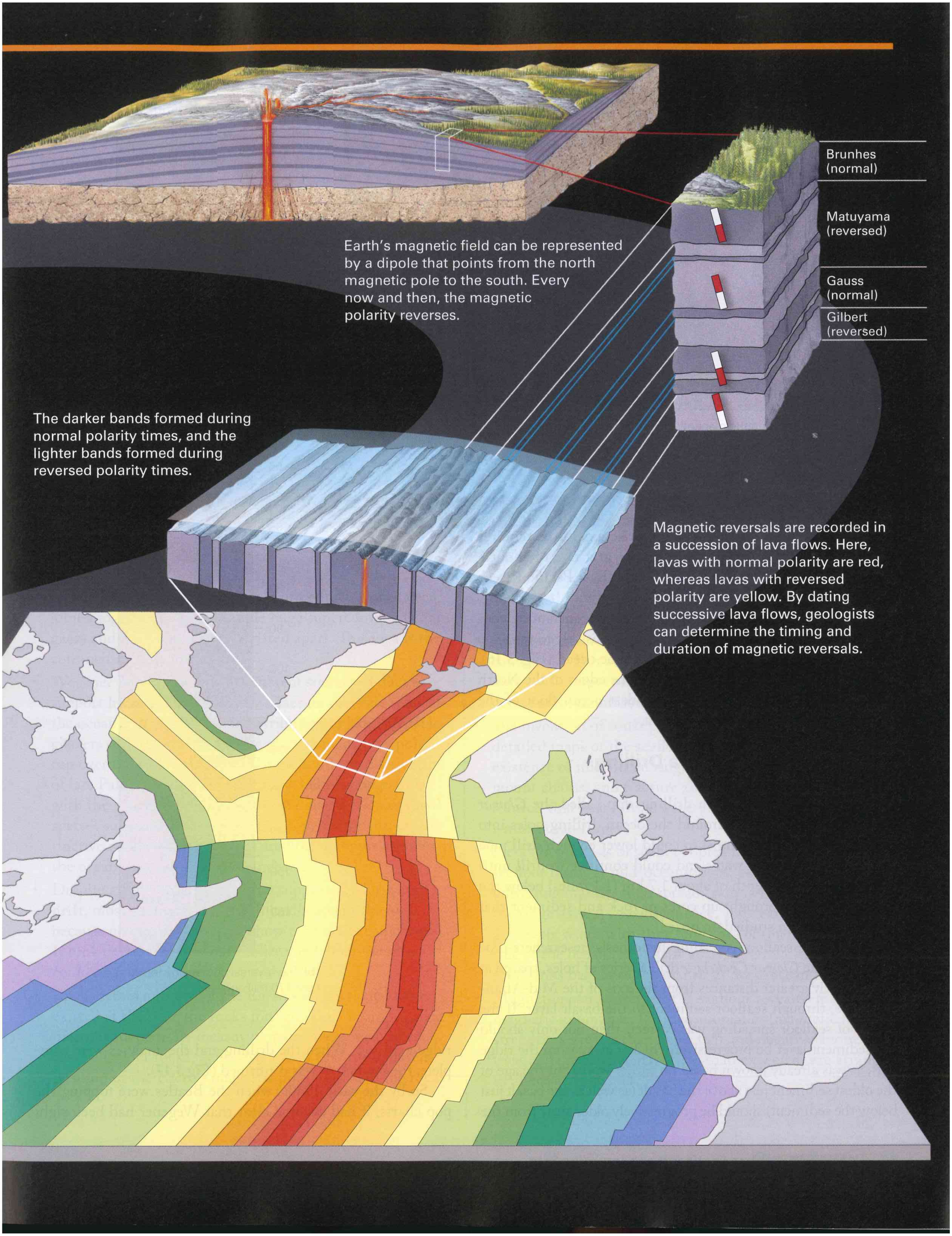
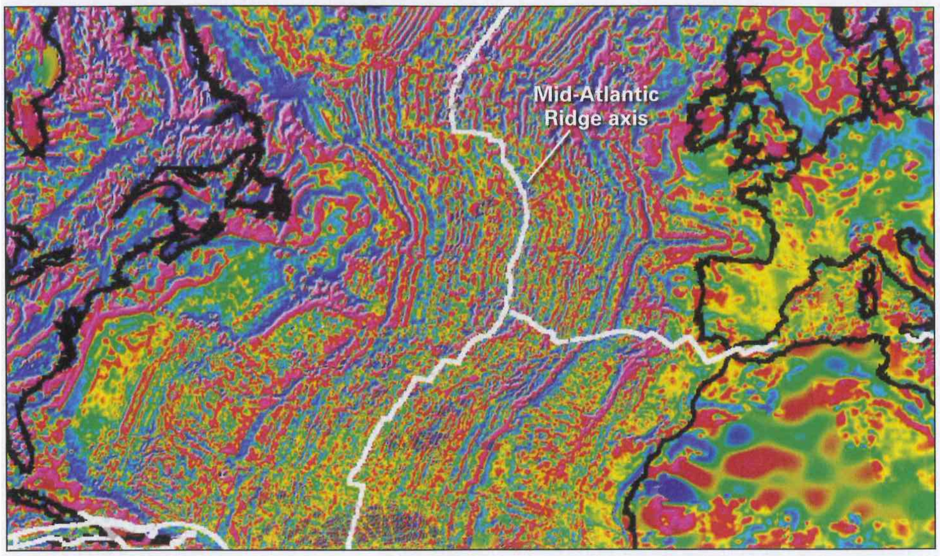
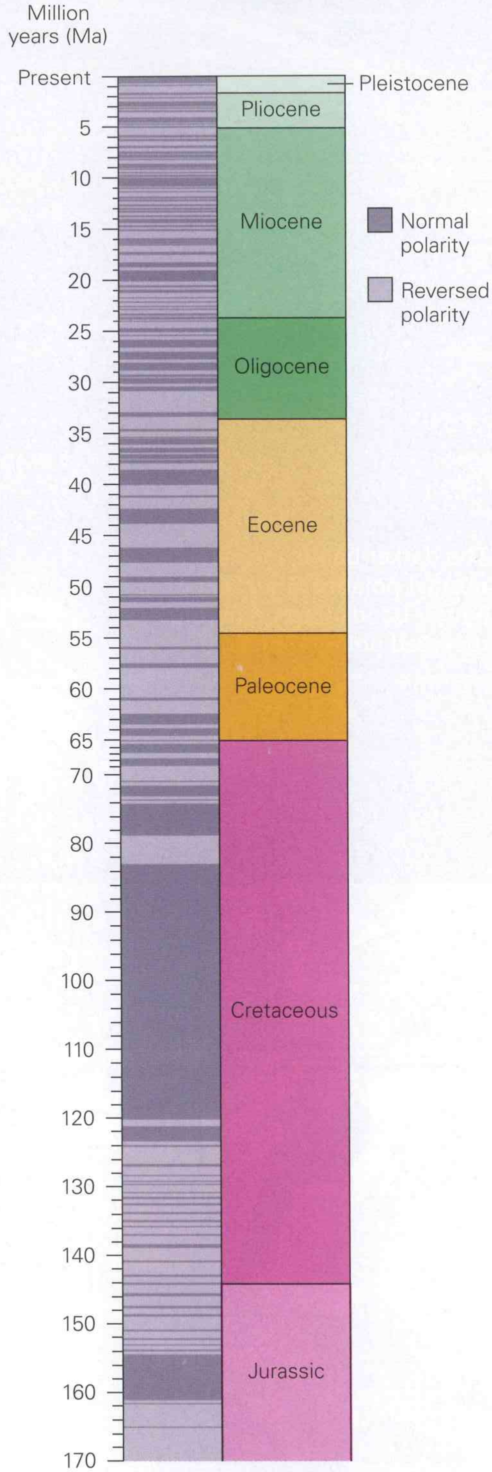

Brunhes
(normal)
Matuyama
(reversed)
Gauss
(normal)
Gilbert
(reversed)
Earth's magnetic field can be represented by a dipole that points from the north magnetic pole to the south. Every now and then, the magnetic polarity reverses.
The darker bands formed during normal polarity times, and the lighter bands formed during reversed polarity times.
Magnetic reversals are recorded in a succession of lava flows. Here, lavas with normal polarity are red, whereas lavas with reversed polarity are yellow. By dating successive lava flows, geologists can determine the timing and duration of magnetic reversals.

FIGURE 3.16 Magnetic anomalies across the width of the ocean permit determination of reversal chronology back further in time.



(a) A digital map showing the magnetic anomalies of the North Atlantic, and of adjacent continents. Note the striped pattern of the seafloor. (Anomalies on land don't show this pattern because they are controlled by the distribution of different rock types.) *Source*: Korhonen, et al., 2007, © CCGM-CGMW.



(b) The reversal chronology for the past 170 million years.

seafloor lies about 225 km from the rise axis. This requires the seafloor to move away from the rise at a rate of about 5 cm per year, so the spreading rate for the East Pacific Rise is about 10 cm per year.

If you assume that the spreading rate was constant for tens to hundreds of millions of years, then it is possible to estimate the age of stripes right up to the edge of the ocean (**Fig. 3.16**). Using this approach, the anomalies on the edges of the North Atlantic are about 175 Ma, so the oldest ocean floor of the North Atlantic formed about 175 Ma.

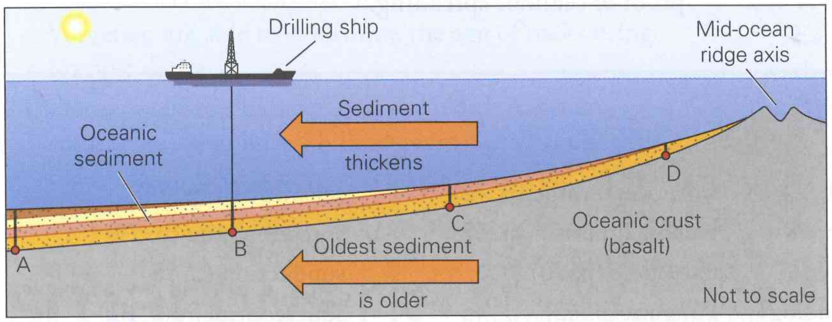
Evidence from Deep-Sea Drilling

In the late 1960s, a research drilling ship called the *Glomar Challenger* set out to sail around the ocean drilling holes into the seafloor. This amazing ship could lower enough drill pipe to drill in 5-km-deep water and could continue to drill until the hole reached a depth of about 1.7 km (1.1 miles) below the seafloor. Drillers brought up cores of rock and sediment that geoscientists then studied on board.

To test the seafloor-spreading hypothesis, researchers proposed that the *Glomar Challenger* drill a series of holes, spaced at progressively greater distances from the axis of the Mid-Atlantic Ridge, through seafloor sediment to the basalt layer. If the model of seafloor spreading was correct, then not only should the sediment layer be progressively thicker away from the ridge axis, as was already known based on earlier work, but the age of the oldest sediment just above the basalt (as well as the basalt just below the sediment) should be progressively older away from the ridge axis, too. When the drilling and the analyses were complete, the prediction was confirmed (**Fig 3.17**).

So by the early 1960s, when the Beatles were topping the pop charts, it had become clear that Wegener had been right all along—continents do move. But, though the case for such movement had been greatly strengthened by the discovery of apparent polar-wander paths, it really took the proposal and proof of seafloor spreading to make believers of most geologists. Very quickly, as we will see in the next chapter, these ideas became the basis of the theory of plate tectonics.

FIGURE 3.17 Drilling into the sediment layer of the ocean floor confirmed that the age of the oldest sediment in contact with ocean-crust basalt gets older the farther away it is from the ridge. For example, Point A is older than Point B.



Take-Home Message

The Earth's magnetic polarity flips every now and then. As a result, different stripes of ocean floor formed at mid-ocean ridges preserve different polarities. These cause marine magnetic anomalies. The discovery of these anomalies, as well as documentation that the seafloor gets older away from the ridge axis, proved that the seafloor-spreading hypothesis is correct.

QUICK QUESTION: What determines the widths of marine magnetic anomalies?

CHAPTER SUMMARY

- Alfred Wegener proposed that continents had once been joined together to form a single huge supercontinent (Pangaea) and had subsequently drifted apart. This idea is the continental-drift hypothesis.
- Wegener drew from several different sources of data to support his hypothesis: (1) coastlines on opposite sides of the ocean match up; (2) the distribution of late Paleozoic glaciers can be explained if the glaciers made up a polar ice cap over the southern end of Pangaea; (3) the distribution of late Paleozoic equatorial climatic belts is compatible with the concept of Pangaea; (4) the distribution of fossil species suggests the existence of a supercontinent; (5) distinctive rock assemblages that are now on opposite sides of the ocean were adjacent on Pangaea.
- Despite all the observations that supported continental drift, most geologists did not initially accept the idea because no one could explain how continents could move. It took decades of new data collection before the idea could be reconsidered.
- Rocks retain a record of the Earth's magnetic field that existed at the time the rocks formed. This record is called paleomagnetism. By measuring paleomagnetism in successively older rocks, geologists found that the apparent position of the Earth's magnetic pole relative to the rocks changes through time. Successive positions of the pole define an apparent polar-wander path.
- Apparent polar-wander paths are different for different continents. This observation can be explained if continents move with respect to one another while the Earth's magnetic poles remain roughly fixed.
- The invention of sonar permitted explorers to make detailed maps of the seafloor. These maps revealed the existence of mid-ocean ridges, deep-ocean trenches, seamount chains, and fracture zones. Other measurement showed that heat flow is generally greater near the axis of a mid-ocean ridge.
- Hess's hypothesis of seafloor spreading states that new seafloor forms at mid-ocean ridges, above a band of upwelling mantle, then spreads symmetrically away from the ridge axis. As a consequence, an ocean basin gets progressively wider with time, and the continents on either side of the ocean basin drift apart. Eventually, the ocean floor sinks back into the mantle at deep-ocean trenches.
- Magnetometer surveys of the seafloor revealed marine magnetic anomalies. Positive anomalies (magnetic field strength is greater than expected) and negative anomalies (magnetic field strength is less than expected) are arranged in alternating stripes.

- During the 1950s, geologists documented that the Earth's magnetic field reverses polarity every now and then. The record of reversals, dated by isotopic techniques, is called the magnetic-reversal chronology.
- A proof of seafloor spreading came from the interpretation of marine magnetic anomalies. Seafloor that forms when the Earth has normal polarity results in positive anomalies, whereas seafloor that forms when the Earth has reversed polarity results in negative anomalies. Anomalies are symmetric with respect to a mid-ocean ridge axis, and their widths are proportional to the duration of polarity chrons. Study of anomalies allows us to calculate the rate of spreading.
- Drilling of the seafloor confirmed that its age increases away from the mid-ocean ridge axis and served as another proof of seafloor spreading.

GUIDE TERMS

abyssal plain (p. 72)
apparent polar-wander path (p. 70)
bathymetry (p. 72)
continental drift (p. 63)
fracture zone (p. 72)
heat flow (p. 74)
magnetic declination (p. 67)
magnetic dipole (p. 67)
magnetic inclination (p. 68)
magnetic poles (p. 67)
magnetic-reversal chronology (p. 78)
magnetic reversal (p. 78)
marine magnetic anomaly (p. 77)
mid-ocean ridge (p. 72)
paleomagnetism (p. 67)
paleopole (p. 70)
Pangaea (p. 62)
polarity chron (p. 78)
ridge axis (p. 72)
seafloor spreading (p. 75)
seamount (p. 72)
seismic belt (p. 74)
spreading rate (p. 79)
subduction (p. 75)
supercontinent (p. 62)
trench (p. 72)
volcanic arc (p. 72)

REVIEW QUESTIONS

1. What was Wegener's continental-drift hypothesis?
2. How does the fit of the coastlines around the Atlantic support continental drift?
3. Explain the distribution of late Paleozoic glaciation.
4. How does the distribution of climatic belts support continental drift?
5. Was it possible for a dinosaur to walk from New York to Paris when Pangaea existed? Explain your answer.
6. Why were geologists initially skeptical of Wegener's continental-drift hypothesis?
7. What is paleomagnetism and how does it form?
8. Describe how the angle of inclination of the Earth's magnetic field varies with latitude. How can paleomagnetic inclination be used to determine the ancient latitude of a continent?
9. Describe the basic bathymetric characteristics of mid-ocean ridges, deep-ocean trenches, and seamount chains.
10. Describe the hypothesis of seafloor spreading.
11. How did the observations of heat flow and seismicity support the hypothesis of seafloor spreading?
12. What is a magnetic reversal?
13. What is a marine magnetic anomaly? How is it detected?
14. Describe the pattern of marine magnetic anomalies across a mid-ocean ridge. How do geologists explain the pattern?
15. How do geologists calculate rates of seafloor spreading?
16. Did drilling into the seafloor contribute further proof of seafloor spreading? If so, how?

ON FURTHER THOUGHT

The following questions will be answered, in large part, by Chapter 4. But by thinking about them now, you can get a feel for the excitement of discovery that geologists enjoyed in the wake of the proposal of seafloor spreading.

17. Alfred Wegener's writings implied that all continents had been linked to form Pangaea from the formation of the Earth until Pangaea's breakup in the Mesozoic. Modern geologists do not agree. Geologic evidence suggests that

Pangaea itself was formed by the late Paleozoic collision of continents that had been separate during most of the Paleozoic and that other supercontinents had formed and broken up prior to the Paleozoic. What geologic evidence led geologists to this conclusion? (Hint: Keep in mind that modern geologists, unlike Wegener, understand that mountain belts such as the Appalachians form when two continents collide and that modern geologists, unlike Wegener, are able to determine the age of rocks using isotopic dating.)

18. Dating methods indicate that the oldest rocks on continents are almost 4 billion years old, whereas the oldest ocean floor is only 200 million years old. Why?

19. The geologic record suggests that when supercontinents break up, a pulse of rapid evolution, with many new species appearing and many existing species becoming extinct, takes place. Why might this be? (Hint: Consider how the environment, both global and local, might change as a result of breakup, and keep in mind the widely held idea that competition for resources drives evolution.)

20. Why are the marine magnetic anomalies bordering the East Pacific Rise in the southeastern Pacific Ocean wider than those bordering the Mid-Atlantic Ridge in the South Atlantic Ocean?

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This chapter's Smartwork features:

- Interactive labeling problems on Earth's magnetic field.
- Visual exercises on the movements of Pangaea.
- Detailed questions on the chronology of magnetic polarity reversals.

GEOTOURS

This chapter's GeoTour exercises (A, B) feature:

- Topography of the ocean floor
- Continental drift

Another View This image was produced by Christoph Hormann, using computer rendering techniques. It shows the Caucasus Mountains between the Black Sea and the Caspian Sea. This range is forming due to the collision between two moving continental masses.