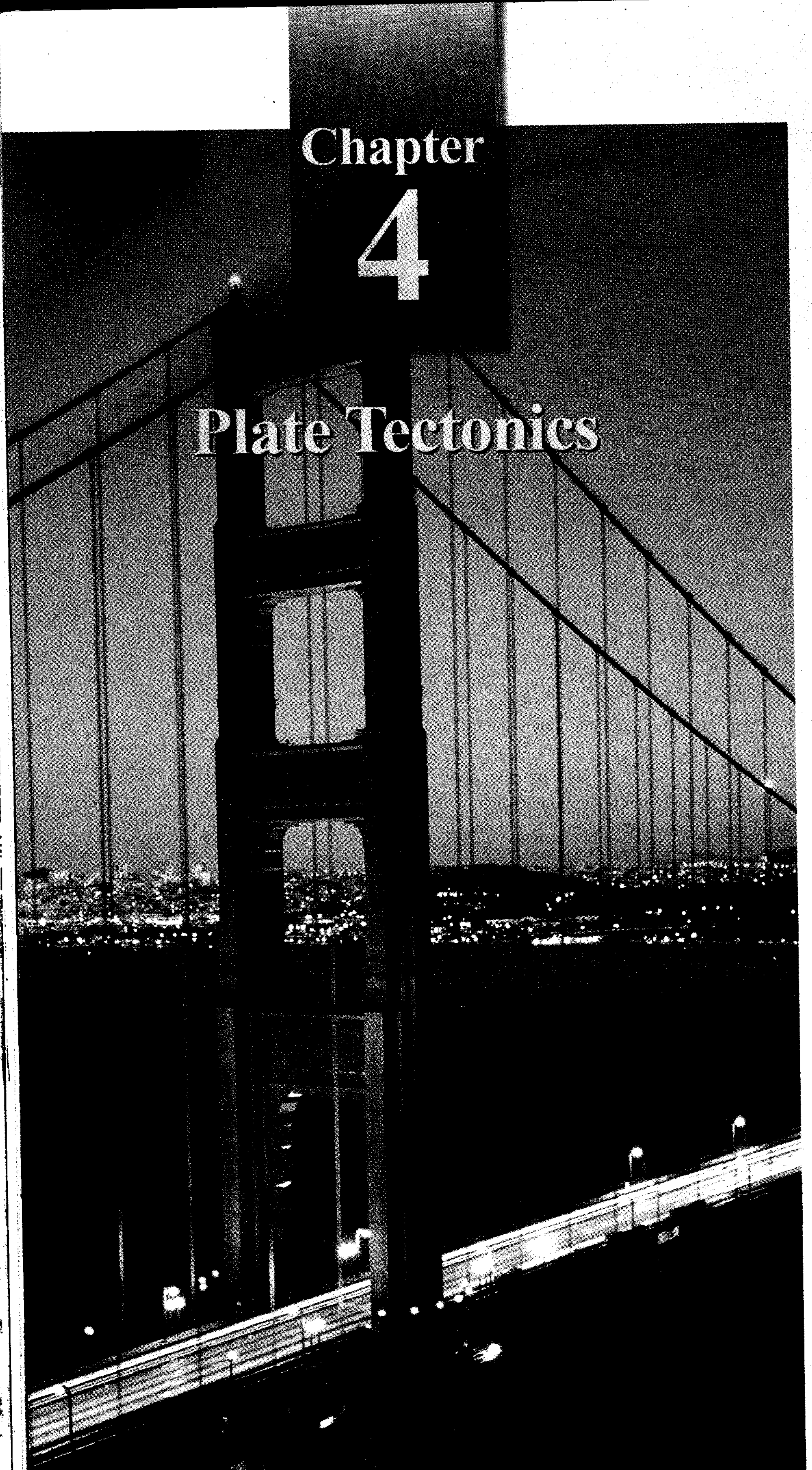
Chapter 4

Plate Tectonics



The earth is in constant motion. The planet spins on its axis and orbits the sun. Earth scientists also believe that the surface of the earth itself is in motion, broken up into plates that drift slowly around the planet, a process called plate tectonics. Plate tectonics has shaped the San Francisco Bay area, which includes crust from the ocean floor as well as sediments possibly from past continents. In this chapter, you will learn how plate tectonics causes changes in the earth's crust.

Chapter Outline

4.1 Continental Drift
- Evidence of Continental Drift
- Seafloor Spreading

4.2 The Theory of Plate Tectonics
- Lithospheric Plate Boundaries
- Causes of Plate Motion
- Suspect Terranes

◀ San Francisco is built on crust from the ancient ocean floor and possibly past continents.

4.1 Continental Drift

One of the most exciting recent theories in earth science began with observations made more than 400 years ago. As explorers such as Christopher Columbus and Ferdinand Magellan sailed the oceans of the world, they brought back information about new continents and their coastlines. Mapmakers used the information to chart the new discoveries and to make the first reliable world maps.

As people studied the maps, they were impressed by the similarity of the continental shorelines on either side of the Atlantic Ocean. The continents looked as though they would fit together, like parts of a giant jigsaw puzzle. The east coast of South America seemed to fit perfectly into the west coast of Africa. Greenland seemed to fit between North America and northwestern Europe.

These observations soon led to questions. Were the continents once part of the same huge landmass? If so, what caused this landmass to break apart? What caused the continents to move to their present locations? These questions eventually led to the formulation of hypotheses.

In 1912, a German scientist, Alfred Wegener, proposed a hypothesis called **continental drift,** which stated that the continents had moved. Wegener hypothesized that the continents once formed part of a single landmass, which he named **Pangaea** (pan-JEE-uh), meaning "all lands." Surrounding Pangaea was a huge ocean, **Panthalassa,** meaning "all seas." According to Wegener, about 200 million years ago, Pangaea began breaking up into smaller continents, which drifted to their present locations. Wegener speculated that this motion may have crumpled the crust in places, producing mountain ranges such as the Andes on the western coast of South America.

Section Objectives

- **Explain Wegener's hypothesis of continental drift.**
- **List evidence for Wegener's hypothesis of continental drift.**
- **Describe seafloor spreading.**

Evidence of Continental Drift

In addition to the similarities in the coastlines of the continents, Wegener soon found other evidence to support his hypothesis. If the continents had once been joined, he reasoned, research should

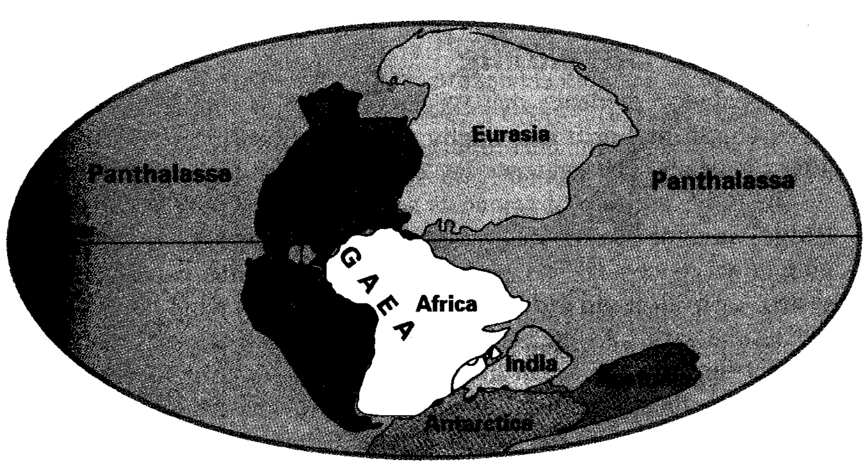


Figure 4–1. This map shows Pangaea as Alfred Wegener envisioned it.

Figure 4–2. These *Mesosaurus* bones were discovered in Sao Paulo, Brazil. Identical fossil bones of *Mesosaurus* were found in western Africa, giving scientists strong evidence of continental drift.

uncover fossils of the same plants and animals in areas that had been adjoining parts of Pangaea. Wegener knew that identical fossil remains of *Mesosaurus,* a small, extinct land reptile that lived 270 million years ago, had already been found in both eastern South America and western Africa. Wegener knew that it was impossible for these reptiles to have swum across the Atlantic. And there was no evidence of any land bridges that might have connected the continents at some earlier time. Wegener thus concluded that South America and Africa must have been joined at one time.

Geologic evidence also supported Wegener's hypothesis of continental drift. The age and type of rocks in the coastal regions of widely separated areas, such as western Africa and eastern Brazil, matched closely. Mountain chains that ended at the coastline of one continent seemed to continue on landmasses across the ocean. The Appalachians, for example, extend northward along the eastern United States, while mountains of similar age and structure are found in Greenland and northern Europe. If these three landmasses are assembled in a model of Pangaea, the mountains fit together in one continuous chain.

Evidence of changes in climatic patterns added strength to Wegener's hypothesis. Geological research revealed layers of debris from glaciers in southern Africa and South America, areas that today have much warmer climates. Other fossil evidence—such as the coal deposits in the eastern United States, Europe, and Siberia—indicated that tropical or subtropical swamps covered much of the land area in the Northern Hemisphere. If the continents were once joined and positioned over the South Pole, Wegener suggested, these climatic differences would be easy to explain.

Despite the evidence supporting the hypothesis of continental drift, Wegener's ideas met with strong opposition. Many scientists rejected the hypothesis because it did not satisfactorily explain the force causing continental drift. In an effort to convince the scientific community that his hypothesis was valid, Wegener spent the rest of his life searching for evidence of that force. Unfortunately, Wegener died in 1930, while on an expedition to Greenland. He never found an explanation of what caused continents to move.

Seafloor Spreading

The conclusive evidence that Wegener sought to support his hypothesis of continental drift was finally discovered nearly two decades after his death. The evidence lay on the ocean floor.

In 1947, a group of scientists set out to map the **Mid-Atlantic Ridge,** an undersea mountain range with a steep, narrow valley running down its center. The Mid-Atlantic Ridge is one part of an entire system of **mid-ocean ridges** 65,000 km long that wind their way around the earth. As the scientists examined rock samples that they brought up from the ocean floor, they made a startling discovery. Contrary to most scientists' assumptions, the ocean floor was very young compared with the age of continental rocks. None of the oceanic rocks found were more than 150 million years old. The oldest continental rocks are about 4 billion years old. Why do you suppose scientists found this information surprising?

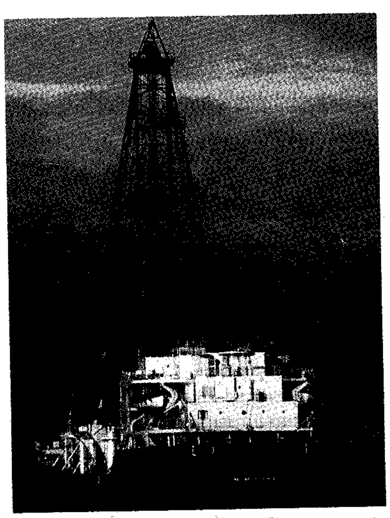
The Renewal of the Ocean Floor

After analyzing the data gathered from the Mid-Atlantic Ridge, Harry Hess, a geologist at Princeton University, suggested the following hypothesis. Suppose, he said, that the valley at the center of the ridge was actually a break, or rift, in the earth's crust and that molten rock, or magma, from deep inside the earth was welling up through the rift. This upwelling would be possible, Hess reasoned, if the ocean floor was moving away from both sides of the ridge. As the ocean floor moved away from the ridge, it was replaced by rising magma that cooled and solidified into new rock. Another

EARTH BEAT

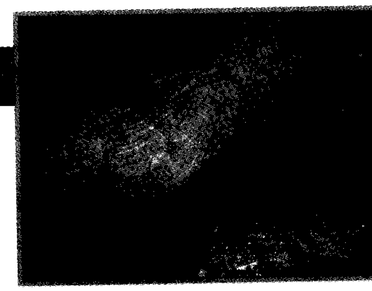
Evidence of Seafloor Spreading

Deep under the Atlantic Ocean lies a mountain range so vast that it dwarfs the Himalayas. This mountain range is called the Mid-Atlantic Ridge, the mid-ocean ridge at the diverging boundary between the North American and Eurasian plates and the South American and African plates.



Explorations of the Mid-Atlantic Ridge have enabled scientists to obtain firsthand evidence of seafloor spreading. For 15 years, scientists aboard the *Glomar Challenger,* shown at left, traveled more than 575,000 km and collected nearly 100 km of core samples from 635 drill holes. Scientists examining the fossils embedded in the samples discovered that cores drilled closest to the ridge had the youngest fossils. The fossils proved to be progressively older as samples were taken farther from the ridge. This find supported the idea that new crust forms along the ridge as older crust moves aside.

With the help of deep-diving submarines, scientists were able to explore the rift valley



that bisects the mid-ocean ridge. The crew on board the submarine *Archimede* were among the first to witness magma bubbling up from the mantle. A year later, cameras on board the *Alvin* photographed lava formations that had emerged from the mantle and hardened in the rift valley. One of these photographs is shown above. The lava formations provided further evidence of seafloor spreading.

If you had six core samples collected from the ridge outward, how many samples would you have to test to determine whether the samples on the right or the left were closer to the mid-ocean ridge? Why?

geologist, Robert Dietz, named this movement **seafloor spreading.** Hess suggested that if the ocean floor was moving, the continents might also be moving. Perhaps seafloor spreading was the force that Wegener had failed to find to support his hypothesis of continental drift.

Still, Hess's ideas were just hypotheses. The proof would come years later, in the mid-1960's, and would be discovered through paleomagnetism, the study of the past magnetic properties of rocks.

Paleomagnetism of the Ocean Floor

If you have ever used a compass to determine direction, you know that the earth acts as a giant magnet, with both a north and a south pole. The compass needle aligns with the field of magnetic force that extends from one pole to the other.

IMPACT ON SOCIETY

Living on the Mid-Atlantic Ridge

Although most of the earth's mid-ocean ridges lie completely underwater, part of the Mid-Atlantic Ridge rises above sea level just south of the Arctic Circle. This exposed section of the Mid-Atlantic Ridge forms the island country of Iceland. Since its founding by Vikings over 1,000 years ago, the inhabitants of Iceland have had to contend with the constant geological activity associated with seafloor spreading.

Separation of the earth's crust along the Mid-Atlantic Ridge affects Iceland's landscape in several ways. Tectonic motion, for example, causes frequent earthquakes. Iceland is also one of the most volcanically active areas in the world. It contains about 200 volcanoes and averages one eruption every five years. Magma flowing up from the mantle creates numerous hot springs, geysers, and sulfurous gas vents. Scientists estimate that one-third of the total lava flow from the earth in the last 500 years has occurred on Iceland.

Despite its numerous volcanoes, much of Iceland's lava comes not from isolated eruptions but rather from cracks, or fissures, in the crust. In a recent rifting episode that lasted nearly 10 years, a series of fissures spit out 35 km^2 of molten basalt. Over the course of this event, individual fissures grew as much as 8 m in width. At present, seafloor spreading adds an average of 2.5 cm of new material each year to Iceland. At this rate, Iceland will grow 25 km in width during the next million years.

If geologists want to locate the youngest rocks on Iceland, where should they look? Where should they look to find the oldest rocks? Why?

A similar phenomenon occurs when magma cools and solidifies. Certain iron-bearing minerals within the rock become magnetized. When the rock hardens, the magnetic orientation of the minerals becomes permanent and points to the north.

Scientists discovered, however, that this was not always the case. From the beginning of the nineteenth century, they had been finding rocks with magnetic orientations that pointed south. Some scientists concluded that the earth's magnetic field must have reversed itself at times during the earth's history. This conclusion was verified by dating rocks with different magnetic orientations. All the rocks with magnetic fields pointing north fell into the same time periods—periods of normal polarity. All the rocks with magnetic fields pointing south also fell into similar time periods—periods of reverse polarity. The scientists discovered that throughout the earth's history the magnetic field has reversed itself many times.

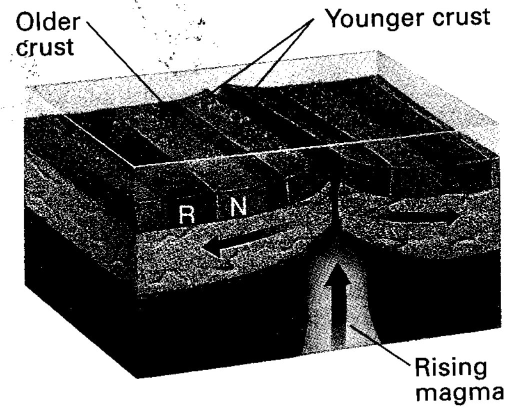


Figure 4–3. The stripes in the crust are shown here to illustrate the earth's alternating magnetic field. Dark stripes represent the ocean floor with reversed polarity (R), while the lighter stripes show normal polarity (N).

At the same time these discoveries about the earth's magnetic field were being made, scientists were also finding puzzling magnetic patterns on the ocean floor. These patterns, when drawn in on maps of the ocean floor, showed alternating bands of normal and reversed magnetism. As molten rock rises from the rift in a mid-ocean ridge, it quickly cools and hardens and its magnetic orientation becomes fixed. Its magnetic orientation will reflect the polarity of the earth's magnetic field at that time, either normal or reversed.

Scientists' confidence in the validity of this idea grew when they discovered that the striped patterns of magnetism on one side of a ridge are mirror images of the striped patterns on the other side of the ridge. This discovery supported Hess's idea that molten rock from a rift cools, hardens, and then moves away in opposite directions on both sides of the ridge. The ocean floor, it seemed, was indeed spreading.

Finally, in 1965, two groups of scientists working independently of each other discovered a previously unknown reversal in the earth's magnetic field. One group discovered the reversal in rocks on land, and the other group discovered the reversal in rocks on the ocean floor. The dates of both reversals were exactly the same. This was clear evidence that the earth's magnetic polarity does reverse itself and that the ocean floor does spread. Scientists reasoned that seafloor spreading provides a way for the continents to be moved over the surface of the earth. Here, at last, were the discoveries that Wegener had sought, the scientific evidence he needed to verify his hypothesis of continental drift.

Section 4.1 Review

1. What observation first led to Wegener's hypothesis of continental drift?
2. What types of evidence support Wegener's hypothesis?
3. Describe the process of seafloor spreading.
4. Explain how scientists know that the earth's magnetic poles have reversed themselves many times during earth's history.