大陸移動説・その誕生・死・および復活

## Chapter 1

# The Theory of Continental Drift: Its Birth, Death, and Revival

**Wegener's Idea**

In 1912 the German scientist Alfred Wegener (1880–1930) proposed a new theory.* He maintained that the continents on either side of the Atlantic—the North American and South American continents and the European-African continent—were once joined and that they had split and drifted apart into their present positions. He insisted that all other continents, including India, Australia, Africa, and Antarctica, also belonged to the one gigantic protocontinent. He named this great hypothetical continent *Pangaea.* Figure 1-1 illustrates the process of continental breakup. Wegener believed that Pangaea was united until the late Carboniferous period, about 300 million years ago, and then began to split apart, ending up in the present distribution of continents. Since Pangaea was the only continent, it was surrounded by one enormous ocean. No individual oceans, such as the Atlantic, Indian, or Antarctic, existed at that time. This was the essential idea of continental drift. It was a spark that generated a new view of the earth.

The source of Wegener's idea was the realization that the outlines of the continents fit like the pieces of a jigsaw puzzle. This conformity can be seen by anyone who looks closely at the coastlines along

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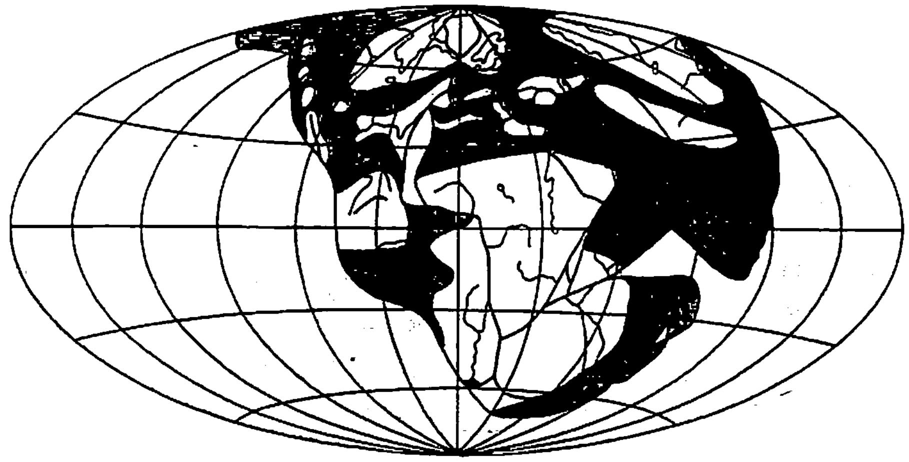
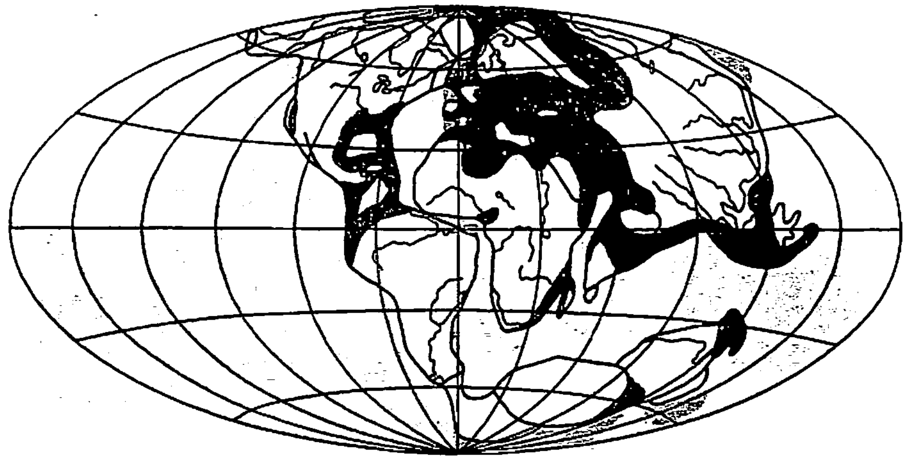
*It is true that the idea of continental drift dates back, long before Wegener, to A. Snider (in 1858) and even to F. Bacon (in 1620). But it was Wegener who first made the case an important scientific issue.

Late Carboniferous (300 million years ago)



Eocene (50 million years ago)



Early Pleistocene (1.5 million years ago)

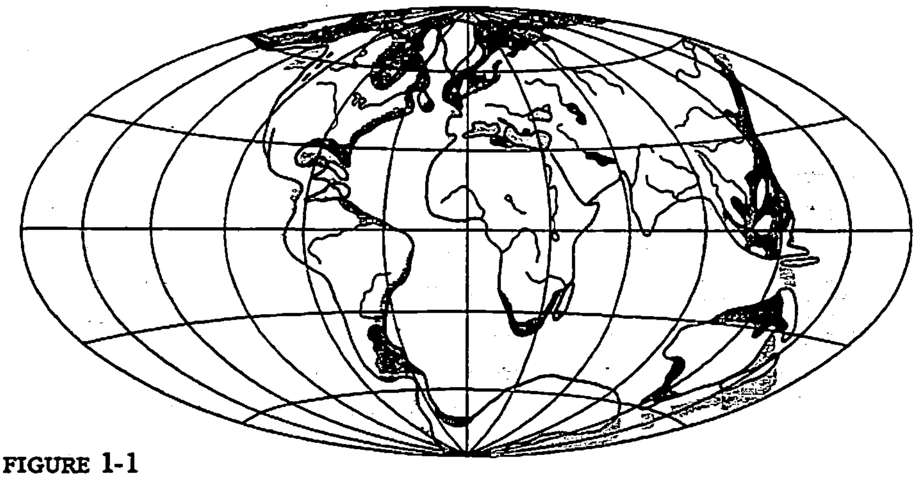


FIGURE 1-1
Reconstruction of the map of the world for three periods according to Wegener's theory of continental drift. Africa is placed in its present-day position as a standard of reference. The heavily shaded areas represent shallow seas. Ages in millions of years have been added. [After A. Wegener, *The Origin of Continents and Oceans*. Dover, 1924.]

FIGURE 1-2
Alfred Wegener. [Photo from Historical Pictures Services, Inc., Chicago.]

the Atlantic Ocean. The idea, simple as it was, was considered preposterous at the time because it conflicted with the universal belief that the earth was immobile.

Wegener (Figure 1-2), a meteorologist by profession, was one of the pioneers in the field of high-altitude meteorological observation. Also his exploration of the previously unpenetrated continent of Greenland contributed to the research in this area. The culmination of these diverse activities was the conception and development of his theory of continental drift. It began as a simple idea, but Wegener did not allow it to remain as such: he pursued it resolutely and systematized the theory. It was because of this perseverance that he was a great scientist. Ideas occur to any scientist from time to time. But he fails to develop most of them, and then forgets them because they seem either too fantastic or impractical. The majority of them are indeed useless. Wegener confessed that he himself considered the possiblity of continental drift to be fantastic and impractical, and at first did nothing about it. However, unlike many scientists who abandon interesting ideas and regret it later, Wegener began to develop his seemingly simple theory. His search for new knowledge started with the study of geology and paleontology, fields remote from his speciality. This project, conceived in 1910, was interrupted by his expeditions to Greenland and his military service during World War I, in which he was injured. Yet such obstacles did not deter him. In 1915 he published his monumental work, *Die Entstehung der Kontinente und Ozeane (The Origin of Continents and Oceans)*, and by 1923 had revised it three times. In 1924, he published *Die Klimate der Geologischen Vorzeit (The Climate Through Geological Time)* with a meteorologist, W. Köppen. During this period he also published a great many other papers. These works were the fruit of his revolutionary view of the earth as developed from the concept of continental drift. It was as if modern solid earth science had evolved within the mind of this one man who was tens of years ahead of everyone else.

## The Geologic Method

As a meteorologist, Wegener needed more than anything else a knowledge of geology for his pursuit of the history of continental drift. We, too, need an understanding of the basics of geology in order to grasp Wegener's ideas.

The two following fundamental principles that geologists apply when studying the history of the earth are particularly important:

(1) *The law of superposition.* If one stratum (or layer) overlies another, the top stratum is younger than the bottom one.

(2) *The law of faunal assemblage.* Strata that contain fossils of the same species of animals and plants were produced in the same period.

The first law is self-evident: without the existence of the prior stratum, the new stratum could not be deposited on top of it. This law enables us to detect the chronological relationships of the stratified rocks in one place.

The law of faunal assemblage gives us clues about the time relationships among strata scattered in different places. Everyone knows that all forms of life are constantly undergoing evolution. The process might seem slow to us, but considered on a geological time scale it is actually quite rapid. Primitive life forms first appeared on the earth about three billion years ago, and gradually evolved into more complex creatures. This one-way trend of evolution—from the simple to the complex—has enabled us to identify the chronological age of the strata by the fossils (such as trilobites and dinosaurs) preserved within them. Figure 1-3 gives the geological ages as determined by the fossils of animals and plants. The study of fossils is called paleontology and constitutes quite an elaborate system of science. These names of geological eras, periods, and epochs—each with its own legitimate and interesting origin—will be mentioned throughout this book.

Informative though it is, the paleontologic method has two intrinsic limitations. The first is the amount of time that we can go back. As shown in Figure 1-3, it is only in the strata of the past 600 million years or so that plant and animal fossils are complex enough that we can use them to compare the ages of the strata. There are not enough fossils in the older strata to date them. This early period with few or no fossils is in a way a prehistoric, or biological, "dark age," and is called the Precambrian era. The second limitation is that it cannot provide us with "absolute" chronology, since it uses the evolution of animals and plants as its clock. It can determine, for instance, that stratum A is older than B, but it cannot tell us how old either stratum is or how much older A is than B.

Such limitations have been overcome in recent years, thanks to the development of methods of absolute age determination. From the spontaneous disintegration of such radioactive elements as the uranium, thorium, strontium, and potassium that are contained in rocks in small amounts, we can determine the absolute age of the rocks. These radioactive elements constantly and regularly transform into other elements in accord with what is called the law of disintegration. This transformation can be considered a kind of evolution, too, but unlike that of plants and animals, the exact rate of transformation has been determined by physicists. The absolute ages given in Figure 1-3 have been obtained by this method.

Geological strata consist of either igneous rocks or sedimentary rocks. Igneous rocks are primary rocks formed by the cooling and

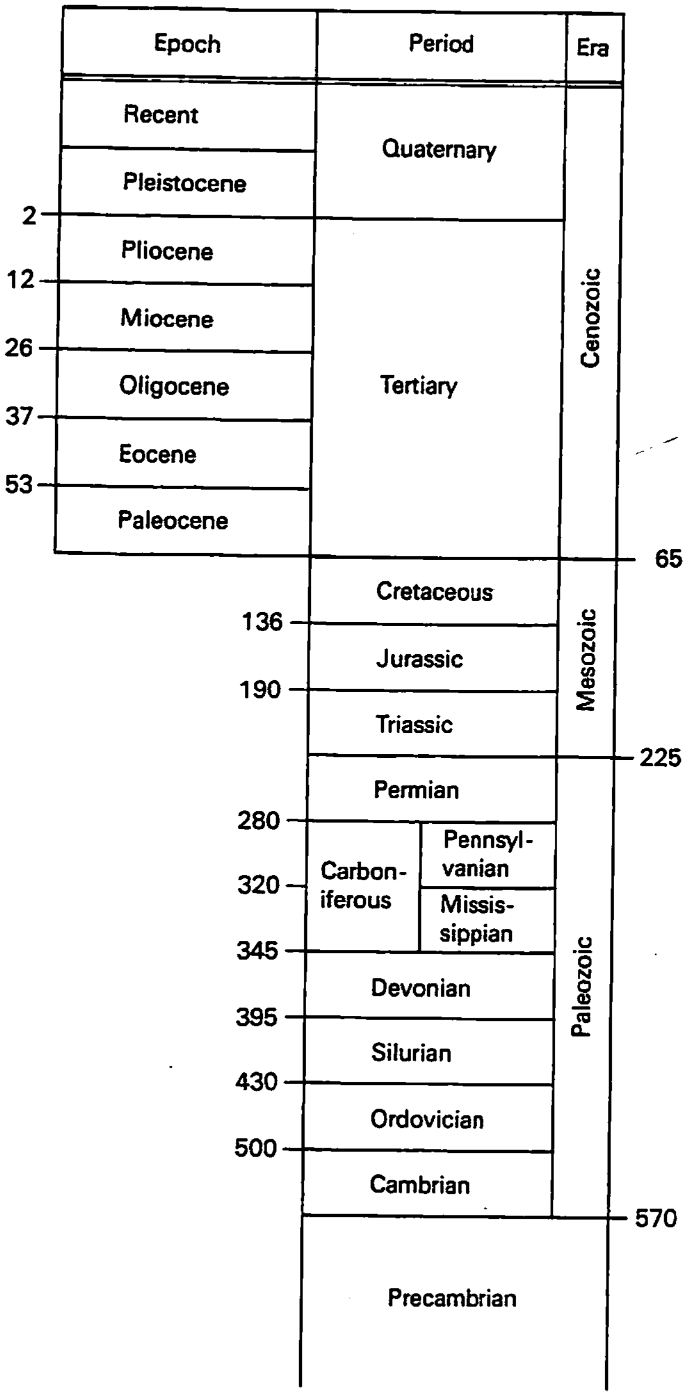


FIGURE 1-3
The geologic time scale. The numbers at the sides of the column are ages in millions of years. [After F. Press and R. Siever, *Earth*. W. H. Freeman and Company. Copyright © 1974.]

solidification of magma; sedimentary rocks are secondary rocks formed as a result of erosion and deposition. Sediments are called secondary because most of the particles transported by water and deposited were originally parts of other rocks on land. Most of the rocks we see in strata at the present time are sedimentary rocks. Thus the surface of the land is almost completely covered with sedimentary rocks—even mountain ranges as high as the Alps and the Himalayas, meaning that these great mountain tops were once under water!

Suppose some region is elevated high above sea level: at this point in time deposition ceases and erosion takes over. Even the highest mountains are gradually eroded into level land. The history of an elevated region that has undergone erosion is very difficult to trace because no sedimentary record exists and the history can be studied only indirectly through the record of erosion. If this region is submerged once again, the deposition process will resume and a more complete record of the geologic history will start to accumulate. Any geologist knows for a fact that the rocks forming many of the mountains were once deposited underwater, but the initial idea can be quite a shock. I remember well my own surprise when I first heard it.

## The Land Bridge

If the continents now scattered in the world oceans once formed a single enormous continent, the strata that existed before the breakup would have to be related to one another. Moreover, the strata that formed after the split would be unrelated. To establish this hypothesis and thus confirm his theory of continental drift, Wegener set out to gather evidence. His skepticism about the concept, he explains, was overcome when he came across a paleontological paper discussing the possibility that Brazil had once been linked to Africa. It came as a surprise to Wegener to find that such an assertion had already been put forth, quite independently of his hypothesis of continental drift. But it is exactly this point that I find interesting, because it seems to demonstrate the importance of the *perspective* from which one interprets scientific data. As an amateur in paleontology, Wegener was unaware of any evidence suggesting the ancient connection among continents, and yet paleontologists had long been studying this very possibility. The established interpretation of this concept, however, was entirely different from Wegener's. It was the land-bridge theory.

Having surveyed the distribution of fossils of such animals as monkeys, earthworms, and snails, and of various kinds of plants, paleontologists observed that close affinities prevailed between Africa and South America, Europe and North America, Madagascar and India. For example, since such organisms as snails cannot swim across vast oceans, it was presumed that two continents containing nearly identical snail fossils must have once been connected by land—a land bridge. Whereas Wegener interpreted this distribution as indication that a single continent had once existed and subsequently split into several parts, the traditional paleontological interpretation of the same phenomenon assumed the immovability of continents and thus the existence of a land bridge. The observed phenomena were the same, but they were interpreted from different viewpoints, so that two vastly different theories resulted.

If land bridges had indeed connected the continents, the one joining Africa and South America could not have been a long, narrow protrusion across the Atlantic. Here, one of continental scale would seem more likely. Since this hypothetical bridge no longer existed, the task was to explain the disappearance of such a land mass. The most popular way of accounting for its immersion was to ascribe it to a grandiose depression of the earth's crust. Thus, the land bridge theory assumed that a land mass the size of a continent can "become" a sea. This view was essentially the same as the one that asserted that the distribution of land and ocean is determined by the *vertical* movement of the earth's crust. In the theory of continental drift, the *horizontal* movement of continents is the central phenomenon. This is the fundamental difference in the two hypotheses.

## The Earth's Crust

Before discussing continental drift further, let us examine the nature of the earth's crust. Of the various ways of examining the interior of the earth, the most direct is drilling. Drilling a hole much deeper than 10 kilometers, however, is beyond our present technology. The next most direct method is to survey the earth's interior by studying the propagation of earthquake waves. When an earthquake occurs, seismic waves, originating at the focus of the quake, travel through the earth's interior. Seismic waves are of two basic types. The first type, primary or *P* waves, travel through the earth just as sound waves travel through the air. *P* waves transmit the changes in *volume*, the alternating compression and expansion of the earth. Secondary or *S* waves transmit the distortion of the *shape* of the earth's material. The particle motion of *P* waves is in the direction of propagation, and that of *S* waves is perpendicular to the direction of its propagation. The distinction between the two types of waves can be seen in Figure 1-4. *P* waves travel faster than *S* waves (approximately 1.7 times faster).

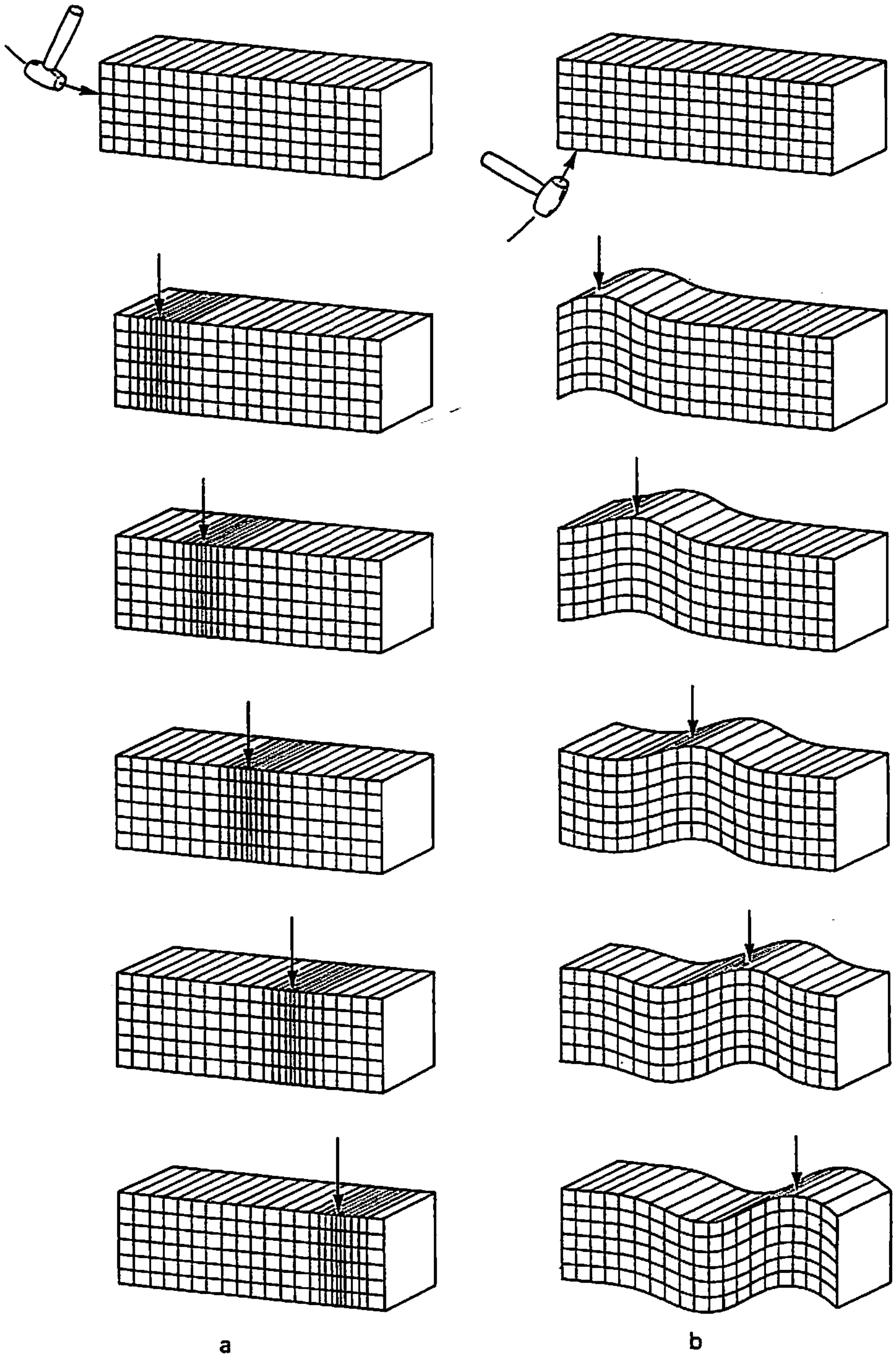


FIGURE 1-4
The passage of a seismic wave pulse in a block of material. Repeated hammer blows or cyclic shock will generate a train of waves. The arrow indicates the crest of the wave: (a) *P* wave; (b) *S* wave.

The earthquake is usually felt in two successive shocks: first, a light jolt and then a heavier rocking one. The first indicates the arrival of the *P* waves and the second, the *S* waves. *S* waves can travel through solid material but not through fluid, whereas *P* waves can travel through both solid and fluid substances.

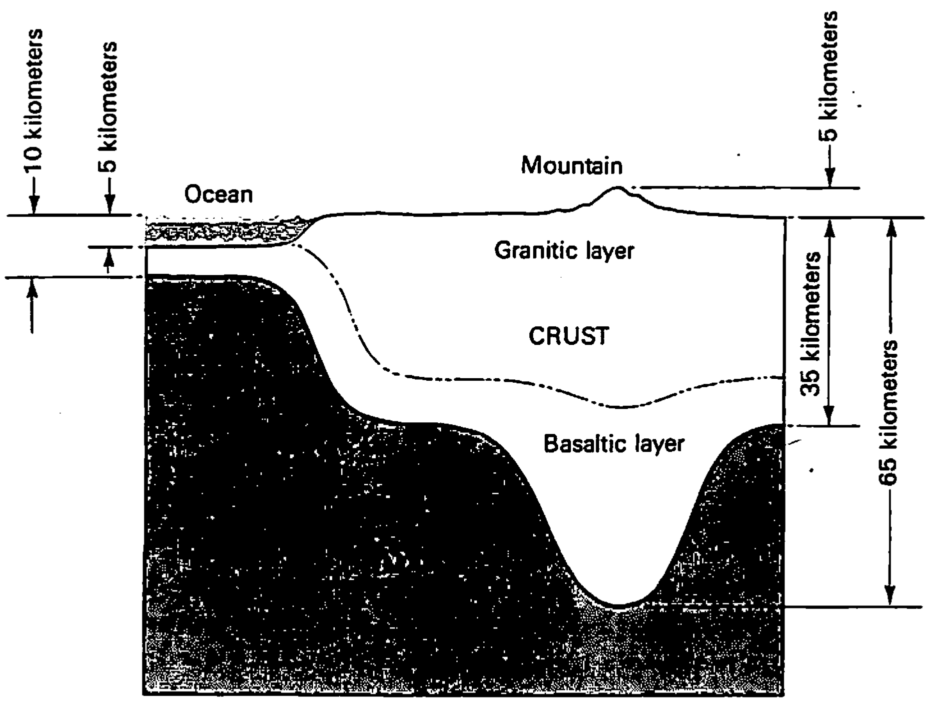


FIGURE 1-5
Schematic cross section of the earth's crust.

Investigation of the propagation of seismic waves originating from either natural or artificial earthquakes reveals that above a certain depth the waves travel slowly. But once the wave reaches this depth, its velocity increases sharply: the velocity of $P$ waves, for example, jumps from about six or seven kilometers per second to about eight kilometers per second.

The surface layer above this boundary is called the *crust*, and the layer below it is called the *mantle*. The boundary itself is called the *Mohorovičić discontinuity* after the Yugoslavian seismologist who discovered it in 1909. This discontinuity is often called simply the Moho or M discontinuity.

The continental crust (from 30 to 50 kilometers thick) is much thicker than that of the ocean floor, which is only several kilometers thick, as shown in Figure 1-5. The crust in continental regions consists of an upper layer of granitic rocks and a lower layer of basaltic rocks in the form of what geologists call *gabbro*. These rocks vary widely in chemical and mineral composition. Also, rocks of similar composition can vary in texture, depending on the mode of formation. All these differences have generated numerous names that are often unfamiliar to laymen. We will be concerned here with only a few of the major rock *types*, which are listed in the table at the end of the book. Rocks of basaltic composition are quite different from granitic rocks. The basalts are dark, fairly heavy, and "primitive" in the sense that they have formed from magma derived directly from the mantle. Granitic rocks are lighter both in color and density, and many have a chemistry suggestive of geologic "recycling." Although much of the crust is too deep to be sampled directly, we have been able to guess at their composition by comparing the seismic velocity (the velocity of earthquake-produced seismic waves traveling through these layers) with seismic velocities in rocks of known composition measured in the laboratory. Therefore, when we say, for example, that the upper layer of continental crust consists of granitic rocks, what we mean is that the layer has the same seismic wave velocity as granitic rocks. It may not really be granitic rock, because rocks with different compositions can have the same velocity. Under the oceans, the crust consists of a thin top layer of sediments and two underlying layers called the second and the third layers. The second layer is presumably composed of volcanic, or *extrusive*, rocks such as basalt, and its *intrusive* equivalent, gabbro.* Existence of basalt at the top part of the second layer has been verified by the Deep Sea Drilling Project (described in Chapter 3). It is not yet known what the third layer consists of. It too may be either a form of gabbro or a rock called serpentinite (see the table). Thus the ocean crust is distinguished by its relative thinness and its lack of a granitic layer. (Apparently rocks that are much heavier than granite—such as peridotite and eclogite—compose the upper part of the mantle.) The thinness of the ocean crust has been verified by seismic experiments only since the 1950s. Consequently the structure of the crust as conceived of in Wegener's day was not exactly the same as that shown in Figure 1-5, owing to the lack of data. However, geologists at that time already had the right idea. They had concluded that the continental crust was substantially different from the crust beneath the ocean floor; they also suspected that there were no continents with thin "oceanic" crusts nor ocean floors with thick "continental" crusts.

This belief was supported by gravity studies, which revealed that underneath a region of elevated topography is a buried root of low-density material. Since the crust consists of rocks lighter than the

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*[*Extrusive*](#) rocks are formed when volcanic magma cools at the earth's surface. They can be recognized by their texture, which is either glassy or fine-grained as a result of rapid cooling. *Intrusive* rocks are formed when the magma cools and solidifies at depth, and they can be recognized by a coarser texture consisting of larger grains, a result of slow cooling. *Gabbro* is an intrusive rock type and is the equivalent of volcanic basalt.

material of the mantle, this phenomenon was interpreted as an indication that the crust is thicker where the earth's surface is higher. In a sense, the crust seems to be floating on the mantle, much like an iceberg in the ocean. According to Archimedes' Principle, any iceberg must have a deep root in order to maintain its buoyancy. The loftier the iceberg, the deeper its root. Apparently this principle also applies to the crust: the elevated continents have thicker crusts than the low-lying oceans. This phenomenon is called *isostasy*. It signifies that the mere presence of water does not make an ocean: rather, it is the structural difference in the earth's interior that is responsible for the division of land and ocean. A continent cannot sink to make an ocean, as long as the basic law of buoyancy holds. Thus a continent *cannot* be easily transformed into an ocean, or vice versa. Wegener emphasized this point and thus refuted the land-bridge theory. Modern seismic and gravity studies of the ocean floor show that Wegener was right.

## Direct Linkage

The most convincing evidence of direct linkage between the continents is the distribution of ancient glaciers. Glaciation occurs at irregular intervals on the earth. In the present Quaternary period, which has lasted about two million years, the earth has passed through several glacial periods separated by interglacial periods. During the last such Ice Age, which ended only about 10 thousand years ago, most of Europe and North America were under thick layers of ice. During the period preceding the Quarternary period, however, the earth had been free from glaciation for more than 100 million years. Why glaciations occur only at certain times is still unknown and provides an interesting topic for debate, but one that space does not allow us to examine here.

What concerns us at this point is the type of evidence glaciers have left in the course of the earth's history. A thick continental glacier scrapes against the rocks as it moves, leaving unique traces called glacial striations; along the way it carves such topographic features as steep-walled glacial valleys. It also crushes and grinds up rocks, transports these fragments downstream, and deposits them at the front of the glacier as it melts. The resulting sedimentary deposits are so characteristic that their glacial origin can be recognized by the trained eye of the geologist even though millions of years may have elapsed since the glacier's melting. Examination of glacial distribu-

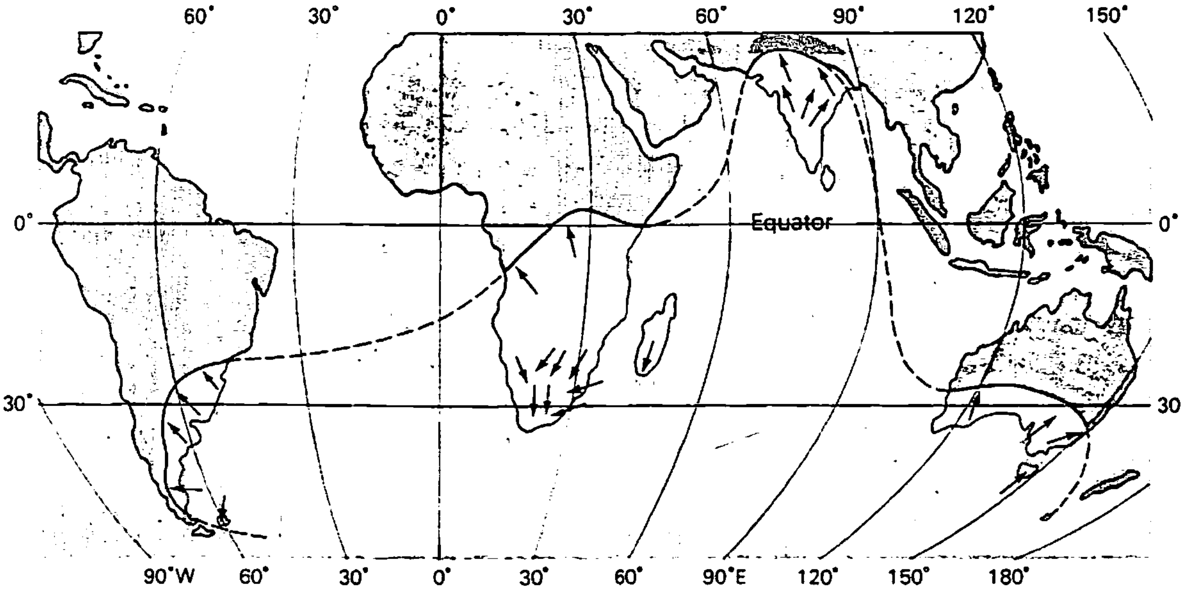

FIGURE 1-6
Map showing the distribution of the late Carboniferous glaciations of Gondwanaland with the continents in their present positions: arrows indicate directions of ice flow. [After A. Holmes, *Principles of Physical Geology*. Thomas Nelson and Sons, Ltd., Middlesex. The Ronald Press Company, New York, 2nd ed.; copyright © 1965.]

tion in the earth's ancient geological history reveals that glaciation was extensive in the Permo-Carboniferous period, approximately 300 million years ago. This glaciation affected all the continents in the Southern Hemisphere. If we look at a map of this glaciation (Figure 1-6), something about the distribution of the glaciers immediately strikes us: tropical regions such as India and Africa were under ice, but there is hardly any trace of glaciation in the rest of the Northern Hemisphere during this period, even on land masses near the present North Pole.

The theory of continental drift provides us with a clear-cut explanation. Figure 1-7 shows the original continent of Gondwanaland.* Note that the glacial areas form a nearly circular icecap over the polar region of Gondwanaland. It was probably because of this impressive evidence that the continental drift theory attracted enthusiastic supporters from the Southern Hemisphere, such as A. L. Du Toit of South Africa and S. W. Carey of Tasmania, even after the theory was

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*Gondwanaland was the giant continental mass of the Southern Hemisphere, consisting of the present southern continents. Its previous existence has been inferred from the distribution of such fossils as the Carboniferous flora *Glossopteris*. Taking the land-bridge theory as a basis, the 19th-century Austrian geologist E. Suess proposed the name Gondwanaland—the Gonds are an Indian aboriginal tribe.

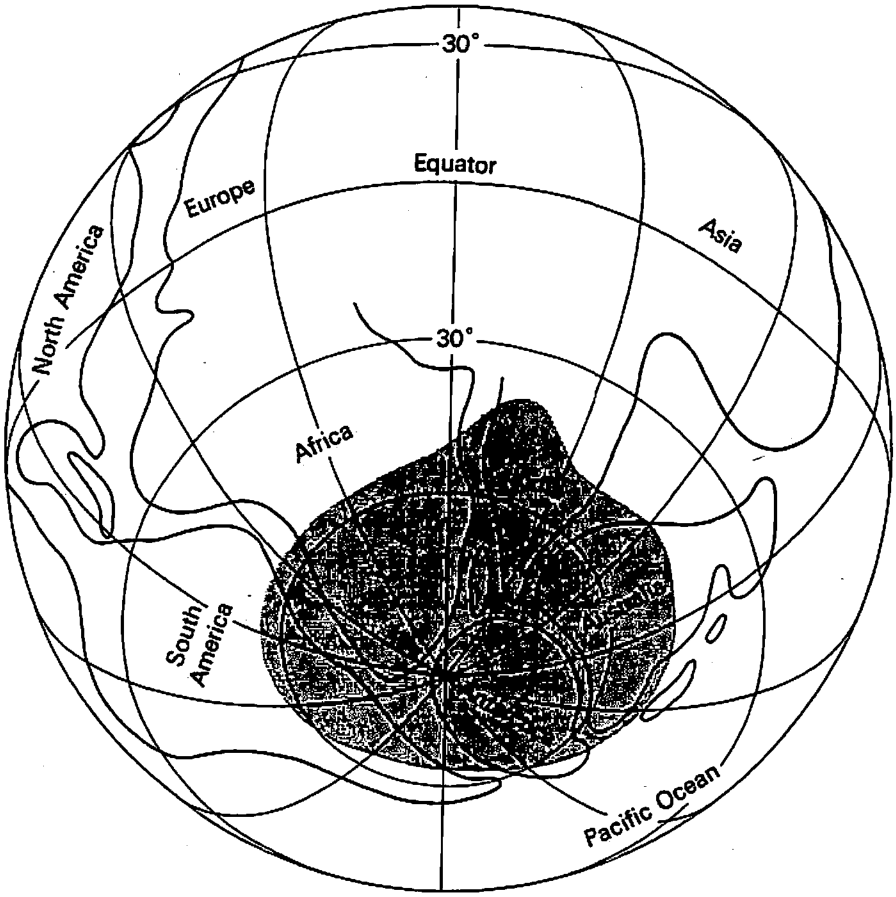

FIGURE 1-7
Map showing the distribution of the late Carboniferous glaciations of Gondwanaland with the continents reassembled, as interpreted by A. Wegener. [After A. Holmes, *Principles of Physical Geology*. Thomas Nelson and Sons, Ltd., Middlesex. The Ronald Press Company, New York, 2nd ed.; copyright © 1965.]

virtually abandoned by the majority of geoscientists of the Northern Hemisphere. The geologists from the Southern Hemisphere had themselves seen the ancient glacial traces, and knew they could be explained only if it could be proved the continents had moved.

## The Contraction Theory and Continental Drift

As we saw in the introduction, one of the major geophysical issues enumerated by Dr. Adams was that of *orogenesis*, or the origin of great mountain ranges. How did those towering mountain ranges—

the Alps, the Himalayas, the Rockies, and the Andes—originate? Some of the thick strata that form these mountains are sediments deposited on the sea floor long ago, indicating that such mountains were somehow elevated from that floor. It is awesome to think that where a mountain now towers there once existed an ocean basin in which a layer of sediments, 10,000 meters thick, was deposited. Yet many such basins, called *geosynclines*, have formed on the sea floor, only to be lifted up later to form mountains. What could account for such an upheaval?

The previous leading theory on orogenesis was predicated on the notion of a contracting earth. It in turn was based on another theory, the "hot-origin" hypothesis of the earth, which assumed that the planet was once a ball of "fire" or incandescent gas, which subsequently condensed and gradually cooled down. Most geological surveys of mountain ranges reveal a tilting of the strata. In many areas the strata are bent into a wavelike pattern called *folding*, which consists of alternating arches (*anticlines*) and troughs (*synclines*); in some formations, the folding is so extreme that the strata are upside down as in Figure 1-8. The contraction theory seemed to explain this phenomenon of folding. According to the theory, as the surface of the hot earth began to cool, solidify, and contract, its volume decreased. The interior, however, was still hot. Because of the tension produced in the rapidly shrinking outer layer, cracks began to form on the surface, just like the cracks that form in drying mud. Geosynclines might have occurred within such giant cracks, where water could gather and where deposition could take place. The interior too would eventually cool, so that its volume would decrease. This contraction would begin to exert compression on the already cooled surface. Like a suit of clothes that is too large, the crust was now too big for the shrinking interior, and wrinkles formed. This was the explanation for folded mountain ranges.

The theory sounded plausible but it had yet to be proved quantitatively. In an attempt to do so, geologists first determined the degree to which strata in mountain ranges had been compressed. From these results it was calculated that the entire earth had to have cooled by thousands of degrees to produce enough contraction to form a single mountain range several thousand meters high. Such extreme cooling seemed unlikely. To complicate matters further, each mountain range was formed at a different time, some of them quite recently. It seemed impossible that the earth could have cooled by thousands of degrees for each of them. This problem had already been pointed

FIGURE 1-8
Example of sharply folded strata of Tertiary bedded sandstone, Kii Peninsula, Japan. [Photo by F. Kumon, Kyoto University.]

out in Wegener's day, and since then the contraction theory has lost ground.

Today, as a consequence of various cosmological studies, even the basic assumption of an earth that has cooled from an incandescent hot state is in serious doubt. So the once prevalent contraction theory no longer seems like a plausible explanation of the origin of mountains. Wegener declared that no contraction was necessary to produce the folding of strata and the formation of mountains. He contended that the leading edge of an advancing continent would encounter resistance and, as a result, compress and fold. As North and South America drifted westward, leaving the Atlantic Ocean in their wake, a chain of mountain ranges formed along their leading edge; the Sierra Nevada and adjacent mountain ranges in North America and the Andes in South America. Wegener further suggested that when Gondwanaland split, India drifted northward and eventually collided with the Asian continent. The overriding of India by Asia in the zone of collision caused the Himalayas to form.

Meteorologist Wegener's continental drift theory was a breakthrough in the complex field of orogenesis, which for years had been the awkward and misunderstood stepchild of the professional geologist. The challenge posed by Wegener's bold theory was welcomed by some geologists, but the majority were skeptical of such simple logic.

As already mentioned, many of the strata forming today's mountain ranges originally accumulated under the sea in thicknesses often exceeding 10 thousand meters. All such strata, the scholars of that day agreed, had been deposited in shallow water. But if the sea was shallow, how could such thick deposits have accumulated? The only explanation seemed to be that the sea floor had sunk as more and more layers of deposits accumulated, so that the ocean depth remained constant. Thus, the deposits sank deeper and deeper into the earth. Today, the same strata rise high above sea level. At some point the process of depression of the sedimentary basin, or geosyncline, must have somehow reversed so that the strata were thrust upward into mountains. Why did the basins form in exactly those places that subsequently became mountains? We see that for this problem too Wegener's theory provided the key.

## What Moved the Continent?
## A Challenge to Geophysics

The theory of continental drift presented a challenge to classical geology because it provided a simple and logical explanation for so many geologic processes. However, it posed an even greater challenge to geophysics.

The question it raised was basic. What kind of force could cause the continents to move distances of several thousand kilometers? What was the driving mechanism of continental drift? That is, an explanation of *effect* was meaningless if the *cause* could not be identified: so even if Wegener's theory of continental drift did provide lucid explanations for many geological effects, such as ancient glaciation and mountain building, it could scarcely be regarded as scientific unless it could also explain what had originally caused the continental movements. Although he knew how crucial this initial cause was to his theory, Wegener never succeeded in explaining it. It was not easy, even for a man such as Wegener, to move the "immovable" earth.

As Figure 1-1 shows, Wegener proposed that Gondwanaland was first located around Antarctica. Later it began to split and left the South Polar region. This made Wegener suspect that continents in general move away from the poles and drift toward the equator. He named the force behind this phenomenon the *pole-fleeing force*, and explained its origin as follows: Because the earth rotates on its axis, there is a centrifugal force of rotation. This force deflects the pull of gravity slightly so that it is directed *not* toward the center of the earth but toward the equator, though only very slightly. Consequently, Wegener reasoned, continents floating on the earth gradually move toward the equator. This hypothesis was barraged by objections founded on the actual magnitude of the force; as computations made by various scientists showed, the pole-fleeing force is extremely small. In fact, it is several millions of times smaller than the force of gravity. But Wegener insisted that, however small it may be, a force acting continuously for a long time can, in the end, move a continent. Many others continued to believe, however, that a far greater force would be necessary to displace the continents floating upon the solid mantle. Moreover, the force would have to be great enough to fold and hoist once flat layers of sediments into mountains several thousand meters high—an impossible task for the pole-fleeing force.

The westward drift of the two American continents Wegener attributed to the tidal attraction of the sun and the moon. This theory, too, was refutable. The famous British geophysicist, Sir Harold Jeffreys, led the opposition. In each edition of his well known and sophisticated book *The Earth*, Jeffreys (1970) criticizes Wegener's theory of continental drift as theoretically impossible.

## The Death of the Theory

Until the late 1920s, Wegener's theory of continental drift remained the subject of heated controversy. Then interest declined almost completely—first, because the theory contradicted the commonly accepted belief of the time that the earth was solid and hard, and, second, because Wegener had failed to provide a satisfactory explanation for the force that had set the continents in motion. Scientists could not accept Wegener's supposition that continental drift had occurred in the earth's recent history—say, the last 200 million years, which constitutes only a very small percent of the earth's total age of 4500 million years. They reasoned that if continental drift were possible at all, it could have occurred only during the earlier part of the earth's history when it was still hot and soft. Their reasoning was of course based on the "hot origin" hypothesis, the dominant theory of the time. Thus the theory of continental drift, born in 1912, was virtually dead by the 1930s. Only a few diehard supporters remained—a handful of geologists of the Southern Hemisphere who were still faced with the fact of the Permo-Carboniferous glacial distribution among the continents in that part of the earth.

### The Structure of the Earth

Abandoned by most scientists for twenty years or so, the theory of continental drift experienced a dramatic comeback in the late 1950s. Strengthened by new evidence, it is currently forcing us to change our view of the earth. This revival will be more clearly understood if we summarize a few additional basic facts about the earth. First, the structure of the earth's interior is studied by seismological methods. These methods are somewhat analogous to tapping on a watermelon to see if it is ripe. Like the sound we get when we tap the watermelon, seismic waves reveal the internal state of the earth. They tell us the earth is layered like an onion, consisting of the exterior crust, a solid mantle that extends to a depth of 2900 kilometers below the surface, an outer core believed to be liquid, and finally a solid inner core about 1100 kilometers in radius at the center of the earth (see Figure 1-9). The crust consisting of the lighter-weight granite and other rock types, has a low density. Each successive layer has a higher density than the one above it. The mantle, beginning at the Mohorovičić discontinuity, consists of heavier rocks such as peridotite. Until recently it was thought that the mantle was entirely solid, but we now suspect that at certain depths the rocks are so close to their melting point that they are able to flow plastically. The outer layer of the core is generally thought to consist mainly of liquid iron mixed with such elements as nickel, carbon, silicon, or sulfur. (This liquid state of the outer core has a direct bearing on the earth's magnetism, as we shall see in the following discussion.) The inner core is composed of the same elements in their solid form.

### The Earth's Magnetism

As everyone knows, a compass needle invariably points to the north or nearly so. As early as the 14th century, sailors were using this phenomenon for navigational purposes. William Gilbert (1600), physician to Queen Elizabeth I, explained the phenomenon by proposing that the earth itself was a huge spherical magnet with its poles

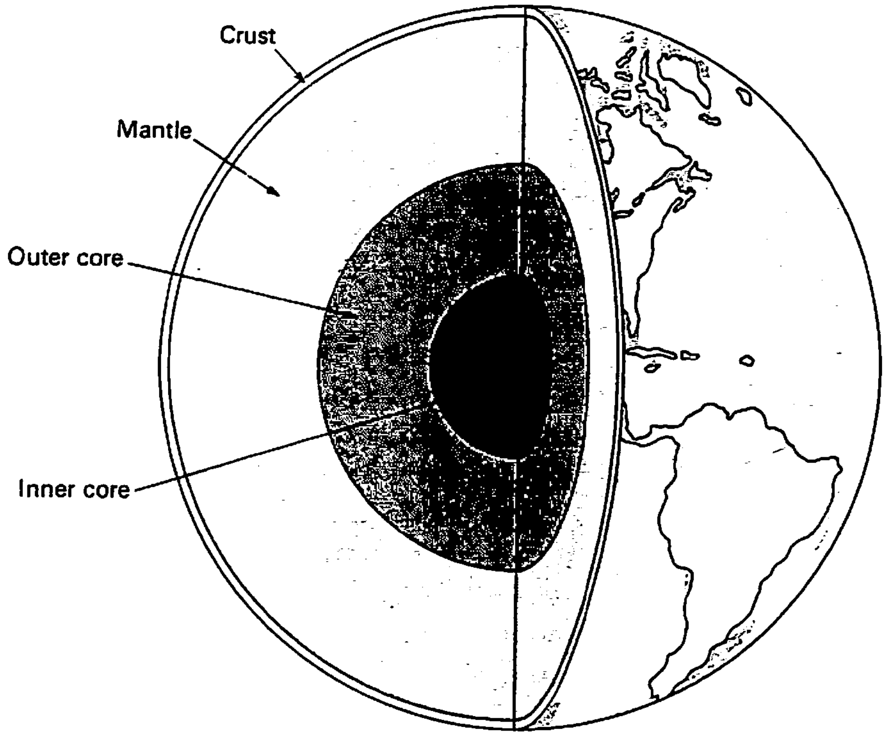

FIGURE 1-9
Cross section of the earth. Note that the thickness of the crust is exaggerated.

situated almost at the geographical poles as shown in Figure 1-10. If so, and because unlike magnetic poles attract each other and like ones repel, magnetic compass needles would naturally tend to point one end to the north and the other to the south. This was Gilbert's insight. The N and S poles of a magnet should thus be called, more properly, the north-seeking and south-seeking poles. (It is interesting to note that the earth's magnetic pole at the geographic north pole is

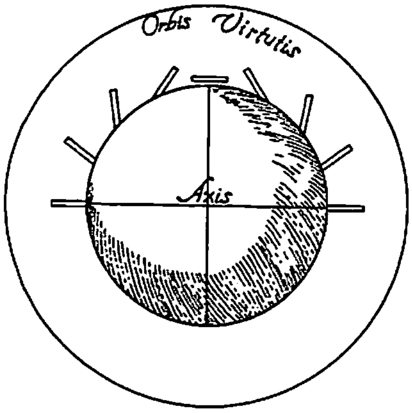

FIGURE 1-10
Spherical magnet earth of W. Gilbert. [After W. Gilbert, *De Magnete, Maneticisque Corporibus, et de Magno Magnete Tellure Physiologica Nova*. Short, 1600; Dover, New York.]

in fact a magnetic south-seeking pole; it has to be in order to attract the north-seeking pole of a compass.)

Gilbert's explanation was right but—as always happens in scientific research—it produced another question: why is the earth a magnet? This is a tough one. Recall that the origin of the earth's magnetic field was also listed by Dr. Adams in 1947 as one of the most difficult unsolved problems in geophysics. The simplest of all theories of the origin of geomagnetism was the assumption that the center of the earth was a huge permanent magnet. It was well-known that, among the common metals, only iron and nickel could be permanent magnets. (Such materials are called *ferromagnetic*.) Since the earth's core consists mainly of iron and nickel, the explanation of the earth's magnetism seemed obvious. This assumption, however, tunred out to be wrong for a simple reason. All ferromagnetic substances lose their ferromagnetism when heated beyond a certain temperature. That is, a magnet does not remain a magnet once it has reached a certain temperature, which is called the *Curie point* (770°C for iron and 358°C for nickel). It was then evident that the iron and nickel in the core could not form a permanent magnet since the temperature in the core was certainly higher than the Curie points of either metal. Since the outer part of the earth's core is liquid as revealed by seismic waves, its temperature is obviously higher than the melting point of iron and nickel, and laboratory experiments demonstrate that the Curie points of iron and nickel are much lower than their melting temperatures. In fact, it is only about the outer 50 kilometers of the earth that is cool enough to permit any material to be ferromagnetic.

Another hypothesis was that any rotating body was inevitably magnetized as a consequence of its rotation. The late English Nobel laureate physicist P. M. S. Blackett, who proposed the hypothesis, pointed out that the magnetism of such celestial bodies as the sun, certain stars, and the earth, could all be explained as being due to their rotations. He emphasized that such an explanation was not founded on the established laws of physics but required the positing of an entirely new concept. Blackett set out to prove his theory by developing an amazingly precise magnetometer in the late 1940s. However, his efforts failed, disproving his own hypothesis. Fortunately, in reporting his failure, he gave a remarkably full description of his sophisticated and precise measurements in a well known article entitled, "Negative Experiment" (1952). Indeed, in a deeper sense, the experiment was not a failure because of the extraordinarily sensitive magnetometer he developed to make the experiment. This magnetometer later proved to be a most useful tool when Blackett began to study the magnetism of rocks, and these experiments made a vital contribution to the revival of the theory of continental drift. Models of Blackett's magnetometer are now found in many geophysical laboratories all over the world.

Of the many theories that have been proposed, only one explanation of the origin of the earth's magnetic field has survived—that in which the earth is viewed as an electromagnet rather than as a permanent magnet. A magnetic field can be generated either by a permanent magnet made of ferromagnetic minerals or by an electric current. In the 1950s such scientists as W. M. Elsasser of the United States and Sir Edward Bullard of England concluded that, since the earth was too hot to be a permanent magnet, it must be some sort of electromagnet, and they began to explore vigorously the possibility that a geomagnetic field was produced by electric currents in the earth.

In order to provide enough flow of electricity to create the geomagnetic field, the electric conductivity of the earth's interior would have to be as high as that of metal. The iron core is the only part of the earth that could possibly have such a high electrical conductivity. In addition, an electromotive force or voltage must be constantly present to keep the electric currents flowing and maintain the geomagnetic field for a geologically long time. In other words, the earth's core has to be more than a good electrical conductor through which electric currents pass: it must also act as a dynamo or generator. This concept of the origin of geomagnetism is called the *dynamo theory*.

However it is almost inconceivable that a mechanism like the generators we are accustomed to—complicated pieces of machinery with insulated wires—would exist inside the earth's core. Yet in the 1960s, young geophysicists from the United States (G. Backus) and England (A. Herzenberg) proved that it was possible, at least theoretically, that a body like the earth's core could act as a dynamo. In 1963 F. J. Lowes and I. Wilkinson of England succeeded in constructing a generator somewhat similar to the one described in the theory. H. Takeuchi, Y. Shimazu and T. Rikitake of Japan also contributed to the development of this model. However, the theory has not yet been completely established. As electronic computers have become more and more powerful, the theoretical calculations have also become more and more sophisticated, and additional complications in the theory have been disclosed. Perhaps it is accurate to say that the origin of the earth's magnetic field remains a great mystery. But theoreticians are willing to concede at least the possibility that the earth could have a dynamo-generated magnetic field.

The dynamo theory as it stands today assumes an extremely complex chain of processes taking place in the earth's core. We will not describe all of these processes here, but it is important to recognize that the following conditions are necessary if the earth is to work as a generator:

(1) the core of the earth must consist of a substance that conducts electric current as easily as metal does;
(2) the substance must be in a liquid form;
(3) this conducting liquid must be stirred up in some way, the stirring process providing the energy needed to sustain the field.

These conditions make it almost imperative that the core of the earth consist of liquid metal that is probably iron—the most common and abundant metal in the universe.*

## Paleomagnetism: The History of the Earth's Magnetic Field

At first glance, continental-drift theory and geomagnetism seem to have little in common. Yet it was shown in the late 1950s that the two are actually quite closely related. The first step in this recognition occurred when geophysicists questioned whether the compass needle always pointed to the north. If the geomagnetic field is produced by a "permanent" magnet, the history of the earth's magnetism must have been a boring record of consistency; but if we consider geomagnetism as an electromagnetism produced by a "dynamo," its history can vary a great deal. The dynamo concept was supported by the following observation. In present-day Tokyo, the compass needle deviates 6° to the west of exact north. The angle of deviation is called

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*The famous American geophysicist F. Birch wrote in his classic paper (1952) the following:

> Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth; a few examples of equivalents follow:

| High-pressure form | Ordinary meaning |
|---|---|
| certain | dubious |
| undoubtedly | perhaps |
| positive proof | vague suggestion |
| unanswerable argument | trivial objection |
| pure iron | uncertain mixture of all the elements |

the *declination*. An interesting fact is that the declination changes in the course of time; 150 years ago the compass needle in Tokyo was recorded to have pointed 3° to the east. This phenomenon is widely known throughout the world and is called the *secular variation* of geomagnetism. The actual measurement and recording of geomagnetism began only 300 years ago. Naturally this is too short a period to provide information about the changes that have taken place throughout geological time. It is important, however, to note that even within the span of human history, geomagnetism has changed considerably. How much greater might those changes have been throughout the long span of geological time? Answers to this interesting question may reveal the nature of geomagnetism. But how are we to study geomagnetism as it was a million years ago? The magnetic field is just a "field" that, if it changes with time, leaves no indication of its former condition—it is therefore extremely difficult to trace its history. Nevertheless an interesting possibility was discovered: the permanent magnetization of natural rocks sometimes provides us with a "fossil" that contains a trace of the magnetic field as it once was. Among the various kinds of natural rocks, let us consider volcanic rocks—which are cooled and solidified magma. An examination of volcanic rocks such as basalt reveals surprisingly strong magnetism. Of course its strength is but one thousandth of that of the usual magnet that can attract iron and suspend nails. Yet, with a sensitive device, it is a reasonably easy task to determine the direction of magnetization of volcanic rocks. But why are they magnetized in the first place? The answer is as follows: when a volcanic rock comes into existence, that is, when it is erupted from a volcano, it is incandescent lava and its temperature is much higher than the Curie point. As the lava cools through the Curie point its magnetic moment is set in the direction of the geomagnetic field at that time and remains in this condition permanently. This "fossilized" magnetization is characteristic of all volcanic rocks. It was investigated by, among others, J. G. Königsberger of Germany, T. Nagata of Japan, and E. Thellier of France, in the 1940s. The famous French Nobel laureate L. Néel provided an ingenious theoretical explanation to this pehnomenon, called *thermoremanent magnetization*. Once the mechanism of such magnetization had been established, it became possible, at least in theory, to trace the history of the earth's magnetic field by measuring the magnetization direction of rocks from various geological periods.

This field of study is called *paleomagnetism*. Paleomagnetism rose in popularity in the 1950s and disclosed many new facts, the most remarkable among them being those related to the revival of the continental drift theory! Before treating this important aspect of paleomagnetism, however, let us digress to examine another issue that is equally important to the theme of this book.

## Reversal of the Earth's Magnetism or Self-Reversal of Rock Magnetism?

The study of paleomagnetism has traditionally been very active in France and Japan. B. Brunhes and M. Matuyama were the foremost pioneers in this field. Brunhes discovered, as early as 1906, that some rocks are magnetized in the opposite direction to the present geomagnetic field and proposed the possibility that the earth's magnetic field had been reversed when these rocks were formed. Matuyama in the 1920s found that about half the volcanic rocks from Japan and Korea that he measured were magnetized in the same direction as the earth's magnetic field at present. But the other half were magnetized in the opposite direction. On the basis of this study Matuyama concluded that the earth's magnetic field had reversed near the beginning of the Ice Age, in the early Pleistocene. This was a bold assertion at the time. Late in the 1950s, however, the same evidence turned up repeatedly in Iceland, France, England, the United States, the USSR, and elsewhere. A. Cox, R. Doell, and B. Dalrymple of the United States and I. McDougall, D. Tarling, and F. Chamelaun of Australia investigated this issue thoroughly and established the reversal history of the geomagnetic field for the last several million years.

I must confess that I too have a deep personal interest in this problem. In 1951, when I was an undergraduate student at the University of Tokyo, I was performing a series of experiments under the guidance of T. Nagata. I was examining the way in which the ferromagnetic minerals that are contained in various volcanics acquire thermoremanent magnetism when cooled through the Curie point in a magnetic field. The procedure was to heat the samples, which were contained in silica glass tubes, to above the Curie point and then cool them in a magnetic field. In the course of these experiments, I noticed that one of the samples, which consisted of ferromagnetic grains extracted from a pumice of the Japanese volcano Haruna, had been magnetized in the opposite direction to that of the applied magnetic field in my laboratory. Such an observation could have been the result of my having mismarked the orientation of the sample; certainly the acquisition of magnetization in a direction opposite to an applied field appeared impossible or totally absurd as long as the fundamental laws of physics held true. But the observation was unmistakably real. Being a lazy student, I did not trouble to repeat the heating and cooling experiments for each sample, but instead had put several samples together in a furnace. Therefore, when I found that only one of them had been magnetized in a direction opposite to all the others, I knew there was no chance of a mistake. Both my professor and I were completely perplexed by this odd phenomenon. But before long we realized that it could be an important discovery. We avidly conducted various experiments and devised a "theory" to explain the physical cause of this phenomenon of *reverse thermoremanent magnetism*, as we named it. About that time, T. Rikitake drew our attention to a paper by L. Néel (1951), in which such a phenomenon was theoretically predicted. The paper had been published in France at about the same time we were discovering the phenomenon in Tokyo. We were impressed by his insight. Later we learned that Néel's work had been inspired by an American geologist John Graham, who had written a letter to Néel asking if such a phenomenon might be theoretically possible. In fact, what prompted Graham's question was the frequent natural occurrence of rocks that are magnetized in a direction opposite to the present geomagnetic field. Instead of assuming the reversal of the geomagnetic field, he wondered if some rocks might have an intrinsic property of reverse magnetization! John Graham died in 1971, but will be long remembered for his imaginative and ingenious ideas on many aspects of earth science.

Upon the discovery of the self-reversal of remanent magnetization in rocks, some scientists, myself included, suggested that we need not assume the reversal of the geomagnetic field in the geological past. In fact, for several years papers on this subject flowed in continuously from numerous parts of the world. These were all studies of rocks that were naturally magnetized in the opposite direction from the earth's magnetism, and the objective was to see whether they, like the rock from Mt. Haruna, could also self-reverse the direction of magnetization. The results of the papers proved, contrary to our expectation, that such rocks were quite rare. Although self-reversal was found to be an uncommon occurrence requiring a very special kind of ferromagnetic mineral, this particular kind of thermoremanent magnetization was such a fascinating phenomenon that I devoted myself to a quest for its mechanism for a good six years. The ultimate cause of this phenomenon was found to be different from the original models proposed by either Néel or us. Rather, it appears to be related to highly intricate quantum-mechanical interactions taking place within minerals contained in the sample. The problem is today still the subject of investigation by young scientists around the world.

The evidence, then, is so overwhelming that we must, at least for the present, concede that the earth's magnetism *did* reverse frequently during the geologic past. The significance of the reversal of geomagnetism to the new view of the earth will be made clear in Chapter 2.

## Poles Move and So Do Continents

If we take a sample of lava from Japan's Mt. Fuji and measure the direction of its remanent magnetism, it is possible to deduce the position of the earth's magnetic pole when that lava poured forth. The earth's magnetic field can be approximately represented by a regular dipolar pattern (Figure 1-11) that closely resembles the field produced by a bar magnet placed at the earth's center. This pattern enables us to determine the position of the South and North Poles by examining the direction of the magnetic lines of force at any given location. For a variety of reasons, however, the earth's magnetic field does not form a perfect dipolar pattern. The pattern is actually far more complex. Thus no accurate position of the pole can be calculated if the calculation is based on the assumption of a perfect dipole field. Nevertheless such computations are approximately correct—especially when a sufficiently large number of measurements are made and their average is taken—as has been demonstrated by current measurements of many rocks of recent age all over the world. If we assume the field was also a dipole in the past, the positions of the geomagnetic pole in earlier ages may be estimated from measurements of the direction of the natural remanent magnetism of older rocks. This assumption—that the earth's magnetic field was always dipolar—is an important one, but it is still only an *assumption.*

The study of paleomagnetism developed mainly in Japan and France during the late 1940s and early 1950s. Then in the mid-1950s it was taken up by British scientists who applied it with skill and enthusiasm to the examination of rocks of many ages from all over the world in order to survey extensively the history of the earth's magnetic field. Led by P. M. S. Blackett and S. K. Runcorn, they exerted an enormous effort in this work. It is a well known fact that the highly sensitive magnetometer developed by Blackett for his "negative experiment" (described earlier in this chapter) was of great

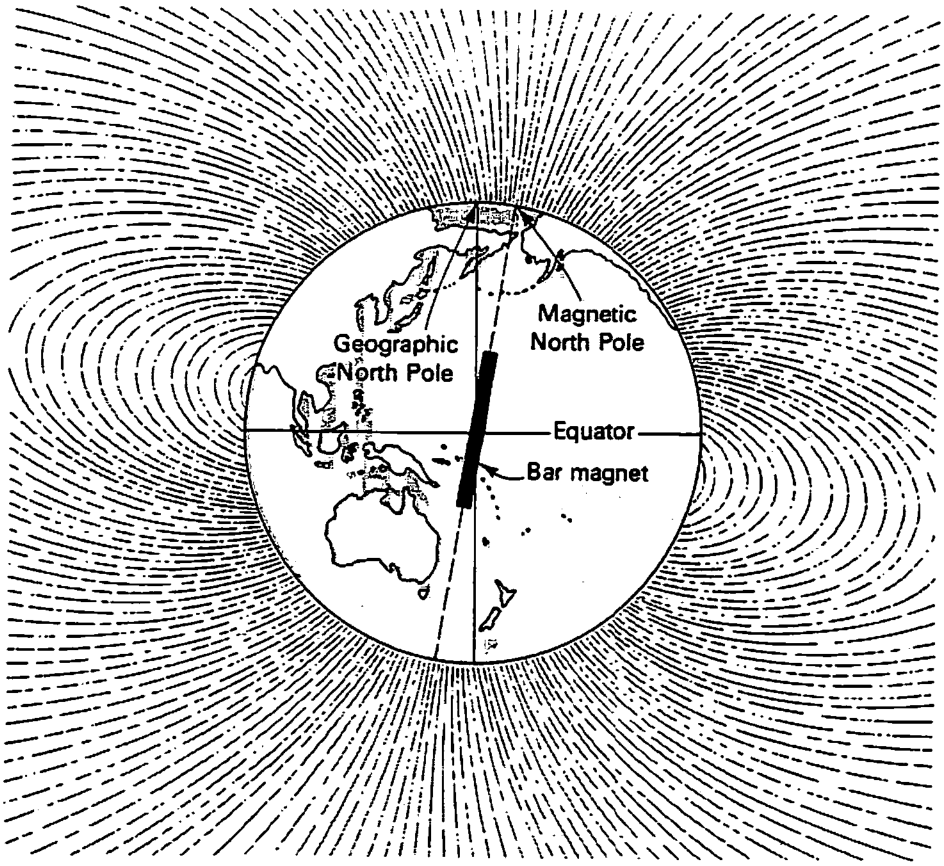

FIGURE 1-11
The earth's magnetic field is much like the field that would be produced if a giant bar magnet were placed at the earth's center and slightly inclined (11°) from the axis of rotation. [After F. Press and R. Siever, *Earth*. W. H. Freeman and Company, San Francisco. Copyright © 1974.]

assistance in these projects. The British enthusiasm for this seemingly unexciting task at that particular time puzzled those of us working in Japan. The English are said to have an unconditional love of nature and the earth—perhaps this was the reason, but the discerning scientific leadership of Runcorn and Blackett seems to have had a significant influence as well. Although the British scientists might have appeared to be engrossed simply in examining the magnetism of rocks, their efforts must have been motivated by a great deal of foresight on someone's part. Whatever the impetus, they scattered themselves throughout the world, collecting and examining rocks. By 1957 they had achieved brilliant results.

Runcorn and his group attempted to represent the earth's magnetic field in the past by the position of the ancient magnetic pole. This was the best possible way to analyze uniformly the results obtained

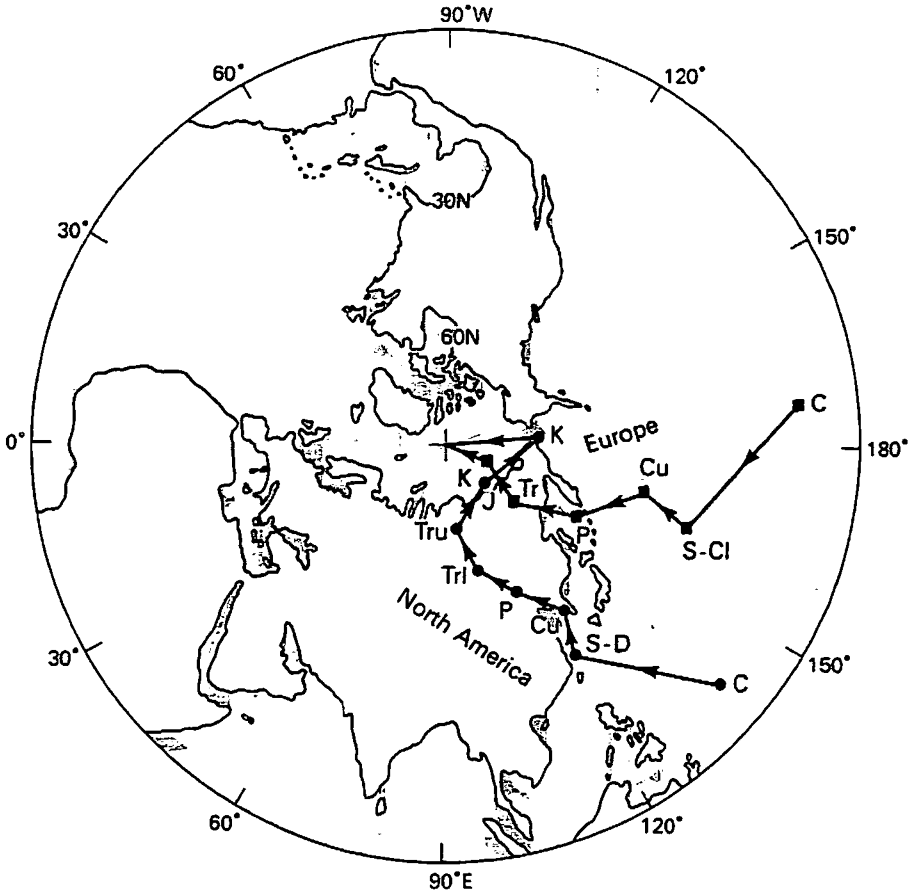

FIGURE 1-12
Comparison of the apparent polar-wandering paths for North America (circles) and Europe (squares). The circles and squares themselves represent the essentially stable regions of each continent for the different geologic periods. The following letter symbols are used to designate the various periods: K—Cretaceous; Tr—Triassic; Tru—Upper Triassic; Trl—Lower Triassic; P—Permian; Cu—Upper Carboniferous; S-D—Silurian-Devonian; S-Cl—Silurian Lower Carboniferous; C—Cambrian. [After N. W. McElhinny, *Paleomagnetism and Plate Tectonics*. Cambridge University Press, 1973.]

from rocks collected from locations that were such large distances apart. First the rocks from England and the European continent were examined to determine the position of the magnetic pole in each geologic period from the Precambrian era to the present. The result is plotted on the map in Figure 1-12. If the magnetic pole has not changed its position throughout the earth's history, the plot will point to a single spot. However the result conclusively shows a systematic movement of the pole. About 250 million years ago during the Permian period, the magnetic pole was located north of where the Japanese islands are at present—quite a distance away from the present North Pole. Five hundred million years ago, during the Cambrian period, it was much farther away in the Pacific. This phenomenon is called *polar wandering*.

Interestingly enough the path of polar wandering, as determined paleomagnetically, roughly corresponded to the path of yet another pole traced by an entirely different method. This other pole was the paleoclimatological pole, which was found by the location of fossils of ancient plants and animals. This observation implied that the various locations of the ancient paleomagnetic poles were indicative of changes in the orientation of the earth's rotation axis. The underlying assumption was that, in the past, the polar regions had been cold and the equatorial regions warm, and that the fossils of life forms indicate the former latitude of localities at which they are sampled today. Based on this kind of analysis, such scientists as Wegener, Köppen and Kreichgauer had already talked about polar wandering as early as the 1910s. The coincidence of the paths of the magnetic pole and that of the paleoclimatological pole, though far from exact, must have encouraged the British scientists.

Runcorn and his group conducted their intensive search for the path of the magnetic pole, using rocks not only from Europe but from North America as well. The result is also shown in Figure 1-12. To be noted are the loci of the paleomagnetic poles as estimated from the rocks of England and Europe and from those of the North American continent. Anyone can see that the paths for each are similar, and form such a coherent pattern that it is hard to dismiss polar wandering as false or accidental. Furthermore, careful scrutiny will reveal that these two lines, although they are quite similar, are *not* identical. The discrepancy appears to be systematic. S. Runcorn and E. Irving, examined this discrepancy closely, and came up with an idea that was to revive the theory of continental drift.

Their idea was a simple one. If paleomagnetists had been alive during the Permian period, 250 million years ago, they would have found that paleomagnetic poles for rocks forming at that time at different sites all over the world would coincide, just as they do today—in particular, those from Europe and North America. Now let us see what happens if North America moves away from Europe. A paleomagnetic pole behaves as if it were attached to a continent by a rigid rod because it is determined from paleomagnetic measurements, which tell us that the ancient pole was at a certain distance along a specified great circle from a sampling site. If a continent moves, the pole moves with it. So if North America has moved away from Europe since the Permian period, its pole has moved with it,

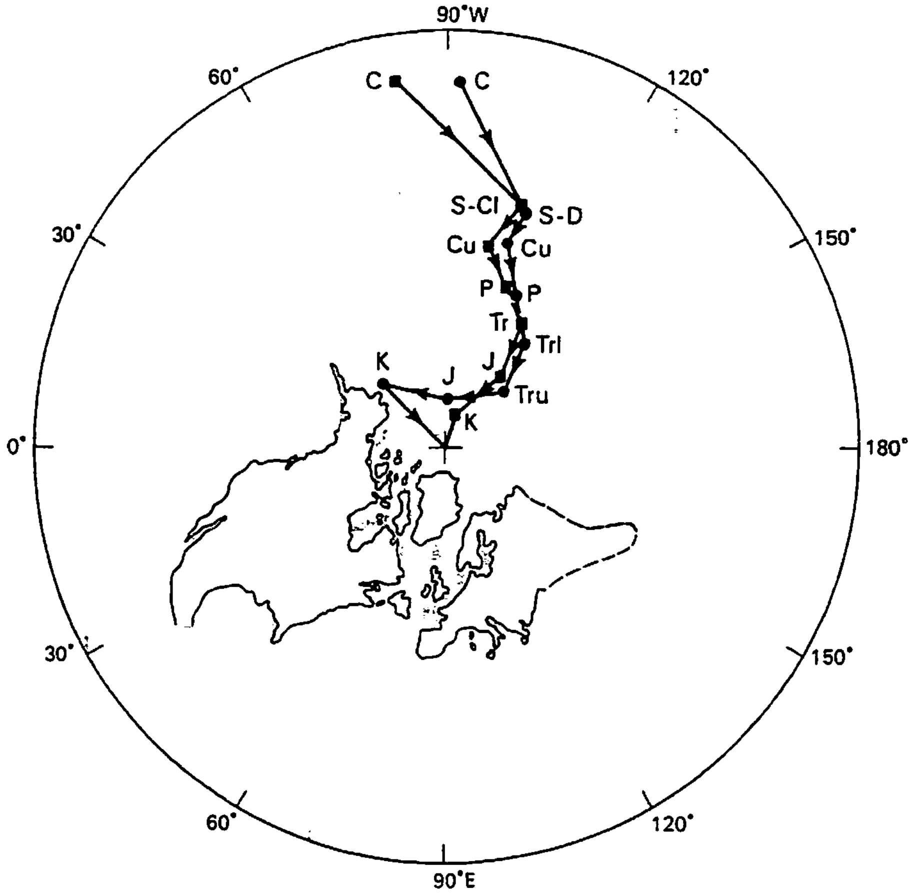

FIGURE 1-13
The two polar-wandering paths in accord with the fit of the North Atlantic proposed by Bullard and others. As in Figure 1-12, the circles (North America) and squares (Europe) represent the stable regions of each continent for each period. K—Cretaceous; Tr—Triassic; Tru—Upper Triassic; Trl—Lower Triassic; P—Permian; Cu—Upper Carboniferous; S-D—Silurian-Devonian; S-Cl—Silurian Lower Carboniferous; C—Cambrian. [After N. W. McElhinny, *Paleomagnetism and Plate Tectonics*. Cambridge University Press, 1973.]

and we can no longer expect the two to coincide. Runcorn and Irving found that the poles for North America and Europe were distinctly different, demonstrating that the two continents had moved apart. They also found that if they pursued Wegener's ideas and closed up the Atlantic to restore the continents to their former position, the magnetic poles coincided, as illustrated in Figure 1-13. Their research revived the theory of continental drift and provided completely independent evidence in support of it.

During my stay at Cambridge University from 1958 through 1959, nearly every time I was introduced to a geophysicist, I was greeted with such questions as "Do you believe in continental drift?" or "Do you believe in the reversal of the earth's magnetic field?" Being a little unfamiliar with the inclination of British scientists to favor such ideas as continental drift, my answer used to be a half-hearted "Well, yes, but with reservations." I was aware of what was being discovered at the time, and I knew the evidence was quite solid, but my enthusiasm could not quite match that of the English.

As I've already mentioned, why the British should revive the continental drift theory at that particular time through their ardent studies of rock magnetism seemed a mystery to others of us. Scientists who had been active when the theory of continental drift was still popular were already too old to be acquainted with the new field of paleomagnetism, and yet in most countries the younger scientists who explored this new field of paleomagnetism were not really familiar with the theory of continental drift. England, however, was probably an exception, owing largely, I believe, to the excellent textbook *Principles of Physical Geology* (1965) by the late Edinburgh University professor, Arthur Holmes. In this book, the then unpopular theory of continental drift was still vividly discussed along with Holmes' famous theory of convection in the mantle.

## The Theory of Convection in the Mantle

As we have seen, the theory of continental drift was abandoned in the 1930s because no satisfactory explanation of what causes continental movement was produced. Of the many hypotheses suggested by Wegener but not developed by him rigorously, only one has survived: that the mantle undergoes thermal convection similar to that seen in a kettle of soup on a stove: as the soup at the bottom is heated it expands, becomes less dense, and rises to the top. At first the proposal that a similar process takes place in the earth might seem absurd because the mantle is solid. However a number of materials, like cool tar and "silly putty" will break like a solid if they're bent quickly but will flow slowly like a liquid if gentle forces are applied to them over a long period of time. During very long periods of time even ice is able to flow plastically, and so can the mantle. Arthur Holmes maintained it was this flow due to convection that provided the driving mechanism for continental drift. He likened the flow to, in his words, "an endless travelling belt"—or what we today refer to as a "conveyor belt"—and asserted that even a continent could be carried along by it.

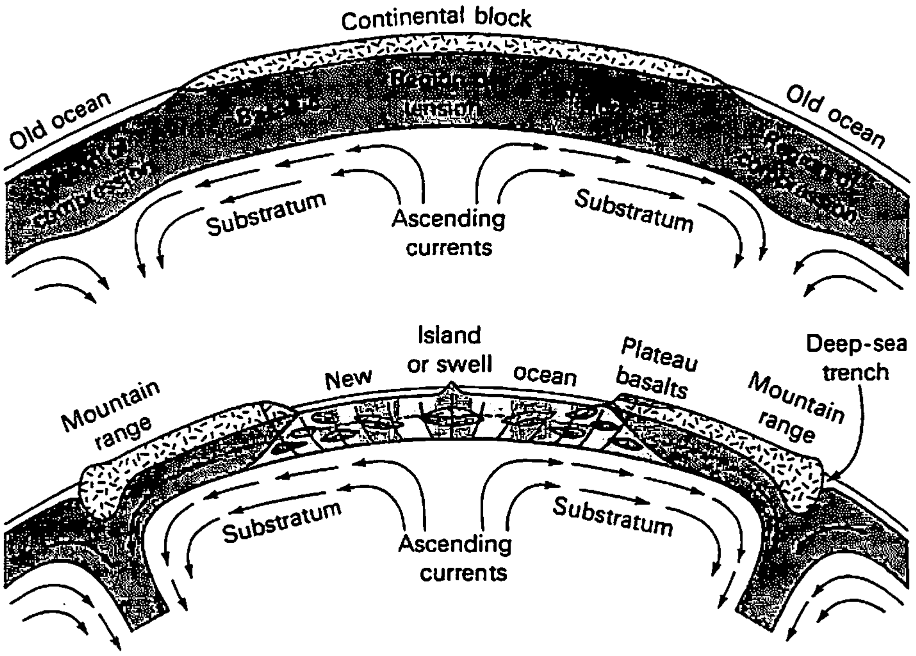

FIGURE 1-14
Model demonstrating mantle convection as a possible mechanism of continental drift. It shows a continent being pulled apart by rising mantle currents, with new ocean developing from the growing rift. In the vicinity of a descending current, a mountain range and bordering deep-sea trench develop. [After A. Holmes, *Principles of Physical Geology*. Thomas Nelson and Sons, Ltd., Middlesex. The Ronald Press Company, New York, 2nd ed.; copyright © 1965.]

All of the other theoretical mechanisms for continental drift had been founded on the fixed idea that the continent itself pushes its way through the solid mantle. Once theoretical studies conducted by geophysicists had shown this propulsion was impossible, geophysicists lost interest in the continental drift theory.

Holmes theorized that if the flow within the mantle welled up in the middle of a continental mass and parted to each side, the continent would split and the two halves would drift apart. The Atlantic Ocean has formed in such an expanding rift. The mechanism of this theory is represented in Figure 1-14.

Holmes' theory, which he first proposed in 1929, survived without receiving much active opposition, probably because his ideas were too far ahead of the times. If we examine the model in Figure 1-14 closely, we cannot help but recognize its striking affinity to the new view of the earth—the sea-floor spreading hypothesis, to be described in later chapters. We will refer to the problem of the convection in the mantle elsewhere in this book.

British scientists continued their remarkable exploration of this fundamentally revolutionary concept of earth's science until the end of the 1950s. Then, in the 1960s, the scientists of the new world arrived on the scene.

### A Modern Jigsaw Puzzle

Wegener first conceived the idea of continental drift upon trying to fit together the two Atlantic coastlines. This method was later extended to establish conformity between the fossils of ancient plants and animals and between the geologic strata of each continent. Some scientists, like Wegener, found that continental conformity was very close, whereas others reported large gaps and areas of overlap. All the attempts to assess the fit one way or the other were criticized as too subjective. In recent years, more objective methods have been developed.

Sir Edward Bullard and his colleagues (1965) settled the argument by programming an electronic computer to try all possible rearrangements and find which fit the best. They discovered that the contour line at a depth of about 1000 meters, rather than the present coastline, fitted best (Figure 1-15). They made the quite reasonable suggestion that this line be considered as the contour of the original continent. The fit determined by the computer is amazingly good. Although overlaps and gaps do exist, they are extremely small. It would thus seem that the electronic computer has proved that the continents fit together almost as perfectly as the pieces of a puzzle. Assuming that this conformity was not purely coincidental (as is the boot shape of the Italian peninsula for example), Bullard concluded that it strongly suggested that these continents originally formed one continental mass.

Another method was developed by P. Hurley (1968) of the United States and his colleagues from Brazil. A number of geological features on both sides of the Atlantic match, but it was always suspected that an element of subjectivity had influenced the matching process. These workers made it possible to see how well the continents fit together objectively by determining the absolute ages of rocks with the radiometric method, which is almost entirely objective. In this method, as explained near the beginning of this chapter, the rate of spontaneous disintegration of radioactive elements with long half lives is the basis for determining the age of rocks with as much certainty as can be provided by modern physics. With this technique,

FIGURE 1-15
Map showing the conformity of the continents bordering on the Atlantic. The black areas along the coastlines represent the continental overlaps, and the white areas the gaps. Also matched are the ages of the rocks in South America and Africa. The dark circles denote rocks older than two billion years; the light circles denote the younger group approximately 600 million years old. [After P. M. Hurley, "The Confirmation of Continental Drift." Copyright © 1968 by Scientific American, Inc. All rights reserved.]

Hurley and others analyzed the ages of enormous numbers of ancient rocks from the eastern part of South America and from the western part of Africa, as shown in Figure 1-15. The dated rocks of the two continents fall neatly into two groups: those more than two billion years old and those approximately 600 million years old. Both ages are older than the proposed split of Gondwana. The regions of the same age were found to match across the Atlantic as they should. A typical example, pointed out in the figure, is the region considered to be originally a part of the ancient African continental block, now isolated on the coast near São Luis, Brazil. In view of these findings, it became increasingly difficult to dismiss the continental-drift theory as the wild idea of a meteorologist who dabbled in geology.