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Chapter 6

The New View of the Earth

New Global Tectonics

We have seen that the theory of continental drift underwent sever stormy and controversial decades, during which it was almost com pletely discarded for a substantial period. It was revived by advance in paleomagnetism, strengthened by marine geophysics, and brough to maturity by the sea-floor spreading hypothesis, after which rapidly evolved into what is now called plate tectonics.

We have also seen that there are many ways to study the earth. Bu if we are to move toward what might be called a "new view of th earth," we must synthesize the results obtained through the variou approaches. Neither the sea-floor spreading hypothesis nor plate tec tonics alone can fully support this new perspective that will eventu ally lead to an understanding of the way the earth continues to work yet both are indispensable to such an understanding. In the nev view, the earth is perceived as a mobile body, whereas in the tradi tional, opposing view it is regarded as immobile. Some describe thi conflict as one between the mobilists (or drifters) and the fixists.

To summarize the concepts on which the mobilist view is founded a continent is part of a lithospheric plate, and it moves with that plate The lithosphere itself forms at the oceanic ridges. As soon as it form by cooling, it begins to behave as a rigid plate. Several large and smal lithospheric plates constitute the earth's surface. It is further postulated that all the large-scale phenomena occurring on the earth's surface at present can be attributed to the relative motions of the plates. When an oceanic plate collides with a continental plate, the oceanic plate descends, or subducts, beneath the continental plate, forming an oceanic trench. Subduction of an oceanic plate creates not only trenches, but also the island arcs. The activity of such an island arc epitomizes orogenesis itself. Where plates on which continents or island arcs rest collide with one another, a different kind of orogenesis occurs. Instead of subduction, continents and arcs form folded mountains. By this type of orogenesis, mountain ranges such as the Himalayas and the Alps are formed.

However, still to be answered is the basic question of what is causing these activities. Recall that it was Arthur Holmes who postulated in the 1920s that convection currents within the mantle cause the movement that carries continents, much as they would be carried along by a conveyor belt. This concept never died. It was kept alive, and provided a basis for the sea-floor spreading hypothesis proposed in the 1960s by Hess, Dietz, Wilson, and others. For the origin of island arcs and oceanic trenches, the late D. T. Griggs developed a theory in the 1930s, maintaining that they form where the flow of the mantle convection descends. This theory also survived to provide a framework for plate tectonics. At this point let us once again examine what is involved in "convection within the mantle."

What Is Convection?

Everyone knows that a pot of boiling water shows a circulatory movement. When there is a disparity of density within a fluid, the heavier portion descends while the lighter portion rises to the surface. The convection that is observed within the pot is called thermal convection because it is caused by a density difference in the water created by a temperature difference. Thus if a potful of water is heated from below, the heated portion at the bottom expands, becomes light, and floats to the surface where it is cooled and becomes heavy, only to go down again. As it circulates in this way, the water is gradually heated throughout and gives off heat into the air. In short, thermal convection is a mode of transferring heat from the flame beneath the pot to the air above the pot. The convection that occurs within the mantle is also considered to be thermal convection. The deeper portion of the mantle is heated and expands, thus causing a circulatory flow.

Scientific investigation of such a simple and familiar phenomenon as the churning pot of water, however, was long neglected. H. Bénard of France was the first one to conduct the basic experimental research on thermal convection. The result of his experiment was published in 1906. In this experiment Bénard placed a thin film (between 0.5 and 1 millimeter) of paraffin on top of an iron cylinder and heated the cylinder from below. Bénard found that convection in the paraffin did not occur until the cylinder reached a certain temperature. He kept heating it past this point and observed that the heated portions began to ascend from everywhere, while the circumferential areas of such portions started to descend. After a while a regular hexagonal pattern appeared on the surface, as shown in Figure 6-1. The heated portion rises to the surface at the center of each hexagon in this pattern, and the cooled portion descends at the sides of the hexagon. Stirring cannot disrupt this regular pattern for long. In other words, the hexagonal pattern, called *Bénard's cells,* is stable. Bénard also discovered that the ratio between the thickness of the layer of liquid and the horizontal size of these regular hexagons—the length of their side, for instance—was close to one.

The theoretical study of Bénard's findings as a physical phenomenon, however, had to wait until 1916 when a paper by the famous Lord Rayleigh was published. He noted that heat from below does not necessarily cause convection as long as the heat can be conducted through the liquid to the air by normal thermal conduction. However, if there is too much heat to be transferred by thermal conduction, the heat accumulates at the bottom and the liquid there expands, becomes lighter, and starts to ascend. This is the beginning of convection. The viscosity of the liquid, however, tends to inhibit convection. In liquids with low viscosity, such as water, convection can occur readily, but in sticky liquids, such as oatmeal, convection is greatly hampered. This is the reason that oatmeal, for example, takes so long to cool.

Taking these factors into consideration, Rayleigh came up with the theoretical condition necessary for convection to occur. He maintained that when a nondimensional quantity defined as $R = \alpha\beta g h^4/k\eta$ reaches a certain number (about 1000 in actuality), thermal convection begins. If R is less than this number, the heat is transmitted only by ordinary conductivity. In the expression for R, h is the depth of the liquid layer; α is the coefficient of thermal expansion representing the fractional volume expansion caused by raising the temperature one degree; β is the temperature gradient, that is, the rate at which temperature increases with depth within the layer; and g rep-

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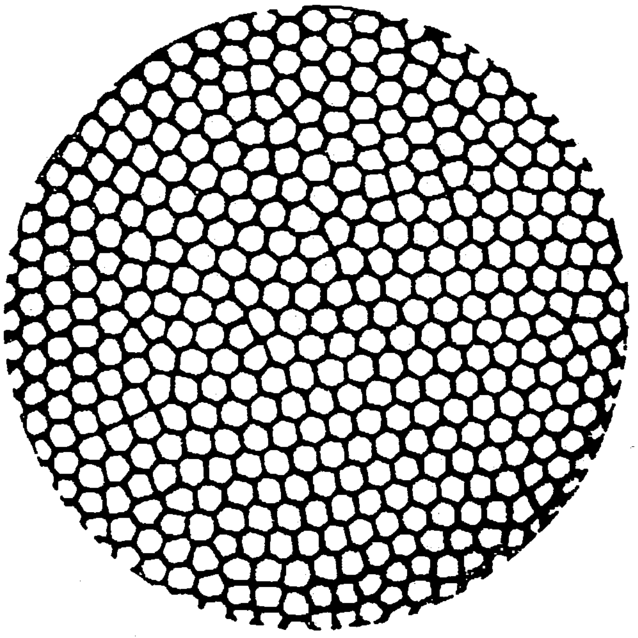

FIGURE 6-1
Bénard cells in paraffin. A drawing of one of Bénard's original photographs. [After S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*. The Clarendon Press, 1961.]

resents the force of gravity. In the denominator, k is the thermal diffusivity, and η is the viscosity. Qualitatively, the tendency for convection to occur as R increases can be comprehended quite readily. In the formula of R, the quantities that help convection are included in the numerator, and those inhibiting it are included in the denominator. Rayleigh's theory thoroughly confirmed the results of Bénard's experiments. The phenomena and theory described above have been named Bénard-Rayleigh convection, and the quantity R is now called the *Rayleigh number*. The value of the Rayleigh number at which convection starts is called the *critical Rayleigh number*.

It was found at the time of Bénard's experiment that the surfaces of the sides of the hexagons, where the cooled portions descend, were slightly more elevated than the surfaces of the centers, where the heated portions ascend. This fact did not seem to conform to mantle convection, because the ascending portions within the mantle rise to form oceanic ridges while the descending portions form oceanic trenches—exactly the opposite of Bénard's result. This riddle haunted a large number of scientists until the 1950s when M. J. Block of the United States and J. R. A. Pearson of England came up with an answer. It was surface tension that had played a trick on scientists. Astonishingly, according to Block and Pearson, the fluid motion observed in Bénard's experiment was caused not by thermal convection, but by the motion induced in the liquid by the changes of surface tension due to temperature variations. Since the importance of surface tension does decrease where the liquid layer is thick, Rayleigh's *theory* remains valid for thermal convection provided the layers are thick enough. The fact is, however, that Bénard's experiment, which Rayleigh had tried to theorize, had little bearing on the problem of thermal convection itself.

Convection Within the Mantle

If we are to maintain that thermal convection occurs within the mantle, the applicability of Rayleigh's condition must first be examined. The first obstacle is the fact that the mantle is a solid body. Isn't a solid body one that never flows? However, consider an important fact that is not intuitively obvious. No matter how solid it is, no substance can permanently withstand the prolonged action of forces. A tall iron pillar, for instance, will not be able to support itself indefinitely but will bend and collapse in the course of a long period of time. Thus a solid body, even a crystalline substance like ice, actually does flow. It is simply that in most solids the rate of flow is imperceptibly slow. Can the earth's mantle too be fluid? As we saw in Chapter 1, the very fact that isostasy occurs means the mantle must have the property of flow: the great mountain ranges float on the mantle in accord with Archimedes' principle of buoyancy, and this principle is applicable only to fluids. The history of the Scandinavian peninsula is a good example of the fluid earth in action. Until about 10,000 years ago the peninsula was covered with a thick continental glacier and the land surface was depressed like a loaded raft. At the end of the last Ice Age the ice melted away, relieving the peninsula of the great weight of the ice sheet. This disturbed the isostatic equilibrium, and to regain equilibrium the Scandinavian peninsula started to rise and is still rising at a rate of several millimeters a year. The simplest explanation is that the mantle acts like a fluid with a viscosity of 10^{21} poises, a "poise" being the standard unit of viscosity. This phenomenon is called *postglacial rebound.*

Another indication of the earth's fluidity is its shape—an ellipsoid. The earth is not completely spherical because the centrifugal force of the earth's rotation causes it to bulge at the equator. This fact seems to prove that the earth as a whole can also act as a fluid body. It is

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thus an almost indisputable fact that in the course of long periods of time the earth's mantle flows in response to small but persistent forces. If we take all the relevant elements into consideration, the Rayleigh number for convection throughout the earth's entire mantle would be from 10^6 to 10^8, which is many orders of magnitude greater than the critical Rayleigh number (about 1000). Thus the earth's mantle fully satisfies Rayleigh's condition for convection.

With a viscosity value as great as 10^{21} in the denominator, it might seem that the Rayleigh number, R, would never have a large value. However, the depth of the entire mantle, h, which is included in the numerator to the fourth power, is so great that the Rayleigh number is very large, even with a large viscosity or a small thermal gradient (0.3°C per kilometer, for example). Insofar as one considers the mantle as a regular fluid (usually called a Newtonian fluid), the presence of convection seems natural and inevitable. It is not unlike the boiling in a kettle of water.

However, Rayleigh demonstrated only the condition necessary for the onset of convection under a set of idealized circumstances—not the kind of convection current that would actually occur under conditions in which the Rayleigh number was much greater than the critical value. A number of unresolved questions about mantle convection remain.

For one thing, the mantle—which we can regard in this discussion as a viscous fluid layer—exists as a spherical shell, rather than in the flat layer employed in Rayleigh's model. Moreover the heating of the liquid is not only from below, but the liquid mantle itself contains heat sources in the form of radioactivity. In order to understand this problem more realistically, there are many more factors to be considered. For instance, various physical properties, which were assumed constant in the Rayleigh theory, are actually functions of temperature and pressure. Viscosity, in particular, is known to be strongly dependent on temperature: it easily varies by many orders of magnitude with temperature variations of less than, say, 100°C.

More serious is the fact that we do not know for sure whether the flow property of the mantle is like that of ordinary fluids or Newtonian fluids. The definition of viscosity itself in the equations of motion then becomes ambiguous. Although perhaps not all of these factors should bother us, it is likely that some of them are very crucial. Certainly a formidable mathematical problem is posed: that of solving the equations of the motions of a deformable, rotating spherical shell whose viscosity may be non-Newtonian. We know this shell is highly stratified into a lithosphere, an asthenosphere, and a deeper mantle, and that it is being heated internally as well as from below. The worst of the difficulties is that the values of the important quantities—especially those concerned with viscosity—are so little known that realistic models are not easily identifiable, even if high-powered computing capabilities were available. Despite all these difficulties, however, an enormous amount of effort is being expended in attempts to advance our understanding of the convection within the mantle.

Models and Reality

The famous Indian astronomer, S. Chandrasekhar of the University of Chicago, extended in 1949 the Rayleigh theory of thermal convection to spherical bodies, including spheres such as the earth that contain another spherical body (the core) inside. The results of his studies indicate that large-scale convection, with a flow encircling the whole earth, will occur only if the core is small. As the core grows, causing the thickness of the mantle to decrease, the pattern of convection cells undergoes abrupt changes, making the cell size smaller.

S. K. Runcorn welcomed Chandrasekhar's theory and used it to explain continental drift in 1965. He proposed that at one time the continents were floating on large convection cells. At certain stages in the earth's history, the growing core caused abrupt changes in the pattern of convection flow. These changes created instability in the position of the continents, causing them to split and drift apart (Figure 6-2). As proud as Runcorn was of his elegant thesis, it nevertheless met with a barrage of opposition. Some argued that since the actual state of the earth's interior was remote from the model to which the Rayleigh-Chandrasekhar theory was applied, and since the Rayleigh number within the mantle might be far greater than the value of the critical Rayleigh number, a simple pattern of convection flow, as postulated by Chandrasekhar, could not exist. Others maintained that a simple model was not at all applicable to the actual mantle in which viscosity varies. These were only a few of the many questions raised in response to this interesting idea.

A fundamental assumption has been that, given enough time, the earth can act as an ideal Newtonian fluid. Yet no one is absolutely sure that this is fact. We know little about what kind of flow properties the mantle has. We do not even know precisely what it consists of. The application of rheology (the science that investigates the

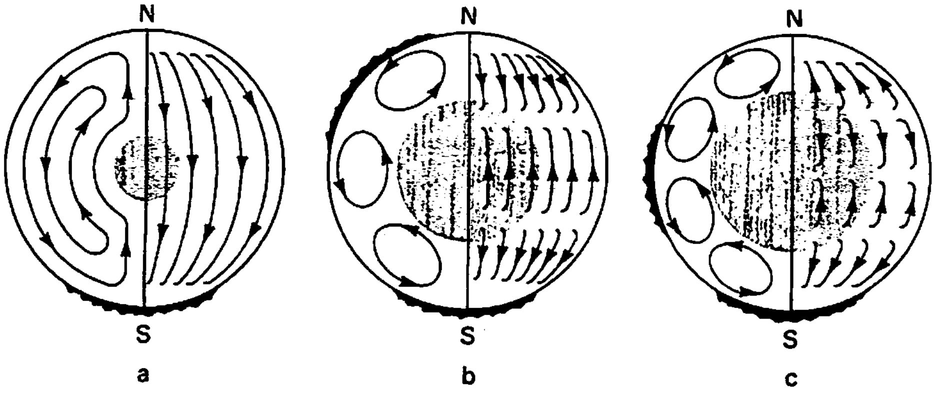

FIGURE 6-2
Convection in the mantle with different sizes of core. Parts (a) through (c) show the successive increases in the core size, the resulting changes in the pattern of convection flow, and the splitting of the continents. [Redrawn with permission of *Nature*.]

deformation and flow properties of matter) to the rocks of the mantle is still in its infancy. Although rocks that were once part of the mantle itself can be obtained, it is almost impossible to strain them at a rate slow enough to be relevant to geological phenomena. Despite this difficulty, rock deformation experiments have been inaugurated by D. Griggs and others, who are pioneers in the field of mantle rheology and convection. Even though these experiments are still far from conclusive, they have already suggested that the earth's mantle may have a property that is different from that of normal Newtonian fluids. In Newtonian fluids, the rate of strain or flow of the substance is proportional to the stress; in the earth's substance, however, the rate seems to increase exponentially by many powers proportionate to the stress. If so, flow in the mantle may be localized, as a jet current is. The flow will be slow in most areas, but once it is locally accelerated for some reason, its velocity will greatly increase. Although some investigators continue to insist the mantle behaves as a Newtonian fluid, the question raised by the rheology experiments—no matter how difficult—cannot be avoided and must be confronted by earth scientists today.

The difficulties are extremely complex. Various kinds of phase changes, like that between ice and water, as well as chemical changes, must occur within the mantle. When the ascending portion of the mantle reaches the surface through convection, a part of it probably separates to form the oceanic crust. At the same time, within the mantle itself, iron may be melting and sinking to the bottom, adding to the core. These are only a few of the many complex factors involved in mantle convection. It is not surprising, therefore, that an assumption by some—that the phenomena of sea-floor spreading and oceanic trench formation have been conclusively explained by a simple model—has been harshly criticized as too optimistic. This is only one example of the problem posed by the relationship between models and reality. Desirable though it may be to be able to explain a complex phenomenon by means of a simple model, reality may in fact be too complex: models are only models after all. Yet to reject any attempt at making simple models by flatly stating that one can never grasp even the physical principles of seemingly complex phenomena is self-defeating and unreasonable. Our present inability to quantify realistically the theory of mantle convection does not justify discounting it altogether. Such would no more reflect a scientific attitude than does undue optimism.

Those who recognize the possible importance of the layered nature of the mantle, especially the existence of the soft asthenosphere in the upper mantle, tend to maintain that the convection current does not run through the whole mantle but is confined to the asthenosphere. Such a stand, though reasonable, raises another problem. The Rayleigh theory and other more sophisticated theories all require that the *aspect ratio*—that is, the ratio of the horizontal scale of convection cells to the vertical scale—be close to one. Experiments also support this conclusion. The cells, then, in order to exist in the mantle should also have a horizontal scale comparable to the thickness of the asthenosphere—a few hundred kilometers.

However, the movements observed on the earth's surface—continental drift and sea-floor spreading—occur across a much larger horizontal scale, on the order of many thousands of kilometers. This disparity between the two horizontal lengths has bothered many scientists. At this point, however, H. Takeuchi and M. Sakata of Japan showed that if one devises a model of the whole mantle as composed of a low viscosity asthenosphere and a high viscosity lower mantle, the flow pattern, at least at the onset of convection, should be like that shown in Figure 6-3. Here, the flow is concentrated in the upper soft layer and the return flow is distributed deep into the underlying high viscosity layer. This means that the horizontal scale of the whole cell can be much larger than the depth of the asthenosphere. This result seems to explain to some extent the disparity between the two hori-

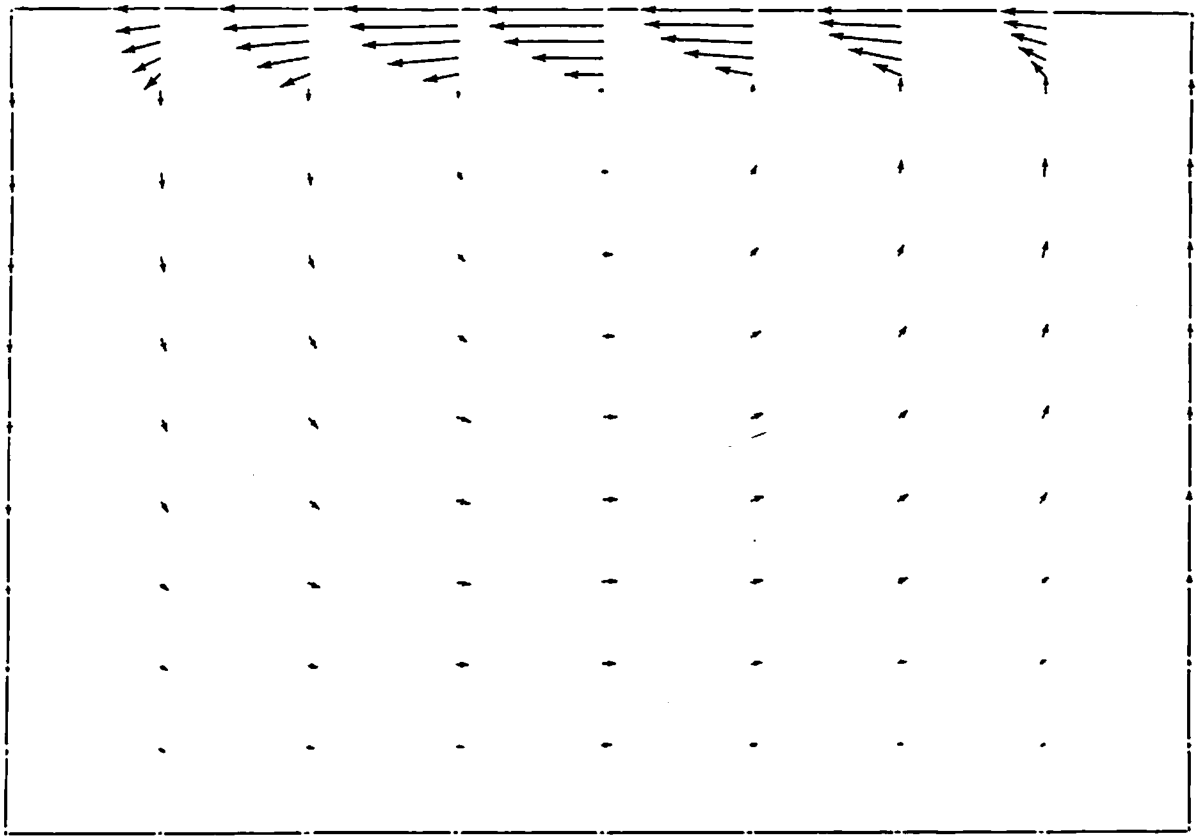

FIGURE 6-3
A possible flow pattern in which viscosity increases with depth. [After H. Takeuchi and M. Sakata, "Convection in a Mantle with Variable Viscosity." *J. Geophys. Res.* 75, p. 921, 1970. Copyrighted by American Geophysical Union.]

zontal scales. However, I continue to feel that the problem of the aspect ratio of convection cells has not been solved. We will come back to this topic in another section.

Hypothesis Versus Fact

In a field such as earth science, in which repeated demonstrations of phenomena with the use of artificial experiments is intrinsically difficult, the conflict of model versus fact is acute. Scientists often discuss whether to believe or disbelieve in hypotheses such as sea-floor spreading and plate tectonics, but belief is not really the issue. These are "working hypotheses," and the first condition to be fulfilled by a hypothesis is that it explain one or more phenomena in such a way that our understanding is increased. Whether a hypothesis is scientifically sound or not must be evaluated in terms of other standards in addition to its workability. Obviously we cannot "accept" just any hypothesis, but if a working hypothesis were to be immediately rejected unless it could be completely verified, what would be the point of formulating it to begin with? A useful hypothesis will become stronger and more profound, the more stringently it is checked against reality. Often this process occurs as follows: one adopts a working hypothesis, which prompts him to predict something as a logical consequence of the hypothesis, and the prediction is then tested by independent observations or experiments. At some point in this process, insurmountable difficulties may be encountered. The hypothesis will then have to be abandoned. Nevertheless, by the time the hypothesis is abandoned, our knowledge will be more advanced than it was before the hypothesis existed. This is the nature of a hypothesis: and when we present one, we are in fact saying, "We are not stating this as a fact. We are only proposing that a phenomenon be considered in this way, and we are continuing in our attempt to examine the workability of this approach." Is there any other way?

The Thermal History of the Earth: An Example of a Developing Hypothesis

Conclusive answers to questions on the origin of the earth may never be attained. Only a little over thirty years ago, people believed the primordial earth was a ball of fire that had spun off from the sun, and the history of the earth was thought to be that of a cooling process. It was in the 19th century that scientists—led by such forerunners as the famous Lord Kelvin—had studied the thermal history of the earth on the basis of the assumption that the earth had evolved from a hot mush to its present cool hardened state. Then, at the turn of the century, A. Becquerel and M. Curie discovered radioactivity and the radioactive elements that exist in the earth's interior. This made scientists realize that even if the earth is cooling, it also contains a heat source within it. Soon they were busy recalculating the thermal history of the earth to take this heat source into account. Even without the heat source, the earth is so large that it would not cool readily. The presence of a heat source would further inhibit the cooling process. Calculation showed that, if the earth containing heat sources was originally hot, it could not have cooled to the present state! Thus, the concept of the earth as a once hot ball of fire that had gradually cooled was challenged. In the 1940s, the astronomer's concept of the origin of the sun and the solar system underwent a considerable change: some even proposed an entirely different idea. The earth could not have originated in the sun, they insisted; rather, it is an accumulation of cool cosmic dust.

At approximately the same time, a number of findings were added to our knowledge of the thermal conductivity of the earth's interior—another critical factor in the study of the earth's thermal history. Thermal conductivity had formerly been treated as a constant in a simple thermal conduction equation. However, it was found to decrease as temperature increased, meaning the earth is even more difficult to cool than was previously suspected. By the end of the 1950s, however, scientists came up with the prediction that thermal conductivity would increase once the temperature passed beyond about 1000 to 1200°C because heat can be transmitted by radiation, even in such substances as rocks. Simple theoretical considerations by S. P. Clark, based on the law of thermal radiation, indicated that thermal conductivity by radiation would increase in proportion to the cube of the absolute temperature. In essence, at high temperature rocks are nearly transparent to heat. Numerous calculations incorporating this radiative conductivity have been made on the thermal history of the earth.

Because of the many factors that had to be considered, the equations for the earth's thermal history became increasingly complex until they defied almost any attempt to solve them. What saved the day was none other than the advent of high-speed computers at the end of the 1950s. Scientists such as E. A. Lubimova of the USSR and G. J. F. MacDonald of the United States calculated, with the aid of numerous models, what the conditions of the earth might have been in the beginning in order to end up in its present state, taking all the known factors into consideration. The earth at present has a large-scale layered structure of core and mantle. Any theory of the earth's history must explain this primary feature. To form such a structure, total melting of the earth early in its history was assumed to be the most likely explanation. This argument was one of the strongest foundations of the hot-origin hypothesis.

The studies of Lubimova and MacDonald, however, demonstrated that even if the earth had originated in a cool condition 3 to 4½ billion years ago, there would still have been sufficient heat to melt

the mantle, causing iron to accumulate in the center to form the co
and lighter elements to rise to the surface to form the crust. T
cold-origin hypothesis was greatly supported by this demonstrati
But the models these scientists used for their calculations were
solid bodies, so that the only mode of heat transfer they consider
was conduction and radiation in a solid body.* Although they spo
of the large-scale motions within the earth that would be needed
form the core-mantle structure, their calculations were based stric
on solid state conduction theory until the melting point was reach
and sometimes computations were made in the same way for t
temperature range beyond the melting point!

If mantle convection on a grand scale has been taking place c
tinually, both below and above the melting point—as we maintain
this book—it would be meaningless to calculate the earth's past co
dition without taking into consideration heat transmission by conv
tion. If convection occurs within the earth, the earth would ha
cooled much more rapidly, just as clear soup cools much faster th
thick oatmeal. D. Tozer of England convincingly pointed out
1969, that the earth starts to convect at a certain temperature bel
the melting point, so that the uppermost temperature in the earth
effectively controlled by this softening temperature, regardless of t
initial conditions. So far, however, a thorough study of the therm
history of the earth from this perspective has yet to be completed.

If indeed the earth was formed by gathering cold cosmic dust th
was gradually warmed, the heavy iron particles melting and gatheri
in the center to form the core, an enormous amount of gravitation
energy must have been released as heat. F. Birch, an authority
solid earth geophysics, was one of the first to point out that the ener
released by the settling iron would be great enough to heat the who
earth by about 1000°C and to melt it all at once. In that case, calcul
tions in which such a great heat source was not taken into conside
tion would be pointless. Recently, D. Anderson suggested that
cosmic gas condensed and started to accrete, the core materials a
creted first, thereby forming the layered structure of the core a
mantle of the earth at the time of its formation. This suggestion w
based on the cosmological consideration that the iron forming t

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*In the late 1960s, however, it was discovered by Y. Fukao, H. Mizutani, and
(all of Japan), and by J. Aronson and R. McConnell of the United States, that t
importance of the radiative contribution to thermal conductivity in earth-formi
materials is much smaller than that assumed in these calculations.

core was one of the earlier condensates of cosmic gas. If so, one need not account for the gravitational energy of iron settling. The resolution of the problem, however, depends on a better understanding of the process by which the earth and planets were in fact formed. Additional important factors require more cosmogonic insight. If the earth is an accretion of cosmic dust that was originally scattered throughout space and then accumulated to form a ball—the earth—an enormous amount of gravitational energy must have been transformed into heat as this happened. This energy is considered to be orders of magnitude greater than the energy released during the separation of the core from the mantle! If the accretion of the earth was a rapid process, the heat would have been effectively trapped in the earth; if it was slow, the heat would be radiated into space. Thus, depending on how rapidly the earth grew, it is possible that very high temperature may have prevailed during the earth's formation.

Radioactive heat sources, as is well known, decay with time. This means that more heat was generated by radioactivity in the past. Some radioisotopes, such as aluminum-26 (^{26}Al), iron-60 (^{60}Fe), and chlorine-36 (^{36}Cl), decay so rapidly that they are now extinct. But at the time matter was synthesized in the universe, it is estimated that a great quantity of these short-lived radioisotopes were also born. If the birth of the earth was not much later than, say, 10^7 years after nucleosynthesis, those isotopes could also have contributed greatly to the earth's heat.

Generally, it was thought that the accretion of the earth took some 10^8 years or more. If so, neither heat source—the gravitational energy of accretion or the short-lived radioactivity—was very influential in the process. But recently several lines of evidence from geochemistry and cosmochemistry, as well as theories of cosmogony, have indicated that the accretion process could have been much more rapid. H. Mizutani and T. Matsui of Japan have suggested it might have taken about 10^3 years! If they are right, the earth in the beginning must have had a tremendous amount of heat. Thus Tozer's softening temperature would have been easily attained, meaning that the earth has been steadily convecting ever since to expel the heat. The formation of the core would have been rapidly completed during this process. Such a possibility would seem to revive the century-old hot-origin hypothesis. But the logic behind it is entirely different.

One of the reasons the hot-origin hypothesis was rejected was the fact that the earth, as a gigantic solid body, would be hard to cool. If active mantle convection is assumed, however, such an obstacle can be overcome. Furthermore, the idea that the earth's internal heat source would inevitably create a condition of extremely high temperature seems dubious when mantle convection is taken into consideration.

In summing up these possibilities, it becomes clear that it is time for us to discard the fixed idea of the earth as a nonflowing solid object, and reconsider the earth's thermal history from the perspective of a working hypothesis in which it is maintained that the earth flows. In this context, the prospect of combining the study of the earth's thermal history and the concepts of plate tectonics (oddly enough the two areas have thus far been pursued independently) is a most interesting one. A truly exciting synthesis can be anticipated.

As we look back on the past research conducted on the earth's history, we discover that certain basic questions, such as whether the earth was hot or cold to start with, or whether it was ever completely molten, continue to recur. Yet, one cannot brand the research that has taken place in between as pointless, for each time we have returned equipped with a deeper understanding in our search for the truth.

The Remaining Questions

Although the prevailing view of the earth has shifted from a fixist to a mobilist one, a great many questions still remain. It is common to find that hypotheses once considered to be reasonably sound to the first order of approximation are in fact fraught with unresolved difficulties upon further examination. It may be that the theories of sea-floor spreading and plate tectonics are reaching that point. V. V. Beloussov of the USSR is one scientist who has been sharply critical of the new view. In an article entitled "Against the hypothesis of sea-floor spreading" (1970), he points out many of the difficulties inherent in the sea-floor spreading hypothesis. Although the crux of his objection is that the new view cannot explain continental geology to his satisfaction, part of his attack focuses on the proposed origin of the ocean floor. On both sides of the oceanic ridge axis are symmetrical belts of various kinds—the most typical being the geomagnetic stripes. Examination of a geomagnetic profile, such as that in Figure 3-3, will show that the anomalies are stronger near the ridge axis and weaker as one moves away from the axis. The underground structure of the mid-oceanic ridges, as estimated by seismic prospecting or by the examination of gravity in the area, likewise exhibits modulation that varies in relation to the proximity of the ridge axis: that is, the second layer is thick on the crest whereas the third layer becomes

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thicker as the distance from the axis increases. If the ocean floor is spreading as if on a conveyer-belt system, the present ocean floor, now hundreds of kilometers away from the ridge crest, must once have been on top of the crest. Why then, Beloussov argues, isn't the structure of the crest similar to that of the distant sea floor? This is a good point, and one that many scientists are trying to explain. There seems to be some hope of doing so by considering the changes that take place in the properties of the oceanic crust as it spreads, such as weathering, hydration, and other metamorphic processes.

Another aspect of Beloussov's attack concerns the distribution of sediment on the upper layer of the ocean floor. On the ridge crest the sediments are almost entirely absent, whereas the sediment layer thickens increasingly the further it is from the ridge. Qualitatively, this condition supports the sea-floor spreading hypothesis, since the implication is that the ridge crest is younger than the areas farther away from it. Quantitatively, however, it does not quite satisfy the requirements of the theory; specifically, the thickness of the layer does not increase constantly as the theory would lead us to suppose, but somewhat haphazardly. Beloussov cites this as another difficulty that must be resolved if the sea-floor spreading hypothesis is to be confirmed. But here again the vast information gathered by the Deep Sea Drilling Project (DSDP) has come to the rescue. The thickness of the sediments seems to decrease with increasing distance of the ocean floor from an equatorial zone of high biogenic sedimentation rate, so that the distribution of thickness deviates from a simple function of distance from ridges.

Marine sediments pose yet another question. When the ocean floor descends into the mantle at the oceanic trenches, what becomes of the sediment that is carried on top of the floor? Won't it be jammed between the oceanic and continental plates, severely folded, and then plastered on the bottom of the trenches? Observation of the trenches, however, proves otherwise. Very little sediment is to be found on the bottom of the trenches, and what little there is does not seem to have been disturbed much. If we suppose that subduction has been taking place for the past 100 million years and that the sediment thickness of the subducting ocean floor averages 200 meters, about 20 kilometers of sediment should have accumulated in the oceanic trenches by now. Moreover, the deep trench receives constant sedimentation from the land. The quantity of such trench sediments could easily be more than that carried by the oceanic plate. Altogether, there should be a great quantity of sediments in the trench. But in actuality most trenches have only a thin veneer of undeformed sediments along the

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bottom. What is the reason for such a discrepancy? Beloussov asks. It was an enigma for some time. But now, thanks to the powerful deep-penetrating seismic-reflection profiling techniques, the locations of the missing sediments are being disclosed. Records like that shown in Figure 2-3 are being accumulated for analysis.

Figure 6-4 shows the concept now held by scientists. The "missing" sediments are all piled up in the landward wall of the trench in a most spectacular manner. Both oceanic sediment veneer and the sediments from the land are split into thin slices by thrust faults and folded, thereby forming an intricate complex structure called the *accretionary prism* (see also Figure 5-23). It is suspected that, in many places, not only the soft sediments but also slivers of igneous basement (oceanic crust) itself are accreted to this structure.

Deformed marine sediments have been recognized by geologists for years and described by them as *geosynclinal* sediments. In many of these geosynclinal deposits have been found igneous rocks called *ophiolites,* whose origin was always a mystery. It now seems highly likely that the ophiolites are old pieces of oceanic crust thrust up against the continents along with ocean floor sediments to form the geosynclines. What actually takes place at the subduction zones will certainly be one of the most important subjects to be investigated in the years to come. The International Phase of Ocean Drilling (IPOD) is a continuation of DSDP, which terminated in 1975. In this international endeavor, drilling at subduction zones is considered to be one of the prime objectives. It is hoped that deep drilling in the walls on the continent side of the trenches will provide us with the information needed to solve these important problems.

Another question that Beloussov has labeled a mystery is that of the "migrating oceanic ridges" (see pages 102 through 109). The oceanic ridge is thought to be the place at which mantle convection ascends and the ocean floor is produced. Can such a region move about merely to satisfy the geometric requirements of plate motions? Beloussov contends that to infer further that an oceanic ridge can itself descend into an oceanic trench is completely self-contradictory. His point is well taken, but the apparent contradiction is resolved if one accepts an alternative theory about the nature of the ridges: they may not represent the upwellings of deep mantle convection currents but instead may be passive windows from which asthenospheric materials emerge to form new plates.

Even more mysterious than the migrating ridges are the so-called "fracture zones." Explaining fracture zones as transform faults was J. T. Wilson's dramatic contribution (1965). Yet Wilson himself has

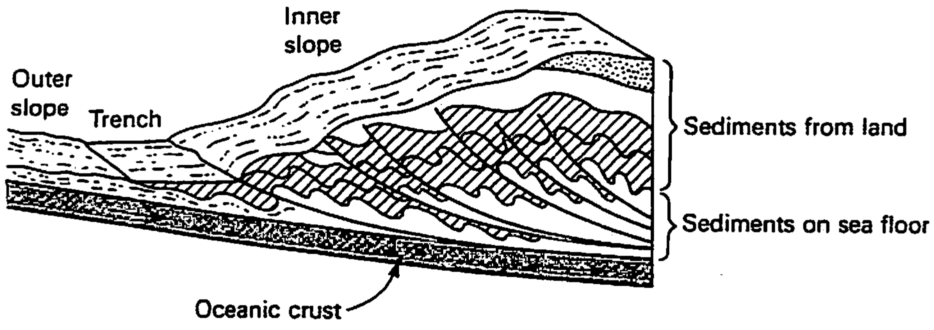

FIGURE 6-4
A model of the inner slope of a trench. The arrows indicate the movement of the ocean crust. [After D. R. Seely, P. R. Vail, and G. Walton, "A Trench Slope Model," in C. A. Burk and C. L. Drake, Eds., *The Geology of Continental Margins.* Springer-Verlag, 1974.]

not provided a thorough explanation of why the ridges were offset in the first place. If the oceanic ridge is a zone in which a convection flow upwells, why should the ridge fracture clumsily into transform faults? A smooth curve would be much more probable since the substance involved here is fluidal. Influenced by all those considerations, scientists are now inclined to believe that the ridges are indeed passive windows rather than surface manifestations of deep convection. But if ridges are not produced by convection currents in the mantle, what happens to the very basic concept that mantle convection drives the motions of the plates? To summarize, proponents of continental drift were at a loss for a driving mechanism when the idea of mantle convection as the force appeared like a Messiah to save the theory. Now, ironically enough, mantle convection seems to be on the verge of rejection by those who most strongly support the sea-floor spreading hypothesis and plate tectonics.

In a relentless barrage of criticism, Beloussov and the American petroleum geologist A. Meyerhoff have pointed out the danger of making careless generalizations in the attempt to explain a complex phenomenon on the basis of just one of its superficial manifestations. (Such explanations can be likened to that by the astronomers who observed dots on the planet Mars and linked them to demonstrate the existence of canals there.) In other words, it is all too easy to "see" with eyes already blinded by the beholder's own anticipation of what he expects to find. Beloussov's own explanation of marine geology is equally subject to criticism, however. In brief, he seems to believe that the continents are ancient and are gradually "oceanizing." The development of the ocean is caused by some activity that took place first in the peripheral regions of the present ocean. At present, "oceanization" has progressed to the region of the mid-oceanic ridge. (This explains the progressively younger age of the ocean floor towards the ridges!) Beloussov does not seem to have a convincing explanation for the physicochemical mechanism of "oceanization." He suggests that some kind of hot liquid seeps from the mantle that causes the continental crust to transform into oceanic crust. Many petrologists, however, consider such a process to be utterly impossible. And yet, to discount Beloussov's theory altogether, simply because it is theoretically difficult, would be narrow-minded, especially if a careful examination of "oceanization" from a variety of perspectives proves it to be far more plausible than other hypotheses. "Oceanization," then, is yet another working hypothesis. Who knows, it may be the prelude to a still *newer* view of the earth.

The Driving Mechanism (1): A Summary of the Possibilities

Now, to return to plate tectonics, recall that identification of the driving mechanism is fundamental. What are the plausible proposals? We have seen that the simple convection current hypothesis has numerous difficulties. The problem of the horizontal scale of the cells (page 180) and that of migrating ridges (page 109) were already sufficient to make us doubt the importance of convective flow in the asthenosphere. In 1973, however, E. Artyushkov, a young Soviet geophysicist, produced an even more devastating argument against mantle convection. He argued convincingly that the viscosity of the asthenosphere, particularly under oceanic areas, should be one or two orders of magnitude smaller than the usually assumed value, estimated from the postglacial rebound (page 176) for Scandinavia and North America. Therefore, the mechanical force exerted at the bottom of the lithosphere owing to the flows in the asthenosphere would be much too weak to be significant. He maintained that, although there may indeed be flows in the asthenosphere, they are of no importance to plate motion. Whether Artyushkov was absolutely right or not, the general question of the driving mechanism seemed to require far more serious thought.

D. Forsyth and I (1975) started to seek some of the answers to this basic question in 1972 when I was a visiting professor at M.I.T. The

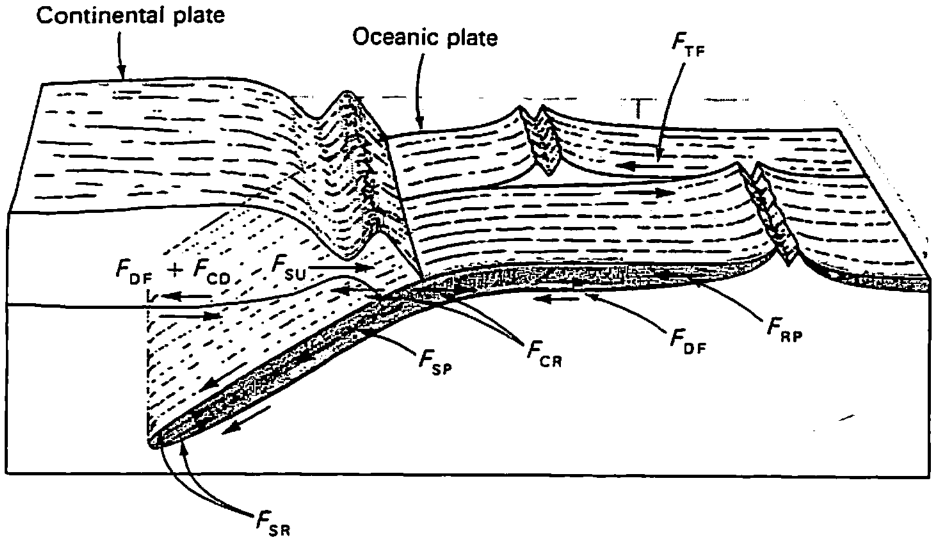

FIGURE 6-5
Possible forces acting on the lithospheric plates. [From D. Forsyth and S. Uyeda, "On the Relative Importance of the Driving Forces of Plate Motion." *Geophys. J.* 43, p. 165, 1975.]

work seemed unpromising and we interrupted it until 1974, when both of us happened to be working at the Lamont-Doherty Geological Observatory. Needless to say, the problem has not been ultimately resolved, and a number of other scientists are working on the subject. Although some appear to have opinions similar to ours, a good many of them have differing views. What follows is merely a description of our own approach to the problem.

The first step was to review the major driving mechanisms that have been suggested in recent years by geophysicists who recognized the difficulties inherent in simple mantle convection. These forces are shown in Figure 6-5. Let us examine them.

Mantle Drag Force. It is clear that, when a large plate moves, there must be a net mass flow in the deeper mantle from trench to ridge, balancing the mass transport. Thus there is little doubt that flow occurs in the mantle. Classical mantle convection theory assumes that the flow directly below the plate drives the plate and is thus flowing in the direction of the plate's movement, so that the return flow must take place deeper in the mantle. But if the plate is driven by some other force or forces, as we shall explain, the return flow can be directly below the plate and the asthenosphere will then act as a brake on the plate motion. Whether it is driving or resistive, the *mantle drag force* F_{DF} on the plate is proportional to the area and to the velocity of the plate relative to the asthenosphere. Since the viscosity of the asthenosphere under the continents may be higher, an additional term, *continental drag* F_{CD}, is used for the mantle drag force that operates on the continental part of the plate.

Ridge Push. Although ridges may be formed passively, they have an elevated topography and deep low-density roots. Such a ridge, even though isostatically in equilibrium, has a higher potential energy than older sea floor on which there are no ridges. Thus the ridges tend to spread out, thereby producing a *ridge push force* F_{RP} on both sides of the plates. Several geophysicists have contended that this force is the principal driving mechanism.

Slab Pull and Slab Resistance. The subducting slab underneath the trenches is considered to be colder and thus denser than the surrounding mantle. Several geophysicists have suggested that the negative buoyancy due to the density difference should pull the slab downwards, and that this *slab pull force* F_{SP} is transmitted to the whole plate as a major driving force (Elsasser, 1969). Theoretical calculations indicate that the slab pull can be an order of magnitude greater than the ridge push F_{RP}. Since this force is due to the gravitational body force, it is simply proportional to the density difference between the slab and the surrounding mantle and is independent of the slab's velocity as long as the velocity is great enough (say, greater than 5 centimeters per year). When the downgoing velocity is smaller, heat conduction from the surrounding material will significantly lessen the temperature difference, and therefore the density difference between the downgoing slab and the surrounding mantle. As the slab plunges into the mantle, pulled by F_{SP}, it should meet *slab resistance* F_{SR}, which, for the sake of simplicity, may be designated as proportional to the velocity of underthrusting. It is thought that the resistance is concentrated at the leading edge of the slab because, at a shallow depth, the mantle is likely to be soft.

Suction. We have seen that, around the edge of the Pacific, trenches tend to migrate seaward, as do the overthrusting continental plates so that the area of the Pacific Ocean is decreasing while that of the Atlantic Ocean is increasing. In 1971 Elsasser explained this fact by assuming a *suction force* F_{SU}. Although the physical nature of this force and the degree of its importance are not altogether clear, we will list it for the sake of completeness and consider it to be independent of the velocity of plate motions.

Colliding Resistance and Transform Fault Resistance. Plates are expected to experience various resistances to their motion. Slab resistance F_{SR}, explained above, operates at the leading edge of the slab, whereas the mantle drag forces F_{DF} and F_{CD} operate at the lower surface of the plate. Both these resistances occur between the plate and the deeper mantle. The resistance terms, *colliding resistance* F_{CR} and *transform fault resistance* F_{TF}, are the resistances between plates. Most shallow earthquakes are caused by these "interplate" resistances. F_{CR} is the resistance at the colliding (or converging) boundary. We believe that the magnitude of these forces is independent of the relative velocity—the velocity of relative motion—between plates. It may sound strange at first to say that resistive forces are equal regardless of their relative velocity. But since earthquakes take place when the stress reaches a critical value, it may be reasonable to assume that greater relative velocity results in greater seismicity and not greater stress. The same applies to the resistive force F_{TF} at the transform fault. Although the magnitude of these forces is velocity independent, the direction is controlled by the relative velocity: that is, the forces act in a direction antiparallel to that of relative plate motion. It is also worth noting that these forces acting on two plates are exactly equal in magnitude and work in the opposite direction as a consequence of Newton's law of action and reaction.

In summary, the possible driving forces are slab pull F_{SP}, ridge push F_{RP}, and suction F_{SU}, and the resistive forces are slab resistance F_{SR}, colliding resistance F_{CR}, and transform fault resistance F_{TF}. Whether the mantle drag forces F_{DF} and F_{CD} are driving or resistive depends on the direction of relative motions between the plate and the underlying asthenosphere.

How could we find out which of the above forces are more important than others? This could only be done through a careful examination of the actual observed motions of plates. We studied 12 plates, as shown in Figure 6-6. The direction and velocity of *relative* motions *between the plates* are determined by plate tectonic analysis as explained in Chapter 4. But since some forces (F_{FD}, F_{CD}, F_{SP}) are dependent on the plates' velocities relative to the *mantle*—their *absolute* velocities—we had to obtain these velocities also. To do so, we assumed that a worldwide system of *hot spots* remained fixed in space relative to the deep mantle. Now, what are hot spots?

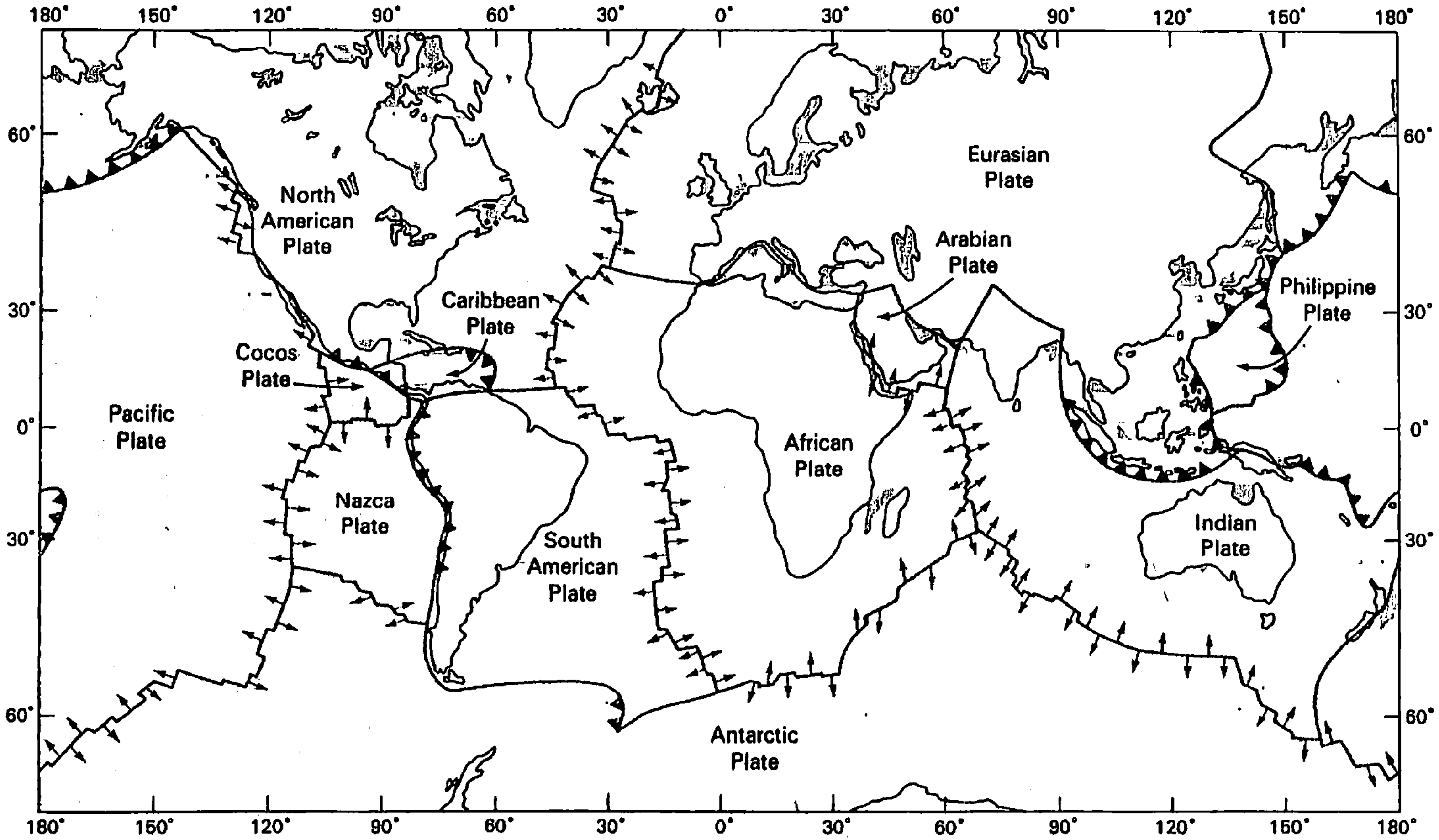

FIGURE 6-6
Twelve plates and their motions. Triangles along boundaries indicate direction of underthrusting where a downgoing slab can be identified by the occurrence of intermediate or deep focus earthquakes. Small arrows on ridge boundaries indicate approximate direction of relative motion. [After D. Forsyth and S. Uyeda, "On the Relative Importance of the Driving Forces of Plate Motion." *Geophys. J.* 43, p. 163, 1975.]

Hot Spots

In 1965, J. T. Wilson, the founder of the tranform fault hypothesis, made another suggestion. He noted that at certain locations on the earth, such as Hawaii and Iceland, volcanoes have been active for long periods of time. The source of magma for these volcanoes is believed to be located deep below the lithosphere so that the position of volcanic activity is fixed relative to the mantle. When a plate moves past such a magma-producing spot, the surface volcanoes are carried away with the plate, but the source continues its activity from the fixed position. As a result, a long chain of volcanoes, such as the Hawaiian volcanic chain (Figure 6-7a), will form. In fact, it was known that the age of the volcanism on the island chain increases according to their distance from the presently active island of Hawaii, situated at the southeastern end. (Figure 6-7b).

When such a spot happens to be on an actively spreading ridge, like Iceland, chains of volcanic islands or seamounts are formed on both sides of the ridge because the plates on both sides are spreading away from each other. Wilson identified several more examples of such volcanoes and their associated chains of extinct volcanoes. He called these spots *hot spots*. He proposed, in effect, that the "absolute" motions of a plate were imprinted on the sea floor in the form of a ridge made up of extinct volcanoes. Once again Wilson had presented an extremely viable, although this time theoretically unproven, hypothesis.

Later, W. J. Morgan extended this idea and demonstrated that the velocities of the "absolute" motions of plates during the Cenozoic era could be determined as shown in Figure 6-8. These are the motions that are in accord with the relative motions specified by plate tectonics and that satisfy the condition that the proposed hot spots must be stationary relative to each other and to the mantle.

Morgan, taking the idea a step further, argued that hot spots are maintained by a quite localized upwelling of the mantle convection current, and that the mantle flow associated with hot spots, upwelling in plumes and descending slowly everywhere else, may be the major driving mechanism of plate motions. Although these later speculations are subject to debate, the reasonably fixed positions of hot spots appear to be substantiated by further critical examinations.

Therefore, in our discussion on plate motions, we tentatively adopted the worldwide system of hot spots as an "absolute" frame of reference for determining the motion of the plates relative to the mantle.

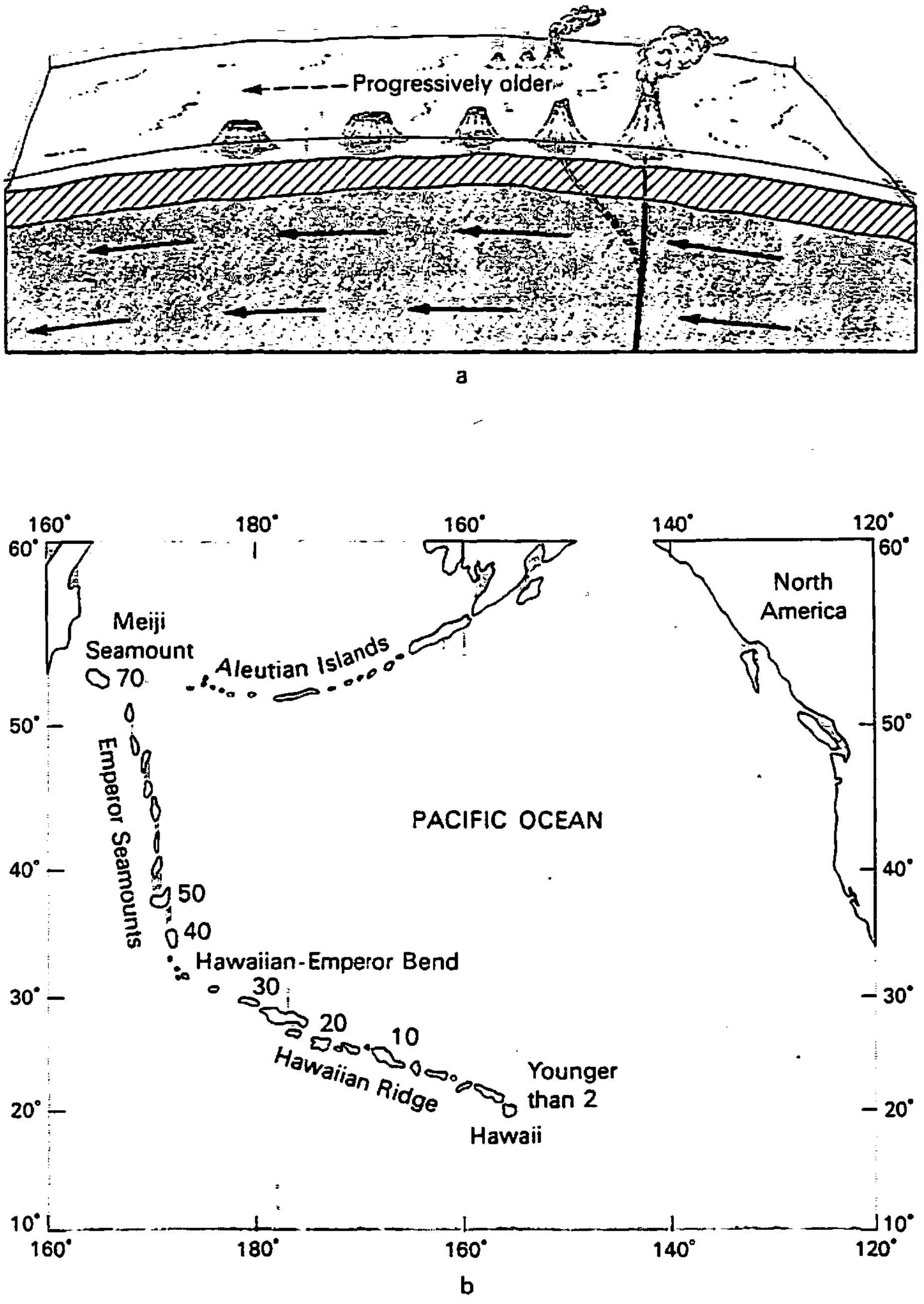

FIGURE 6-7
(a) Model demonstrating the way in which the Hawaiian volcanic island chain would have formed according to the hot-spot hypothesis. [After J. T. Wilson, "Continental Drift," Copyright © 1963 by Scientific American, Inc. All rights reserved.]
(b) Ages, in millions of years, of volcanoes in the Hawaiian-Emperor chain. [After D. A. Clague et al., "Petrology and K-Ar Ages of Dredged Volcanic Rocks from the Western Hawaiian Ridge and the Southern Emperor Seamount Chain." *GSA Bull.* 86, p. 991, 1975.]

The Driving Mechanism (2): A Sinking-Slab Model

The absolute motions given in Figure 6-8 constituted our basic data. Our task was to deduce the driving mechanism from these data. We first noticed a remarkable regularity in the plate motions. That is, the velocity of a plate is always large when the plate has a substantial underthrusting trench boundary and vice versa. Readers will readily agree that this regularity is an outstanding one. The Cocos, Pacific, Nazca, Philippine, and Indian Plates are plates having substantial underthrusting boundaries, and for each the average velocity (the velocity averaged over the area of each plate) is between 6 and 9 centimeters per year, whereas all other plates have an average velocity of less than 4 centimeters per year, and most of those less than 2 centimeters per year. To demonstrate this regularity, we plotted the average velocity of each plate against its fractional trench length (that is, the fraction of trench length in the total boundary) as shown in Figure 6-9. This observation seemed to tell us that among the various driving forces, the trench pull F_{SP} should be the most important one. We also examined the correlation between plate velocity and other geometrical factors such as the plate's area, the area of the continental part, the total length of ridges, the length of transform faults, and the length of the overthrusting side of the trench. This provided us with some more interesting clues. In particular we observed that velocity was not clearly correlated with these factors except for the continental area of a plate.

The fact that the velocity has no correlation with the area of a plate is important. If the forces acting at the plate boundaries are driving forces and the mantle drag is the major resistance, such a lack of correlation is hard to understand. For instance, the Nazca, Cocos, and Pacific Plates are very similar except in area. Therefore, if mantle drag is the principal resistive force, the Pacific Plate, having by far the greatest area, should move much more slowly. Both Morgan and McKenzie noted in the early 1970s this lack of correlation between the area and velocity of plates, and concluded that the plate velocity is determined primarily by the mantle flow, and not by forces at the boundaries.

However, we recognized an alternative interpretation: the mechanical coupling between the plate and the mantle beneath may be weak in oceanic areas, as Artyushkov maintains (page 190), so that mantle drag has little influence on the velocity of the plates. We chose this alternative as our working hypothesis.

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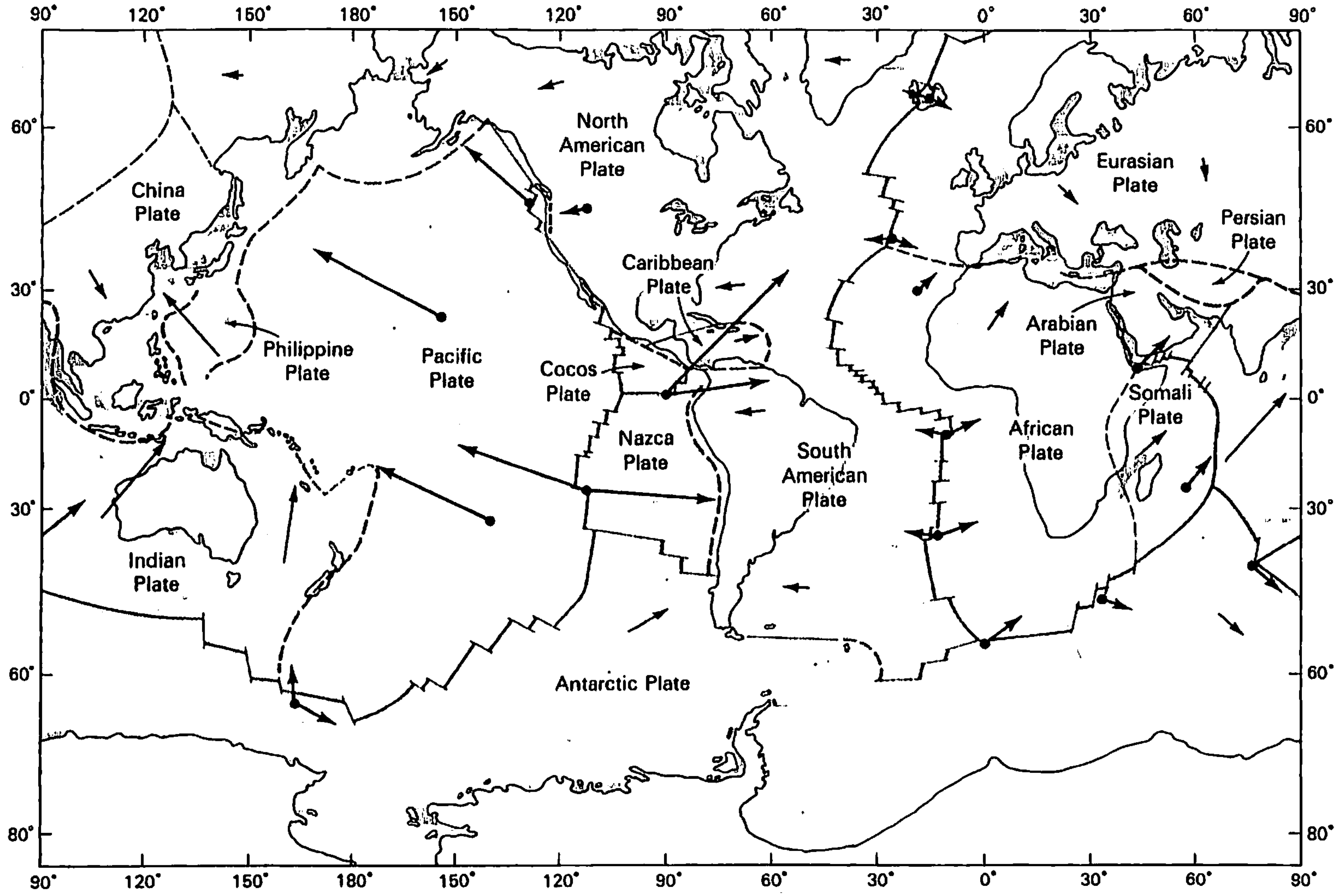

FIGURE 6-8
Present motions of plates over hot spots. The relative motions were determined from fault strikes and spreading rates on rise boundaries; with an appropriate constant rotation added, absolute motion of each plate over the mantle was determined. The lengths of arrows are proportional to the plate speed. [After J. Morgan, "Deep Mantle Convection Plumes and Plate Motions." *Amer. Assoc. Petrol. Geol. Bull.* **56**, p. 203, 1972. Redrawn with permission of the author.]

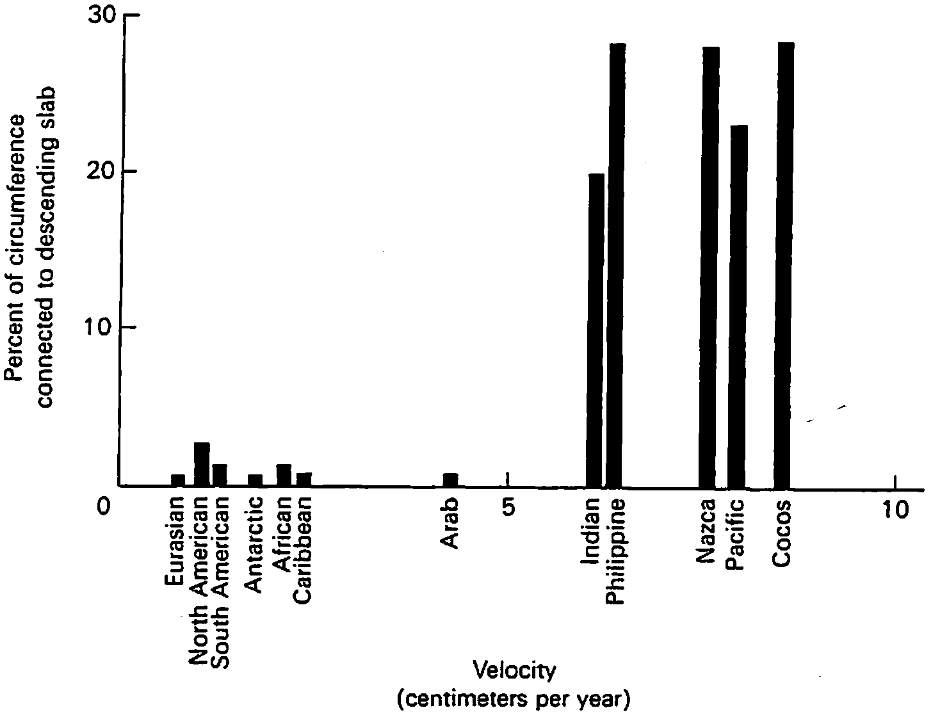

FIGURE 6-9
The percentage of plate circumference connected to the downgoing slab versus the absolute average velocity of plates. [From D. Forsyth and S. Uyeda, "On the Relative Importance of the Driving Forces of Plate Motion." *Geophys. J.* 43, p. 163, 1975.]

We found the correlation between velocity and continental area to be significant. Plates like those carrying Eurasia, North and South America, Antarctica, and Africa all have large continental areas and their velocities are all less than 2 centimeters per year. To us this finding indicated that the resistance due to mantle drag is stronger under the continents than under the oceans.

The velocity of a plate has no obvious correlation with the total length of the ridges along its border, with the total length of transform faults, or with the total length of trench, provided the plate is on the overthrusting side of the trench. We have already seen that, for the plate in the underthrusting side of the trench, the plate velocity does correlate with trench length. This correlation indicated to us that ridges and the overthrusting sides of trenches are much less important agents in driving the plates than are the descending slabs, and that transform faults are not important resistive agents. In other words, F_{RP} F_{TF} and F_{SU} are smaller than F_{SP}. This is not to say that ridges are not pushing the plates away laterally, because the plates on either side of the Mid-Atlantic Ridge are certainly moving apart, though slowly. It is only to say that probably the ridge push F_{RP} is much smaller than the slab pull F_{SP}.

The inferences so far are that, as a driving force, the slab pull F_{SP} is much greater than any other driving force, and continental drag F_{CD} is the only significant resistive force. Now, if we recall Newton's basic law of motion (that forces must balance in order to keep a body in constant motion), and if we assume that the plates are essentially in constant motion, then the forces acting on each plate must balance. In our analysis we noticed that oceanic plates having a long underthrusting trench are under strong driving force F_{SP}, but that the resistive forces F_{DP} and F_{TF}, are small. In order to balance the force, our conclusion was that the slab resistance F_{SR} must be the main resistive force. Thus, the following model was presented. First, the body force F_{SP} due to the excess mass in the downgoing slab is very large. F_{SP} pulls the plate attached to it and the rate of the slab's descent into the mantle increases until this force is nearly balanced by the viscous resistive force F_{SR} acting on the slab. The quite uniform rate of descent of 6 to 9 centimeters per year observed for the Pacific, Nazca, Cocos, Indian, and Philippine Plates represents the point of balance, which is, in effect, the *terminal velocity* of a dense body falling in a viscous medium. It is analogous to a man falling through the air with a parachute.

All other plates not attached to long subducting trenches are moving at a velocity of less than 4 centimeters per year. Most of these plates have large continents that are probably more strongly anchored to the deep mantle. But the fact that the Indian Plate, which has fairly large continents (India and Australia) and a long trench (the Sumatra-Java Trench) is moving fast, seems to suggest that the dominant factor in determining velocity is the presence or absence of a large descending slab and not the presence or absence of continents.

Forsyth and I have examined the validity of the above model more quantitatively and found it workable. If the model is accurate, we can say that the velocity of plates having descending slabs is determined by the balance between the two large forces F_{SP} and F_{SR} acting on the descending slab, and that it is almost completely independent of the surface geometry of the plate. We believe this conclusion to be an important one about the driving mechanism of plate motions. It would be an interesting project to examine the applicability of this model to the ancient plate motions deduced from plate tectonics.

Of course, the whole system is a kind of thermally convecting one. The body force F_{SP} is due to the density difference, which is essentially the same type of force that drives simple convection. Thus we are not rejecting thermal convection, but saying that the plates are an important part of the convecting system and are not passively driven by an underlying convective flow system.

Our analysis did not allow us to assess the relative importance of the smaller forces F_{RP}, F_{TF}, F_{SU}, and F_{DF} with confidence, because the magnitude of these forces is roughly comparable to the noise level of our data. Thus our next step is to tackle this problem so that we can gain a more complete understanding of the driving forces. For this purpose, *intraplate* earthquakes will provide key information, because the earthquakes occurring within a plate, though quite rare, can reveal the stress state within the plate resulting from all the forces. L. Sykes and M. Sbar at Lamont-Doherty Geological Observatory, and S. Solomon and his colleagues at M.I.T. are currently making valuable investigations in this area.

The "new view" has made a truly great contribution to our understanding of the earth, but we are still faced with innumerable important problems. Scientists of various nations have been confronting these problems dauntlessly one by one. A number of international programs have been initiated for this purpose. One is the Geodynamics Project that commenced operations in 1972. The International Phase of Ocean Drilling (IPOD), which started in 1975, is another.

In conclusion, majority opinion has just begun to shift toward a mobilist view of the earth, and a great deal remains to be studied in the future. Figure 6-10 illustrates the current version of continental drift envisioned by R. S. Dietz and J. C. Holden (1970). It shows the breakup of Pangaea and the changes in world geography throughout the ages, as viewed from the perspective of sea-floor spreading and plate tectonics. As part (f) of the figure shows, it is even possible to visualize how the world may look 50 million years from now! It would be interesting to compare this description with the drift proposed by Wegener, discussed at the very beginning of this book (see Figure 1-1). Indeed, the "insight" exhibitied by this great man remains impressive even today. Nevertheless the time may come when even the "new view" will be shown to contain some fatal flaw and so become obsolete. But at present our main challenge is to continue doing everything possible to pursue its implications for all branches of earth science, and to test them in the crucibles of experiment and observation. If we are successful, we may yet arrive at a comprehensive understanding of the earth.

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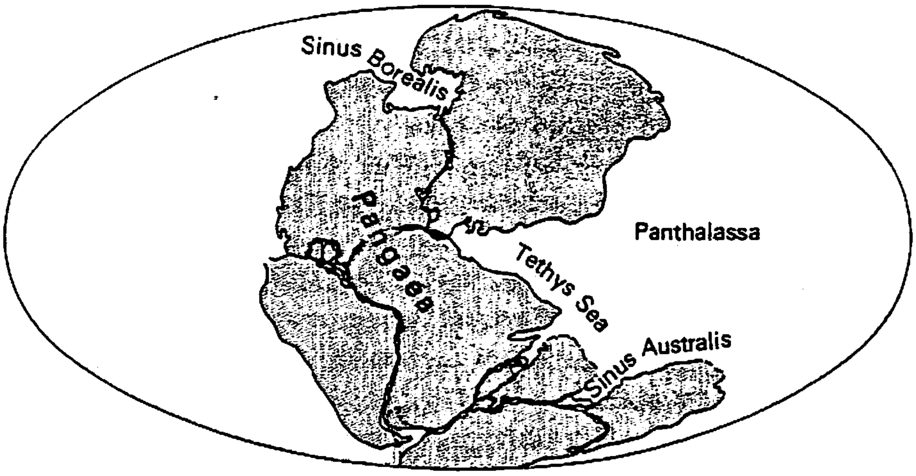
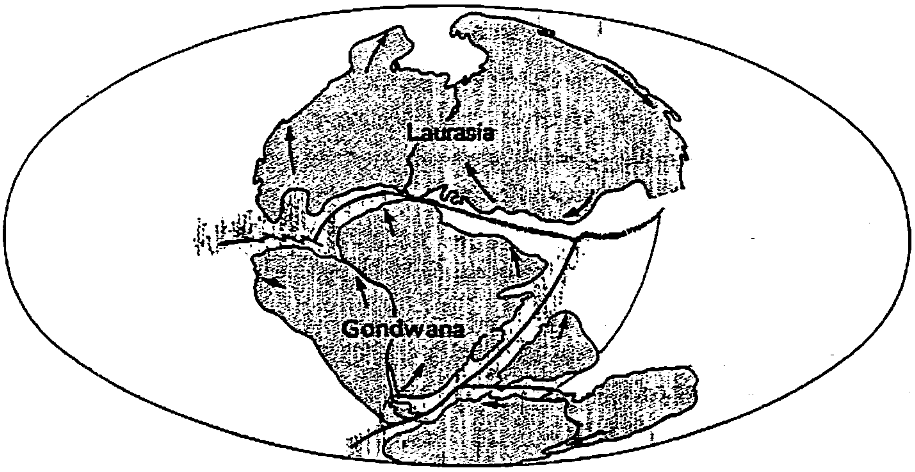
FIGURE 6-10
(a) The ancient land mass Pangaea as it may have looked 200 million years ago. Panthalassa, the ocean surrounding Pangaea, evolved into the present Pacific Ocean, and the present Mediterranean Sea is a remnant of the Tethys Sea.



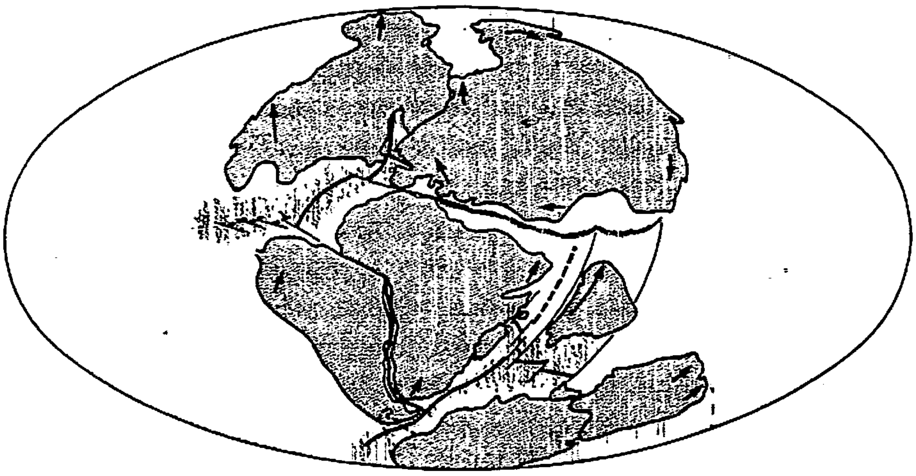
a 200 million years ago

(b) World geography at the end of the Triassic period, 180 million years ago, after about 20 million years of drift. The land mass has now become two supercontinents Laurasia and Gondwana. The light gray areas represent the new ocean floor. Spreading zones are represented by heavy lines, transform faults by fine lines, and subduction zones by hatched lines (where a line is broken, this indicates some uncertainty that the feature was present at the time). Arrows depict motions of continents since drift began.

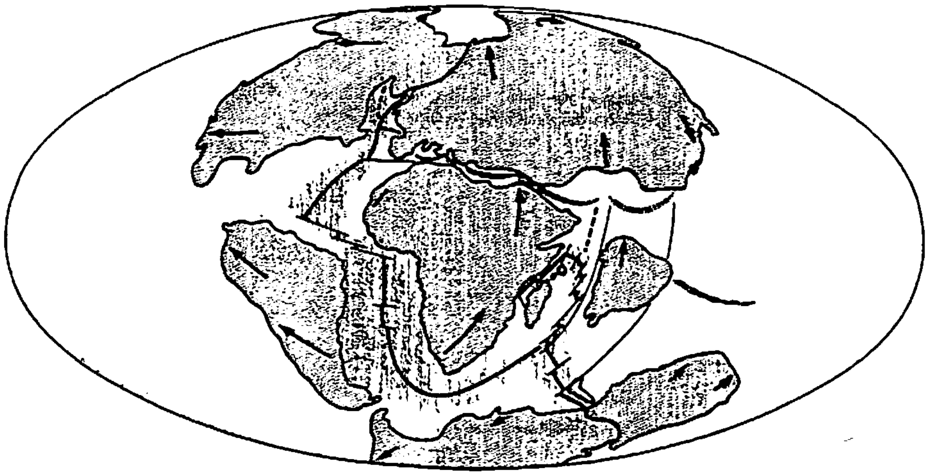


b 180 million years ago

(c) World geography at the end of the Jurassic period, 135 million years ago, after about 65 million years of drift.

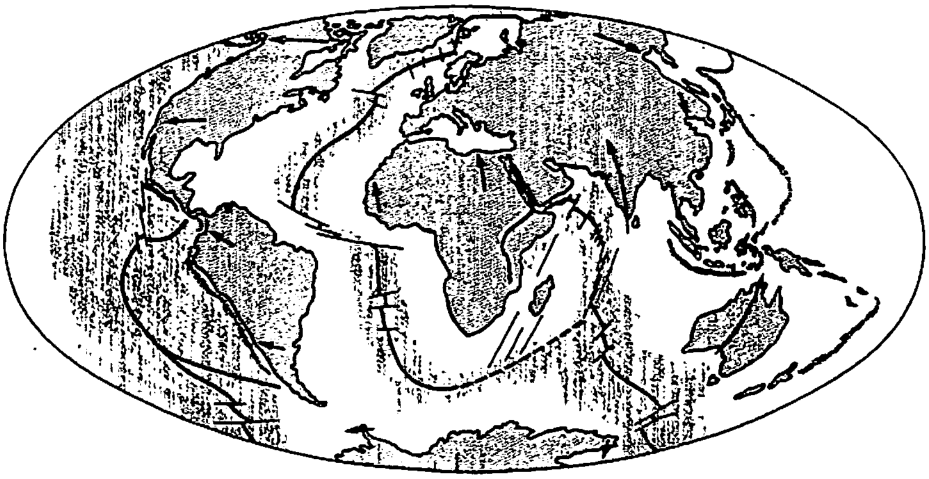


c 135 million years ago



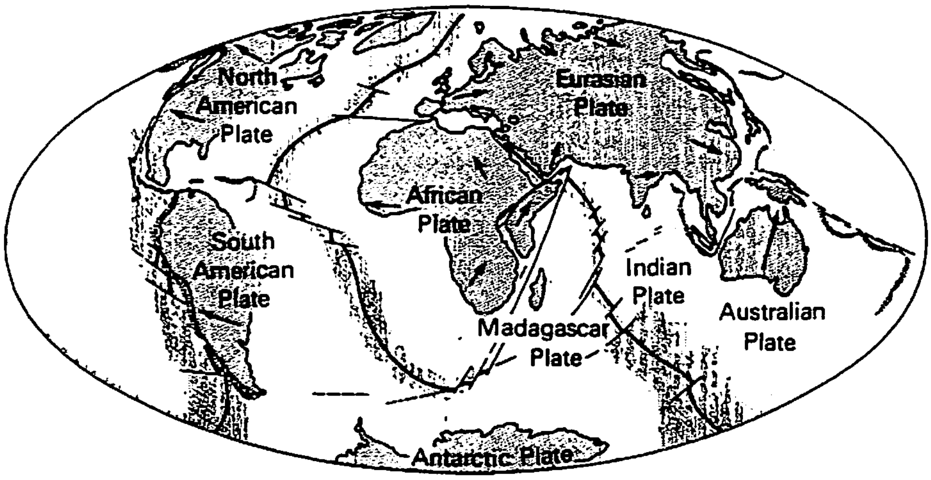
d 65 million years ago

(d) World geography at the end of the Cretaceous period, 65 million years ago, after some 135 million years of drift.



e Today

(e) World geography today, showing sea floor produced during the past 65 million years, in the Cenozoic period.



f 50 million years from today

(f) World geography as it may look some 50 million years from now if present-day plate movements continue. [Parts (a) through (f) after R. S. Dietz and J. C. Holden, "The Breakup of Pangaea." Copyright © 1970 by Scientific American, Inc. All rights reserved.]

Typical rocks of the continental crust, oceanic crust, and upper mantle

Rock	Location	Density (grams per cubic centimer)
Granite	Upper continental crust	2.7
Basalt	Oceanic crust, probably lower continental crust	2.9
Eclogite (heavy rock, high-pressure form of basalt)	Possibly upper mantle	3.4
Peridotite (heavy greenish rock)	Probably upper mantle	3.2
Serpentinite (hydrated form of peridotite)	Possibly lower crust	2.6

Seismic P-wave velocity (kilometers per second)	Mineral content (volume percent)	Composition (weight percent)
5.8–6.2	30% orthoclase 30% quartz 25% plagioclase 15% biotite 15% hornblende 15% others	70% silicon dioxide 15% aluminum oxide 4% potassium oxide 4% sodium oxide 2% calcium oxide 5% others
6.4–7.0	50% plagioclase 35% pyroxene 5% olivine 10% others (iron oxide, etc.)	48% slilicon dioxide 18% aluminum oxide 10% calcium oxide 8% magnesium oxide 6% ferrous oxide 3% ferric oxide 3% sodium oxide 4% others
8	45% garnet 45% pyroxene 10% others (amphibole, etc.)	Same as basalt
8	85% olivine 10% pyroxene 5% others (spinel, garnet, etc.)	44% silicon dioxide 37% magnesium oxide 6% ferrous oxide 5% aluminum oxide 4% calcium oxide 2% ferric oxide 2% others
6–7	Mainly serpentine	Same as peridotite, with about 10% water