Chapter 4

Plate Tectonics

プレート・テクトニクス

Plate: A New Concept

Once the sea-floor spreading hypothesis began to prove itself viable, almost everyone was attracted to it. Geophysicists began to greet one another with the question, "Do you believe in sea-floor spreading?" And they found themselves answering, "Yes." In 1967–68, special sessions on the sea-floor spreading hypothesis were held at geophysical meetings throughout the world, and hundreds of papers and reports were submitted, most of them attempting to demonstrate how effectively the sea-floor spreading hypothesis explained the phenomenon that each scientist was studying. Among the countries actively involved in solid earth science, only Russia and Japan appeared to remain skeptical. In most other countries the hypothesis was extremely popular. Once the transform fault hypothesis was enthusiastically accepted, many scientists were eager to explore the ultimate logic of the sea-floor spreading hypothesis.

Now let us examine once again the distribution of earthquake epicenters shown in Figures 2-4 and 3-10. It seems obvious that the earthquakes occur mostly along oceanic ridges, along transform faults and island arcs, and in orogenic belts like the Andes and the Alpine-Himalayan region. In contrast only a few earthquake foci are scattered over the vast areas that are surrounded by these earthquake belts. Since earthquakes are thought to originate on faults that are ruptured as a result of accumulated stress, the areas without earthquake foci are either devoid of such stress or are incapable of forming faults even under stress. Although it is known that rocks tend to lose their brittleness and become ductile under high temperature and pressure, it seems unlikely that the concentration of earthquakes in narrow belts is because these belts are cold and brittle whereas the rest of the crust is warm and ductile. A more plausible explanation is that the belts of epicenters divide the earth's surface into blocks that are strong and fairly rigid, and that these blocks move relative to each other, causing earthquakes along their margins while leaving the inner structure of the blocks intact.

It had been suggested that the earth's surface layer is highly rigid to a depth of about 70 kilometers, and that a softer layer lies below. This conjecture was the result of highly sophisticated studies of the propagation of seismic waves made during the 1960s. F. Press synthesized all of the available information to arrive at his discovery of the remarkable variation in the velocity of seismic shear waves that prevails at different depths, shown in Figure 4-1. To generate his model of the earth, of which only the uppermost part is shown in Figure 4-1, Press used what is called a Monte Carlo method. In this method a high-speed electronic computer seeks, in a series of random trials, models that will satisfy various geophysical observations. In this model, the *S*-wave velocity jumps from about 3.6 kilometers per second to 4.6 kilometers per second at a very shallow depth that corresponds to the Moho discontinuity. The velocity keeps increasing with depth to about 70 kilometers where it drops to about 4.2 kilometers per second. Deeper in the mantle the velocity gradually increases again. Wave velocity should increase with pressure under normal circumstances: therefore, something unusual must be occurring at the depth of 70 kilometers. Don Anderson and others proposed a convincing explanation for the cause of this decrease. They attributed it to the partial melting of the mantle.

Mantle material is a composite of silicates with extremely complex melting properties—so complex that petrologists, after an enormous amount of research, are just beginning to understand them. We do know, however, that the mantle does not melt completely at a single temperature, as ice does. Instead the melting takes place within a certain temperature range. In the beginning of the melting process only a small part of the material melts. This phenomenon of partial melting causes a drop in seismic-wave velocity, especially in the shear velocity. The temperature at which melting begins is called the *solidus temperature*. It can be easily inferred from the seismic data that partial melting has softened the mantle at a depth between 70 and 260 kilometers. The softened layer, the *asthenosphere*, lies at a

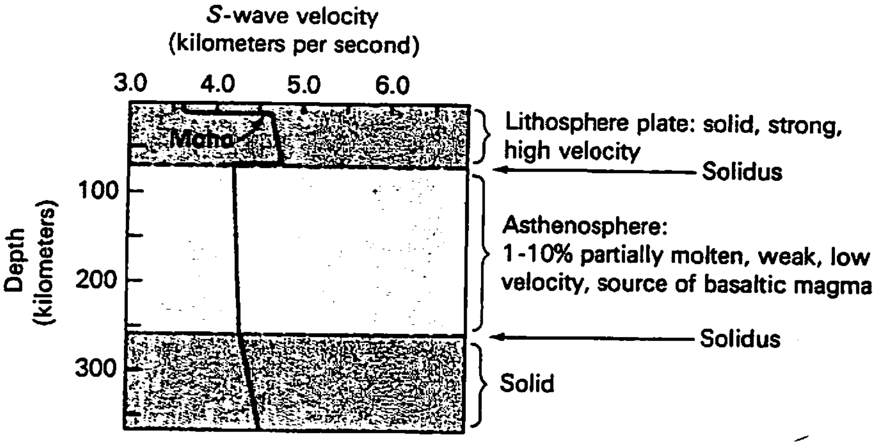


FIGURE 4-1
A modern view of the structure of the outermost layers of the earth is illustrated by a plot of S-wave velocity against depth. Note how velocity changes at the 70-kilometer depth mark the boundary between the lithosphere and the partially molten asthenosphere. [After F. Press and R. Siever, *Earth*. W. H. Freeman and Company. Copyright © 1974.]

depth of approximately 70 kilometers beneath the rigid outer layer, the *lithosphere*.

Once this information has been assembled, the earth's outer layers can be envisioned as a rigid lithosphere, consisting of several blocks or plates, which covers an underlying softer asthenosphere. Both the drifting of the continents and the spreading of the sea-floor may be ascribed to the movements of these rigid plates. Furthermore, their interaction is believed to be the cause not only of earthquakes, but also of many other important phenomena on the earth's surface, such as volcanic activity, oceanic trenches, and oceanic ridges.

This hypothesis, which has come to be known as the theory of *plate tectonics*, was advanced by D. McKenzie and R. Parker (1967) and independently by W. J. Morgan (1968). X. Le Pichon, a French oceanographer working at Lamont-Doherty Geologic Observatory, was one of the first to see the importance of this theory and quickly applied it to reveal the movements between most of the larger plates. We will now examine the remarkably simple but equally profound ideas advanced by these young scientists.

Testing the Hypothesis

There are three major types of plate boundaries, as Figure 4-2 clearly shows. One is the boundary created when two plates are moving apart from one another. Typically, it is found at a mid-oceanic ridge where

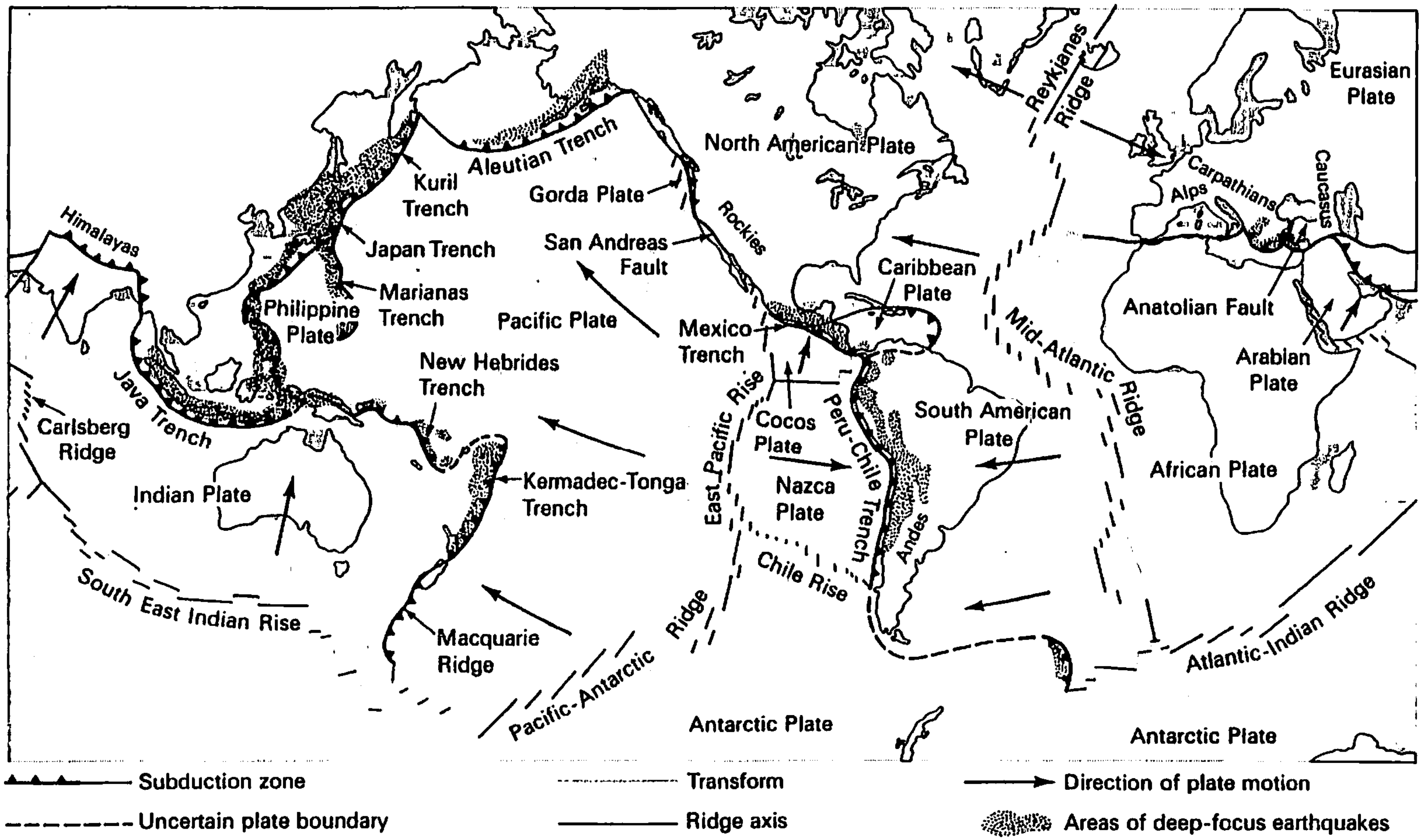


FIGURE 4-2
The earth's lithosphere is broken into large rigid plates, each moving as a distinct unit. The relative motions of the plates, assuming the African plate to be stationary, are shown by the arrows. Plate boundaries are outlined by earthquake belts. Plates separate along the axes of mid-ocean ridges, slide past each other along transform faults, and collide at subduction zones. [After J. F. Dewey, "Plate Tectonics." Copyright © 1972 by Scientific American, Inc. All rights reserved.]

new plates are being formed. It is called an *accreting*, or *diverging boundary*. Another type of boundary is created where two plates are moving toward one another. This is called a *converging boundary*. Oceanic trenches and certain mountain ranges, such as the Himalayas, are located along such boundaries. At the trenches, oceanic plates are thought to descend, or *subduct*, into the earth, whereas at the Himalayas two continental plates are in collision. Boundaries that occur along trenches are also called *consuming boundaries*. The third type of plate boundary occurs along transform faults, where the relative plate motion is parallel to the boundary.

Let us now consider two rigid plates A and B on a globe, as shown in Figure 4-3a, which are separated by oceanic ridges and transform faults at one boundary and by oceanic trenches and transform faults at the other. Geometrically, the only possible movement of the rigid plates is in a direction parallel to the transform faults, and such movement can be described as a rotation around a pole, ${}_{A}P_{B}$. Transform faults, which indicate the directions of such relative motion between plates (A and B in this example), lie on latitude circles around the pole ${}_{A}P_{B}$. The ridges, which are usually at right angles to the transforms, thus lie along the longitudinal, or meridional, circles. Since most trenches do not strike perpendicular to the transform faults, they do not lie meridionally. Now, if we draw a map on a Mercator projection, with ${}_{A}P_{B}$ as the pole, all the transform faults between plates A and B will lie parallel to the lines of latitude and the ridges will lie parallel to the lines of longitude as in Figure 4-3b. The direction of the relative motion between two plates can also be assessed from the first motion of an earthquake occurring at the plate boundary. The direction of seismic slip should also lie parallel to the latitude circle (for the same reason the transform fault does), as shown by the arrows in Figure 4-3b.

D. McKenzie and R. Parker (1967) studied earthquake-source mechanisms along the boundary of the Pacific Plate, with this idea in mind: if indeed the interactions of rigid plates cause earthquakes, an analysis of earthquakes along trenches, transforms, and ridges bordering the Pacific Plate should all reveal the same direction of motion for the Pacific Plate in relation to the neighboring plate. They found that this was true, and that the location of the pole describing the motion of the Pacific Plate relative to the North American Plate was at 50° north, 85° west (Figure 4-4). They obtained the position of this pole of rotation from the direction of the San Andreas Fault—a transform fault—and the average direction of fault motion of the aftershocks in the Kodiak Island region that followed the Great

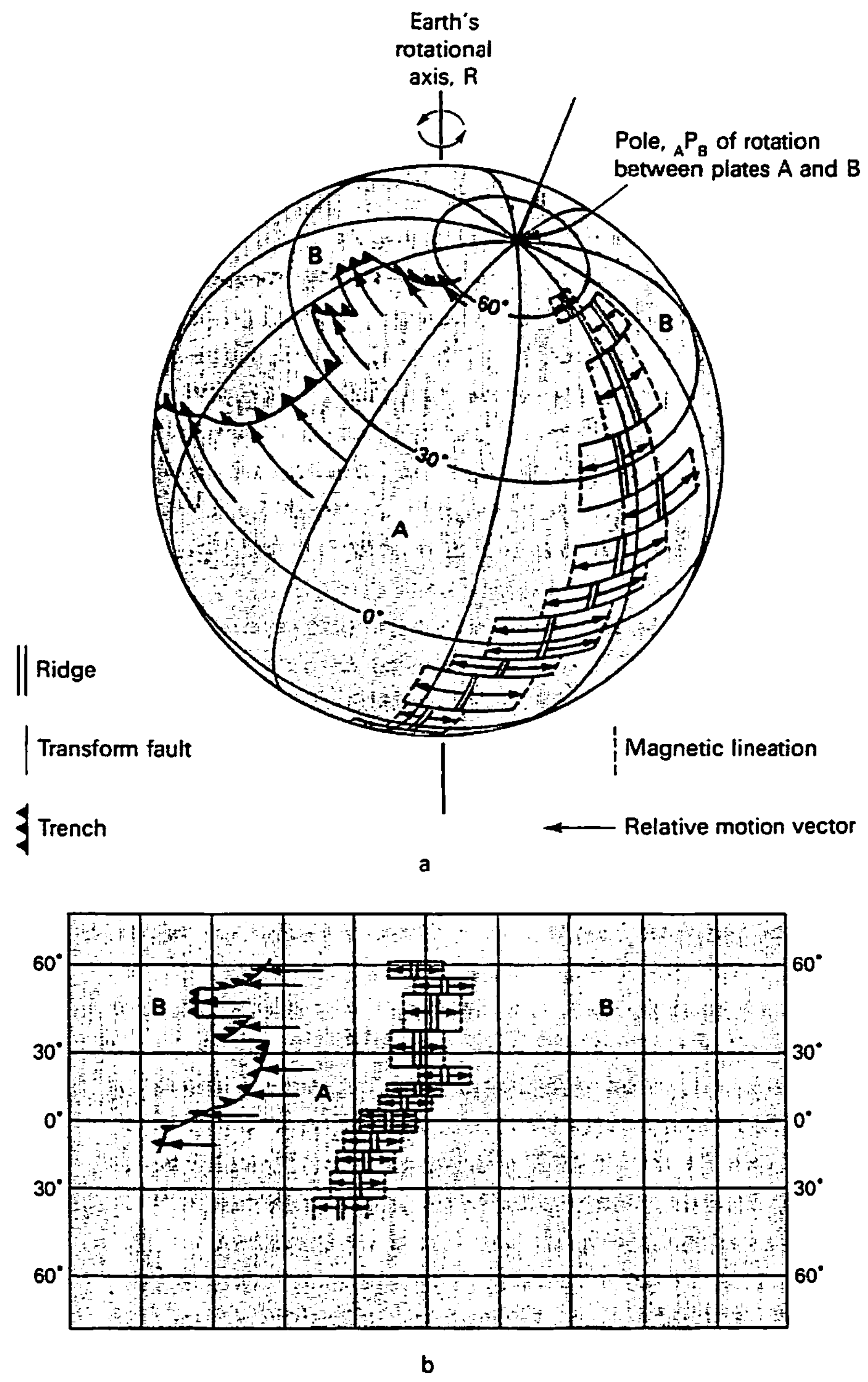


FIGURE 4-3
(a) The rotation of rigid plates on a sphere. At right is a spreading ridge with transform faults. At left is a plate boundary formed by trenches and transform faults. $_AP_B$ is the pole of relative rotation between plates A and B, which should not be confused with R, the pole of the earth's rotation. The arrows indicate both direction and speed of relative motion. Note that the spreading rate, indicated by the length of each arrow, is larger at lower latitudes, and the direction of the relative motion is parallel to the transform faults.
(b) A Mercator projection of the globe shown in (a). Projection is made on the pole $_AP_B$. Note that all transform faults and relative-motion vectors are now parallel to latitude lines, and that ridges and magnetic lineations are parallel to longitude lines. The width of magnetic lineation and the length of the arrows are now independent of latitude.

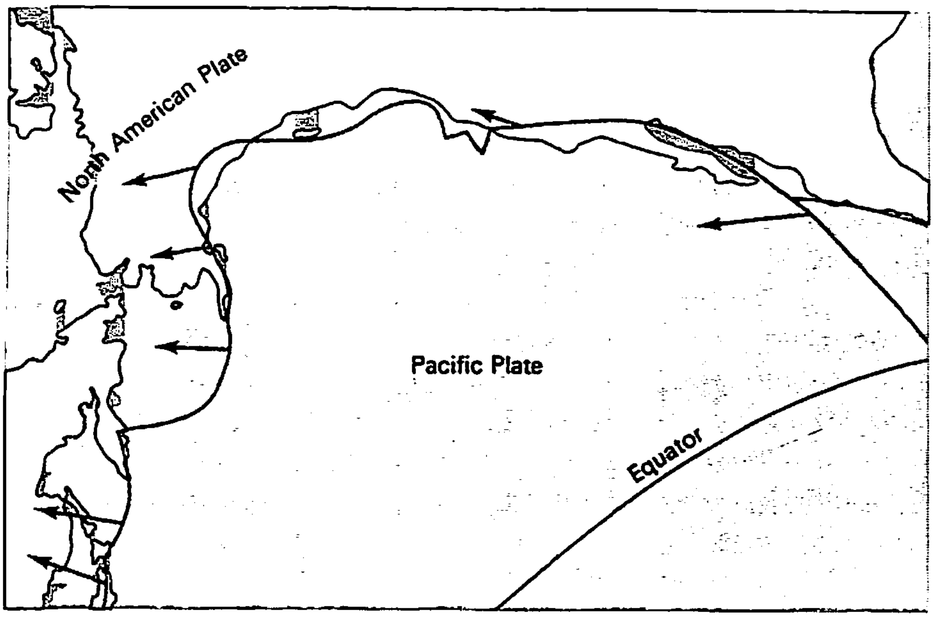


FIGURE 4-4
A Mercator projection of the Pacific with a pole at 50° North, 85° West. The arrows show the direction of motion of the Pacific Plate relative to the North American Plate. If both plates are rigid, all relative-motion vectors must be parallel to each other and to the upper and lower boundaries of the figure that are parallel to the circles of latitude. [After D. P. McKenzie and R. L. Parker, "The North Pacific: An Example of Tectonics on a Sphere." *Nature* **216**, p. 1276, 1967.]

Alaskan Earthquake of 1964. (The pole should be located at the intersection of great circles taken perpendicular to these two directions, if the plate hypothesis is correct.)

In the meantime, W. J. Morgan was thoroughly examining the observed widths of the striped patterns of geomagnetic anomaly and the direction of transform faults. Let us examine Figure 4-3a once again. Now, if the rigid-plate hypothesis is correct, one can see that (given the geometric requirement that the only possible direction of plate movement is parallel to the transform faults) the speed of the relative movement between two plates, or, in other words, the speed of both sea-floor spreading and subduction, represented by the lengths of the arrows in Figure 4-3a, should increase with increasing distance from the pole $_AP_B$. It can be shown, in fact, that the speed should be proportional to the cosine of the angle of latitude. Hence, the relative plate movement at the pole $_AP_B$ will be zero, while the spreading rate will be maximum at a distance 90° from $_AP_B$. According to the sea-floor spreading and Vine-Matthews-Morley hypotheses, the spreading rate can be determined by the width of the magnetic stripes. So, theoretically, the pole of rotation between two plates can be estimated also from the distribution of the width of magnetic stripes. In other words, the pole can be estimated independently from both the distribution of the directions of transform faults, or seismic first-motion data, and from the distribution of the widths of magnetic stripes. If the pole of rotation is correctly estimated, the magnetic stripes should look like the dashed lines in Figure 4-3a. They are parallel to the meridional lines and they decrease in width toward the pole ${}_AP_B$ as the spreading speed (represented by the lengths of the arrows) decreases toward the pole. Here, it may be seen that all of these magnetic stripes will become parallel and of constant width in the Mercator projection in Figure 4-3b, just as all the longitudinal circles that converge at ${}_AP_B$ in Figure 4-3a are converted to the north-south parallel lines in Figure 4-3b. The lengths of arrows also become constant.

These relations, which are intrinsic to the Mercator projection, can be used to check the validity of plate tectonic concepts graphically. Figure 4-5 is such an example. It shows a Mercator projection of the world map drawn about a pole of rotation. The position of the pole was determined from the distribution of the sea-floor spreading rates—that is, the width of magnetic stripes—in the East Pacific Rise. In this map all the transform faults of the East Pacific Rise do indeed lie parallel to the lines of latitude. This indicates that the pole that has been determined from the distribution of the directions of transform faults coincides with the pole that has been determined from the distribution of the spreading rate. Thus it now seems almost certain that the Pacific Plate and the plate east of the East Pacific Rise (the Antarctic Plate) have undergone relative rotation about this pole since at least the time at which the anomaly stripe used for the analysis was formed (70 million years ago). These findings were widely read by earth scientists before their publication in about 1967, and were the source of lively debate. Now they started to greet one another with the query, "Do you believe in plate tectonics?"

It is intriguing to note, in Figure 4-5, that the direction of many of the faults to the north, which H. W. Menard calls "fossil faults," do not lie parallel to the lines of latitude but are off by 30°. Would this mean that, long ago, the relative motion of rotation in the northeast Pacific, as represented by these faults, was not the same as that of the plates in the south Pacific? This was perplexing to some. However, the discrepancy is not so puzzling when one realizes that the motions deduced from the present methods are strictly the *relative* motions between two neighboring plates. In discussing motion along the San

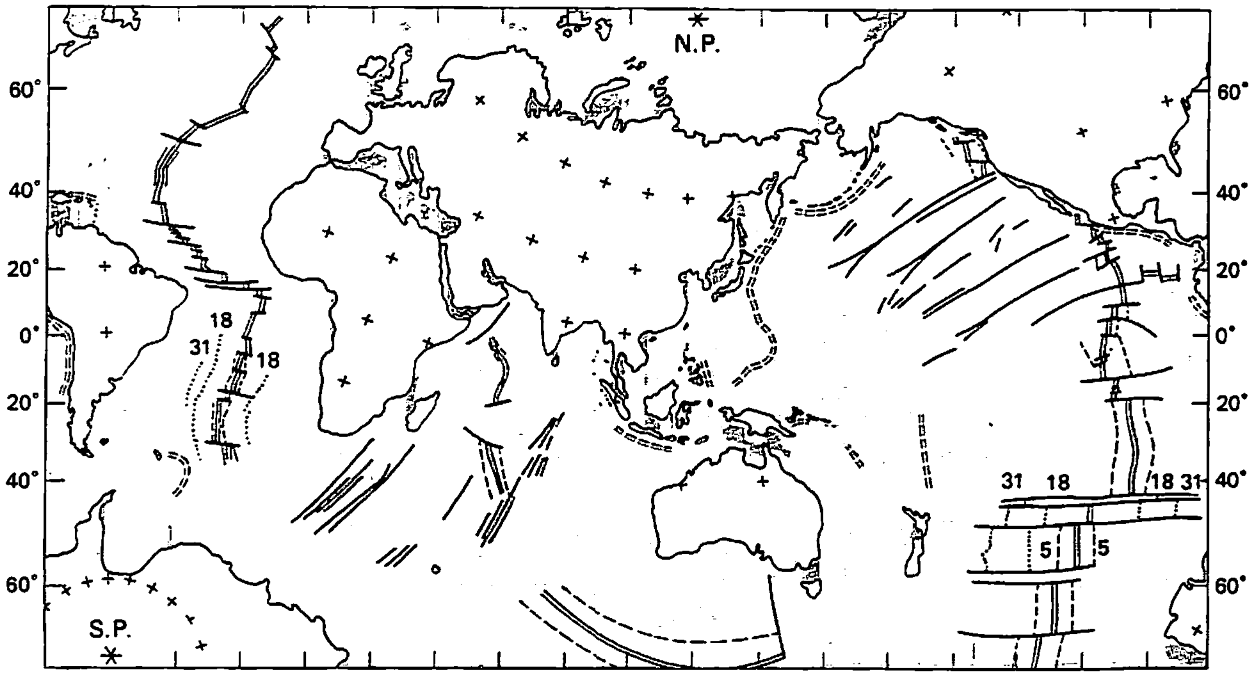


FIGURE 4-5
A Mercator map of the world drawn about the pole of rotation of the plates in the Southeast Pacific. The numbers at the magnetic stripes are anomaly numbers. Anomalies 5, 18, and 31 correspond to the ages 10, 45, and 70 millions of years ago. [After X. Le Pichon, "Sea-Floor Spreading and Continental Drift," *J. Geophys. Res.* **73**, p. 3661, 1968. Copyrighted by American Geophysical Union.]

Andreas Fault, for example, it is correct to say either, "the Pacific Plate is moving northwest relative to the North American Plate," or "the North American Plate is moving southeast relative to the Pacific Plate." The direction of the fault reveals the direction the plates are moving relative to each other, but it doesn't tell us that one plate is moving and the other is stationary. Therefore a plate can remain rigid and also have nonparallel sets of transform faults when portions of the boundary face different plates (Figure 4-6). In earlier times the northern and southern parts of the Pacific Plate *did* face different plates, and the transforms along the two boundaries had different directions. The plate that was bounded by the northern part of the East Pacific Rise was not the same plate as the one in the south, and it was consumed and disappeared some 30 million years ago when that part of the East Pacific Rise collided with the North American Plate. This remarkable story will be told in the following sections of this chapter.

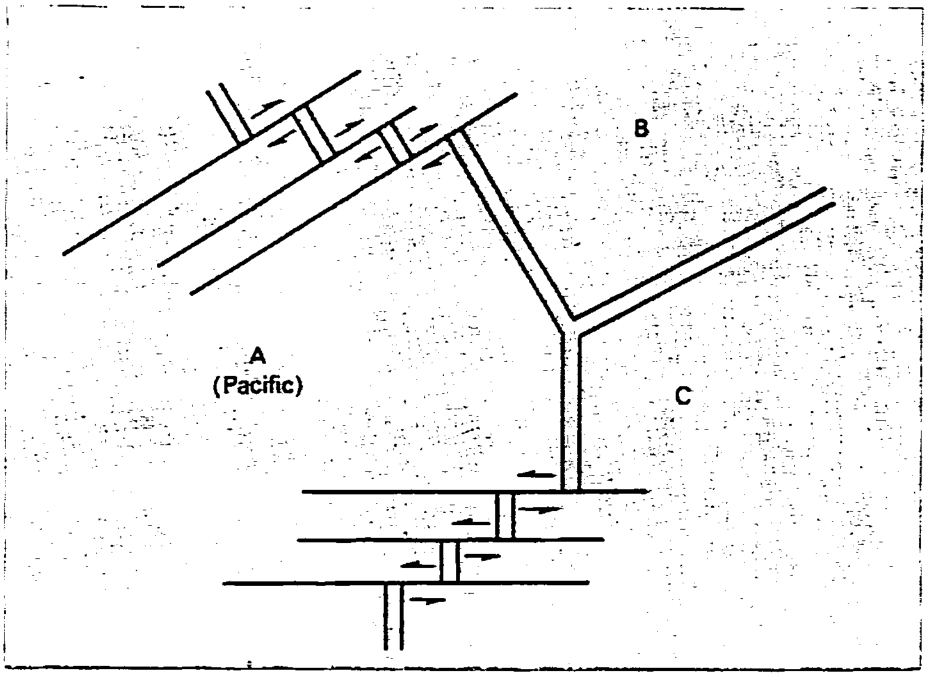


FIGURE 4-6
Schematic diagram showing nonparallel transform faults can be formed when one plate (A) has more than one neighboring plate (B and C).

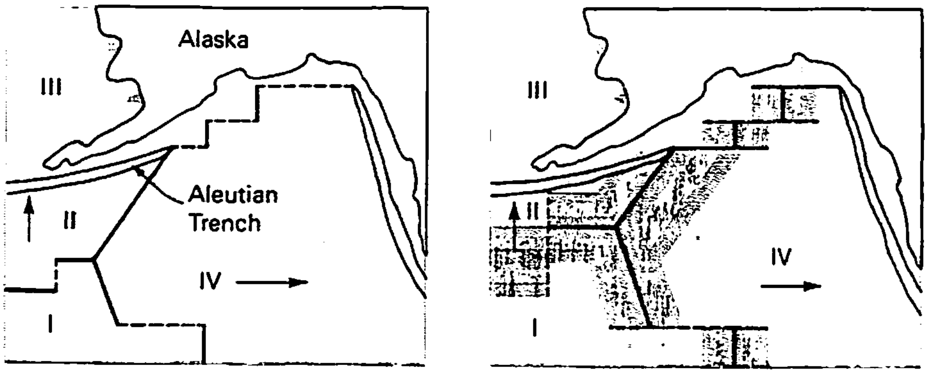
The Migration of Oceanic Ridges in the North Pacific

Recall that the magnetic stripes in the east Pacific bend abruptly in the Gulf of Alaska (Figure 3-10). This bend was discovered by the American scientist G. Peter and his colleagues during 1966 and 1967, and was named the *Great Magnetic Bight.* They extended their survey area westward and traced the lineations trending in an eastwest direction up to the Emperor Seamounts at the western end of the Aleutian Islands. Since the east-west lineations south of the Aleutians are the continuation of those in the southeast Pacific, they presumably become younger as they approach the Aleutian Trench. As we stressed toward the end of the preceding chapter, this pattern appeared to violate the basic concept of sea-floor spreading—the postulate that new sea floor is formed at the ridges and spreads toward the trenches.

Part of this dilemma had already been resolved in 1966 by Vine in his analysis of stripes off the coasts of California, Oregon, and Washington. There the stripes get younger eastward, again as they approach the location of an ancient trench that is no longer active. Vine reasoned that a rise ancestral to the East Pacific Rise once lay off the coast of California, and was separated from the coast by a trench. The rise migrated toward the trench until eventually the two met and annihilated each other. Lithosphere that had formed east of the rise has been subducted beneath North America. On lithosphere formed west of the ancient rise, the magnetic stripes get younger to the east. The reason for this, Vine explained, was that originally the stripes were getting younger toward the rise, in accord with the theory of sea-floor spreading; however, the rise has now vanished in the ancient trench.

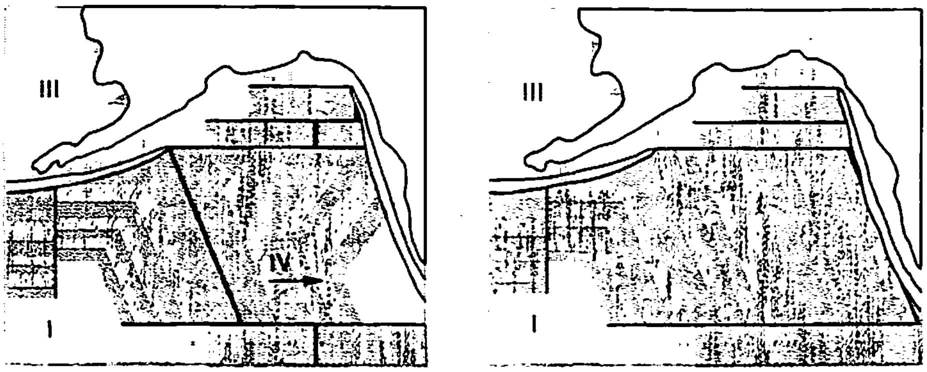
Following Vine's lead, in 1968, W. C. Pitman and D. Hayes proposed a strange yet plausible explanation for the enigma of the stripes south of the Aleutians (Figure 4-7). They maintained that in the late Cretaceous period (around 75 million years ago) there were three active oceanic ridges in the northeast Pacific radiating from a common point (Figure 4-7a). The sea floor was spreading away from the crest of each ridge. (In the figure the trenches are presented merely for the purpose of reference—their exact position is not known.) In order to examine the process that took place when the three plates were being produced by the three oceanic ridges, let us suppose that plate I, representing the Pacific Basin, is fixed. This is entirely legitimate, because this way all the motions are taken to be relative to plate I. Since each plate was growing along its ridge boundaries, with plate I held immobile, it is necessary that plates II and IV must have migrated away from plate I toward the north and east respectively. At the same time the ridge separating plates I and II was migrating northward and the ridge separating plates I and IV was migrating eastward, adding new ocean floor to plate I (Figure 4-7b). Finally the ridge between plates I and II disappeared into the Aleutian Trench (Figure 4-7c), while the ridge between plates I and IV descended beneath the American continent, leaving behind magnetic stripes that are younger toward the north and east (Figure 4-7d), in accord with Vine's interpretation to the south. Ingenious as this explanation is from a geometrical point of view, the idea that oceanic ridges should descend into oceanic trenches seemed a bit strained. Does the rising rim of a convection cell sink into the descending rim? This point was vehemently criticized by the opponents of the sea-floor spreading hypothesis. We will come back to this problem later.

The possibility that the oceanic ridge itself migrates is quite intriguing. In fact, this suggestion had been made earlier, prompted by certain observations. The African continent, as Figure 4-2 shows, is



a Late Cretaceous
(about 75 million years ago)

b Late Cretaceous
(about 70 million years ago)



c Early Paleocene
(about 60 million years ago)

d Early Pliocene
(about 6 million years ago)

FIGURE 4-7
Schematic diagrams of four stages in the development of the lineations of the Northeast Pacific. The arrows indicate the motions relative to Plate I (the Pacific Plate). [After W. C. Pitman and D. E. Hayes, "Sea-Floor Spreading in the Gulf of Alaska." *J. Geophys. Res.* 73, p. 6571, 1968. Copyrighted by American Geophysical Union.]

surrounded by oceanic ridges in three directions. The Antarctic continent is even more completely surrounded by spreading ridges. Given these conditions, it would be geometrically impossible for new sea floor to be produced at all these ridges and to spread toward the continents unless, of course, there are trenches along the coasts that consume the sea floor as it spreads. There are no trenches around these continents, however. The oceanic ridges surrounding the African and Antarctic continents, then, *must* be migrating farther and farther away from those continents as they produce more and more sea floor.

An interesting corollary of plate tectonics is the geometrical requirement that there must be points at which three plates meet. These points have been named *triple junctions* by D. McKenzie and W. J. Morgan (1969). Depending on the types of boundaries meeting at the point of intersection there can be various types of triple junctions. The point at which three ridges meet in the Gulf of Alaska, in Figure 4-7, is an example. This type of junction is called an R-R-R junction, R symbolizing ridge. Similarly, all the combinations of R, T (trench), and F (transform fault) can form triple junctions, such as T-T-T, F-F-F, R-T-F, and so on.

In their important paper in 1969 on the theory of triple junctions, McKenzie and Morgan demonstrated that, on the basis of simple geometrical considerations, some types of triple junctions are stable whereas others are not: when the same plate configuration can be maintained through time, the triple junction is stable. In addition, they determined the conditions under which the velocities of each plate combine to make stable triple junctions. They pointed out that, even though the motions of each plate remain unchanged, the evolution of the triple junction can alter the nature (or type) of the plate boundaries. Such an alteration, they suggested, may be an important cause of tectonic changes over time. An important and dramatic example of this assertion was provided in the tectonic history of western North America, as will be shown in the next section.

An Oceanic Ridge That Collided with the North American Continent

Let us examine Figure 4-8. The most active earthquake and volcanic zones in the world are in an area known as the *circum-Pacific orogenic belt*. These zones include the Aleutian Islands in the north, the Kuriles, the islands of Japan, the Izu-Bonin and Marianas Islands, down through the Ryukyus, the Philippines, and New Guinea, and the Tonga and Kermadec Islands and New Zealand in the south; they include also the west coasts of Central and South America. Although the prefix "circum-" implies an unbroken circle around the Pacific Ocean, there are breaks in the orogenic belt along the west coast of the North American continent and between Australia and the Antarctica. These two regions are also distinguished in Figure 4-8 as areas devoid of deep- and intermediate-focus earthquakes.

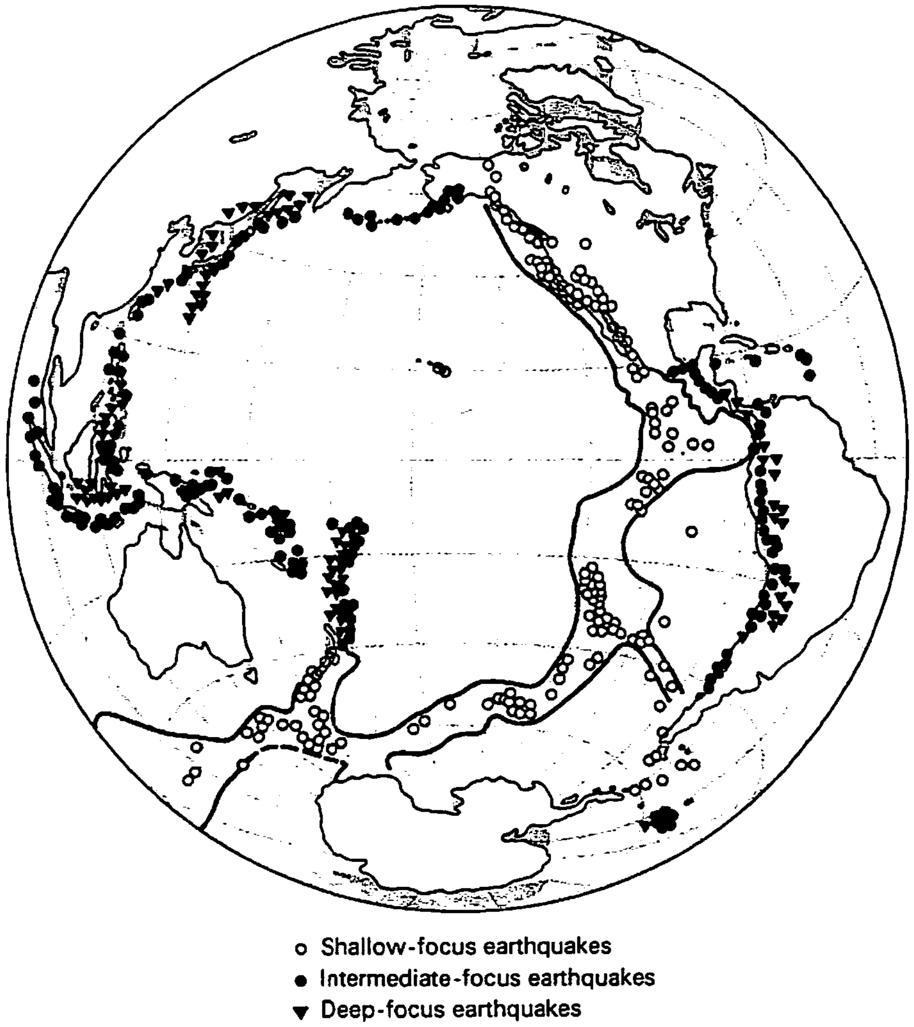


FIGURE 4-8
The circum-Pacific belt is interrupted by the East Pacific Rise. [After R. W. Girdler, "Research Note—How Genuine Is the Circum-Pacific Belt?" *Geophys. J.* 8, p. 537, 1964.]

R. Girdler of England pointed out in 1964 that "circum-Pacific" is not an appropriate term because the circle is broken. He explained this observation by stating that, whereas the ocean floor is descending on both sides of the Pacific, a mid-oceanic ridge exists on the west coast of the North American continent and in the area between Australia and the Antarctica. This fact was already known but it received renewed attention, thanks to Girdler's insistence. Recall that on the west coast of the North American continent there is no trench, nor are there deep-focus earthquakes. The only notable feature is the San

Andreas Fault, along which shallow earthquakes occur. As a matter of fact, the San Andreas Fault is a transform fault that links the East Pacific Rise with the Juan de Fuca and Gorda Ridges (see Figure 3-6). It is a gap in the presently active orogenic belt. In the same region, however, there are in the coastal ranges extensive belts of sedimentary deposits that show that a trench once existed there like the one existing along the west coast of South America today.

What we must note again here is that the oceanic ridges themselves have migrated, so that the magnetic lineations off North America represent only one side of the East Pacific Rise. We recall Vine's explanation that the East Pacific Rise was once situated in the northeastern Pacific, producing ocean floor as it is doing in the southeastern Pacific today. The spreading ocean floor advanced toward the east and descended beneath a then existing trench off the coast of North America. This explanation certainly appeared to be helpful to an understanding of the geological structure of the west coast of North America. An American geologist W. Hamilton, among others, had proposed a similar idea, and suspected that the sunken portion of the East Pacific Rise is now under the *Basin and Range Province*, causing the well-known peculiar features of that region. The Basin and Range Province covering much of Nevada, Arizona, and Utah exhibits high heat flow and extensional tectonics, just what we would expect in an area underlain by an active rift.

At this point McKenzie and Morgan's idea of an evolving triple junction came along. Their ingenious suggestion was soon elaborated in great detail by Tanya Atwater (1970), then a graduate student at Scripps Institution of Oceanography. Atwater made a careful analysis of the striped pattern of geomagnetic anomalies off the North American coast, tracing the history of how the oceanic ridge collided with the American continent and disappeared. As is apparent in Figure 3-10, both sides of the oceanic ridge (the East Pacific Rise) are visible in the south of the Gulf of California, whereas only the west side is visible in the north of the Gulf. If the ocean floor spreads symmetrically on both sides of the ridge, in accord with the sea-floor spreading hypothesis, the east side of the ridge must be under the American continent. In the model presented by Vine, McKenzie, Morgan, and Atwater, a continuous trench existed along the western United States until 30 million years ago. The new sea floor produced by the East Pacific Rise was constantly descending into this trench, generating volcanoes and deep-focus earthquakes. At present, however, this descent—and the volcanic and earthquake activity—has ceased, leaving behind such "fossils" as volcanic rocks.

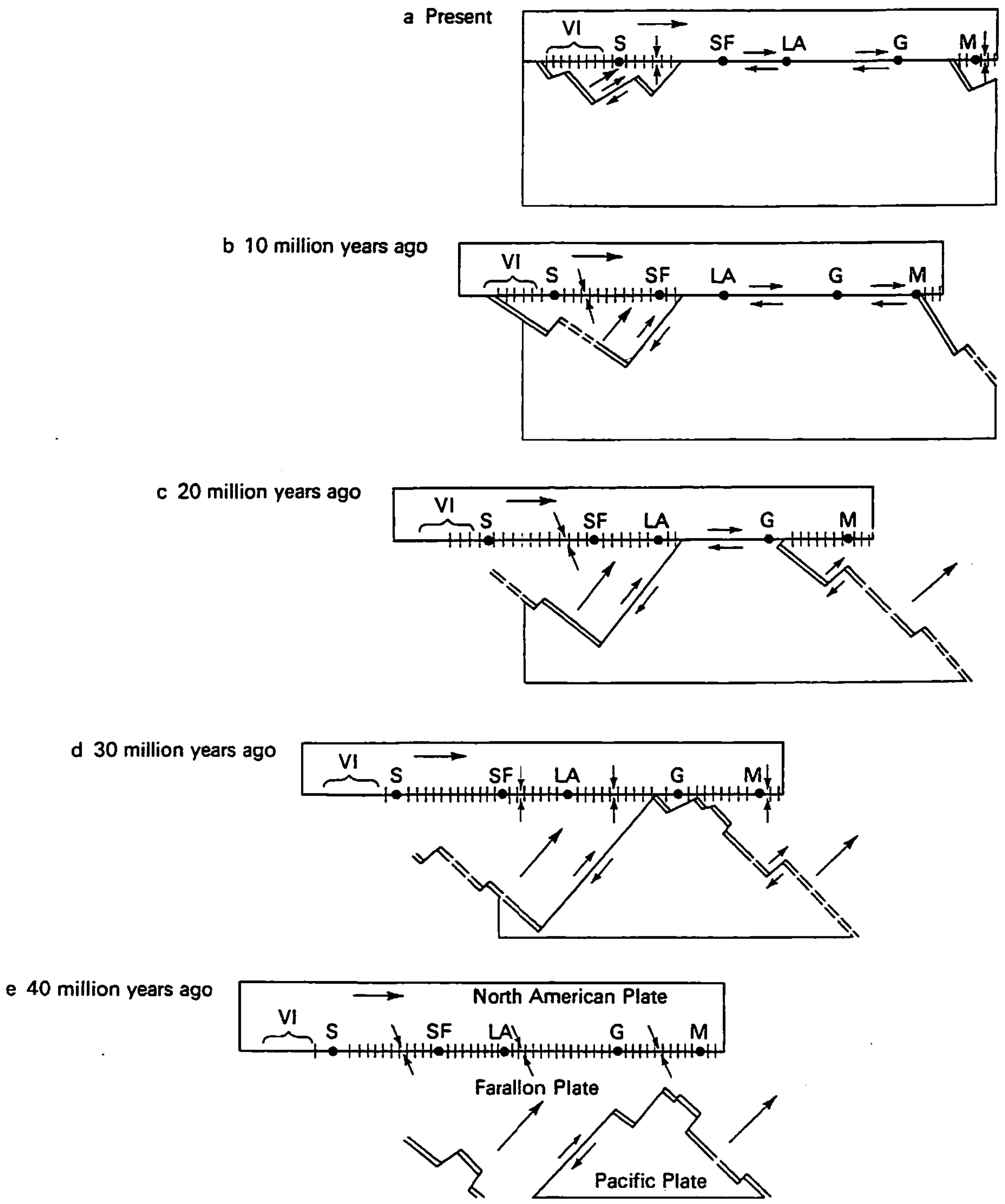


FIGURE 4-9
Schematic model of plate interactions, based on the assumption that the North American and Pacific plates moved with a constant relative motion of 6 centimeters per year parallel to the San Andreas fault. The coast is approximated as parallel to the San Andreas fault. Farallon-Pacific plate motions are approximated from the observed magnetic anomalies. The letter symbols refer to the following locations: VI—Vancouver Island; S—Seattle; SF—San Francisco; LA—Los Angeles; G—Guaymas; M—Mazatlán. The long arrows show motions of plates relative to the Pacific plate and the short arrows show relative motions along plate boundaries. [After T. Atwater, "Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of Western North America," *Bull. GSA* **81**, p. 3513, 1970. Redrawn with permission of the author.]

Figure 4-9 represents one plausible model of the history of the interactions between the East Pacific Rise and the North American continent, as analyzed from the magnetic stripes. For those who find this model complicated, it might be helpful to refer to Figure 3-6 in which a similar concept is illustrated. (It may also be easier to understand if Figure 3-6 is turned sideways so that the San Andreas Fault extends horizontally.) Part (a) in this model represents the present period. Parts (b), (c), (d), and (e) show the progressively older periods. The Farallon Plate is the symmetrical counterpart to the main Pacific Plate, which formed on the east side of the East Pacific Rise. It vanished beneath the North American continent, leaving only a small segment behind on the east side of the Juan de Fuca and Gorda Ridges. The consumption of the Farallon Plate ceased when the East Pacific Rise and the North American continent collided, as shown in Figure 4-9. After the collision, the San Andreas Fault—a transform fault—began its activity on the west coast of North America. The initial contact between the East Pacific Rise and the North American continent is thought to have occurred about 30 million years ago (Figure 4-9d). From that time on, the two triple junctions (the T-F-F type in the north and the F-R-T type in the south) have been moving apart, thus lengthening the San Andreas Fault, and the relative movement between the two main plates now in contact has been parallel to the San Andreas Fault. This story provides a lucid, even revolutionary explanation for the geological history of western North America, and, at the same time, establishes the concept of the collision of ridge and trench even more firmly. The evidence, though difficult to accept, was overwhelming. Now we come to the question, what is a ridge?

Oceanic Ridges

When the sea-floor spreading hypothesis was introduced, the postulate that an oceanic ridge was in fact a portion of the convection current welling up from within the mantle was rarely questioned. But this period of blissful ignorance did not last long. Once it was ascertained that oceanic ridges could migrate and that they either descended into the depth of the earth or were somehow annihilated, it also became apparent that they needed to be thoroughly re-examined in terms of the concept of the plate tectonics.

One of the ideas resulting from this re-examination was that oceanic ridges were simply cracks or "windows" in the plates that had been caused by their motions, and that these cracks were then

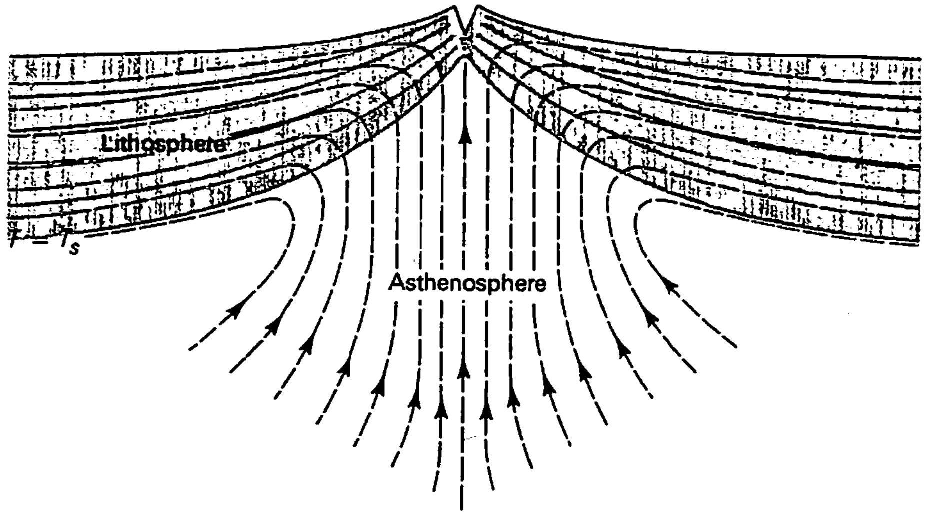


FIGURE 4-10
Schematic diagram of material flow (broken lines with arrows) and isotherms (solid lines) showing the thickening of the plate by cooling from above. The solidus temperature T_s is the isotherm that represents the temperature between partially molten states: the solid lithosphere above is cooler than T_s, and the asthenosphere below is hotter.

filled by the ascending magma from the mantle. Then the oceanic ridges could migrate and they could eventually collide with oceanic trenches and be annihilated. Interpreted in a slightly different way, this idea could mean that oceanic ridges and the upwelling zone of mantle convection are not necessarily the same. Nonetheless, it is inevitable that hot material from the asthenosphere wells up at the oceanic ridges, since that is where the lithosphere is cracked and pulled apart. As the material approaches this opening, the pressure decreases so that partial melting accelerates. The basaltic magma then separates and cools, forming the crust of the sea floor. The plates then move farther away from one another. As the newest sea floor, which is the hottest and therefore mechanically the weakest, lies at the crests of the oceanic ridges, this continues to be the location of the cracking of the lithosphere. For this reason, the new material from below emerges in the ridge-crest area. This is why sea-floor spreading continues to be localized at the oceanic ridges. The oceanic crust is formed largely by intrusions of dikes of basaltic magma filling vertical cracks, but direct extrusion of magma onto the sea floor also occurs, as has been proved by dredging in oceanic ridge regions. Eruptions on the sea floor can be identified by the presence of lava with a unique morphology—called *pillow lava*—which is formed by rapid solidification owing to the presence of ocean water. Basalt magma quenched in this way acquires strong thermo-

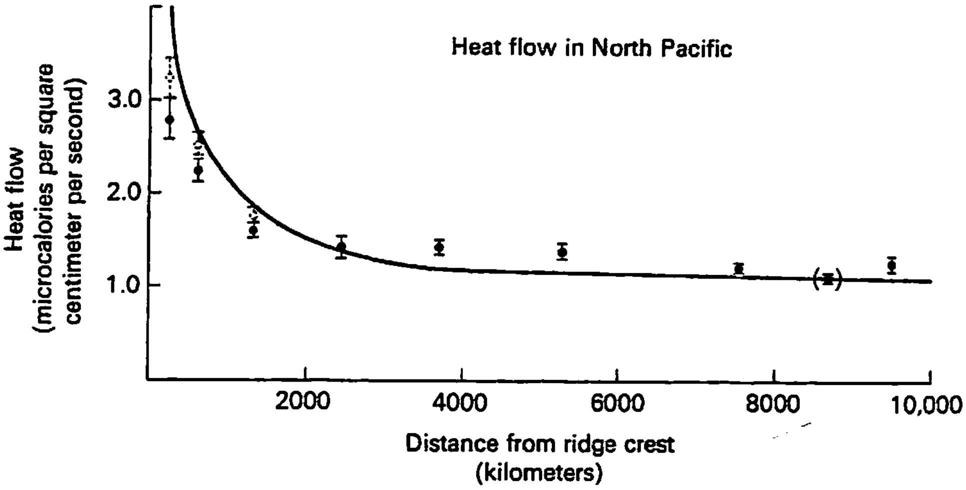


FIGURE 4-11
Comparison of observed heat-flow averages (represented by the symbol I in the north Pacific with the theoretical profile (the curve) for a lithosphere 75 kilometers thick. Open symbols represent observed values increased by 15% to account for possible biasing effect near the ridge (see text). Note that the observed averages decrease with increasing distance from the ridge. [After J. G. Sclater and J. Francheteau, "The Implication of Terrestrial Heat Flow Observations on Current Tectonic and Geochemical Models of the Crust and Upper Mantle of the Earth." *Geophys. J.* **20**, p. 509, 1970. Redrawn with permission of the authors.]

remanent magnetism, which may produce the magnetic anomalies observed above the sea floor.

As the new sea floor spreads away from both sides of the ridge, it gradually cools from the surface downward and thickens. Surfaces within the lithosphere, or a plate, along which the temperature is constant can be represented by isotherms, as shown in Figure 4-10. The isotherm for the solidus temperature T_s (the temperature at which melting begins) is especially important because rocks above the level of this isotherm have completely solidified as the lithosphere, whereas rocks below it are partially melted and constitute the asthenosphere. The actual value of T_s depends on the mineralogical composition of the upper mantle and on whether water exists there or not. It is expected to vary from 1000°C to 1200°C for wet and dry mantle.

As mentioned previously, the heat flow from the sea floor is highest at the ridge crest and gradually decreases farther away from the crest. Earlier, scientists attributed this phenomenon to mantle convection, but the plate model we are discussing in this section seems to explain it more adequately: the decrease in heat flow is caused by a gradual cooling of the plate.

Figure 4-11 shows how the heat flow through the Pacific Ocean floor decreases with increasing distance from the ridge and hence with increasing age. The theoretical profile for the plate model, and agreement between it and the observations is quite satisfactory, except for the crestal zone of the ridge. Along ridge crests, many observations reveal unusually low heat flow as well as high heat flow, and this makes the average value of actual heat flow much lower than the theoretical one (page 55). C. Lister considers this discrepancy to be the result of a gigantic hydrothermal system that exists within the upper layers of the crust near the ridge crest. Within this system, heat is released into the ocean not only through the usual solid conduction through the rocks but also by the circulation of water through cracks in the rocks. Much vigorous investigation is being carried out to clarify the nature of hydrothermal circulation in the oceanic crust.

Another observation, by J. Sclater and J. Francheteau, provided the most important supportive evidence for the plate model. They noticed that the observed decrease in heat flow away from the ridge means that the isotherms are sloping downward away from the ridge, causing the plate to grow thicker (see Figure 4-10). The solidified portion of the plate is also gradually cooling and becoming denser, the corresponding decrease in volume being due to thermal contraction. As a result, the lithosphere sinks several kilometers deeper into the mantle and the depth of the ocean becomes greater over the colder and older parts of the sea floor. Sclater and others investigated the relationship between the depth of the oceans and the age of the sea floor and confirmed this reasoning. In Figure 4-12 the observed topography of the Pacific sea floor is compared with a theoretical model. The agreement is indeed remarkable. For example, it is a well known fact of oceanography that the eastern Pacific region is shallow and the western region deep, and yet it is a thrill to observe that the plate model can explain it as a universal and inevitable consequence of a simple phenomenon like thermal contraction.

The foregoing discussion summarizes the present plate tectonic model for the production of plates at oceanic ridges. The supportive details for these concepts will have to wait for future research. A. Miyashiro and his colleagues, for instance, have gathered a great many metamorphic rocks from the sea floor. The basaltic rocks that constitute the solidified crust must have been buried by some kind of mechanism to be metamorphosed and then exposed on the sea floor once again by actions such as fault movement. Another equally or even more important problem appears to be the actual geological, tectonic, or petrological processes that generate the ocean crust beneath the crest of mid-oceanic ridges. But to solve such a problem

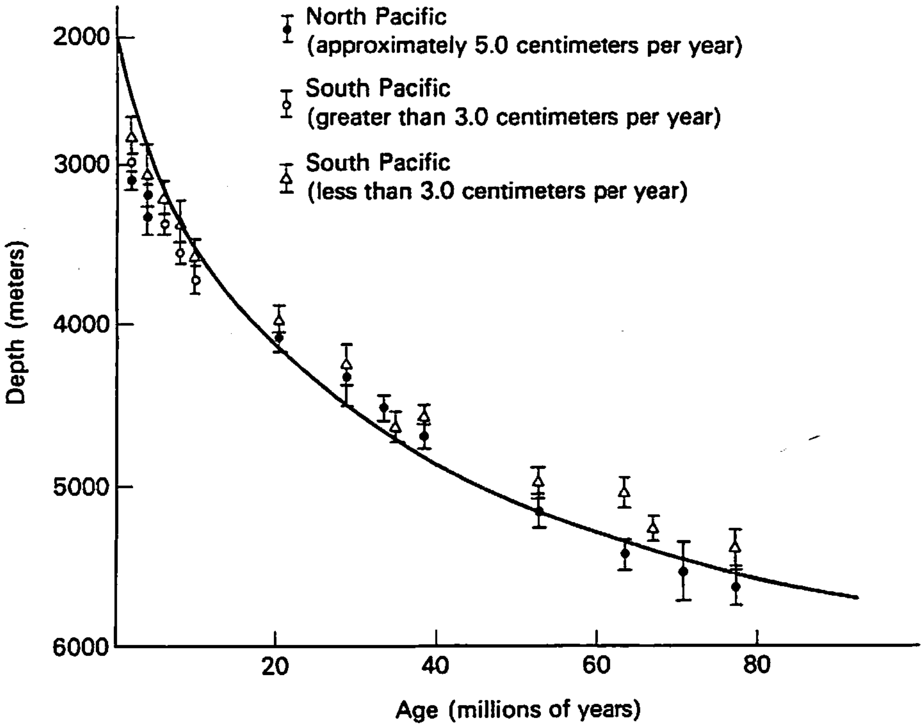


FIGURE 4-12
The average depth in the north and south Pacific plotted against the age of the oceanic crust. The symbols represent the various spreading rates indicated in the figure. The theoretical profile represented by the curve (proposed by Sclater and Francheteau) is for a lithosphere 100 kilometers thick. [After J. G. Sclater et al., "Elevation of Ridges and Elevation of the Central Eastern Pacific." *J. Geophys. Res.* *76*, p. 7888, 1971. Copyrighted by American Geophysical Union.]

one must employ techniques that have a resolving power much higher than is available in usual surface ship observation. A cooperative investigation by the United States and France—the FAMOUS Project (French American Mid-Ocean Undersea Study)—has been conducted recently in the crestal zone of the north Mid-Atlantic Ridge. Large numbers of research vessels and submersibles were employed in this joint goal of revealing what is actually happening at ocean ridge crests. Detailed heat-flow and magnetic measurements, rock samples, and high resolution photographs were obtained at the ridge crest itself and at nearby fracture zones. These showed that the process of spreading is much more complicated than previous observations from surface ships had led us to believe. In fact, in many places, the ridge was found to spread much faster on one side than on the other, and even at large angles to its axis.

The Mesozoic Magnetic Stripes in the North Pacific

Ever since the well developed magnetic lineations in the northwestern corner of the Pacific off Japan and the Kuriles were discovered (see Figure 3-15), I had been attempting to correlate them with similar magnetic lineations in the eastern Pacific. At first it was thought that the lineations off Japan, being in the area farthest from the East Pacific Rise, might be those of the oldest crust produced by the Rise, and that this crust had migrated across the entire Pacific to be consumed in the Japan-Kurile trenches. But meanwhile scientists had discovered the Great Magnetic Bight (Figure 3-10) in the Gulf of Alaska and traced the datable Cenozoic anomaly lineations as far west as the eastern side of the Emperor Seamounts. Furthermore, the ages of the lineations in that area were believed to be younger toward the north—just the opposite of the order one would expect if the Japanese lineations were formed by the East Pacific Rise. The Japanese anomaly profiles did not correlate with those east of the Emperor Seamounts either. This discrepancy remained an enigma.

Early in 1972, when I was visiting the Lamont-Doherty Geological Observatory, I met R. Larson just as he was on the point of discovering a possible solution to the enigma. The prospect was most exciting to me because the problem had been on my mind for years. At that time, he and C. Chase had data that showed the existence of three sets of unidentified magnetic lineations, the Japanese, the Hawaiian, and the Phoenix, all in the Pacific (Figure 4-13). The crust of the Pacific Basin had been magnetically dated (see the shaded areas in Figure 3-10) back for a period of about 76 million years by the so-called Cenozoic magnetic isochrons. But beyond that there were no magnetic lineations! This vast area with no magnetic signature is called the magnetic quiet zone. The situation was the same in the Atlantic Ocean.

As discussed in Chapter 3, several explanations of the quiet zone had been proposed. Indeed, under such circumstances, theories vary greatly, depending on the philosophy of the scientist. Some scientists suspected that the lack of magnetic lineations indicated that the sea floor had been produced by a mechanism other than sea-floor spreading, and that the sea-floor spreading hypothesis itself did not apply to earlier periods of geological history. Others believed that the older sea floor had been produced by the sea-floor spreading mechanism, but that its magnetic lineations had subsequently been erased. The simplest theory was one that maintained that no reversals in the

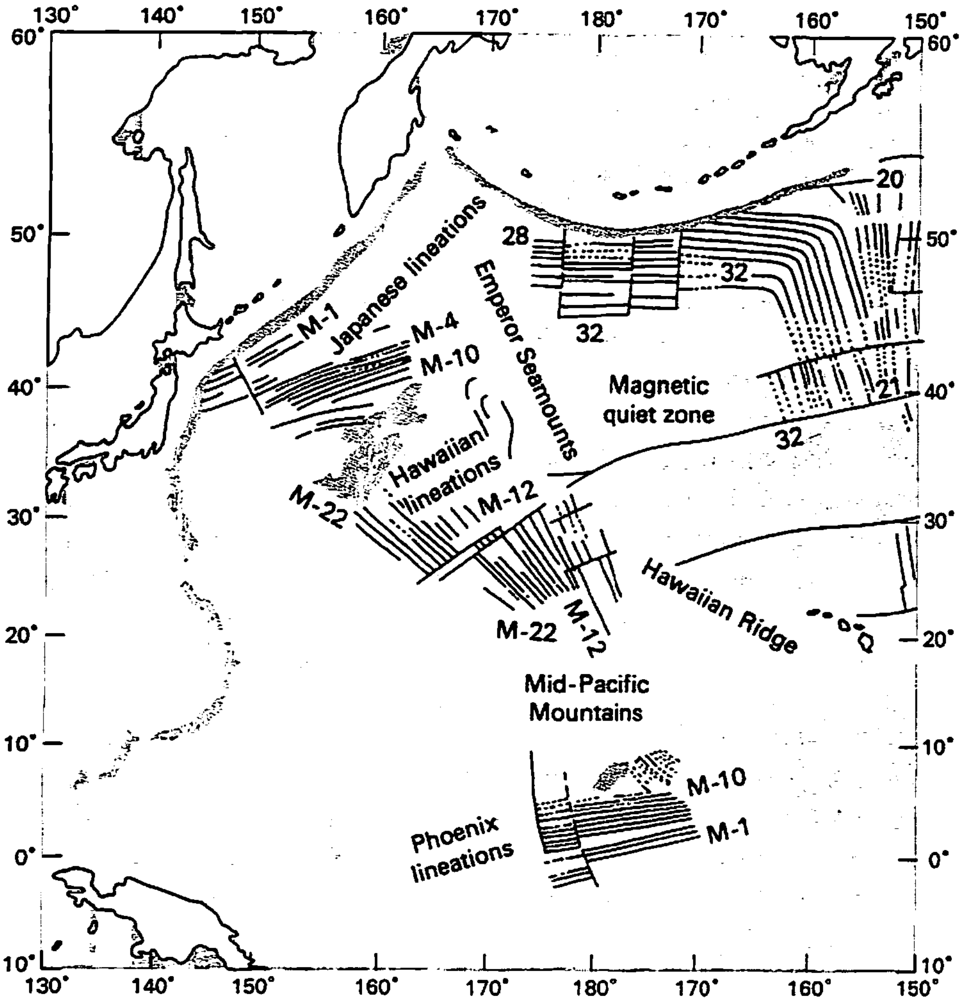


FIGURE 4-13
Mesozoic and Cenozoic magnetic lineations in the northwest Pacific. The Mesozoic lineations are designated by M, with M-1 being the youngest. Numbers without M are anomaly numbers for Cenozoic lineations (like those given for the lineations in Figure 3-8). [After R. L. Larson and C. G. Chase, "Late Mesozoic Evolution of the Western Pacific Ocean." *GSA Bull.* 83, p. 3627, 1972.]

earth's magnetic field had taken place during the period in which that particular portion of the sea floor was produced. While speculation continued, a detailed picture of the three sets of unidentified lineations began to emerge from the Pacific areas, which were even farther away from the ridge than the magnetic quiet zone.

Larson and Chase (1972) had confirmed that these three western Pacific sets of lineations were indeed isochrons, and that they were formed at the same period as a set of lineations in the western Atlantic outside the magnetic quiet zone. These Atlantic lineations, discovered by P. Vogt, are called the Keathly set. What was more remarkable was that Larson and Chase, using the information from the Deep Sea Drilling Project, were able to determine the age of these lineations to be 110–150 million years old—back in the Mesozoic era. The lineations were named M-1, M-2, M-3, and so on, with M standing for Mesozoic and M-1 being the youngest (Figure 4-13). This work of Larson and Chase was an important breakthrough and their conclusions are fully incorporated in the compilations of the age of the ocean basin (Figures 3-10 and 3-14).

Thus the history of sea-floor spreading was traced back as far as the Mesozoic era, and a clue to the enigma of the north Pacific was found, although minute details are still unknown. At the same time, the history of the earth's magnetic field reversals was extended back from 76 million years to 150 million years—almost double the length of time. Compare Figure 4-14 with Figure 3-9. Figure 4-14 shows the long epoch of normal polarity between 85 million and 110 million years ago, which produced the Cretaceous quiet zone. It may be noticed that there is another long epoch of polarity in the Upper Jurassic, older than 148 million years. This corresponds to the very oldest part of the oceans and is called the Jurassic quiet zone. Also because the absence of geomagnetic reversals during these periods was known from earlier paleomagnetic studies of rocks found on land, the two lines of paleomagnetic research fit together beautifully.

The Northward Movement of the Pacific Plate

Synthesizing all of the information discussed above, we come to the conclusion that sea-floor spreading has been going on since at least the time of formation of the oldest existing sea floor; it created first the Jurassic quiet zone, the Mesozoic sequence, then the Cretaceous quiet zone, and then the so-called Cenozoic magnetic sequence beginning with "anomaly 32" (see Figures 4-13 and 3-10).

The method Larson and Chase used to identify lineations that were far away from one another was a highly sophisticated technique developed by a Dutch scientist, H. Shouten. This method enables us to estimate even the magnetic latitude that a particular portion of the sea floor or the oceanic ridge possessed when that portion of sea floor was generated. This might imply that, by studying the magnetic lineations, paleomagnetism of the sea floor is possible. If we accept the postulate that the position of the geomagnetic pole, when averaged over a period of 10,000 years or so, coincides with the earth's

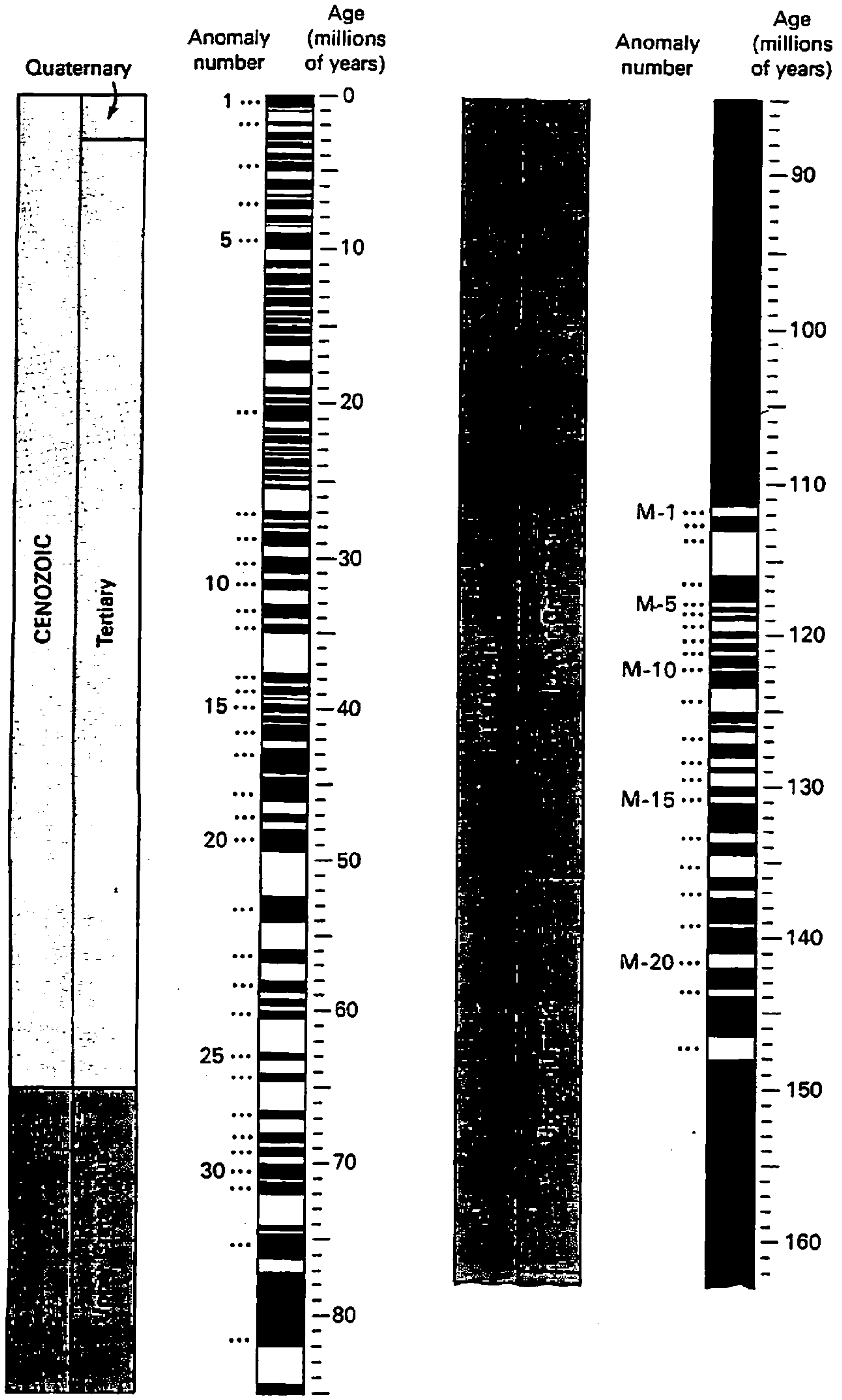


FIGURE 4-14
Geomagnetic reversal time scale from the present to the beginning of the Upper Jurassic (162 million years ago). [After R. L. Larson and W. C. Pitman, "Worldwide Correlation of Mesozoic Magnetic Anomalies and Its Implications." *GSA Bull.* 83, p. 3645, 1972.]

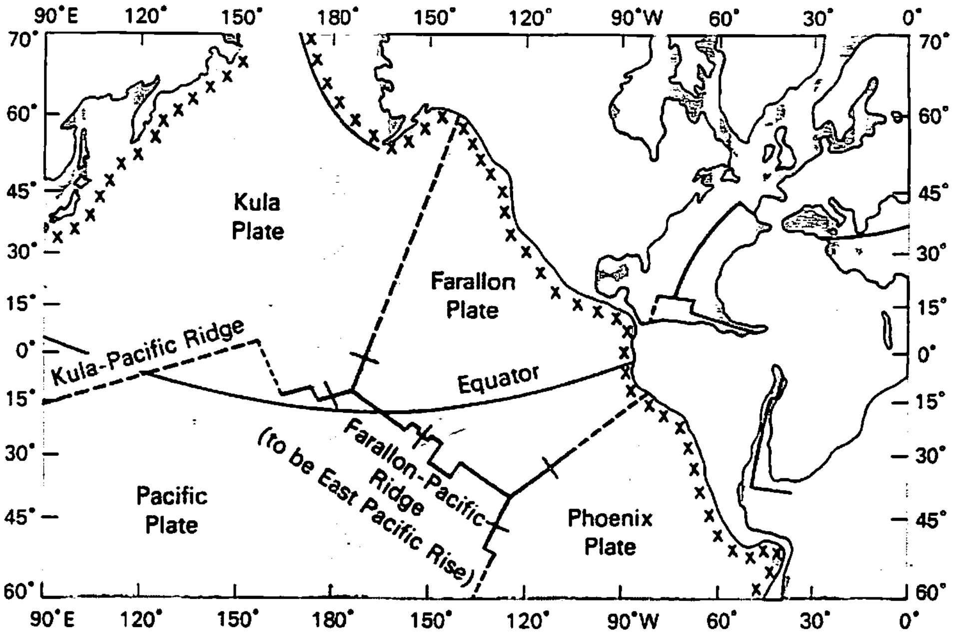


FIGURE 4-15
A possible plate configuration of the Pacific Ocean 110 million years ago. The crosses represent the subduction zones. [After R. L. Larson and W. C. Pitman, "Worldwide Correlation of Mesozoic Magnetic Anomalies and Its Implications." *GSA Bull.* 83, p. 3645, 1972.]

rotational pole, then in principle we should be able to use paleomagnetism to determine the drift of oceanic plates, just as it was used to prove and measure continental drift. R. Larson and W. Pitman (1972) demonstrated the possible condition of the Pacific Ocean approximately 110 million years ago in Figure 4-15. According to their description, there were at least four plates, five oceanic ridges, and two R-R-R type triple junctions in the Pacific during that period. The Pacific Plate has been migrating to the north ever since, traveling 6000 kilometers or more and taking with it the oceanic ridges from which the sea floor continued to spread. The Farallon Plate was descending beneath the west coast of North America and the Kula Plate* was descending beneath the Aleutians at the same time that it was sinking beneath the Japan and Kurile Trenches. At present, both the Kula Plate and the Kula-Pacific Ridge have disappeared whereas the Pacific Plate, to the south of the Kula-Pacific Ridge, is in the process of underthrusting.

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*The name *Kula* was proposed by J. A. Grow and T. Atwater in their paper on the Aleutian Arc (1970), Kula meaning "all gone" in an Athabaskan Indian dialect.

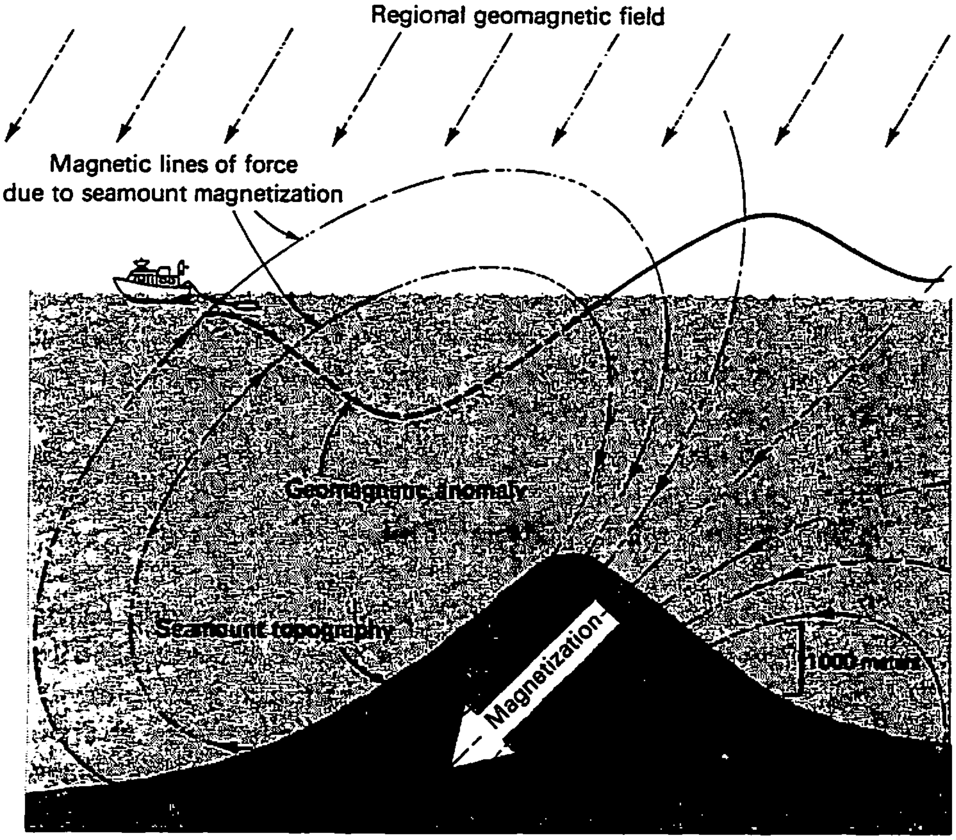

FIGURE 4-16
Schematic illustration of a magnetic cross section of a seamount. The geomagnetic anomaly field produced by the magnetization of the seamount is represented by the magnetic lines of force. The anomaly field is positive (solid curve) when it tends to enhance the regional field at the sea surface, and negative (broken curve) when it tends to cancel the regional field. Although only one cross section is shown here, profiles of cross sections are used for computation.

V. Vacquier, I, and others have long been working on the paleomagnetism of the sea floor from a different approach. Many of the innumerable seamounts that exist on the sea floor originated as undersea volcanoes and are strongly magnetized. If we can determine the direction and intensity of that magnetization, we should be able to use such information in the same way we use paleomagnetism in rocks on land. Yet, because seamounts lie thousands of meters deep on the sea floor, it is practically impossible to gather oriented samples. Therefore, we sailed crisscross over the seamounts, surveying the topography of the sea floor in great detail as well as the geomagnetic anomalies caused by the seamounts. The results of this survey enabled us to determine by computer the direction and intensity of magnetization of the seamounts (Figure 4-16). By 1964 we had estimated, on the basis of this research, that the seamounts scattered in the Pacific off the coast of Japan—which are considered to be Cretaceous in age—have migrated northward since their birth, spanning a distance of more than 6000 kilometers. This was fully supported by Larson and Chase's research, which they undertook in 1972, utilizing an entirely different method. We congratulated each other on the agreement of our results.

Since the Mesozoic era, nearly 10,000 kilometers of oceanic plate along with oceanic ridges seems to have descended beneath Japan. This is an important factor in the history of the Japanese island arc, as we shall see in the next chapter.

A Possible Cause of Marine Transgression

We have already discussed how the rate of sea-floor spreading can be deduced from the width and the age of the magnetic lineations. Therefore, if we consider the Cretaceous magnetic quiet zone as an extremely wide stripe, the average spreading rate of the sea floor when such a magnetic quiet zone was being produced can also be inferred. Larson and Pitman did just that, and came up with an estimated spreading rate during this period—between 110 and 85 million years ago—which was about three times greater than that of other ages. They called it a *pulse* of sea-floor spreading and maintained that both sea-floor spreading and the subduction of oceanic plates into the trenches during this period was particularly intensive. They further suggested that this could have been the cause of mountain-building activity during that period, which was also believed to have been extensive.

Taking this idea a step fruther, in 1971 O. Hallam of England presented the theory that great marine transgressions could be attributed to pulses of rapid sea-floor spreading. Throughout the geological ages, there have been periods in which the land was deeply invaded by sea water. This phenomenon is called *transgression*. The opposite phenomenon in which the sea water retreats is called *regression*. These phenomena were well known in geology, but their cause has remained a mystery. We have discussed the condition of a newborn plate produced by sea-floor spreading: hot and elevated, it gradually cools down and shrinks, and the water above it gets deeper. If, during a pulse period, plates were produced several times faster than in normal periods, however, the sea floor would be generally more elevated because of the existence of wider areas of young hot plate that had not yet cooled off or shrunk. This would make the oceans of the world much shallower. Just as water would spill over the rim of a bowl if the bottom were raised, sea water would overflow and invade deeply into the land, causing transgression. When the pulse period was over, the sea water would retreat and regression occur. In 1973 J. Hays and W. Pitman applied Hallam's idea in a most ingenious way: they correlated a well known transgression that took place during the Cretaceous period with the rapid pulse in sea-floor spreading inferred from the magnetic lineations.

Such challenging attempts to elucidate geological riddles are truly exciting to observe; but not all scientists believe in ideas such as the pulse of sea-floor spreading. The skeptics question the validity of the spreading rates deduced from the widths of magnetic stripes, especially in the quiet zone. The width of the stripe may be measured accurately, but the times at which it started and ended are not yet quite established. This topic will be one of great interest in the immediate future of plate tectonics.

Plate Tectonics and Orogenesis

By 1969, the concept of plate tectonics had already challenged the most basic problem of geology, namely orogenesis. Acceptance of plate tectonics would be much greater today if applied solely to activities that are presently taking place on the earth, or to a geometrical description of the sea-floor spreading process that has occurred in the past 80 million or even 150 million years—a reasonably easy period to trace. However, its application to geological activities of the earlier pre-Mesozoic period is considered by a number of geologists to be capricious at best. Two young geologists, John Dewey and John Bird, are the champions of its application to earlier periods. They are endeavoring to investigate the outermost limits of the implications inherent in plate tectonics, and maintain that the process of plate tectonics has been taking place for at least the past billion years of the earth's history. The theory of continental drift maintains that at one time the Atlantic did not exist. Dewey and Bird (1970) extended the possible course of events even further back in history and suggested that there was once an ocean that might be called the Proto Atlantic. In fact, such an idea had been previously raised by J. Tuzo Wilson and others.

If we believe the downthrusting of an oceanic plate into a trench is the origin of orogeny, and we then try to explain all of the Paleozoic orogenic zones—such as the Appalachians of North America and the Caledonian Mountains (which lie across Scotland and Scandinavia) in Europe—we need an ocean floor to be underthrust! So orogenic zones along which underthrusting has occurred are interpreted as evidence for the earlier existence of oceans. Looking for clues like this, Dewey, Bird, and their predecessors have thoroughly studied the results of the vast amount of precise geological research that has been done on the North Atlantic region, including Newfoundland, Greenland and Canada—data representing many years of scientific endeavor. They have concluded that the Atlantic must have once been open before it closed, and that subduction of the ocean floor took place at the trenches of the Proto Atlantic. This subduction was similar to what is happening today in the Pacific margin, causing deep earthquakes, igneous activity, metamorphism, and so forth. These activities created the Caledonian-Appalachian Mountain belt. The continued consumption of the oceanic plate of the Proto Atlantic finally caused the closure of the ocean to form part of Pangaea. Collision of the continents perhaps culminated in the formation of soaring mountain belts. Afterwards, when Pangaea started to break up again, the present Atlantic was created. When the new ocean reopened, however, the coastlines along it were not identical to that of the original Proto Atlantic. Instead the ancient orogenic belt on either side of the Proto-Atlantic was divided into complicated fragments. Dewey further presented a simple but daring model for orogenic cycles, arguing that since the surface dimension of the earth is constant, if one ocean, the Pacific for example, expands, the other, the Atlantic, will shrink. If the Atlantic expands, as it is doing at present, the dimension of the Pacific will decrease. Based on this hypothesis, an explanation of the long history of repeated orogenic cycles has been attempted in the manner demonstrated in Figure 4-17.

According to this idea, there are three types of oceans—the Atlantic, the Pacific, and the Mediterranean types. Both the Atlantic and the Pacific types are spreading at the ridges, but one is expanding and the other is contracting. The difference between them lies in the fact that subduction of the oceanic plate is going on in the Pacific type at the continental margin, whereas no subduction is taking place in the Atlantic type. The Mediterranean type is contracting and *not* spreading (Figure 4-17c and f). It has a subducting boundary but no ridge.

In this model, continental margins are classified into two types—the Atlantic type and the Pacific type—depending on whether sub-

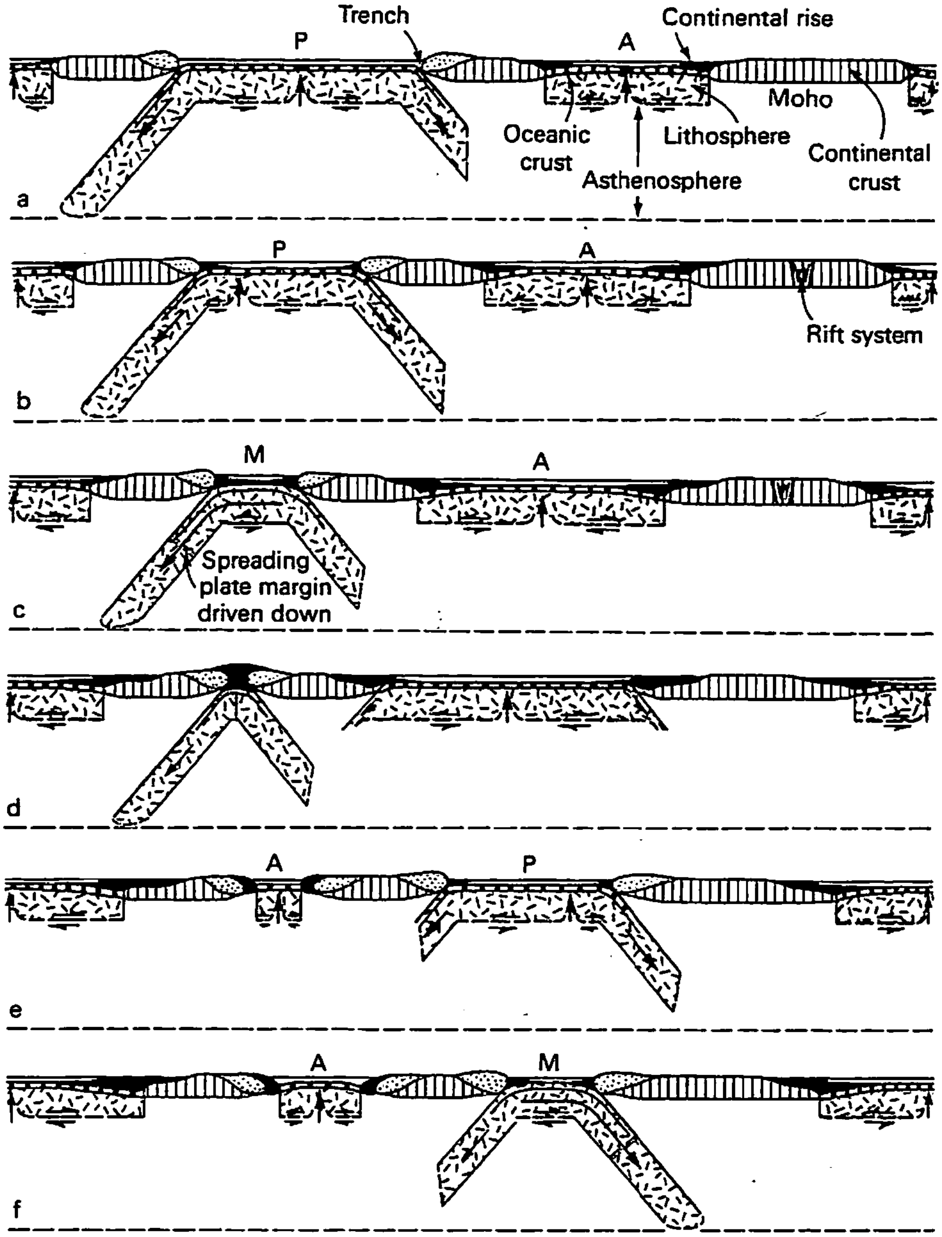

FIGURE 4-17
Schematic sections along a great circle of the globe showing the sequential development of the three main phases of ocean development: the Pacific type (P); the Atlantic type (A); the Mediterranean type (M). Parts (a), (b), and (c) show the spreading-expanding process that generates the A type phase in the ocean at the right. Simultaneously the ocean at the left, is undergoing the process of spreading-contracting—the P type phase, part (b)—and that of nonspreading-contracting—the M type phase, part (c). In (d) the ocean at the left has been closed, so that the expanding of the Atlantic phase at the right has to stop. In (e) the P type phase at the right and the A type phase at the left have started. If the ridge subducts (f), the ocean at the right becomes M type. [After J. F. Dewey, "Continental Margins: A Model for Conversion of Atlantic Type to Andean Type." *Earth Planet. Sci. Letters* 5, p. 189, 1969.]

duction is occurring or not. The processes that are taking place in each type of continental margin are vastly different. In the Atlantic type, the sea is slowly subsiding as the plate cools and receives sediments from the continent, whereas in the Pacific type, all sorts of active orogenic events such as earthquakes and volcanic eruptions are occurring. For these reasons, the two types of continental margins are also classified as *passive* or *active* margins.

Dewey contended that once the process of oceanic development had gone through stages A to F in Figure 4-17 it began again. Thus oceans would evolve from the Atlantic type to the Pacific type and possibly through the Mediterranean type during any one orogenic cycle.

Even though Dewey and Bird are geologists themselves, their hypotheses are in direct opposition to traditional geological theories. Often a geologist instinctively avoids a simple generalization because he knows his area of specialization in such great detail that it is usually very easy for him to point out examples that cannot be explained by someone else's idealized theory. For this reason, Dewey and Bird's idea has not been well received by some geologists. Although it has not yet been verified as a scientific fact, it would seem worthwhile for geologists to try to find out whether this generalization is on the right track. To a geophysicist like me, the idea is fascinating. But the physical or chemical validity of a working hypothesis such as this can be verified only after the hypothesis itself has been clearly formulated. It will be difficult to examine the hypothesis from a theoretical point of view if it is expressed in a way that is vague, confused, or overly complex. Once the cause and effect of the phenomena are logically and clearly formulated, however, it becomes possible to examine its mechanism from a physical or mathematical point of view. Dewey and Bird have used their geological observations to suggest how events might have happened. But the problem of *why* things happened that way still seems to require further basic investigation. Why, for example, do igneous activity and metamorphism always occur when the cold oceanic plate subducts?