GP60/EE60

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Handout #4

CHAPTER 20

GLOBAL PLATE TECTONICS: THE UNIFYING MODEL

Geologists have rejected the picture of a rigid Earth with fixed continents and ocean basins. Most now believe that the Earth's lithosphere is broken into about a dozen plates, which for reasons not fully understood move over the interior. Plates are created along the crests of mid-ocean ridges and are pushed down into the mantle near deep-sea trenches. Continents, embedded in the lithosphere, drift along with the moving plates. Plate tectonics gives new life to the old ideas of continental drift and explains the distribution of many large-scale geologic features and zones of activity—narrow belts of mountains, mid-ocean ridges, deep-sea trenches, volcanic and seismic activity—in terms of their association with plate margins.

Just a few years after the proposal of plate-tectonics theory, on the occasion of an international geophysical meeting in Moscow, an interesting exchange took place between two western participants—a younger man who had achieved prominence because of his work on plate tectonics and a well-known older scientist. The setting was a party in the apartment of a Soviet geophysicist, and the conversation was well lubricated by vodka. The din of cocktail party chatter stopped suddenly when the younger man called out to his older colleague, "Dr. ———, everyone tells me how brilliant you were in your younger days. If that's the case, why didn't you discover sea-floor spreading and plate tectonics twenty years ago?" The explosive response of the older man needn't be recorded, but the question, properly generalized, is indeed thought-provoking. Why did this concept, which unifies so much of geological thought, "arrive" so late in the history of the subject?

Actually, a key element of the concept—large-scale displacement of continents—had been around for a long time. The jigsaw-puzzle fit of the coasts on both sides of the Atlantic had not escaped the notice of early natural philosophers. Francis Bacon remarked on the parallelism of the facing shores of the Atlantic in 1620. As early as 1858 Antonio Snider published maps in France depicting continental drift. At the close of the nineteenth century, the Austrian geologist Eduard Suess put some of the pieces of the puzzle together and postulated the former existence of a single giant continent—Gondwanaland, made up of the combined present-day southern continents. Early in this century, Alfred Wegener, a German meteorologist, cited as further evidence of continental drift the remarkable similarity of rocks, geologic structures, and fossils on opposite sides of the Atlantic. In the years following, Wegener continued to build the case for continental drift; he postulated that a supercontinent called Pangaea, once made up of all the present continents, began to break up some 200 million years ago, with ocean filling the widening gaps (see Figure 1-14).

Although the theory received serious attention for about a decade, "continental drift" never caught on except among some geologists in Europe and South Africa. Although they could point not only to geographic matching but also to geological similarities in rock ages and structural trends, the proponents could not come up with a plausible driving force. Drift advocates buttressed their speculation with special pleading, selecting evidence patently favorable to their views, evidence that was far from incontrovertible. But there were significant arguments—accepted now as good evidence of drift—based on fossil and climatological data. The evolution of vertebrates and land plants showed similarities in development on different continents up to the supposed breakup time; thereafter these organisms showed divergent evolutionary paths. The distribution of Permian glacial deposits in South America, Africa, India, and Australia was difficult to explain in terms of separate glaciers, some close to the equator. Drift advocates noted that if the southern continents are reassembled into Gondwanaland in the South-Polar region, a single continental glacier could account for all the glacial deposits. "It has always happened that after several distinguished palaeontologists have presented evidence favourable to continental drift, some other equally distinguished ones have proceeded to point out other facts that are made more difficult to explain"—so argued Sir Harold Jeffreys in his influential book *The Earth* (1929). Geology and paleontology were not enough. Independent, diverse, corroborative evidence from geophysics would be needed to persuade the scientific establishment to abandon prevailing ideas and elevate an unorthodox speculation to the level of a generally accepted theory.

In 1928, Arthur Holmes invoked the mechanism of thermal convection in the mantle as the driving force. Holmes proposed that subcrustal convection currents "dragged the two halves of the original continent apart, with consequent mountain building in the front where the currents are descending, and the ocean floor development on the site of the gap, where the currents are ascending." Holmes came close to expressing the modern notions of plates, divergence, and subduction when he speculated that a subcrustal basaltic layer serves as a conveyor belt that carries a continent along to the place where the belt turns downward into the mantle, leaving the continent resting on top. Nevertheless, Holmes himself recognized the tenuous nature of his views. He wrote that "purely speculative ideas of this kind, specially invented to match the requirements, can have no scientific value until they acquire support from independent evidence."

Convincing evidence began to emerge as a result of extensive exploration of the sea floor during the years following World War II. In particular, the mapping of the mid-Atlantic ridge and the discovery of the deep, cracklike valley, or rift, running down its center line sparked much speculation. In the early 1960s Harry Hess of Princeton University suggested that sea floors separate along the rifts in mid-ocean ridges and that new sea floor forms by upwelling of mantle materials in these cracks, followed by lateral spreading (see Figure 16-37). Vine and Mathews' work showed how the oceanic magnetic patterns (see Chapter 19) could be explained by Hess's concept. Thus was born the theory of sea-floor spreading. Within a few years abundant confirmation was available from the study of such diverse evidence as that provided by worldwide magnetic anomaly surveys, the observation of earthquake mechanisms, the measurement of heat flow, and the determination of the thickness and age of the sedimentary layers of the sea floor.

It remained for the next generation of geophysicists to broaden the concept of continental drift and sea-floor spreading into the more general theory of plate tectonics. Beginning about 1967, they extended the idea of Hess and Canadian geophysicist J. T. Wilson about the mobility of the lithosphere by identifying the separate lithospheric plates and discussing their relative motions and the phenomena that occur at their boundaries. By the end of the 1960s the evidence became so persuasive that most Earth scientists, except for a few prominent holdouts, embraced these concepts. Textbooks were revised, and specialists began to think of the implications that the new discoveries held for their own fields.

Let us return to the question of why these new concepts became generally accepted so late in the history of geology. There are different styles among scientists. Some scientists—those with particularly inquiring, uninhibited, and synthesizing minds—perceive great truths before others. Although their perceptions may turn out to be false, these individuals are often the first to see the great generalizations of science. Most scientists, however, proceed more cautiously and wait out the slow process of gathering supporting evidence. The concepts of continental drift and sea-floor spreading were slow to be accepted simply because the audacious ideas came so far ahead of the firm evidence. The oceans had to be explored, a new worldwide network of seismographs had to be installed and used, the magnetic stratigraphy had to be painstakingly worked out, and the deep sea had to be drilled before the majority could be convinced. In a well-known European laboratory, a list was compiled (in good humor) of the names of Earth scientists in the order of the date of their acceptance of sea-floor spreading as a confirmed phenomenon. The names of scientists of distinction appear at both the top and the bottom of the list.

Plate Tectonics: A Review and Summary

Plate tectonics is the conceptual framework of this book, and we have already introduced the basic ideas in earlier chapters. In this chapter we draw together and review the diverse lines of evidence that support the theory of plate tectonics, using primarily illustrations you have already seen in earlier chapters. We will begin with a discussion of rock associations and orogeny within the framework of plate tectonics. The fragmentation of Pangaea since the Jurassic will be reviewed, together with some speculation about continental drift and extinct plates in the pre-Jurassic. The chapter will close with some brief remarks on the driving mechanism of plate tectonics, but you shouldn't expect more than vague speculations, for the subject is just beginning to receive serious study.

THE MOSAIC OF PLATES

According to the theory of plate tectonics, the lithosphere is broken into a dozen or so rigid plates whose outlines are shown on the map inside the back cover. The plates slide over a partially molten, plastic asthenosphere in the general directions shown. Plate tectonics works on Earth because of the rigidity of the lithosphere, which enables plates with horizontal dimensions of thousands of kilometers to move as distinct mechanical units. According to the relative motions of adjacent plates, we can define three kinds of plate boundaries: (1) boundaries of divergence or spreading, typically ocean ridges; (2) fracture zones, or transform faults; and (3) boundaries of convergence (see Figure 18-13).

Boundaries of divergence are zones along which plates separate. In the process of plate separation, partially molten mantle material upwells along linear ocean ridges, and new lithosphere is created along the trailing edges of the diverging plates. Such boundaries are characterized by active basaltic volcanism, shallow-focus earthquakes caused by tensile (stretching) stresses, and high rates of heat flow. The outpouring of magma along ocean ridges and the building of the oceanic lithosphere are volumetrically the most significant form of volcanism. Figures 1-13, 1-17, 14-8, 14-11, 16-19, and 16-37 emphasize the different aspects of divergence zones.

Typically transform faults are boundaries along which plates slide past one another, with neither creation nor destruction of lithosphere. Sometimes marked by scarps, transform faults are characterized by shallow-focus earthquakes with horizontal slips. Occasionally there occur "leaky" transforms, in which some volcanism and slight plate separation accompanies the transform. Examples are in Figures 1-17, 18-13, and 19-17.

Boundaries of convergence are zones along which the leading edge of one plate overrides another, the overridden plate being subducted, or thrust into the mantle, where lithosphere is resorbed. The thrusting mechanisms that operate along these collision boundaries tend to produce volcanic island arcs (Figure 20-1), deep-sea trenches, shallow- and deep-focus earthquakes, adjacent mountain ranges of folded and faulted rocks, and both basaltic and andesitic volcanism. Here again the rigidity and strength of the lithosphere is an important aspect of its large-scale sinking and recycling at deep-sea trenches. The weight of the sinking plate may pull the entire plate down and thus serve as an important part of the driving

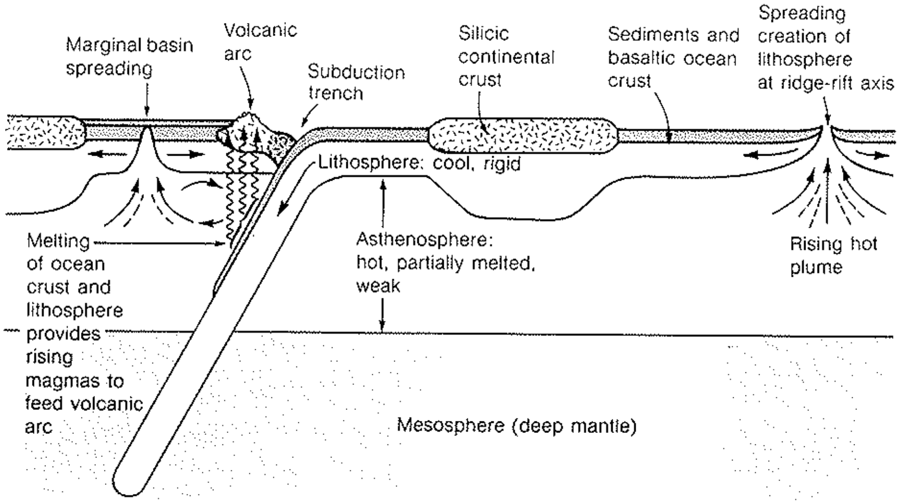

Figure 20-1

Cross section of the upper mantle. The lithosphere is a rigid plate of solidified rock that rides on the partially molten asthenosphere. It is approximately 70 km (40 miles) thick under oceans and perhaps 100–150 km thick under continents. The continent is embedded in the plate and moves along with it. The lithosphere forms at mid-ocean ridges from a rising plume of partially molten rock; it sinks back into the mantle in subduction zones, where it remelts. Arrows in the plastic asthenosphere indicate directions of possible convective motions. Secondary convection currents may form small spreading centers in a marginal basin. The Sea of Japan, for example, formed in this way. Located behind an island arc volcanic chain, it separates the chain from a continent.

mechanism of plate tectonics. Convergence boundaries are illustrated in Figures 1-16, 14-8, 14-11, 16-37, and 20-1.

Each plate is bounded by some combination of these three kinds of boundaries, as can be seen on the inside of the back cover. For example, the Nazca plate in the Pacific is bounded on three sides by zones of divergence, along which new lithosphere forms, and on one side by the Peru–Chile trench, where lithosphere is consumed. Continental margins may or may not coincide with plate boundaries. If they do, the continents tend to remain "afloat" because continental plates are thicker and too buoyant to be readily subducted. Where two plates with continents at their leading edges converge, the crust thickens to form great mountain ranges like the Himalayas.

The global sum of plate creation and consumption is approximately zero. The Earth would otherwise change size in order to accomodate the new sea floor, and this doesn't seem to be happening. Instead, the plates form and disappear and change in size and shape as they evolve.

THE STRUCTURE AND EVOLUTION OF PLATES

Figure 20-1 depicts some of the structural details of a rigid lithospheric slab, a plate, from its region of generation at a ridge axis to its region of subduction, where it is resorbed. Both oceanic and continental crust cap the plate; the continent, embedded in the moving plate, is carried along passively by it. Thus, in a real sense, continental drift is simply a consequence of plate movements. Underneath is the plastic, partially molten asthenosphere—source of the raw materials that build new lithosphere. Once heated and partially melted, subducted lithosphere becomes a source of magma, which rises to feed the overlying volcanic chain. A generalized heat-flow profile (see Figure 14-8) shows a large amount of heat emerging along the ridge axis, less from the older, cooled slab, and more from the volcanic chain of the subduction zone and the marginal basin behind it, where a small region of secondary spreading occurs.

Geophysicists have made theoretical studies and computer models of the evolution of a plate, from its creation out of hot rising matter at ocean ridges through its spreading and cooling phase to its subduction, with reheating, melting, and final resorption in the underlying mantle. The models help explain some important geological and geophysical observations: the major features of the ocean floors, the variation of heat flow from the sea floor, the occurence of volcanism at plate margins, and the location and mechanism of earthquakes in the subducted slab.

Ocean depths increase with age, t, of the sea floor in a remarkably simple manner (Figure 20-2). For the first 80 million years the data fit a curve in which ocean depth increases as $\sqrt{t}$. This is precisely the relationship predicted if a plate cools and contracts as it spreads. Beyond 80 million years ocean depths tend to flatten out, compared to the theoretical cooling curve, as would be expected if a small amount of heat is flowing into the plate from the underlying hot asthenosphere. The deepening of the sea floor with age is one of the most important lines of evidence in support of the concept of sea-floor spreading.

When a cold plate is subducted, it remains cooler than the surrounding hot mantle for about 12 million years, only gradually warming as it penetrates more deeply. Slow-moving plates heat up and are assimilated at shallower depths, perhaps 400 km (250 miles), than fast-moving plates, which can penetrate to about 700 km before heating to the point of assimilation. The process of subduction involves very large forces, and in a general way these forces must be responsible for the deep-focus earthquakes that occur only in downgoing plates (see Chapter 18). The sudden failures associated with earthquakes take place until the plates become so warm that stress is relieved by slow plastic deformation rather than by faulting. This seems to be the likely explanation for the fact that no earthquakes occur below 700 km (Figure 20-3).

RATES OF PLATE MOTION

The velocities of moving plates are measured by dating ocean-floor magnetic anomalies (using the time scale of magnetic stratigraphy) and dividing the age of each anomaly into the distance between it and the ridge axis. The procedure was outlined graphically in Chapter 19 (see Figures 19-17, 19-18, and 19-21).

The worldwide pattern of sea-floor spreading is being worked out by using a combination of magnetic, seismic, and bathymetric data. The charts used earlier (see Figure 19-21 and inside the back cover) map the world's zones of spreading, subduction, and fracture; their geographic locations were obtained from the positions of ocean ridges, deep-sea trenches, earthquake epicenters, and other indications of activity. On the basis of spreading rates determined from magnetic data, isochrons (contours that connect points of the same age) were drawn to show the age of the sea floor in millions of

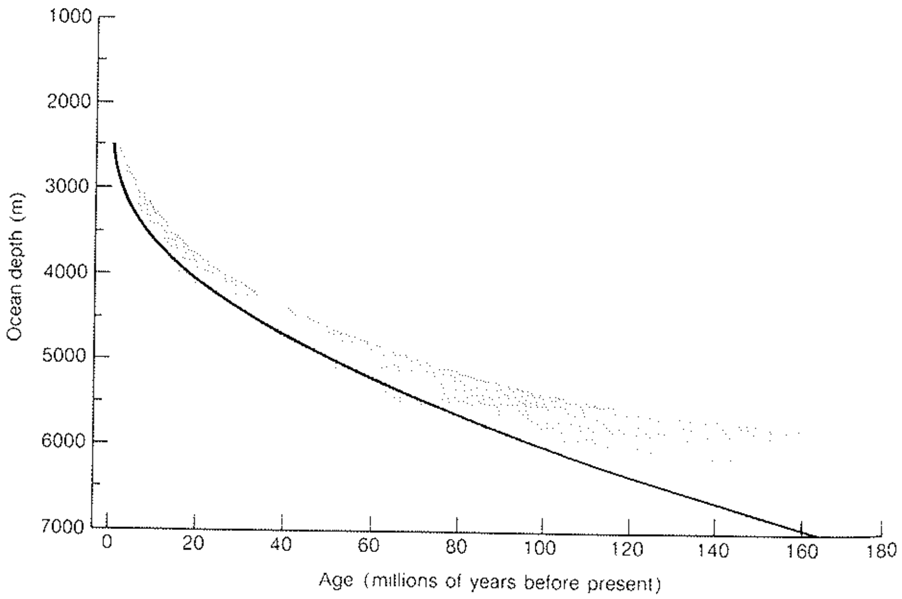

Figure 20-2

Mean ocean depths for the Atlantic and Pacific oceans plotted as a function of the age of the sea floor are shown by the brown band. The theoretical curve (black) assumes the depth is proportional to the square root of age. [After B. Parsons and J. G. Sclater.]

years. The distance from a ridge axis to a 50-million-year isochron, for example, indicates the extent of new ocean floor created in that period. In Figure 19-21, note the closer spacing of the isochrons in the Atlantic than in the Pacific, where the spreading rate is higher. Because the fracture zones offset the isochrons, the age of the sea floor changes abruptly across a fault. A summary of the rates and directions of plate motions, measured in centimeters per year relative velocity, is given in Figure 20-4. The fast-moving plates (Pacific, Nazca, Cocos, and Indian) have the common fea-

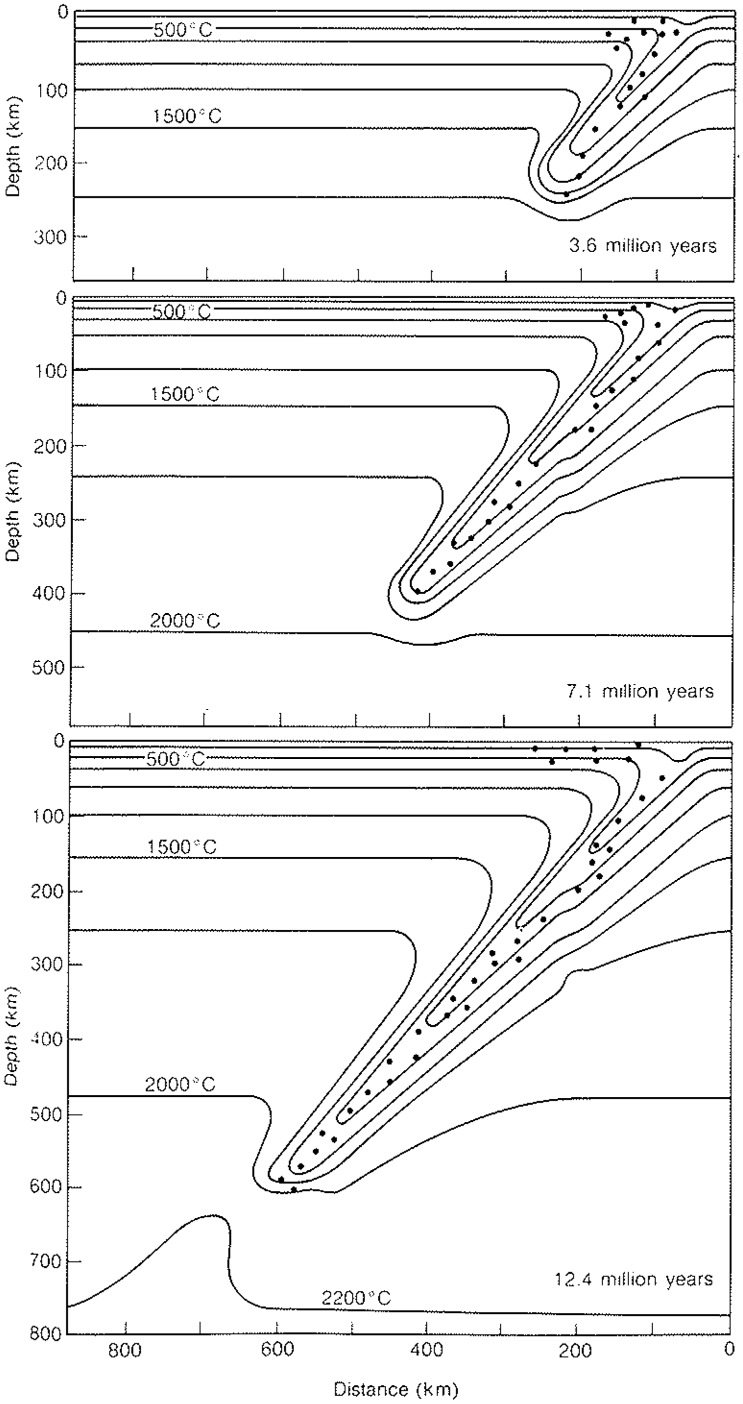

Figure 20-3

The evolution of descending slabs is described by computer models made by M. N. Toksöz. These diagrams depict the fate of a plate subducted at a rate of 8 cm/year. Contours show computed temperatures in plate and adjacent mantle. Note that temperatures in the plate are several hundred degrees cooler than those in the adjacent mantle. After 12 million years, the plate reaches the temperature of the surrounding mantle at a depth of 600–700 km and loses its original identity. At shallow depths, earthquakes (dots) occur in the cooler, brittle center of the slab, but none occur deeper than 700 km, where the plate is assimilated.

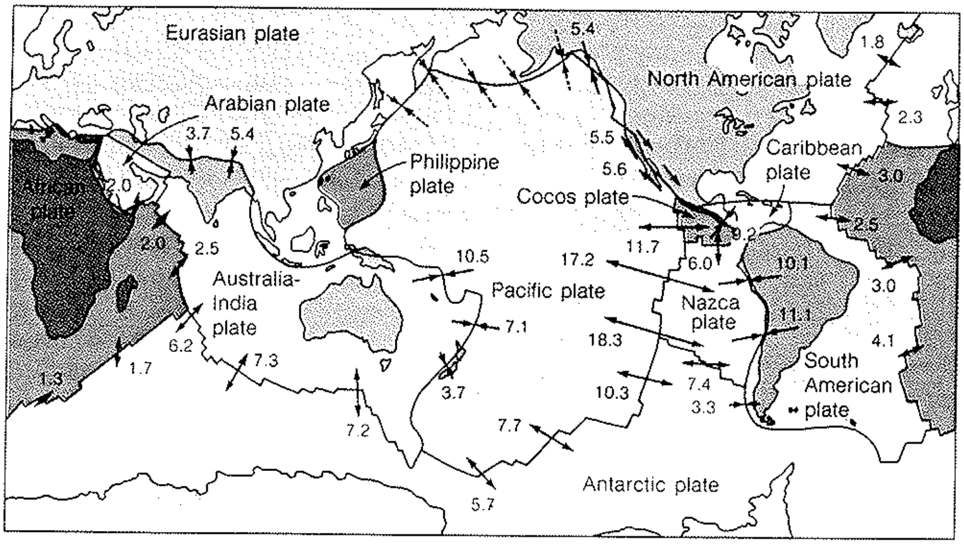

Figure 20-4

Relative velocities and directions of plate separation and convergence in centimeters per year. Opposed arrowheads indicate convergence at trenches, except for Himalayas. Diverging arrowheads indicate plate separation at ocean ridges. Parallel and opposed arrowheads, as along the San Andreas fault in California, indicate transform faults, where plates slide past each other. [From "Convection Currents in the Earth's Mantle" by D. P. McKenzie and F. Richter. Copyright ©1976 by Scientific American, Inc. All rights reserved.]

ture that a large fraction of their peripheries is being subducted. In contrast, the slowly moving plates (North and South America, Africa, Eurasia, and Antarctica) have large continents embedded in them and do not have significant attachments of downgoing slabs. An attractive hypothesis consistent with these observations associates rapid plate motions with the "pull" exerted by large-scale downgoing slabs, and slow plate motions with the "drag" associated with embedded continents.

The first results announced by the Deep Sea Drilling Project represented a great triumph for the magneticians who worked out spreading rates. The goal of this joint project of major oceanographic institutions and the National Science Foundation was to drill through the sediments of the sea floor at many places in the world's oceans. Studying the sedimentary cores makes it possible to work out the history of the ocean basin directly, in contrast to the indirect methods of magnetic anomalies. Since sedimentation begins as soon as an ocean forms, the age of the oldest sediments in the core, those closest to the basaltic bedrock, dates the ocean floor at that spot. The age is obtained from the fossils found in the cores. No sediments older than about 150 million years have been found, attesting to the "youth" of the sea floor. The sediments become older with increasing distance from mid-ocean ridges, confirming the prediction of the sea-floor-spreading hypothesis. Figure 20-5 is a plot of the ages determined from drill cores from the Atlantic and Pacific oceans against ages predicted from magnetic data. It is remarkable how closely the experimental points approach the straight line with slope of 1, which represents perfect agreement. This agreement clinches the concept of magnetic stratigraphy and the hypothesis of sea-floor spreading. The fact that the ocean floor is everywhere younger than about 200 million years attests to the efficiency with which the oceanic lithosphere is created, spreads, and is recycled back into the mantle.

As an interesting aside, we have included a photograph of the drilling vessel *Joides Resolution* (Figure 20-6). It is 470 ft long, and amidships it carries a drilling derrick 200 ft high. The only ship of its kind in the world, it can lower drill pipe several kilometers to the sea floor and drill thousands of meters into the sediments and underlying volcanic rock. For the ship to accomplish such a feat required a technological breakthrough. A means had to be devised to hold the ship stationary, regardless of current, wind, or waves, during drilling. Otherwise, the drill pipe would break off.

The problem was solved by developing a positioning device that uses sound waves from acoustic beacons planted on the sea floor. Any change in the ship's position is sensed by a computer that monitors the time of arrival of the sound pulses. The same computer controls bow and stern side thrusters and the ship's main propulsion to keep the vessel on station. Deep-sea drilling was the answer to those who said when lunar exploration started, "Better to explore the ocean's bottom than the backside of the Moon." We ended up doing both.

GEOMETRY OF PLATE MOTION

Since the individual plates behave as rigid bodies, several interesting and useful geometric consequences follow. By "rigid" we simply mean that the distances among three points on the same plate—say, New York, Miami, and Bermuda—do not change, no matter how the plate moves. But the distance between New York and Lisbon, of course, increases because the two cities are on different plates that are being separated along a narrow zone of spreading on the mid-Atlantic ridge. Listed here are some geometric principles, mostly self-evident, that govern the sliding of plates on a planet.

1 Along transform-fault boundaries, no overlap, buckling, or separation occurs; the two plates merely slide past each other without changing the surface area. Look for a transform fault if you want to deduce the direction of plate motions, because the orientation of the fault *is* the direction of relative sliding of two plates, as Figures 1-17 and 18-13 show. Surface area obviously changes at zones of convergence or divergence where plates are subducted or created. The plates can move perpendicularly or obliquely to the trend of convergent boundaries, which are therefore not as reliable indicators of directions of movement as transform faults or divergence zones.

2 Magnetic anomaly stripes and isochrons are roughly parallel and are symmetrical with respect to the ridge axis along which they were created. Look at Figure 19-17 to see why this must be so. Since each magnetic strip or isochron marks the edge of an earlier plate margin, isochrons that are of the same age but on opposite sides of an ocean ridge can be brought together to show the positions of the plates and the configuration of the continents as they were in that earlier time. By this means we can reconstruct, for example, the opening of the Atlantic Ocean, as shown in Figure 20-7.*

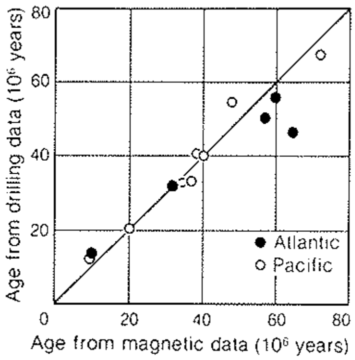

Figure 20-5

A comparison of ages of igneous rocks at different distances from mid-ocean ridges with ages obtained from fossils in the sediments immediately above the igneous rock. The igneous rocks were dated from their magnetic anomaly pattern. The sediments were recovered by deep-sea drilling operations. The 45° line is a theoretical one, implying perfect agreement between these two methods of dating the sea floor. The confirmation of the magnetic ages by deep-sea drilling, shown by the close fit of the experimental points to the theoretical line, lends strong support to the concept of sea-floor spreading. [After C. L. Drake.]

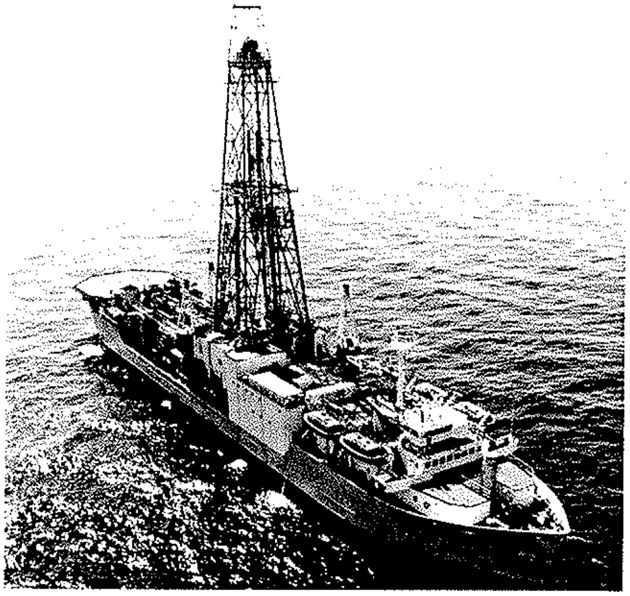

Figure 20-6

The deep-sea drilling vessel *Joides Resolution,* capable of recovering cores of sediment and underlying igneous rock from the floor of the deepest oceans. The Ocean Drilling Program was originally an American one; it is now jointly supported and operated by a number of countries. [From Texas A&M University.]

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*The Great Pyramid of Egypt is aimed slightly east of true north. Did the ancient Egyption astronomers make a mistake in orienting the pyramid 40 centuries ago? Probably not. Over this period of time Africa drifted enough to rotate the pyramid out of alignment with true north.

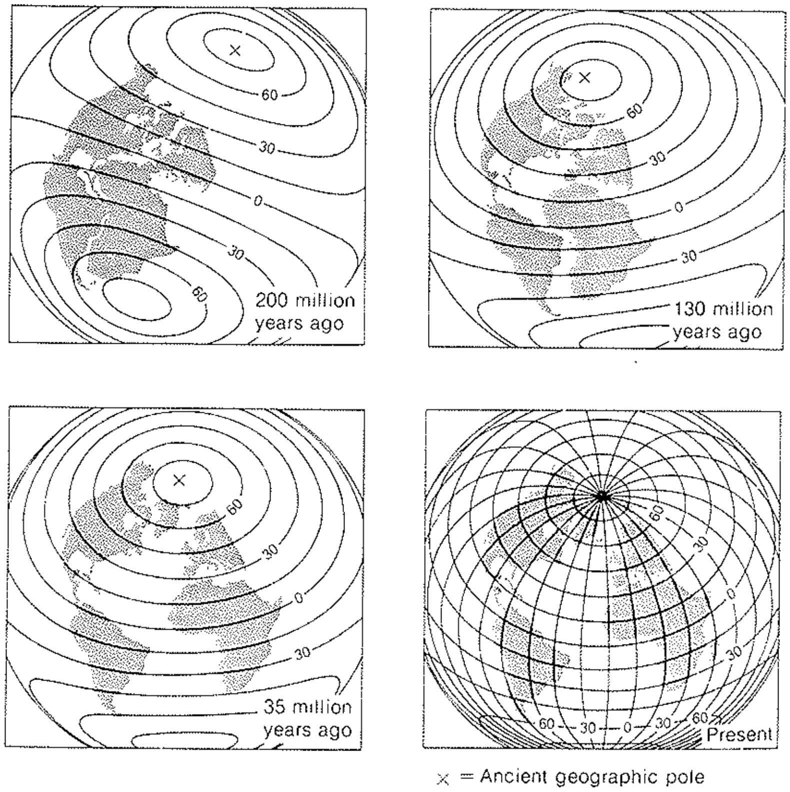


Figure 20-7

Magnetic and deep-sea drilling data are used to chart the northward drift of the continents and the opening of the Atlantic Ocean over the past 200 million years. The central Atlantic, the Caribbean, and the Gulf of Mexico began to form about 200 million years ago in Triassic time, when Africa and South America drifted away from North America. The south Atlantic opened about 150 million years ago with the separation of South America from Africa. As the continents drifted apart, they also migrated in a northerly direction to their present positions. Note that the equator passed through the southern parts of the United States and Europe in Triassic time. [From J. D. Phillips and D. Forsyth, *Bulletin of the Geological Society of America*, v. 83, p. 1579, 1972.]

3 The point at which three plates meet is called a **triple junction.** Figure 20-8 shows an example of a point at which a spreading zone, a subduction zone, and a transform fault meet. If the relative motion between two pairs of plates is known, we can solve for the third by using a simple equation (Box 20-1).

The point where the Pacific, Cocos, and Nazca plates meet (see inside the back cover) is an actual triple junction. Three spreading zones meet at this junction, as shown in the enlarged view in Figure 20-9. The unknown motion, found by vector addition, was that between the Nazca and Pacific plates, the motions between the Pacific–Cocos and Cocos–Nazca plates having been worked out from transform faults and magnetic anomaly stripes. The arrows show the resultant plate movements. Note also how the isochrons bend to become parallel to the spreading centers, where they originated, and how they are offset by the transform faults. The spacing of the isochrons reflects the spreading rates, which are largest for the Pacific–Nazca plates and least for the Cocos–Nazca plates.

Up to this point we have considered plates sliding on a plane. Although much can be learned about plate motions by making this simplification, plates actually move on the Earth's spherical sur-

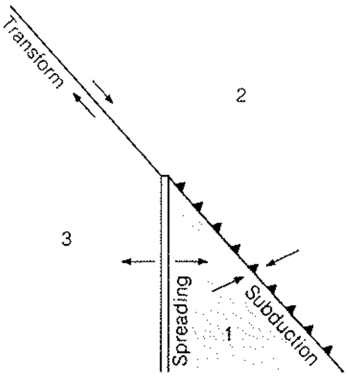


Figure 20-8

A triple junction. Plates 1, 2, and 3 meet at the intersection of a spreading zone, a subduction zone, and a transform fault. The arrows depict relative motion between adjacent plates.

Box 20-1

Solving for the Relative Motions of Plates

Velocity is a **vector** quantity, one that has both direction and magnitude. A simple example of how vectors are added is shown above (a). If a man walks single blocks north on Avenue A, east on First Street, south on Avenue B, he ends up at a place he could have reached directly by walking one block east on Second Street. In vector addition this direct route is equal to the sum of the segments that make up the long route.

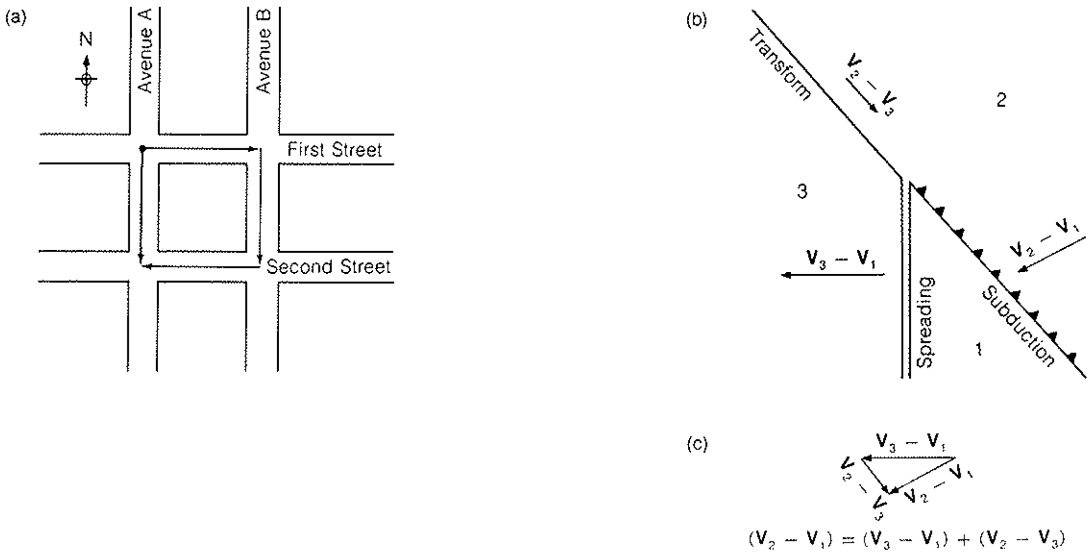
In part (b) of the figure at the right, let the velocities of the three plates meeting at a triple junction be V_1, V_2, and V_3 respectively. The velocity of plate 2 relative to plate 1 is $V_2 - V_1$; $V_2 - V_3$ and $V_3 - V_1$ are the other possible relative plate velocities. It is clear that the sum of the relative velocities of the plates, taken in order around the triple junction, must be zero, since

$$(V_2 - V_1) + (V_3 - V_2) + (V_1 - V_3) = 0$$

or, after rearrangement

$$(V_2 - V_1) = (V_3 - V_1) + (V_2 - V_3)$$

This enables us to solve for $V_2 - V_1$, the direction and amount of relative motion across the subduction zone because the directions of the vectors $V_2 - V_3$ and $V_3 - V_1$ are parallel to the transform and perpendicular to the spreading axis respectively, and the magnitudes of the relative motions can be obtained from the magnetic stripes. Part (c) of the figure shows the solution for $V_2 - V_1$ in terms of vector addition.



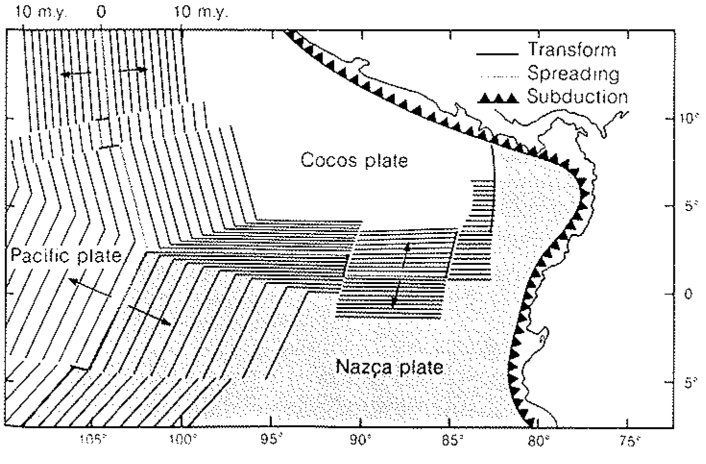


Figure 20-9

Triple junction formed by the intersection of the Pacific, Nazca, and Cocos plates, three spreading zones in the southeast Pacific Ocean. The schematic isochrons parallel the ridge axes from which they migrate as the sea floor ages and spreads. The spacing between isochrons is a measure of the spreading velocities. [After "The Galápagos Triple Junction" by R.N. Hey, K. S. Deffeyes, G. L. Johnson, and A. Lowrie, *Nature*, v. 237, p. 20, 1972.]

face. Box 20-2 explains how plate movements on a sphere can be described. With the application of these geometric principles to find spreading directions and magnetic anomalies to deduce spreading rates, the relative motions of the lithospheric plates are being worked out worldwide. Some results have already been pictured in Figures 19-21 and 20-4.

However, geophysicists are searching for ways to measure the absolute motions of individual plates rather than their motions relative to each other. If the hot spots discussed in Chapter 16 turn out to be fixed in the mantle below plates, then the string of extinct volcanoes trailing from the hot spot would record the movement of individual plates as they glide over the mantle (see Figure 16-38).

An exciting and new technique for measuring plate motions involves bouncing pulses of light from ground-based lasers off the orbiting Laser Geodynamics Satellite (Lageos). Since the motion of the satellite is known precisely, the ground sites can be positioned with respect to one another by timing the round trip of the laser pulse. The measurements are repeated thousands of times over a period of a few years in order to detect changes in the distances between the ground sites. NASA scientists have recently announced preliminary results of continental motions that agree overall in magnitude and direction with those found from the geological methods described in the preceding pages. In a sense the satellite serves as the outside observer, independently validating the theories and methods of Earth-bound geologists as they reconstruct plate motions from the geologic record. Taken together, the short-term Lageos observations and the long-term geologic data imply that plate motions are roughly constant over a time scale from years to tens of millions of years. This is currently a subject of active research.

Sea-floor Spreading and Continental Drift: Rethinking Earth History

One of us (F. P.) once helped write a paper dealing with the permanence of ocean basins. If he were allowed to expunge from the scientific record the one contribution he regrets the most, this would be it. The notion of the stability of global geographic features was not only a main tenet of the old geology but seems to be firmly rooted in the human psyche. We now know that on the geologic time scale the sea floor is far from permanent. The present ocean basins are being created by spreading and recycled by subduction on a time scale of about 200 million years, which is about 4% of the age of the Earth. The likelihood of finding extensive older remnants of sea floor is slight. Continents, on the other hand, are mobile but permanent features. They are too buoyant to be subducted. They may be fragmented, moved, reassembled, deformed, and eroded at their surfaces, but their bulk does not seem to be much diminished. Old terrains with ages of around 3.5–3.8 billion years can still be found. Continents grow with time by the gradual accumulation of materials along their margins. New continental strips can therefore be added on in different places at different times, depending on the history of fragmentation, movement, and reassembly.

With the emergence of these revolutionary ideas, geologists are rethinking Earth history. Most of the evidence for plate tectonics comes from the sea floor, a relatively simple place compared to the enormously complicated continents. Just how plate tectonics explains continental geology is now receiving much attention. New developments reported in nearly every issue of the geological journals show that the subject has definitely been revitalized. Rock associations, volcanism, metamorphism, the evolution of mountain chains—all are being reexamined in the framework of plate tectonics. Some of the new interpretations that we describe in this chapter may not stand the test of time. In this connection, future editions of this book may show some changes, not so much in the big picture of plate tectonics as in the details of fitting regional geology into the overall framework. We have to avoid the temptation to fall back on plate tectonics for easy explanations of everything geological. It is not clear, for example, how or whether the origin of such structures as the Ozarks, the Black Hills, the Colorado Plateau, or such intracontinental, sediment-filled depressions as the Michigan basin are related to plate movement. Nevertheless, a strong lithosphere, which is a prerequisite for plate tectonics, evolved as much as 4 billion years ago. It is reasonable to infer that the known geologic record has been dominated by plate tectonics throughout its entire length.

ROCK ASSEMBLAGES AND PLATE TECTONICS

The only record we have of past geologic events is the incomplete one found in the rocks that have survived erosion or subduction. Since only sea floor younger than 200 million years (the last 4% of

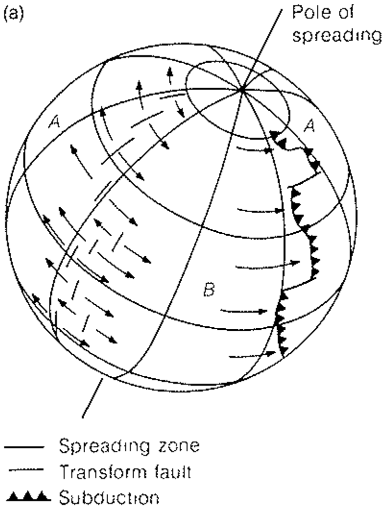
Box 20-2

Plate Motions on a Spherical Earth

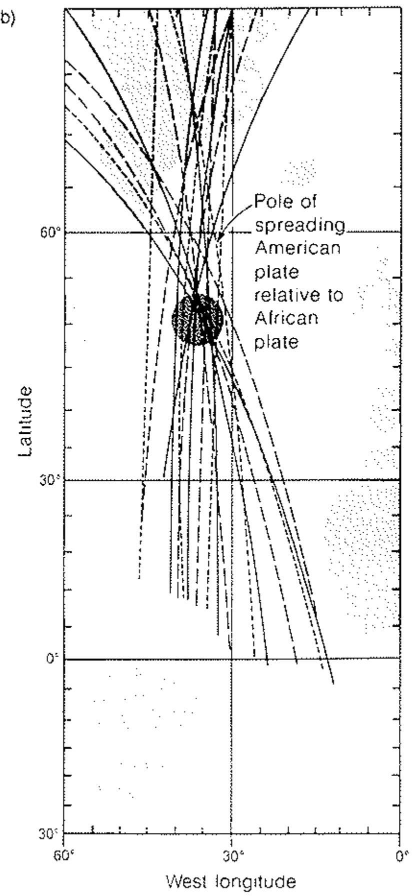
Geometry allows us to describe the separation of two plates on a sphere—for example, plate *A* and plate *B* in figure (a)—as a rotation of *B* with respect to *A* about some pole of rotation, called a pole of spreading. Note on the diagram of plates inside the back cover that along mid-ocean ridges where plates separate, the axis of spreading is not continuous but is offset by transform faults, approximately at right angles to the axis. Why this occurs is not fully understood, but it appears to be easier for plates to break apart this way with the plates typically sliding by each other at the transform fault, rather than pulling apart or overlapping there. Because of this geometry, if we imagine latitudes and longitudes drawn with respect to the pole of spreading, the transform faults lie on lines of latitude, and lines perpendicular to them are longitudes that converge at the pole of spreading. To understand why this must be so, consider the following analogy: If a tennis ball were sliced in two parts and put back together, we could rotate the two parts along the cut (as a transform fault). The cut would also describe a latitude centered on a pole of rotation, which can be located by drawing longitudes perpendicular to the cut. The intersection of two or more such longitudes is the pole of rotation. On a model of Earth, if great circles are drawn perpendicular to transform faults between a pair of plates, their intersection locates the pole of spreading, which together with the spreading rate completely describes the relative motion of the two plates. The spreading rate is zero at the pole of spreading and increases to a maximum 90° away at the equator of spreading, as the figure indicates. This maximum equatorial value is frequently cited as the spreading rate between plates.

To see how a pole of spreading is located in practice, refer again to the inside of the back cover, which shows the zone of spreading and the transform faults that separate the African and American plates. Great circles perpendicular to the transform faults intersect near the point 58°N, 36°W, off the southeast coast of Greenland (b). This is the pole of spreading of these two great plates. Don't bother going there, for there is nothing to be seen. The pole of spreading has no physical significance. It serves only as a construction point, a convenience for describing the relative motion of plates merely by giving the latitude and longitude of this point.

(a)



(b)



[After W. J. Morgan, "Rises, Trenches, Great Faults, and Crustal Blocks," *Journal of Geophysical Research,* v. 73, pp. 1959–1982, 1968.]

Earth history) has survived subduction, we must focus on the continents to find the evidence for most of Earth history. Some of the methods of reading the rock record have been described in earlier chapters. Here we explore the nature of the rock assemblages that characterize different plate-tectonic regimes as a first step in unraveling the history of past plate motions. Our aim is to reconstruct the process of continent fragmentation and ocean development, to locate the sites of vanished oceans, and to recognize the sutures that mark ancient plate collisions.

Of the three kinds of plate boundaries, we might expect distinct suites (assemblages) of rocks to be associated with plate divergence and convergence. At transform faults no distinct or characteristic rock assemblages are to be expected. Discontinuities across the fault are found, however, since rock formations formed and altered elsewhere have slipped past one another, and once-continuous formations or structural features are displaced.

Using data gathered from deep-diving submarines, dredging, deep-sea drilling, and seismic exploration, geologists are piecing together a remarkable picture of the creation of oceanic crust along the axis of mid-ocean ridges—the boundary between diverging plates on the sea floor (Figure 20-10). With mantle convection and plate separation, hot mantle rises and begins to melt with the decrease of pressure. The basaltic melt floats upward and fills a shallow magma chamber. Magma from the chamber repeatedly intrudes the rift between the spreading plates and solidifies as vertical sheets of dikes—dikes intruding dikes to

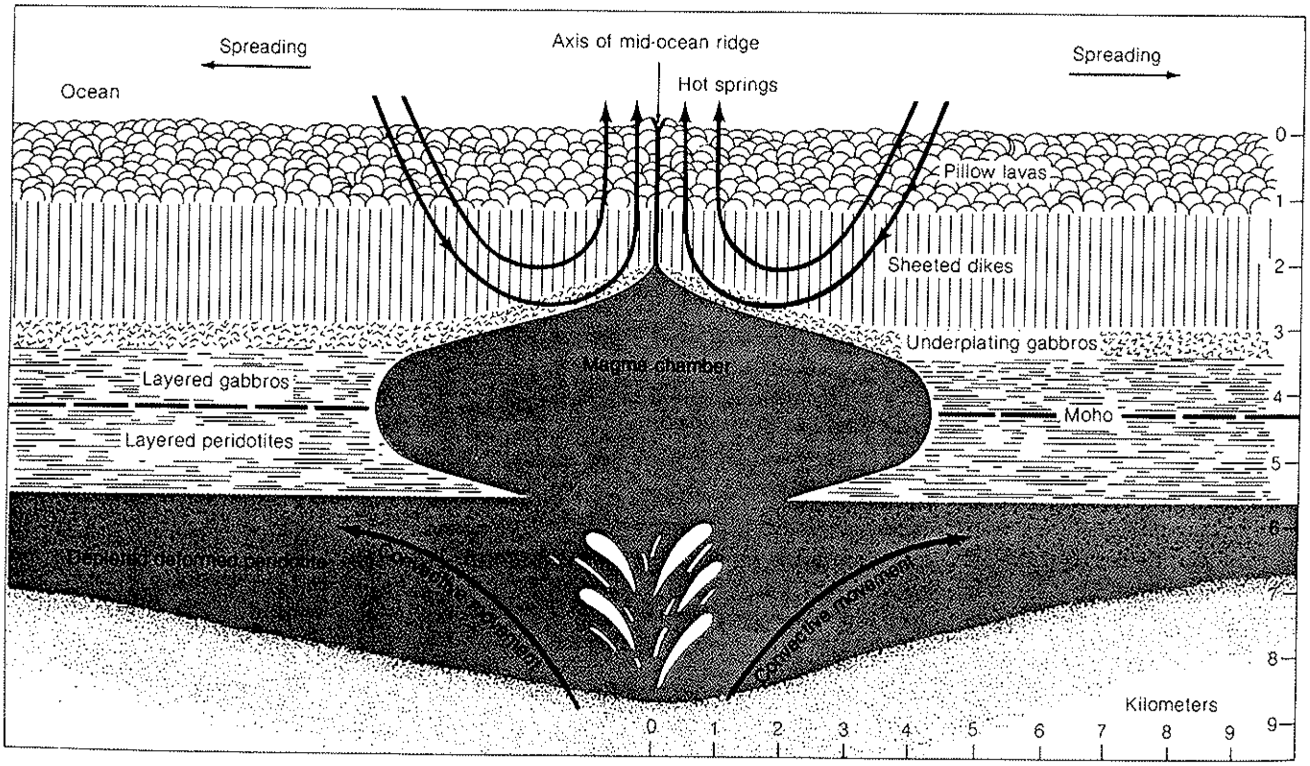


Figure 20-10

Formation of oceanic crust at a submarine spreading center. Magma, the melt from rising hot mantle, floats upward and fills a shallow chamber. Magma injected into the rift between the separating plates solidifies as vertical sheeted dikes. Pillow lavas form when lavas spill onto the sea floor. Gabbros and peridotites, formed from crystallization in the chamber, underly the sheeted dikes. A thin blanket of deep-sea sediments (not shown) covers the ocean crust. Fresh injections of magma keep the process going and sea-floor spreading moves the newly formed crust away. Seawater circulates through the system, leaching from the magma important minerals, which are precipitated where the hot springs emerge into the cold ocean. The sequence of deep-sea sediments, pillow basalts, and gabbros is called an ophiolite suite. Ophiolites found on land are slices of ancient sea floor caught up in a plate collision. [After "Ophiolites" by I. G. Gass. Copyright © 1982 by Scientific American, Inc. All rights reserved.]

form a structure that has been likened to a pack of cards standing on edge. Basalt spilling out on the sea floor freezes as pillow lavas—the characteristic form of undersea volcanism—forming a cover over the sheeted dikes. The roof of the magma chamber, cooled by circulating seawater, cools the adjacent magma, which crystallizes and plates to the roof as a coarse-grained gabbro below the sheeted dikes. Within the magma chamber, minerals crystallize and form layered gabbros and peridotites below. The Moho is the boundary between them. A thin blanket of deep-sea sediments (not shown) covers the ocean crust.

With sea-floor spreading, the zones of lavas, dikes, gabbros, and peridotites are transported away from the mid-ocean factory where this unique sequence of rocks that make up the oceanic crust is assembled—almost like a production line. The magma chamber is periodically replenished by fresh injections of basaltic liquid to keep the process going. The mid-ocean ridge is also a factory for the formation of massive ore bodies of sulfides of iron, copper, and other minerals. In this case circulating seawater is the important agent—sinking through the porous volcanic rocks, becoming heated, and leaching these elements from the magma and hot rocks. When the heated, enriched seawater rises and reenters the cold ocean, the ore-forming minerals precipitate.

The combination of deep-sea sediments, submarine basaltic lavas, and mafic igneous intrusions like that shown in Figure 20-10 has been found on land. Known as **ophiolite suites,** they have puzzled geologists for over a hundred years. Plate tectonics explains these exotic rocks as fragments of oceanic crust transported by sea-floor spreading and raised above sea level in an episode of plate collision. The narrow ophiolite zones found in convergence features like the Alpine–Himalayan belt and the Ural and Appalachian belts are slices of ocean crust and mantle thrust onto land when an ancient ocean finally disappeared as two continents collided.

Ophiolites found on land have helped geologists reconstruct the deeper features of the process of ocean crust formation depicted in Figure 20-10. A geologist can literally walk across the Moho of the ocean crust on some of the more complete ophiolite sequences preserved on land.

When convection currents in the mantle initiate an episode of divergence within a continent (Figure 20-11), the continental crust and underlying lithosphere are stretched and thinned. A long, narrow rift develops, with great downdropped crustal blocks. Hot ductile mantle rises and fills the space created by the thinned crust, increasing the heat flow to the surface and initiating the volcanic eruption of basaltic rocks in the rift zone. The rifting might slow down or stop before the continent splits apart—as exemplified by the famous rift valleys of East Africa or the Rhine

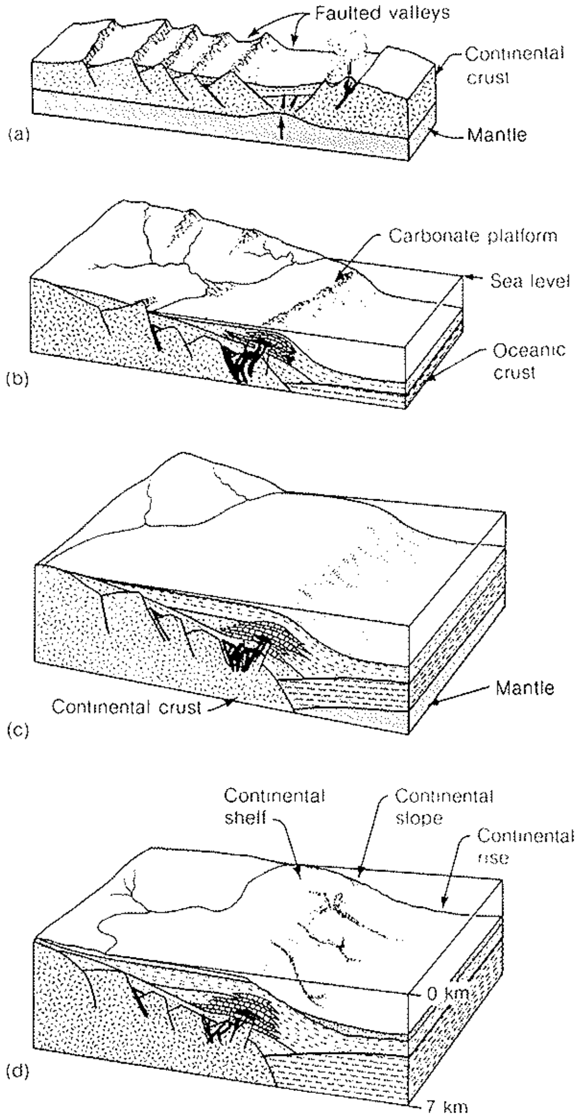


Figure 20-11

The development of a geosyncline on a rifted continental margin off the Atlantic coast of the United States. A rift develops in Pangaea as the ancient continent stretches and thins. Volcanics and Triassic nonmarine sediments are deposited in the faulted valleys (a). Sea-floor spreading begins, the lithosphere cools and contracts under the receding continental margins, which subside below sea level. Evaporites, deltaic deposits, and carbonates (b) are deposited and then covered by Jurassic and Cretaceous sediments derived from continental erosion (c and d). The Atlantic margins of Europe, Africa, and South America have similar histories.

Valley, both or which are still mildly active. There are examples of ancient continental rifts that were "aborted" as much as 2 billion years ago in northwestern Canada.

If the divergence continues to the point of separation of the two segments of continent, the widening rift is flooded and a new ocean basin forms and grows. The receding continental margins subside gradually as the underlying lithosphere cools and contracts. **Continental shelf deposits** are sedimentary rock assemblages that are laid down in an orderly sequence under tectonically quiet conditions in a geosyncline at a receding continental margin. Figure 20-11 models the orderly sequence of deposits in the geosynclines that are still forming off the Atlantic coasts of North and South America and Europe and Africa. The continental margins there were formed when the American plates separated from the European and African plates beginning about 200 million years ago. Resting on the offshore shelf is a wedge-shaped deposit of sediments eroded from the continent and carried into shallow water. Because the trailing edge of the continent slowly subsides, the geosyncline continues to receive sediments for a long time. The load of the growing mass of sediment further depresses the crust isostatically, so that the geosyncline can receive still more material from land. For every 3 m of sediments received, the crust sinks 2 m. The result of these two effects is that the geosynclinal deposits can accumulate in an orderly fashion to thicknesses of 10 km or more. At the same time, the supply of sediments is sufficient to maintain the shallow-water environment of the geosyncline, or miogeosyncline, as we called it in Chapter 12.

The deposits show all of the characteristics of shallow-water conditions (see Chapter 12). At the bottom of the entire sequence are rift valleys containing basaltic lavas and nonmarine deposits formed during the early stages of continental fissuring. In the early stages of shelf deposition, sandy materials started to fill the depression. Much was dropped on the continental slope, only to be moved later to the continental rise by turbidity currents. In deep water, very thick deposits can be built up in this way. As the shelf miogeosyncline builds up, deposition may become dominated by shales and carbonate platform deposits—indicators of a decrease in the supply of detritus from the continent.

Think what might happen to these geosynclines if the orderly, sequentially layered, gently dipping sediments were to become the leading edge of a plate in collision. In the following sections we describe some of the many possibilities.

Just as the events that take place in a convergence boundary are different from divergence boundary phenomena, so do the rock assemblages have different characteristics. The main features of ocean–ocean or ocean–continent collision are shown in transverse section in Figure 20-12. If the overriding plate is oceanic, a volcanic island arc develops—Japan is an example. If the overriding plate is a continent, a continental-margin magmatic belt, such as the Andes, develops. Thick marine sediments, mostly turbidites, eroded from the continent or the island arc, rapidly fill the long marginal depressions. In descending, the cold oceanic slab stuffs the region below the inner wall of the trench with these sediments and possibly with deep-sea materials brought with the incoming plate. Regions of this sort are enormously complex and highly variable, as they include turbidites and ophiolitic shreds scraped off the downgoing slab by the edge of the overriding plate—all highly folded, intricately sliced, and metamorphosed. They are difficult to map in detail but recognizable by their distinctive mix of materials and structural features. Such a chaotic mess has been called a **mélange.** The metamorphism is the kind characteristic of high pressure and low temperature because the material may be carried relatively rapidly to depths as great as 30 km, where recrystallization occurs in the environment of the cold slab. Somehow, perhaps by buoyancy and mountain building, the material rises back to the surface much later. Find a mélange and you can't be too far from the place of downturn of an ancient plate, long since consumed, but leaving this relic of its existence.

Refer again to Figure 20-12. Parallel to the mélange is a magmatic belt that makes up the arcuate system of volcanoes, intrusions, and metamorphic rocks formed on the edge of the overriding plate. Here the conditions are dominated by the rise of magma from the descending plate. At the interface, where the descending plate slides past the overriding one, heat from the adjacent hot mantle and perhaps friction is great enough to melt the upper part of the downturned slab, including the subducted wet sediments and ocean crust. The liquids rise buoyantly from depths of 100–200 km to erupt and build the volcanic chains on the leading edges of plates. The characteristic igneous rocks produced are andesitic lavas and granitic intrusives. Island arcs, built up from the sea floor, may contain larger amounts of basalt; continental

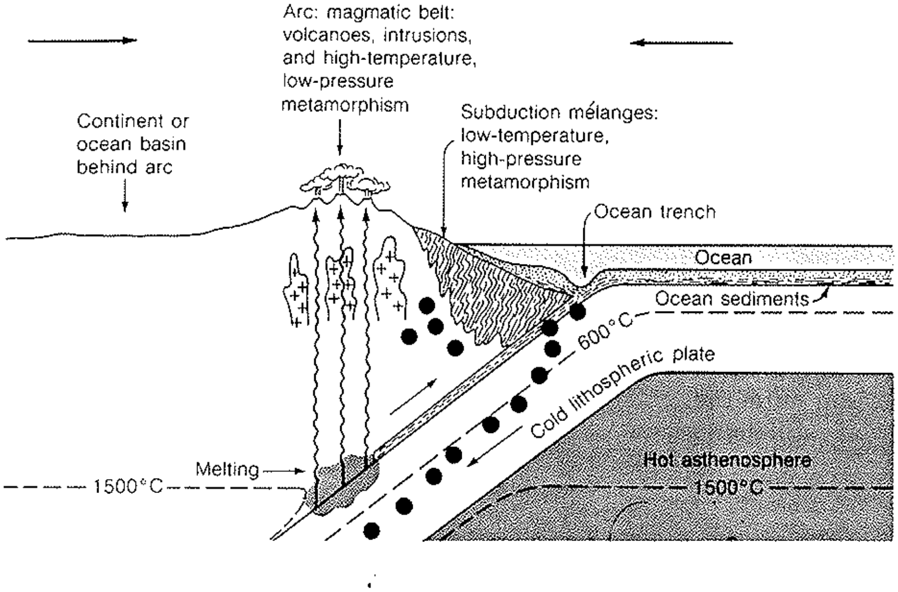


Figure 20-12

Geologic features and activities associated with plate collisions and subduction: ocean trenches, mélange deposits, magmatic belts, metamorphism, volcanism, earthquakes (dots). The drawing is not to scale; the thickness of lithosphere is about 70 km, depth of the ocean trench 10km, and the distance from trench to arc is 300–400 km.

margins typically erupt rhyolitic ignimbrite and are intruded by granitic batholiths below (see Chapter 16). In contrast to that in a mélange, the metamorphism in the magmatic belts is typically the result of recrystallization under conditions of high temperatures and low pressures. This is because the hot fluids rise close to the surface, delivering much heat to a low-pressure environment.

Paired belts of mélange and magmatism (see Figure 20-12) are the signature of subduction. The essential elements of these features of collision have been found in many places in the geologic record. One can see mélange in the Franciscan Formation of the California Coast ranges and magmatism in the parallel belt of the Sierra Nevada to the east (Figure 20-13). This paired belt marks the Mesozoic boundary between the colliding Pacific and American plates. It even shows the polarity of the convergence by the location of mélange on the west and magmatism on the east; the Pacific plate was the subducted one. Other paired belts—for example, in Japan—can be found along the continental margins framing the Pacific basin. The central Alps, a European example, were produced by the convergence of a Mediterranean plate with the European continent.

Seismic reflection profiles (see Box 18-1) are beginning to provide "x-ray" views of layers deep within the crust. Figure 20-14, a remarkable example of this new technique, shows the Australian plate being subducted under the Eurasian plate at the Java trench.

OROGENY AND PLATE TECTONICS

Orogeny means mountain making, particularly by folding and thrusting of rock layers. In the framework of plate tectonics, orogeny occurs primarily at the boundaries of colliding plates, where marginal sedimentary deposits are crumpled and magmatism and volcanism are initiated.

Consider first some scenarios of plate convergence. In Figure 20-15a, a plate with a continent at the leading edge collides with another plate carrying a continent. In the early stage, during which the convergence is between continent and subducted oceanic lithosphere, a magmatic belt, folded mountains, and mélange deposits may be features of the overriding continental boundary. Foreign masses may be carried into the collision zone and thrust onto the continent. An example exists today along the Pacific coast of South America, where the American and Nazca plates are colliding. Look at the illustration inside the back cover to see the setting of the plates. The Andes, from which the name of the volcanic rock andesite is derived, lie in the magmatic belt; subduction is taking place under the Peru–Chile trench.

In a later stage, continent may meet continent, as shown in Figure 20-15b. Since continental crust is too light for much of it to be carried down, the plate motions could be slowed or halted. The motion of collision might be absorbed within a wide zone of intense deformation involving folding and subhorizontal thrust faults. Another possibility, the one depicted in the figure, is that the plate motions continue, with subduction ceasing at the continent–continent suture but starting up anew elsewhere. Cold and dense as the descending slab is, chunks of it may break off, fall freely into the mantle, and be resorbed. As Figure 20-15c shows, the suture is marked by a mountain range made up of either folded or thrust rocks, or both, coincident with or adjacent to the magmatic belt, and by a much-thickened continental crust. A prime example of continent–continent collision is the Himalayas, which began forming some 25 million years ago when a plate carrying India ran into the Asiatic plate (the collision and uplift are still going

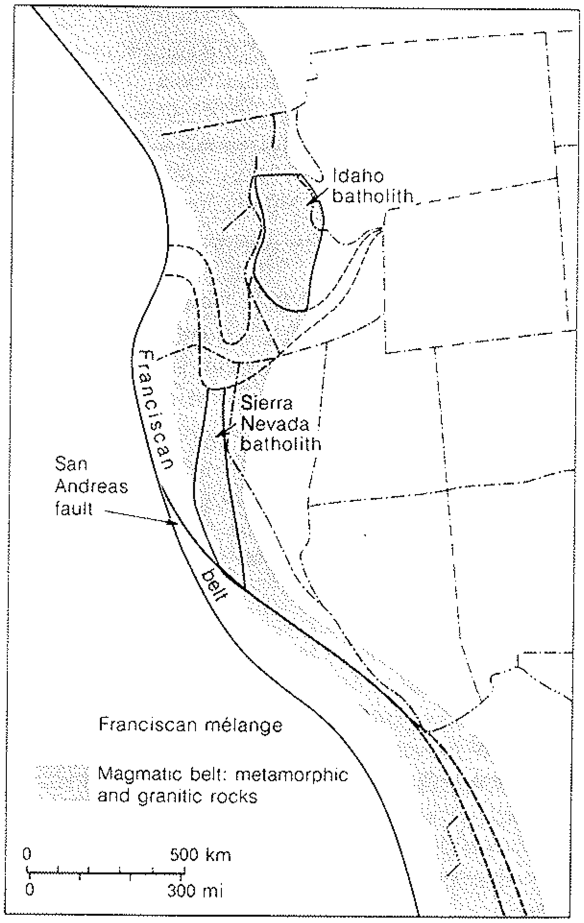


Figure 20-13

This paleogeologic map of the western United States shows the geology of the region as it was at the beginning of Tertiary time. The paired mélange and magmatic belts indicate a collision of the Pacific and American plates in Mesozoic time, the Pacific plate being the subducted one. [After "Cenozoic Tectonics" by W. Hamilton and W. B. Myers, *Reviews of Geophysics*, v. 4, p. 541, 1966.]

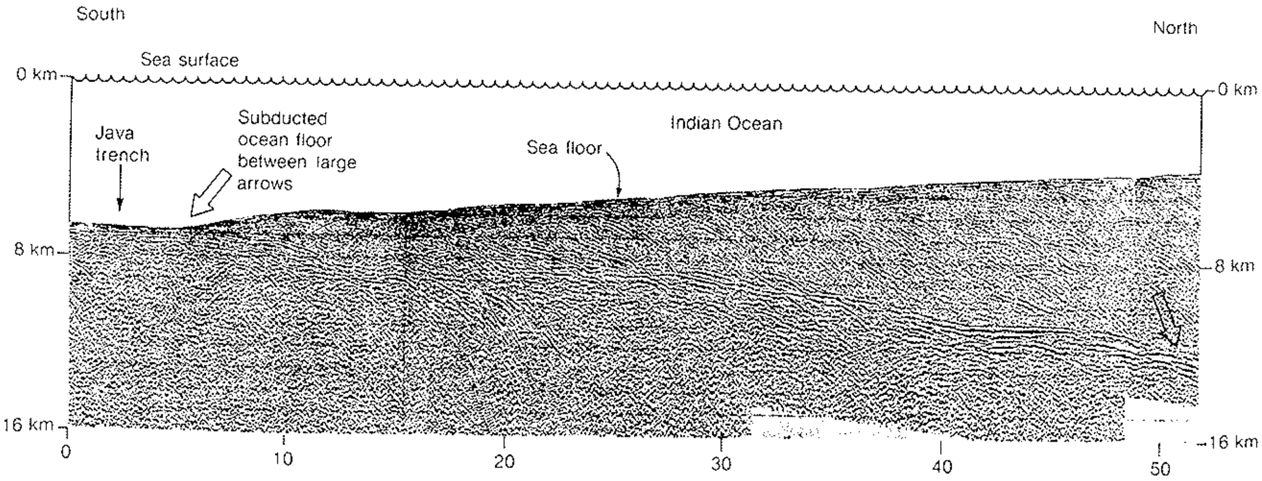


Figure 20-14

Seismic reflection profile across the Java trench subduction zone south of Bali, along longitude 112°E. Subducted ocean floor (between large arrows) dips about 6° under overthrust wedge of highly deformed sediments. The ocean floor can be followed from the beginning of subduction at the north wall of the trench to a depth of 12 km below sea level. [Courtesy of R. H. Beck and P. Lehner, Shell Internationale Petroleum.]

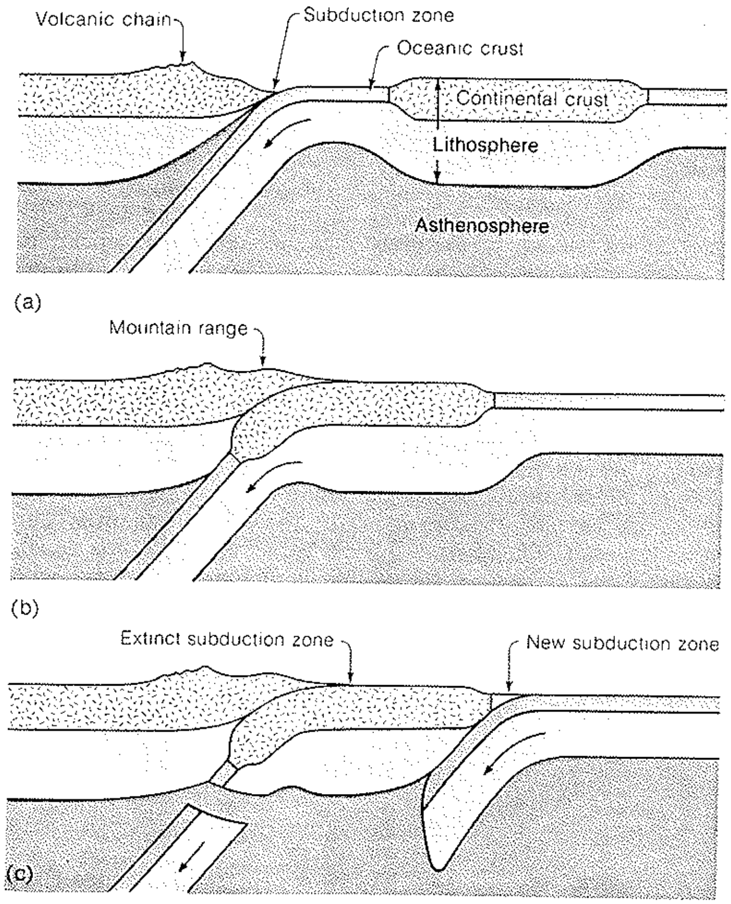


Figure 20-15

Possible stages in plate collisions. (a) Convergence between plates with continental and oceanic lithosphere at leading edges. Magmatic belt, folded mountains, and mélange deposits are features of the overriding continental boundary. (b) Collision of continents, producing a mountain range, magmatic belt, and thickened continental crust. Since the continent is too buoyant to be carried down into the mantle, plate motions may be brought to a halt. (c) Alternatively, the plate may break off and a new subduction zone be started elsewhere. An extinct subduction zone may show as a scar in the form of a mountain belt within a continent. Examples are the Ural Mountains and the Himalayas. Not shown are foreign masses, such as fragments of continent, island arcs, and slices of sea floor brought in by the subducting ocean plate and accreted to the continent. After "Plate Tectonics" by J. F. Dewey. Copyright © 1972 by Scientific American, Inc. All rights reserved.

on). This may be how the root underlying the Himalayas originated (see Chapter 19). The plate-tectonic cycle of the rifting of a continent, the opening of an ocean basin by sea-floor spreading, its closing, a continent–continent collision, and the formation of an intracontinental mountain belt has been called the **Wilson cycle,** after the Canadian geologist J. Tuzo Wilson. Wilson first suggested the idea that an ancient ocean closed to form the Appalachian mountain belt and then reopened and widened to the present-day Atlantic Ocean. The power of the plate-tectonics concept is evident in the statement that much of the geology of continents can be described in terms of a succession of Wilson cycles! However, a modification of the concept of rigidity of plates and the role of accreted fragments must be considered, as we will do in the next section and the next chapter.

A remarkable new method of imaging the sea floor from an orbiting satellite, as if the seawater were drained away, is described in Box 20-3. All of the major sea-floor features associated with sea-floor spreading are revealed (Plate 8), including many not previously found by ship surveys.

DISPLACED TERRANES

Geologists have come across blocks within orogenic belts of continents that are internally consistent, but that are abruptly discontinuous and alien to their surroundings. They are called **displaced,** or **suspect, terranes.** They are variable in size and contrast sharply with rocks of adjacent provinces in stratigraphy, structure, and magmatic and metamorphic history. Fossils indicate different environments and ages than those of surrounding terranes, and the paleomagnetic poles imply that the

Box 20-3

Charting the Sea Floor by Satellite

The rich geology of the sea floor—its ridges, trenches, seamounts, fracture zones—became apparent only after decades of ship soundings. In those regions where few ships travel, our knowledge remains fragmentary. Recently, however, scientists have developed a new tool, one that enables a satellite to "see through" the ocean and chart the topography of the sea floor, gathering data in mere months. The new method makes use of an altimeter mounted on a satellite. The altimeter sends pulses of radar beams that are reflected back from the ocean below, giving measurements of the distance between the spacecraft and the sea surface with a precision of a few centimeters. The height of the sea surface depends on waves and ocean currents, but also on changes of gravity caused by the topography and composition of the underlying sea floor. For example, the gravitational attraction of a seamount can cause water to "pile up" above it, producing a bulge in the sea surface as much as 5 m (16 ft) above average sea level. Similarly, the diminished gravity over a deep-sea trench would show as a depression of the sea surface of as much as 60 m (192 ft). In this way bottom features can be inferred from satellite data and displayed as if the seas were drained away. In Plate 8, white areas correspond to shallow regions, blue to deep regions, and red to intermediate depths. Clearly visible is the raised red and white stripe between Europe and North America that marks the mid-Atlantic ridge and its associated fracture zones, the trail of a hot spot in the Pacific marked by the Emperor–Hawaiian seamount chain, the major deep-sea trenches in dark blue at subduction boundaries. New features not known from ship surveys have already been found, and future surveys may reveal even deeper structures, such as convection currents in the mantle. The methodology for making geotectonic images was developed by W. F. Haxby of Columbia University, who supplied Plate 8.

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block originated in a different latitude. These are now believed to be fragments of other continents, island volcanic arcs or slices of ocean crust that were swept up and plastered onto a continent in the process of plate collisions. The Appalachian orogenic belt from Newfoundland to the southeastern United States may contain slices of ancient Europe, Africa, oceanic islands, and crust. As many as 100 terranes are regarded as suspect in the Cordilleran orogenic belt of western North America (Plate 9). Displaced terranes have also been found in Japan, Southeast Asia, China, and Siberia, but their original locations have yet to be worked out.

THE GRAND RECONSTRUCTION

At the close of the Paleozoic, some 250 million years ago, there was a single supercontinent, Pangaea, stretching from pole to pole (see Figure 1-14). The fragmentation of Pangaea as a result of plate tectonics and continental drift over Mesozoic and Cenozoic time to form the modern continents and oceans is documented in the well-preserved record of magnetic reversal stripes on the ocean floor. But what of the pre-Pangaean distribution of continents? What were their shapes and where were they located? There is growing evidence that Pangaea was formed by the collision of continental blocks—not the same continents we know today but continents that existed earlier in the Paleozoic. The ocean-floor record for this period has been destroyed by subduction, so we must rely on the older evidence preserved on continents to identify and chart the movements of these paleocontinents. Old mountain belts like the Appalachians and the Urals mark the collision boundaries of the paleocontinents. Rock assemblages there reveal ancient episodes of rifting and subduction. Rock types and fossils also indicate the distribution of shallow seas, glaciers, lowlands, mountains, and climatic conditions. Paleomagnetic data can be used to find the latitude and the north–south orientation of the paleocontinents. Latitudes can also be checked by paleoclimatic data. Although it is not possible to assign longitudinal position to the paleocontinents, the relative sequence of continents around the globe can be pieced together from the fossil record. One of the first efforts to depict the pre-Pangaean configuration of continents using these methods is shown in Figure 20-16. The ability of modern science to recover the geography of this strange world of hundreds of millions of years ago is truly impressive. Geologists may be able to

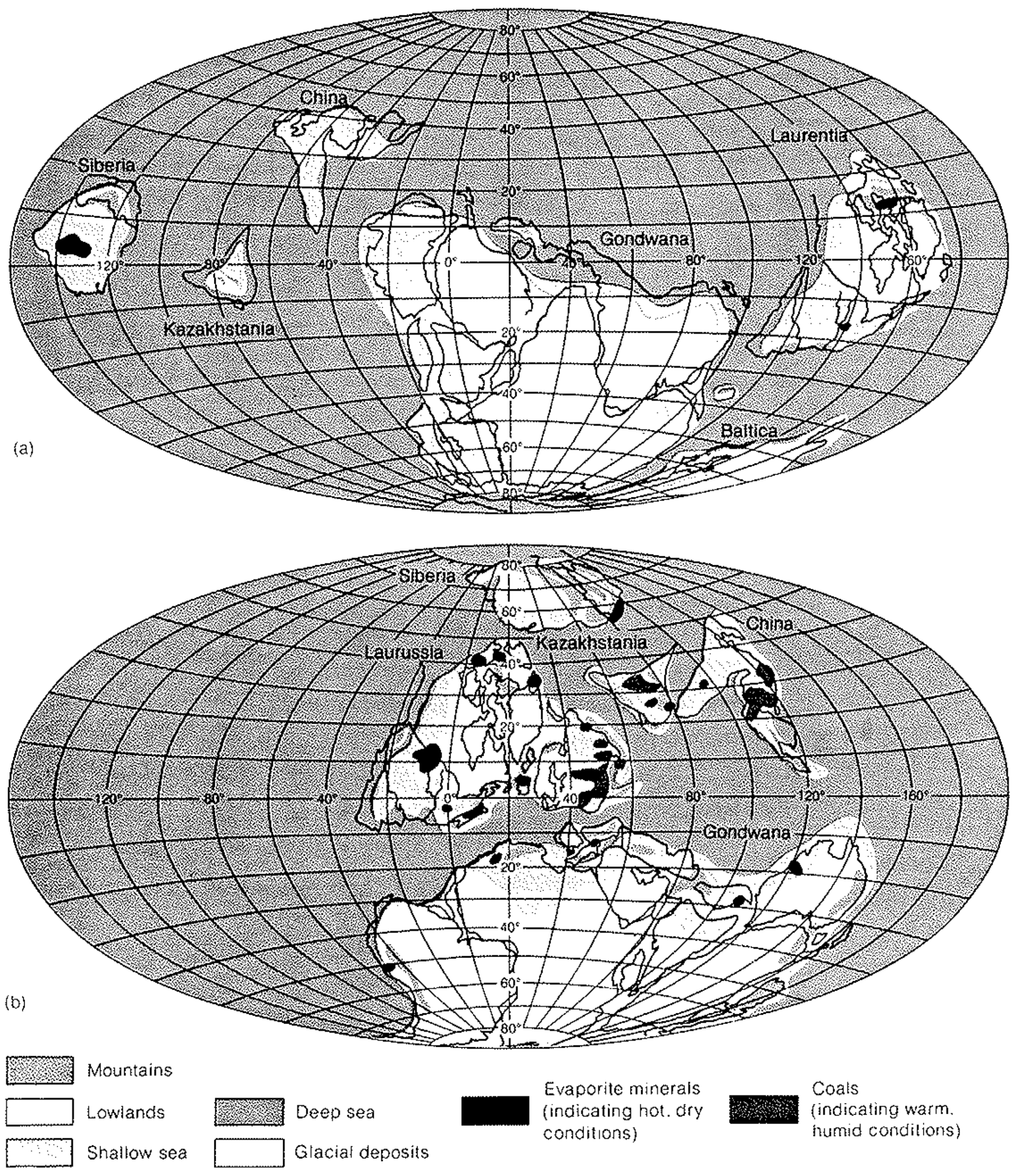


Figure 20-16

(a) Paleocontinents in the Middle Ordovician, about 475–490 million years ago. At that time the continents consisted of Gondwana (made up of South America, southern Europe, Africa, the Near East, India, Australia, New Zealand, and Antarctica), Laurentia (North America and Greenland), Baltica (most of northern Europe and European Russia), Kazakhstania (Central Asia), China (China, Malaysia), and Siberia. (b) Paleocontinents in Early Carboniferous, about 340–360 million years ago. Gondwana has moved across the South Pole, entering the opposite hemisphere; Baltica has collided with Laurentia to form a larger continent, Laurussia. The continents are assembling for the collisions that formed the supercontinent Pangaea at the end of the Paleozoic. [After R. K. Bambach, C. R. Scotese, and A. M. Ziegler, *American Scientist*, January 1980.]

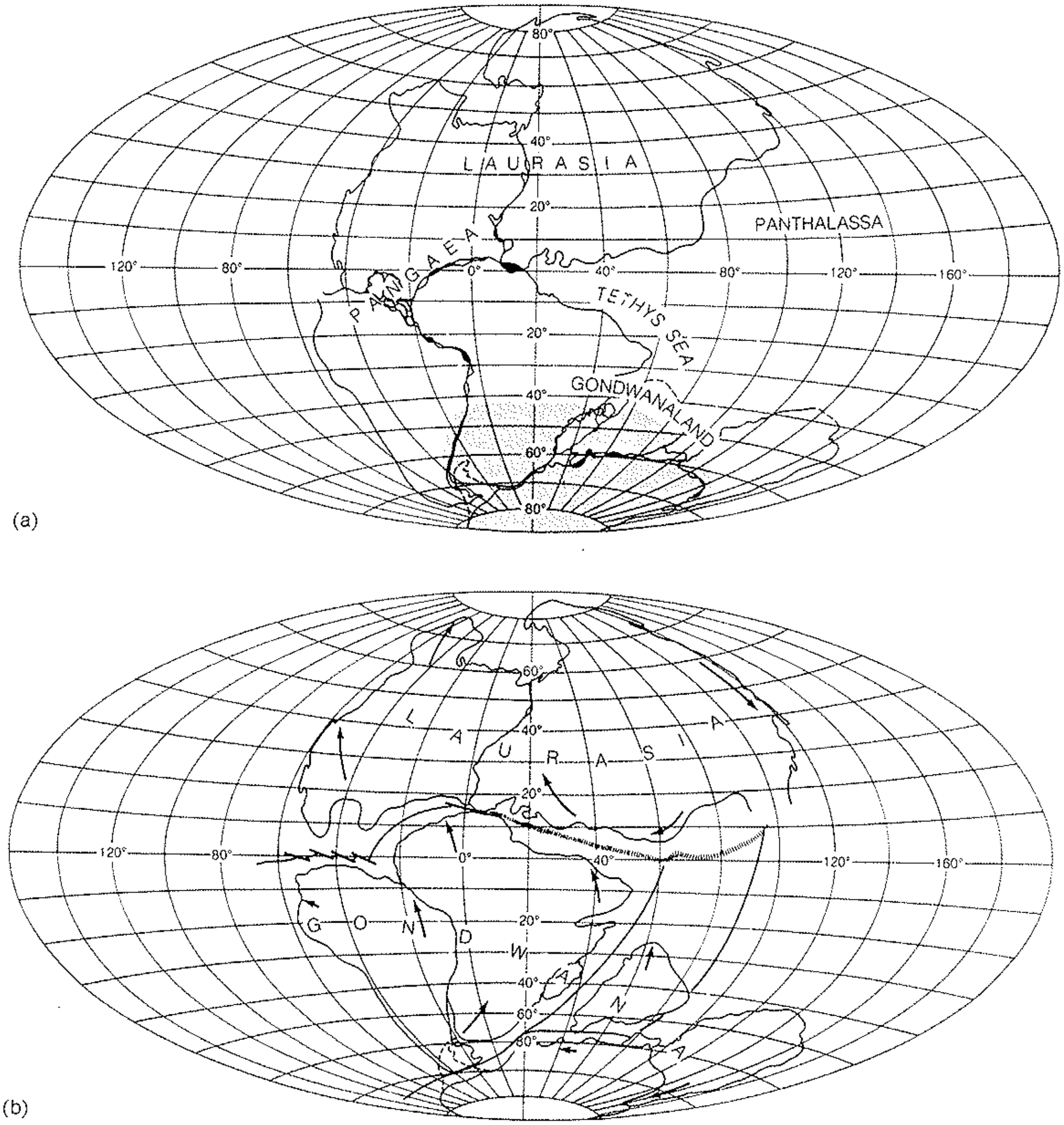
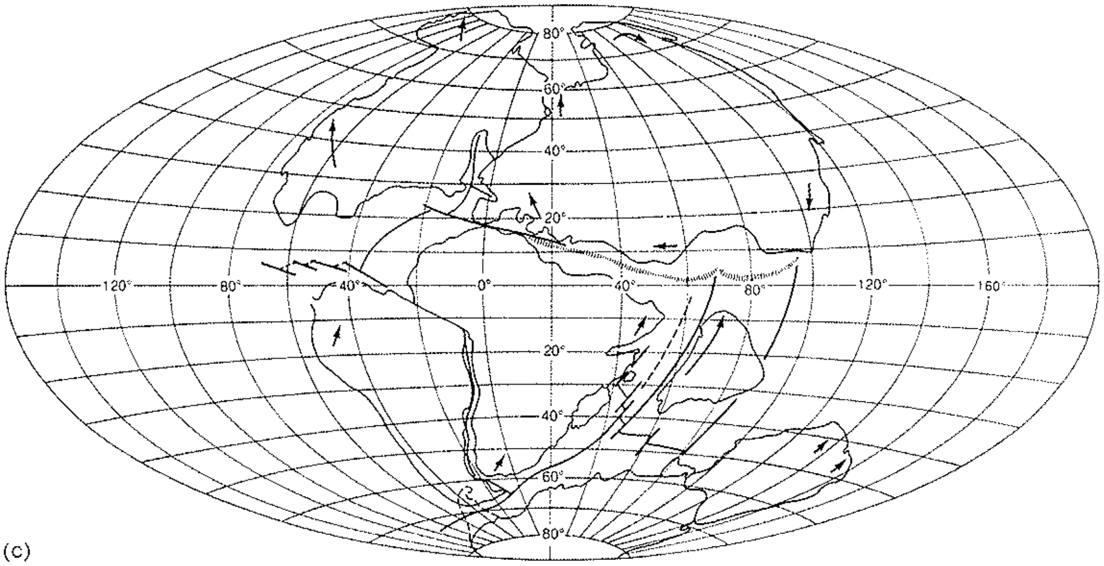


Figure 20-17

The breakup of Pangaea. (a) The ancient landmass Pangaea, meaning "all lands," may have looked like this some 200 million years ago at the close of the Paleozoic and the begining of the Mesozoic. Panthalassa ("all seas") evolved into the present Pacific Ocean, and the present Mediterranean Sea is a remnant of the Tethys. Permian glacial deposits are found in widely separated areas, such as South America, Africa, India, and Australia. This distribution is simply explained by postulating a single continental glacier flowing over the South-Polar regions of Gondwanaland in Permian time, before the breakup of the continents. The probable extent of the glacier is shown by shading. (b) One view of world geography at the end of the Triassic Period, 180 million years ago, after some 20 million years of drift. New ocean floor is shown in color. Spreading zones are represented by dark brown lines, transform faults by black lines, and subduction zones by hatched lines. Arrows depict motions of continents since drift began. (c) World geography at the end of the Jurassic Period, 135 million years ago, after some 65 million years of drift. Ocean floor created in the preceding 45 million years is shown in color. (d) World geography at the end of the Cretaceous Period, 65 million years ago. Color indicates new ocean floor created after some 135 million years of drift. (e) World geography today. Color shows sea floor produced during the past 65 million years, in the Cenozoic Period. [After "The Breakup of Pangaea" by R. S. Dietz and J. C. Holden. Copyright © 1970 by Scientific American, Inc. All rights reserved.]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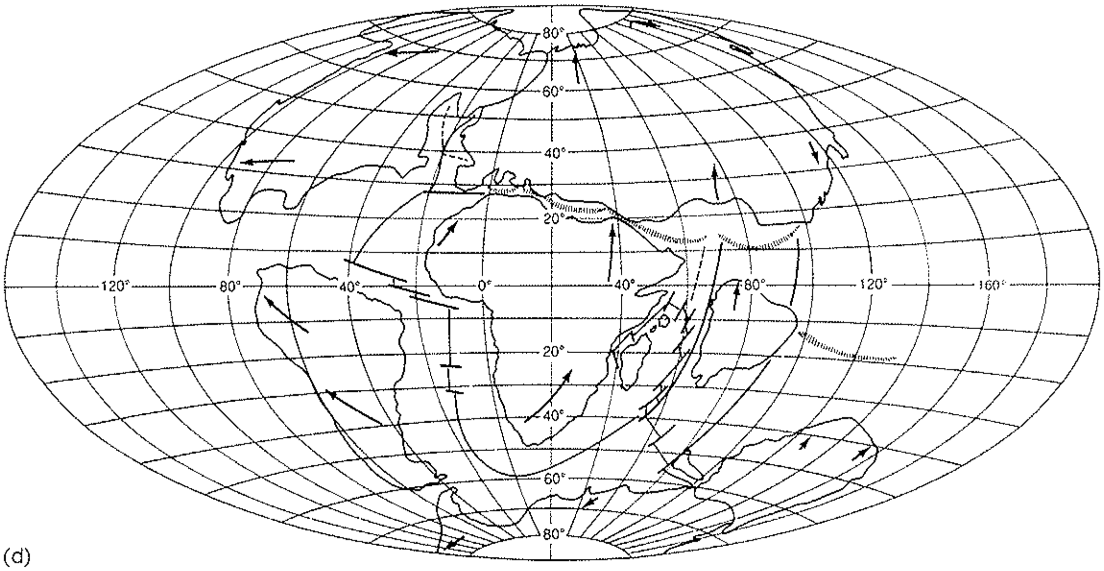
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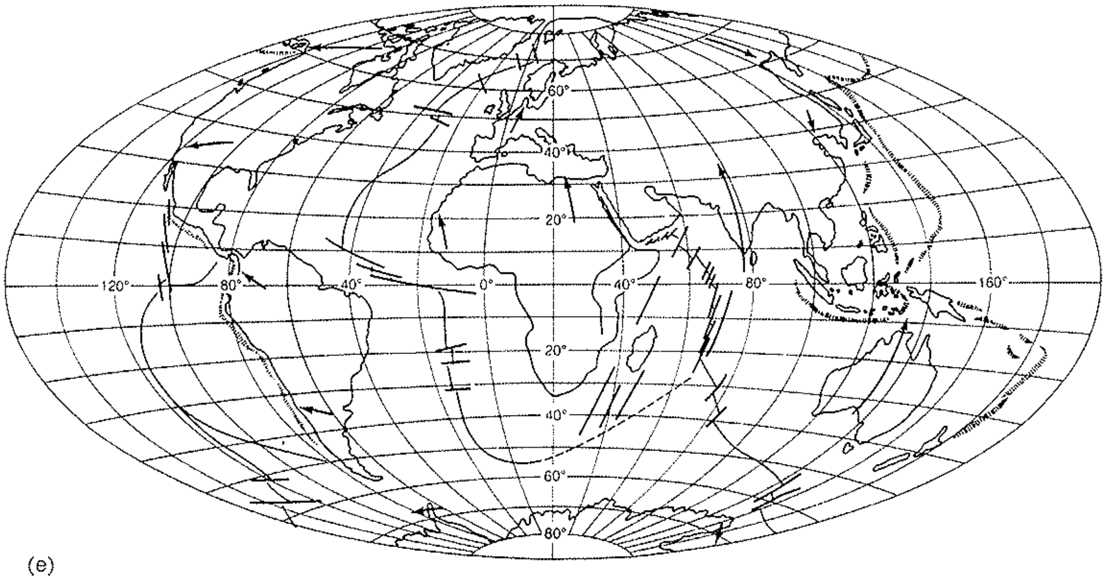
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(e)

continue to sort out more details of this complex jigsaw puzzle, whose individual pieces change shape over geologic time.

Figure 20-17 reconstructs the most recent breakup of Pangaea as we now understand it. Figure 20-17a shows the world as it looked in Permian times, a little more than 200 million years ago. Pangaea was an irregularly shaped landmass surrounded by a universal ocean called Panthalassa, the ancestral Pacific. The Tethys Sea, between Africa and Eurasia, was the ancestor of part of the Mediterranean. The fit of North and South America with Europe and Africa is very good in detail when taken at the outer edge of the continental shelves, instead of at the present shorelines, which are some distance from the original rift. It is the fit for which we have the firmest evidence. The positions of Central America, India, Australia, and Antarctica are less certain.

The breakup of Pangaea was signaled by the opening of rifts from which basalt poured. Relics of this great event can be found today in the Triassic basalt flows all over New England. Radioactive dating of these flows provides the estimate of about 200 million years for the beginning of drift.

The geography of the world after 20 million years of drift—at the end of the Triassic some 180 million years ago—is sketched in Figure 20-17b. The Atlantic has opened, the Tethys has contracted, and the northern continents (Laurasia) have all but split away from the southern continents (Gondwana). New ocean floor has also separated Antarctica–Australia from Africa–South America. India is off on a trip to the north.

By the end of the Jurassic Period, 135 million years ago, drift had been under way for 65 million years. The big event at this time is the splitting of South America from Africa, which signals the birth of the southern Atlantic (Figure 20-17c). The North Atlantic and Indian oceans are enlarged, but the Tethys Sea continues to close. India continues its northward journey.

The close of the Cretaceous Period 65 million years ago sees a widened south Atlantic, the splitting of Madagascar from Africa, and the close of the Tethys to form an inland sea, the Mediterranean (Figure 20-17d). After 135 milion years of drift, the modern configuration of continents becomes discernible.

The modern world, produced over the past 65 million years, is shown in Figure 20-17e. India has collided with Asia, bringing its trip to an end. Australia has separated from Antarctica. Nearly half of the present-day ocean floor was created in this period. Figure 20-18 shows several schematic sections that summarize modern plate, ocean, continent, and island arc relationships for the American, African, Eurasian, and Indian plates.

Most of the modern Pacific Ocean basin consists of the Pacific plate side of the East Pacific Rise spreading zone, as can be seen inside the back cover and in Figure 20-18b. This implies that an area equal to most of the Pacific Ocean has disappeared by subduction under the Americas in the past 130 million years. As much as 7000 km (4300 miles) of Pacific sea floor may have been thrust under North America!

Not one branch of geology, except perhaps crystallography, remains untouched by this grand reconstruction of the continents. Economic geologists are using the fit of the continents to find mineral and oil deposits by correlating the formations in which they occur on one continent with their predrift continuations on another continent. Paleontologists are rethinking some aspects of evolution in the light of continental drift. For example, during most of the age of reptiles, the continents we know today were grouped together in two supercontinents, Laurasia and Gondwanaland. These continents were fragmented during most of the age of mammals, with faunas developing on the daughter continents isolated from one another. Is this why mammals diversified into so many more orders than the reptiles did, and in a much shorter period of time? Structural geologists and petrologists are extending their sights from regional mapping to the world picture, for the concept of plate tectonics provides the means of interpreting such geologic processes as sedimentation and orogeny in global terms. For example, the Caledonian mountain belt that runs along the northwest margin of Europe is the predrift continuation of the Appalachian belt, and the trend of the Andes may be followed into Antarctica and Australia, as Figure 20-19 shows.

Oceanographers are reconstructing currents as they might have existed in the ancestral oceans, to understand better the modern circulation and to account for the variations in deep-sea sediments. Paleoclimatologists are "forecasting" backward in time to describe temperature, winds, the extent of continental glaciers, and the level of the sea as they were in predrift times. What better testimony to the triumph of this once-outrageous hypothesis than its ability to revitalize and shed light on so many diverse topics!

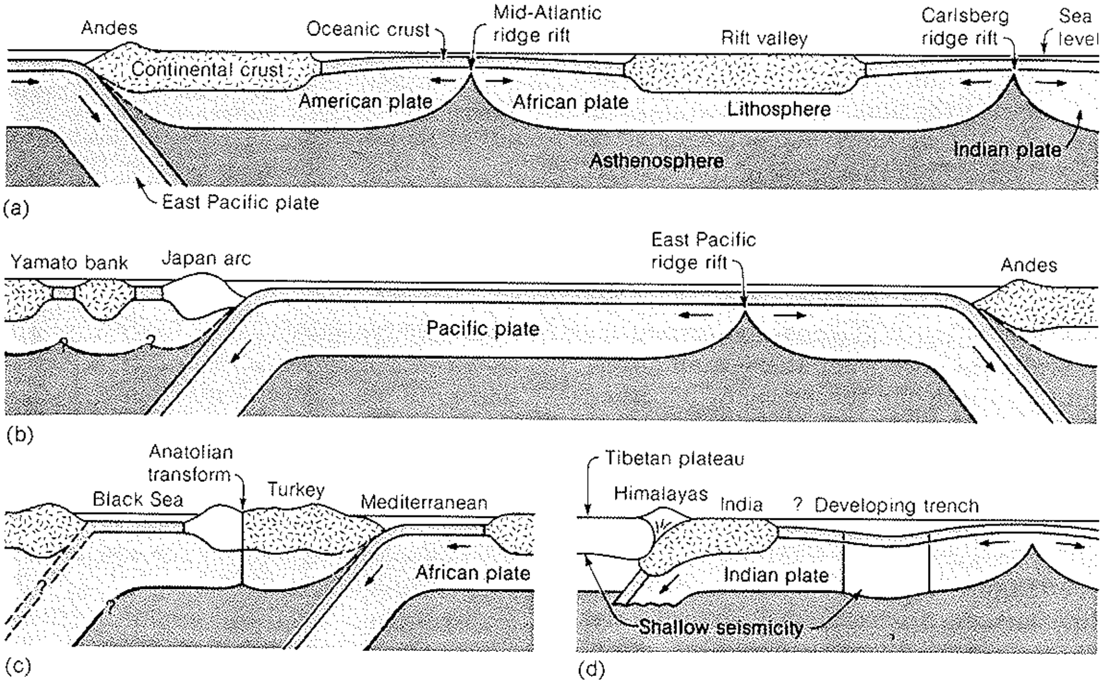

Figure 20-18

Schematic sections showing modern plate, ocean, continent, and island arc relationships. [After "Mountain Belts and New Global Tectonics" by J. F. Dewey and J. M. Bird, *Journal of Geophysical Research*, v. 75, pp. 2625–2647, 1970.]

The Driving Mechanism of Plate Tectonics

Up to this point everything we have discussed might be categorized as descriptive plate tectonics. The geometry and rates of plate motions, the consequences of plate separation and collision have been described. But what drives it all? We will not

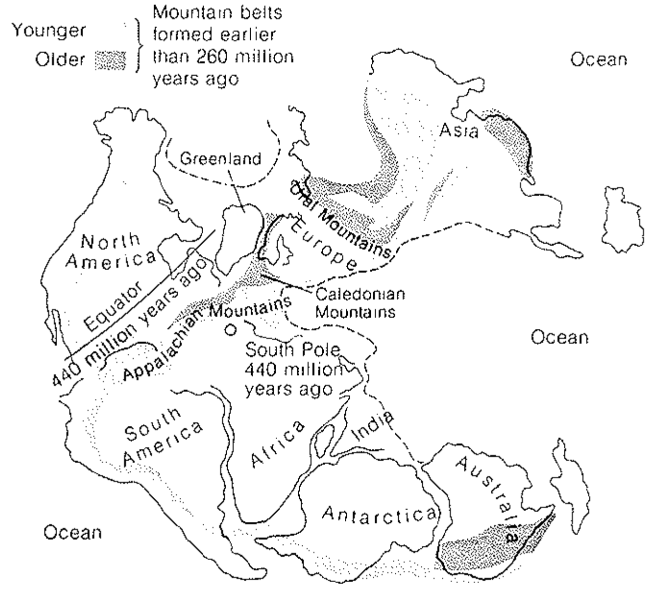

Figure 20-19

When the ancient continent of Pangaea is reconstructed, the Caledonian Mountains of Europe and the Appalachian Mountains form a continuous belt believed to have been formed in a plate collision between the pre-Pangaean continents. The continuity of the mountain belts that extends from the Americas across Antarctica and western Australia supports the reconstruction. The Urals and other old mountains contain ophiolite zones, marking these sutures as the sites of vanished oceans. [After "Plate Tectonics" by J. F. Dewey. Copyright © 1972 by Scientific American, Inc. All rights reserved.]

fully understand plate tectonics until we can answer this question. The International Geodynamics Project enlisted the efforts of thousands of scientists in seeking the underlying cause of plate motions.

It is generally accepted that most of the mantle is a hot solid, capable of flowing like a liquid at a speed of about a centimeter per year, about the rate at which your fingernails grow. The lithosphere is broken into rigid plates, somehow responsive in their motions to the flow in the underlying mantle.

As is generally the case when there is an abundance of data in search of a theory, many hypotheses have been advanced. Some would have plates pushed by the weight of the ridges at the zones of spreading or pulled by the heavy downgoing slab at subduction zones. Others hold that the plates are dragged along by currents in the underlying asthenosphere. Figure 20-20 shows some of these ideas. In line with the discussion in Chapter 14, we agree with those who view the process not in piecemeal but as a highly complex convective flow, involving rising, hot, partially molten materials and sinking, cool, solid materials, under a variety of conditions ranging from melting to solidification and remelting. A significant part of the mantle must be involved, for slabs are known to penetrate to depths of some 700 km before being completely resorbed. Figure 20-20c shows one of the first computer models of the process—one that neglects some of the effects just mentioned, but that nevertheless accounts for many observations. A rising plume of hot material, heated from below, reaches the surface at a center of spreading. It moves away from the center, cools near the surface, and the cooled boundary becomes solid, strong lithosphere. Finally becoming heavier after it has cooled, the lithospheric slab sinks back into the mantle in a subduction zone, where it is reassimilated, to be heated and to rise again in the future. Another theory (Figure 20-20d) proposes that hot, narrow, jet-like plumes rise from the bottom of the mantle, feed the growing plate, and drive it laterally away from spreading centers, where the plumes mostly occur. These same plumes are evidenced at the surface by hot spots. Among the problems left to the next generation of Earth scientists is the incorporation of such important details as the shapes of plates, the history of their movements, and the formation and growth of continents into an explanation of the distribution of convective currents in time and space.

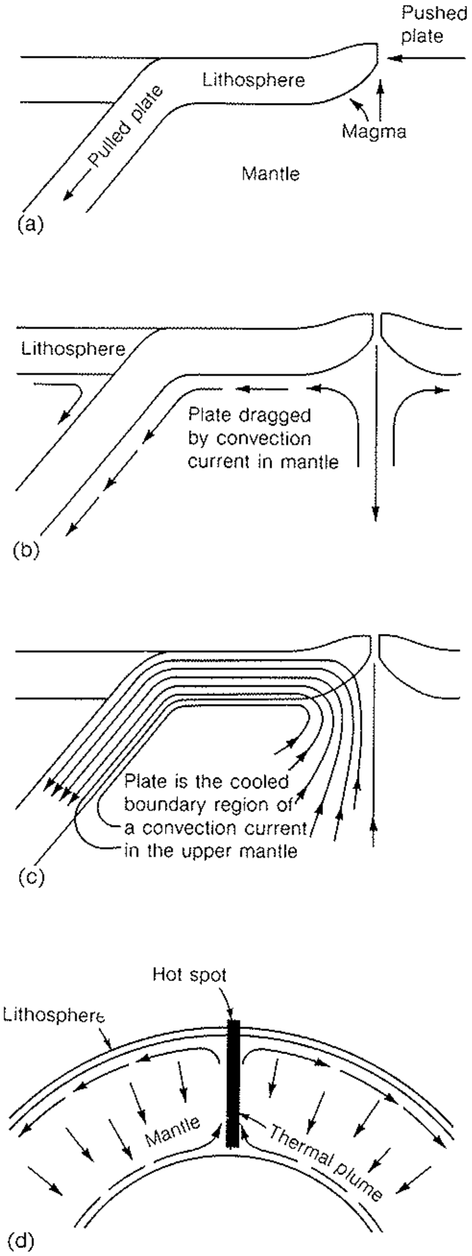

Figure 20-20

Possible driving mechanism of plate tectonics (a) The plate is pushed by the weight of the ridges at centers of spreading or is pulled by cool, heavy downgoing slab or both. (b) The plate is dragged by convection current in mantle. (c) the plate is the cooled, brittle, boundary region of a convection current in the hot, plastic upper mantle. (d) Jetlike thermal plume rises from great depth, causes hot spots at mid-ocean ridges, and spreads laterally, dragging the plates. Downward return flow occurs throughout the rest of the mantle.

Summary

1 According to the theory of plate tectonics, the lithosphere is broken into about a dozen rigid, moving plates. Three types of plate boundaries are defined by the relative motion between plates: boundaries of divergence, boundaries of convergence, and transform faults.

2 In addition to earthquake belts, many large-scale geologic features are associated with plate boundaries, such as narrow mountain belts and chains of volcanoes. Boundaries of convergence are recognized by deep-sea trenches, inclined earthquake belts, mountains and volcanoes, and paired belts of mélange and magmatism. The Andes Mountains and the trenches of the west coast of South America are modern examples. Divergent boundaries (for example, the mid-Atlantic ridge) typically show as seismic volcanic mid-ocean ridges. A characteristic deposit of this environment is the ophiolite suite. Transform faults, along which plates slide past one another, can be recognized by their topography, seismicity, and offsets in magnetic anomaly bands. Ancient convergences may show as old mountain belts, such as the Appalachians.

3 The age of the sea floor can be measured by means of magnetic anomaly bands and the stratigraphy of magnetic reversals worked out on land. The procedure has been verified and extended by deep-sea drilling. Isochrons can now be drawn for most of the Atlantic and for large sections of the Pacific, enabling geologists to reconstruct the history of the opening and closing of these oceans. Based on this method and on geological and paleomagnetic data, the fragmentation of Pangaea over the last 200 million years can be sketched.

4 Although plate motions can now be described in some detail, the driving mechanism is still a puzzle. An attractive hypothesis proposes that the upper mantle is in a state of convection, with hot material rising under divergence zones and cool material sinking in subduction zones. The plates, according to this model, would be the cooled, upper boundary region of the convection cell.

Exercises

1 Summarize the principal geologic features of transform faults, subduction zones, and divergence zones.

2 Explain the following in the context of plate tectonics: (a) Iceland. (b) San Andreas fault of California. (c) Ural Mountains. (d) Aleutian trench. (e) Earthquakes in Italy and Turkey. (f) Andes Mountains. (g) Hawaiian Islands.

3 How do we know that spreading along the East Pacific Rise is faster than along the mid-Atlantic ridge?

4 What would an astronaut look for on Mars to find out if plate tectonics is an active process on the planet?

5 How would you recognize the boundaries between ancient plates no longer in existence?

6 Can you think of a way not mentioned in the text, by which to measure absolute motions of individual plates rather than relative motions between plates?

7 Rich oil deposits are found on the continental shelf of Nigeria. Using the plate-tectonics concept, where would you suspect the possible existence of oil deposits in the Western Hemisphere?

8 If Earth's lithosphere were thicker it might be too strong to break into plates. If this were the case, how might the geologic environment differ from what we know today?

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