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entists—those with particularly inquiring, uninhibited, and synthesizing minds—perceive great truths in advance of others. Although their perceptions may frequently turn out to be false, these individuals are often the first to comprehend 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 world-wide 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 is being assembled (in good humor) to record the names of Earth scientists in the order of the date of their acceptance of sea-floor spreading as a confirmed phenomenon. It is interesting that 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 forms 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 rather than words for material repeated from earlier chapters. The geometry of plate motions is discussed, as well as the geological phenomena associated with plate boundaries. We will begin 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 the reader 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 number of moderately rigid plates whose outlines are shown in the illustration inside the front cover. The plates slide over a partially molten, plastic asthenosphere, and their relative directions of motion are shown in the figure. According to the relative motions of adjacent plates, we can define three kinds of plate boundaries, or marginal zones: (1) zones of divergence or spreading, typically ocean ridges; (2) fracture zones, or transform faults; and (3) zones of convergence (Fig. 17-15).

Zones of divergence are boundaries 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 is volumetrically the most significant form of volcanism. Figures 1-15, 1-19, 13-10, 13-13, 15-21, and 15-38 emphasize the different aspects of divergence zones.

Transform faults are boundaries along which plates slide past one another, with neither creation nor destruction of lithosphere. Occasionally marked by scarps, transform faults are characterized by shallow-focus earthquakes with horizontal slips. Examples were given in Figures 1-19, 17-15, and 18-17.

Zones of convergence are boundaries 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 deep-sea trenches, shallow- and deep-focus earthquakes, adjacent mountain ranges of folded rocks, and both basaltic and andesitic volcanism. Convergence zones were illustrated in earlier chapters (Figs. 1-18, 13-10, 13-13, and 15-38).

Each plate is bounded by some combination of these three kinds of zones, as can be seen on the inside of the front 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 "floating" because continental plates are thicker and more buoyant and are not readily subducted. Where two plates with continents at their leading edges converge, the crust thickens to form great mountain ranges like the Himalayas.

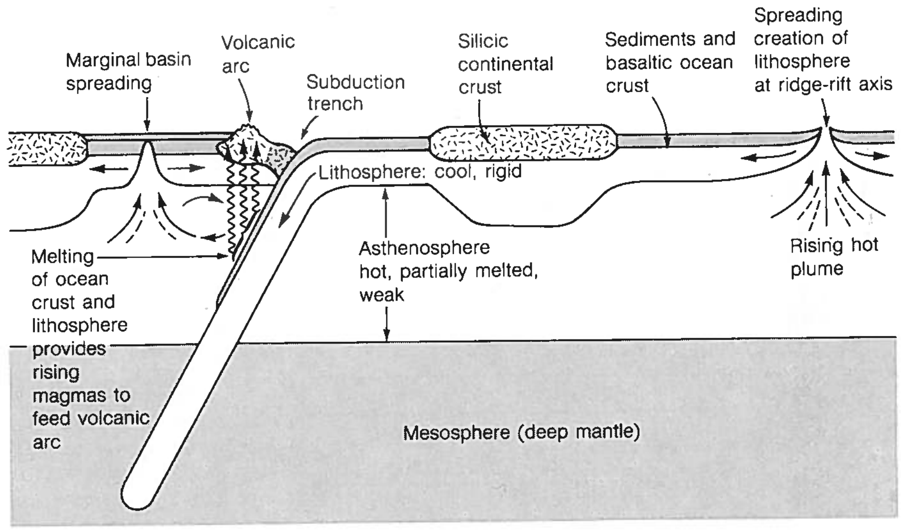

Figure 19-3
Cross section of the upper mantle. The lithosphere is a plate of solidified rock that "rides" on the partially molten asthenosphere. It is approximately 70 km thick under oceans and perhaps 100 to 150 km thick under continents. The continent is embedded in the plate and moves along with it. 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 plastic asthenosphere indicate directions of possible convective motions. Secondary convection currents may form small spreading centers in a marginal basin, a small ocean like the Sea of Japan, situated behind an island-arc volcanic chain, and separate the chain from a continent.

The global sum of plate creation and consumption is approximately zero. The Earth would otherwise change size in order to accommodate 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 19-3 depicts some of the structural details of a rigid lithospheric slab, or what we call 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 Fig. 13-10) shows a large amount of heat coming out along the ridge axis, a lesser amount from the older, cooled slab, and higher heat flow 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 provide understanding of some important geological and geophysical observations: the major bathymetric features of the oceans, the variation of heat flow from the sea floor, the occurrence of volcanism at plate margins, and the location and mechanism of earthquakes in the subducted slab.

When ocean depths are plotted as a function of age, t, of the sea floor, a remarkably regular and simple curve results (Fig. 19-4). For the first 80 million years the data fit a curve in which ocean depth increases as $\sqrt{t}$, precisely the relationship predicted by the thermal contraction of a spreading, cooling plate. Beyond 80 million years ocean depths tend to flatten out, as would be expected if a small amount of heat is added to the bottom of the plate from the underlying hot asthenosphere.