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C. M. R. Fowler
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Chapter 1
Introduction

Geophysics, the physics of the Earth, is a huge subject that includes the physics of space and the atmosphere, of the oceans and of the interior of the planet. The heart of geophysics, though, is the theory of the solid Earth. We now understand in broad terms how the Earth's surface operates, and we have some notion of the workings of the deep interior. These processes and the means by which they have been understood form the theme of this book. To the layperson, geophysics means many practical things. For Californians, it is earthquakes and volcanoes; for Texans and Albertans, it is oil exploration; for Africans, it is groundwater hydrology. The methods and practices of applied geophysics are not dealt with at length here because they are covered in many specialized textbooks. This book is about the Earth, its *structure* and *function* from surface to centre.

Our search for an understanding of the planet goes back millennia to the ancient Hebrew writer of the Book of Job and to the Egyptians, Babylonians and Chinese. The Greeks first measured the Earth, Galileo and Newton put it in its place, but the Victorians began the modern discipline of geophysics. They and their successors were concerned chiefly with understanding the structure of the Earth, and they were remarkably successful. The results are summarized in the magnificent book *The Earth* by Sir Harold Jeffreys, which was first published in 1924. Since the Second World War the function of the Earth's surface has been the focus of attention, especially since 1967 when geophysics was revolutionized by the discovery of *plate tectonics*, the theory that explains the function of the uppermost layers of the planet.

The rocks exposed at the surface of the Earth are part of the *crust* (Fig. 1.1). This crustal layer, which is rich in silica, was identified by John Milne (1906), Lord Rayleigh and Lord Rutherford (1907). It is on average 38 km thick beneath continents and 7–8 km thick beneath oceans. Beneath this thin crust lies the *mantle*, which extends down some 2900 km to the Earth's central *core*. The mantle (originally termed *Mantel* or 'coat' in German by Emil Wiechert in 1897, perhaps by analogy with Psalm 104) is both physically and chemically distinct from the crust, being rich in magnesium silicates. The crust has been derived from the mantle over the aeons by a series of melting and reworking processes. The boundary between the crust and mantle, which was delineated by Andrya

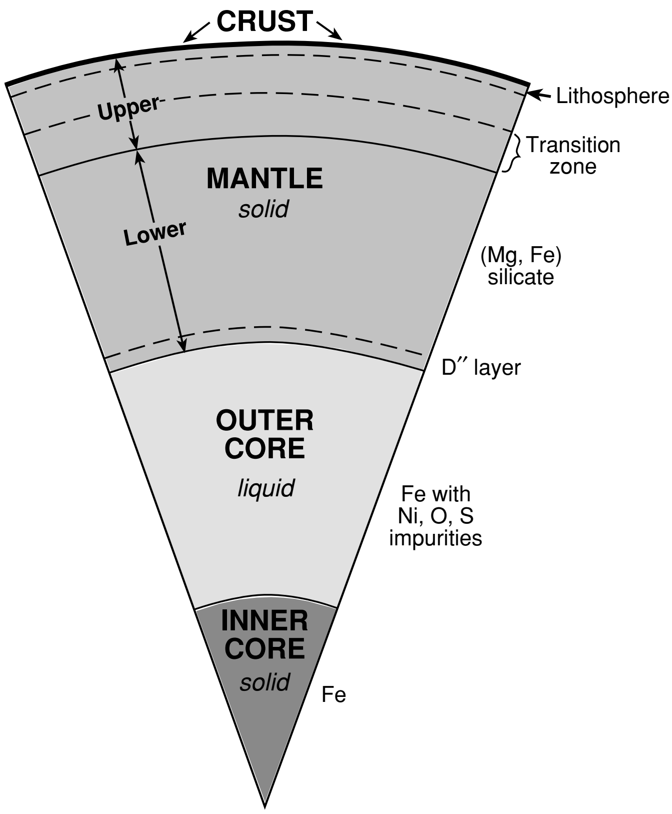

Figure 1.1. The major internal divisions of the Earth.

Mohorovičić in 1909, is termed the Mohorovičić discontinuity, or *Moho* for short. The core of the Earth was discovered by R. D. Oldham in 1906 and correctly delineated by Beno Gutenberg in 1912 from studies of earthquake data (Gutenberg 1913, 1914). The core is totally different, both physically and chemically, from the crust and mantle. It is predominantly iron with lesser amounts of other elements. The core was established as being fluid in 1926 as the result of work on tides by Sir Harold Jeffreys. In 1929 a large earthquake occurred near Buller in the South Island of New Zealand. This, being conveniently on the other side of the Earth from Europe, enabled Inge Lehmann, a Danish seismologist, to study the energy that had passed through the core. In 1936, on the basis of data from this earthquake, she was able to show that the Earth has an *inner core* within the liquid outer core. The inner core is solid.

The presence of ancient beaches and fossils of sea creatures in mountains thousands of feet above sea level was a puzzle and a stimulation to geologists from Pliny's time to the days of Leonardo and Hutton. On 20 February 1835, the young Charles Darwin was on shore resting in a wood near Valdivia, Chile, when suddenly the ground shook. In his journal *The Voyage of the Beagle* Darwin (1845) wrote that 'The earth, the very emblem of solidity, has moved beneath our feet like a thin crust over a fluid.' This was the great Concepción earthquake. Several days later, near Concepción, Darwin reported that 'Captain Fitz Roy found beds of putrid mussel shells still adhering to the rocks, ten feet above high water level: the inhabitants had formerly dived at low-water spring-tides for these shells.' The volcanoes erupted. The solid Earth was active.

By the early twentieth century scientific opinion was that the Earth had cooled from its presumed original molten state and the contraction which resulted from this cooling caused surface topography: the mountain ranges and the ocean basins. The well-established fact that many fossils, animals and plants found on separated continents must have had a common source was explained by either the sinking of huge continental areas to form the oceans (which is, and was then recognized to be, impossible) or the sinking beneath the oceans of land bridges that would have enabled the animals and plants to move from continent to continent.

In 1915 the German meteorologist Alfred Wegener published a proposal that the continents had slowly moved about. This theory of *continental drift*, which accounted for the complementarity of the shapes of coastlines on opposite sides of oceans and for the palaeontological, zoological and botanical evidence, was accepted by some geologists, particularly those from the southern hemisphere such as Alex Du Toit (1937), but was generally not well received. Geophysicists quite correctly pointed out that it was physically impossible to move the continents through the solid rock which comprised the ocean floor. By the 1950s, however, work on the magnetism of continental rocks indicated that in the past the continents must have moved relative to each other; the *mid-ocean ridges*, the Earth's longest system of mountains, had been discovered, and continental drift was again under discussion. In 1962 the American geologist Harry H. Hess published an important paper on the workings of the Earth. He proposed that continental drift had occurred by the process of *seafloor spreading*. The mid-ocean ridges marked the limbs of rising convection cells in the mantle. Thus, as the continents moved apart, new seafloor material rose from the mantle along the mid-ocean ridges to fill the vacant space. In the following decade the theory of plate tectonics, which was able to account successfully for the physical, geological and biological observations, was developed. This theory has become the unifying factor in the study of geology and geophysics. The main difference between plate tectonics and the early proposals of continental drift is that the continents are no longer thought of as ploughing through the oceanic rocks; instead, the oceanic rocks and the continents are together moving over the interior of the Earth.

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Chapter 2
Tectonics on a sphere: the geometry of plate tectonics

2.1 Plate tectonics

The Earth has a cool and therefore mechanically strong outermost shell called the *lithosphere* (Greek *lithos*, 'rock'). The lithosphere is of the order of 100 km thick and comprises the crust and uppermost mantle. It is thinnest in the oceanic regions and thicker in continental regions, where its base is poorly understood. The *asthenosphere* (Greek *asthenia*, 'weak' or 'sick') is that part of the mantle immediately beneath the lithosphere. The high temperature and pressure which exist at the depth of the asthenosphere cause its viscosity to be low enough to allow viscous flow to take place on a geological timescale (millions of years, not seconds!). If the Earth is viewed in purely mechanical terms, the mechanically strong lithosphere floats on the mechanically weak asthenosphere. Alternatively, if the Earth is viewed as a heat engine, the lithosphere is an outer skin, through which heat is lost by conduction, and the asthenosphere is an interior shell through which heat is transferred by convection (Section 7.1).

The basic concept of *plate tectonics* is that the lithosphere is divided into a small number of nearly rigid *plates* (like curved caps on a sphere), which are moving over the asthenosphere. Most of the deformation which results from the motion of the plates – such as stretching, folding or shearing – takes place along the edge, or boundary, of a plate. Deformation away from the boundary is not significant.

A map of the *seismicity* (earthquake activity) of the Earth (Fig. 2.1) outlines the plates very clearly because nearly all earthquakes, as well as most of the Earth's volcanism, occur along the plate boundaries. These *seismic belts* are the zones in which differential movements between the nearly rigid plates occur. There are seven main plates, of which the largest is the Pacific plate, and numerous smaller plates such as Nazca, Cocos and Scotia plates (Fig. 2.2).

The theory of plate tectonics, which describes the interactions of the lithospheric plates and the consequences of these interactions, is based on several important assumptions.

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1. The generation of new plate material occurs by *seafloor spreading*; that is, new oceanic lithosphere is generated along the active mid-ocean ridges (see Chapters 3 and 9).
2. The new oceanic lithosphere, once created, forms part of a rigid plate; this plate may, but need not, include continental material.
3. The Earth's surface area remains constant; therefore the generation of new plate by seafloor spreading must be balanced by destruction of plate elsewhere.
4. The plates are capable of transmitting stresses over great horizontal distances without buckling, in other words, the relative motion between plates is taken up only along plate boundaries.

Plate boundaries are of three types.

1. Along *divergent* boundaries, which are also called accreting or constructive, plates are moving away from each other. At such boundaries new plate material, derived from the mantle, is added to the lithosphere. The divergent plate boundary is represented by the *mid-ocean-ridge system*, along the axis of which new plate material is produced (Fig. 2.3(a)).
2. Along *convergent* boundaries, which are also called consuming or destructive, plates approach each other. Most such boundaries are represented by the *oceanic-trench*, *island-arc* systems of *subduction zones* where one of the colliding plates descends into the mantle and is destroyed (Fig. 2.3(c)). The downgoing plate often penetrates the mantle to depths of about 700 km. Some convergent boundaries occur on land. Japan, the Aleutians and the Himalayas are the surface expression of convergent plate boundaries.
3. Along *conservative* boundaries, lithosphere is neither created nor destroyed. The plates move laterally relative to each other (Fig. 2.3(e)). These plate boundaries are represented by *transform faults*, of which the San Andreas Fault in California, U.S.A. is a famous example. Transform faults can be grouped into six basic classes (Fig. 2.4). By far the most common type of transform fault is the ridge–ridge fault (Fig. 2.4(a)), which can range from a few kilometres to hundreds of kilometres in length. Some very long ridge–ridge faults occur in the Pacific, equatorial Atlantic and southern oceans (see Fig. 2.2, which shows the present plate boundaries, and Table 8.3). Adjacent plates move relative to each other at rates up to about 15 cm yr^{-1}.

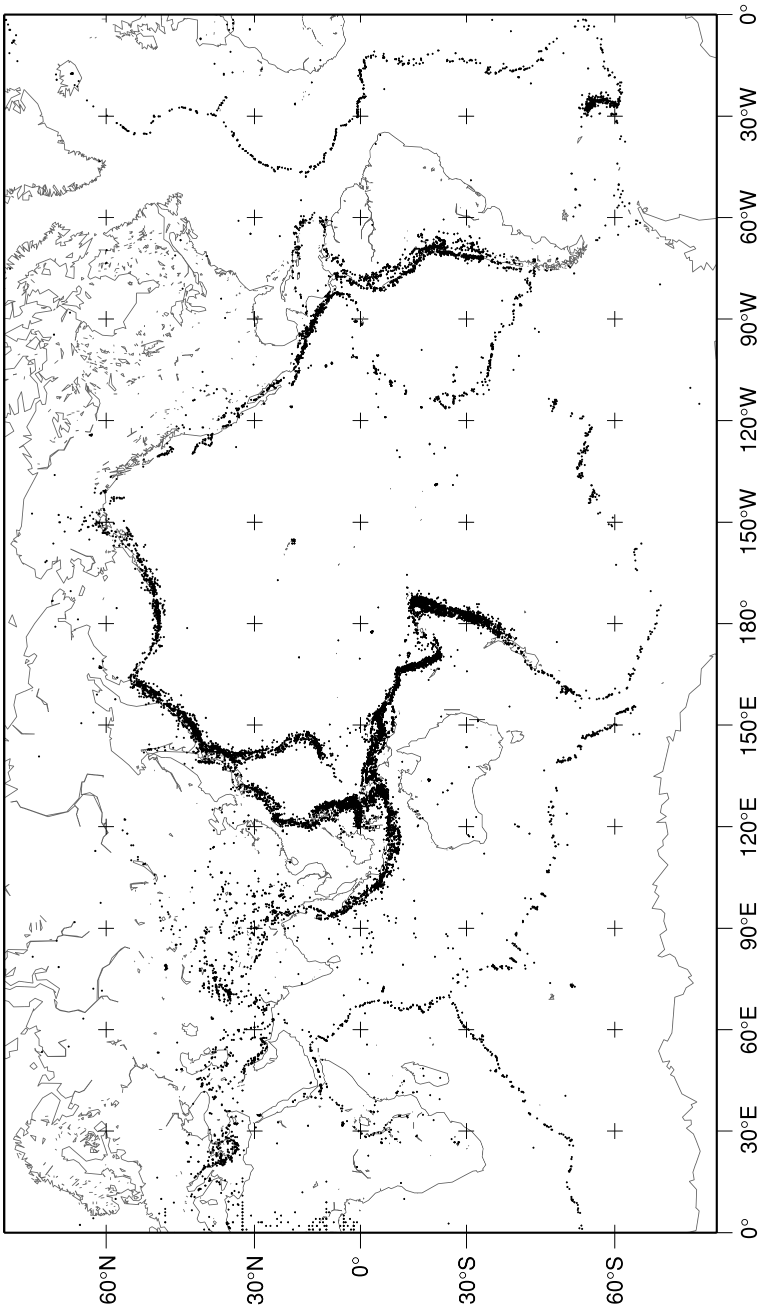

Figure 2.1. Twenty-three thousand earthquakes with magnitudes greater than 5.2 occurred between 1978 and 1989 at depths from 0 to 700 km. These earthquakes clearly delineate the boundaries of the plates. (From ISC catalogue.)

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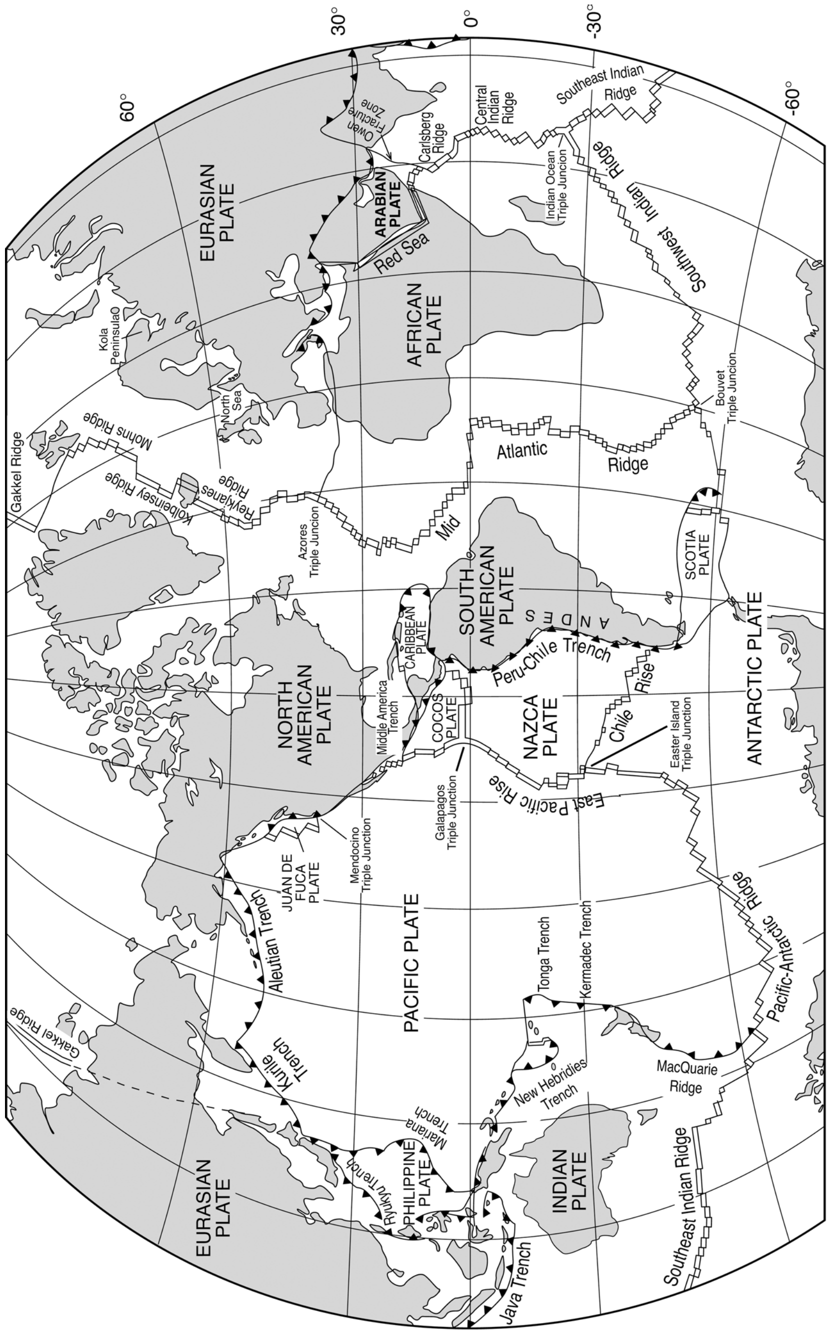

Figure 2.2. The major tectonic plates, mid-ocean ridges, trenches and transform faults.

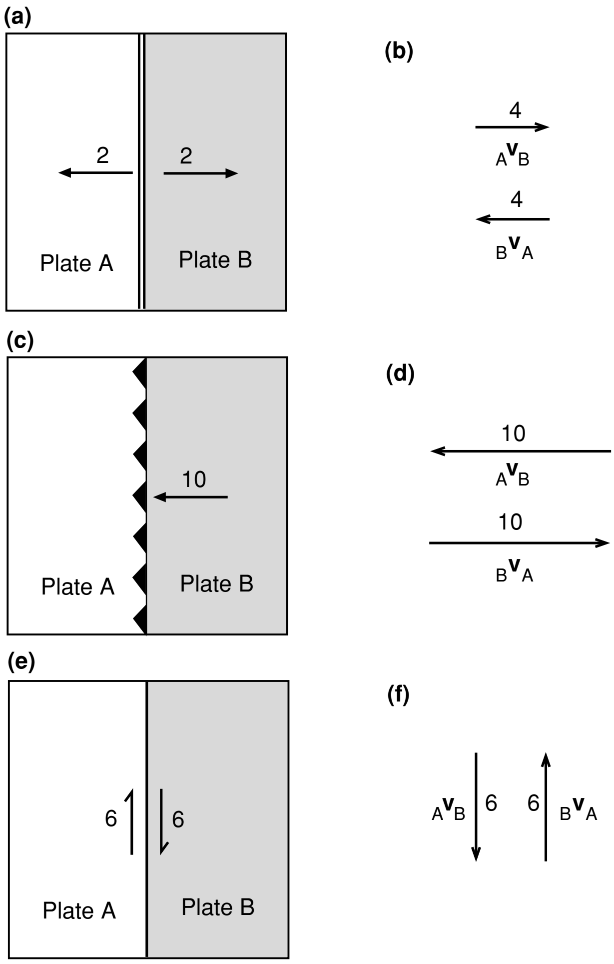

Figure 2.3. Three possible boundaries between plates A and B.
(a) A *constructive* boundary (mid-ocean ridge). The double line is the symbol for the ridge axis, and the arrows and numbers indicate the direction of spreading and relative movement of the plates away from the ridge. In this example the half-spreading rate of the ridge (half-rate) is 2 cm yr^{-1}; that is, plates A and B are moving apart at 4 cm yr^{-1}, and each plate is growing at 2 cm yr^{-1}. (b) The relative velocities $_A\mathbf{v}_B$ and $_B\mathbf{v}_A$ for the ridge shown in (a).
(c) A *destructive* boundary (subduction zone). The barbed line is the symbol for a subduction zone; the barbs are on the side of the overriding plate, pointing away from the subducting or downgoing plate. The arrow and number indicate the direction and rate of relative motion between the two plates. In this example, plate B is being subducted at 10 cm yr^{-1}. (d) The relative velocities $_A\mathbf{v}_B$ and $_B\mathbf{v}_A$ for the subduction zone shown in (c).
(e) A *conservative* boundary (transform fault). The single line is a symbol for a transform fault. The half-arrows and number indicate the direction and rate of relative motion between the plates: in this example, 6 cm yr^{-1}. (f) The relative velocities $_A\mathbf{v}_B$ and $_B\mathbf{v}_A$ for the transform fault shown in (e).

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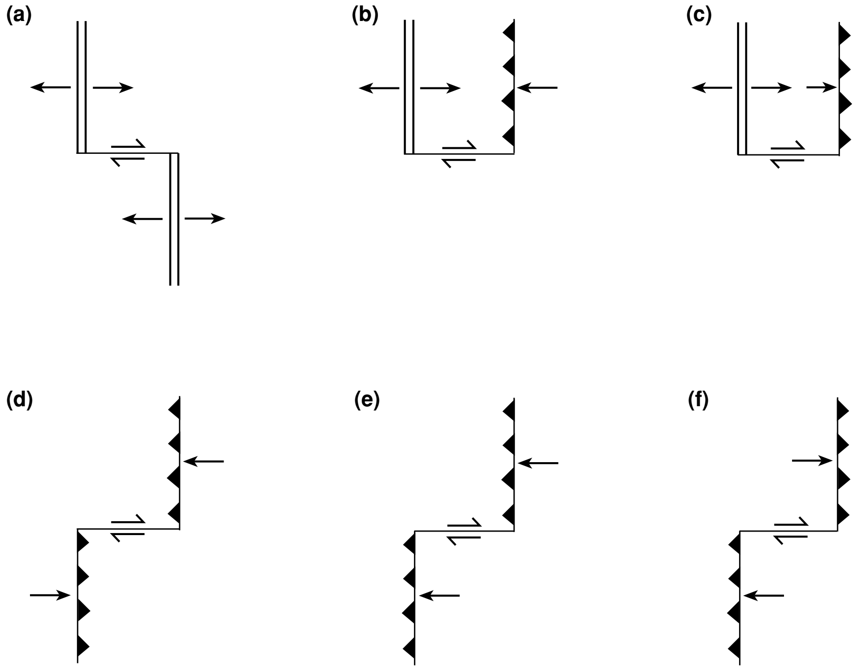

Figure 2.4. The six types of dextral (right-handed) transform faults. There are also six sinistral (left-handed) transform faults, mirror images of those shown here. (a) Ridge–ridge fault, (b) and (c) ridge–subduction-zone fault, (d), (e) and (f) subduction-zone–subduction-zone fault. (After Wilson (1965).)

The present-day rates of movement for all the main plates are discussed in Section 2.4.

Although the plates are made up of both oceanic and continental material, usually only the oceanic part of any plate is created or destroyed. Obviously, seafloor spreading at a mid-ocean ridge produces only oceanic lithosphere, but it is hard to understand why continental material usually is not destroyed at convergent plate boundaries. At subduction zones, where continental and oceanic materials meet, it is the oceanic plate which is subducted (and thereby destroyed). It is probable that, if the thick, relatively low-density continental material (the continental crustal density is approximately 2.8×10^3 kg m^{-3}) reaches a subduction zone, it may descend a short way, but, because the mantle density is so much greater (approximately 3.3×10^3 kg m^{-3}), the downwards motion does not continue. Instead, the subduction zone ceases to operate at that place and moves to a more favourable location. Mountains are built (*orogeny*) above subduction zones as a result of continental collisions. In other words, the continents are rafts of lighter material, which remain on the surface while the denser oceanic lithosphere is subducted beneath either oceanic or continental lithosphere. The discovery that plates can include both continental and oceanic parts, but that only the oceanic parts are created or destroyed, removed the main objection to the theory of *continental drift*, which was the unlikely concept that somehow continents were ploughing through oceanic rocks.