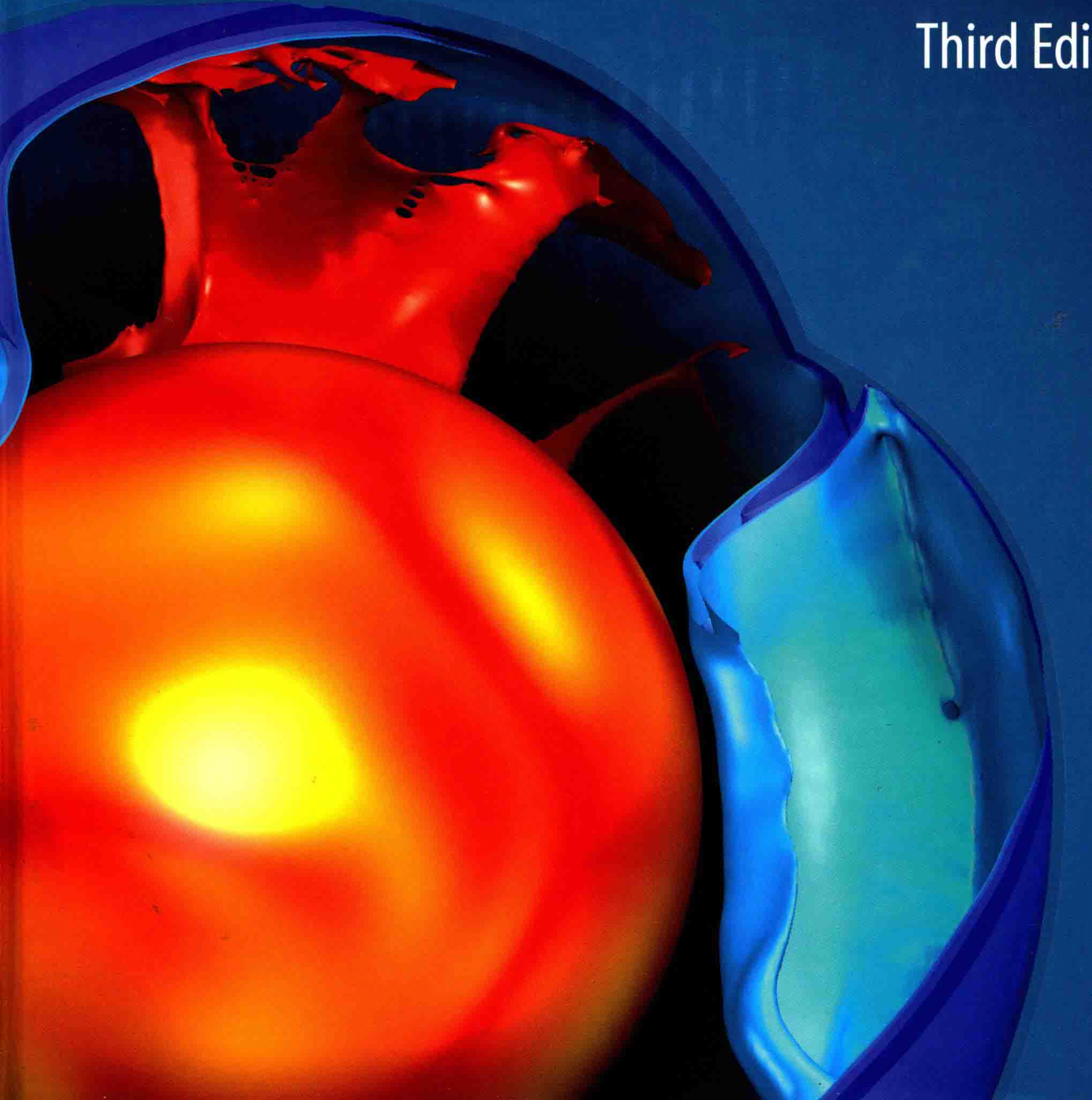
Donald Turcotte | Gerald Schubert

GEODYNAMICS

Third Edition



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THIRD EDITION

"*Geodynamics* continues to be the essential introduction to how the solid Earth evolves, through tectonic, volcanic, and near-surface activity as well as processes deep within our planet. It sets the standard for rigor, clarity, and accessibility to all geoscience students. With important new computational tools in this edition, providing hands-on programming examples in MATLAB, the authors have enhanced even further the enormous utility of this excellent book."
Professor David Bercovici, Department of Geology and Geophysics, Yale University

"The definitive reference in the field; a unique book that is invaluable for students and researchers alike. The new chapters on numerics and computation are a great addition that bring it firmly into the modern computational era. Highly recommended!"
Professor Paul J. Tackley, Institut für Geophysik, ETH Zürich

"For the past 30 years, *Geodynamics* has served as the primary textbook in the field. The core of the book provides a deterministic, physics-based exposition of solid-earth processes at a mathematical level accessible to most students. This third edition's new sections provide numerical solutions to problems in heat conduction, flexure, faulting, and thermal convection, making the connection between the fundamental analytical solutions and the more sophisticated numerical methods used by researchers today. The numerical examples can be run with MATLAB software or emulators such as Octave or Python."
Professor David T. Sandwell, Scripps Institution of Oceanography, UC San Diego

Essential reading for any Earth scientist, this classic textbook has been providing advanced undergraduate and graduate students with the fundamental tools needed to develop a quantitative understanding of the physical processes of the solid Earth for over thirty years. This third edition has two new chapters covering numerical modeling and geophysical MATLAB applications, and the text is now supported by a suite of online MATLAB codes, that enable students to grasp the practical aspects of computational modeling.

- Fully updated, including new material on planetary geophysics and other cutting edge topics.
- Key figures are now available in color.
- Exercises within the text allow students to put the theory into practice as they progress through each chapter, and selected answers support self-study.
- Carefully selected further reading encourages readers to delve deeper into topics of interest.

Donald L. Turcotte is Distinguished Professor Emeritus in the Department of Geology, University of California, Davis. In addition to this book, he is author or co-author of three books and over 400 research papers, including *Fractals and Chaos in Geology and Geophysics* (Cambridge University Press, 1992 and 1997) and *Mantle Convection in the Earth and Planets* (with Gerald Schubert and Peter Olson; Cambridge University Press, 2001). Professor Turcotte is a Fellow of the American Geophysical Union, Honorary Fellow of the European Union of Geosciences, and Fellow of the Geological Society of America, and is also a member of the National Academy of Sciences and the American Academy of Arts and Sciences. He is the recipient of several medals, including the Day Medal of the Geological Society of America, the Wegener Medal of the European Union of Geosciences, the Bowie and Whitten Medals of the American Geophysical Union, the Regents (New York State) Medal of Excellence, and Caltech's Distinguished Alumnus Award.

Gerald Schubert is Distinguished Professor Emeritus in the Department of Earth, Planetary and Space Sciences at the University of California, Los Angeles. He is co-author with Donald Turcotte and Peter Olson of *Mantle Convection in the Earth and Planets* (Cambridge University Press, 2001) and author of over 530 research papers. He has participated in a number of NASA's planetary missions and has been on the editorial boards of many journals, including *Icarus*, *Journal of Geophysical Research*, *Geophysical Research Letters*, and *Annual Reviews of Earth and Planetary Sciences*. Professor Schubert is a Fellow of the American Geophysical Union and a recipient of the Union's James B. MacElwane medal and the Harry H. Hess medal. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences.

Preface to the Third Edition

This textbook deals with the fundamental physical processes necessary for an understanding of plate tectonics and a variety of geological phenomena. We believe that the appropriate title for this material is *geodynamics*. The contents of this textbook evolved from a series of courses given at Cornell University and UCLA to students with a wide range of backgrounds in geology, geophysics, physics, mathematics, chemistry, and engineering. The level of the students ranged from advanced undergraduate to graduate.

Approach

We present most of the material with a minimum of mathematical complexity. In general, we do not introduce mathematical concepts unless they are essential to the understanding of physical principles. For example, our treatment of elasticity and fluid mechanics avoids the introduction or use of tensors. We do not believe that tensor notation is necessary for the understanding of these subjects or for most applications to geological problems. However, solving partial differential equations is an essential part of this textbook. Many geological problems involving heat conduction and solid and fluid mechanics require solutions of such classic partial differential equations as Laplace's equation, Poisson's equation, the biharmonic equation, and the diffusion equation. All these equations are derived from first principles in the geological contexts in which they are used. We provide elementary explanations for such important physical properties of matter as solid-state viscosity, thermal coefficient of expansion, specific heat, and permeability. Basic concepts involved in the studies of heat transfer, Newtonian and non-Newtonian fluid behavior, the bending of thin elastic plates, the mechanical behavior of faults, and the interpretation of gravity anomalies are emphasized. Thus it is expected that the student will develop a thorough understanding of such fundamental physical laws as Hooke's law of elasticity, Fourier's law of heat conduction, and Darcy's law for fluid flow in porous media.

The first chapter reviews plate tectonics; its main purpose is to provide physics, chemistry, and engineering students with the geological background necessary to understand the applications considered throughout the rest of the textbook. We hope that the geology student can also benefit from this summary of numerous geological, seismological, and paleomagnetic observations. This chapter also summarizes the geological and geophysical characteristics of the other planets and satellites of the solar system. Chapter 2 introduces the concepts of stress and strain and discusses the measurements of these quantities in the Earth's crust. Space-based geodetic observations have revolutionized our understanding of surface strain fields associated with tectonics. We introduce the reader to satellite data obtained from the global positioning system (GPS) and synthetic aperture radar interferometry (INSAR).

Chapter 3 presents the basic principles of linear elasticity. The bending of thin elastic plates is emphasized and is applied to problems involving the bending of the Earth's lithosphere. Chapter 4 deals mainly with heat conduction and the application of this theory to temperatures in the continental crust and the continental and oceanic lithospheres. Heat transfer by convection is discussed and applied to a determination of temperature in the Earth's mantle. Surface heat flow measurements are reviewed and interpreted in terms of the theory. The sources of the Earth's surface heat flow are discussed. Problems involving the solidification of magmas and extrusive lava flows are treated. We also present in this chapter the Culling model for the diffusive erosion and deposition of sediments. The basic principles involved in the interpretation of gravity measurements are given in Chapter 5. We show

how geoid anomalies are directly related to the forces required to maintain topography.

Fluid mechanics is studied in Chapter 6; problems involving mantle convection and postglacial rebound are emphasized. We combine a pipe-flow model with a Stokes-flow model in order to determine the structure and strength of plume heads and plume tails. The relationship between hotspot swells and the associated plume flux is also introduced. In addition to the steady-state boundary-layer model for the structure of mantle convection cells, we introduce a transient boundary-layer model for the stability of the lithosphere.

Chapter 7 deals with the rheology of rock or the manner in which it deforms or flows under applied forces. Fundamental processes are discussed from a microscopic point of view. The mechanical behavior of faults is discussed in Chapter 8 with particular attention being paid to observations of displacements along the San Andreas fault. Chapter 9 discusses the principles of fluid flow in porous media, a subject that finds application to hydrothermal circulations in the oceanic crust and in continental geothermal areas. Chapter 10 introduces the basic concepts of chemical geodynamics. The object is to utilize geochemical data, particularly the isotope systematics of basalts, to infer mantle dynamics. Questions addressed include the homogeneity of the mantle and the fate of subducted lithosphere.

The contents of this textbook are intended to provide the material for a coherent one-year course. In order to accomplish this goal, some important aspects of geodynamics have had to be omitted. In particular, the fundamentals of seismology are not included. Thus the wave equation and its solutions are not discussed. Many seismic studies have provided important data relevant to geodynamic processes. Examples include (1) the radial distribution of density in the Earth as inferred from the radial profiles of seismic velocities; (2) important information on the locations of plate boundaries and the locations of descending plates at ocean trenches provided by accurate determinations of the epicenters of earthquakes; and (3) details of the structure of the continental crust obtained by seismic reflection profiling using artificially generated waves. An adequate treatment of seismology would have required a very considerable expansion of this textbook. Fortunately, there are a number of excellent textbooks on this subject.

A comprehensive study of the spatial and temporal variations of the Earth's magnetic field is also considered to be outside the scope of this textbook. A short discussion of the Earth's magnetic field relevant to paleomagnetic observations is given in Chapter 1. However, mechanisms for the generation of the Earth's magnetic field are not considered.

In writing this textbook, several difficult decisions had to be made. One was the choice of units; we use SI units throughout. This system of units is defined in Appendix A. We feel there is a strong trend toward the use of SI units in both geology and geophysics. We recognize, however, that many cgs units are widely used. Examples include μcal cm^{-2} s^{-1} for heat flow, kilobar for stress, and milligal for gravity anomalies. For this reason we have often included the equivalent cgs unit in parentheses after the SI unit, for example, MPa (kbar). Another decision involved the referencing of original work. We do not believe that it is appropriate to include a large number of references in a basic textbook. We have credited those individuals making major contributions to the development of the theory of plate tectonics and continental drift in our brief discussion of the history of this subject in Chapter 1. We also provide references to data.

New to this edition

The principal addition to the third edition of *Geodynamics* is the inclusion of numerical methods and numerical solutions. Many problems in geodynamics are nonlinear, and the applicable equations must be solved numerically. In our numerical solutions we utilize MATLAB. This is a computer programming language that is widely used and is widely available. MATLAB codes are used to obtain numerical solutions to problems and to plot results. An introduction to MATLAB and a short discussion of some numerical methods are given in Chapter 11. Chapter 12 provides MATLAB codes to solve a variety of geodynamic problems. Included are applications to problems discussed in previous chapters and additional problems not previously considered. Solutions to some of these problems involve the use of more sophisticated mathematical methods than are generally employed throughout the book. MATLAB solutions to selected problems in the text are given in Appendix D.

Pedagogical features

- The problems are an integral part of this textbook and are located within each chapter enabling students to put the theory into practice as they work through the book. It is only through solving a substantial number of exercises that an adequate understanding of the underlying physical principles can be developed. Answers to selected problems are provided in Appendices C and D and online so that students who are self-studying can easily check their work. Problems utilizing MATLAB are highlighted in the text M, with accompanying MATLAB codes and solutions available online at www.cambridge.org/geodynamics. The text is supported by clear figures, with key images now available in color in the book and additional color figures online.
- Each chapter begins with a short introduction, helping the reader to focus on what the chapter will cover and how this fits into the rest of the book.
- Chapters conclude with a summary, providing a review of the important concepts discussed in that chapter.
- A list of recommended reading is given at the end of each chapter. In many instances these are textbooks and reference books, but in some cases review papers are included. In each case, the objective is to provide background material for the chapter or to extend its content.

Online resources

Supporting online resources for instructors and students are available at www.cambridge.org/geodynamics. These include:

- MATLAB codes for computational problems;
- selected answers to problems;
- JPEGs and PowerPoint presentations of figures from the book;
- additional color figures.

Acknowledgments

Many of our colleagues have read all or parts of various drafts of this textbook.

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Contents

1

Plate Tectonics

In this Chapter

The plate tectonic model provides a framework for understanding many geodynamic processes. Earthquakes, volcanism, and mountain building are examples. The plate velocities, 10–100 mm yr^{-1}, imply a fluid-like behavior of the solid Earth. Hot mantle rock can flow (behave as a fluid) on geological time scales due to solid-state creep and thermal convection. The hot mantle rock is cooled by heat loss to the Earth's surface resulting in a *cold thermal "boundary layer."* This boundary layer is rigid and is referred to as the lithosphere. The surface *lithosphere* is broken into a series of plates that are in relative motion with respect to each other. This motion results in *"plate tectonics."*

Plates are created at *mid-ocean ridges*, where hot mantle rock ascends. Partial melting in the ascending rock produces the magmas that form the *basaltic ocean crust*. The surface plates reenter the mantle at *ocean trenches* (*subduction*). The cold rock in the plate (lithosphere) is denser than the adjacent hot mantle rock. This results in a downward gravitational body force that drives the motion of the surface plate. Complex volcanic processes at subduction zones generate the *continental crust*. This crust is thick and light and does not participate in the plate-tectonic cycle. Thus the continental crust is about a factor of 10 older, on average, than the oceanic crust (1 Ga versus 100 Ma).

Interactions between plates at plate boundaries are responsible for a large fraction of the *earthquakes* that occur. Earthquakes are caused by episodic ruptures and displacements on preexisting faults. These displacements provide the relative motions between surface plates. Plate boundary processes are also responsible for a large fraction of the surface *volcanism*.

However, surface volcanism also occurs within plate interiors. At least a fraction of this volcanism can be attributed to *mantle plumes* that impinge on the base of the lithosphere. Mantle plumes are thin conduits of hot solid mantle rock that ascend from great depths.

One important consequence of plate tectonics is *continental drift*. Oceans open and close. The western and eastern boundaries of the Atlantic Ocean fit together like a jigsaw puzzle. New oceans are created at rifts in the continental crust. An example of a young ocean is the Red Sea. Oceans also close, resulting in *continental collisions*. An example is the Himalaya mountain belt that is the result of a continental collision between India and Asia.

A major goal of this book is to provide a fundamental understanding of why our planet has plate tectonics. Heat is being produced within the Earth due to the decay of radioactive isotopes. The interior of the Earth is hot and its surface is cold. The hot rock is less dense than the cold rock, leading to a gravitational instability. Because the hot mantle behaves as a fluid on geological time scales, this instability causes thermal convection. The plate tectonic cycle is one consequence of thermal convection in the Earth's mantle.

We also discuss *comparative planetology* in this chapter. Our knowledge of the structure and behavior of the other terrestrial planets, Mercury, Venus, and Mars, as well as major planetary satellites, the Moon and the satellites of Jupiter and Saturn, is summarized. Two important examples are the constraints on the early solar system obtained from lunar samples returned by the Apollo missions and the lack of plate tectonics on Venus. Considering the similarities in composition and size between the Earth and Venus, the absence of plate tectonics on Venus is a surprise.

1.1 Introduction

Plate tectonics is a model in which the outer shell of the Earth is divided into a number of thin, rigid plates that are in relative motion with respect to one another. The relative velocities of the plates are of the order of a few tens of millimeters per year. A large fraction of all earthquakes, volcanic eruptions, and mountain building occurs at plate boundaries. The distribution of the major surface plates is illustrated in Figure 1.1.

The plates are made up of relatively cool rocks and have an average thickness of about 100 km. The plates are being continually created and consumed. At ocean ridges adjacent plates diverge from each other in a process known as *seafloor spreading*. As the adjacent plates diverge, hot mantle rock ascends to fill the gap. The hot, solid mantle rock behaves like a fluid because of solid-state creep processes. As the hot mantle rock cools, it becomes rigid and accretes to the plates, creating new plate area. For this reason ocean ridges are also known as *accreting plate boundaries*. The accretionary process is symmetric to a first approximation so that the rates of plate formation on the two sides of a ridge are approximately equal. The rate of plate formation on one side of an ocean ridge defines a half-spreading velocity u. The two plates spread with a relative velocity of $2u$. The global system of ocean ridges is denoted by the heavy dark lines in Figure 1.1.

Because the surface area of the Earth is essentially constant, there must be a complementary process of plate consumption. This occurs at *ocean trenches*. The surface plates bend and descend into the interior of the Earth in a process known as *subduction*. At an ocean trench the two adjacent plates converge, and one descends beneath the other. For this reason ocean trenches are also known as *convergent plate boundaries*. The worldwide distribution of trenches is shown in Figure 1.1 by the lines with triangular symbols, which point in the direction of subduction.

A cross-sectional view of the creation and consumption of a typical plate is illustrated in Figure 1.2. That part of the Earth's interior that comprises the plates is referred to as the *lithosphere*. The rocks that make up the lithosphere are relatively cool and rigid; as a result, the interiors of the plates do not deform significantly as they move about the surface of the Earth. As the plates move away from ocean ridges, they cool and thicken. The solid rocks beneath the lithosphere are sufficiently hot to be able to deform freely; these rocks comprise the *asthenosphere*, which lies below the lithosphere. The lithosphere slides over the asthenosphere with relatively little resistance.

As the rocks of the lithosphere become cooler, their density increases because of thermal contraction. As a result, the lithosphere becomes gravitationally unstable with respect to the hot asthenosphere beneath. At the ocean trench the lithosphere bends and sinks into the interior of the Earth because of this negative buoyancy. The downward gravitational body force on the descending lithosphere plays an important role in driving plate tectonics. The lithosphere acts as an elastic plate that transmits large elastic stresses without significant deformation. Thus the gravitational body force can be transmitted directly to the surface plate and this force pulls the plate toward the trench. This body force is known as *trench pull*. Major faults separate descending lithospheres from adjacent overlying lithospheres. These faults are the sites of most great earthquakes. Examples are the Chilean earthquake in 1960, the Alaskan earthquake in 1964,

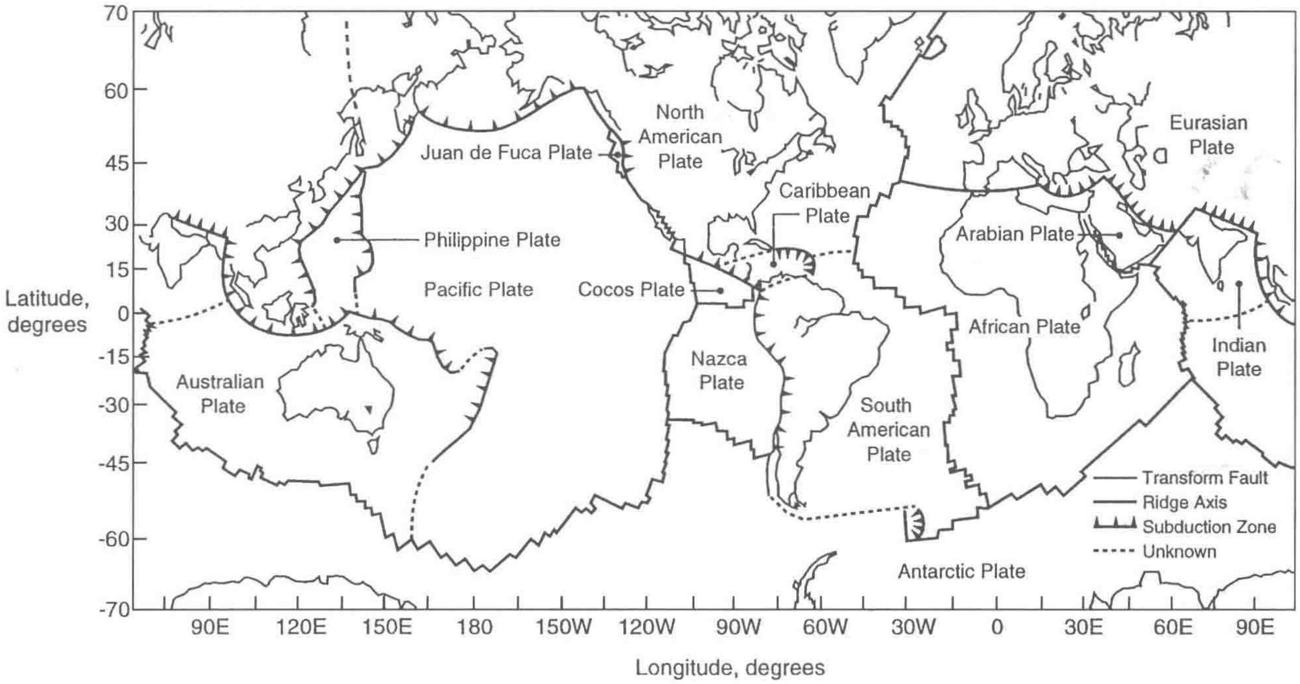

Figure 1.1 Distribution of the major plates. The ocean ridge axis (accretional plate margins), subduction zones (convergent plate margins), and transform faults that make up the plate boundaries are shown.

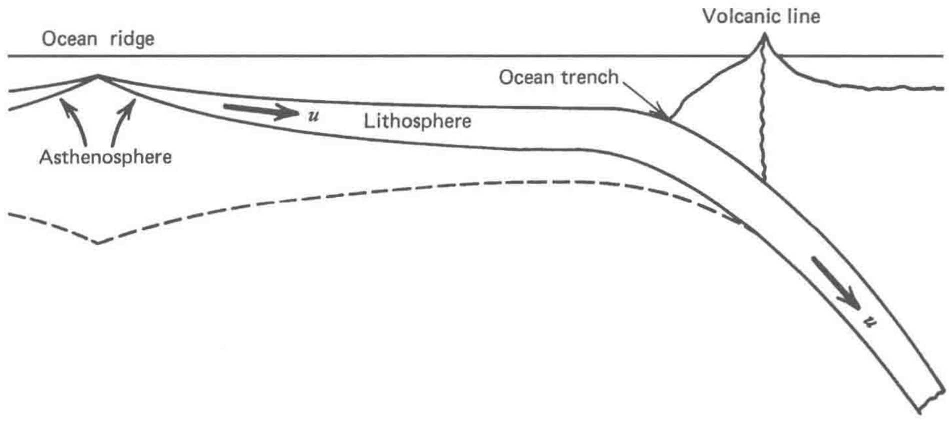

Figure 1.2 Accretion of a lithospheric plate at an ocean ridge and its subduction at an ocean trench. The asthenosphere, which lies beneath the lithosphere, is shown along with the line of volcanic centers associated with subduction.

the Sumatra earthquake in 2004, and the Tohoku, Japan, earthquake in 2011. These are the largest earthquakes that have occurred since modern seismographs have been available. The locations of the descending lithospheres can be accurately determined from the earthquakes occurring in the cold, brittle rocks of the lithospheres. These planar zones of earthquakes associated with subduction are known as *Wadati–Benioff zones*.

Lines of active volcanoes lie parallel to almost all ocean trenches. These volcanoes occur about 125 km above the descending lithosphere. At least a fraction of the magmas that form these volcanoes are produced near the upper boundary of the descending lithosphere and rise some 125 km to the surface. If these volcanoes stand on the seafloor, they form an *island arc*, as typified by the Aleutian Islands in the North Pacific. If the trench lies adjacent to a continent, the volcanoes grow from the land surface. This is the case in the western United States, where a volcanic line extends from Mount Baker in the north to Mount Shasta in the south. Mount St. Helens, the site of a violent eruption in 1980, forms a part of this volcanic line. These volcanoes are the sites of a large fraction of the most explosive and violent volcanic eruptions. The eruption of Mount Pinatubo in the Philippines in 1991, the most violent eruption of the twentieth century, is another example. A typical subduction zone volcano is illustrated in Figure 1.3.

The Earth's surface is divided into continents and oceans. The oceans have an average depth of about 4 km, and the continents rise above sea level. The reason for this difference in elevation is the difference in the thickness of the crust. Crustal rocks have a different composition from that of the mantle rocks beneath and are less dense. The crustal rocks are therefore gravitationally stable with respect to the heavier mantle rocks. There is usually a well-defined boundary, the *Moho* or Mohorovičić discontinuity, between the crust and mantle. A typical thickness for *oceanic crust* is 6 km; *continental crust* is about 35 km thick. Although oceanic crust is gravitationally stable, it is sufficiently thin so that it does not significantly impede

Figure 1.3 Izalco volcano in El Salvador, an example of a subduction zone volcano (NOAA–NGDC Howell Williams).

the subduction of the gravitationally unstable oceanic lithosphere. The oceanic lithosphere is continually cycled as it is accreted at ocean ridges and subducted at ocean trenches. Because of this cycling the average age of the ocean floor is about 10^8 years (100 Ma).

On the other hand, the continental crust is sufficiently thick and gravitationally stable so that it is not subducted at an ocean trench. In some cases the denser lower continental crust, along with the underlying gravitationally unstable continental mantle lithosphere, can be recycled into the Earth's interior in a process known as *delamination*. However, the light rocks of the upper continental crust remain in the continents. For this reason the rocks of the continental crust, with an average age of about 2×10^9 years (2 Ga), are much older than the rocks of the oceanic crust. As the lithospheric plates move across the surface of the Earth, they carry the continents with them. The relative motion of continents is referred to as *continental drift*.

Much of the historical development leading to plate tectonics concerned the validity of the hypothesis of continental drift: that the relative positions of continents change during geologic time. The similarity in shape between the west coast of Africa and the east coast of South America was noted as early as 1620 by Francis Bacon. This "fit" has led many authors to speculate on how these two continents might have been attached. A detailed exposition of the hypothesis of continental drift was put forward by Frank B. Taylor (1910). The hypothesis was further developed by Alfred Wegener beginning in 1912 and summarized in his book *The Origin of Continents and Oceans* (Wegener, 1946). As a meteorologist, Wegener was particularly interested in the observation that glaciation had occurred in equatorial regions at the same time that tropical conditions prevailed at high latitudes. This observation in itself could be explained by *polar wander*, a shift of the rotational axis without other surface deformation. However, Wegener also set forth many of the qualitative arguments that the continents had formerly been attached. In addition to the observed fit of continental margins, these arguments included the correspondence of geological provinces, continuity of structural features such