Geodynamics

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.

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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.

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