GEODYNAMICS

Second Edition

First published in 1982, Don Turcotte and Jerry Schubert's *Geodynamics* became a classic textbook for several generations of students of geophysics and geology. In this second edition, the authors bring this classic text completely up-to-date. Important additions include a chapter on chemical geodynamics, an updated coverage of comparative planetology based on recent planetary missions, and a variety of other new topics.

Geodynamics provides the fundamentals necessary for an understanding of the workings of the solid Earth. The Earth is a heat engine, with the source of the heat the decay of radioactive elements and the cooling of the Earth from its initial accretion. The work output includes earthquakes, volcanic eruptions, and mountain building. *Geodynamics* comprehensively explains these concepts in the context of the role of mantle convection and plate tectonics. Observations such as the Earth's gravity field, surface heat flow, distribution of earthquakes, surface stresses and strains, and distribution of elements are discussed. The rheological behavior of the solid Earth, from an elastic solid to fracture to plastic deformation to fluid flow, is considered. Important inputs come from a comparison of the similarities and differences between the Earth, Venus, Mars, Mercury, and the Moon. An extensive set of student exercises is included.

This new edition of *Geodynamics* will once again prove to be a classic textbook for intermediate to advanced undergraduates and graduate students in geology, geophysics, and Earth science.

Donald L. Turcotte is Maxwell Upson Professor of Engineering, Department of Geological Sciences, Cornell University. In addition to this book, he is author or co-author of 3 books and 276 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. 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 Whitten Medal of the American Geophysical Union, the Regents (New York State) Medal of Excellence, and Caltech's Distinguished Alumnus Award. Professor Turcotte is a member of the National Academy of Sciences and the American Academy of Arts and Sciences.

Gerald Schubert is a Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics 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 400 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. He is a member of the American Academy of Arts and Sciences.

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Preface

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.

In all cases we present the material with a minimum of mathematical complexity. We have not introduced 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 problems are an integral part of this textbook. 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.

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. Since plate tectonics is a continuously evolving subject, this material may be subject to revision. Chapter 1 also briefly 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. 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 briefly 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 also treated. The basic principles involved in the interpretation of gravity measurements are given in Chapter 5. Fluid mechanics is studied in Chapter 6; problems involving mantle convection and postglacial rebound are emphasized. 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. Finally, 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.

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 1. 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. At the end of each chapter a list of recommended reading is given. 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.

Many of our colleagues have read all or parts of various drafts of this textbook. We acknowledge the contributions made by Jack Bird, Peter Bird, Muawia Barazangi, Allan Cox, Walter Elsasser, Robert Kay, Suzanne Kay, Mark Langseth, Bruce Marsh, Jay Melosh, John Rundle, Sean Solomon, David Stevenson, Ken Torrance, and David Yuen. We particularly wish to acknowledge the many contributions to our work made by Ron Oxburgh and the excellent manuscript preparation by Tanya Harter.

Preface to the Second Edition

As we prepared our revisions for this second edition of *Geodynamics* we were struck by the relatively few changes and additions that were required. The reason is clear: this textbook deals with fundamental physical processes that do not change. However, a number of new ideas and concepts have evolved and have been included where appropriate.

In revising the first chapter on plate tectonics we placed added emphasis on the concept of mantle plumes. In particular we discussed the association of plume heads with continental flood basalts. We extensively revised the sections on comparative planetology. We have learned new things about the Moon, and the giant impact hypothesis for its origin has won wide acceptance. For Venus, the Magellan mission has revolutionized our information about the planet. The high-resolution radar images, topography, and gravity data have provided new insights that emphasize the tremendous differences in structure and evolution between Venus and the Earth. Similarly, the Galileo mission has greatly enhanced our understanding of the Galilean satellites of Jupiter.

In Chapter 2 we introduce the crustal stretching model for the isostatic subsidence of sedimentary basins. This model provides a simple explanation for the formation of sedimentary basins. 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). In Chapter 4 we introduce the plate cooling model for the thermal structure of the oceanic lithosphere as a complement to the half-space cooling model. We also present in this chapter the Culling model for the diffusive erosion and deposition of sediments. In Chapter 5 we show how geoid anomalies are directly related to the forces required to maintain topography.

In Chapter 6 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.

Finally, we conclude the book with a new Chapter 10 on chemical geodynamics. The concept of chemical geodynamics has evolved since the first edition was written. 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, the fate of subducted lithosphere, and whether whole mantle convection or layered mantle convection is occurring.

The use of SI units is now firmly entrenched in geology and geophysics, and we use these units throughout the book. Since *Geodynamics* is meant to be a textbook, large numbers of references are inappropriate. However, we have included key references and references to sources of data in addition to recommended collateral reading.

In addition to the colleagues who we acknowledge in the preface to the first edition, we would like to add Claude Allègre, Louise Kellogg, David Kohlstedt, Bruce Malamud, Mark Parmentier, and David Sandwell. We also acknowledge the excellent manuscript preparation by Stacey Shirk and Judith Hohl, and figure preparation by Richard Sadakane.

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