Mantle Convection in the Earth and Planets

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Preface

This book gives a comprehensive and connected account of all aspects of mantle convection within the Earth, the terrestrial planets, the Moon, and the Galilean satellites of Jupiter. Convection is the most important process in the mantle, and it sets the pace for the evolution of the Earth as a whole. It controls the distribution of land and water on geologic time scales, and its influences range from the Earth's climate system, cycles of glaciation, and biological evolution to the formation of mineral and hydrocarbon resources. Because mantle convection is the primary mechanism for the transport of heat from the Earth's deep interior to its surface, it is the underlying cause of plate tectonics, formation and drift of continents, volcanism, earthquakes, and mountain building processes. It also shapes the gravitational and magnetic fields of the Earth. Mantle convection plays similar, but not identical, roles in the other planets and satellites.

This book is primarily intended as a research monograph. Our objective is to provide a thorough treatment of the subject appropriate for anyone familiar with the physical sciences who wishes to learn about this fascinating subject. Some parts of the book are quite mathematical, but other parts are qualitative and descriptive. Accordingly, it could be used as a text for advanced coursework in geophysics and planetary physics, or as a supplementary reference for introductory courses.

The subject matter has been selected quite broadly because, as noted above, mantle convection touches on so many aspects of the Earth and planetary sciences. A comprehensive index facilitates access to the content and an extensive reference list does the same for the relevant literature. A list of symbols eases their identification. We highlight major unanswered questions throughout the text, to focus the discussion and suggest avenues of future research. There are numerous illustrations, some in color, of results from advanced numerical models of mantle convection, laboratory experiments, and global geophysical and planetary data sets. Many complex geodynamical processes are explained using simple, idealized mathematical models.

We begin with a historical background in Chapter 1. Qualitative evidence for the drift of the continents over the Earth's surface was available throughout much of the first half of the twentieth century, while at the same time a physical understanding of thermal convection was being developed. However, great insight was required to put these together, and this happened only gradually, within an atmosphere of enormous controversy. The pendulum began to swing towards acceptance of continental drift and mantle convection in the 1950s and 1960s as a result of paleomagnetic data indicating that continents move relative to one another and seafloor magnetic data indicating that new seafloor is continually created at mid-ocean ridges.

The concepts of continental drift, seafloor spreading, and mantle convection became inseparably linked following the recognition of plate tectonics in the late 1960s. Plate tectonics unified a wide range of geological and geophysical observations. In plate tectonics the surface of the Earth is divided into a small number of nearly rigid plates in relative motion. Chapter 2 presents an overview of plate tectonics, including the critical processes beneath ridges and deep-sea trenches, with emphasis on their relationship to mantle convection. This chapter also introduces some other manifestations of convection not so closely related to plate tectonics, including volcanic hot spots that mark localized plume-like mantle upwellings, and the evidence for delamination, where dense lower portions of some plates detach and sink into the underlying mantle.

To understand mantle convection we need to know what the Earth is like inside. In Chapter 3 we discuss the internal structure of the Earth and describe in detail the properties of its main parts: the thin, solid, low-density silicate crust, the thick, mostly solid, high-density silicate mantle, and the central, partially solidified, metallic core. Seismology is the source of much of what we know about the Earth's interior. Chapter 3 summarizes both the average radial structure of the Earth and its lateral heterogeneity as revealed by seismic tomography. The chapter also describes the pressure-induced changes in the structure of mantle minerals, including the olivine–spinel and spinel–perovskite + magnesiowüstite transitions that occur in the mantle transition zone and influence the nature of mantle convection.

Radiogenic heat sources and high temperatures at depth in the Earth drive mantle convection, and the cooling of the Earth by convective heat transfer in turn controls the Earth's temperature. The Earth's thermal state is the subject of Chapter 4. Here we discuss the geothermal heat flow at the surface, the sources of heat inside the Earth, the thermal properties of the mantle including thermal conductivity and thermal expansivity, and the overall thermal state of the Earth. Chapter 4 includes analysis of the oceanic lithosphere as the upper thermal boundary layer of mantle convection and considers the thermal structure of the continental lithosphere. The adiabatic nature of the vigorously convecting mantle is discussed and the D″ layer at the base of the mantle is analyzed as the lower thermal and compositional boundary layer of mantle convection. The thermal structure of the core is reviewed. Mechanisms of magma migration through the mantle and crust are treated in considerable detail.

Mantle convection requires that the solid mantle behave as a fluid on geological time scales. This implies that the solid mantle has a long-term viscosity. In Chapter 5, the physical mechanisms responsible for viscous behavior are discussed and the observations used to deduce the mantle viscosity are reviewed, along with the relevant laboratory studies of the viscous behavior of mantle materials.

In Chapter 6, the equations that govern the fluid behavior of the mantle are introduced. The equations that describe thermal convection in the Earth's mantle are nonlinear, and it is not possible to obtain analytical solutions under conditions fully applicable to the real Earth. However, linearized versions of the equations of motion provide important information on the onset of thermal convection. This is the subject of Chapter 7. A variety of approximate solution methods are introduced in Chapter 8, including the boundary layer approximation that explains the basic structure of the oceanic lithosphere. Concepts of dynamical chaos are introduced and applied to mantle convection. Numerical solutions of the mantle convection equations in two and three dimensions are given in Chapters 9 and 10, respectively. Observations and theory relevant to mantle plumes are presented in Chapter 11. In Chapter 12, geochemical observations pertinent to mantle convection are given along with the basic concepts of chemical geodynamics. Chapter 13 discusses the thermal history of the Earth and introduces the approximate approach of parameterized convection as a tool in studying thermal evolution.

Mantle convection is almost certainly occurring within Venus and it may also be occurring, or it may have occurred, inside Mars, Mercury, the Moon, and many of the satellites of the outer planets. Observations and theory pertaining to mantle convection in planets and satellites are given in Chapter 14. Mercury, Venus, Mars, the Moon, and the Galilean satellites of Jupiter – Io, Europa, Ganymede, and Callisto – are all discussed in detail. Each of these bodies provides a unique situation for the occurrence of mantle convection. Tidal heating, unimportant in the Earth and the terrestrial planets, is the primary heat source for Io. The orbital and thermal evolutions of Io, Europa, and Ganymede are strongly coupled, unlike the orbital and thermal histories of the Earth and inner planets. The rheology of ice, not rock, controls mantle convection in the icy satellites Ganymede and Callisto. Among the many questions addressed in Chapter 14 are why Venus does not have plate tectonics and whether Mars once did. Methods of parameterized convection are employed in Chapter 14 to study the thermal evolution of the planets and satellites.

The results presented in this book are summarized in Chapter 15. Throughout the book questions are included in the text to highlight and focus discussion. Some of these questions have generally accepted answers whereas other answers remain controversial. The discussion given in Chapter 15 addresses the answers, or lack of answers, to these questions.

Our extensive reference list is a testimony to several decades of substantial progress in understanding mantle convection. Even so, it is not possible to include all the pertinent literature or to acknowledge all the significant contributions that have led to our present level of knowledge. We apologize in advance to our colleagues whose work we may have unintentionally slighted. We point out that this oversight is, in many cases, simply a consequence of the general acceptance of their ideas.

Many of our colleagues have read parts of various drafts of this book and their comments have substantially helped us prepare the final version. We would like to acknowledge in this regard the contributions of Larry Cathles, Robert Kay, David Kohlstedt, Paul Tackley, John Vidale, Shun Karato, and Orson Anderson. A few of the chapters of this book were used in teaching and our students also provided helpful suggestions for improving the text. Other colleagues generously provided figures, many of which are prominently featured in our book. Illustrations were contributed by David Sandwell, Paul Tackley, Henry Pollack, David Yuen, Maria Zuber, Todd Ratcliff, William Moore, Sami Asmar, David Smith, Alex Konopliv, Sean Solomon, Louise Kellogg, Laszlo Keszthelyi, Peter Shearer, Yanick Ricard, Brian Kennett, and Walter Mooney. The illustration on the cover of this book was prepared by Paul Tackley. Paul Roberts diligently worked on the weakly nonlinear stability theory of Section 8.8 and provided the solution for hexagonal convection presented in Section 8.8.2.

Credit for the preparation of the manuscript is due to Judith Hohl, whose patience, dedication, and hard work were essential to the completion of this book. Her TeX skills and careful attention to detail were invaluable in dealing with the often complicated equations and tables. She is also responsible for the accuracy and completeness of the large reference list and was helped in the use of TeX and BibTeX by William Moore, whose ability to modify the TeX source code enhanced the quality of the manuscript and rescued us from a number of dire situations. Others who assisted in manuscript preparation include Sue Peterson, Nanette Anderson, and Nik Stearn. Cam Truong and Kei Yauchi found and copied hundreds of references. Richard Sadakane skillfully prepared the majority of the figures.