Mantle Convection in the Earth and Planets

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Contents

Preface *page* xiii

1 Historical Background **1**
- 1.1 Introduction 1
- 1.2 Continental Drift 5
- 1.3 The Concept of Subsolidus Mantle Convection 8
- 1.4 Paleomagnetism 11
- 1.5 Seafloor Spreading 12
- 1.6 Subduction and Area Conservation 13

2 Plate Tectonics **16**
- 2.1 Introduction 16
- 2.2 The Lithosphere 25
- 2.3 Accretional Plate Margins (Ocean Ridges) 26
- 2.4 Transform Faults 28
- 2.5 Subduction 29
  - 2.5.1 Rheology of Subduction 33
  - 2.5.2 Dip of Subduction Zones 34
  - 2.5.3 Fate of Descending Slabs 35
  - 2.5.4 Why are Island Arcs Arcs? 35
  - 2.5.5 Subduction Zone Volcanism 36
  - 2.5.6 Back-arc Basins 38
- 2.6 Hot Spots and Mantle Plumes 39
- 2.7 Continents 42
  - 2.7.1 Composition 42
  - 2.7.2 Delamination and Recycling of the Continents 44
  - 2.7.3 Continental Crustal Formation 47
- 2.8 Plate Motions 48
- 2.9 The Driving Force for Plate Tectonics 52
- 2.10 The Wilson Cycle and the Time Dependence of Plate Tectonics 57

3 Structure and Composition of the Mantle **63**
- 3.1 Introduction 63
- 3.2 Spherically Averaged Earth Structure 63
- 3.3 The Crust 68
  - 3.3.1 Oceanic Crust 69

3.3.2 Continental Crust 71
3.4 The Upper Mantle 74
3.4.1 Radial Structure of the Upper Mantle 75
3.4.2 Upper Mantle Composition 80
3.5 The Transition Zone 84
3.5.1 The 410 km Seismic Discontinuity 84
3.5.2 The 660 km Seismic Discontinuity 86
3.6 The Lower Mantle 92
3.7 The D″ Layer and the Core–Mantle Boundary 94
3.8 The Core 97
3.9 Three-dimensional Structure of the Mantle 101
3.9.1 Upper Mantle Seismic Heterogeneity and Anisotropy 103
3.9.2 Extensions of Subducted Slabs into the Lower Mantle 106
3.9.3 Lower Mantle Seismic Heterogeneity 113
3.9.4 Topography of the Core–Mantle Boundary 116

4 Mantle Temperatures and Thermodynamic Properties 118
4.1 Heat Conduction and the Age of the Earth 118
4.1.1 Cooling of an Isothermal Earth 118
4.1.2 Cooling of a Molten Earth 123
4.1.3 Conductive Cooling with Heat Generation 125
4.1.4 Mantle Convection and Mantle Temperatures 127
4.1.5 Surface Heat Flow and Internal Heat Sources 128
4.2 Thermal Regime of the Oceanic Lithosphere 132
4.2.1 Half-space Cooling Model 132
4.2.2 Plate Cooling Model 139
4.3 Temperatures in the Continental Lithosphere 143
4.4 Partial Melting and the Low-velocity Zone 151
4.5 Temperatures, Partial Melting, and Melt Migration Beneath Spreading Centers 153
4.5.1 Melt Migration by Porous Flow 154
4.5.2 Melt Migration in Fractures 166
4.6 Temperatures in Subducting Slabs 176
4.6.1 Frictional Heating on the Slip Zone 176
4.6.2 Phase Changes in the Descending Slab 180
4.6.3 Metastability of the Olivine–Spinel Phase Change in the Descending Slab 185
4.7 The Adiabatic Mantle 188
4.8 Solid-state Phase Transformations and the Geotherm 191
4.9 Temperatures in the Core and the D″ Layer 200
4.10 Temperatures in the Transition Zone and Lower Mantle 204
4.11 Thermodynamic Parameters 207
4.11.1 Thermal Expansion 207
4.11.2 Specific Heat 209
4.11.3 Adiabatic Temperature Scale Height 209
4.11.4 Thermal Conductivity and Thermal Diffusivity 210

5 Viscosity of the Mantle 212
5.1 Introduction 212

5.1.1 Isostasy and Flow 212
5.1.2 Viscoelasticity 212
5.1.3 Postglacial Rebound 213
5.1.4 Mantle Viscosity and the Geoid 215
5.1.5 Mantle Viscosity and Earth Rotation 215
5.1.6 Laboratory Experiments 215
5.2 Global Isostatic Adjustment 216
5.2.1 Deformation of the Whole Mantle by a Surface Load 217
5.2.1.1 Half-space Model 217
5.2.1.2 Spherical Shell Model 222
5.2.1.3 Postglacial Relaxation Time and Inferred Mantle Viscosity 223
5.2.2 Ice Load Histories and Postglacial Sea Levels 224
5.2.3 Evidence for a Low-viscosity Asthenosphere Channel 227
5.3 Changes in the Length of Day 230
5.4 True Polar Wander 231
5.5 Response to Internal Loads 232
5.6 Incorporation of Surface Plate Motion 237
5.7 Application of Inverse Methods 238
5.8 Summary of Radial Viscosity Structure 240
5.9 Physics of Mantle Creep 240
5.10 Viscosity Functions 248

6 Basic Equations 251
6.1 Background 251
6.2 Conservation of Mass 251
6.3 Stream Functions and Streamlines 253
6.4 Conservation of Momentum 254
6.5 Navier–Stokes Equations 255
6.6 Vorticity Equation 257
6.7 Stream Function Equation 257
6.8 Thermodynamics 259
6.9 Conservation of Energy 262
6.10 Approximate Equations 265
6.11 Two-Dimensional (Cartesian), Boussinesq, Infinite Prandtl Number Equations 274
6.12 Reference State 274
6.13 Gravitational Potential and the Poisson Equation 279
6.14 Conservation of Momentum Equations in Cartesian, Cylindrical, and Spherical Polar Coordinates 280
6.15 Navier–Stokes Equations in Cartesian, Cylindrical, and Spherical Polar Coordinates 281
6.16 Conservation of Energy Equation in Cartesian, Cylindrical, and Spherical Polar Coordinates 286

7 Linear Stability 288
7.1 Introduction 288
7.2 Summary of Basic Equations 288
7.3 Plane Layer Heated from Below 290

7.4 Plane Layer with a Univariant Phase Transition Heated from Below 297
7.5 Plane Layer Heated from Within 303
7.6 Semi-infinite Fluid with Depth-dependent Viscosity 307
7.7 Fluid Spheres and Spherical Shells 308
7.7.1 The Internally Heated Sphere 313
7.7.2 Spherical Shells Heated Both from Within and from Below 316
7.7.3 Spherical Shell Heated from Within 318
7.7.4 Spherical Shell Heated from Below 320
7.8 Spherical Harmonics 323

8 Approximate Solutions 330
8.1 Introduction 330
8.2 Eigenmode Expansions 331
8.3 Lorenz Equations 332
8.4 Higher-order Truncations 337
8.5 Chaotic Mantle Mixing 344
8.6 Boundary Layer Theory 350
8.6.1 Boundary Layer Stability Analysis 350
8.6.2 Boundary Layer Analysis of Cellular Convection 353
8.7 Single-mode Mean Field Approximation 361
8.8 Weakly Nonlinear Stability Theory 367
8.8.1 Two-dimensional Convection 367
8.8.2 Three-dimensional Convection, Hexagons 370

9 Calculations of Convection in Two Dimensions 376
9.1 Introduction 376
9.2 Steady Convection at Large Rayleigh Number 378
9.3 Internal Heat Sources and Time Dependence 382
9.4 Convection with Surface Plates 385
9.5 Role of Phase and Chemical Changes 390
9.6 Effects of Temperature- and Pressure-dependent Viscosity 393
9.7 Effects of Temperature-dependent Viscosity: Slab Strength 396
9.8 Mantle Plume Interaction with an Endothermic Phase Change 401
9.9 Non-Newtonian Viscosity 404
9.10 Depth-dependent Thermodynamic and Transport Properties 405
9.11 Influence of Compressibility and Viscous Dissipation 408
9.12 Continents and Convection 408
9.13 Convection in the D″ Layer 413

10 Numerical Models of Three-dimensional Convection 417
10.1 Introduction 417
10.2 Steady Symmetric Modes of Convection 418
10.2.1 Spherical Shell Convection 418
10.2.2 Rectangular Box Convection 428
10.3 Unsteady, Asymmetric Modes of Convection 440
10.4 Mantle Avalanches 454
10.5 Depth-dependent Viscosity 470
10.6 Two-layer Convection 473
10.7 Compressibility and Adiabatic and Viscous Heating 477

10.8 Plate-like Rheology 488
10.9 Three-dimensional Models of Convection Beneath Ridges and Continents 498

11 Hot Spots and Mantle Plumes 499
11.1 Introduction 499
11.2 Hot Spot Tracks 501
11.3 Hot Spot Swells 505
11.4 Hot Spot Basalts and Excess Temperature 508
11.5 Hot Spot Energetics 510
11.6 Evidence for Mantle Plumes from Seismology and the Geoid 514
11.7 Plume Generation 518
11.8 Plume Heads and Massive Eruptions 525
11.9 Plume Conduits and Halos 529
11.10 Instabilities and Waves 533
11.11 Dynamic Support of Hot Spot Swells 537
11.12 Plume–Ridge Interaction 543
11.13 Massive Eruptions and Global Change 545

12 Chemical Geodynamics 547
12.1 Introduction 547
12.2 Geochemical Reservoirs 547
12.3 Oceanic Basalts and Their Mantle Reservoirs 549
12.4 Simple Models of Geochemical Evolution 551
  12.4.1 Radioactivity 551
  12.4.2 A Two-reservoir Model with Instantaneous Crustal Differentiation 553
  12.4.3 Application of the Two-reservoir Model with Instantaneous Crustal Addition to the Sm–Nd and Rb–Sr Systems 555
  12.4.4 A Two-reservoir Model with a Constant Rate of Crustal Growth 556
  12.4.5 Application of the Two-reservoir Model with Crustal Growth Linear in Time to the Sm–Nd System 558
  12.4.6 A Two-reservoir Model with Crustal Recycling 561
  12.4.7 Application of the Two-reservoir Model with Crustal Recycling to the Sm–Nd System 563
12.5 Uranium, Thorium, Lead Systems 565
  12.5.1 Lead Isotope Systematics 565
  12.5.2 Application to the Instantaneous Crustal Differentiation Model 569
12.6 Noble Gas Systems 573
  12.6.1 Helium 574
  12.6.2 Argon 577
  12.6.3 Xenon 579
12.7 Isotope Systematics of Ocean Island Basalts 580
12.8 Summary 583

13 Thermal History of the Earth 586
13.1 Introduction 586

13.2 A Simple Thermal History Model 587
13.2.1 Initial State 587
13.2.2 Energy Balance and Surface Heat Flow Parameterization 588
13.2.3 Temperature Dependence of Mantle Viscosity and Self-regulation 590
13.2.4 Model Results 591
13.2.5 Surface Heat Flow, Internal Heating, and Secular Cooling 594
13.2.6 Volatile Dependence of Mantle Viscosity and Self-regulation 596
13.3 More Elaborate Thermal Evolution Models 602
13.3.1 A Model of Coupled Core–Mantle Thermal Evolution 602
13.3.2 Core Evolution and Magnetic Field Generation 607
13.4 Two-layer Mantle Convection and Thermal Evolution 611
13.5 Scaling Laws for Convection with Strongly Temperature Dependent Viscosity 617
13.6 Episodicity in the Thermal Evolution of the Earth 625
13.7 Continental Crustal Growth and Earth Thermal History 627

14 Convection in the Interiors of Solid Planets and Moons 633
14.1 Introduction 633
14.1.1 The Role of Subsolidus Convection in the Solar System 634
14.1.2 Surface Ages and Hypsometry of the Terrestrial Planets 635
14.2 Venus 640
14.2.1 Comparison of Two Sisters: Venus versus Earth 640
14.2.2 Heat Transport in Venus 647
14.2.3 Venusian Highlands and Terrestrial Continents 656
14.2.4 Models of Convection in Venus 657
14.2.5 Topography and the Geoid: Constraints on Convection Models 661
14.2.6 Convection Models with a Sluggish or Stagnant Lid 664
14.2.7 Convection Models with Phase Changes and Variable Viscosity 667
14.2.8 Thermal History Models of Venus 672
14.2.9 Why is There no Dynamo in Venus? 678
14.3 Mars 681
14.3.1 Surface Tectonic and Volcanic Features 681
14.3.2 Internal Structure 686
14.3.3 The Martian Lithosphere 687
14.3.4 Radiogenic Heat Production 690
14.3.5 Martian Thermal History: Effects of Crustal Differentiation 691
14.3.6 Martian Thermal History: Magnetic Field Generation 698
14.3.7 Martian Thermal History Models with a Stagnant Lid 706
14.3.8 Convection Patterns in Mars 708
14.3.9 Summary 715
14.4 The Moon 716
14.4.1 The Lunar Crust: Evidence from the Apollo Missions 716
14.4.2 Differentiation of the Lunar Interior: A Magma Ocean 718
14.4.3 Lunar Topography and Gravity 719
14.4.4 Early Lunar History 722
14.4.5 Is There a Lunar Core? 726

14.4.6 Crustal Magnetization: Implications for a Lunar Core and Early Dynamo 726
14.4.7 Origin of the Moon 727
14.4.8 Lunar Heat Flow and Convection 727
14.4.9 Lunar Thermal Evolution with Crustal Differentiation 728
14.4.10 Lunar Isotope Ratios: Implications for the Moon's Evolution 731
14.5 Io 736
14.5.1 Volcanism and Heat Sources: Tidal Dissipation 736
14.5.2 Some Consequences of Tidal Dissipation 739
14.5.3 Io's Internal Structure 740
14.5.4 Models of Tidal Dissipation in Io 742
14.5.5 Models of the Thermal and Orbital Dynamical History of Io 746
14.6 Mercury 748
14.6.1 Composition and Internal Structure 748
14.6.2 Accretion, Core Formation, and Temperature 750
14.6.3 Thermal History 752
14.7 Europa, Ganymede, and Callisto 756
14.7.1 Introduction 756
14.7.2 Europa 756
14.7.3 Ganymede 760
14.7.4 Callisto 761
14.7.5 Convection in Icy Satellites 763

15 Nature of Convection in the Mantle 767
15.1 Introduction 767
15.2 Form of Downwelling 774
15.2.1 Subduction 774
15.2.2 Delamination 778
15.3 Form of Upwelling 778
15.3.1 Accretional Plate Margins 778
15.3.2 Mantle Plumes 780
15.4 Horizontal Boundary Layers 782
15.4.1 The Lithosphere 782
15.4.2 The D″ Layer 783
15.4.3 Internal Boundary Layers 784
15.5 The General Circulation 784
15.6 Time Dependence 786
15.7 Special Effects in Mantle Convection 787
15.7.1 Solid-state Phase Transformations 788
15.7.2 Variable Viscosity: Temperature, Pressure, Depth 789
15.7.3 Nonlinear Viscosity 789
15.7.4 Compressibility 790
15.7.5 Viscous Dissipation 791
15.8 Plates and Continents 791
15.8.1 Plates 791
15.8.2 Continents 792
15.9 Comparative Planetology 792
15.9.1 Venus 793

15.9.2 Mars 794
15.9.3 The Moon 794
15.9.4 Mercury and Io 795
15.9.5 Icy Satellites 795

References 797

Appendix: Table of Variables 875

Author Index 893

Subject Index 913

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.