

## Contents

Preface	<i>page</i> xv
Acknowledgments	xvii
<b>1 Introduction</b>	<b>1</b>
1.1 A Brief History of Seismology	2
1.1.1 Recent Advances	14
1.2 Exercises	16
<b>2 Stress and Strain</b>	<b>19</b>
2.1 The Stress Tensor	19
2.1.1 Example: Computing the Traction Vector	21
2.1.2 Principal Axes of Stress	22
2.1.3 Example: Computing the Principal Axes	23
2.1.4 Deviatoric Stress	24
2.1.5 Values for Stress	25
2.2 The Strain Tensor	26
2.2.1 Values for Strain	29
2.2.2 Example: Computing Strain for a Seismic Wave	29
2.3 The Linear Stress–Strain Relationship	30
2.3.1 Units for Elastic Moduli	33
2.4 Exercises	33
<b>3 The Seismic Wave Equation</b>	<b>39</b>
3.1 Introduction: The Wave Equation	39
3.2 The Momentum Equation	40
3.3 The Seismic Wave Equation	42
3.3.1 Potentials	45
3.4 Plane Waves	45
3.4.1 Example: Harmonic Plane Wave Equation	46
3.5 Polarizations of <i>P</i> - and <i>S</i> -Waves	47
3.6 Spherical Waves	50
3.7 Methods for Computing Synthetic Seismograms <sup>†</sup>	50
3.7.1 Discrete Modeling Methods <sup>†</sup>	53
3.7.2 Equations for 2-D Isotropic Finite Differences <sup>†</sup>	56
3.8 Exercises	60

<b>4</b>	<b>Ray Theory: Travel Times</b>	<b>63</b>
4.1	Snell's Law	63
4.2	Ray Paths for Laterally Homogeneous Models	65
4.2.1	Example: Computing $X(p)$ and $T(p)$	68
4.2.2	Ray Tracing through Velocity Gradients	68
4.3	Travel Time Curves and Delay Times	69
4.3.1	Reduced Velocity	70
4.3.2	The $\tau(p)$ Function	70
4.3.3	Example: Computing $\tau(p)$	73
4.3.4	Low-Velocity Zones	73
4.4	Summary of 1-D Ray Tracing Equations	75
4.5	Spherical Earth Ray Tracing	77
4.5.1	The Earth-Flattening Transformation	78
4.6	Three-Dimensional Ray Tracing <sup>†</sup>	80
4.7	Ray Nomenclature	82
4.7.1	Crustal Phases	82
4.7.2	Whole Earth Phases	83
4.7.3	<i>PKJKP</i> : The Holy Grail of Body Wave Seismology	85
4.8	Global Body Wave Observations	85
4.8.1	Uses of Global Body-Wave Phases	90
4.9	Exercises	94
<b>5</b>	<b>Inversion of Travel Time Data</b>	<b>99</b>
5.1	One-Dimensional Velocity Inversion Theory	99
5.2	Straight-Line Fitting	101
5.2.1	Example: Solving for a Layer Cake Model	102
5.2.2	Other Ways to Fit the $T(X)$ Curve	103
5.3	$\tau(p)$ Inversion	104
5.3.1	Example: The Layer Cake Model Revisited	106
5.3.2	Resolving $\tau(p)$ and the Slant-Stack Method	106
5.3.3	Linear Programming and Regularization Methods	109
5.4	Summary: One-Dimensional Velocity Inversion	110
5.5	Three-Dimensional Velocity Inversion	111
5.5.1	Setting Up the Tomography Problem	112
5.5.2	Example: Toy Tomography Problem	116
5.5.3	Solving the Tomography Problem	117
5.5.4	Tomography Complications	119
5.5.5	Finite Frequency Tomography and Full Waveform Inversion	121
5.6	Earthquake Location	122
5.6.1	Iterative Location Methods	128

	Contents	xi
5.6.2	Relative Event Location Methods	128
5.7	Exercises	131
<b>6</b>	<b>Ray Theory: Amplitude and Phase</b>	<b>137</b>
6.1	Energy in Seismic Waves	137
6.2	Geometrical Spreading in 1-D Velocity Models	140
6.3	Reflection and Transmission Coefficients	142
6.3.1	<i>SH</i> -Wave Reflection and Transmission Coefficients	143
6.3.2	Example: Computing <i>SH</i> Coefficients	146
6.3.3	Vertical Incidence Coefficients	146
6.3.4	Energy-Normalized Coefficients	147
6.3.5	Dependence on Ray Angle	149
6.4	Turning Points and Hilbert Transforms	153
6.5	Propagator Matrix Methods for Modeling Plane Waves <sup>†</sup>	155
6.6	Attenuation	160
6.6.1	Example: Computing Intrinsic Attenuation	161
6.6.2	$t^*$ and Velocity Dispersion	161
6.6.3	The Absorption Band Model <sup>†</sup>	164
6.6.4	The Standard Linear Solid <sup>†</sup>	166
6.6.5	Earth's Attenuation	168
6.6.6	Observing $Q$	170
6.6.7	Nonlinear Attenuation	171
6.6.8	Seismic Attenuation and Global Politics	172
6.7	Exercises	172
<b>7</b>	<b>Reflection Seismology and Related Topics</b>	<b>175</b>
7.1	Background	175
7.2	Zero-Offset Sections	176
7.3	Common Midpoint Stacking	178
7.3.1	Example: Computing Normal Moveout	180
7.4	Sources and Deconvolution	182
7.5	Migration	185
7.5.1	Huygens's Principle	186
7.5.2	Diffraction Hyperbolas	186
7.5.3	Example: Computing Diffraction Hyperbolas	188
7.5.4	Migration Methods	188
7.6	Velocity Analysis	192
7.6.1	Example: Estimating Layer Velocity and Thickness	195

<b>xii</b>	<b>Contents</b>	
	7.6.2 Statics Corrections	196
	7.7 Back-projection	197
	7.7.1 The Adjoint Operator as an Inversion Method <sup>†</sup>	199
	7.8 Receiver Functions	200
	7.9 The Language of Reflection Seismology	205
	7.10 Exercises	205
<b>8</b>	<b>Surface Waves and Normal Modes</b>	<b>209</b>
	8.1 Love Waves	209
	8.1.1 Solution for a Single Layer	212
	8.1.2 Example: Computing Love Wave Dispersion	213
	8.2 Rayleigh Waves	213
	8.3 Dispersion	218
	8.4 Global Surface Waves	219
	8.5 Observing Surface Waves	222
	8.5.1 Example: Measuring Group and Phase Velocity	223
	8.6 Normal Modes	226
	8.7 Exercises	232
<b>9</b>	<b>Earthquakes and Source Theory</b>	<b>237</b>
	9.1 Green's Functions and the Moment Tensor	237
	9.2 Earthquake Faults	241
	9.2.1 Non-Double-Couple Sources	244
	9.3 Radiation Patterns and Beach Balls	246
	9.3.1 Example: Plotting a Focal Mechanism	253
	9.4 Far-Field Pulse Shapes	255
	9.4.1 Directivity	257
	9.4.2 Example: 2004 Sumatra Earthquake Directivity	259
	9.4.3 Source Spectra	260
	9.4.4 Empirical Green's Functions	263
	9.5 Stress Drop	264
	9.5.1 Example: Estimating Stress Drop	267
	9.5.2 Self-Similar Earthquake Scaling	268
	9.6 Radiated Seismic Energy	270
	9.6.1 Earthquake Energy Partitioning <sup>†</sup>	273
	9.7 Earthquake Magnitude	276
	9.7.1 The <i>b</i> -Value	282
	9.7.2 Example: Use of <i>b</i> -Value	284
	9.7.3 The Intensity Scale	285
	9.8 Finite Slip Modeling	287
	9.9 The Heat Flow Paradox	290

	Contents	xiii
9.9.1 Why Are Faults Weak?	292	
9.10 Exercises	293	
<b>10 Earthquake Prediction</b>	<b>299</b>	
10.1 The Earthquake Cycle	299	
10.2 Earthquake Triggering	306	
10.3 Searching for Precursors	311	
10.4 Are Earthquakes Unpredictable?	313	
10.5 Exercises	314	
<b>11 Seismometers and Seismographs</b>	<b>319</b>	
11.1 Seismometer as Damped Harmonic Oscillator	319	
11.2 Short-Period and Long-Period Seismographs	324	
11.3 Modern Seismographs	326	
11.4 Exercises	329	
<b>12 Earth Noise</b>	<b>331</b>	
12.1 Earth's Background Noise	331	
12.2 Cross-Correlation Analysis of Ambient Noise	333	
12.3 Exercises	338	
<b>13 Anisotropy</b>	<b>341</b>	
13.1 Rays and Wavefronts for Anisotropy	341	
13.2 Eigenvalue Equation for Anisotropic Media	342	
13.2.1 Slowness Surfaces	344	
13.2.2 Snell's Law at an Interface	345	
13.3 Weak Anisotropy	346	
13.4 Hexagonal Anisotropy	347	
13.5 Shear-Wave Splitting	349	
13.5.1 Linear Polarization Analysis	350	
13.5.2 Estimating Shear-Wave Splitting Parameters	351	
13.5.3 Example: Shear-Wave Splitting Observed at RSON	353	
13.5.4 SKS Splitting	354	
13.5.5 Example: SKS Splitting Analysis for RSON	356	
13.5.6 Shear-Wave Splitting Observations	356	
13.6 Mechanisms for Anisotropy	358	
13.7 Earth's Anisotropy	361	
13.8 Exercises	363	

<b>xiv</b>	<b>Contents</b>	
	<b>Appendix A The PREM Model</b>	<b>365</b>
	<b>Appendix B Math Review</b>	<b>369</b>
	B.1 Vector Calculus	369
	B.2 Complex Numbers	373
	<b>Appendix C The Eikonal Equation</b>	<b>377</b>
	<b>Appendix D Python Functions</b>	<b>381</b>
	<b>Appendix E Time Series and Fourier Transforms</b>	<b>387</b>
	E.1 Convolution	387
	E.2 Fourier Transform	388
	E.3 Hilbert Transform	389
	<b>Appendix F Kirchhoff Theory</b>	<b>393</b>
	F.1 Kirchhoff Applications	398
	F.2 How to Write a Kirchhoff Program	399
	F.3 Kirchhoff Migration	400
	Bibliography	403
	Index	419