

SEISMIC DATA ANALYSIS

Processing, Inversion, and Interpretation of Seismic Data

ÖZ YILMAZ

Volume I

Stephen M. Doherty, Editor

Society of Exploration Geophysicists

Post Office Box 702740, Tulsa, OK 74170-2740

TABLE OF CONTENTS

PREFACE TO THE FIRST EDITION

PREFACE

Volume I

INTRODUCTION

Processing of Seismic Data, 4
Inversion of Seismic Data, 10
Interpretation of Seismic Data, 18
From Seismic Exploration to Seismic Monitoring, 22

Chapter 1

FUNDAMENTALS OF SIGNAL PROCESSING

1.0 Introduction, 25

1.1 The 1-D Fourier Transform, 26

Analog versus Digital Signal, 28
Frequency Aliasing, 30
Phase Considerations, 34
Time-Domain Operations, 36
Convolution, 38
Crosscorrelation and Autocorrelation, 39
Vibroseis Correlation, 41
Frequency Filtering, 41
Practical Aspects of Frequency Filtering, 44
Bandwidth and Vertical Resolution, 46
Time-Variant Filtering, 48

1.2 The 2-D Fourier Transform, 48

Spatial Aliasing, 51

1.3 Worldwide Assortment of Shot Records, 67

Wave Types, 70

1.4 Gain Applications, 81

Geometric Spreading Correction, 81
Programmed Gain Control, 85
RMS Amplitude AGC, 85
Instantaneous AGC, 87
Relative Trace Balancing, 89

1.5 Basic Data Processing Sequence, 90

Preprocessing, 91
Deconvolution, 92
CMP Sorting, 93
Velocity Analysis, 93
Normal-Moveout Correction, 94
Multiple Attenuation, 94

- Dip-Moveout Correction, 94
- CMP Stacking, 95
- Poststack Processing, 95
- Migration, 95
- Residual Statics Corrections, 122
- Quality Control in Processing, 122
- Parsimony in Processing, 124

Exercises, 150

Appendix A: A Mathematical Review of the Fourier Transform, 153

- A.1 The 1-D Fourier Transform, 153
- A.2 The z -Transform, 155
- A.3 The 2-D Fourier Transform, 156

References, 156

Chapter 2 DECONVOLUTION

2.0 Introduction, 159

2.1 The Convolutional Model, 162

- The Convolutional Model in the Time Domain, 167
- The Convolutional Model in the Frequency Domain, 170

2.2 Inverse Filtering, 171

- The Inverse of the Source Wavelet, 172
- Least-Squares Inverse Filtering, 173
- Minimum Phase, 175

2.3 Optimum Wiener Filters, 179

- Spiking Deconvolution, 180
- Prewhitening, 181
- Wavelet Processing by Shaping Filters, 183
- Predictive Deconvolution, 185

2.4 Predictive Deconvolution in Practice, 190

- Operator Length, 190
- Prediction Lag, 193
- Percent Prewhitening, 203
- Effect of Random Noise on Deconvolution, 207
- Multiple Attenuation, 209

2.5 Field Data Examples, 211

- Prestack Deconvolution, 213
- Signature Deconvolution, 217
- Vibroseis Deconvolution, 219
- Poststack Deconvolution, 222

2.6 The Problem of Nonstationarity, 222

- Time-Variant Deconvolution, 227
- Time-Variant Spectral Whitening, 231
- Frequency-Domain Deconvolution, 233
- Inverse Q Filtering, 234
- Deconvolution Strategies, 241

Exercises, 247

Appendix B: Mathematical Foundation of Deconvolution, 249

- B.1 Synthetic Seismogram, 249
- B.2 The Inverse of the Source Wavelet, 251
- B.3 The Inverse Filter, 252
- B.4 Frequency-Domain Deconvolution, 253

- B.5 Optimum Wiener Filters, 255
- B.6 Spiking Deconvolution, 258
- B.7 Predictive Deconvolution, 260
- B.8 Surface-Consistent Deconvolution, 262
- B.9 Inverse Q Filtering, 266

References, 270

Chapter 3

VELOCITY ANALYSIS AND STATICS CORRECTIONS

3.0 Introduction, 271

3.1 Normal Moveout, 274

- NMO for a Flat Reflector, 274
- NMO in a Horizontally Stratified Earth, 280
- Fourth-Order Moveout, 280
- NMO Stretching, 283
- NMO for a Dipping Reflector, 285
- NMO for Several Layers with Arbitrary Dips, 287
- Moveout Velocity versus Stacking Velocity, 288

3.2 Velocity Analysis, 288

- The Velocity Spectrum, 292
- Measure of Coherency, 295
- Factors Affecting Velocity Estimates, 302
- Interactive Velocity Analysis, 311
- Horizon Velocity Analysis, 312
- Coherency Attribute Stacks, 318

3.3 Residual Statics Corrections, 324

- Residual Statics Estimation by Traveltime Decomposition, 336
- Residual Statics Estimation by Stack-Power Maximization, 344
- Traveltime Decomposition in Practice, 345
- Maximum Allowable Shift, 346
- Correlation Window, 361
- Other Considerations, 362
- Stack-Power Maximization in Practice, 365

3.4 Refraction Statics Corrections, 370

- First Breaks, 374
- Field Statics Corrections, 375
- Flat Refractor, 375
- Dipping Refractor, 377
- The Plus-Minus Method, 377
- The Generalized Reciprocal Method, 379
- The Least-Squares Method, 379
- Processing Sequence for Statics Corrections, 381
- Model Experiments, 382
- Field Data Examples, 395

Exercises, 432

Appendix C: Topics in Moveout and Statics Corrections, 437

- C.1 The Shifted Hyperbola, 437
- C.2 Moveout Stretch, 439
- C.3 Equations for a Dipping Reflector, 441
- C.4 Traveltime Decomposition for Residual Statics Estimation, 442
- C.5 Depth Estimation from Refracted Arrivals, 444
- C.6 Equations for a Dipping Refractor, 445

- C.7 The Plus-Minus Times, 447
- C.8 Generalized Linear Inversion of Refracted Arrivals, 448
- C.9 Refraction Traveltime Tomography, 453
- C.10 L_1 -Norm Refraction Statics, 456

References, 460

Chapter 4 MIGRATION

4.0 Introduction, 463

- Exploding Reflectors, 467
- Migration Strategies, 470
- Migration Algorithms, 471
- Migration Parameters, 474
- Aspects of Input data, 475
- Migration Velocities, 475

4.1 Migration Principles, 476

- Kirchhoff Migration, 481
- Diffraction Summation, 484
- Amplitude and Phase Factors, 485
- Kirchhoff Summation, 485
- Finite-Difference Migration, 486
- Downward Continuation, 486
- Differencing Schemes, 488
- Rational Approximations for Implicit Schemes, 489
- Reverse Time Migration, 491
- Frequency-Space Implicit Schemes, 492
- Frequency-Space Explicit Schemes, 493
- Frequency-Wavenumber Migration, 494
- Phase-Shift Migration, 498
- Stolt Migration, 500
- Summary of Domains of Migration Algorithms, 501

4.2 Kirchhoff Migration in Practice, 502

- Aperture Width, 502
- Maximum Dip to Migrate, 509
- Velocity Errors, 509

4.3 Finite-Difference Migration in Practice, 520

- Depth Step Size, 521
- Velocity Errors, 525
- Cascaded Migration, 525
- Reverse Time Migration, 530

4.4 Frequency-Space Migration in Practice, 530

- Steep-Dip Implicit Methods, 535
- Depth Step Size, 537
- Velocity Errors, 544
- Steep-Dip Explicit Methods, 549
- Dip Limits of Extrapolation Filters, 549
- Velocity Errors, 552

4.5 Frequency-Wavenumber Migration in Practice, 559

- Maximum Dip to Migrate, 559
- Depth Step Size, 566
- Velocity Errors, 567
- Stolt Stretch Factor, 572

Wraparound, 575

Residual Migration, 575

4.6 Further Aspects of Migration in Practice, 579

Migration and Spatial Aliasing, 581

Migration and Random Noise, 619

Migration and Line Length, 621

Migration from Topography, 626

Exercises, 626

Appendix D: Mathematical Foundation of Migration, 628

D.1 Wavefield Extrapolation and Migration, 628

D.2 Stationary Phase Approximations, 638

D.3 The Parabolic Approximation, 639

D.4 Frequency-Space Implicit Schemes, 641

D.5 Stable Explicit Extrapolation, 644

D.6 Optimum Depth Step, 646

D.7 Frequency-Wavenumber Migration, 649

D.8 Residual Migration, 651

References, 652

Chapter 5

DIP-MOVEOUT CORRECTION AND PRESTACK MIGRATION

5.0 Introduction, 655

Salt-Flank Reflections, 657

Fault-Plane Reflections, 657

DMO and Stacking Velocities, 657

Turning-Wave Reflections, 665

5.1 Principles of Dip-Moveout Correction, 668

Prestack Partial Migration, 670

Frequency-Wavenumber DMO Correction, 672

Log-Stretch DMO Correction, 677

Integral DMO Correction, 679

Velocity Errors, 681

Variable Velocity, 684

Turning-Wave Migration, 685

5.2 Dip-Moveout Correction in Practice, 692

Salt Flanks, 692

Fault Planes, 693

DMO and Multiples, 705

DMO and Coherent Linear Noise, 716

Other Considerations, 716

Aspects of DMO Correction — A Summary, 722

5.3 Prestack Time Migration, 725

DMO Correction and Common-Offset Migration, 728

Salt Flanks, 729

Fault Planes, 742

Common-Reflection-Point versus Common-Reflection-Surface Stacking, 769

5.4 Migration Velocity Analysis, 775

Prestack Stolt Migration, 776

Common-Offset Migration of DMO-Corrected Data, 777

Prestack Kirchhoff Migration, 788

Velocity Analysis Using Common-Reflection-Point Gathers, 788

Focusing Analysis, 798

Fowler's Velocity-Independent Prestack Migration, 803

Exercises, 815**Appendix E: Topics in Dip-Moveout Correction and Prestack Time Migration, 817**

- E.1 Reflection Point Dispersal, 817
- E.2 Equations for DMO Correction, 820
- E.3 Log-Stretch DMO Correction, 823
- E.4 The DMO Ellipse, 826
- E.5 Nonzero-Offset Traveltime Equation, 827
- E.6 Prestack Frequency-Wavenumber Migration, 831
- E.7 Velocity Analysis by Wavefield Extrapolation, 833

References, 834**Chapter 6****NOISE AND MULTIPLE ATTENUATION****6.0 Introduction, 837**

- Coherent Linear Noise, 838
- Treatment of Coherent Linear Noise by Conventional Processing, 840
- Reverberations and Multiples, 843
- Treatment of Reverberations and Multiples by Conventional Processing, 857
- Spatially Random Noise, 876

6.1 Multiple Attenuation in the CMP Domain, 877

- Periodicity of Multiples, 877
- Velocity Discrimination Between Primaries and Multiples, 887
- Karhunen-Loeve Transform, 887
- Modeling of Multiples, 896

6.2 Frequency-Wavenumber Filtering, 898

- Random Noise and Frequency-Wavenumber Filtering, 904
- Statics Corrections and Frequency-Wavenumber Filtering, 905
- Dip Filtering of Coherent Linear Noise, 905
- Frequency-Wavenumber Multiple Attenuation, 907

6.3 The Slant-Stack Transform, 920

- Physical Aspects of Slant Stacking, 920
- Slant-Stack Transformation, 923
- Practical Aspects of Slant Stacking, 924
- Slant-Stack Parameters, 928
- Time-Variant Dip Filtering, 931
- Slant-Stack Multiple Attenuation, 932

6.4 The Radon Transform, 938

- Velocity-Stack Transformation, 942
- The Discrete Radon Transform, 943
- The Parabolic Radon Transform, 944
- Practical Considerations, 945
- Impulse Response of the Velocity-Stack Operator, 948
- Field Data Examples, 948
- Radon-Transform Multiple Attenuation, 953

6.5 Linear Uncorrelated Noise Attenuation, 960

- Design of Spatial Prediction Filters, 966
- Field Data Examples, 966

Exercises, 976**Appendix F: Multichannel Filtering Techniques for Noise and Multiple Attenuation, 977**

- F.1 Analysis of Guided Waves, 977
- F.2 Wavefield Extrapolation in the $\tau - p$ Domain, 980
- F.3 Mathematical Foundation of the Discrete Radon Transform, 982

- F.4 Free-Surface Multiple Attenuation, 989
- F.5 Water-Bottom Multiple Attenuation, 992
- F.6 Spatial Prediction Filter, 995

References, 998

INDEX, xxv

Volume II

Chapter 7

3-D SEISMIC EXPLORATION

7.0 Introduction, 1001

- The Need for Imaging in Three Dimensions, 1003

7.1 3-D Survey Design and Acquisition, 1010

- Migration Aperture, 1010
- Spatial Sampling, 1017
- Other Considerations, 1018
- Marine Acquisition Geometry, 1018
- Cable Feathering, 1019
- 3-D Binning, 1019
- Crossline Smearing, 1020
- Strike versus Dip Shooting, 1027
- Land Acquisition Geometry, 1028

7.2 Processing of 3-D Seismic Data, 1030

- 3-D Refraction Statics Corrections, 1036
- Azimuth Dependence of Moveout Velocities, 1036
- 3-D Dip-Moveout Correction, 1046
- Inversion to Zero Offset, 1048
- Aspects of 3-D DMO Correction — A Summary, 1050
- Velocity Analysis, 1050
- 3-D Residual Statics Corrections, 1050
- 3-D Migration, 1051
- Trace Interpolation, 1065

7.3 3-D Poststack Migration, 1073

- Separation versus Splitting, 1073
- Impulse Response of the One-Pass Implicit Finite-Difference 3-D Migration, 1074
- Two-Pass versus One-Pass Implicit Finite-Difference 3-D Migration in Practice, 1076
- Explicit Schemes Combined with the McClellan Transform, 1082
- The Phase-Shift-Plus-Correction Method, 1088

7.4 3-D Prestack Time Migration, 1099

- 3-D DMO Correction Combined with 3-D Common-Offset Migration, 1112
- Crossline Migration, 1129
- 3-D Migration Velocity Analysis, 1131
- Aspects of 3-D Prestack Time Migration — A Summary, 1137

7.5 Interpretation of 3-D Seismic Data, 1156

- Time Slices, 1156
- 3-D Visualization, 1156
- Removal of Opacity, 1158
- Seed Detection, 1159
- Structural Interpretation, 1161
- Stratigraphic Interpretation, 1171

Exercises, 1195

Appendix G: Mathematical Foundation of 3-D Migration, 1198

- G.1 Implicit Methods, 1198
- G.2 Explicit Methods, 1200
- G.3 3-D Phase-Shift Migration, 1203
- G.4 3-D Stolt Migration, 1204
- G.5 Trace Interpolation, 1204
- G.6 3-D Nonzero-Offset Traveltime Equation, 1208

References, 1209

Chapter 8

EARTH IMAGING IN DEPTH

8.0 Introduction, 1213

- Lateral Velocity Variations, 1222

8.1 Layer Replacement, 1226

- Wave-Equation Datuming, 1229
- Poststack Layer Replacement, 1230
- Prestack Layer Replacement, 1231
- Field Data Example, 1237

8.2 2-D Poststack Depth Migration, 1238

- Image Rays and Lateral Velocity Variations, 1238
- Time versus Depth Migration, 1244
- Iterative Depth Migration, 1247
- Iteration with Zero-Offset Data, 1250
- Iteration with CMP-Stacked Data, 1258
- Iteration with Prestack Data, 1265
- Iteration in Practice, 1265

8.3 2-D Prestack Depth Migration, 1273

- Shot-Geophone Migration, 1274
- Shot-Profile Migration, 1280
- Sensitivity of Image Accuracy to Velocity Errors, 1280
- Field Data Examples, 1295

8.4 3-D Poststack Depth Migration, 1304

- 3-D Poststack Time versus Depth Migration, 1304
- Two-Pass versus One-Pass 3-D Poststack Depth Migration, 1313
- Implicit versus Explicit 3-D Poststack Depth Migration, 1314
- 3-D Poststack Datuming, 1321

8.5 3-D Prestack Depth Migration, 1321

- Kirchhoff Summation, 1324
- Calculation of Traveltimes, 1324
- The Eikonal Equation, 1325
- Fermat's Principle, 1331
- Summation Strategies, 1331
- Migration Aperture, 1333
- Operator Antialiasing, 1333
- 3-D Common-Offset Depth Migration, 1335

Exercises, 1342**Appendix H: Diffraction and Ray Theory for Wave Propagation, 1342**

- H.1 The Kirchhoff Integral, 1342
- H.2 The Eikonal Equation, 1346
- H.3 Finite-Difference Solution to the Eikonal Equation, 1349

References, 1351

Chapter 9 EARTH MODELING IN DEPTH

9.0 Introduction, 1353

Inversion Methods for Data Modeling, 1355
 Inversion Procedures for Earth Modeling, 1356
 Velocity-Depth Ambiguity, 1357
 Model Representation and Visualization, 1360

9.1 Models with Horizontal Layers, 1365

Dix Conversion, 1365
 Coherency Inversion, 1369
 Near-Surface Layer with Laterally Varying Velocities, 1382

9.2 Model with Low-Relief Structure, 1387

Stacking Velocity Inversion, 1392
 Coherency Inversion, 1404
 Velocity Resolution, 1404

9.3 Model with Complex Overburden Structure, 1404

Image-Gathers, 1406
 Constant Half-Space Velocity Analysis, 1415

9.4 Model Building, 1415

Time-to-Depth Conversion, 1416
 Time Structure Maps, 1416
 Interval Velocity Maps, 1417
 Depth Structure Maps, 1425
 Calibration to Well Tops, 1426
 Layer-by-Layer Inversion, 1433
 Structure-Independent Inversion, 1450

9.5 Model Updating, 1450

Residual Moveout Analysis, 1462
 Reflection Traveltime Tomography, 1469
 Limitations in Resolving Velocity-Depth Ambiguity by Tomography, 1479
 Turning-Ray Tomography, 1512

Exercises, 1524

Appendix J: Data Modeling by Inversion, 1525

J.1 The Generalized Linear Inversion, 1525
 J.2 The GLI Formalism of Deconvolution, 1526
 J.3 Applications of the GLI Technique, 1530
 J.4 Dix Conversion, 1534
 J.5 Map Processing, 1539
 J.6 Reflection Traveltime Tomography, 1545
 J.7 Threshold for Velocity-Depth Ambiguity, 1553

References, 1554

Chapter 10 STRUCTURAL INVERSION

10.0 Introduction, 1557

10.1 Subsalt Imaging in the North Sea, 1558

Estimation of the Overburden Model, 1562
 Estimation of the Substratum Model, 1562
 Model Verification, 1563

10.2 Subsalt Imaging in the Gulf of Mexico, 1574

Layered Earth Model Estimation, 1574

- Structure-Independent Model Estimation, 1577
- 10.3 Imaging Beneath Irregular Water Bottom in the Northwest Shelf of Australia, 1597**
 - Earth Modeling and Imaging in Depth, 1597
- 10.4 Imaging Beneath Volcanics in the West of Shetlands of the Atlantic Margin, 1597**
 - Earth Modeling and Imaging in Depth, 1607
- 10.5 Imaging Beneath Shallow Gas Anomalies in the Gulf of Thailand, 1620**
 - Earth Modeling and Imaging in Depth, 1620
- 10.6 3-D Structural Inversion Applied to Seismic Data from the Southern North Sea, 1626**
 - Estimation of the Overburden Model, 1626
 - Model Representation by Tessellation, 1630
 - 3-D Coherency Inversion, 1630
 - 3-D Poststack Depth Migration, 1637
 - Estimation of the Substratum Model, 1638
- 10.7 3-D Structural Inversion Applied to Seismic Data from the Central North Sea, 1651**
 - 3-D Coherency Inversion Combined with 3-D Poststack Depth Migration, 1665
 - 3-D Stacking Velocity Inversion Combined with 3-D Image-Ray Depth Conversion, 1674
- 10.8 3-D Structural Inversion Applied to Seismic Data from Offshore Indonesia, 1674**
 - Model Building, 1678
 - Model Updating, 1678
 - Imaging in Depth, 1690
 - Volume-Based Interpretation, 1690
- 10.9 3-D Structural Inversion Applied to Seismic Data from the Northeast China, 1703**
 - 3-D DMO Processing, 1720
 - 3-D Prestack Time Migration, 1720
 - From RMS to Interval Velocities, 1742
 - Structural Inversion, 1742
 - Structural and Stratigraphic Interpretation, 1744
- Exercises, 1778**
- Appendix K: Seismic Modeling, 1779**
 - K.1 Zero-Offset Traveltime Modeling, 1779
 - K.2 Zero-Offset Wavefield Modeling, 1781
 - K.3 Nonzero-Offset Wavefield Modeling, 1781
 - K.4 Elastic Wavefield Modeling, 1790
- References, 1792**

Chapter 11 RESERVOIR GEOPHYSICS

- 11.0 Introduction, 1793**
 - Elastic Waves and Rock Properties, 1794
- 11.1 Seismic Resolution, 1801**
 - Vertical Resolution, 1801
 - Lateral Resolution, 1803
- 11.2 Analysis of Amplitude Variation with Offset, 1807**
 - Reflection and Refraction, 1808
 - Reflector Curvature, 1813
 - AVO Equations, 1816
 - Processing Sequence for AVO Analysis, 1839
 - Derivation of AVO Attributes by Prestack Amplitude Inversion, 1851
 - Interpretation of AVO Attributes, 1862
 - 3-D AVO Analysis, 1863
- 11.3 Acoustic Impedance Estimation, 1863**
 - Synthetic Sonic Logs, 1864

	Processing Sequence for Acoustic Impedance Estimation, 1865
	Derivation of Acoustic Impedance Attribute, 1866
	3-D Acoustic Impedance Estimation, 1872
	Instantaneous Attributes, 1896
11.4	Vertical Seismic Profiling, 1907
	VSP Acquisition Geometry, 1907
	Processing of VSP Data, 1907
	VSP-CDP Transform, 1908
11.5	4-D Seismic Method, 1911
	Processing of 4-D Seismic Data, 1912
	Seismic Reservoir Monitoring, 1913
11.6	4-C Seismic Method, 1915
	Recording of 4-C Seismic Data, 1919
	Gaiser's Coupling Analysis of Geophone Data, 1922
	Processing of <i>PP</i> Data, 1926
	Rotation of Horizontal Geophone Components, 1926
	Common-Conversion-Point Binning, 1933
	Velocity Analysis of <i>PS</i> Data, 1946
	Dip-Moveout Correction of <i>PS</i> Data, 1959
	Migration of <i>PS</i> Data, 1961
11.7	Seismic Anisotropy, 1961
	Anisotropic Velocity Analysis, 1965
	Anisotropic Dip-Moveout Correction, 1968
	Anisotropic Migration, 1980
	Effect of Anisotropy on AVO, 1998
	Shear-Wave Splitting in Anisotropic Media, 1999
	Exercises, 2000
	Appendix L: Mathematical Foundation of Elastic Wave Propagation, 2001
	L.1 Stress-Strain Relation, 2001
	L.2 Elastic Wave Equation, 2007
	L.3 Seismic Wave Types — Body Waves and Surface Waves, 2008
	L.4 Wave Propagation Phenomena — Diffraction, Reflection, and Refraction, 2012
	L.5 The Zoeppritz Equations, 2014
	L.6 Prestack Amplitude Inversion, 2019
	References, 2024
	INDEX, xvii