CONTENTS

Preface *xvii*

Part I. General Concept and Historical Review

General Concept of Active Geophysical Monitoring

1 Seismicity Precursors for Active Monitoring of Earthquakes **5**

1. Introduction 5
2. Seismicity Precursors 7
   - 2.1. Parkfield M6, 2004 7
   - 2.2. Loma Prieta M7.0 1989 11
   - 2.3. Seismic noise 14
3. Discussion 16
   - 3.1. Similarity of precursor patterns 16
   - 3.2. Precursor mechanism 17
   - 3.3. Probability and earthquakes 22
   - 3.4. Active monitoring and earthquake prediction 22
   - 3.5. Short-term predictions and earthquake triggering 24
4. Conclusions 25

Acknowledgments 25

References 26

2 Large-scale Geophysical Surveys of the Earth's Crust Using High-power Electromagnetic Pulses **29**

1. Introduction 29
2. General Concept of the Application of High-power Electromagnetic Pulses in Geophysical Surveys 31
3. Analysis of the Geoelectrical Structure of the Earth's Crust and Upper Mantle 34
   - 3.1. Study of the geoelectrical structure of the earth's crust in the Ural Mountains 34
   - 3.2. Analysis of a deep geoelectrical structure of the eastern part of the Baltic shield 35
   - 3.3. Deep geoelectrical structure of the Northern Tien Shan region 39
4. EM Soundings with a Powerful Source in Seismically Active Regions 40
   - 4.1. EM soundings for earthquake prediction 40
   - 4.2. Influence of a high-power electromagnetic pulse on the spatial-temporal structure of seismicity 43

5. EM Exploration for Oil and Gas with the Use of Geophysical MHD Facilities 45
5.1. EM sounding for oil and gas on land 45
5.2. EM exploration for oil and gas on a shelf 48
6. Deep Electromagnetic Studies in Ore-prospective Regions 49
7. Conclusions 52
References 52

3 Elements of Active Geophysical Monitoring Theory 55

1. Introduction 55
2. Main Properties of the Integral Precursor 56
3. Multidisciplinary Model of Integral Precursor and Combined Inverse Problems 61
4. Methods for Vibroseismic Monitoring of Seismic Prone Zones 64
5. Conclusions 68
Acknowledgments 68
References 69

4 Seismic Active Monitoring System Concept 73

1. Introduction 73
2. System Concept 74
3. Force Signal Signatures 74
3.1. Pseudo-random sequence signal 76
3.2. Pseudo-random sequence modulation 80
4. Quadrature Signal Processing 82
4.1. Parameter definition 83
4.2. Waveform modulation/demodulation 84
4.3. Matched filtering 85
4.4. Signal detection and timing algorithm 86
5. Conclusions 89
References 90

Active Monitoring Targets

5 Detection of Transient Phenomena Due to Active Scatterers 93

1. Introduction 93
2. Structure Sensitivity of a Medium 94
2.1. Examples of structure sensitive property 95
2.2. Active scatterers in the earth's interior 95
3. Observables of Active Scatterers 97
3.1. Scattering characteristics of active scatterers 98
3.2. Anisotropy and dispersion of active scatterers 99
3.3. Temporal variations of reflectors at subducting boundary 100

4. Discussions and Conclusions 100
Acknowledgments 101
References 101

6 Active Vibromonitoring: Experimental Systems and Fieldwork Results 105

1. Introduction 105
2. Active Vibromonitoring Experiments 108
3. Data Processing and Results 110
4. Vibromonitoring Experimental Systems 115
5. Conclusions 118
Acknowledgments 119
References 119

7 Reliable Measurement Method to Reveal a Peculiar Dielectric Dispersion in Wet Rocks by Means of ACROSS 121

1. Introduction 121
2. Measurement System 123
   2.1. Bias caused by stray capacitance 124
   2.2. Bias due to electrochemical reaction at the electrodes 126
   2.3. Noise and uncertainty in measurement 127
3. Measurement of Moist Grains 128
   3.1. Sample and measurement condition 128
   3.2. Result of measurement 129
4. Discussion 131
   4.1. Short summary on measurement technology 131
   4.2. The $1/f$ type dielectric dispersion and its physical mechanism 131
5. Conclusion 132
References 132

8 Active Geophysical Monitoring of Hydrocarbon Reservoirs Using EM Methods 135

1. Introduction 135
2. Principles of Reservoir Production Monitoring using Marine EM Methods 136
3. Overview of the Numerical Modeling Technique 137
4. Computer Simulation of HC Reservoir Monitoring using EM Methods 140
   4.1. Model 1: HC reservoir and a salt dome structure 140
   4.2. Model 1: Forward modeling results 141
   4.3. Model 2: HC reservoir and a salt dome in an area with a rough sea-bottom bathymetry 145
   4.4. Model 2: Forward modeling results 146
5. Conclusions 149
Acknowledgments 158
References 159

Part II. Theory and Technology of Active Monitoring

Technology of Active Monitoring

9 Acquisition of Crosswell Seismic Monitoring Data 165

1. Introduction 165
2. Optimal Acquisition Parameters 167
3. Acquisition Hardware 167
4. Field Tests 168
5. Conclusions 175

Acknowledgments 176

References 176

10 EM-ACROSS System and Corresponding Tensor Transfer Functions in Diffusion Field Region 177

1. Introduction 177
2. Basic Equations for the Electromagnetic Field and the Transfer Function in EM-ACROSS 178
3. The EM-ACROSS Observation System 180
4. Results of the Trial Observation 181
5. Properties of the Transfer Function 185
   - 5.1. Static tensor properties of the transfer function and the information on the underground conditions 185
   - 5.2. Temporal variations 187
6. Conclusions 190

References 190

11 Design and Workout of ACROSS Transmitters Using Air Bearings 193

1. Introduction 193
2. Construction of an ACROSS Transmitter Using Air Bearings 195
3. Working Mechanism of a Hydrostatic Air Bearing 195
4. Preliminary Test 196
5. Test Trial of Air Bearings for Generation of 2000 N 198
6. Workout of the Trial Air Bearings 200
7. Conceptual Design of a 2×10^5 N Class ACROSS Transmitter Using Air Bearings 205
8. Conclusion 208

Acknowledgments 208

References 209

Signal Processing and Accuracy Control in Active Monitoring

12 Stacking Strategy for Acquisition of an ACROSS Transfer Function 213

1. Introduction 213
2. Methodology 214
   2.1. Properties of signals and noise in ACROSS data 214
   2.2. Derivation of optimum weight 216
   2.3. Successive stacking for larger SNR 218
3. Application of optimum weighted stacking method 218
4. Conclusions 225
   Acknowledgments 225
   References 227

13 Secondary Calibration Method of Seismometers by Utilizing ACROSS Signal 229

1. Introduction 229
2. Basic Concept and Method of Analysis 230
   2.1. Basic concept of the current method 230
   2.2. Major features 231
   2.3. Model for the motion of the vibration table and the frequency response model of the seismometer 231
3. Experimental Measurements 234
4. Results and Interpretation 235
5. Discussion 240
6. Conclusions 241
   Acknowledgments 241
   References 242

14 Signal Discrimination of External Geomagnetic Effects Using the Transfer Function Approach with Continuous Wavelet Transform 243

1. Introduction 243
2. Formulation of Signal Discrimination 244
   2.1. Interstation transfer function (ISTF) 244
   2.2. ISTF approach to the magnetotelluric (MT) response function 245
   2.3. Elimination of the external geomagnetic effects 246
3. Application of the Wavelet Transform 246
   3.1. Continuous wavelet transform 246
   3.2. Auto- and cross-correlation functions based on the wavelet transform 248
   3.3. Wavelet-based transfer function and correlation function 249
4. Application to Observed Data 250
5. Verification of the Detectability of Artificial Signals 252
6. Conclusion 256
   References 257

15 Development of Simulation Algorithm for Analyzing Temporal Stability of ACROSS Seismic Source 259

1. Introduction 259
2. Brief Review of Observed Temporal Variations of Near Field Responses 261
   - 2.1. Temporal variations observed at Awaji Island 261
   - 2.2. Relatively stable responses in a large tunnel at the Kazunogawa site 262
   - 2.3. Discussions about the observed results 263
3. Development of Simulation Algorithm of ACROSS Seismic Waves 265
   - 3.1. Simulation model 265
   - 3.2. Displacements excited by a horizontally forced rigid circular disk deployed on a multilayered elastic half space 268
   - 3.3. Compliance function 270
4. Numerical Simulation 272
   - 4.1. Effect of the thickness of the surface layer on the source's rigid motion 273
   - 4.2. Effect of the thickness of the surface layer on the waves excited by the ACROSS seismic source 274
5. Summary 275

References 276

16 Nonlinear Processes in Seismic Active Monitoring 279

1. Introduction 279
2. Nonlinear Phenomena 280
3. Nonlinear Processing of Vibrational Seismograms 283
4. Nonlinear Phenomena in Seismic Monitoring 285
5. Experimental Results 290
6. Discussion 293
7. Conclusions 295

Acknowledgments 295

References 295

Theory of Data Analysis and Interpretation

17 Maxwell's Equations and Numerical Electromagnetic Modeling in the Context of the Theory of Differential Forms 299

1. Introduction 300
2. Differential Forms in Vector Field Theory 301
   - 2.1. Concept of the differential form 301
   - 2.2. Exterior (wedge) product of the differential forms 302
   - 2.3. Canonical representations of the differential forms in three-dimensional Euclidean space 304
   - 2.4. The exterior derivative operation 305

3. Nonstationary Field Equations and Differential Forms 306
3.1. Nonstationary vector fields and differential forms in four-dimensional space E_4 307
3.2. Differential form equations 307
3.3. Exterior derivative of a scalar field and a generalized source 1-form 308
3.4. Exterior derivative of a four-potential and a generalized source 2-form 308
3.5. Exterior derivative of a 2-form and a four-current 309
3.6. Exterior derivatives of a 3-form and a 4-form 309
4. Ampere-type Differential Forms and a Continuity Equation 310
5. Faraday-type Differential Forms and Four-potential 311
6. Maxwell's Equations 313
6.1. Basic equations in the theory of electromagnetic fields 313
7. Integral Formulations of the Differential form Equations for Maxwell's Field and Force field 316
7.1. Faraday's electromagnetic induction law 316
7.2. Integral formulation of Ampere's law 318
7.3. Integral equations for Maxwell's field and force field in the frequency domain 320
8. Numerical Modeling Using Differential Forms 320
9. Conclusions 323
Acknowledgments 323
References 324

18 3D Electromagnetic Holographic Imaging in Active Monitoring of Sea-Bottom Geoelectrical Structures 325

1. Introduction 325
2. Marine Controlled-Source Electromagnetic (MCSEM) Method 327
3. Frequency Domain Electromagnetic (FDEM) Migration of MCSEM Data 328
4. Electromagnetic Imaging Using Joint Migration of Electric and Magnetic Fields 331
5. Regularized Iterative Migration 333
6. Migration of Synthetic MCSEM Data 334
6.1. Model 1 334
6.2. Model 2 337
7. Inversion of Troll Gas Province MCSEM Data 341
8. Conclusion 347
Acknowledgments 348
References 349

19 Foundations of the Method of EM Field Separation into Upgoing and Downgoing Parts and its Application to MCSEM Data 351

1. Introduction 351

2. Integral Transforms of Electromagnetic Fields Using Stratton-Chu Type Integrals 353
2.1. Basic equations of upgoing and downgoing fields 353
2.2. Application of the Stratton-Chu type integrals for field separation 355
3. Spatial Fourier Transform Method of EM Field Separation into Upgoing and Downgoing Parts 359
3.1. Electromagnetic field in the (k, ω) domain 360
3.2. Separation of the observed EM field into upgoing and downgoing components 361
3.3. Convolution form of decomposition operators 364
4. Electromagnetic Field Separation into Upgoing and Downgoing Parts Using Horizontal Gradients 366
5. Numerical Examples of Marine EM Data Decomposition 369
5.1. Model 1 369
5.2. Model 2 372
6. Conclusions 372
Acknowledgments 374
7. Stratton-Chu Integral Formulas 376
8. Stratton-Chu Type Integrals and Their Properties 377
References 379

20 Automatic Travel Time Determination from a Frequency-domain Transfer Function: The Sompi Event Analysis 381

1. Introduction 381
2. Theory 382
2.1. Concept of the model 382
2.2. Model of pulse sequence 382
2.3. Modeling dispersive waves 385
2.4. Modeling observed data 386
2.5. Determination of the complex travel times 387
2.6. Determination of the complex amplitudes 388
2.7. Maximum likelihood approach using linearized model 388
2.8. Determination of the model order 389
2.9. Error estimation by bootstrap method 391
3. Numerical Experiment 392
4. Discussion and Conclusion 393
References 395

21 Effect of Spatial Sampling on Time-lapse Seismic Monitoring in Random Heterogeneous Media 397

1. Introduction 397
2. Proper Spatial Sampling Interval in Seismic Reflection 399
3. Numerical Simulations 400
3.1. Random heterogeneous model 400

3.2. Wave field calculation 401
4. Results 404
4.1. Stacked and migrated sections 404
4.2. Difference sections 408
5. Discussion 417
5.1. Independent time series noise and induced scattered wave noise 417
5.2. Spatial sampling interval and the truncation artifact 417
6. Conclusions 418
References 419

22 Singular Value Decomposition in Active Monitoring Data Analysis 421

1. Introduction 421
2. SVD 422
3. Algorithm 422
4. Numerical Test 425
5. Field Test 426
6. Location of Source and Sites 427
7. Experiment and Data Process 427
8. Discussion 428
References 430

Part III. Case Histories

Regional Active Monitoring Experiments

23 Detection and Continuous Monitoring of Strong Seismic Reflectors at the Subducting Philippine Sea Plate Using ACROSS Methodology 435

1. Introduction 435
2. Evaluation of the Seismic Across for Detection of Reflected Phases 438
3. Results 439
4. Discussion 440
5. Conclusions 445
Acknowledgments 446
References 446

24 Active Seismic Monitoring of the San Andreas Fault at Parkfield 449

1. Introduction 449
2. HRSN 450
3. Vibroseis Monitoring 450
4. Origin of Changes 452
5. Guided-Wave Imaging of SAF Core 453
6. Fault Continuity Testing 456

7. Discussion and Conclusions 459
Acknowledgments 460
References 460

25 Characteristics of ACROSS Signals Transmitted from the Tono Transmitting Station and Observed by Hi-net 463

1. Introduction 463
2. Data and Methods 465
3. Results 466
4. Discussion 468
5. Conclusion and Future Plan 470
Acknowledgments 471
References 472

26 Active Monitoring Using Submarine Cables—Leveraging Offshore Cabled Observatory for Passive Monitoring 473

1. Introduction 473
2. Japanese Cabled Observatories 475
3. Scientific Advances brought by the Cabled Observatories 476
   3.1. Earthquake Studies 476
   3.2. Tsunami Studies 476
   3.3. Geodetic Studies 480
4. Advances in Asperity Study 482
5. Exertion of Earthquake Monitoring Capability 485
6. Discussions 486
   6.1. Passive Monitoring of Seismogenic Processes 486
   6.2. Active Monitoring 487
   6.3. The inclusion of Space-Time Axes in Observations 487
7. Conclusions 488
References 489

27 Seasonal Changes in Vibroseismic Monitoring Experiments in Siberia 493

1. Introduction 493
2. Experiment Using Vibroseismic Monitoring 494
3. Areal Vibroseismic Monitoring 506
4. Discussion 509
5. Conclusions 510
References 510

28 Estimates of Crustal Stress Sensitivity in the Lake Baikal Region, from Active Vibroseismic Monitoring and Solid Earth Tide Data 513

1. Introduction 513
2. Data Processing and Interpretation 518
3. Measurements and Correction of Travel Time and Amplitude Variations 521
4. Statistical Analysis of Wave Arrival and Amplitude Series: Boundary Estimates 522
   - 4.1. Visual examination 522
   - 4.2. Analysis of random-scatter in travel times 523
   - 4.3. Revealing latent relationships using the correlation method 524
   - 4.4. Boundary estimate of velocity sensitivity to stresses 526
   - 4.5. Analysis of amplitude variations 527
5. Boundary Estimate of Wave Amplitude Sensitivity to Crust Stresses 530
6. Conclusions 531

References 531

Author Index *533*

Subject Index *545*