GEOPHYSICAL MONOGRAPH SERIES



Distributed Acoustic Sensing in Geophysics

Methods and Applications

Editors Yingping Li Martin Karrenbach Jonathan B. Ajo-Franklin



Table of Contents

<u>Cover</u>

<u>Series Page</u>

<u>Title Page</u>

<u>Copyright Page</u>

List of Contributors

List of Reviewers

<u>Preface</u>

<u>Part I: Distributed Acoustic Sensing (DAS)Concept,</u> <u>Principle, and Measurements</u>

<u>1 High Definition Seismic and Microseismic Data</u> <u>Acquisition Using Distributed and Engineered Fiber</u> <u>Optic Acoustic Sensors</u>

1.1. DISTRIBUTED ACOUSTIC SENSOR (DAS) PRINCIPLES AND MEASUREMENTS

1.2. DAS SYSTEM PARAMETERS AND COMPARISON WITH GEOPHONES

1.3. DAS WITH PRECISION ENGINEERED FIBER

ACKNOWLEDGMENTS

REFERENCES

TABLE OF VARIABLES

<u>2 Important Aspects of Acquiring Distributed</u> <u>Acoustic Sensing (DAS) Data for Geoscientists</u>

2.1. INTRODUCTION

2.2. FIBER-OPTIC SENSOR

2.3. INTERROGATOR UNIT

2.4. ACQUISITION PARAMETER SELECTION

2.5. PREPROCESSING ISSUES

2.6. PROCESSING ISSUES

2.7. DATA QUALITY: DAS VS. GEOPHONE COMPARISONS

2.8. SUMMARY

REFERENCES

<u>Chapter 3: Distributed Microstructured Optical</u> <u>Fiber (DMOF) Based Ultrahigh Sensitive</u> <u>Distributed Acoustic Sensing (DAS) for Borehole</u> <u>Seismic Surveys</u>

3.1. INTRODUCTION

3.2. PRINCIPLES AND METHODS OF DMOF-DAS

3.3. BOREHOLE SEISMIC SURVEY TESTS AND RESULTS

3.4. DISCUSSIONS

3.5. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>4 Distributed Acoustic Sensing System Based on</u> <u>Phase-Generated Carrier Demodulation Algorithm</u>

4.1. INTRODUCTION

4.2. PRINCIPLE

4.3. EXPERIMENTS AND RESULTS

<u>4.4. FIELD TRIAL OF NEAR-SURFACE</u> <u>SEISMIC EXPERIMENT WITH PGC-DAS</u> <u>SYSTEM</u>

4.5. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

Part II: Distributed Acoustic Sensing (DAS) Applications in Oil and Gas, Geothermal, and Mining Industries

<u>5 Field Trial of Distributed Acoustic Sensing in an</u> <u>Active Room-and-Pillar Mine</u>

5.1. INTRODUCTION

5.2. EXPERIMENTAL METHODS

5.3. CABLE COUPLING COMPARISONS

5.4. DAS SENSITIVITY

5.5. LOCATING A SEISMIC SOURCE

5.6. SURFACE WAVE TRAVEL-TIME TOMOGRAPHY

5.7. *P*-WAVE DIFFERENTIAL TRAVEL-TIME TOMOGRAPHY

5.8. DISCUSSION AND CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>6 On the Surmountable Limitations of Distributed</u> <u>Acoustic Sensing (DAS) Vertical Seismic Profiling</u> (VSP) – Depth Calibration, Directionality, and <u>Noise: Learnings From Field Trials</u>

6.1. INTRODUCTION

6.2. DEPTH CALIBRATION

6.3. DIRECTIONALITY

<u>6.4. NOISE</u>

<u>6.5. OVERCOMING THE FULL SUITE OF</u> <u>CHALLENGES – EXAMPLE FROM DEEP</u> WATER

6.6. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

7 Denoising Analysis and Processing Methods of Distributed Acoustic Sensing (DAS) Vertical Seismic Profiling (VSP) Data

7.1. INTRODUCTION

7.2. FIBER DEPLOYMENT TYPES AND NOISE SOURCES

7.3. CABLE RESONANCE REMOVAL

7.4. RANDOM NOISE SUPPRESSION

7.5. SNR ENHANCEMENT

7.6. CONCLUSION

REFERENCES

8 High-Resolution Shallow Structure at Brady Hot Springs Using Ambient Noise Tomography (ANT) on a Trenched Distributed Acoustic Sensing (DAS) Array

8.1. INTRODUCTION

8.2. DATA AND METHODS

8.3. NCF RESULTS

8.4. DISPERSION MEASUREMENT RESULTS

8.5. SHEAR WAVE VELOCITY MODEL

8.6. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>Part III: Distributed Acoustic Sensing (DAS)</u> <u>Applications in Monitoring of Deformations,</u> <u>Earthquakes, and Microseisms by Fracturing</u>

<u>9 Introduction to Interferometry of Fiber-Optic</u> <u>Strain Measurements</u>

9.1. INTRODUCTION

9.2. SENSITIVITY OF DAS TO FAR-FIELD SOURCES

<u>9.3 Sensitivity of DAS Cross-Correlations to</u> <u>Plane Wave Sources</u>

9.4. THOUGHT EXPERIMENT DEMONSTRATING AMBIENT NOISE INTERFEROMETRY TRENDS

9.5. SIMULATED AMBIENT NOISE INTERFEROMETRY ALONG CABLES

9.6. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>10 Using Telecommunication Fiber Infrastructure</u> <u>for Earthquake Monitoring and Near-Surface</u> <u>Characterization</u>

10.1. INTRODUCTION

10.2. THE SFSO

10.3. CONTINUOUS MONITORING AND ANALYSIS OF LOCAL AND REGIONAL EARTHQUAKES

10.4. CONTINUOUS MONITORING OF NEAR-SURFACE CONDITIONS BY INTEFEROMETRY

10.5. IS THE COUPLING BETWEEN CABLES AND THE GROUND THE LIMITING FACTOR?

<u>10.6. PROCESSING CHALLENGES FOR LARGE</u> <u>DAS ARRAYS IN URBAN ENVIRONMENTS</u>

10.7. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>11 Production Distributed Temperature Sensing</u> <u>versus Stimulation Distributed Acoustic Sensing for</u> the Marcellus Shale

11.1. INTRODUCTION

11.2. METHODOLOGY

11.3. RESULTS AND DISCUSSIONS

11.4. CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>12 Coalescence Microseismic Mapping for</u> <u>Distributed Acoustic Sensing (DAS) and Geophone</u> <u>Hybrid Array: A Model-Based Feasibility Study</u>

12.1. INTRODUCTION

12.2. DAS SYNTHETIC DATA FORMICROSEISMIC EVENTS

12.3. THE LOCATION ALGORITHM FORDAS-GEOPHONE HYBRID ARRAY

<u>12.4. TESTS</u>

12.5. DISCUSSION AND CONCLUSION

REFERENCES

<u>Part IV: Distributed Acoustic Sensing (DAS)</u> <u>Applications in Environmental and Shallow Geophysics</u>

<u>13 Continuous Downhole Seismic Monitoring Using</u> <u>Surface Orbital Vibrators and Distributed Acoustic</u> <u>Sensing at the CO2CRC Otway Project: Field Trial</u> <u>for Optimum Configuration</u>

13.1. INTRODUCTION

13.2. PERMANENT MONITORING AT THECO2CRC OTWAY PROJECT

13.3. FIELD EXPERIMENTS WITH DAS AND SOV SOURCES AT THE CO2CRC OTWAY PROJECT

13.4. OFFSET VSP PROCESSING

13.5. MAY 2017 FIELD TRIAL: CONVENTIONAL SINGLE-MODE FIBER VS. CONSTELLATION FIBER

<u>13.6. NOVEMBER 2017 FIELD TRIAL:</u> <u>PERFORMANCE OF SMALL AND LARGE</u> <u>MOTORS</u>

13.7. SUMMARY AND CONCLUSIONS

ACKNOWLEDGMENTS

<u>REFERENCES</u>

<u>14 Introduction to Distributed Acoustic Sensing</u> (DAS) Applications for Characterization of Near-Surface Processes

14.1. INTRODUCTION

14.2. CONSIDERATIONS FOR DEPLOYMENTS

14.3. SPECIFIC TOPICS IN THIS CHAPTER

14.4. CONCLUSIONS

REFERENCES

<u>15 Surface Wave Imaging Using Distributed</u> <u>Acoustic Sensing Deployed on Dark Fiber: Moving</u> <u>Beyond High-Frequency Noise</u>

15.1. INTRODUCTION

15.2. DARK FIBER NETWORKS: THE ESNET DARK FIBER TESTBED

15.3. STUDY SITE AND DATA ACQUISITION

15.4. DATA CHARACTERISTICS AND ANALYSIS OF NOISE SOURCES

15.5. PROCESSING STRATEGY

15.6. RESULTS

15.7. DISCUSSION

15.8. CONCLUSIONS

ACKNOWLEDGMENTS REFERENCES

<u>16 Using Distributed Acoustic Sensing (DAS) for</u> <u>Multichannel Analysis of Surface Waves (MASW)</u>

16.1. INTRODUCTION

16.2. DAS MEASUREMENT PRINCIPLES

16.3. STUDY AREA AND EQUIPMENT LAYOUT

16.4. LARGE SHAKER SEISMIC SOURCE

16.5. DAS AND GEOPHONE SENSORS

<u>16.6. MULTICHANNEL ANALYSIS OF</u> <u>SURFACE WAVES (MASW)</u>

<u>16.7. SURFACE-WAVE DISPERSION ANALYSIS</u> <u>RESULTS</u>

16.8. DISCUSSION

16.9. SUMMARY AND CONCLUSIONS

ACKNOWLEDGMENTS

REFERENCES

<u>17 A Literature Review: Distributed Acoustic</u> <u>Sensing (DAS) Geophysical Applications Over the</u> <u>Past 20 Years</u>

17.1. INTRODUCTION

17.2. FBG-BASED QDAS GEOPHYSICAL APPLICATIONS

17.3. VARIOUS DAS GEOPHYSICAL APPLICATIONS

17.4. SOME THOUGHTS ON RECENT ADVANCES AND FUTURE APPLICATIONS

<u>17.5. CONCLUSION</u>

ACKNOWLEDGMENTS

REFERENCES

INDEX

End User License Agreement

List of Tables

Chapter 6

Table 6.1 Fields Trials of Active-Source DAS Seismic Applications by Shell ...

Chapter 9

Table 9.1 Plane Wave Particle Displacements and Velocities.

Table 9.2 Plane Wave Particle Velocity, \dot{u}_{θ} , Point-Wise Axial Strain Rate, $\dot{\epsilon}_{\theta}$, ...

<u>Table 9.3 Cross-Correlations of Measurements at</u> ($\underline{x_1}, \underline{y_1}, \underline{z_1}$) in the ($C_{\theta_1}, S_{\theta_1}, 0$) Direc...

Table 9.4 Horizontal Particle Velocity and Point-Wise Axial Strain Rate Res...

Chapter 10

Table 10.1 Local Earthquake Recorded by the SFSO DAS Array.

Table 10.2 Estimates of Relative Amplitudes of the Data Generated by Five L...

Chapter 12

Table 12.1 Comparison of Specifications of Geophone and DAS Arrays.

<u>Table 12.2 CMM Algorithm Parameters Used in</u> <u>This Study.</u>

Chapter 13

Table 13.1 Acquisition Parameters for the May 2017 Field Trial.

Table 13.2 Acquisition Parameters for the November 2017 Field Trial.

Table 13.3 Offset VSP Processing Flow.

Chapter 15

Table 15.1 Upper and Lower Bounds of MC Sampling for Inversion Parameters.

Table 15.2 Location and American Petroleum Institute (API) Identification Nu...

Chapter 16

Table 16.1 Parameters Used in SWAMI Inversion.

Chapter 17

Table 17.1 Review and Introduction for DAS Applications.

Table 17.2 FBG-Based qDAS Applications in Geophysics.

<u>Table 17.3 DAS Principle, Instrument, Installation,</u> <u>Tests, and Advance.</u>

<u>Table 17.4 DAS-VSP (Borehole Seismic)</u> <u>Applications.</u>

Table 17.5 DAS in Downhole Surveillance and Flow Monitoring.

Table 17.6 DAS in Monitoring Hydraulic Fracturing and Microseismicity.

Table 17.7 *DAS in CCS and CO ₂ Injection Monitoring.*

Table 17.8 DAS in Surface Seismic Exploration.

Table 17.9 DAS in Geothermal System, Mining, and Mineral Exploration.

Table 17.10 DAS Monitoring for Safety and Security.

Table 17.11 DAS for Seismology, Fault, and Deformation.

Table 17.12 DAS Data Exchange, Management,Processing, and Deep Learning.

List of Illustrations

Chapter 1

<u>Figure 1.1 Operation principle of distributed</u> <u>acoustic sensing.</u>

Figure 1.2 COTDR.

<u>Figure 1.3 DAS schemas: MOD—intensity and</u> <u>frequency modulator; AOM—acousto-o...</u>

<u>Figure 1.4 DAS optical setup. Distance is</u> <u>proportional to flytime.</u>

<u>Figure 1.5 COTDR response (Equation 1.6) shown</u> <u>in the left panel of the simu...</u>

<u>Figure 1.6 Intensity changes are irregular along</u> <u>distance but harmonic along...</u>

<u>Figure 1.7 Comparison of DAS theoretical response</u> (Equation 1.13) with simul...

<u>Figure 1.8 Comparison of first and second order</u> <u>tracking algorithms for DAS....</u>

<u>Figure 1.9 The left-hand panel shows modeling of</u> <u>raw DAS acoustic data (Equa...</u> <u>Figure 1.10 Illustration of two time-consecutive</u> <u>measurements when DAS outpu...</u>

<u>Figure 1.11 Acoustic measurements using DAS: The</u> <u>left panel represents strai...</u>

<u>Figure 1.12 Comparison of DAS spectral response</u> with that from a 10 m sensor...

<u>Figure 1.13 Low spatial frequency gain in DAS by</u> <u>using long interferometer...</u>

<u>Figure 1.14 DAS with linear optical cable is more</u> <u>sensitive to *P*-wave in VSP...</u>

<u>Figure 1.15 2D spectral representation on upgoing</u> <u>and downgoing acoustic wav...</u>

<u>Figure 1.16 Normalized SNR curve (SNR vs.</u> <u>frequency) for a 3000 m/s wave spe...</u>

<u>Figure 1.17 Sensing optical fiber cable</u> <u>deployments.</u>

<u>Figure 1.18 The left-hand panel shows a single shot</u> <u>of raw acoustic data; th...</u>

<u>Figure 1.19 Comparison of DAS performance with</u> <u>SM and MM optical fiber.</u>

<u>Figure 1.20 Directionality of DAS response: The left</u> <u>and central panels repr...</u>

<u>Figure 1.21 3D VSP: Two intersecting images</u> <u>processed from DAS seismic data ...</u>

<u>Figure 1.22 DAS hydraulic fracture monitoring in</u> <u>the treatment well with a f...</u>

<u>Figure 1.23 DAS hydraulic fracture monitoring in</u> <u>the offset (a) with a fine ...</u>

Figure 1.24 DAS with standard fiber and engineered fiber with precision brig... <u>Figure 1.25 Optical fiber with defined scatter</u> <u>center zones and the correspo...</u>

<u>Figure 1.26 Acoustic measurements using DAS with</u> <u>precision engineered fiber:...</u>

<u>Figure 1.27 Comparison of DAS with engineered</u> <u>fiber spectral response for sp...</u>

<u>Figure 1.28 Ultimate SNR spectral response of DAS</u> with standard and engineer...

<u>Figure 1.29 Displacement noise comparison of DAS</u> (with and without engineere...

<u>Figure 1.30 Maximum strain comparison of first</u> <u>and second order algorithms f...</u>

<u>Figure 1.31 Comparison of DAS with Rayleigh</u> <u>scattering [(a) and (b)] and eng...</u>

<u>Figure 1.32 Comparison of DAS noise spectrums</u> <u>with Rayleigh scattering (a) a...</u>

<u>Figure 1.33 Microseismic event in observation well</u> <u>detected by DAS with engi...</u>

<u>Figure 1.34 Example of low frequency (down to</u> <u>millihertz level) "slow strain...</u>

<u>Figure 1.35 Comparison of geophones (left panel)</u> and DAS with engineered fib...

Chapter 2

<u>Figure 2.1 Options for acquiring DAS VSP data in a</u> <u>well.</u>

<u>Figure 2.2 (Left) Conceptual diagram of an IU</u> (inside the dotted black line)...

<u>Figure 2.3 (Top) Location of first spectral notch for</u> <u>a range of gauge lengt...</u> <u>Figure 2.4 Recommended pulse width as a function</u> of gauge length.

<u>Figure 2.5 (Top) I (blue) and Q (orange) traces;</u> (middle) corresponding rela...

<u>Figure 2.6 Strain rate VSP data collected with a</u> <u>vibrator – (top row) uncorr...</u>

<u>Figure 2.7 (a) single sweep using Frequency 1 –</u> <u>note the prominent fading at...</u>

<u>Figure 2.8 (Left) Strain rate record showing</u> <u>common-mode noise; (right) same...</u>

<u>Figure 2.9 Angular response of the fiber to *P* waves (left) and *S* waves (righ...</u>

<u>Figure 2.10 Relationship among the various</u> <u>products created from a DAS data ...</u>

Chapter 3

Figure 3.1 Schematic principle of the fiber optic DAS system.

Figure 3.2 Schematic of DMOF.

<u>Figure 3.3 Simulated intensity distribution along</u> <u>fiber when the intensity o...</u>

<u>Figure 3.4 The block diagram of the continuous</u> <u>online DMOF fabrication syste...</u>

<u>Figure 3.5 Comparison between the DMOF and the</u> <u>SMF: (a) Spectra of the backs...</u>

<u>Figure 3.6 Working principle of DMOF-DAS: (a)</u> <u>System configuration and (b) p...</u>

<u>Figure 3.7 Sensing performance of the DMOF-DAS</u> <u>system: (a) Photograph of the...</u> <u>Figure 3.8 Field test in the Fushan oil field: (a)</u> <u>Schematic of the zero-off...</u>

<u>Figure 3.9 Recorded seismic data in well using</u> <u>DMOF-DAS: (a) DMOF-DAS VSP da...</u>

Chapter 4

<u>Figure 4.1 Principle of PGC-DAS system with an</u> <u>unbalanced MI.</u>

Figure 4.2 Setup of PGC-DAS system.

<u>Figure 4.3 Phase noise of PGC-DAS system on</u> <u>Channel #4750: (a) Time series a...</u>

<u>Figure 4.4 Intensity map of demodulation</u> <u>magnitude of each channel: (a) Wate...</u>

<u>Figure 4.5 Time domain and STFT spectrogram of</u> <u>sweeping frequency signal.</u>

<u>Figure 4.6 Amplitude response curve of PGC-DAS</u> <u>system.</u>

<u>Figure 4.7 Field trial of near-surface seismic</u> <u>experiment. (a) Plan view of ...</u>

Figure 4.8 Initial data of DAS system and geophone array for *x*-component at ...

Chapter 5

<u>Figure 5.1 (a) Map of the Lafarge-Conco mine</u> (presented with permission of L...

<u>Figure 5.2 (a) Sketch of a cross-section showing the</u> <u>emplacement of co-locat...</u>

<u>Figure 5.3 Waveforms and spectra for different</u> <u>source locations recorded on ...</u>

<u>Figure 5.4 Ambient noise records at Location E (left column) and Location H ...</u>

<u>Figure 5.5 (a) Wavefield for all three cable loops for</u> <u>the source at Locatio...</u>

<u>Figure 5.6 (a) Amplitude decay curves for Loop 1.</u> <u>Crosses show the amplitude...</u>

<u>Figure 5.7 (a) Time vs. channel number plot for</u> <u>Loop 1 for the blast execute...</u>

<u>Figure 5.8 (a) Stacked traces for Loop 1 for the ESS</u> <u>source at Location B. B...</u>

<u>Figure 5.9 (a) Sample ray paths for surface wave</u> <u>tomography using the ESS so...</u>

<u>Figure 5.10 (a) Example waveforms and first</u> <u>arrivals from channel pair 390 a...</u>

<u>Figure 5.11 *P*-wave differential travel-time</u> <u>tomogram.</u>

Chapter 6

<u>Figure 6.1 Absolute depth calibration using DAS</u> <u>receiver scalars (red and bl...</u>

<u>Figure 6.2 Relative depth calibration between time-</u> <u>lapse DAS VSP vintages (i...</u>

<u>Figure 6.3 The impact (before/after) of relative</u> <u>depth calibration on 4D att...</u>

<u>Figure 6.4 Ray contributions in deviated well –</u> <u>directionality consideration...</u>

<u>Figure 6.5 3D/4D DAS VSP from flowing wells: (a)</u> <u>Geometry of 2017 simultaneo...</u>

<u>Figure 6.6 Repeatability of DAS VSP images from</u> <u>flowing wells: (a) From Well...</u>

<u>Figure 6.7 4D signals obtained from DAS VSP in</u> <u>Well W2 (2015–2017) compared ...</u> Chapter 7

<u>Figure 7.1 Three types of DAS-VSP optical fiber</u> <u>deployment in a borehole. (a...</u>

<u>Figure 7.2 DAS-VSP data received by optical fibers</u> <u>freely suspended in the c...</u>

<u>Figure 7.3 Comparison of VSP single-shot record</u> <u>received from (a) flexible o...</u>

<u>Figure 7.4 Diagram of cable resonance</u> <u>interference.</u>

<u>Figure 7.5 The denoising effect of cable resonance.</u> (a) Record before denois...

<u>Figure 7.6 DAS-VSP recording before (a) and after</u> (b) F-X denoising.

<u>Figure 7.7 Before and after improved SNR</u> processing common shot point gather...

Chapter 8

<u>Figure 8.1 Seismic acquisition systems in the Brady</u> <u>Hot Springs geothermal s...</u>

<u>Figure 8.2 (a) Thirty seconds of raw data recorded</u> <u>by Channel 0100 in the so...</u>

<u>Figure 8.3 The data preparation and modeling</u> <u>process used in this study.</u>

<u>Figure 8.4 (a) Correlation coefficient to the</u> <u>reference trace vs. the number...</u>

<u>Figure 8.5 Record section of NCFs between</u> <u>channel pairs along one segment (d...</u>

<u>Figure 8.6 Individual NCFs (black) in a distance bin</u> and the stacked trace (... <u>Figure 8.7 Record section of NCFs between</u> <u>channel pairs along two in-line se...</u>

<u>Figure 8.8 (a) One MASW measurement example.</u> <u>The color represents stacking e...</u>

<u>Figure 8.9 (a) One MFT measurement example. The</u> <u>color represents stacking en...</u>

<u>Figure 8.10 (a) The layered model used in</u> <u>sensitivity kernel computation. (b...</u>

<u>Figure 8.11 (a) Daily average surface temperature</u> of 14 March 2016. (b) Shea...

<u>Figure 8.12 Velocity models at 20 m depth. (a) $V_{\rm s}$ </u> <u>model in this study, (b) V</u>

Chapter 9

<u>Figure 9.1 We study surface waves (indicated by</u> <u>the red and blue bars) that ...</u>

<u>Figure 9.2 Each polar plot shows the amplitude</u> <u>response of a measurement to ...</u>

<u>Figure 9.3 The radius of each line represents the</u> <u>sensitivity of DAS with a ...</u>

<u>Figure 9.4 The radius of each line represents the</u> <u>sensitivity of geophones (...</u>

<u>Figure 9.5 The radius of each line represents the</u> <u>sensitivity of geophones (...</u>

<u>Figure 9.6 The radius of each line represents the</u> <u>sensitivity of geophones (...</u>

<u>Figure 9.7 The radius of each line represents the</u> <u>sensitivity of radial-radi...</u>

Figure 9.8 We study the cross-correlation response of two sensors at $\mathbf{x}_1 = (-...)$ <u>Figure 9.9 Random synthetic point sources emitting</u> <u>Rayleigh waves were recor...</u>

<u>Figure 9.10 A single long radial-radial cross-</u> <u>correlation of synthetic geoph...</u>

<u>Figure 9.11 Random synthetic point sources</u> <u>emitting Love waves were recorded...</u>

<u>Figure 9.12 (Left) A single long transverse</u> <u>transverse cross-correlation of ...</u>

<u>Figure 9.13 (Left) A virtual source is marked in</u> <u>yellow along one fiber line...</u>

<u>Figure 9.14 (Left) A virtual source is marked in</u> <u>yellow along one fiber line...</u>

Chapter 10

<u>Figure 10.1 (Left) Trace of the array overlaid to an</u> <u>aerial photo of the cam...</u>

<u>Figure 10.2 Map of the southwest region of the</u> <u>Stanford campus. It shows the...</u>

<u>Figure 10.3 Data recorded for all the Felt Lake</u> <u>events shown in the same ord...</u>

<u>Figure 10.4 Results of template matching for data</u> <u>recorded by SFSO ((a), JRS...</u>

<u>Figure 10.5 Results of template matching for data</u> <u>recorded by SFSO (a), JRSC...</u>

<u>Figure 10.6 (Left) Virtual source gathers computed</u> <u>by cross-coherency applie...</u>

<u>Figure 10.7 Cross correlations between data</u> <u>recorded by Channel #27 and (lef...</u>

Figure 10.8 Cross correlations between data recorded by Channel #27 and (lef... <u>Figure 10.9 (Left) Frequency spectra of the data</u> <u>recorded by the ODH 3.1 int...</u>

<u>Figure 10.10 The *Alum Rock* event recorded by the</u> <u>ODH 3.1 interrogator. (Left...</u>

<u>Figure 10.11 The *Alum Rock* event recorded by the</u> <u>ODH 4.0 interrogator. (Left...</u>

<u>Figure 10.12 (Left) The different types of identified</u> <u>wave-mode clusters ave...</u>

<u>Figure 10.13 Array geometry automatically</u> <u>estimated by combining a convoluti...</u>

Chapter 11

<u>Figure 11.1 The MIP-3H well trajectory. The lateral</u> <u>landed and stayed in the...</u>

<u>Figure 11.2 Logs acquired along the lateral of the</u> <u>MIP-3H well. Curves from ...</u>

<u>Figure 11.3 Rose diagrams of natural fractures (a)</u> <u>observed along the length...</u>

<u>Figure 11.4 Vertical CT scan of the MIP-3H pilot</u> <u>core (7508–7509 feet). Vert...</u>

<u>Figure 11.5 The incident laser is backscattered in</u> <u>different wavelength Rama...</u>

<u>Figure 11.6 (a) Upper plot shows the measured</u> <u>DTS from May 2016 to May 2018 ...</u>

<u>Figure 11.7 The detrended DTS attribute is</u> <u>averaged to the stage scale. The ...</u>

<u>Figure 11.8 Energy attribute for Stage 5 (a) and</u> <u>Stage 10 (b) stimulation fr...</u>

<u>Figure 11.9 Microseismic events' distribution is</u> <u>illustrated for Stages 7–28...</u> <u>Figure 11.10 (a) A cluster score is calculated for</u> <u>each cluster for every st...</u>

Chapter 12

Figure 12.1 Comparison of spectrum of microseismic synthetic data for an eve...

<u>Figure 12.2 Comparison of spectrum of</u> <u>microseismic synthetic data. (Left) Pa...</u>

<u>Figure 12.3 Event location and receiver array used</u> <u>in this study. Length uni...</u>

<u>Figure 12.4 Workflow to generate the DAS</u> <u>synthetic waveforms in this study....</u>

Figure 12.5 An example of a synthetic waveform of DAS. The event is located ...

<u>Figure 12.6 (Left) High-level design of migration-</u> based event location algor...

<u>Figure 12.7 Event locations estimated by CMM for</u> <u>data set only at the horizo...</u>

<u>Figure 12.8 Event locations (purple) estimated by</u> <u>CMM with automatic receive...</u>

<u>Figure 12.9 An example of a flag for receiver</u> <u>selection and model time picks...</u>

<u>Figure 12.10 Comparison of event location with and</u> <u>without automatic receive...</u>

Chapter 13

Figure 13.1 The CO2CRC Otway Project site location and satellite image. The ...

<u>Figure 13.2 Seismic fold (color bar) given by a</u> <u>combination of seven wells (...</u> Figure 13.3 DAS-SOV VSP records acquired for SOV1 [(a) and (b)] and SOV 2 [(...

Figure 13.4 Amplitude spectrum for the constellation fiber (blue curve) and ...

<u>Figure 13.5 VSP to CDP transform for the</u> <u>constellation fiber (a) and the sta...</u>

<u>Figure 13.6 Crossline from a conventional</u> <u>vibroseis-geophone surface seismic...</u>

<u>Figure 13.7 VSP acquired with DAS using large and</u> <u>small motors at SOV1 [(a) ...</u>

<u>Figure 13.8 Results of VSP to CDP transform for</u> <u>test with sweeps from 0 to 8...</u>

Chapter 15

Figure 15.1 An aerial photograph showing location of the study site and tran...

<u>Figure 15.2 Data characteristics along the dark</u> <u>fiber array. (a) A 10 s reco...</u>

<u>Figure 15.3 (a) Comparison of spectral amplitude of</u> <u>the distinct noise signa...</u>

<u>Figure 15.4 Ambient noise processing flow for $V_{\rm s}$ </u> <u>recovery at intermediate de...</u>

<u>Figure 15.5 Comparison between a 30 minute</u> <u>single virtual shot gather and ph...</u>

<u>Figure 15.6 Data sets and development of a</u> <u>reference $V_s(z)$ model; panel (a)</u>...

<u>Figure 15.7 Results of multimodal inversion of the</u> <u>analyzed 1 km long virtua...</u>

Chapter 16

<u>Figure 16.1 Map of the Garner Valley field site. The</u> <u>thick line is the layou...</u>

<u>Figure 16.2 Subsurface geology at Garner Valley.</u> (a) Shear-wave velocity pro...

<u>Figure 16.3 (a) Mini-Me structure. Locations of</u> <u>eccentric mass shaker and fo...</u>

<u>Figure 16.4 Plots of 63 s of data for a colocated</u> <u>DAS channel 774 (top) and ...</u>

<u>Figure 16.5 (a) Expanded plots of 13 s of data</u> <u>showing passing traffic for a...</u>

<u>Figure 16.6 (a) Plot of 30 m of unfiltered DAS data.</u> <u>Channels are spaced 5 m...</u>

<u>Figure 16.7 Plots (a) through (d) show source</u> <u>synchronous filtered MWCC DAS ...</u>

<u>Figure 16.8 Dispersion curve results for the DAS</u> and GVDA accelerometers num...

<u>Figure 16.9 Dispersion curve results from the DAS</u> <u>crosshatch line, as well a...</u>

<u>Figure 16.10 (a) Modeled dispersion curve obtained</u> <u>by Stokoe et al. (2004) a...</u>

<u>Figure 16.11 Dispersion curves obtained from the</u> <u>DAS long line active source...</u>

Chapter 17

<u>Figure 17.1 Trend of collected journal and</u> <u>conference papers/abstracts relat...</u>

<u>Figure 17.2 Histogram of papers presented at the</u> <u>SEG DAS workshops since 201...</u>

Geophysical Monograph Series

212 The Early Earth: Accretion and Differentiation James Badro and Michael Walter (Eds.)

213 Global Vegetation Dynamics: Concepts and Applications in the MC1 Model *Dominique Bachelet and David Turner (Eds.)*

214 Extreme Events: Observations, Modeling and Economics *Mario Chavez, Michael Ghil, and Jaime Urrutia-Fucugauchi (Eds.)*

215 Auroral Dynamics and Space Weather Yongliang Zhang and Larry Paxton (Eds.)

216 Low-Frequency Waves in Space Plasmas Andreas Keiling, Dong-Hun Lee, and Valery Nakariakov (Eds.)

217 Deep Earth: Physics and Chemistry of the Lower Mantle and Core *Hidenori Terasaki and Rebecca A. Fischer (Eds.)*

218 Integrated Imaging of the Earth: Theory and Applications *Max Moorkamp, Peter G. Lelievre, Niklas Linde, and Amir Khan (Eds.)*

219 Plate Boundaries and Natural Hazards *Joao Duarte and Wouter Schellart (Eds.)*

220 Ionospheric Space Weather: Longitude and Hemispheric Dependences and Lower Atmosphere Forcing *Timothy Fuller-Rowell, Endawoke Yizengaw, Patricia H. Doherty, and Sunanda Basu (Eds.)*

221 Terrestrial Water Cycle and Climate Change Natural and Human-Induced Impacts *Qiuhong Tang and Taikan Oki (Eds.)*

222 Magnetosphere-Ionosphere Coupling in the

Solar System *Charles R. Chappell, Robert W. Schunk, Peter M. Banks, James L. Burch, and Richard M. Thorne (Eds.)*

223 Natural Hazard Uncertainty Assessment: Modeling and Decision Support Karin Riley, Peter Webley, and Matthew Thompson (Eds.)

224 Hydrodynamics of Time-Periodic Groundwater Flow: Diffusion Waves in Porous Media Joe S. Depner and Todd C. Rasmussen (Auth.)

225 Active Global Seismology Ibrahim Cemen and Yucel Yilmaz (Eds.)

226 Climate Extremes Simon Wang (Ed.)

227 Fault Zone Dynamic Processes Marion Thomas (Ed.)

228 Flood Damage Survey and Assessment: New Insights from Research and Practice Daniela Molinari, Scira Menoni, and Francesco Ballio (Eds.)

229 Water-Energy-Food Nexus - Principles and Practices *P. Abdul Salam, Sangam Shrestha, Vishnu Prasad Pandey, and Anil K Anal (Eds.)*

230 Dawn-Dusk Asymmetries in Planetary Plasma Environments *Stein Haaland, Andrei Rounov, and Colin Forsyth (Eds.)*

231 Bioenergy and Land Use Change Zhangcai Qin, Umakant Mishra, and Astley Hastings (Eds.)

232 Microstructural Geochronology: Planetary Records Down to Atom Scale Desmond Moser, Fernando Corfu, James Darling, Steven Reddy, and Kimberly Tait (Eds.) **233** Global Flood Hazard: Applications in Modeling, Mapping and Forecasting *Guy Schumann, Paul D. Bates, Giuseppe T. Aronica, and Heiko Apel (Eds.)*

234 Pre-Earthquake Processes: A Multidisciplinary Approach to Earthquake Prediction Studies *Dimitar*

Ouzounov, Sergey Pulinets, Katsumi Hattori, and Patrick Taylor (Eds.)

235 Electric Currents in Geospace and Beyond Andreas Keiling, Octav Marghitu, and Michael Wheatland (Eds.)

236 Quantifying Uncertainty in Subsurface Systems *Celine Scheidt, Lewis Li, and Jef Caers (Eds.)*

237 Petroleum Engineering *Moshood Sanni (Ed.)*

238 Geological Carbon Storage: Subsurface Seals and Caprock Integrity *Stephanie Vialle, Jonathan Ajo-Franklin, and J. William Carey (Eds.)*

239 Lithospheric Discontinuities *Huaiyu Yuan and Barbara Romanowicz (Eds.)*

240 Chemostratigraphy Across Major Chronological Eras *Alcides N. Sial, Claudio Gaucher, Muthuvairavasamy Ramkumar, and Valderez Pinto Ferreira (Eds.)*

241 Mathematical Geoenergy:Discovery, Depletion, and Renewal *Paul Pukite, Dennis Coyne, and Daniel Challou (Eds.)*

242 Ore Deposits: Origin, Exploration, and Exploitation Sophie Decree and Laurence Robb (Eds.)

243 Kuroshio Current: Physical, Biogeochemical and Ecosystem Dynamics *Takeyoshi Nagai, Hiroaki Saito, Koji Suzuki, and Motomitsu Takahashi (Eds.)*

244 Geomagnetically Induced Currents from the Sun to the Power Grid *Jennifer L. Gannon, Andrei Swidinsky,*

and Zhonghua Xu (Eds.)

245 Shale: Subsurface Science and Engineering *Thomas Dewers, Jason Heath, and Marcelo Sánchez (Eds.)*

246 Submarine Landslides: Subaqueous Mass Transport Deposits From Outcrops to Seismic Profiles *Kei Ogata, Andrea Festa, and Gian Andrea Pini (Eds.)*

247 Iceland: Tectonics, Volcanics, and Glacial Features *Tamie J. Jovanelly*

248 Dayside Magnetosphere Interactions *Qiugang Zong, Philippe Escoubet, David Sibeck, Guan Le, and Hui Zhang (Eds.)*

249 Carbon in Earth's Interior Craig E. Manning, Jung-Fu Lin, and Wendy L. Mao (Eds.)

250 Nitrogen Overload: Environmental Degradation, Ramifications, and Economic Costs Brian G. Katz

251 Biogeochemical Cycles: Ecological Drivers and Environmental Impact *Katerina Dontsova, Zsuzsanna Balogh-Brunstad, and Gaël Le Roux (Eds.)*

252 Seismoelectric Exploration: Theory, Experiments, and Applications *Niels Grobbe, André Revil, Zhenya Zhu, and Evert Slob (Eds.)*

253 El Niño Southern Oscillation in a Changing Climate *Michael J. McPhaden, Agus Santoso, and Wenju Cai (Eds.)*

254 Dynamic Magma Evolution *Francesco Vetere (Ed.)*

255 Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes Richard. E. Ernst, Alexander J. Dickson, and Andrey Bekker (Eds.)

256 Coastal Ecosystems in Transition: A Comparative Analysis of the Northern Adriatic and **Chesapeake Bay** *Thomas C. Malone, Alenka Malej, and Jadran Faganeli (Eds.)*

257 Hydrogeology, Chemical Weathering, and Soil Formation Allen Hunt, Markus Egli, and Boris Faybishenko (Eds.)

258 Solar Physics and Solar Wind Nour E. Raouafi and Angelos Vourlidas (Eds.)

259 Magnetospheres in the Solar System *Romain Maggiolo, Nicolas André, Hiroshi Hasegawa, and Daniel T. Welling (Eds.)*

260 Ionosphere Dynamics and Applications Chaosong Huang and Gang Lu (Eds.)

261 Upper Atmosphere Dynamics and Energetics *Wenbin Wang and Yongliang Zhang (Eds.)*

262 Space Weather Effects and Applications Anthea J. Coster, Philip J. Erickson, and Louis J. Lanzerotti (Eds.)

263 Mantle Convection and Surface Expressions Hauke Marquardt, Maxim Ballmer, Sanne Cottaar, and Jasper Konter (Eds.)

264 Crustal Magmatic System Evolution: Anatomy, Architecture, and Physico-Chemical Processes Matteo Masotta, Christoph Beier, and Silvio Mollo (Eds.)

265 Global Drought and Flood: Observation, Modeling, and Prediction Huan Wu, Dennis P.Lettenmaier, Qiuhong Tang, and Philip J Ward (Eds.)

266 Magma Redox Geochemistry *Roberto Moretti and Daniel R. Neuville (Eds.)*

267 Wetland Carbon and Environmental Management *Ken W. Krauss, Zhiliang Zhu, and Camille L. Stagg (Eds.)*

268 Distributed Acoustic Sensing in Geophysics: Methods and Applications *Yingping Li, Martin Karrenbach, and Jonathan B. Ajo-Franklin (Eds.)*