Passive Seismic Monitoring of Induced Seismicity

Fundamental Principles and Application to Energy Technologies

The past few decades have witnessed remarkable growth in the application of passive seismic monitoring to address a range of problems in geoscience and engineering from large-scale tectonic studies to environmental investigations. Passive seismic methods are increasingly being used for surveillance of massive, multi-stage hydraulic fracturing and development of enhanced geothermal systems. The theoretical framework and techniques used in this emerging area draw on various established fields, such as earthquake seismology, exploration geophysics and rock mechanics. Based on university and industry courses developed by the author, this book reviews all the relevant research and technology to provide an introduction to the principles and applications of passive seismic monitoring. It integrates up-to-date case studies and interactive online exercises, making it a comprehensive and accessible resource for advanced students and researchers in geophysics and engineering as well as for industry practitioners.

David W. Eaton is Professor of Geophysics in the University of Calgary's Department of Geoscience, where he served as Department Head from 2007 to 2012. He is presently co-director of the Microseismic Industry Consortium, a novel initiative dedicated to the advancement of research, education and technological innovations in microseismic methods and their practical applications for resource development. His current research is focused on microseismic monitoring and induced seismicity, intraplate earthquake swarms and the lithosphere–asthenosphere boundary beneath continents.

"It is now well established that human activities in the subsurface create induced seismicity. While large events can be extremely problematic from both a seismic hazard and operational safety perspective, smaller induced events, known as microseismic events, can tell us a great deal about changes in the subsurface. Eaton provides a clear and comprehensive description of such seismicity, starting from first principles and then progressively taking the reader through to real examples and case studies. A focus is on seismicity associated with oil and gas exploitation, but the book will also appeal to scientists interested in seismicity in a range of other settings (e.g., geothermal, mining, etc.). Eaton has crafted an excellent seismology text for students and earthquake seismologists in general."

– Professor Michael Kendall, University of Bristol

"*Passive Seismic Monitoring of Induced Seismicity* is a comprehensive textbook covering basic theoretical concepts of seismic and ancillary topics through to practical implementation in industrial settings. The book is an essential reference text on this topical technology."

– Dr Shawn Maxwell, IMaGE

"This comprehensive text is a much-needed and timely overview of topics related to seismic monitoring of induced earthquakes. It not only provides a thorough treatment of how microseismic monitoring is done and the data are analyzed, it provides a valuable overview of how and why injection-induced seismicity occurs."

– Professor Mark Zoback, Stanford University

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David W. Eaton
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Preface

The past few decades have witnessed remarkable growth in the application of passive seismic monitoring to address a range of problems in geoscience and engineering, from large-scale tectonic studies to environmental investigations. Microseismic methods are a prime example of a passive-seismic approach applied to the study of brittle deformation in rocks. These methods are increasingly being used for in situ monitoring of fracture processes, including hydraulic-fracture stimulation of tight reservoirs, development of enhanced geothermal systems, assessment of caprock integrity for CO_2 sequestration, life-cycle reservoir monitoring for heavy-oil production and monitoring of mining operations. The theoretical framework and techniques used in this emerging discipline draw from various established fields, such as earthquake seismology, exploration geophysics and rock mechanics. The aim of this book is to synthesize research and technology within this topic, which at present is widely scattered across disparate scientific and engineering communities and published in discipline-specific journals and conference proceedings.

This book is grounded in seismology, but draws from related disciplines including reservoir engineering and rock-, fracture-, earthquake-, continuum- and geo-mechanics. It provides an introduction to the principles and applications of microseismic monitoring and is aimed at undergraduate and graduate students in geophysics or engineering, as well as working geoscience professionals. The applications of microseismic methods are myriad and include surveillance of hydraulic stimulation for unconventional hydrocarbon development and enhanced geothermal systems, monitoring and verification of long-term underground storage such as CO_2, and ensuring the safety of workers in deep underground mines. The theoretical underpinnings of passive-seismic monitoring include mathematical aspects of seismology, mechanics and signal processing, so it is assumed that readers will have a suitable background that includes mathematics and physics at the junior undergraduate level. A strong fundamental knowledge of these topics is key to achieving a quantitative understanding of the important industrial applications.

The interdisciplinary nature of passive-seismic monitoring means that mathematical expressions are rife with conflicting notation coming from established usage, across different disciplines, of identical symbols with utterly different meanings. This has necessitated a rather large dose of creativity in the use of subscripts and modifiers, in order to define a set of unique symbols for parameters and expressions that are used repeatedly. Nevertheless, some repetition of common symbols is virtually unavoidable, where the meaning is context sensitive. For example, it is contextually clear, thoughout this book, whether E is used to represent energy or Young's modulus. Similarly, specific terminology has evolved within different disciplines that can, at times, be virtually incomprehensible to those outside that field. In an effort to reduce this barrier to understanding, a Glossary is included here as

Appendix A. Throughout the text, new terms (many of which appear in the Glossary) are introduced using *italics*.

With a few exceptions, SI units are used in this book, although this usage may seem slightly foreign to those who are accustomed to the use of units of measure such as “barrels” and “psi.” One exception to the use of SI units is permeability, for which the non-standard unit of Darcies is more convenient. The following list of Symbols specifies the units, as applicable, for repeatedly used quantities.

This book is largely based on notes and interactive online materials from a graduate course that I have developed, entitled *Introduction to Microseismic Methods*. While delivering this course, guest speakers, students and industry participants have broadened my knowledge horizons considerably. I am deeply indebted to all, especially guest speakers who have graciously contributed their expertise. In addition, this course has been energized by research and academic–industry interactions that occurred as part of the Microseismic Industry Consortium. A number of field datasets have been acquired since 2011, under the auspices of the Microseismic Industry Consortium; these field experiments provided data examples that are used throughout this book. To my knowledge, this level of university-led field data acquisition is unparalleled. Although it has presented daunting challenges, these field activities have provided important insights, hands-on experience and unique training opportunities for students and postdoctoral researchers.

There are numerous individuals whom I wish to thank for their help in preparing this book. Colleagues from academia and industry are sincerely thanked for providing reviews and critical feedback on sections of this book, including Ed Krebes, Jan Dettmer, Jeff Priest, Ron Wong, Shawn Maxwell, Peter Duncan, Gail Atkinson, Ryan Shultz, Yajing Liu, Hersh Gilbert, Chris Clarkson and Hadi Ghofrani. Current and former students and postdoctoral researchers also contributed many ideas and suggestions, including help with preparing figures and proofreading. I am particularly appreciative of contributions from Nadine Igonin, Jubran Akram, Hongliang Zhang, Suzie Jia, Megan Zecevic, Thomas Eyre, Kim Pike, Anton Biryukov and Ron Weir. In addition, I am very grateful to Sarah Reid, who provided tireless and skilled assistance with figures. Mirko van der Baan is sincerely thanked for his collegial partnership in the Microseismic Industry Consortium. Finally, my heartfelt thanks go to my wife, Pam, who endured months of my irrational work hours and distraction while this book was taking shape.

Symbols

$\widehat{M}_{max}$	Maximum observed magnitude in an event sequence
α	Biot's coefficient. Unitless
$\boldsymbol{\epsilon}$	Strain tensor. Unitless
$\hat{\boldsymbol{\gamma}}$	Unit polarization vector
$\boldsymbol{\kappa}$	Permeability tensor. Units: m^2 (1 Darcy $\approx 10^{-12}$ m^2)
$\boldsymbol{\sigma}$	Stress tensor. Units: Pa
$\Delta\tau$	Co-seismic stress drop (scalar). Units: Pa
δ	Dirac delta
δ_T	Thomsen parameter for transverse isotropy. Unitless
δ_{ij}	Kronecker delta
ϵ_{ijk}	Alternating tensor
η	Dynamic viscosity. Units: Pa s (1 Poise = 0.1 Pa s)
γ	Spring damping factor
γ_T	Thomsen parameter for transverse isotropy. Unitless
κ	Permeability (scalar). Units: m^2 (1 Darcy $\approx 10^{-12}$ m^2)
λ	Lamé parameter. Units: Pa
λ_g	Geophone damping factor. Unitless
$\hat{\mathbf{n}}$	Unit normal vector
$\hat{\mathbf{S}}_{\mathbf{Hmax}}$	Unit vector in direction of maximum horizontal stress
$\hat{\mathbf{S}}_{\mathbf{Hmin}}$	Unit vector in direction of minimum horizontal stress
$\mathbf{b}$	Intermediate axis for moment-tensor source
$\mathbf{C}$	Covariance matrix
$\mathbf{k}$	Wavevector. Units radians/m
$\mathbf{m}$	Model vector
$\mathbf{s}$	Slowness vector. Units: s/m
$\mathbf{T}$	Traction vector. Units: Pa
$\hat{\mathbf{p}}$	Axis of compression for moment-tensor source
$\hat{\mathbf{t}}$	Axis of tension for moment-tensor source
$\mathbf{u}$	Displacement vector. Units: m
$\mathcal{C}$	Cohesion. Units: Pa
$\mathcal{L}$	Characteristic slip distance. Units: m
$\mathcal{S}$	Unconfined compressive strength. Units: Pa
$\mathcal{T}$	Tensile strength. Units: Pa
$\mathcal{T}_0$	Iinitial tensile strength. Units: Pa
$\mathcal{T}_R$	Residual tensile strength. Units: Pa
μ	Shear modulus. Units: Pa

μ_i	Coefficient of internal friction. Unitless
μ_r	Coefficient of residual friction. Unitless
μ_s	Coefficient of static friction. Unitless
ν	Poisson's ratio. Unitless
ω	Angular frequency. Units: radians/s
Φ	Scalar wave potential. Units: m^2
ϕ	Porosity. Unitless
ϕ_σ	Stress parameter representing the relative magnitude of stress components. Unitless
ϕ_i	Angle of internal fraction. Units: radians
ϕ_j^{ab}	jth element of the discrete cross-correlation between time series a and b
Ψ	Vector wave potential. Units: m^2
$\psi'(k_x, z, \omega)$	Time-reversed wavefield. Arguments are horizontal wavenumber, k_x, depth, z and angular frequency, ω
$\psi(\mathbf{x}, \omega)$	Zero-offset wavefield. Arguments are position $\mathbf{x}'$ and angular frequency, ω
$\psi_m(\mathbf{x}, \omega)$	Migrated image. Arguments are position $\mathbf{x}$ and angular frequency, ω
ρ	Density. Units: kg/m^3
ρ_F	Fluid density. Units: kg/m^3
ρ_M	Matrix density. Units: kg/m^3
Σ	Seismogenic index. Unitless
σ_1	Maximum principal stress. Units: Pa
σ_2	Intermediate principal stress (in three dimensions) or minimum principal stress (in two dimensions). Units: Pa
σ_3	Minimum principal stress (in three dimensions). Units: Pa
σ_n	Normal stress. Units: Pa
$\sigma_{\theta\theta}$	Hoop stress. Units: Pa
σ_{rr}	Radial stress (from Kirsch equations). Units: Pa
τ	Shear stress. Units: Pa
τ_d	Rupture time constant. Units: s
τ_r	Rupture rise time. Units: s
$\tau_{\theta r}$	Shear stress (from Kirsch equations). Units: Pa
Θ	Angular width of borehole breakout. Units: degrees or radians
$\tilde{\alpha}$	Angle between slip vector and fault plane. Units: radians
$\tilde{\delta}$	Fault dip angle. Units: degrees or radians
$\tilde{\epsilon}_i$	ith component of strain in Voigt notation. Unitless
$\tilde{\lambda}$	Rake angle. Units: degrees or radians
$\tilde{\mu}$	Coefficient of dynamic friction. Unitless
$\tilde{\mu}_0$	Steady-state sliding friction. Unitless
$\tilde{\phi}$	Fault strike angle. Units: degrees or radians
$\tilde{\sigma}_i$	ith component of stress in Voigt notation. Units: Pa
$\tilde{\theta}_i$	Picked backazimuth at the ith receiver. Units: degrees or radians
$\tilde{C}$	Consequence
$\tilde{C}_{ij}$	ijth component of stiffness matrix in Voigt notation. Units: Pa

$\tilde{E}$	Exposure
$\tilde{H}$	Hazard
$\tilde{R}$	Risk
$\tilde{t}_i$	Picked arrival time at the ith receiver. Units: s
ε_T	Thomsen parameter for transverse isotropy. Unitless
φ	Complex phase. Units: radians
A	Wave amplitude. Units: m
a, b	Rate-state friction parameters. Unitless
a_j, p_j	Poles and zeros of the instrument response
b	Gutenberg–Richter b value
C_F	Correlation integral, used to determine the fractal dimension
c_{ijkl}	$ijkl$th component of the elastic stiffness tensor. Units: Pa
D	Fractal dimension
E	Young's modulus. Units: Pa
$F(\mathbf{x}, t)$	Image function. Arguments are position $\mathbf{x}$ and time t
g_a	Amplifier gain. Units: dB
G_{cr}	Energy release rate. Units: J/m^2
H_g	Geophone instrument response
H_s	Seismometer instrument response
I'_j	jth stress invariant. Units: Pa
K	Bulk modulus (various subscripts used for elements of poroelastic media). Units: Pa
K_I	Stress intensity factor. Units: Pa m$^{1/2}$
k_N	Nyquist wavenumber. Units: m^{-1}
k_x	Spatial wavenumber in the x-direction. Units: m^{-1}
K_{IC}	Fracture toughness. Units: Pa m$^{1/2}$
m	Mass. Units: kg
M_0	Seismic moment. Units: N m
m_b	Body-wave magnitude
M_c	Magnitude cut-off (threshold) for Gutenberg-Richter relation
M_L	Local magnitude
M_S	Surface-wave magnitude
M_W	Moment magnitude
M_{ij}	ijth component of the seismic moment tensor. Units: N
P	Pore pressure. Units: Pa
P_B	Formation breakdown pressure. Units: Pa
$P_E(M)$	Probability to observe one or more earthquakes above magnitude M within a fixed time interval (e.g. one year)
P_F	Fracture propagation presure. Units: Pa
P_{net}	Net pressure. Units: Pa
Q	Quality factor. Unitless
R^k_P, R^k_S	Characteristic function at the kth receiver for P and S waves
s	Slowness of a medium (reciprocal of velocity). Units: s/m
S_g	Geophone sensitivity scalar. Units: V/m/s

S_i	Sensor sensitivity factor. Units: (m/s)/V
S_s	Seismometer sensitivity scalar. Units: V/m/s
S_V	Vertical stress. Units: Pa
S_{Hmax}	Maximum horizontal stress. Units: Pa
S_{Hmin}	Minimum horizontal stress. Units: Pa
s_{ijkl}	$ijkl$th component of the compliance tensor. Units Pa^{-1}
$V(t,p)$	Vespagram. Arguments are time (t) and slowness (p)
v_g	Group velocity. Units: m/s
v_L	Love wave velocity. Units: m/s
$V_N(t,p)$	Nth root vespagram
v_P	P-wave velocity. Units: m/s
v_R	Rayleigh-wave velocity. Units: m/s
v_r	Rupture velocity. Units: m/s
v_S	S-wave velocity. Units: m/s
xi_c	Instrument scaling factor. Units: (m/s)/V
Z_N	Normal compliance. Units: Pa^{-1}
Z_T	Transverse compliance. Units: Pa^{-1}
FCP	Fracture closure pressure. Units: Pa
ISIP	Instantaneous shut-in pressure. Units: Pa