# Bulletin of the BSSA Bulletin of the Seismological Society of America

Vol. 110 • No. 5 • October 2020

## **SPECIAL SECTION**

<b>Observations, Mechanisms, and Hazards of Induced Seismicity</b> <i>Guest Editors: Ruijia Wang, Matthew Weingarten, Cornelius Langenbruch, and</i> <i>Heather R. DeShon</i>	
Introduction to the Special Section on Observations, Mechanisms, and Hazards of Induced Seismicity Ruijia Wang, Matthew Weingarten, Cornelius Langenbruch, and Heather R. DeShon	1999
Minimal Clustering of Injection-Induced Earthquakes Observed with a Large-n Seismic Array Elizabeth S. Cochran, Alexander Wickham-Piotrowski, Kilian B. Kemna, Rebecca M. Harrington, Sara L. Dougherty, and Andres F. Peña Castro	2005
Automated Microseismic Processing and Integrated Interpretation of Induced Seismicity during a Multistage Hydraulic-Fracturing Stimulation, Alberta, Canada Germán Rodríguez-Pradilla and David W. Eaton	2018
Aftershock Sequence and Statistics of the 2017 <i>M</i> <sub>w</sub> 5.5 Pohang, South Korea, Earthquake: Implications of Fault Heterogeneity and Postseismic Relaxation <i>Jeong-Ung Woo, Minook Kim, Junkee Rhie, and Tae-Seob Kang</i>	2031
Stress-Drop Scaling of the 2016 Gyeongju and 2017 Pohang Earthquake Sequences Using Coda-Based Methods Gyeongdon Chai, Seung-Hoon Yoo, Junkee Rhie, and Tae-Seob Kang	2047

Bulletin of the R

### **ON THE COVER**

Gas pipelines in Alberta, Canada, where a significant number of earthquakes are associated with hydrocarbon production. This issue contains a special section of 33 papers on induced seismicity throughout the world.

Image credit: iStock.com/wolv

Spectral Characteristics of Ground Motion from Induced Earthquakes in the Fort Worth Basin, Texas, Using the Generalized Inversion Technique <i>SeongJu Jeong, Brian W. Stump, and Heather R. DeShon</i>	2058
Ground-Motion Attenuation, Stress Drop, and Directivity of Induced Events in the Groningen Gas Field by Spectral Inversion of Borehole Records <i>Gabriele Ameri, Christophe Martin, and Adrien Oth</i>	2077
Probabilistic Moment Tensor Inversion for Hydrocarbon-Induced Seismicity in the Groningen Gas Field, The Netherlands, Part 1: Testing Daniela Kühn, Sebastian Heimann, Marius P. Isken, Elmer Ruigrok, and Bernard Dost	2095
Probabilistic Moment Tensor Inversion for Hydrocarbon-Induced Seismicity in the Groningen Gas Field, the Netherlands, Part 2: Application Bernard Dost, Annemijn van Stiphout, Daniela Kühn, Marloes Kortekaas, Elmer Ruigrok, and Sebastian Heimann	2112
Description of Seismic Sources in Underground Mines: Theory Dmitriy Malovichko	2124
Rupture Directivity of the 2019 <i>M</i> <sub>w</sub> 5.8 Changning, Sichuan, China, Earthquake and Implication for Induced Seismicity <i>Wei Li, Sidao Ni, Chong Zang, and Risheng Chu</i>	2138
3D Crustal Structure and Seismicity Characteristics of Changning—Xingwen Area in the Southwestern Sichuan Basin, China <i>Kezhen Zuo, Cuiping Zhao, and Haijiang Zhang</i>	2154
Joint Focal Mechanism Inversion Using Downhole and Surface Monitoring at the Decatur, Illinois, CO <sub>2</sub> Injection Site Nadège Langet, Bettina Goertz-Allmann, Volker Oye, Robert A. Bauer, Sherilyn Williams-Stroud, Anna Maria Dichiarante, and Sallie E. Greenberg	2168

#### **MAILING & SUBSCRIPTION INFORMATION** -

Subscriptions to the *Bulletin of the Seismological Society of America (BSSA)*: Information regarding institutional subscriptions can be found at www.seismosoc. org/subscriptions. Eligible members of the Seismological Society of America receive online access to *BSSA*. Individuals may apply for membership or determine eligibility by visiting www.seismosoc.org.

Bulletin of the Seismological Society of America (BSSA) is the premier journal of advanced research in earthquake seismology and related disciplines. It first appeared in 1911. Each issue is composed of scientific papers on the various aspects of seismology, including investigation of specific earthquakes, theoretical and observational studies of seismic waves, inverse methods for determining the structure of the Earth or the dynamics of the earthquake source, seismometry, earthquake hazard and risk estimation, seismotectonics, and earthquake engineering. Special issues focus on important earthquakes or rapidly changing topics in seismology.

*BSSA* (ISSN 0037-1106) is published bimonthly in February, April, June, August, October, and December by the Seismological Society of America, 400 Evelyn Avenue, Suite 201, Albany, CA 94706- 1375. Periodicals postage paid at Berkeley, California and at additional mailing offices. © 2020 by the Seismological Society of America. Printed in the U.S.A. by The Sheridan Press, Hanover, Pennsylvania. Postmaster: send address changes to: BSSA, 400 Evelyn Avenue, Suite 201, Albany, CA 94706-1375.

Authorization to photocopy items for internal or personal use, or for the internal or personal use of specific clients, is granted by the Seismological Society of America provided that the appropriate fee of \$3 per copy is paid directly to the Copyright Clearance Center, ISSN 0037-1106, 222 Rosewood Drive, Danvers, MA 01923, USA; +1-978-750-8400. Prior to photocopying items for educational classroom use, please contact Copyright Clearance Center at the above address. Consent for reproduction as described above does not extend to other types of copying, such as copying for general distribution, for advertising or promotional purpose, for creating new collective works, or for resale. For permission to reprint material please contact Seismological Society of America, 400 Evelyn Avenue, Suite 201, Albany, CA 94706-1375, USA. Email: info@seismosoc.org or contact Copyright Clearance Center at www.copyright.com. SSA recommends that the credit line for any reuse of material from BSSA read "authors, article title, journal title, volume number, page number(s), year, © Seismological Society of America."

Analysis of Microseismicity and Reactivated Fault Size to Assess the Potential for Felt Events by CO <sub>2</sub> Injection in the Illinois Basin Sherilyn Williams-Stroud, Robert Bauer, Hannes Leetaru, Volker Oye, Frantisek Stanek, Sallie Greenberg, and Nadege Langet	2188
A Long-Lived Swarm of Hydraulic Fracturing-Induced Seismicity Provides Evidence for Aseismic Slip Thomas S. Eyre, Megan Zecevic, Rebecca O. Salvage, and David W. Eaton	2205
Static Ground Displacement for an Induced Earthquake Recorded on Broadband Seismometers <i>Megan Zecevic, Thomas S. Eyre, and David W. Eaton</i>	2216
Induced Seismicity in the Delaware Basin, West Texas, is Caused by Hydraulic Fracturing and Wastewater Disposal Alexandros Savvaidis, Anthony Lomax, and Caroline Breton	2225
Complex Shear-Wave Anisotropy from Induced Earthquakes in West Texas Regan Robinson, Aibing Li, Alexandros Savvaidis, and Hongru Hu	2242
Activation Rate of Seismicity for Hydraulic Fracture Wells in the Western Canada Sedimentary Basin Hadi Ghofrani and Gail M. Atkinson	2252
Factors Influencing the Probability of Hydraulic Fracturing-Induced Seismicity in Oklahoma Rosamiel Ries, Michael R. Brudzinski, Robert J. Skoumal, and Brian S. Currie	2272
A Study on the Largest Hydraulic-Fracturing-Induced Earthquake in Canada: Observations and Static Stress-Drop Estimation <i>Bei Wang, Rebecca M. Harrington, Yajing Liu, Honn Kao, and Hongyu Yu</i>	2283
Understanding Vectorial Migration Patterns of Wastewater-Induced Earthquakes in the United States <i>Lisa Johann and Serge A. Shapiro</i>	2295
Evolution of Faulting Induced by Deep Fluid Injection, Paradox Valley, Colorado Roger P. Denlinger and Daniel R. H. O'Connell	2308
Dynamic Fault Interaction during a Fluid-Injection-Induced Earthquake: The 2017 <i>M</i> <sub>w</sub> 5.5 Pohang Event Kadek Hendrawan Palgunadi, Alice-Agnes Gabriel, Thomas Ulrich, José Ángel López-Comino, and Paul Martin Mai	2328
Exploring Physical Links between Fluid Injection and Nearby Earthquakes: The 2012 <i>M</i> <sub>w</sub> 4.8 Timpson, Texas, Case Study <i>Dawid Szafranski and Benchun Duan</i>	2350
The Intensity of Ground Motions from Induced Earthquakes with Implications for Damage Potential <i>Gail M. Atkinson</i>	2366

A New Procedure for Evaluating Ground-Motion Models, with Application to Hydraulic-Fracture-Induced Seismicity in the United Kingdom <i>Gemma Cremen, Maximilian J. Werner, and Brian Baptie</i>	2380
Reconciling Ground Motions and Stress Drops for Induced Earthquakes in the Western Canada Sedimentary Basin Joanna M. Holmgren, Gail M. Atkinson, and Hadi Ghofrani	2398
Risk-Informed Recommendations for Managing Hydraulic Fracturing– Induced Seismicity via Traffic Light Protocols Ryan Schultz, Greg Beroza, William Ellsworth, and Jack Baker	2411
Epistemic Uncertainties in Local Earthquake Locations and Implications for Managing Induced Seismicity Alexander Garcia-Aristizabal, Stefania Danesi, Thomas Braun, Mario Anselmi, Lucia Zaccarelli, Daniela Famiani, and Andrea Morelli	2423
Short-Term Probabilistic Hazard Assessment in Regions of Induced Seismicity Ganyu Teng and Jack W. Baker	2441
Risk from Oklahoma's Induced Earthquakes: The Cost of Declustering Jeremy Maurer, Deborah Kane, Marleen Nyst, and Jessica Velasquez	2454
Earthquakes Induced by Wastewater Injection, Part I: Model Development and Hindcasting Iason Grigoratos, Ellen Rathje, Paolo Bazzurro, and Alexandros Savvaidis	2466
Earthquakes Induced by Wastewater Injection, Part II: Statistical Evaluation of Causal Factors and Seismicity Rate Forecasting <i>Iason Grigoratos, Ellen Rathje, Paolo Bazzurro, and Alexandros Savvaidis</i>	2483
ARTICLES	
Probabilistic Space- and Time-Interaction Modeling of Mainshock Earthquake Rupture Occurrence Luis Ceferino, Anne Kiremidjian, and Gregory Deierlein	2498
Deep Neural Networks for Earthquake Detection and Source Region Estimation in North-Central Venezuela Ruben Tous, Leonardo Alvarado, Beatriz Otero, Leonel Cruz, and Otilio Rojas	2519
Magnetic Field Variations in Alaska: Recording Space Weather Events on Seismic Stations in Alaska Adam T. Ringler, Robert E. Anthony, David C. Wilson, Abram C. Claycomb, and John Spritzer	2530
Cross-Correlation Analysis of Long-Term Ambient Seismic-Noise Recordings in the Caribbean Netherlands to Monitor the Volcanoes on Saba and St. Eustatius <i>Reinoud Sleeman and Elske de Zeeuw-van Dalfsen</i>	2541

3D Physics-Based Numerical Simulations of Ground Motion in Istanbul from Earthquakes along the Marmara Segment of the North Anatolian Fault	2559
Maria Infantino, Ilario Mazzieri, Ali Guney Ozcebe, Koberto Paolucci, and Marco Stupazzini	
New GMPEs for the Sagami Bay Region in Japan for Moderate Magnitude Events with Emphasis on Differences on Site Amplifications at the Seafloor and Land Seismic Stations of K-NET	2577
Jinjun Hu, Jingyang Tan, and John X. Zhao	

# ERRATUM

Constraints of Crustal Heterogeneity and Q(f) from Regional (<4 Hz)	
Wave Propagation for the 2009 North Korea Nuclear Test	2598
Kim B. Olsen, Michael Begnaud, Scott Phillips, and Bo Holm Jacobsen	