Introduction to the Special Section on Observations, Mechanisms and Hazards of Induced Seismicity

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Abstract

This is the preface that summarizes the special section in BSSA 2020.

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Introduction to the Special Section on Observations, Mechanisms and Hazards of Induced Seismicity

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Introduction

The increasing rate and magnitude of induced seismicity over the last decade has generated public interest and spurred research across a broad range of geoscientists and stakeholders. Here, induced seismicity is broadly defined to include earthquakes associated with geothermal exploration, hydrocarbon production, waste-water disposal, carbon sequestration and gas storage. Innovations in energy technologies have led to rapid changes in how humans interact with and change the surface and subsurface and with increased earthquake rates come changes in earthquake hazard and risk. To understand and mitigate these the changes over the last 10 years, the scientific community produced over 10,000 peer-reviewed papers and several Special Sections and review papers on induced earthquakes (e.g., *Atkinson et al.,* 2020; *Schultz et al.,* 2020a; *Keranen and Weingarten,* 2018; *Eaton and Rubinstein et al.,* 2015; *Naghizadeh*, 2014; *Lasocki et al.,* 2008). Induced seismicity opens unique research opportunities to advance earthquake physics and forecasting. Fluid injection sites are natural laboratories where earthquake nucleation, rupturing and interaction can be studied under well-known and even adjustable conditions. It allows quantitative analyses of physical causes and the development of physics-based earthquake forecasting methods.

This Special Section of the Bulletin of the Seismological Society of America is designed to capture a snapshot of scientific advancement in the field of induced seismicity. The collection of papers reveal common threads and persistent untested hypotheses to help define a path forward for physical understanding and reduction of hazard and risk associated with induced seismicity. Toward that goal we organized the sections according to the natural course of the science itself: Observations, Mechanisms and Modeling, and Hazard and Risk. What follows is a brief summary of the 33 papers included in this Special Section.

Observations

Recent advances in seismic and geodetic monitoring have allowed for more detailed observations of induced and triggered seismicity, providing insight into both interplate and intraplate faulting and earthquake physics. The Special Section hence begins with Observations. Case studies remain fundamental. As infrastructure in the form of seismic networks and innovative new technologies are deployed, the Special Section reflects the new source zones and mechanisms for triggering earthquakes, including via hydraulic fracturing. Increased sensitivity through use of large-N and borehole instrumentation allows for resolving smaller-magnitude earthquakes, beginning to overlap with microseismic range. The waste-fluid injection induced earthquake papers in this Special Section are not limited to the Central United States nor to shale gas or enhanced oil recovery activities.

The Special Section begins with a regional case study of Oklahoma earthquakes under the LASSO nodal experiment (*Cochran et al.,* 2020). The catalog of small magnitude earthquakes under the large-N network reveals a mix of strike-slip and normal faulting earthquakes that statistically occur in single event clusters (independent earthquakes) rather than multi-event clusters. The predominance of single event clusters is interpreted as evidence that events are directly driven by stress changes due to local saltwater disposal. This type of clustering is reminiscent of geothermal fields, as evidenced by the 2017 Mw 5.5 Pohang earthquake sequence, which has been linked to development of a geothermal well (*Ellsworth, et al.,* 2019). *Woo et al.* (2020) use unsupervised data-mining with an energy ratio method to build out an earthquake catalog for the 2017 Mw 5.5 Pohang earthquake sequence. *Rodríguez-Pradilla and Eaton* (2020) introduce a novel workflow for automatic detection, phase picking and location of microseismic events from a hydraulic fracturing stimulation in Canada. They combine this methodology with local 3D seismic data to illuminate a complex network of Devonian-aged, left-lateral strike-slip faults that have been reactivated as right-lateral strike-slip faults in the modern stress regime. The large catalogs also provide detailed time and space constraints on b-values and p-values, that in the case of Pohang are interpreted as evidence for locally complex fault structures and material properties (*Woo et al.*, 2020).

Chai et al. (2020) use stress drop to explore similarities and differences between the Pohang earthquake (Mw5.5, 2017) and the Gyeongju natural event (Mw5.6, 2016). They find that stress drops are lower for the proposed induced earthquake compared to the nearby presumably natural event. Using both regional and local networks in northern British Columbia and north

Texas, both *Wang et al.* (2020) and *Jeong et al.* (2020) report, however, that stress drops for induced earthquakes echo tectonic ones; the observations are for the largest reported hydrofracking sequence (Mw4.6, 2015) and mid-magnitude wastefluid injection (<Mw4.0) earthquakes, respectively. *Ameri et al.* (2020) report stress drops for small (M<2.5 earthquakes) recorded by a unique borehole network in the Groningen field; while the stress drops are less than 1MPa, there is evidence of directivity effects even at these small magnitudes. The observation of directivity effects on stress drop values also arises in study of events in western Canada (*Holmgren et al.,* 2020). The magnitude range and methodologies differ across these papers, and the Special Section provides interesting insight into the uncertainties and strengths of the approaches to constrain stress drops.

While the non-double-couple components associated with injection induced earthquakes remains debated, *Kühn et al.* (2020) demonstrate the possibility of resolving trustworthy isotropic and CLVD (compensated-linear-vector-dipole) components in the Groningen field via a new probability base approach. They also systematically evaluate the parameter trade-offs, and uncertainties by providing numerous comparisons in a cutting edge interactive supplement (https://data.pyrocko.org/scratch/grond-reports/groningen/#/). Utilizing this moment tensor inversion method, *Dost et al.* (2020) analyze M≥2 Groningen events and report well-resolved normal fault orientations consistent with faults imaged in industrial seismic sections and events with a consistent negative isotropic component. The rupture of multiple fault segments is also observed for the Pohang sequence (*Woo et al.,* 2020), providing another explanation for the high non-DC components. *Malovichko* (2020) also provides an important theoretical contribution on moment tensors based on mining induced earthquakes. He accounts for heterogeneous structures around a seismic source and calculates their effect on the equivalent seismic moment tensor representation. The numerical examples illustrate the effectiveness of the new framework, benchmarking the results against the traditional (excavation-free) approach and a Kirchhoff-type representation approach.

The Special Section also contains two important early case studies of the 2019 Mw 5.8 earthquake in Changning, Sichuan Basin, China. The earthquake occurred in a region with both wastefluid injection due to salt-mining and active hydraulic fracturing for shale gas. *Li et al.* (2020) calculate a rupture directivity and a moment tensor for the mainshock and ultimately suggest a potential association with wastefluid injection. *Zuo et al.* (2020) use local earthquake data to solve for revised earthquake locations and 3D Vp, Vs, and Vp/Vs models. They report seismicity on pre-existing small-scale faults throughout the region and suggest the 2019 earthquake occurred when the fault network was weakened by injection, but that many small clusters of seismicity recorded nearer shale gas production wells are in fact directly triggered by hydraulic fracturing.

Similarly, injection induced earthquakes associated with the CO2 sequestration project in the Illinois Basin near Decatur, U.S. occur on pre-existing crustal faults. The downhole and surface monitoring provide *Langet et al.* (2020) waveforms to constrain focal mechanisms of 23 M0-1 earthquakes on an EW orientated fault they conclude is near critical stress in the modern stress regime. *Williams-Stroud et al.* (2020) take an integrated approach, combining earthquake data with seismic reflection, geology, and injection information from two wells to explore the space and time distribution of induced seismicity. The study provides an estimate for possible earthquake size based on source characteristics and fault length.

The Observation section of the Special Section ends with an exploration of how the community is beginning to understand the relative roles of seismic versus aseismic movements in the subsurface. *Eyre et al.* (2020) take advantage of long-time monitoring in Alberta, Canada, to constrain the aseismic contribution to a hydraulic-fracturing swarm. They describe a new hypothesis whereby aseismic loading of asperities is driven by fluid overpressure rather than by fluid migration. *Zecevic et al.* (2020) demonstrate that micrometer-scale static displacements can be obtained from broadband stations within 10 km of an Mw4.1 event, suggesting that near-source high-quality seismic recordings can also capture displacements generally thought to be the realm of geodesy.

Mechanisms and Modeling

Accelerated by the emergence of detailed observation, this Special Section also includes several papers that lead to new insights on the mechanism of induced seismicity (*Foulger et al.,* 2018). Coupled physical models of induced seismicity reveal complex interactions beyond effective stress reduction, including aseismic processes, dynamic rupture effects, and elastic stress effects in the solid constituent of rocks. In addition, large-scale statistical studies of hydraulic fracturing reveal some of the site-specific and operational factors which lead to an increased likelihood of induced seismicity. The papers in this Special Section as a whole reflect the evolution toward the integration of sophisticated seismologic techniques, geology, hydrology and fault physics to provide insight into the physical triggering mechanisms of induced earthquakes and their aftershock sequences.

Texas has historically exhibited a range of triggering mechanisms (*Frohlich et al.,* 2016), as reflected in this Special Section. The Permian Basin of West Texas is a particularly challenging region to study induced seismicity as both hydraulic-fracturing and waste-water disposal take place over wide areas. To decipher the causality between these activities and earthquakes, *Savvaidis et al.* (2020) first build an oil- and gas- operation database and then pair the industry data with the Texas Seismic Network earthquake catalog. The study uses a probabilistic, distance-time associator to link earthquake events with waste-water disposal and hydraulic fracturing operations and concludes that while both cause induced earthquakes, hydraulic-fracturing is the dominant driver of induced seismicity in West Texas. *Robinson et al.* (2020) utilize the Ms>2 earthquakes to examine the anisotropy in the Delaware Basin, also an area of both injection and hydrologic fracturing induced earthquakes, and in the Snyder area, where carbon dioxide injection takes place. They find the fast axes of shear-wave-splitting roughly agrees with regional crustal maximum stress orientation, emphasizing the existence of dense, complex fracturing systems.

One commonality between several papers that focus on mechanistic interpretation is that site-specific geologic factors weigh heavily in the likelihood of hydraulic fracturing induced seismicity. Depending on a hydraulic fracturing well's location within the Western Canada Sedimentary Basin (*Ghofrani and Atkinson,* 2020) or the state of Oklahoma (*Ries et al.,* 2020) there is a factor of 10 difference in the likelihood of hydraulic fracturing induced seismicity. *Ghofrani and Atkinson* (2020) show that 0.8% of wells in the Western Canada Sedimentary Basin are associated with M≥3 earthquakes and that the rate varies significantly with region and formation. *Ries et al.* (2020) conduct a large-scale statistical study of 1612 hydraulic fracturing wells in Oklahoma and suggest the variation in hydraulic-fracturing induced seismicity is highly associated with formation depth, as deeper formations are more likely to be overpressured with faults closer to criticality. They also find that injection volume is less important than the type of injection fluid, with a ~50% lower probability of seismicity with the use of gel compared to slickwater. *Wang et al.* (2020) also observe the contribution of local pre-existing fault structure to induced seismicity. They found the maximum magnitude of a hydraulic fracturing induced event in Canada to be greater than that predicted by injected volume alone, emphasizing the importance of pre-existing tectonic fault structures.

Two papers in this Special Section specifically considered poroelastic coupling from waste-water disposal injection induced seismicity. *Johann and Shapiro* (2020) develop a novel model to couple poroelastic stresses and pore pressure of waste-water disposal in Southern Kansas. Combining their numerical model with spatiotemporal cross-correlation, they find that the long-range evolution of induced seismicity in the region is reflective of the directional propagation of stress change caused by large-scale permeability anisotropy. *Delinger and O'Connell* (2020) revisit the classic case study of induced seismicity at Paradox Valley, Colorado, USA. They develop a fully coupled poroelastic model to calculate Mohr-Coulomb failure criterion and explain the occurrence of waste-water disposal earthquakes. They find most earthquakes occurred on Reidel-style shear fractures at acute angles to the strike of the fault zones illuminated by earthquake hypocenters. They interpret the sharp decrease in seismicity rate in the past decade to be attributable to a reduction in injection rate (i.e., reducing pore pressure gradients).

The Mechanisms section concludes with two papers that explicitly modeled the physics of induced earthquake rupture. *Palgunadi et al.* (2020) develop a high-resolution 3D dynamic fault simulation of the Pohang earthquake to investigate the induced rupture process under variable stress and fault geometry assumptions. They show that static Mohr-Coulomb failure analysis alone is unable to generate dynamic rupture consistent with the observed faulting style and reveal that rupture occurred on a dynamically weak secondary fault via "rupture jumping". *Szafranski and Duan* (2020) integrate a dynamic rupture model with a fluid flow model in order to model both the size and mechanism of the 2012 Mw 4.8 Timpson, TX mainshock. The dynamic rupture model follows the evolution of the aftershock sequence and provides constraints on physical parameters linking waste-fluid injection to fault failure.

Hazard and Risk

Previous focus sections mostly attracted papers on observations and mechanisms. The final part of this Special Section is focusing on the challenge of assessing, forecasting and managing induced seismic hazard and risk. It reflects the responsibility taken by scientists in reaction to the high public interest and reminds us of the societal relevance of induced earthquakes.

Regulatory efforts have led to a decrease of induced seismicity rates and associated hazards and risks in some well-studied regions of seismic concern (e.g., OCC, 2017). However, cases continue to emerge in newly developed regions around the world. Damaging magnitude thresholds (Mw=5) have been exceeded and significant economic losses and even several fatalities have been reported in some regions (*Lee et al., 2019*, *Lei et al.,* 2019). Successful mitigation of induced seismic hazards and risks need a collaborative and open effort of regulators, industrial operators and scientists. Implementation of science-based hazard mitigation strategies rely on publicly available injection data and earthquake catalogs. Efforts to assess, forecast and mitigate time-dependent induced seismic hazard and risk in regions with no prior history of earthquakes remains an ongoing challenge. Most induced earthquakes occur on previously unknown (unmapped) faults (*Schoenball and Ellsworth, 2017*). In addition, severity and number of earthquakes caused by the same level of subsurface stress changes vary by orders of magnitude depending on the geographic location.

To better understand the damage level of moderate shallow induced events, *Atkinson* (2020) compares the ground motions between M>3.5 induced earthquakes in western Canada and central U.S. with natural ones from California. The results leave the two categories comparable and significant damage is limited to the very-near-source zone (e.g., < 5km) of M>4.7 events. To evaluate the performance of ground motion models (GMMs), *Cremen et al.* (2020) develop a procedure that quantitatively compares the distribution of residuals from a GMM with the distribution expected for an exact fit of the model to the underlying observations. They apply the evaluation on several GMMs and optimize the best model for hydraulic-fracturing induced seismicity in the UK. *Holmgren et al.* (2020) reconcile stress drop estimates from EGF (Empirical Green's Function) studies with those inferred from GMPEs (Ground Motion Prediction Equations). They suggest that source and path effects (i.e., rupture directivity) could impact the calculation of GMPEs, and that stress drops obtained via EGF approaches may help guide the calibration of regional GMPEs. Regarding effective hazard and risk management for stakeholders, *Schultz et al.* (2020b) detail the factors to consider when designing the “traffic-light-protocol” for hydraulic-fracturing sites. They suggest that red-light magnitude should be chosen conservatively and recommend yellow-lights two magnitudes smaller for achievable mitigation. *Garcia-Aristizabal et al*. (2020) emphasize the challenge in induced seismicity management introduced by uncertainty in source parameters (i.e., hypocenter location), which is often underestimated. They illustrate such challenges via a logic-tree based ensemble modeling and tested various velocity models, picking methods as well as source location inversion packages. The applicability to induced earthquakes lies in the authors' interest in providing a rapid but informed decision-making process to regions where stoplight procedures have been implemented based on location (and magnitude) accuracy for fairly small earthquakes.

Teng and Baker (2020) introduce analysis frameworks for short-term seismic hazard with two types of injection-induced earthquakes differentiated: (mainly) hydraulic-fracturing induced cases in west Texas, and (mainly) waste-water disposal induced cases in Oklahoma-Kansas. They find seismic hazard for the latter scenario is more comparable to that for tectonic environments driven by mainshocks (i.e., California). Considering the emerging need to develop induced seismic risk models, *Maurer et al.* (2020) systematically test the effect declustering on induced seismic risk calculation in Oklahoma. They conclude that (1) different declustering algorithms have drastically different outcomes in terms of risk, (2) declustering induced seismicity generally results in a lower b-value suggesting potentially higher risk compared to full catalog analysis and (3) taking into account spatial and temporal evolution of seismicity is important to understand the impact on high exposure regions as the main driver of risk. *Grigoratos et al.* (2020a) present a semi-empirical model to hindcast induced seismicity in Oklahoma and Kansas given fluid injection history. *Grigoratos et al.* (2020b) employ the model to confirm that 76% of the recent surge in seismicity rates in Oklahoma is driven by wastewater disposal. They find that for stable or slightly decreasing future disposal rates the occurrence probability of potentially damaging Mw ≥ 5.5 earthquakes between 2018 and 2026 is as high as 45%.

Outlook & Challenges

The Special Section on Induced Earthquakes highlights the rapid evolution within the scientific community in collecting innovative observations, designing sophisticated physics-based models, understanding physical triggering mechanisms, and developing forecasting methodologies to improve hazard and risk estimations. Better scientific and industry data permit more accurate measurement and calibration of physical models. These models are often used to explain observations, establish causal mechanism or forecast future hazard. However, physical models of induced seismicity have reached a level of sophistication that often rely on established laboratory parameter ranges as opposed to direct observation. Few direct measurements of hydrogeologic or mechanical properties typically exist, such as in-situ reservoir or basement permeability, downhole pressure over time, fault damage zone width and character. Several case studies of induced earthquakes reveal the power of timely incorporation of industrial data into induced seismicity monitoring and modeling, and while the collaboration between industry and academia has shown promising results, the transparency is non-uniform across the world. One other important challenge is that risk management policies also vary from region to region. The scientific community also continues to grapple with how best to incorporate science-based recommendations from researchers into accurate short- and long-term hazard estimates and balanced regulations to yield reduction of risk. Taken together, and as highlighted by this Special Section, the induced seismicity scientific community has made excellent progress over the past 7+ years of research in all three key scientific areas: Observations, Mechanisms and Modeling, and Hazard and Risk.

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