Preface to the Focus Section on Injection-Induced Seismicity

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The ongoing, dramatic increase in seismicity in the central United States that began in 2009 is believed to be the result of injection-induced seismicity (Ellsworth, 2013). Although the basic mechanism for activation of slip on a fault by subsurface fluid injection is well established (Healy *et al.*, 1968; Raleigh *et al.*, 1976; Nicholson and Wesson, 1992; McGarr *et al.*, 2002; Ellsworth, 2013), the occurrence of damaging $M \geq 5$ earthquakes and the dramatic increase in seismicity in the central United States has brought heightened attention to this issue. The elevated seismicity is confined to a limited number of areas, and accumulating evidence indicates that the seismicity in these locations is directly linked to nearby industrial operations. This *Seismological Research Letters* (*SRL*) focus section presents a selected set of seven technical papers that cover various aspects of this topic, including basic seismological and ground-motion observations, case studies, numerical simulation of fault activation, and risk mitigation.

Rubinstein and Babaie Mahani (2015) provide a primer on fluid injection and induced seismicity with an intended audience spanning the public, media, industry, and academic scientists. They describe the fluid injection processes used by the oil and gas industry, the underlying physical mechanisms for induced seismicity, and several widespread misconceptions about these processes and their relationships to hydraulic fracturing. Within the oil and gas industry, processes that involve large-volume fluid injection into the subsurface include: (1) wastewater injection that involves long-term disposal of brines that are coproduced with oil; (2) hydraulic fracturing that involves injection under high pressure of fluids mixed with additives to create a permeable network of fractures to enhance hydrocarbon production; and (3) enhanced oil recovery that involves the injection of fluids into a depleted oil reservoir. Among these processes, wastewater injection is the mechanism most frequently associated with felt earthquakes. Recent wastewater injection–induced earthquakes include the 2011 **M** 5.6 Prague, Oklahoma, earthquake (Keranen *et al.*, 2013), the 2011 **M** 5.3 Trinidad, Colorado, earthquake (Rubinstein *et al.*, 2014), and the 2011 **M** 4.7 Guy-Greenbrier, Arkansas, earthquake (Horton, 2012).

Lamontagne *et al.* (2015) document observations from a regional seismograph network in New Brunswick, Canada, that was deployed in 2012, with the aims of defining the regional, natural seismicity of several sub-basins as well as monitoring any seismicity induced by hydraulic fracturing in the area. Parts of New Brunswick have significant potential for future unconventional oil and gas development, but there is considerable public sensitivity to the issue of induced seismicity. During two periods of hydraulic fracturing in September 2009–November 2010 and August–September 2014, no seismicity was observed. Relatively shallow focal depths for natural events in this area represent a challenge for distinguishing between natural and induced seismicity.

Taking advantage of recently augmented seismic network coverage in Alberta, Canada, Eaton and Babaie Mahani (2015) estimate focal mechanisms for several recent induced earthquakes of moderate magnitude. Following nearly two decades of relative quiescence, an **M** 3.8 reverse-slip event occurred on 9 August 2014 near Rocky Mountain House. It is the largest event within an earthquake cluster that has been active since the late 1970s. This seismicity is believed to be induced by the poroelastic stress changes caused by conventional gas production (Baranova *et al.*, 1999). An M_L 4.4 event on 23 January 2015 with inferred oblique-normal sense of slip appears to be linked with hydraulic fracture stimulation in the Duvernay shale play. This is the largest event in the Crooked Lake sequence, which has been episodically active since December 2013. Eaton and Babaie Mahani (2015) highlight inter-regional differences in which hydraulic fracturing appears to be a more significant cause of fluid-injection-induced seismicity in western Canada compared with large-volume wastewater disposal, the dominant cause of induced earthquakes in the United States.

Novakovic and Atkinson (2015) discuss ground-motion scaling relations, based on over 900 events within a magnitude range from 1 to 4 recorded using a recently installed regional network in Alberta, Canada. The majority of these events are inferred to be induced by activities associated with oil and gas production. Insights are derived from residuals with respect to both empirical and simulation-based expressions for pseudospectral acceleration at 1.0, 3.33, and 10.0 Hz, providing baseline information for evaluating if ground-motion attributes of induced events differ significantly from those of natural earthquakes.

Kaven *et al.* (2015) provide a summary of U.S. Geological Survey (USGS) microseismic monitoring of the Decatur, Illinois, carbon capture and storage (CCS) demonstration site, where roughly 1 million tons of supercritical CO_2 were injected into a sandstone saline aquifer between 2011 and 2014. A local monitoring network of 13 stations was installed in July–August 2013 by the USGS, with data freely available through Incorporated Research Institutions for Seismology. Three clusters of seismicity have been identified with estimated magnitudes ranging from −1.13 to 1.26. Focal mechanism solutions for six events are consistent with right-lateral strike-slip motion on preexisting faults that are favorably oriented with

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respect to the regional stress field. The observed pattern of seismicity is indicative of pore pressure diffusion away from the injection location, likely due to anisotropic and heterogeneous permeability of the host aquifer.

Dieterich *et al.* (2015) investigate spatiotemporal patterns of seismicity from long-term fluid injection with RSQSim, a computationally efficient 3D boundary element code that incorporates a rate–state fault-friction model (Richards-Dinger and Dieterich, 2012). Their results show that the state of stress prior to injection is critical in determining how a fault responds to fluid injection. Increasing initial shear stress in the model results in (1) accelerating the onset of seismicity, (2) increasing earthquake productivity, (3) increasing maximum magnitude, (4) increasing the spatial extent of seismicity, and (5) increasing the likelihood of extended post–shut-in seismicity. Moreover, they show that while the persistence of seismicity after shut-in occurs because of the time needed for excess pore pressure to diffuse, the primary mechanism appears to be delayed nucleation resulting from rate–state properties of faults. Their results also support models that link the maximum magnitude of induced earthquakes to the total injected fluid volume (McGarr, 2014). Arguments are presented that the portion of seismic moment release that can be attributed to changes in pore-fluid pressure decreases as both earthquake magnitudes and the mean value of initial stress increase.

Walters *et al.* (2015) describe a flexible and comprehensive risk-assessment workflow for projects involving large-volume wastewater injection and/or hydraulic fracturing. This framework builds upon and synthesizes a growing body of literature on this topic. The main factors considered are: (1) seismic hazard, as quantified using established probabilistic seismic-hazard assessment methods; (2) operational factors such as injection rate and proximity of the injection site to known faults; and (3) exposure, also known as vulnerability, which takes into consideration infrastructure, population density, and local risk tolerance for fluid injection activities. A risk matrix approach is developed and illustrated using examples of induced seismicity from the central United States, western Canada, and the United Kingdom. The role of traffic-light systems for risk management and effective communication between stakeholders and the public is also elaborated.

The seven papers in this *SRL* focus section provide a snapshot of current research on injection-induced seismicity. They cover many aspects pertinent to this complex problem and highlight areas where more research is needed. Most importantly, they help provide a sound scientific framework for future regulatory developments.

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