Introduction to this special section: Induced seismicity

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In the last several years, significant progress has been made in elevating the understanding of induced seismicity as it relates to oil and gas operations. Much of the initial work in response to increased anthropogenic seismicity in the United States and Canada that began in 2009 served to document the phenomena and provide the link between the effect and the potential causes. We are now entering a second phase of research in which work is being done on many fronts — some assessing early models and assumptions on earthquake triggering, others testing potential practical risk-mitigation tools, and a few documenting case histories that are beginning to shine a light on the details of the processes.

This special section of *The Leading Edge* highlights some of the recent work that has been done across academic institutions, research organizations, oil and gas service providers, and oil and gas companies. We have organized this special section into four case histories followed by four risk-assessment and mitigation papers. Due to space constraints, one risk-assessment paper, by Mousavi et al., is being made available exclusively in the SEG Digital Library (https://library.seg.org/toc/leedff/37/2) and in *TLE*'s Digital Edition (http://www.tleonline.org). Additional stress orientation data from the Permian Basin are also available as supplementary material to Lund Snee and Zoback's paper in the SEG Digital Library.

To lead off this special section, Willacy et al. describe the induced seismicity associated with production and subsidence at Groningen Field, the Netherlands. Data recorded using a shallow subsurface array are processed using a full-waveform event location and moment-tensor inversion workflow. Results show the microseismic events are spatially correlated to faulting within Groningen Field and possess moment-tensor characteristics consistent with normal faulting.

One of the conundrums for establishing effective induced seismicity mitigation procedures in Oklahoma is that the induced seismicity rarely occurs on known faults. Schoenball et al. use high-resolution, relative earthquake locations to reveal previously unknown faults and then analyze a specific sequence near Guthrie and Langston, Oklahoma, in detail, detecting a clear spatial and temporal pattern in the reactivation of various basement strike-slip faults. They complete their investigation with a geomechanical analysis of fault slip potential.

Karimi et al. summarize extensive experience in seismic monitoring in western Canada to develop lessons learned from data sets acquired for completion-operations support and regulatory compliance. They postulate that these data sets can provide valuable insight in understanding induced seismicity. The five lessons learned detail that (1) understanding the nature of the seismicity is important, (2) the recording network controls the usefulness of the data, (3) sufficient data can reduce magnitude uncertainty, (4) ground-motion measurements complement magnitudes in traffic-light protocols, and (5) risk-mitigation protocols require high-resolution seismic monitoring.

Much emphasis is currently placed on induced seismicity associated with fluid injection (e.g., saltwater disposal, hydraulic fracturing treatments, etc.). Hough and Bilham investigate earthquake sequences in the 1930s and 1940s in the southwestern Los Angeles Basin, California, that are potentially related to depletion. They show local seismicity is likely related to reservoir production, which led to 8.8 m of subsidence at the surface. Seismicity only halted once water flooding was introduced in the 1950s.

Kao et al. point out that traffic-light protocols (TLPs) have commonly been implemented in areas with elevated seismic risk due to oil and gas injection operations, but the effectiveness of the TLPs in mitigating the risk has not been thoroughly assessed. The authors provide an excellent discussion of British Columbia and Alberta, Canada, TLPs during several years beginning in 2014. Within this time, six "red-light" events, with moment magnitude >4.0 were observed and classified as induced. Some of these red-light events were preceded by yellow-light events, providing the operators an opportunity to modify their operations. Several red-light events either had no preceding yellow-light events or occurred after injection operations had ceased, pointing out the possible limitations of TLPs.

Lund Snee and Zoback present a compilation of new stress measurements for the Permian Basin of west Texas and southeast New Mexico. They then subdivide the basin into areas of similar stress states and, in the process, document rotations of S_{Hmax} within the Delaware Basin and Northwest Shelf. Using publicly available fault orientations, they then evaluate the potential of the faults in an area to slip in response to a modest increase in pore pressure, as could happen in response to injection. The paper provides important base data and a methodology for oil and gas operators to be able to evaluate the potential for fault slip in response to current and future injection operations in a petroleum province that contains the most active unconventional oil and gas development activity in North America.

Estimating the strength of the largest earthquake that can be induced or triggered by injection remains an unsolved problem. Eaton and Igonin review three hypotheses based on quite different physical models. The forecast models considered are (1) a geometric approach using inferred stimulated volume dimensions, (2) a putative linear relationship between maximum

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seismic moment and net injected volume, and (3) a probabilistic approach based on seismic-activity rate. They emphasize the importance of considering all three models when assessing the potential hazard.

Probabilistic seismic hazard analysis assesses the maximum ground motion that may occur within a certain timeframe, say 50 years. This is achieved by examining recorded earthquake catalogs, assuming they are representative of future hazard. Induced seismicity is, however, a strongly time-varying process related to the level of industrial activity. For this reason, the U.S. Geological Survey has released one-year seismic hazard updates. Mousavi et al. investigate the uncertainty in the 2016 and 2017 models using bootstrapping, thus revealing which regions have the most and least uncertainty in one-year ground-motion predictions, as well as identifying the inherent factors causing this spread. This final paper is available in *TLE*'s expanded Digital Edition and in the SEG Digital Library.

Looking forward, we expect to see continued work in the seismologic side of this issue. Efforts within the oil and gas industry are making progress on the engineering part of this problem — namely, how do we prevent induced earthquakes from happening in the first place. The first signs of success are on the horizon with the drop in the seismicity rate in Oklahoma in response to changes in injection. We expect future work to further focus on practical mitigation measures even as we continue to document the variety of induced seismic behavior. TLE