

RFF REPORT

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# Induced Seismicity Impacts of Unconventional Oil and Gas Development

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*This report was produced as part of [The Community Impacts of Shale Gas and Oil Development](#), an RFF initiative.*

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## Summary

This report provides an overview of the existing state of research on induced seismicity related to both unconventional and conventional oil and gas development in the United States. We provide background on this issue, a summary of the most relevant takeaways from each study, and judgments about the state of this body of literature. The topics we discuss include the causes of induced seismicity, the hazards associated with induced seismicity, what makes an area more likely to experience induced seismicity, and monitoring and mitigation potential. We also review several economic studies assessing the valuation of earthquake risk in the residential housing market, with one study focused on induced seismicity specifically, and one survey on the acceptability of seismicity that discusses induced seismicity. We additionally critique the current breadth of the literature using a “span chart,” which summarizes the literature along a key dimension: how many elements of the damage function model (which links oil and gas activities to burdens, concentrations, exposures, impacts, and monetary value) are covered by a given study.

- In all, our review looks at the findings of 45 studies. The large majority of studies are retrospective, concerned with establishing association with oil and gas activities for specific events or changes in the rate of seismic events regionally. This literature finds that the change in the rate of seismic events in the central and eastern United States is largely attributable to oil and gas operations, namely wastewater injection. A number of seismic events in Texas, Oklahoma, Ohio, and other areas that have been studied have been attributed to oil and gas operations.
- Only recently have studies attempted more forward-looking analyses, with two

studies establishing methods to predict the probability of future induced seismic events and a third proposing monitoring methods.

- Three studies analyzing oil- and gas-related induced seismicity assess above-ground impacts, including on the Oklahoma housing market, the acceptability of earthquakes (via a survey), and shaking intensity.
- Though the literature specifically addressing above-ground impacts is sparse, given the robust literature connecting seismicity to oil and gas activities as well as the robust literature on natural earthquakes, we feel comfortable saying there is an increase in physical damage related to the increase in shaking with higher magnitude earthquakes. The literature connecting oil and gas activities to seismicity is large and of high quality, and as large magnitude earthquakes have been linked to these activities through the literature, we are able to infer that there is an increase in damage to buildings based on the relationship between shaking intensity and magnitude.
- Almost none of the literature, however, addresses how induced seismicity related to oil and gas development affects the stress of residents experiencing this seismicity. One survey begins to address this issue by touching on the acceptability of induced seismicity, but the survey is not directed at those experiencing this seismicity. One study reports findings on property value impacts related to induced seismicity.

## Community Risk-Benefit Matrix

The Community Risk-Benefit Matrix identifies specific areas of concern related to impacts addressed by the team’s literature review (left column of the matrix), as well as

impacts for which RFF experts have conducted original research and analysis. (See page 3 for the section of the matrix related to this review, on the induced seismicity impacts of unconventional oil and gas development.)

The matrix indicates the quality of the literature for each impact, judged subjectively with the color indicating whether we find the studies analyzing an impact to be, on average, of a certain quality. Impacts may be assessed by multiple low-quality studies and a medium-quality study, for example, and we would consider this body of literature to be low quality. A high-quality classification indicates that we trust the results of such studies, including the accuracy, magnitude, and direction of the results—meaning, in a practical sense, that it has no serious or fatal flaws (such as inadequate methodologies) that would lead us to question the results. A study is considered low quality if we believe we cannot trust the results because the study has multiple, serious flaws (e.g., methodology, data, focus, or study design are inadequate to reliably estimate outcomes). A study is considered medium quality if it does not fit in the other two categories. A study is therefore medium quality if it has any such major flaw or if either the methodology, data, focus, or study design lead to questionable results for a number of reasons. Generally, we find the magnitude and direction of these results to be informative, but question the precision.

Lastly, we summarize the findings reported by the literature for each impact—whether the studies as a whole report increases, decreases, or no relationship between the impact and an increase in unconventional oil and gas development. The “heterogeneous” classification indicates that the literature reports different outcomes across areas. The “inconsistent” classification indicates that the literature reports contradictory results (i.e., two studies find an increase or decrease for a certain impact in the same context).

View or download the entire matrix, including all sections that correspond with each of the literature reviews by topic produced as part of this initiative:

[WHIMBY \(What's Happening in My Backyard?\): A Community Risk-Benefit Matrix of Unconventional Gas and Oil Development](#)

## COMMUNITY RISK-BENEFIT MATRIX LITERATURE REVIEW: INDUCED SEISMICITY IMPACTS OF UNCONVENTIONAL OIL AND GAS DEVELOPMENT

KEY

Seismicity		
Impact	Findings	Results
Damage to buildings	↑	Increase in seismicity associated mainly with wastewater injection and also hydraulic fracturing operations, depending on geological conditions and land use patterns.
Stress and anxiety	~	Only one survey includes questions about the acceptability of induced seismicity as part of a larger study.

	Higher quality: The majority of studies reviewed for an impact are of higher quality. Where there is one study of higher quality, it is marked as such.
	Medium quality: The majority of studies reviewed for an impact are of medium quality. Where there is one study of medium quality, it is marked as such.
	Lower quality: The majority of studies reviewed for an impact are of lower quality. Where there is one study of lower quality, it is marked as such.
	Not reviewed: Research on an impact was not reviewed.
↑	Increase: Studies show a positive, robust association with an impact (an increase in incidence or magnitude).
↓	Decrease: Studies show a negative, robust association with an impact (a decrease in incidence or magnitude).
↑↓	Heterogeneous: Across regions or areas, studies report robust results that differ.
Ø	No association: Studies report results that showed no association.
~	Inconsistent: Studies report differing (contradictory) results.

## 1. What Is Induced Seismicity?

Since 2009, the central and eastern United States have seen a dramatic increase in the rate of earthquakes—the region averaged 24 earthquakes of moment magnitude 3 or larger ( $M_{3+}$ )<sup>1</sup> per year from 1973 to 2008.<sup>2</sup> The region now averages 318 per year, with 1,010 earthquakes occurring in 2015 alone (Fitzpatrick and Petersen 2016). Oklahoma surpassed California, historically the most seismically active region in the United States, in the number of  $M_{3+}$  earthquakes per year in 2014 (USGS n.d. a). And in 2015, north-central Oklahoma saw an almost 900-fold increase in its rate of  $M_{3+}$  earthquakes from that of before 2009 (Langenbruch and Zoback 2016).

This sudden change in seismic hazard can largely be attributed to induced seismicity—earthquakes caused by the reactivation of pre-

existing faults and fractures due to stress changes from human activities, such as deep wastewater injection, carbon storage, geothermal activities, enhanced oil and gas recovery, surface changes, and sometimes hydraulic fracturing (TNO 2014). Though these types of earthquakes have largely occurred in the past several years, induced seismicity has been known to occur since the middle of the twentieth century. Some of the earliest documented cases that have been studied include the Rocky Mountain Arsenal (RMA; a deep injection well for hazardous chemicals that caused an  $M_{4.8}$ <sup>3</sup> event in 1967 near Denver) and the US Geological Survey's Rangely, Colorado, fluid injection and seismicity control experiments that took place from 1969 to 1973 (Raleigh, Healy, and Bredehoeft 1976; Healy et al. 1968; Hermann, Park, and Wang 1981).

Most induced earthquakes in the central United States are caused by the deep injection of briny wastewater from oil and gas production into underground formations for disposal. Induced earthquakes related to the oil and gas industry can also be caused by enhanced oil and gas recovery (in which liquids and/or gases are injected into oil-bearing formations to stimulate production). And less commonly in the United States, though more prevalent in Canada, hydraulic fracturing can also cause induced seismicity (British Columbia Oil and Gas Commission 2012; Rubinstein and Mahani 2015; Atkinson et al. 2016; Bao and Eaton 2016).

Underground injection for wastewater disposal and enhanced oil recovery is

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<sup>1</sup> Earthquake magnitudes (denoted by “M” in this document) refer to moment magnitude, or  $M_w$ , which measures the size of an earthquake in terms of the energy released. This is a new measure that “gives the most reliable estimate of earthquake size” (USGS n.d. b). “Moment is a physical quantity proportional to the slip on the fault times the area of the fault surface that slips; it is related to the total energy released in the [earthquake]. The moment can be estimated from seismograms (and also from geodetic measurements). The moment is then converted into a number similar to other earthquake magnitudes by a standard formula” (USGS n.d. b).  $M_L$ , or “local magnitude,” is best known as the Richter scale and is also used in a few studies discussed in this review. This measure is valid for only certain frequency and distance ranges, so other measures, such as  $M_w$ , were developed (USGS n.d. b). Both  $M_w$  and  $M_L$  are logarithmic in scale. For a comparison of magnitude and shaking intensity above-ground, see USGS.

<sup>2</sup> The central and eastern US is analyzed in the US Geological Survey’s [seismic hazard forecast](#) that assesses new seismic hazards due to seismicity as well natural earthquakes in a region.

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<sup>3</sup> An earthquake of this size is generally felt by all with some disturbances, such as broken windows or moved furniture. See the [US Geological Survey](#) for more information on the relationship between magnitude and intensity.

regulated under the US Environmental Protection Agency's (EPA's) Underground Injection Control (UIC) program, which covers solution mining wells, industrial and municipal waste disposal wells, hazardous and radioactive waste wells, and more. The injection wells related to oil and gas operations are known as Class II wells, which include wells for enhanced oil recovery activities, wastewater disposal, and storage of hydrocarbons.

Most Class II injection wells, in fact, are not associated with induced seismicity. In the United States, 35,000 wastewater disposal wells and 80,000 enhanced oil recovery wells are currently active—yet only a handful of these wells cause earthquakes felt above ground (Rubinstein and Mahani 2015). Induced earthquakes generally have lower maximum magnitudes than tectonic earthquakes; to date, the largest potentially induced earthquake was recorded in Pawnee, Oklahoma on September 3, 2016, of magnitude 5.8 (USGS 2016a).<sup>4</sup> Most induced events, however, are small in magnitude and short in duration (GWPC and IOCC 2015).

### ***1.1. Why Has Induced Seismicity become a Problem Recently?***

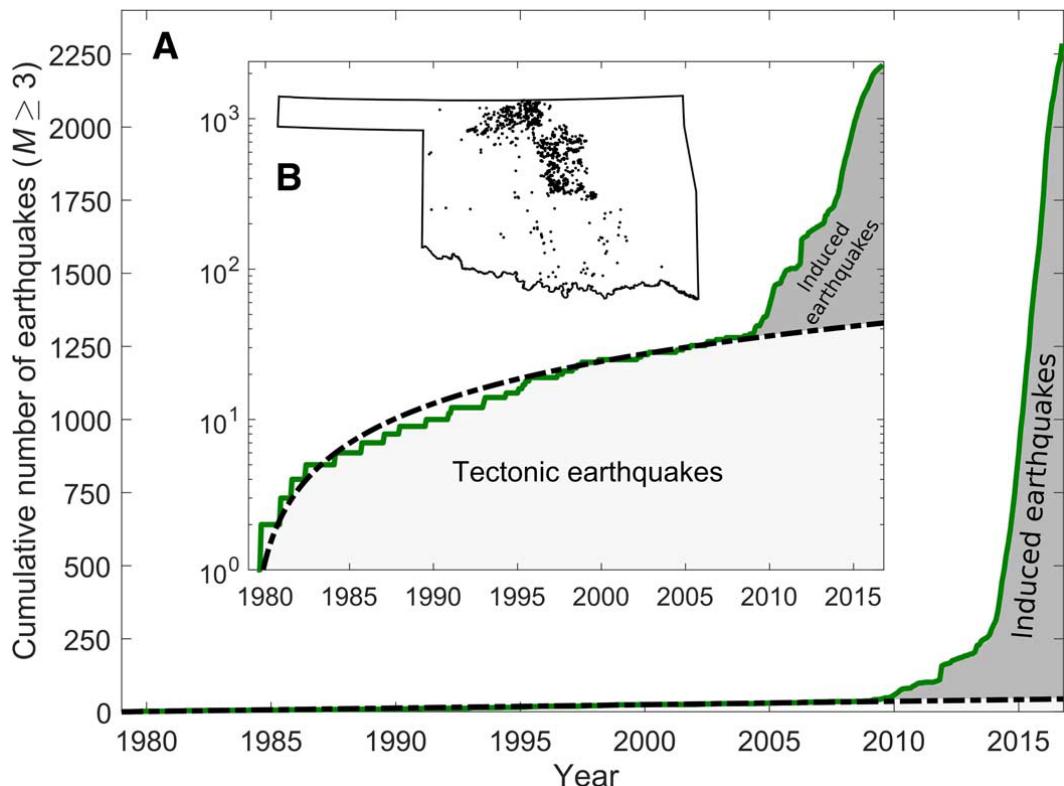
The sudden increase in induced seismicity beginning around 2009 is associated with the increased use of unconventional oil and gas production methods, including the drilling of horizontal wells, development of shale formations, and dewatering (which made economical the production of oil and gas from formations that hold significant amounts of water) (Murray 2015). The water produced as

a byproduct of these activities has been so voluminous and so briny that, due in part to market factors, it has been difficult to put it to another use or recycle it for oil and gas operations. The wastewater must be treated or directly disposed, and underground injection provides a method for doing so in a way that is both economical and relatively safe (aside from induced seismicity). Operators in Oklahoma are currently exploring options to transport some wastewater to locations beyond where it is produced.

These new unconventional oil and gas production techniques have allowed resources in central and north-central Oklahoma specifically (where the largest increase in earthquakes has occurred) to be redeveloped, and have led to a large increase in produced water volumes. Murray (2016) presents estimates of the median water-to-oil and water-to-gas ratios of several plays in Oklahoma. The water-to-gas ratios range from 3.02 in the Missourian to 17.73 in the Mississippian, and the water-to-oil ratios range from 1.63 in the Missourian to 12 in the Mississippian. Ohio, by contrast, has a very low water-to-oil ratio, of 1 (as of 2012). There, the injected water is often spent hydraulic fracturing fluid (the liquid and sand that is injected into a well to stimulate oil or gas production), as opposed to produced water (Horton 2012; Kim 2013; Rubinstein and Mahani 2015; Veil 2015). However, a large share of water injected in Ohio is from New York, West Virginia, and Pennsylvania (CSIS 2017).

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<sup>4</sup> We use the term “potentially” here because we did not find studies assessing the relationship between this event and oil and gas activities. Establishing a causative link is a complicated process discussed further below.

**FIGURE 1. TECTONIC AND INDUCED EARTHQUAKES ( $M \geq 3$ ) IN OKLAHOMA (1979 TO SEPTEMBER 2016)**

Source: Langenbruch and Zoback 2016.

Notes: The cumulative number of earthquakes is presented in linear (A) and logarithmic scales (B). The map shows the epicenters of earthquakes in Oklahoma.

The situation is particularly extreme in Oklahoma and Texas, where, respectively, 1.087 billion and 1.92 billion barrels per year were injected in 2012, compared to an average of 135 million barrels per year in the 29 other states reported by Veil (2015). Notably, however, in North Dakota (another boom state), more gas and oil than water was produced in 2012, meaning the state had water-to-oil and water-to-gas ratios of less than 1. New York oil and Alaska gas likewise had ratios less than 1 in 2012. Arkansas and Wyoming, also large oil- and gas-producing states, both have some of the highest water-to-oil ratios, at 26.6 and 26.2, respectively, though they injected a fraction of what Oklahoma and Texas injected in 2012 (Veil 2015).

## 1.2. What Differentiates Induced Seismicity from Natural Earthquakes?

Although distinguishing induced from natural seismicity can be complicated, there are a few tell-tale characteristics of induced events. First, induced earthquakes typically occur at shallower depths than natural earthquakes. The former generally occur in the top 6 kilometers (km) of the Earth's crust in Oklahoma, for example, while the latter have maximum depths of 25 to 30 km (GWPC and IOGCC 2015). Llenos and Michael (2013), analyzing rate changes in seismicity in Arkansas and Oklahoma, found a few key differences between natural and induced earthquakes as well. Earthquakes that occur near "active injection wells occur closer together than those that occur before, after, or far from active injection," with higher aftershock productivity (Llenos and Michael

2013, 2850). The study presents a robust statistical method for distinguishing seismic rate changes caused by natural forces and changes from induced seismicity. The study found that significant changes in the underlying triggering process occurred, meaning changes in the background rate of earthquakes as well as aftershock productivity may aid in distinguishing anthropogenic rate changes from natural rate changes.

Additionally, an earthquake swarm (a series of earthquakes occurring in a relatively short amount of time) propagating away from an injection well over time, for example, provides evidence that the swarm is induced, as the pore pressure front from the injection advances over time (Kim 2013). Such hypotheses can be tested using estimates of pressure changes and fluid migration. Van der Elst et al. (2016), however, did find that the limits on the maximum magnitudes for induced earthquakes are as large as statistically expected, suggesting that induced earthquakes have a tectonic (as opposed to injection-related) control on magnitude. The authors state that “induced earthquake magnitudes should be treated with the same maximum magnitude bound that is currently used to treat seismic hazard from tectonic earthquakes” (Van der Elst et al. 2016, 4575).

## 2. Literature Review

Much of the literature surrounding induced seismicity focuses primarily on evaluating patterns and trends of seismicity or attempting to establish causation for specific events—both with a focus on proving that either changes in regional seismicity or specific earthquake events were due to human activity (oil and gas operations in this case). Both levels of analysis aid in evaluating whether seismicity is linked to injection as well as assisting in the development of mitigation and response strategies (GWPC and IOCC 2015). Furthermore, several studies use

geomechanical modeling and two studies using probabilistic models to analyze induced seismicity. A handful of studies address above-ground impacts. This section will provide an overview of the larger focus and topics covered in these studies, with analysis of the results discussed throughout later sections of the report.

Assessing these more general patterns of seismicity and rate changes proves difficult because historic records of small events are often incomplete, as “most of the sensitive systems needed to monitor such events have been deployed during only the last few decades” (GWPC and IOCC 2015, 19). Furthermore, the wide spacing of seismic stations leads to uncertainty in locating the epicenters and depths of earthquakes, and local networks are often deployed following larger events (GWPC and IOCC 2015). Studies that assess these regional or general patterns include Keranen et al. (2014), Gono (2015), Rutqvist et al. (2013), Zhang et al. (2013), Frohlich et al. (2016), Hornbach et al. (2016), Weingarten et al (2015), Llenos and Michael (2013), Frohlich (2012), Rubinstein et al. (2014), Walsh and Zoback (2015), Goebel et al. (2015), Van der Elst et al. (2013), and Van der Elst et al. (2016).

Evaluating specific seismic events is more complicated, as it is difficult to “clearly and uniquely differentiate between induced and tectonic earthquakes using long-established seismological methods” (GWPC and IOCC 2015, 2). The use of other disciplines, such as statistics, are necessary (GWPC and IOCC 2015). Many studies use spatial and temporal correlation to evaluate causality, analyzing whether an event occurred near an injection well or within a certain amount of time following the start of injection or injection rate changes, and so on. Such analysis, however, is unable to address factors such as underlying stress, the location of preexisting faults, and other geomechanical factors (GPWC and

IOCC 2015). “Evaluating causation can be a significant and time-intensive process, entailing locating the seismic event(s) accurately, locating critically stressed faults that may have been reactivated, identifying the detailed temporal and spatial evolution of seismic events where fault slip first occurs and of any associated aftershocks, characterizing the subsurface stress near and on the fault, and developing a physical geomechanics/reservoir engineering model that would evaluate whether an induced subsurface pore pressure change could initiate an earthquake” (GWPC and IOCC 2015, 22). Studies that use such methods to evaluate the relationship between oil and gas activities and specific seismic events include Justinic et al. (2013); Gan and Frohlich (2013); Hornbach et al. (2015); Shirzaei et al. (2016); McNamara et al. (2015); Kim (2013); Keranen et al. (2013); Sumy et al. (2014); Horton (2012); Yeck et al. (2016); Frohlich et al. (2011); Frohlich and Brunt (2013); Block et al. (2014); Ake et al. (2005); Skoumal, Brudzinski, and Currie (2015); Holland (2011); Holland (2013); and Friberg, Besana-Ostman, and Dricker (2014). Although these studies all address causation in some way, the rigor with which they are able to do so varies.

Modeling can additionally aid in analyzing geomechanical factors—such as pore pressure diffusion, “microseismicity” (essentially akin to the energy released by dropping a gallon of milk on the floor),<sup>5</sup> fluid migration, and other hydrogeologic conditions—which allows for a more precise identification of the mechanism through which injection may cause seismicity. Studies focusing on both general patterns and specific events include Keranen et al. (2014);

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<sup>5</sup> The energy released by dropping a gallon of milk is comparable to an M2.0 earthquake, which is similar to the microseismicity associated with hydraulic fracturing.

Gono (2015); Rutqvist et al. (2013); Zhang et al. (2013); Dieterich, Richards-Dinger, and Kroll (2015); McClure and Horne (2011); and Hornbach et al. (2015). A better understanding of these mechanisms is important to inform improved regulations to mitigate seismic risk.

Modeling can also be used for more forward-looking studies that assess the probability of seismic risk and perhaps aid in moving towards prediction of this risk. Walsh and Zoback (2016) model the potential for fault slip on mapped faults in two regions in Oklahoma, while Langenbruch and Zoback (2016) present a statistical model to assess the probability of seismicity in a large area in Oklahoma. The first study assesses the probability of slip on known faults; the second works to assess future probabilities of seismicity associated with injection rates regionally (including on unknown faults).

Field testing—in which experiments are conducted with injection wells to test hypotheses regarding the interaction of injection parameters and seismicity—is another area in which the literature remains limited, especially as this relates to oil and gas activities. The early experiments in Rangeley, Colorado, tested hypotheses in an area that had experienced seismicity related to enhanced oil recovery (Raleigh, Healy, and Bredehoeft 1976). Ake et al. (2005) described the results of experiments for brine injection at Paradox Valley, Colorado, though this injection is not related to oil and gas activities.

Few studies, however, address the above-ground impacts of induced seismicity—including structural damage, human impacts (such as anxiety), or measured shaking. Hough (2014), for example, compared the ground motions caused by induced seismicity and the shaking caused by tectonic earthquakes.

Even fewer studies address the economic impacts and anxiety communities face due to

induced seismicity. Liu, Ferreira, and Brewer (2016) provide the only study attempting to address these effects, analyzing the housing market impacts of induced seismicity from the 2011 earthquake sequence in Prague, Oklahoma. McComas et al. (2016) additionally provide one of the only studies analyzing perceptions of induced seismicity for energy development—though some studies do analyze perceptions and impacts of induced seismicity caused by other activities, such as geothermal energy and carbon capture and storage. Due to the largely narrow focus of the majority of this literature, little is known about the above-ground impacts of induced seismicity.

### **3. Earthquake Events Analyzed in the Literature**

Table 1 on the following page lists the strongest earthquakes analyzed by the studies covered in this review and their suspected causes. Some studies examined swarms of earthquakes whereas others only analyzed one event. It is important to note that not all of the studies analyze earthquake events or a series of earthquakes, such as modeling studies or those assessing above-ground impacts. This table therefore does not include all of the studies discussed throughout this review, and is additionally not a comprehensive list of all earthquakes induced by oil and gas activity. The magnitudes are reported as moment magnitudes (see p. 4 for a description) unless otherwise specified.

The strongest earthquake analyzed in the literature covered in this review is the 2011 Prague, Oklahoma, earthquake, at M5.7, studied by Sumy et al. (2014) and Keranen et al. (2013)—though this quake was actually triggered by the main shock, which was M5.0. The smallest magnitude earthquakes analyzed in these studies are the result of hydraulic fracturing (as opposed to wastewater injection). The distances estimated from the

cause of the earthquake and epicenter are the smallest for hydraulic fracturing (ranging from directly below the wells to 2 km away from the wells), and the greatest distances (9.65 km to greater than 10 km) appear to occur when multiple injection wells are suspected to be the cause of seismicity, based on our review and summarized in Table 1.

## **4. Causes of Induced Seismicity Related to Oil and Gas Operations**

The majority of induced seismicity events discussed in this literature review are caused by deep underground injection of wastewater. There are, however, examples of other oil and gas operations that have caused induced seismicity, though they are less common or of smaller magnitudes than induced seismicity from wastewater injection in the United States.

### **4.1. Extraction**

Some studies showed that extraction (production) wells may also be correlated with seismicity—such as Frohlich and Brunt (2013), who studied injection and production wells in the Eagle Ford shale play—though modeling of the subsurface hydrology and stress would be necessary to address causality. Hornbach et al. (2015) also found that a combination of both brine production and wastewater disposal likely caused the November 2013 earthquakes in Azle, Texas. Though there is evidence for induced seismicity associated with production, this is not the main reason seismicity has increased in the central United States.

### **4.2. Fracking**

While hydraulic fracturing is known to cause microseismicity (see definition on p. 8), it sometimes also causes “felt” seismicity (Rutqvist et al. 2013; Zoback 2016a). Induced seismicity felt above ground associated with hydraulic fracturing has occurred in the

United States, though it is less common than injection-related seismicity depending on the region. Induced seismicity from fracturing is more prevalent in Alberta and British Columbia in Canada (British Columbia Oil and Gas Commission 2012; Bao and Eaton 2016; Atkinson et al. 2016). Even in the western Canadian sedimentary basin, where

hydraulic fracturing development has been focused, Atkinson et al. (2016) found that only about 0.3 percent of fracking operations are associated with seismicity—though with thousands of wells drilled annually, the issue is still significant in the region.

**TABLE 1. LARGEST MAGNITUDE EARTHQUAKES ANALYZED IN EACH STUDY**

Study	Magnitude ( $M_w$ )*	Estimated Cause	Distance to cause	Date	Location
<b>Shirzaei et al. (2016)</b>	4.8	Two wastewater injection wells	Within ~10 km	May 2012	Eastern Texas
<b>McNamara et al. (2015)</b>	4.3	Wastewater injection from 3 wells, one injecting into the Arbuckle formation, above the basement <sup>§</sup>	Within 9.65 km	Oct. 2014	Cushing, OK
<b>Kim (2013)</b>	3.9	Deep wastewater injection well	~1 km	Dec. 2011	Youngstown, OH
<b>Horton (2012)</b>	4.7	Multiple wastewater injection wells	Within 6 km	Feb. 2011	Central AR
<b>Yeck et al. (2016)</b>	5.1	Far-field pressure from clustered, high-rate injection wells	> 12 km	Feb. 2016	Fairview, OK
<b>Keranen et al. (2013)</b>	4.8, 5.0, and 5.7	5.0 induced by wastewater injection; 4.8 and 5.7 triggered by stress transfer	Within 1.5 km	Nov. 2011	Prague, OK
<b>Sumy et al. (2014)</b>	4.8, 5.0, and 5.7	5.0 foreshock, induced by fluid injection, triggered cascading failure of earthquakes	Within 1.5 km	Nov. 2011	Prague, OK
<b>Frohlich et al. (2011)</b>	3.3	Wastewater injection well	0.5 km	May 2009	Dallas-Fort Worth, TX
<b>Rubinstein et al. (2014)</b>	5.3	Wastewater injection from two nearby wells	2 km	Aug. 2011	Raton Basin, CO–NM border
<b>Justinic et al. (2013)</b>	2.8 $M_{blg}$ <sup>†</sup>	Two fluid injection wells, one high-rate	Within 3.2 km	June 2009	Cleburne, TX
<b>Hornbach et al. (2015)</b>	3.6	Combination of brine production and wastewater injection	Within 10 km	Nov. 2013	Azle, TX
<b>Block et al. (2014)</b>	4.4 $M_L$	Single, long-term brine injection well	8.2 km	Jan. 2013	Paradox, CO
<b>Ake et al. (2005)</b>	4.3	Single, long-term brine injection well	Within 8 km	May 2000	Paradox, CO
<b>Friberg, Besana-Ostman, and Dricker (2014)</b>	2.2	Hydraulic fracturing near a fault	Directly below wells	Oct. 2013	Harrison County, OH
<b>Skoumal, Brudzinski, and Currie (2015)</b>	3 $M_L$	Hydraulic fracturing	~850 m	March 2014	Poland Township, OH
<b>Holland (2011; 2013)</b>	2.9	Hydraulic fracturing	2 km	Jan. 2011	South-Central, OK
<b>Frohlich and Brunt (2013)</b>	4.8	Oil/water extraction <sup>‡</sup>	Within 5 km	Oct. 2011	Eagle Ford Shale, TX

*Notes:* Most studies look at series (or swarms) of earthquakes occurring over a short period or even years. The magnitude listed is that of the maximum moment magnitude analyzed by the study.

<sup>†</sup> $M_{blg}$  refers to the “short-period body-wave magnitude...used in the tectonically ‘stable’ eastern part of North America. ... This magnitude is measured from peak motions.” (McCalpin 2009).

<sup>‡</sup>The study also reviewed other earthquakes occurring in a two-year survey and found those to be associated with fluid injection as well, though this specific earthquake was estimated to be caused mainly by extraction.

<sup>§</sup>Basement rock is the rock layer below which sedimentary rocks are not found.

Holland (2011; 2013); Friberg, Besana-Ostman, and Dricker (2014); and Skoumal, Brudzinski, and Currie (2015) found evidence of earthquakes induced by hydraulic fracturing in, respectively, south-central Oklahoma; Harrison County, Ohio; and Poland Township, Ohio. The January 2011 south-central Oklahoma sequence caused a range of  $M_L$  0.6 to 2.9 earthquakes, with the preferred hypothesis being that the fluid pressure diffused through a more permeable fault or fracture system to a critically stressed fault (Holland 2013; see page 4 for a definition of  $M_L$ ). The October 2013 Harrison County earthquakes showed no correlations with maximum injection pressure or fluid volume, and were likely caused by hydraulic linkage to a fault (Friberg, Besana-Ostman, and Dricker 2014). The Poland Township earthquakes, ranging from  $M_L$  ~1 to 3, may have been caused by elevated pressures from hydraulic fracture fluids or pressurized formation waters that entered a fault or fracture system, either from intersecting a well borehole or from the fractures normally caused during fracking well stimulation (Skoumal, Brudzinski, and Currie 2015).

### **4.3. Enhanced Oil Recovery**

Enhanced oil recovery is a process by which water, steam, or carbon dioxide are injected into an oil- and gas-producing formation through a Class II injection well in order to stimulate production. These operations generally keep fluid pressure in reservoirs about equal (as they are used in the extraction reservoir). Enhanced oil recovery wells make up about 80 percent of Class II injection wells (EPA n.d.). While earthquakes induced by enhanced oil recovery have occurred—as discussed by Nicholson and Wesson (1992); Gibbs et al. (1973); Raleigh, Healy, and Bredehoeft (1976); and Gan and Frohlich (2013)—the discussion of enhanced oil recovery is outside of the scope of this exercise.

### **4.4. Wastewater Disposal**

Wastewater disposal is the source of the majority of induced seismicity discussed in this review. The water being disposed is primarily salt water produced with oil and gas; the fluid used in the hydraulic fracturing process is generally a small fraction of the produced water, though this fraction varies by formation (EPA n.d.). Any fluids returning to the surface may be injected into disposal wells. The majority of disposal wells are in Texas, California, Oklahoma, and Kansas. Wastewater disposal wells make up about 20 percent of Class II injection wells (EPA n.d.).

## **5. Hazards Associated with Induced Seismicity and Community Impacts**

The main impact of induced seismicity is ground shaking, which can cause damage to buildings, as well as human stress (GWPC and IOCC 2015). Structural damage to modern buildings generally occurs only if earthquakes are greater than M5.0 (GWPC and IOCC 2015), and few induced earthquakes have been above this magnitude. Several induced earthquakes have caused documented damage—including, for example, the M5.7 earthquake of 2011 in Prague, Oklahoma; the M5.3 earthquake of 2011 in Trinidad, Colorado; and the M4.8 earthquake of 2012 in Timpson, Texas (GWPC and IOCC 2015).

Oklahoma also experienced several large earthquakes in 2016, some in the span of a few weeks. The M5.3 earthquake that occurred on November 7, 2016, in Cushing, Oklahoma caused “substantial” damage, with 40 to 50 buildings damaged with cracks or fallen bricks and facades (Associated Press 2016), and the M5.8 earthquake of September 3, 2016, in Pawnee also caused damage (Liou 2016). The M5.7 earthquake of 2011 in Prague destroyed over a dozen homes and injured two people (USGS 2016b). Though the latter two earthquakes have not yet been proven to be induced, as they occurred just

weeks before the writing of this document, the Oklahoma Corporation Commission's Oil and Gas Division announced the shut-in of dozens of wells in both areas as emergency measures (OCC 2016a; OCC 2016b).

In its June 2016 seismic hazard update (which now includes induced seismic risk), the US Geological Survey updated the chance of having a Modified Mercalli Intensity (MMI) VI or greater in north-central Oklahoma to 5 percent to 12 percent, similar to the chances of California's damaging earthquakes with some areas with induced earthquakes seeing a hazard that is higher than the 2014 estimate by more than a factor of 3 (Petersen et al. 2016). The MMI index is a measure of above-ground shaking intensity and is rated from I to X. An MMI of VI or greater indicates an earthquake that is strong and felt by all, with slight damage and heavy furniture moved.

Figure 2 on the following page uses these MMI values to create a map of the potential for damage from an earthquake in 2016. The analysis for the central and eastern United States includes both induced and natural earthquakes; on the right side of the map, some of the coloring could be due to tectonic activity (particularly in eastern Arkansas). The analysis for the western states in this map is based on the presumption that the earthquakes are naturally occurring.

How or if ground shaking differs between induced and tectonic earthquakes, however, is less clear. Hough (2014), using data from the US Geological Survey's "Did You Feel It?" system,<sup>6</sup> found that within 10 km of the epicenter, shaking intensities were similar to expected magnitudes for tectonic earthquakes. Outside of this range, however, shaking

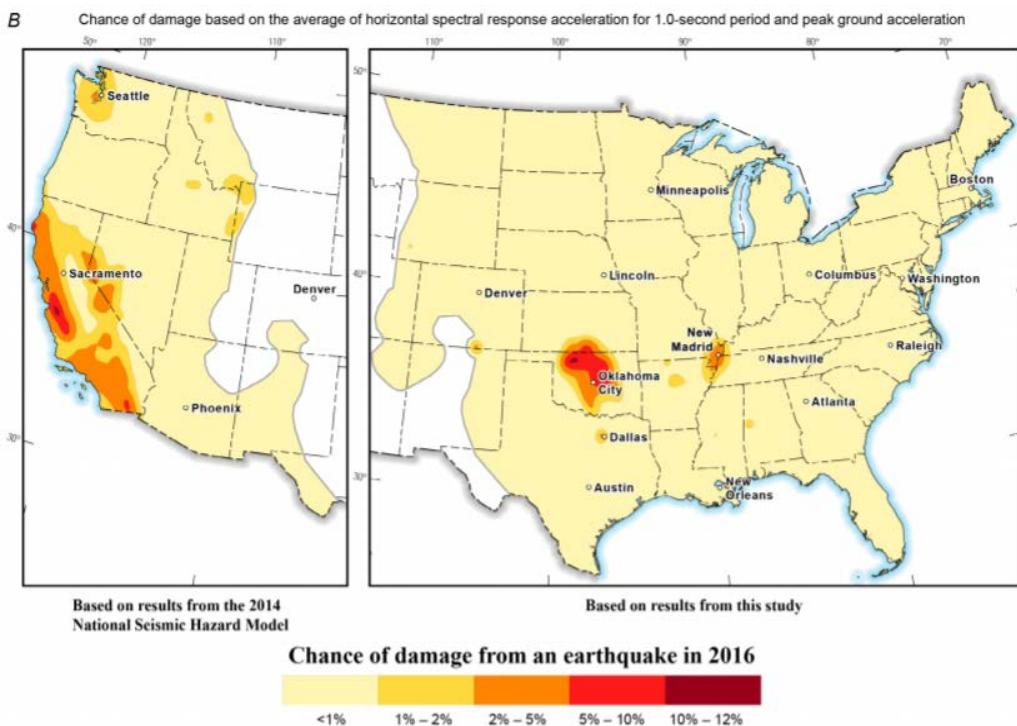
intensities were generally lower than those predicted for tectonic earthquakes.

Aside from news reports and anecdotal evidence, how communities are actually affected by induced seismicity is largely unaddressed in the academic literature. Liu, Ferreira, and Brewer (2016), a dissertation, provide the only attempt (that this review found) to assess the economic impacts of induced seismicity in Oklahoma through an analysis of effects on the housing market. This approach has a history in the economics literature, whereby housing prices have been analyzed with respect to shale gas development, such as Muehlenbachs et al. (2015). This approach has also been used to look at natural disasters, such as flooding, where it has been found that homes within a floodplain experience a drop in market value, as the event acts as an update to resident's and prospective home buyers' views about flood risk (Liu, Ferreira, and Brewer 2016).

Analyzing home sales in eight Oklahoma counties between 2000 and 2015, Liu, Ferreira, and Brewer (2016) looked at whether the 2011 earthquake in Prague, Oklahoma, and also the cumulative intensity of earthquakes prior to a housing transaction affected home values. The study estimates the impact of a home's proximity to production and injection wells on home values with a hedonic price function—estimating a consumer's willingness to pay for a reduction in the probability of earthquakes. The study, when analyzing both production and injection wells, found no effect of injection wells on housing prices. For sales of homes dependent on groundwater following the Prague earthquake, additional production wells within an area had lower housing prices, with the effect decreasing at greater distances.

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<sup>6</sup> <https://earthquake.usgs.gov/data/dyfi/>

**FIGURE 2. CHANCE OF DAMAGE FROM AN EARTHQUAKE IN 2016**

Source: Petersen et al. 2016.

For groundwater-dependent homes within 2 km of a production well, housing prices were 0.95 percent lower following the earthquake; within 10 km, this effect fell to 0.05 percent. This result, however, was not found to be significant within 1 km of a production well, which may reflect income from royalties mitigating the decrease in home prices. The study, however, has a number of counterintuitive findings. One such finding is that after the Prague earthquake, the number of production wells actually increased the value of a home between 0.05 percent and 0.56 percent for homes not dependent on groundwater (and therefore with lower groundwater contamination risk). Yet other results in the paper indicate that groundwater use increases the value of a home, particularly after the earthquake. More work could and should be done to better estimate the impact of induced seismicity on housing values in Oklahoma and elsewhere.

McComas et al. (2016) conducted a web survey of attitudes toward induced seismicity from energy production of 325 US adults (a small sample size), who were asked whether they felt negatively or positively about earthquakes they felt but caused no damage. Participants had more negative feelings about induced earthquakes than natural ones, and attributing the benefits to renewable energy or climate change mitigation did not make induced earthquakes more acceptable. Public engagement was the only option that made induced earthquakes more acceptable: when people believed their peers had a voice in the decision to implement the technology, acceptability of induced seismicity was “significantly higher” (McComas et al. 2016, 27). The participants also generally felt neutral about seismicity (an average of 5 on a scale of 0 to 10) if the energy production and its revenue benefitted local schools and colleges and also if it produced benefits shared widely by people across the planet.

### **5.1. Valuation Studies for Natural Earthquakes**

Though McComas et al. (2016) showed that acceptability varies depending on the cause of the earthquake (natural versus man-made), some of the valuation literature for natural earthquakes is relevant for illuminating the potential impacts of induced seismicity on housing markets.

Murdoch, Singh, and Thayer (1993) analyzed the 1989 M7.1 Loma Prieta earthquake in northern California and three studies analyzed several earthquakes in Japan (Nakagawa, Saito, and Yamaga 2007; Naoi, Seko, and Sumita 2009; Hidano, Hoshino, and Sugiura 2015). These studies found evidence that both increases in earthquake risk and actual earthquake events have a negative impact on property prices. Murdoch, Singh, and Thayer (1993) found a 2 percent decrease in home values, around \$5,800, following the Loma Prieta earthquake. This study also finds that housing values are about \$10,770, or 3.7 percent, lower for a house included in a Special Studies Zone, comparable to the findings in Beron et al. (1997), discussed below.

Beron et al. (1997), like Murdoch, Singh, and Thayer (1993), assessed homeowners' willingness to pay for a reduction or be compensated for an increase in risk following the Loma Prieta earthquake, which damaged or destroyed 20,000 homes. Homeowners' expected loss from inclusion in a higher risk area, the Special Studies Zone—an area where surface faulting has occurred in the last 11,000 years—fell from -\$11,800 before the event to -\$8,800 after the event. The expected lifetime cumulative loss from earthquakes, an amount assessed by homeowners based on what they believe to be their assumed risk, fell from -\$20,000 before the event to -\$13,100 after the event for the six-county Bay area.

Though it may sound surprising that a consumer's willingness to pay for a reduction in the probability of property damage by choosing a location that has a lower chance of damage from earthquakes (or the amount they must be compensated for an increase in risk)—falls following such an event, the authors find that the results are consistent with the notion that consumers "initially overestimate the probability of damage from unlikely events," or that the hazards are initially communicated poorly.

Because an earthquake releases energy that was building up, homeowners in a Special Studies Zone might conclude that after a tectonic earthquake, a second one is not as likely, whereas homeowners in areas with induced seismicity might, in fact, increase their perceived future risk because potential earthquakes there are caused by human activity that will continue in the future. In Oklahoma and other areas experiencing induced seismicity, therefore, residents may potentially increase their willingness to pay for a reduction in the probability of property damage (by moving away from an earthquake-prone area). While the results of the valuation studies would most likely differ if conducted in Oklahoma following induced seismicity, they are indicative of changes in risk perception following earthquakes and the communication of earthquake hazard.

### **6. Factors that Make an Area Prone to Induced Seismicity**

Because all the potential options for disposal of wastewater are problematic to some extent (and underground injection might actually be preferable in some areas), it is important to understand whether regions may be at risk of induced seismicity, preferably prior to the start of injection. The Bakken region in North Dakota, for example, has not faced issues with induced seismicity, whereas Oklahoma has seen the majority of impacts in

the United States. There are a number of factors that can make a region more prone to induced seismicity. Many of these risk factors, however, are often difficult to assess in the absence of earthquakes. In regions that have low levels of natural seismicity, the underlying geology is not studied extensively. In Oklahoma, Ohio, and Arkansas, induced seismicity has led to the discovery of previously unknown faults. Furthermore, areas where more fluids are injected will most likely be more prone to induced seismicity. As was discussed above, oil is produced alongside large amounts of brine in Oklahoma, Texas, and Arkansas, requiring operators to inject more water in those regions than in other areas, such as the Bakken region in North Dakota or Ohio—where less wastewater is produced. Other factors at play include the underlying geology, injection depth, potential for hydraulic communication into basement rocks with large faults (discussed below), and temporal delays as well as spatial uncertainty.

### **6.1. Geology**

Underlying geology plays a critical role in whether an activity will induce an earthquake. The Arbuckle formation in Oklahoma, for example, may be in “hydraulic communication” with the underlying basement, meaning pressure changes can propagate to the basement where faults exist (Walsh and Zoback 2015, 1). When many wells inject into the formation, increases in pore pressure in the Arbuckle may spread away into the basement and eventually trigger seismicity on a critically stressed fault (Walsh and Zoback 2015). Injection wells in central Arkansas also faced similar issues when injecting into the Ozark aquifer, as no formation exists to prevent fluid migration from the Ozark to the basement rock where faults are contained (Horton 2012).

In a two-year survey of seismicity and injection activities in the Barnett shale region

in Texas, Frohlich (2012) found that the wells nearest earthquakes all reported a maximum monthly injection rate of more than 150,000 barrels of water per month. Not all wells with these injection rates, however, were located near earthquakes. The pressure changes caused by these injected fluids must reach a suitably oriented (according to the stress field orientation)<sup>7</sup> or critically stressed fault to cause seismicity. Hornbach et al. (2016) found that seismicity in Texas’s Dallas and Ellis Counties, despite not having any injection wells, is caused by injection in nearby counties. Ellis and Dallas are “down-dip” (located at the lower end of a sloping surface or subsurface layer) from the injection sites, so denser fluids will flow there. Furthermore, the counties are bounded by a low-permeability barrier that blocks this fluid from escaping. Gono (2015), also studying injection and seismicity in the Fort Worth Basin in Texas, found spatial and temporal correlations between seismicity and pore pressure increases, though not all areas with pore pressure increases experience seismic activity, as the pore pressure increase must encounter a favorably oriented fault.

### **6.2. Injection Depth and Communication with Basement Rocks**

Faults that are present in the crystalline basement (a very deep geologic formation below disposal formations) are, for the most part, those that are of concern. Although faults

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<sup>7</sup> “Faults may be more prone to slip under certain stress conditions and geologic circumstances. In a given stress field, the ratio of shear stress to resisting strength on a fault depends on the fault orientation. Resisting strength depends on the stress acting perpendicular to the fault (i.e., the degree of clamping of the fault)” (GWPC and IOCC 2015, 54). This means the same shear stress on two different faults can lead to highly different probabilities of fault slip depending on the direction of the fault.

are present at many different depths, those that reach into or are present in the basement are large enough to cause earthquakes that can be felt and potentially damaging (Zoback 2016b). Hydrogeologic communication between the wastewater injection zone and the basement, where larger and favorably oriented faults may exist, is perhaps the main factor in whether injection will lead to induced seismicity (Zhang et al. 2013, Shirzaei et al. 2016). In some areas, such as the Bakken shale region in North Dakota, there are barriers that prevent this from occurring. In Oklahoma, however, the disposal reservoir associated with the earthquakes—the highly permeable Arbuckle formation—is in communication with the underlying crystalline basement, in which there are optimally oriented faults.

### **6.3. Difficulty in Linking Events to Activities**

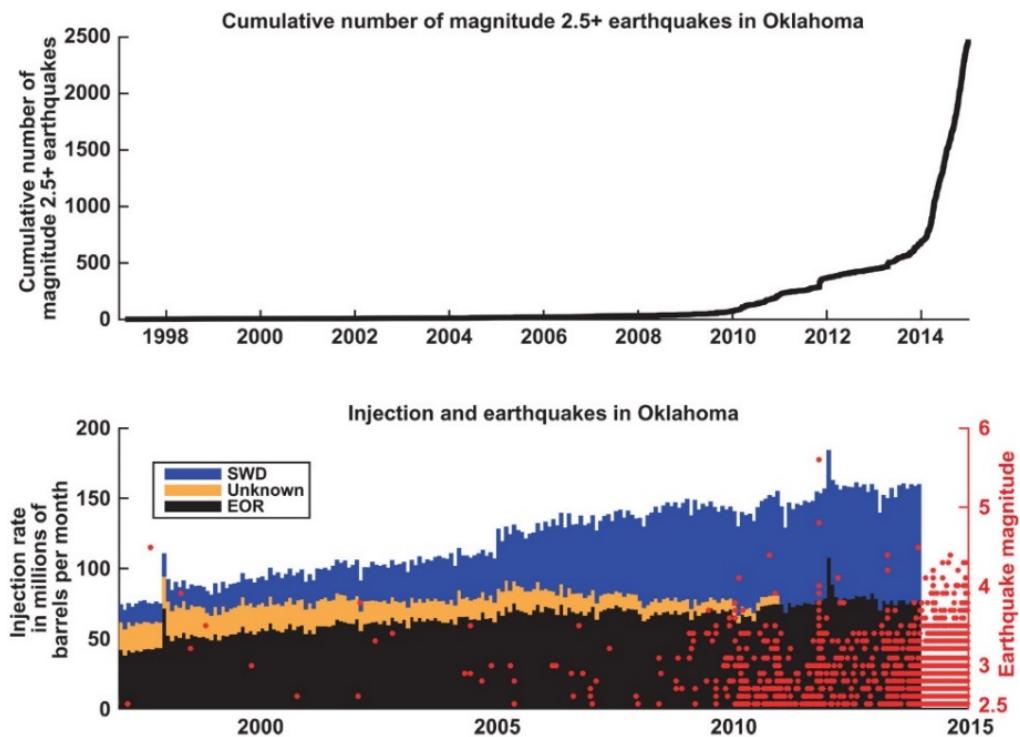
There are a number of reasons why these risk factors may not become evident immediately as injection starts—including temporal displacement, inducement at a distance, and triggering by other earthquakes. A lag in induced seismic events following the start of injection is apparent in many of the studies we reviewed. Some seismicity might begin within months or may take decades to occur following the start of injection. Seismic risk therefore does not become immediately apparent. In a study of the 2011 Prague earthquake, for example, Keranen et al. (2013) reported that felt seismicity did not begin in the area until 17 years following the start of injection. The authors hypothesized that injection over that period of time could have refilled a compartment until a critical volume injected was reached.

Justinic et al. (2013) likewise reported that earthquakes began years after the start of the first injection well and six to eight months following a doubling of injection volume

before felt seismicity occurred in Cleburne, Texas, and Shirzaei et al. (2016) also found a five-year delay in Timpson, Texas. Frohlich (2012) noted that, for the most part, injection wells in the Barnett shale region operated for a year or more before the onset of earthquakes. Hornbach et al. (2016) found a delay of six years from the start of injection in neighboring counties to seismicity in Dallas and Ellis Counties in Texas. As is evident from Figure 3 below, the levels of wastewater injection increased more slowly in Oklahoma than did the number of earthquakes. Higher levels of wastewater injection began years before the rapid increase in the rate of earthquakes occurred—with injection rates doubling over the past 17 years and seismic rates increasing beginning in 2009 (Walsh and Zoback 2015).

Even when injection stops or slows, several studies found that the buildup of pressure caused by fluid injection requires time to return to pre-injection levels (Shirzaei et al. 2016; Langenbruch and Zoback 2016; Horton 2012; National Research Council 2013). Horton (2012) found that following the shutdown of disposal wells associated with a continuous swarm of  $M \leq 4.7$  earthquakes in central Arkansas during 2010 and 2011, the swarm did not stop, though the rate and size of earthquakes decreased in the months following. In modeling seismic rates in Oklahoma, Langenbruch and Zoback (2016) found that despite decreases in injection occurring due to both regulation and economic forces, heightened levels of seismicity will persist for several years before returning to normal (historic) rates. The study found that the probability of an earthquake exceeding a certain magnitude annually returns to 2009 to 2013 levels by 2025. A National Research Council (2013) study noted that despite the fact that injection operations ceased at the Rocky Mountain Arsenal in 1966, earthquakes continued for years, until the late 1980s.

**FIGURE 3. CHART COMPARING CUMULATIVE M2.5+ EARTHQUAKES AND MONTHLY FLUID INJECTION IN OKLAHOMA**



Source: Walsh and Zoback (2015).

Another reason for the difficulty in assessing risk is that although induced seismicity often occurs in close proximity to injection wells or other sources of pressure changes, some studies find that earthquakes can be induced up to 20 or even 35 km away from the source. This means that one community conducting fluid injection activities may impact another nearby community—the issue is therefore more regional than local. Yeck et al. (2016), studying the M5.1 earthquake in Fairview, Oklahoma, for example, found that far-field pressurization from a group of closely located, high-rate injection wells in long-term operation located 12 to 20 km from the earthquake sequence caused a partially unmapped 14 km fault to rupture. Using a 3D model of pore pressure diffusion for injection rates from 89 wells within 50 km of the earthquake swarm that began in 2008 in Jones, Oklahoma, Keranen et al. (2014) found

induced seismicity to occur up to 35 km away from disposal wells.

Induced earthquakes—those where the majority of stress changes are caused by human activities—can also trigger other earthquakes. Earthquakes are considered triggered when other factors (such as underlying stress conditions) are responsible for the majority of a stress change that caused an earthquake. Hornbach et al. (2016) observed seismicity both near injection wells in the Fort Worth basin and more than 10 km away from injection wells in Dallas and Ellis Counties. For the 2011 Prague earthquakes, Keranen et al. (2013) found that the first event, M5.0, was induced by fluid pressure, but the larger M5.7 earthquake (while it can be considered a consequence of injection activities) was triggered by stress transfer from the first event. With faults that are close to failure, induced earthquake events can therefore cause additional seismic activity.

Sumy et al. (2014), conducting a slightly different study that focused on how the M5.0 earthquake in Prague interacted with the

## 7. Seismic Risk: Monitoring and Probabilistic Assessments

Although most of the literature focuses on establishing the causes of regional rate changes or specific seismic events, there is a small subset of recent seismic literature that has implications for both regional and localized risk assessments. Walsh and Zoback (2016) used a probabilistic model to focus on the potential for a known and mapped fault to slip given changes in pore pressure, focusing on Oklahoma. Such a model is limited in its ability to predict actual risk, as many induced earthquakes occur on unmapped faults. Langenbruch and Zoback (2016) were able to advance probabilistic assessments by analyzing the probability of earthquakes in Oklahoma given regional injection rates. This model cannot predict the potential for localized earthquakes (such as the potential for a specific well to cause an earthquake), but it can assess regional policies within Oklahoma (such as the Oklahoma Corporation Commission's recent volume reduction plans<sup>8</sup>) to examine the effect of a policy change on the state or larger regions of the state.

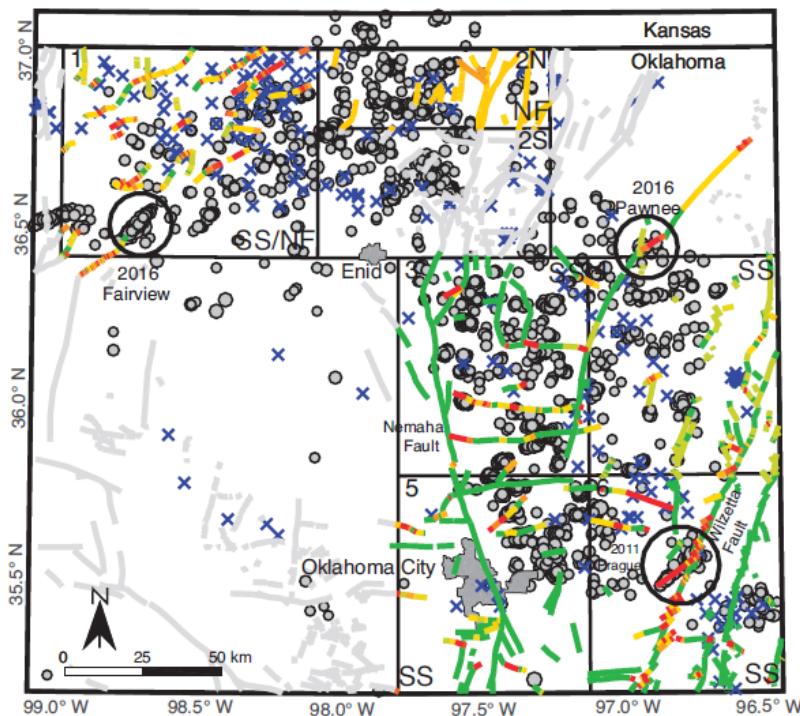
One study, Shirzaei et al. (2016), analyzed the potential for remote sensing of surface changes to indicate subsurface pressure changes, focusing on a series of earthquakes in Texas. The authors found a line-of-sight uplift of above 3 millimeters per year near one pair of injection sites, but found that the 2012

following seismicity, found that the M5.0 foreshock triggered a “cascading failure of earthquakes” along a fault system (1,904) M4.8 earthquake in Timpson, Texas, was actually caused by deeper injection wells outside of this area of uplift. Surface uplift, therefore, may not be indicative of potential hazard. The authors found that these techniques are useful for understanding changes in stress and pore pressure at depth. Although such analysis can aid in assessments of seismic hazard, it is not clear from the results of this study that monitoring surface deformation alone can assess risk.

Two studies (Walsh and Zoback 2016; Langenbruch and Zoback 2016) assess the probability of a future earthquake, though through different methods. Walsh and Zoback (2016) built a model to focus on injection rates as one of the main determinants of seismicity in Oklahoma and performed a quantitative risk assessment to evaluate the conditional probability of fault slip for mapped faults in north-central Oklahoma. The results—a “cumulative distribution function of the pore pressure required to cause slip on each fault segment” (991)—can be used to assess the probability of slip on a known fault from a given pore pressure increase caused by injection in order to avoid injection near a potentially active fault. The authors then mapped known faults with color coding where, in response to a 2 MPa pressure perturbation, faults with <1 percent conditional probability of slip in response are green, those with >33 percent chance are red, and those in between are yellow (see Figure 4 below). The results are said to be very conservative considering the assumptions made regarding geomechanical uncertainties, though they did find that the majority of mapped faults are not likely to be activated by modest pore pressure changes.

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<sup>8</sup> See the Oklahoma Corporation Commission's “Earthquake Response Summary (as of November 19, 2016)” for more information. (<http://www.occeweb.com/News/2016/11-23-16EARTHQUAKE%20ACTION%20SUMMARY.pdf>)

**FIGURE 4. FAULT MAP COLORED WITH CONDITIONAL PROBABILITY OF FAULT SLIP FROM PORE PRESSURE CHANGE**

Source: Langenbruch and Zoback (2016).

Notes: Green represents <1% of a probability of slip in response to 2 MPa pore pressure perturbation; red indicates a >33% change in response to the same pressure change.

The issue with this model is that a large number of induced earthquakes are not associated with mapped faults (Walsh and Zoback 2016). The study used Oklahoma for its analysis, but the results produced by the technique would likely be more accurate in other areas where pressure does not spread as quickly or as far as it does in Oklahoma.

Langenbruch and Zoback (2016) took this probabilistic analysis a step further—toward establishing a model to find the probability of induced seismic hazard more generally, not just for specific known faults. The model predicts the probability of exceeding an M5.0 earthquake based on injection rates and several other parameters in two large areas recently regulated by the Oklahoma Corporation Commission. The authors found that their model was able to predict many of the large earthquakes of 2014 in Oklahoma, and that the probability of exceeding a M5.0

earthquake decreased as injection rates decrease, though the probability remained elevated for several years before returning to historic levels. During peak injection rates in 2015, the probability of an earthquake greater than M5.0 was as high as 80 percent; following the decrease of injection rates due to regulatory intervention and economic changes, the model predicts this probability will fall to 37 percent in 2017. Although the model was successful in predicting many of 2014's large earthquakes, it was not able to predict the M5.7 earthquake in Prague—meaning that, according to the model, the earthquake could have been caused by factors other than injection rates. The model also is not able to predict localized seismicity, as the results are averaged over two large areas in Oklahoma, and does not rule out the potential for fluctuations in seismic hazards on the local level.

A lack of seismic data impedes the possibility of more studies like Langenbruch and Zoback (2016), and, due to undersampling, a lack of information about existing geologic structures diminishes the usefulness of studies such as Walsh and Zoback (2016). Almost all studies in this review echo the importance of quantifying stress and pore pressure changes in the crust in order to predict the occurrence of or an uptick in seismicity. Such data, however, remain elusive for a number of reasons, such as a lack of observations or integration with models (Shirzaei et al. 2016).

## 8. Conclusion

Overall, the literature focuses largely on establishing that earthquakes or regional seismic rate changes are attributable to oil and gas activities. Very few studies address above-ground impacts (Hough 2014; Liu, Ferreira, and Brewer 2016; McComas et al. 2016), with only the latter two addressing how communities and people might be affected by induced seismicity from energy development. Only two studies, Walsh and Zoback (2016) and Langenbruch and Zoback (2016), present probabilistic models that assess existing or future seismic hazard as well as analyze the effectiveness of policy changes meant to mitigate such hazard. Shirzaei et al. (2016) also presented a model that can be used to inform and update hazard assessments using surface deformation data.

More studies, however, are needed regarding the community impacts so that industry and regulatory responses can be better informed and more efficient. Further research in probabilistic or predictive analysis of induced seismic risk would additionally prove beneficial in both informing regulators of risk and aiding in mitigating risk. However, as we discuss in the Appendix, it is difficult for regulators to guarantee that an injection well will not cause seismicity or that a certain

policy change (such as rate reduction, volume reduction, or injection into specific subsurface formations) will definitively prevent any further earthquakes from occurring. However, certain regulations (such as traffic light systems, which we discuss in the Appendix) can mitigate the risk of induced seismicity, particularly when combined with high-quality monitoring.

## 9. Appendix

### 9.1. Methods for Mitigating the Probability of an Earthquake

There is no magic-bullet technique for preventing any induced events from occurring with high-volume, deep-disposal wells in regions that have been shown to be prone to induced seismicity, though several methods have been implemented by jurisdictions to mitigate risk (discussed further below). Here, we discuss what the findings in this literature imply for the ability to mitigate induced seismic risk.

Several studies have shown the potential to manage the number of earthquakes that occur, but the magnitude depends more on the underlying geology and tectonics, of which little is often known. Injection controls, such as volume of fluid injected, injection rate, reservoir size, and other factors, do not appear to have an effect on the upper bounds of induced earthquake magnitudes (Van der Elst et al. 2016; Yeck et al. 2016). Although injection controls can affect nucleation—the fact that an earthquake occurs—they cannot determine magnitude. Van der Elst et al. (2016) argued that “the probability of inducing an earthquake of a given size is directly related to the probability of encountering—and triggering—an appropriately stressed and tectonically connected nucleation site” (4584). Yeck et al. (2016) likewise emphasized “the role preexisting geologic structures play in induced earthquake sequences” (10,205). For hazard

assessments, fault length and orientation, among other factors, are important, though they may not be known until a fault is reactivated and presents seismic activity (McNamara et al. 2015).

Several studies suggest that lowering injection volumes could reduce the probability of an earthquake (McNamara et al. 2015; Weingarten et al. 2015; Langenbruch and Zoback 2016). Studying seismicity near Dallas-Fort Worth, Azle, and Cleburne, Texas, Hornbach et al. (2016) found correlations with injection volumes but not injection rates Ake et al. (2005) found that reducing the rate of injection by one-third significantly reduced the monthly seismic rate. One method that is largely considered not successful in mitigating risk is injecting fluid without pressure at the wellhead (Rubinstein et al. 2014; Weingarten et al. 2015). The weight of the water column can cause pressure and stress changes at seismic depth (Rubinstein et al. 2014).

Another method for mitigating seismicity would be to re-inject wastewater into the reservoir from which it came, where pressure is being released by the production of oil and gas (Zoback 2016a). Additionally, having geologic formations that act as barriers between injection formations and deeper formations with faulting may also help (Zoback 2016a, Shirzaei et al. 2016). Using an analytical-numerical model, Zhang et al. (2013) found that confining units and barriers (effectively a “bottom seal” on injection) had the single largest effect in preventing induced seismicity in the underlying crystalline basement. Avoiding injection in areas with high seismicity seems like an obvious mitigation technique, but Goebel et al. (2015) presented preliminary evidence that areas already prone to natural seismicity, such as Kern County, California, may face lower risks from induced seismicity from fluid injection. Goebel et al. (2015) is the only such study we found that analyzes induced seismicity in the

context of areas of higher seismic risk. More study regarding this topic is necessary before concluding that underground injection in such areas is less risky than injection in areas that have lower risk from natural earthquakes—particularly as one study found that some early twentieth-century earthquakes in the Los Angeles area were probably induced by oil production (Hough and Page 2016).

Policy response to this uncertainty has focused on what are known as traffic light systems to mitigate risk for site-specific operations. Traffic light systems, such as those in Alberta, Ohio, and the United Kingdom, as well as the “advisory” system used in Oklahoma use monitoring and enable different regulations to take effect depending on different levels of seismic activity. In Alberta, for example, if an  $M \geq 2$  earthquake occurs within 5 km of activities, an induced seismicity plan must be implemented and operations can resume with permission from the regulator. For earthquakes above M4.0, however, activities must be halted and can only resume with permission from the regulator. Walters et al. (2015) discussed how to incorporate these anthropogenic factors into seismic risk assessments in more detail. Although such measures do not guarantee that seismicity will not occur, they do provide regulators with a way to manage factors that could increase the risk of nucleation.

## **9.2. Study Span Chart: Seismicity Impacts**

We found 39 studies on induced seismicity from oil and gas development during our literature review—these are presented in the chart on page 24 and grouped in the left column according to their methodologies, with six categories in all. The top row of the chart contains a representation of the impact pathway elements (defined below). The elements covered by each study are shown at a

glance by the color-coded boxes that correspond to the impact pathways.

We found one survey, McComas et al. (2016). We found nine statistical studies, which use data analysis to assess above-ground impacts or the associations among regional seismic trends and certain oil and gas development activities. Frohlich et al. (2016) is labeled as historical. It used a five-question test to analyze historic earthquakes and assess how likely it is that a given earthquake is induced.

We found eight studies using “geomechanic modeling, simulations,” that model regional seismic trends, conduct fault simulations and reactivations, and (in one instance) a specific seismic event. Three studies are labeled probabilistic and predictive or aid in hazard assessments in that they use methodologies that have implications for assessing future changes in seismic rates related to oil and gas operations using a variety of methods described in the literature review. Finally, the seventeen geologic/seismologic studies most often analyze seismic data to characterize specific seismic events—including “relocating” an earthquake, assessing the focal mechanisms, conducting stress analysis, and more. These studies also assess the relationship between these seismic events and oil and gas activities in a number of ways. These six categories are not exclusive—for example, some geologic/seismologic studies may also use some statistical analysis.

It is important to note that this span chart does not portray elements that would determine study quality (which we present in the Community Risk-Benefit Matrix on page 3.) Also, as we can claim no expertise in this academic area, this chart as well as the literature review itself do not address distinctions in geologic or seismological analysis across the papers in these categories (aside from differentiating when such analysis

uses simulation modeling or uses geologic/seismologic analysis of ex post earthquake data).

Another notable takeaway from this chart is that only three studies (Walsh and Zoback 2016; Langenbruch and Zoback 2016; Shirzaei et al. 2016) are probabilistic, or working toward predictive models. Predictive and probabilistic models are important in that they can measure baselines of future activity against which policies can be compared. Such studies enable more effective policy implementation. Only one study of the three mentioned above (Langenbruch and Zoback 2016) predicts future changes in the rate of seismicity as a regional probability. Further research is clearly needed to expand understanding in this area. Further work is also needed to address public concerns about induced seismicity.

## **Impact Pathway Elements**

### *Activities*

Activities can include a number of oil and gas operations, though for seismicity, activities would refer to wastewater disposal, enhanced oil recovery, hydraulic fracturing, and so on. This element can also indicate the general presence of oil and gas development in a community rather than specific activities or processes.

### *Burdens*

Burdens are the initial consequences of the above activities, such as emissions caused by diesel pumps in a fracking operation, or, here, an earthquake event.

### *Exposure*

Exposure measures the amount of a substance or other type of burden that enters the body or the amount and intensity of earthquakes a region might be exposed to over a given time period. Exposure can also include the element of dose or cover a measure of the

number of people or animals exposed to a burden.

### *Impacts*

Impacts include both physical and mental outcomes that affect human or animal populations, such as increased preterm birth or aboveground damage to dwellings from induced seismicity.

### **Scope of the Studies**

Looking down the columns, the vast majority of these studies (36 of 39) address only activities and burdens—these are, for the most part, studies assessing causation between oil and gas activities and specific seismic events or regional changes. McComas et al. (2016) and Liu, Ferreira, and Brewer (2016) are the only studies to address the impacts communities face from induced seismicity. McComas et al. (2016) conducted a survey to assess public attitudes toward seismic events and the acceptability of induced seismic events, whereas Liu, Ferreira, and Brewer (2016) studied housing price changes related to oil and gas development activities and seismicity in Oklahoma. Hough (2014)

indirectly addressed exposure to shaking by analyzing data on shaking intensity for induced earthquakes from the US Geological Survey’s “Did You Feel It?” system. These three studies are far from conclusive regarding the community impacts of earthquakes—policymakers must therefore rely on qualitative reports and anecdotal evidence to assess whether a mitigating response is sufficient. Further, there are no studies that address trade-offs that residents might be willing to make. Perhaps local residents want no risk of induced seismicity, regardless of the cost, or perhaps they are willing to trade off the potential for some induced seismicity for an increase in energy production in the region. More such studies would be needed to address these issues.

**STUDY SPAN CHART: SEISMICITY STUDIES**

	Study	Activities	Burdens	Exposure	Impacts
		Specific activities or the presence of fracking in a community.	Initial consequences of shale development (e.g., earthquakes).	Evidence or amount of exposure (e.g., shaking).	The effects felt by the community (e.g., stress or damage).
Survey	McComas et al. (2016)				
	Liu et al. (2016)				
	Hough (2014)				
	Weingarten et al. (2015)				
Statistical	Llenos and Michael (2013)				
	Frohlich (2012)				
	Rubinstein et al. (2014)				
	Walsh and Zoback (2015)				
	Goebel et al. (2015)				
Historical	Van der Elst et al. (2016)				
	Frohlich et al. (2016)				
	Keranen et al. (2014)				
	Gono (2015)				
Geomechanic Modeling, Simulations	Hornbach et al. (2015)				
	Hornbach et al. (2016)				
	Rutqvist et al. (2013)				
	Zhang et al. (2013)				
	Dieterich et al. (2015)				
Probabilistic/ Predictive and for Hazard Assessment	McClure and Horne (2011)				
	Walsh and Zoback (2016)				
	Langenbruch and Zoback (2016)				
	Shirzaei et al. (2016)				
Geologic/ Seismologic	Justinic et al. (2013)				
	McNarmara et al. (2015)				
	Kim (2013)				
	Keranen et al. (2013)				
	Sumy et al. (2013)				
	Horton (2012)				
	Yeck et al. (2016)				
	Frohlich et al. (2011)				
	Frohlich and Brunt (2013)				
	Block et al. (2014)				
	Ake et al. (2005)				
	Skoumal et al. (2015)				
	Friberg et al. (2014)				
	Holland (2011)				
	Holland (2013)				
	Gan and Frohlich (2013)				
	Van der Elst et al. (2013)				

## References

- Ake, Jon, Kenneth Mahrer, Daniel O'Connell, and Lisa Block. 2005. "Deep-Injection and Closely Monitored Induced Seismicity at Paradox Valley, Colorado." *Bulletin of the Seismological Society of America* 95(2): 664–683. DOI: 10.1785/0120040072.
- Associated Press. 2016. "Substantial damage after earthquake rattles major Oklahoma oil hub." November 07. <http://www.foxnews.com/us/2016/11/07/damage-reported-no-injuries-as-5-0-earthquake-rattles-central-oklahoma.html>.
- Atkinson, Gail M., David W. Eaton, Hadi Ghofrani, Dan Walker, Burns Cheadle, Ryan Schultz, Robert Shcherbakov, Kristy Tiampo, Jeff Gu, Rebecca M. Harrington, Yajing Liu, Mirko van der Baan, and Honn Kao. 2016. "Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin." *Seismological Research Letters* 87(3): 631–647. DOI: 10.1785/0220150263.
- Bao, Xuewei, and David W. Eaton. 2016. "Fault activation by hydraulic fracturing in western Canada." *Science*. DOI: 10.1126/science.aag2583.
- Beron, Kurt J., James C. Murdoch, Mark A. Thayer, and Wim P.M. Vijverberg. 1997. "An analysis of the housing market before and after the 1989 Loma Prieta earthquake." *Land Economics* 73(1): 101–113.
- Block, Lisa V., Christopher K. Wood, William L. Yeck, and Vanessa M. King. 2014. "The 24 January 2013 ML 4.4 earthquake near Paradox, Colorado, and its relation to deep well injection." *Seismological Research Letters* 85(3): 609–624. DOI: 10.1785/0220130188.
- British Columbia Oil and Gas Commission. 2012. "Investigation of observed seismicity in the Horn River basin." <https://www.bcogc.ca/node/8046/download>.
- CSIS (Center for Strategic and International Studies). 2017. "Managing Societal and Environmental Risks/Impacts of Onshore Oil and Gas Development." Workshop. April 20.
- Dieterich, James H., Keith B. Richards-Dinger, and Kayla A. Kroll. 2015. "Modeling Injection-Induced Seismicity with the Physics-Based Earthquake Simulator RSQSim." *Seismological Research Letters* 86(4): 1–8. DOI: 10.1785/0220150057.
- EPA (US Environmental Protection Agency). n.d. "Class II Oil and Gas Related Injection Wells." <https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells>. (Accessed January 13, 2017).
- Fitzpatrick, Jessica, and Mark Petersen. 2016. "Induced Earthquakes Raise Chances of Damaging Shaking in 2016." Science Features, United States Geological Survey (USGS). March 28. [https://www2.usgs.gov/blogs/features/usgs\\_top\\_story/induced-earthquakes-raise-chances-of-damaging-shaking-in-2016/](https://www2.usgs.gov/blogs/features/usgs_top_story/induced-earthquakes-raise-chances-of-damaging-shaking-in-2016/). (Accessed January 12, 2017).
- Friberg, Paul A., Glenda M. Besana-Ostman, and Ilya Dricker. 2014. "Characterization of an Earthquake Sequence Triggered by Hydraulic Fracturing in Harrison County, Ohio." *Seismological Research Letters* 85(6): 1295–1307. DOI: 10.1785/0220140127.
- Frohlich, Cliff. 2012. "Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas." *PNAS* 109(35): 13934–13938. DOI: 10.1073/pnas.1207728109.

- Frohlich, Cliff, and Michael Brunt. 2013. "Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the Mw4.8 20 October 2011 earthquake." *Earth and Planetary Science Letters*. 379: 56–63. DOI: 10.1016/j.epsl.2013.07.025.
- Frohlich, Cliff, Heather DeShon, Brian Stump, Chris Hayward, Matt Hornbach, and Jacob I. Walter. 2016. "A Historical Review of Induced Earthquakes in Texas." *Seismological Research Letters*. 87(4): 1–17. DOI: 10.1785/0220160016.
- Frohlich, Cliff, Chris Hayward, Brian Stump, and Eric Potter. 2011. "The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009." *Bulletin of the Seismological Society of America* 101(1): 327–340. DOI: 10.1785/0120100131.
- Gan, Wei, and Cliff Frohlich. 2013. "Gas injection may have triggered earthquakes in the Cogdell oil field, Texas." *PNAS* 110(47): 18786–18791. DOI: 10.1073/pnas.1311316110.
- Gibbs, J., J. Healy, C. Raleigh, and J. Coakley. 1973. "Seismicity in the Rangely, Colorado, area: 1962–1970." *Bulletin of the Seismological Society of America* 63(5): 1557–1570.
- Goebel, T.H.W., E. Hauksson, F. Aminzadeh, J.-P. Ampuero. 2015. "An objective method for the assessment of fluid injection induced seismicity and application to tectonically active regions in central California." *Journal of Geophysical Research: Solid Earth* 120(10): 7013–7032. DOI: 10.1002/2015JB011895.
- Gono, Valerie. 2015. "On Shaky Ground: Understanding the Correlation between Induced Seismicity and Wastewater Injection in the Fort Worth Basin." Thesis. University of Texas Austin.
- GWPC (Groundwater Protection Council) and IOGCC (Interstate Oil and Gas Compact Commission). 2015. *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*. StatesFirst Induced Seismicity Injection Work Group (ISWG).
- Healy, J.H., W.W. Rubey, D.T. Griggs, and C.B. Raleigh. 1968. "The Denver Earthquakes." *Science* 161(3848): 1301–1310.
- Hermann, R.B., S. Park, and C. Wang. 1981. "The Denver earthquakes of 1967–1968." *Bulletin of the Seismological Society of America* 71(3): 731–745. DOI: 10.1785/0120120109.
- Hidano, Noboru, Tadao Hoshino, and Ayako Sugiura. 2015. "The effect of seismic hazard risk information on property prices: Evidence from a spatial regression discontinuity design." *Regional Science and Urban Economics* 53: 113–122. DOI: 10.1016/j.regsciurbeco.2015.05.005.
- Holland, Austin A. 2011. "Examination of Possibly Induced Seismicity from Hydraulic Fracturing in the Eola Field, Garvin County, Oklahoma." Oklahoma Geological Survey Open-File Report OF1-2011.
- . 2013. "Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma." *Bulletin of the Seismological Society of America* 103(3): 1784–1792. DOI: 10.1785/0120120109.
- Hornbach, Matthew J., Heather R. DeShon, William L. Ellsworth, Brian W. Stump, Chris Hayward, Cliff Frohlich, Harrison R. Oldham, Jon E. Olson, M. Beatrice Magnani, Casey Brokaw, and James H. Luetgert. 2015. "Causal factors for seismicity near Azle, Texas." *Nature*

- Communications* 6: 6728.  
DOI: 10.1038/ncomms7728.
- Hornbach, Matthew J., Madeline Jones, Monique Scales, Heather R. DeShon, M. Beatrice Magnani, Cliff Frohlich, Brian Stump, Chris Hayward, Mary Layton. 2016. "Ellenburger wastewater injection and seismicity in North Texas." *Physics of the Earth and Planetary Interiors* 261(A): 54–68. DOI: 10.1016/j.pepi.2016.06.012.
- Horton, S. 2012. "Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake." *Seismological Research Letters* 83(2): 250–260. DOI: 10.1785/gssrl.83.2.250.
- Hough, Susan E. 2014. "Shaking from injection-induced earthquakes in the central and eastern United States." *Bulletin of the Seismological Society of America* 104(5): 2619–2626. DOI: 10.1785/0120140099.
- Hough, Susan E., and Morgan Page. 2016. "Potentially Induced Earthquakes during the Early Twentieth Century in the Los Angeles Basin." *Bulletin of the Seismological Society of America* 106(6). DOI: 10.1785/0120160157.
- Justinic, Ashley Howe, Brian Stump, Chris Hayward, and Cliff Frohich. 2013. "Analysis of the Cleburne, Texas, Earthquake Sequence from June 2009 to June 2010." *Bulletin of the Seismological Society America* 103(6): 3083–3093. DOI: 10.1785/0120120336.
- Keranen, Katie M., Heather M. Savage, Geoffrey A. Abers, and Elizabeth S. Cochran. 2013. "Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence." *Geology* 41(6): 699–702. DOI: 10.1130/G34045.1.
- Keranen, K.M., M. Weingarten, G.A. Abers, B.A. Bekins, S. Ge. 2014. "Sharp increase in central Oklahoma Seismicity since 2008 induced by massive wastewater injection." *Science* 345(6195): 448–451. DOI: 10.1126/science.1255802.
- Kim, Won-Young (2013). "Induced Seismicity associated with fluid injection into a deep well in Youngstown, Ohio." *Journal of Geophysical Research: Solid Earth* 118: 3506–3518.
- Langenbruch, Cornelius, and Mark D. Zoback. 2016. "How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?" *Science Advances* 2(11). DOI: 10.1126/sciadv.1601542.
- Liou, Tiffany. 2016. "Oklahoma Insurance Commissioner Tours Pawnee Earthquake Damage." News 9. September 8. <http://www.news9.com/story/33052903/oklahoma-insurance-commissioner-tours-pawnee-earthquake-damage>.
- Liu, Haiyan, Susana Ferreira, and Brady Brewer. 2016. "Housing market impacts of wastewater injection induced seismicity risk." Agricultural and Applied Economics Association, 2016 Annual Meeting, July 31–August 2. Boston, Massachusetts.
- Llenos, Andrea L., and Andrew J. Michael. 2013. "Modeling Earthquake Rate Changes in Oklahoma and Arkansas: Possible signatures of Induced Seismicity." *Bulletin of the Seismological Society of America* 103(5): 2850–2861. DOI: 10.1785/0120130017.
- McCalpin, James P. 2009. "Earthquake Magnitude Scales," Appendix 1 in *Paleoseismology*, 2nd ed., edited by James P. McCalpin. Academic Press.
- McClure, Mark W., and Ronald N. Horne. 2011. "Investigation of injection-induced seismicity using a coupled fluid flow and rate/state friction model." *Geophysics*

- 76(6): WC181–WC198.  
DOI: 10.1190/GEO2011-0064.1
- McComas, Katherine A., Hang Lu, Katie M. Keranen, Maria A. Furtney, Hwansuck Song. 2016. "Public perceptions and acceptance of induced earthquakes related to energy development." *Energy Policy* 99: 27–32. DOI: 10.1016/j.enpol.2016.09.026.
- McNamara, D.E., G.P. Hayes, H.M. Benz, R.A. Williams, N.D. McMahon, and R.C. Aster. 2015. "Reactivated faulting near Cushing, Oklahoma: Increased potential for a triggered earthquake in an area of United States strategic infrastructure." *Geophysical Research Letters* 42(20): 8328–8332. DOI: 10.1002/2015GL064669.
- Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins. 2015. "The housing market impacts of shale gas development." *American Economic Review* 105(12): 3633–3659. DOI: 10.1257/aer.20140079.
- Murdoch, James C., Harinder Singh, and Mark Thayer. 1993. "The Impact of Natural Hazards on Housing Values: The Loma Prieta Earthquake." *Journal of the American Real Estate and Urban Economics Association* V21(2): 167–184.
- Murray, Kyle E. 2015. *Class II Saltwater Disposal for 2009-2014 at the Annual-, State-, and County- Scales by Geologic Zones of Completion, Oklahoma*. Open-File Report OF5-2015. Oklahoma Geological Survey.
- . 2016. "Modeling Approach for Estimating Co-Produced Water Volumes and Saltwater Disposal Volumes in Oklahoma." In American Geophysical Union (AGU) Annual Fall Meeting. San Francisco, CA.
- Nakagawa Masayuki, Makoto Saito, Hisaki Yamaga. 2007. "Earthquake risk and housing rents: evidence from the Tokyo metropolitan area." *Regional Science and Urban Economics* 37(1):87–99. DOI: 10.1016/j.regsciurbeco.2006.06.009.
- Naoi, Michio, Miki Seko, and Kazuto Sumita. 2009. "Earthquake risk and housing prices in Japan: Evidence before and after massive earthquakes." *Regional Science and Urban Economics* 39(6): 658–669. DOI: 10.1016/j.regsciurbeco.2009.08.002.
- National Research Council. 2013. *Induced Seismicity Potential in Energy Technologies*. National Academies Press: Washington, DC. DOI: 10.17226/13355. <https://www.nap.edu/catalog/13355/induced-seismicity-potential-in-energy-technologies>
- Nicholson, C., and R. Wesson. 1992. "Triggered earthquakes and deep well activities." *Pure and Applied Geophysics* 139(3): 561–578.
- Oklahoma Corporation Commission. 2016a. "Earthquake Response Summary (As of September 12, 2016)." <https://www.occeweb.com/News/2016/09-12-16EARTHQUAKE%20ACTION%20SUMMARY.pdf>. (Accessed January 17, 2017).
- . 2016b. "Advisory 4 – Cushing Area." November 8. <https://www.occeweb.com/News/2016/09-12-16EARTHQUAKE%20ACTION%20SUMMARY.pdf>. (Accessed January 17, 2016).
- Petersen, Mark D., Charles S. Mueller, Morgan P. Moschetti, Susan M. Hoover, Andrea L. Llenos, William L. Ellsworth, Andrew J. Michael, Justin L. Rubinsteine, Arthur F. McGarr, and Kenneth S. Rukstales. 2016. *2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes*. US Geological

- Survey (USGS). Open-File Report 2016-1035 Version 1.1, June 2016.  
[https://pubs.usgs.gov/of/2016/1035/ofr20161035ver1\\_1.pdf](https://pubs.usgs.gov/of/2016/1035/ofr20161035ver1_1.pdf).
- Raleigh, C.B., J.H. Healy, and J.D. Bredehoeft. 1976. "An experiment in earthquake control at Rangely, Colorado." *Science* 191(4233): 1230–1237. DOI: 10.1126/science.191.4233.1230.
- Rubinstein, Justin L., William L. Ellsworth, Arthur McGarr, and Harley M. Benz. 2014. "The 2001-Present Induced Earthquake Sequence in the Raton Basin of Northern New Mexico and Southern Colorado." *Bulletin of Seismological Society of America* 104(5): 2162–2181. DOI: 10.1785/0120140009.
- Rubinstein, Justin L. and Alireza Babaie Mahani. 2015. "Myths and facts on wastewater injection, hydraulic fracturing, enhanced oil recovery, and induced seismicity." *Seismological Research Letters* 86(4): 1–8. DOI: 10.1785/0220150067.
- Rutqvist, Jonny, Antonio P. Rinaldi, Frédéric Cappa, and George J. Moridis. 2013. "Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs." *Journal of Petroleum Science and Engineering* 107: 31–44. DOI: 10.1016/j.petrol.2013.04.023.
- Shirzaei, Manoocher, William Ellsworth, Kristy Tiampo, Pablo González, and Michael Manga. 2016. "Surface uplift and time-dependent seismic hazard due to fluid injection in eastern Texas." *Science* 353(6306): 1416–1419.
- Skoumal, Robert J., Michael R. Brudzinski, and Brian S. Currie. 2015. "Earthquakes Induced by Hydraulic Fracturing in Poland Township, Ohio." *Bulletin of the Seismological Society of America* 105(1): 189–197. DOI: 10.1785/0120140168.
- Sumy, Danielle F., Elizabeth S. Cochran, Katie M. Keranen, Maya Wei, and Geoffrey A. Abers. 2014. "Observations of static Coulomb stress triggering of the November 2011 M5.7 Oklahoma earthquake sequence." *Journal of Geophysical Research: Solid Earth* 119: 1904–1923. DOI:10.1002/2013JB010612.
- TNO. 2014. "Literature review on Injection-Related Induced Seismicity and its relevance to Nitrogen Injection." TNO 2014 R11761.
- USGS (US Geological Survey). n.d. a. "Earthquake Facts & Earthquake Fantasy." [https://earthquake.usgs.gov/learn/topics/megaqk\\_facts\\_fantasy.php](https://earthquake.usgs.gov/learn/topics/megaqk_facts_fantasy.php). (Accessed January 12, 2017).
- . n.d. b. "Moment magnitude, Richter scale – what are the different magnitude scales, and why are there so many?" <https://www2.usgs.gov/faq/categories/982/8/3357>. (Accessed January 18, 2017).
- . 2016a. "Magnitudes for Oklahoma Earthquakes Shift Upward." September 7. <https://www.usgs.gov/news/magnitudes-oklahoma-earthquakes-shift-upward>. (Accessed January 12, 2017).
- . 2016b. "M5.8 North Central Oklahoma Earthquake of 03 September 2016." October 13. Earthquake Information Center. <https://earthquake.usgs.gov/earthquakes/eqarchives/poster/2016/20160903.pdf>. (Accessed January 17, 2017).
- Van der Elst, Nicholas J., Morgan T. Page, Deborah A. Weiser, Thomas, H.W. Goebel, and S. Mehran Hosseini. 2016. "Induced earthquake magnitudes are as large as (statistically) expected." *Journal of Geophysical Research: Solid Earth* 121(6): 4575–4590. DOI: 10.1002/2016JB012818.
- Van der Elst, Nicholas J., Heather M Savage, Katie M. Keranen, and Geoffrey A. Abers.

2013. "Enhanced Remote Earthquake Triggering at Fluid-Injection Sites in the Midwestern United States." *Science* 341(6142): 164–167. DOI: 10.1126/science.1238948.
- Veil, John. 2015. "US Produced Water Volumes and Management Practices in 2012." Prepared for the Ground Water Protection Council. Veil Environmental, LLC.  
[http://www.gwpc.org/sites/default/files/Produced%20Water%20Report%202014-GWPC\\_0.pdf](http://www.gwpc.org/sites/default/files/Produced%20Water%20Report%202014-GWPC_0.pdf).
- Walsh III, F. Rall, and Mark D. Zoback. 2015. "Oklahoma's recent earthquakes and saltwater disposal." *Science Advances* 1(5): 1–9. DOI: 10.1126/sciadv.1500195.
- . 2016. "Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north central Oklahoma, USA." *Geology* 44(12): 991–994. DOI: 10.1130/G38275.1.
- Walters, Randi Jean, Mark D. Zoback, Jack W. Baker, and Gregory C. Beroza. 2015. "Characterizing and Responding to Seismic Risk Associated with Earthquakes Potentially Triggered by Fluid Disposal and Hydraulic Fracturing." *Seismological Research Letters* 86(4): 1110–1118. DOI: 10.1785/0220150048.
- Weingarten, M., S. Ge, J.W. Godt, B.A. Bekins, and J.L. Rubinstein. 2015. "High-rate injection is associated with the increase in US mid-continent seismicity." *Science Magazine* 348(6241): 1336–1340. DOI: 10.1126/science.aab1345.
- Yeck, W. L., M. Weingarten, H. M. Benx, D. E. McNamara, E. A. Bergman, R. B. Hermann, J. L. Rubinstein, and P. S. Earle. 2016. "Far-field pressurization likely caused one of the largest injection induced earthquakes by reactivating a large preexisting basement fault structure." *Geophysical Research Letters* 43(19): 10,198–10,207. DOI: 10.1002/2016GL070861.
- Zhang, Yipeng, Mark Person, John Rupp, Kevin Ellett, Michael A. Celia, Carl W. Gable, Brend Bowen, James Evans, Karl Bandilla, Peter Mozley, Thomas Dewers, and Thomas Elliott. 2013. "Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injection into basal reservoirs." *Ground Water* 51: 525–538. DOI: 10.1111/gwat.12071.
- Zoback, Mark D. 2016a. "Managing the Risk of Earthquakes Triggered by Waste Water Disposal and Hydraulic Fracturing." Presentation prepared for "The Shale Gas and Oil Wastewater Disposal Cycle: Managing Earthquake and Other Environmental Risks. Resources for the Future, Stanford Woods Institute for the Environment, and Stanford Natural Gas Initiative. October 18.  
<http://www.rff.org/events/event/2016-10/shale-gas-and-oil-wastewater-disposal-cycle-managing-earthquake-and-other>.
- . 2016b. "Managing the Risks of Injection-Induced Seismicity." Keynote presentation, Panel 4, Onshore Unconventional Hydrocarbon Development: Legacy Issues, induced seismicity, and innovations in managing risk. National Academy of Sciences. December 2. <http://nas-sites.org/uhrroundtable/past-events/onshore-workshop/onshore-workshop-panel-4/>.