FLUID INJECTION WELLS CAN HAVE A WIDE SEISMIC REACH

By Shelby L. Peterie, Richard D. Miller, Rex Buchanan, and Brandy DeArmond

Seismologists attribute widespread earthquakes in southern Kansas and northern Oklahoma over the past several years largely to injection of extracted oil field brine deep into Earth's crust. Recently, however, the frequency of earthquakes has increased significantly in areas of Kansas well beyond the initial high-seismicity zones near injection wells.

Because the vast majority of high-volume injection wells in the region are near and south of its border with Oklahoma, Kansas has a unique vantage point for observing far-field effects of injection.

Recent measurements show that subsurface fluid pressures are elevated across south central Kansas, including areas where injection practices have been relatively consistent for decades. The findings

This valve assembly is the aboveground portion of an injection well, which can be used to dispose of fluid deep in the subsurface. Credit: Leonid Eremeychuk/iStock/Getty Images Plus/Getty Images

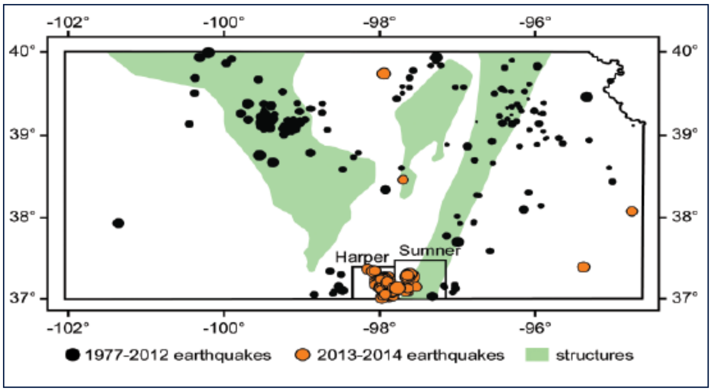

Fig. 1. On this map of Kansas, dark circles show locations of earthquakes reported by USGS and the Kansas Geological Survey from 1977 to 2012; orange circles indicate earthquakes reported by USGS from 2013 to 2014. Nearly all of the recent earthquakes occurred within two southern counties (Harper and Sumner), which have seen a large increase in high-volume fluid injection. Light green areas show prominent subsurface geological structures.

suggest that the cumulative effects of high-volume injection to the south have had an extended influence on fluid pressure in the pores of subsurface rocks.

This regional pressure change has the potential to trigger earthquakes far from the high-volume injection points, especially in areas where fluid pressure may already be elevated from local injection operations.

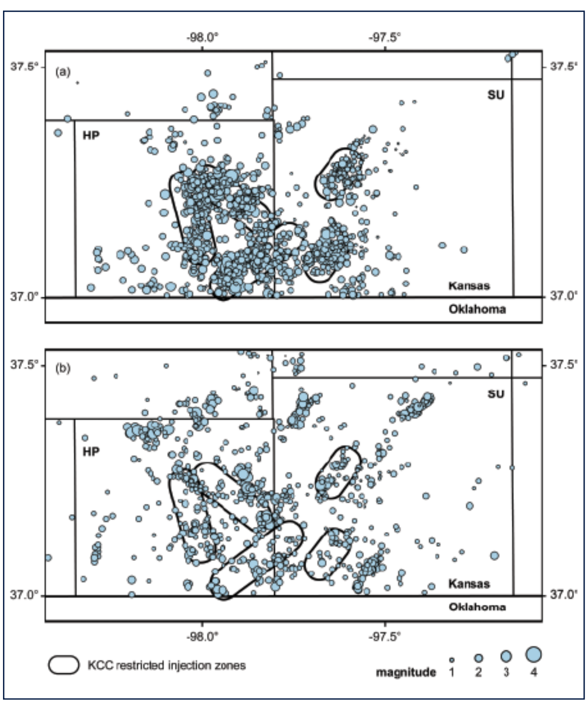

Fig. 2. Earthquakes recorded by the Kansas Geological Survey network in Harper (HP) and Sumner (SU) Counties showed a sharp decrease between (a) January to June 2015, prior to the Kansas Corporation Commission's (KCC) sorder restricting fluid injection volumes, and (b) July to December 2016, a year after the order went into effect. The ellipses show the zones where the Kansas Corporation Commission restricted injection volumes. Credit: Modified from Peterie et al. *[2017]*

Human Activity and Earthquakes

Published studies have long indicated that human activity can cause earthquakes. Such earthquake-inducing processes include fluid injection for enhanced oil recovery, solution mining, hydraulic fracturing, geothermal stimulation, and disposal of waste fluids from industrial or oil and gas operations [*Ellsworth*, 2013].

Fluid injection into deep wells can increase underground pore pressure sufficiently to overcome frictional resistance and trigger slip on faults in the crystalline basement rock near an injection site, especially where large crustal stresses have brought a fault close to failure [*Nicholson and Wesson*, 1990].

Most induced earthquakes are too small to be felt. However, if a fault of sufficient length is subjected to the right stress conditions, the potential exists for triggering an earthquake with ground motion large enough to cause damage. This potential is a concern for both the public and the state agencies that regulate injection wells.

Wastewater Disposal in Deep Wells

Over the past decade, innovations in horizontal drilling and hydraulic fracturing technologies have helped drive interest in extracting oil and gas from the Mississippian limestone in Kansas and Oklahoma. Oil and gas production began to rise in Oklahoma in 2009, followed by Kansas in 2012.

The process of extraction from the Mississippian limestone produces large volumes of highly saline formation water, which is typically disposed of in deep saltwater disposal wells. Operators of many newly completed disposal wells initially were permitted to inject fluid into the ground at rates 3–4 times historical levels.

Most of these high-volume wells inject fluid into a rock formation called the Arbuckle Group (see http://bit.ly/Arbuckle-Group), made up of highly permeable Cambrian-Ordovician age sedimentary rocks. With no underlying confining layer in many places, these rocks are hydraulically linked to the Precambrian granite basement that lies below. Such basement rocks typically have many faults, mapped and unmapped, but generally with sparse historical earthquake activity.

Oklahoma and Kansas Earthquakes

Kansas and Oklahoma are located in a tectonically stable region with low risk for damaging natural earthquakes. Before 2009, both states had a history of seismic activity, with an average of one to two earthquakes of magnitude 3 or larger occurring annually.

A historically unprecedented increase in the rate and magnitude of earthquakes followed the dramatic rise in saltwater disposal in the area. Oklahoma began experiencing an unusually large number of earthquakes in 2009, followed by south central Kansas in 2013.

In 2014, the U.S. Geological Survey (USGS) reported 42 earthquakes of magnitude 3 or larger in Kansas, including a magnitude 4.9 temblor, the largest recorded in Kansas using modern instruments. All but a few epicenters

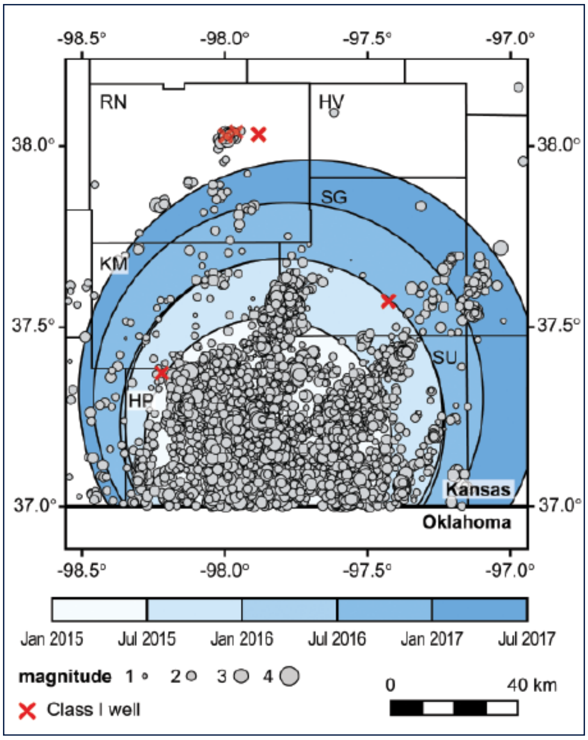

Fig. 3. Nearly 7,000 earthquakes (gray) were recorded by the Kansas Geological Survey seismic network in Harper (HP), Sumner (SU), Sedgwick (SG), and Reno (RN) Counties from January 2015 through June 2017. Shaded blue circles represent the concentration of earthquake epicenters at 6-month intervals and demonstrate the progression of earthquakes with time to the north and northeast. Injection rates for industrial injection wells (red crosses) in some counties with recent earthquake swarms have remained consistent for years, if not decades. Credit: Modified from Peterie et al. *[2018]*

were located within five distinct zones in Harper and Sumner Counties, a part of the state with few reported earthquakes in previous years (Figure 1).

Fluid Injection in Kansas

Numerous industries in Kansas use underground injection control wells for fluid disposal. The state currently manages 50 deep industrial wastewater wells (Class I), regulated by the Kansas Department of Health and Environment, and approximately 5,000 saltwater disposal wells (Class II), regulated by the Kansas Corporation Commission.

Cumulative injection volumes in most areas of the state have been consistent for the past several years. However, by far the most dramatic change in approved volume increases occurred in south central Kansas. The annual saltwater disposal volume in Harper County alone increased from the historical rate of about 10 million barrels to more than 100 million barrels by 2015.

In response to the increased earthquake activity in south central Kansas, Governor Sam Brownback in January 2014 appointed a task force consisting of representatives from the Kansas Geological Survey (KGS), the Kansas Department of Health and Environment, and the Kansas Corporation Commission to consider the matter. The task force developed a response plan for mitigating induced earthquakes and recommended enhanced seismic monitoring.

Monitoring Seismic Activity

In early 2015, KGS installed six temporary seismograph stations in south central Kansas to closely monitor and better understand the seismic activity. During the first 6 months of monitoring, earthquake epicenters persisted in dense clusters primarily within the same high-seismicity zones identified in 2014.

Conversations with the Oklahoma Geological Survey and the Oklahoma Corporation Commission made it clear that restrictions on individual disposal wells did not always reduce seismic activity. Indeed, the majority of the Oklahoma and Kansas earthquakes do not directly correlate with injection operations at a single nearby well. Rather, the widespread seismicity appears to be a result of cumulative injection in numerous disposal wells [*Walsh and Zoback,* 2015].

Hence, the Kansas Corporation Commission took a geologically based mitigation approach designed to reduce pore pressure around known active fault zones.

Earthquake clustering was used to identify likely basement structures sensitive to changes in deep fluid pressure. The commission ordered reduced injection volumes for saltwater disposal wells located within a set of ellipses defined around the high-seismicity zones in Harper and Sumner Counties. By July 2015, saltwater disposal rates were reduced to near the maximum historical rate in the area prior to the uptick in earthquakes.

Earthquake Migration

A year after saltwater disposal volumes were restricted, earthquake activity within the injection-restricted footprint dropped dramatically. Only about 250 earthquakes of magnitude 2 or larger were recorded in 2016, compared with nearly 800 in 2015 (Figure 2).

However, earthquake epicenters began gradually migrating into other areas at increasingly greater distances from the initial high-seismicity zones. This earthquake migration followed a distinct northern progression, often along linear trends that suggest fault zones [*Peterie et al.,* 2018]. By early 2017, earthquakes had advanced more than 50 kilometers from Harper and Sumner Counties into neighboring counties with a history of minimal earthquake activity (Figure 3).

This unexpected migration does not fit the traditional model of induced seismicity, where locally elevated pressure triggers earthquakes near the causal well. Owners of industrial injection wells (Class I), which had previously operated for years without incident, became concerned that they would be held responsible for earthquakes in their areas and be required to stop injection operations.

As a result, the Kansas Department of Health and Environment intensified a long-standing wastewater reduction effort for these industrial wells. By 2017, some facilities had already implemented comprehensive wastewater reduction programs, and most were continually refining their processes to reduce wastewater disposal.

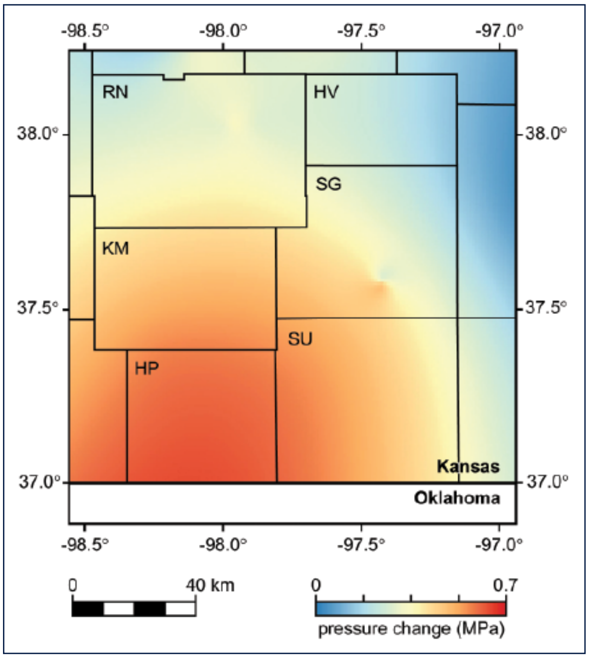

Fig. 4. Preliminary map of the pressure change measured in Class I industrial wastewater disposal wells in 2016 relative to 2002 baseline measurements. Fluid pressure in the Arbuckle Group has increased across south central Kansas and is most prominent in Harper (HP) County, which experienced a sharp increase in high-volume saltwater disposal starting in 2012. MPa = megapascals.

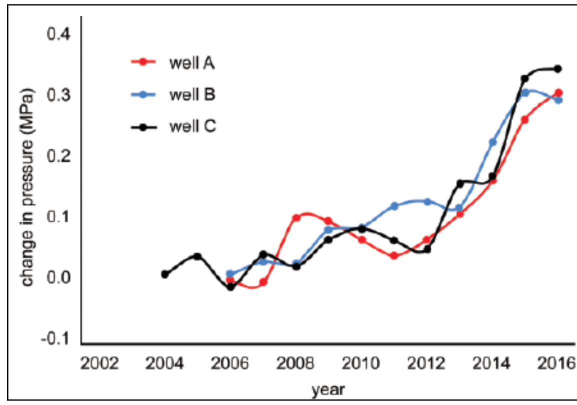

Fig. 5. Changes in bottomhole pressure (relative to baseline) measured at three Class I facilities in Reno County followed nearly identical trends despite the 5- to 10-kilometer separation between facilities and vastly different injection volumes.

Regionally Elevated Fluid Pressure

Numerous studies suggest that a pressure increase of as little as 0.01–0.2 megapascal along a critically stressed fault may be sufficient to trigger an earthquake (by comparison, the air pressure in a car tire is usually about 0.2 megapascal) [e.g., *Keranen et al.*, 2014].

Measurements of pressure at the bottom of wells (bottomhole pressure) that terminate in the Arbuckle Group can provide insight into fluid pressure affecting basement faults. Facilities with active Class I wells, all but one of which terminate in the Arbuckle Group, are required to measure and report bottomhole pressure to the Kansas Department of Health and Environment annually. Bottomhole pressure is not reported for saltwater disposal (Class II) wells, which are subject to different regulatory requirements.

Historically, most Class I facilities measured only small (on the order of 0.05 megapascal) annual bottomhole pressure fluctuations with a relatively flat multiyear trend. Beginning in 2012, increasing bottomhole pressure was measured at several facilities across central Kansas. The most dramatic increase was observed at the southernmost facility, located in Harper County, where by 2016 pressure had increased by more than 0.4 megapascal relative to historical pressures (Figure 4).

Similar but smaller pressure increases were observed in Sedgwick and Reno Counties near areas where earthquakes had advanced in 2016 (Figure 3).

A particularly revealing trend was observed at three facilities in Reno County located within 10 kilometers of an earthquake cluster. Although these facilities inject vastly different disposal volumes and were 5–10 kilometers apart, the bottomhole pressure trends were nearly identical, rising by about 0.2 megapascal in the past few years (Figure 5).

Because annual injection volumes in these and other nearby wells have been consistent for about a decade, it seems highly unlikely that local injection practices alone are responsible for the abrupt and unprecedented increase in formation pressure and seismicity.

Far-Reaching Effects

The combination of regionally elevated Arbuckle Group fluid pressure (most prominent to the south), a gradual northward progression of earthquake trends well outside the initial high-seismicity zones, and the lack of commensurate changes in local injection volumes supports the hypothesis that the observed pressure increases are predominantly influenced by regional increases in high-volume injection as far as 90 kilometers to the south.

It is not surprising that seismic activity has increased in counties with elevated bottomhole pressure. What is surprising is that the observed rise in bottomhole pressures does not appear to correlate with local (within 20 kilometers) injection volumes in or near the wells where these measurements were made. Rather, the rise in fluid pressure closely tracks significant increases in saltwater disposal volumes several counties to the south.

This observation is notable because the largest previously reported distance between a causal well and an induced earthquake (and thus critically elevated pore fluid pressure) is about 20 kilometers [*Keranen et al.*, 2014].

Twofold Effect

Although it is unprecedented to suggest that injection practices could influence fluid pressure and seismic activity much more than 20 kilometers away, the volume of fluid injected into this formation is also unprecedented (Figure 6).

A study of the central and eastern United States found that an earthquake is statistically more likely to occur near wells injecting more than 300,000 barrels per month than near wells injecting at lower rates [*Weingarten et al.*, 2015]. In an area about the size of two counties that spans both sides of the Kansas-Oklahoma border, nearly 50 saltwater disposal wells were each injecting at or above this rate in 2015. Most widely recognized cases of induced seismicity had one or, at most, a few wells injecting near this rate.

The effects of such high-volume injection appear to be twofold. Pressure is locally elevated near a high-volume well shortly after injection begins. This local pressure change directly affects nearby faults and is likely the dominant factor influencing induced earthquakes.

Far-field pressure increases occur as a cumulative effect resulting from fluid migration and pressure diffusion from high-volume injection wells along high-permeability pathways, such as permeable fault zones. Because highly detailed fault maps do not exist for south central Kansas and hydraulic properties can vary widely, predicting fluid flow and migration rates away from an injection site is difficult, at best.

Like local pressure, far-field pressure diffusion triggers earthquakes only where pore fluid pressure exceeds the critical pressure for initiating slip on an appropriately stressed fault. As fluid moves into areas where pressure is locally elevated because of nearby injection operations, a minimal pressure increase may be sufficient to raise absolute pore pressures above the triggering threshold.

This may explain why earthquake swarms have developed in areas with a long history of fluid injection but with no previously known injection-induced earthquakes.

Regulatory Challenges

Because fluid disposal is widespread and generally involves multiple operators regulated by different agencies within the same state and across state borders, developing equitable practices to minimize increased formation pressures poses unique challenges for regulators.

Mitigation of earthquakes caused by local high-volume injection is relatively straightforward: Reduce injection volumes near critically stressed faults sufficiently to reduce pressure below the triggering threshold, and local seismic activity will decrease.

Mitigating earthquakes caused by far-field pressure diffusion is more complex. Just as it took months or years before distant high-volume disposal practices raised the far-field pressure above the triggering threshold, regulatory actions to reduce distant high-volume disposal may take months or years to affect far-field pressure.

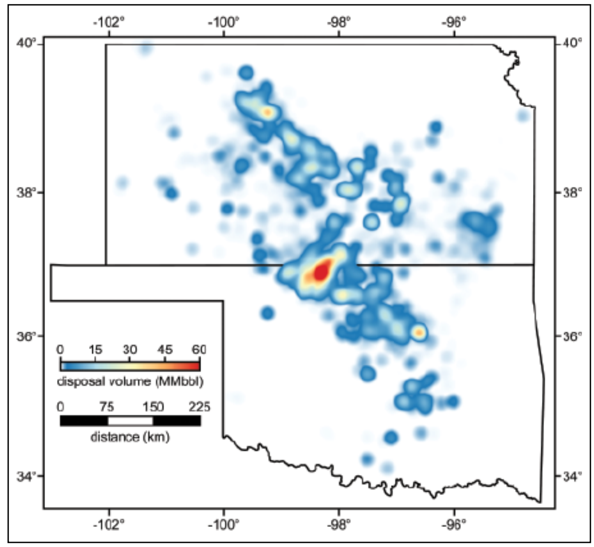

Fig. 6. Volume of fluid injected into the Arbuckle Group in Class II saltwater disposal and Class I wells in Kansas and Class II saltwater disposal wells in Oklahoma in 2015. MMbbl = million barrels.

A member of the Kansas Geological Survey field crew installs a seismic station in south central Kansas. Credit: Shelby Peterie

In addition, because far-field pressure from distant injection combines with local injection pressure to elevate local pressures beyond the earthquake-triggering threshold, seemingly independent injection operations may contribute to triggering earthquakes.

A Cooperative Approach

After recognizing the synergistic effects of local and far-field pressure changes, the Kansas Corporation Commission and the Kansas Department of Health and Environment, the two state agencies that regulate injection wells, met with KGS to discuss the agency's findings.

Industries currently use Arbuckle Group disposal wells for everything from drinking water treatment to oil production and refinement, each of which has unique operational processes, business models, and stakeholders. Not only do two separate agencies regulate injection wells, but also the diversity of industries performing Class I and Class II injection operations, ownership of mineral rights as well as other legal and regulatory issues, and movement of fluids across state lines add to the complexity of seeking efficient solutions.

Both regulating bodies are currently providing data to and meeting with KGS regularly in a collaborative effort to develop and implement recommendations. Joint policies between state agencies to address injection volumes and establishment of other best management practices would be an equitable and effective approach to mitigating induced seismicity from regional pressure changes.

Data used in this study can be found in the supporting information of *Peterie et al.* [2018]. Injection volumes for Oklahoma Class II wells are provided by the Oklahoma Corporation Commission (see http://bit.ly/OCC-data-files).

Acknowledgments

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