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Earthquakes in Kansas Induced by Extremely Far-Field Pressure Diffusion

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Key Points:
- Earthquakes have migrated as far as 90 km from high-volume wells following increased saltwater disposal near the Kansas-Oklahoma border
- Bottomhole pressure measured in the injection interval in southern Kansas increased subsequent to high-volume disposal near the border
- Observations suggest fluid migration and pressure diffusion at unprecedented distances from cumulative fluid disposal in high-volume wells

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S3
- Data Set S3
- Movie S1

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Abstract Pressure diffusion from high-volume saltwater disposal wells near the Kansas-Oklahoma border appears to have contributed to triggering earthquakes as far as 90 km away. Elevated seismicity that began in southern Kansas in 2013 is largely believed to be induced by pore pressure increase from dozens of disposal wells injecting unprecedented volumes. Earthquakes initially occurred in dense swarms near the wells, and in subsequent years migrated into surrounding areas with minimal fluid injection. By 2017, earthquakes advanced 90 km from areas surrounding the high-volume injection wells into areas with considerable fluid injection volumes but historically consistent rates. Fluid pressure within the injection interval in southern Kansas increased subsequent to high-volume saltwater disposal in southern Kansas and northern Oklahoma. Temporal pressure trends across central Kansas suggest that fluid migration and pressure diffusion from cumulative disposal to the south likely induced earthquakes much farther than previously documented for individual injection wells.

Plain Language Summary Fluid injected deep underground is known to cause faults to slip under certain conditions, inducing an earthquake. Published cases of injection-induced seismic activity typically involve only one or at most a few wells injecting large volumes of fluid. An increase in pore pressure caused by fluid injected in one or a few wells is usually large enough to trigger earthquakes only a short distance from the injection point, typically within about 10 km. Beginning in 2012, dozens of disposal wells have injected an unprecedented volume of fluid near the Kansas-Oklahoma border in the central United States. In the years since injection began, seismic activity advanced increasingly beyond the initial earthquake swarms near the causal injection wells. Increasing deep fluid pressure measured across central Kansas suggests that fluid and associated pore pressure increases related to injection near the southern Kansas border migrated and contributed to inducing earthquakes as far as 90 km from the injection point, much farther than previously documented.

1. Introduction

Kansas has a history of natural seismic activity, with a magnitude (*M*) 3 or larger earthquake occurring every 1 to 2 years on average (National Earthquake Information Center (NEIC), 2017; Steeples et al., 1987, 1990). In south central Kansas, where no *M* 3 or larger earthquakes were recorded during nearly 40 years of monitoring, the U.S. Geological Survey (USGS) reported one *M* 3 earthquake in 2013, followed by 41 in 2014. This increased seismic activity followed a similar pattern in Oklahoma, which borders Kansas to the south. The widespread seismicity in Oklahoma has been studied in depth and is largely considered induced as a result of regional high-volume saltwater disposal in the Arbuckle Group (Ellsworth, 2013; Keranen et al., 2014; Langenbruch & Zoback, 2016; Walsh & Zoback, 2015), a thick sequence of sedimentary rocks overlying crystalline basement.

Fluid injection in deep sedimentary units with hydraulic connectivity to basement faults has been attributed to inducing earthquakes in numerous case studies in the central United States (Ake et al., 2005; Hornbach et al., 2015; Horton, 2012). Based on these and other studies (e.g., Deichmann & Giardini, 2009; Healy et al., 1968), the conventional and generally accepted model for induced seismicity holds that locally elevated pore pressure from one to a few wells injecting large fluid volumes reduces the effective stress and induces slip on nearby critically stressed faults (Hubbert & Rubey, 1959; Nicholson & Wesson, 1990). Statistically, an induced earthquake is more likely to occur near wells injecting 10,000 barrels (bbl)/d or more than wells injecting at lower rates (Weingarten et al., 2015), and most documented cases of induced seismicity cite at least one nearby high-volume well injecting at around this rate (Ake et al., 2005; Deichmann & Giardini, 2009; Healy et al., 1968; Hornbach et al., 2015; Horton, 2012). Historically,

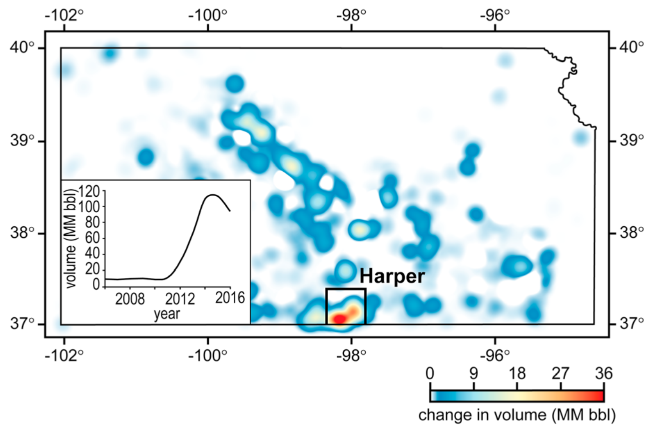

Figure 1. Map of the change in annual injection volume in Class II saltwater disposal wells and Class I wells in Kansas in 2015 (relative to 2006). The distribution is based on injection volume per square kilometer using the kernel density function with a 20 km search radius. Inset: graph of annual injection volumes in Harper County.

induced earthquakes have typically occurred within 10 km of the causal well, distances beyond which pore pressure changes from fluid injection are generally minimal (Nicholson & Wesson, 1990).

Seismic activity in Kansas and Oklahoma differs from previous induced seismicity case studies in two ways. First, while previous cases of induced seismicity can often directly correlate a sequence of earthquakes with operations in a specific well, only a couple of earthquake swarms in these states have been confidently correlated with a particular group of wells (Keranen et al., 2014; Yeck et al., 2016). Rather, the majority of earthquakes in northern Oklahoma and southern Kansas since 2013 are believed to be induced by a cumulative increase in pore pressure from injection in dozens of high-volume wells in this region (Langenbruch & Zoback, 2016; Walsh & Zoback, 2015). Second, recent studies of induced seismicity in Oklahoma suggest far-field pressurization from groups of several high-volume wells likely induced earthquakes at distances of 20 km or possibly more (Keranen et al., 2014; Yeck et al., 2016), farther than previously recognized in cases involving only one to a few wells.

With the majority of high-volume injection located near and south of the border, Kansas has a unique vantage point from which to observe far-field effects of injection. In this paper, we present temporal variation in epicenters of earthquakes recorded by the Kansas Geological Survey (KGS) seismic network. The progression of earthquakes combined with reported injection volumes and sparse Arbuckle Group fluid pressure measurements in south central Kansas provides insight into fluid pressure affecting basement faults and the regional influence of high-volume injection on pore pressure and seismic activity.

2. Fluid Injection in Kansas

Kansas has a decades long history of deep fluid injection in regulated Underground Injection Control wells (Environmental Protection Agency, 2016). Nearly 5,000 saltwater disposal wells (Class II) and 50 industrial wastewater wells (Class I) are active in the state today (Figure S1 in the supporting information). More than half of the Class II saltwater disposal wells and all but one of the Class I wells terminate in the Arbuckle Group. Cumulative injection volumes have been reasonably consistent in most parts of the state for the past several years. Beginning in 2012, a dramatic increase in annual saltwater disposal volumes occurred in south central Kansas (Figure 1 and Data Set S1). In Harper County, the annual disposal volume increased from about 10 million barrels (MMbbl) in 2011 to more than 100 MMbbl in 2015, most of which was injected into the Arbuckle Group. The Arbuckle Group and underlying granite basement are known to be highly fractured due to multiple episodes of tectonic deformation (Baars, 1995; Franseen et al., 2004; Merriam, 1963). Therefore, increased pore fluid pressure within the Arbuckle Group increases the potential for slip on hydraulically connected basement faults.

3. Earthquake Monitoring and Mitigation

3.1. Seismic Network Deployment

In response to the elevated and potentially induced seismicity observed in 2013 and 2014, the KGS installed 13 short-period, three-component seismometers across the state with enhanced network sensitivity in south central Kansas (Figure S2). Details of the network deployment and analysis procedures can be found in Text S1 in the supporting information. The network supplemented a dense USGS array in Harper and Sumner counties. For earthquakes reported by the USGS, locations of equivalent KGS events were typically within 2 km. From January 2015 through June 2017, nearly 7,000 earthquakes ranging in magnitude from *M* less than 1 to *M* 4.1 were recorded by the KGS network in a five-county area in south central Kansas (Data Set S2). Over 80% of these earthquakes had epicenters in Harper and Sumner counties.

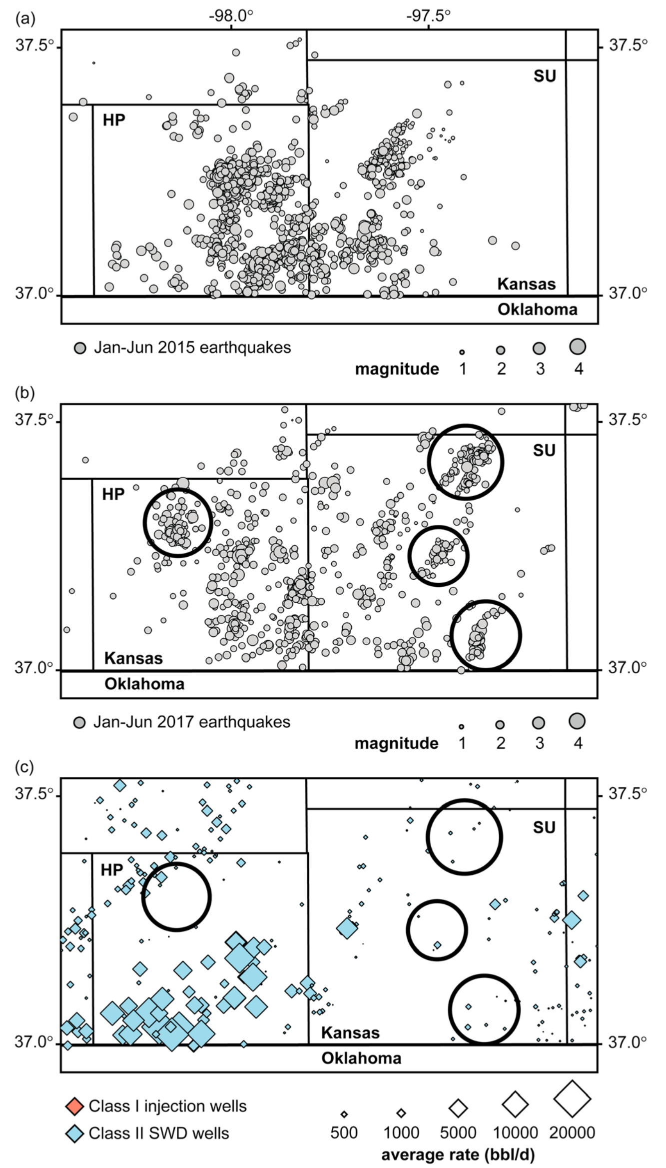

Figure 2. Earthquakes recorded by the KGS seismic network in Harper (HP) and Sumner (SU) counties from (a) January through June 2015 and (b) January through June 2017. (c) Active Class II saltwater disposal wells and Class I injection wells (diamonds) in Harper and Sumner counties, sized relative to the average daily injection rate reported from 2015 to 2016 (2017 injection volumes were not available at the time of publication). The black circles shown in Figures 2a and 2b indicate areas with active earthquake swarms in 2017.

3.2. Mitigation Efforts in Kansas

Because of the lack of direct correlation between earthquake swarms and operations in specific nearby wells, the Kansas Corporation Commission (KCC, the state agency responsible for regulating Class II saltwater disposal wells) took a geologically based mitigation approach designed to reduce pore pressure around active fault zones. Clustering of earthquakes reported by the USGS in 2013 and 2014 was used to identify likely basement structures most sensitive to changes in deep fluid pressure. In March 2015, the KCC ordered a phased reduction in injection volumes for saltwater disposal wells located within several 5 km wide ellipses established around earthquake swarms in Harper and Sumner counties (KCC, 2015). By July 2015, injection rates of affected disposal wells were reduced to less than 8,000 bbl/d, a reduction of 50% or more for two of the highest-rate wells. Around this time, injection volumes were generally reduced near the Kansas-Oklahoma border as a result of economic drivers (i.e., declining oil prices and, thus, reduced production and saltwater disposal), as well as regulatory actions in early 2016 by the Oklahoma Corporation Commission (OCC, 2016).

3.3. Migration of Earthquakes

In early 2015, earthquakes persisted in dense swarms (Figure 2a) at approximately the same locations reported by the USGS during the previous 2 years. By early 2017, earthquake epicenters formed much more diffuse patterns and swarms developed in surrounding areas of Harper and Sumner counties (Figure 2b) where there is little, if any, fluid injection (Figure 2c). Seismic activity migrated increasingly to the north and northeast with time, spreading into surrounding counties (Figure 3). To visualize the spatial distribution of earthquakes as a function of time, the *standard distance* was calculated at 6 month intervals (Figure 3a). Standard distance is a statistical measure that can be used to quantify the degree to which earthquakes are dispersed (Mitchell, 2005). A circle with radius equal to the standard distance represents the area within which 95% of epicenters are located. From 2015 to 2017, the standard distance of earthquakes in south central Kansas increased from 38 km to 70 km, an average rate of 16 km/yr. Earthquakes advanced at a rate broadly consistent with the triggering front (Shapiro et al., 1997) predicted for fluid injection near the southern Kansas border (Text S2 and Figure S3). Many epicenters, most notably in Sumner County, propagated to the northeast along linear trends (Figure 3b). However, seismic activity advanced to the north as spatially sparse single earthquakes and brief swarms with no preferential alignment. By mid-2017, earthquakes migrated into Sedgwick and Reno counties as much as 90 km from the initial swarm locations. Seismic activity persists in Harper and Sumner counties, but at lower rates and different locations than observed in 2015.

4. Arbuckle Group Fluid Pressure

Modeling studies suggest that a pore pressure increase of as little as 0.01 to 0.2 MPa along a critically stressed fault may be sufficient to induce an earthquake (Hornbach et al., 2015; Keranen et al., 2014). Facilities in Kansas with active Class I wells are required to perform a formation pressure fall-off test and measure bottomhole fluid pressure annually. Bottomhole pressure measured in wells that terminate in the Arbuckle Group may provide insight into fluid pressure affecting basement faults. Absolute pressure varies significantly across the state due to natural variation in elevation and hydraulic head. Therefore, to facilitate

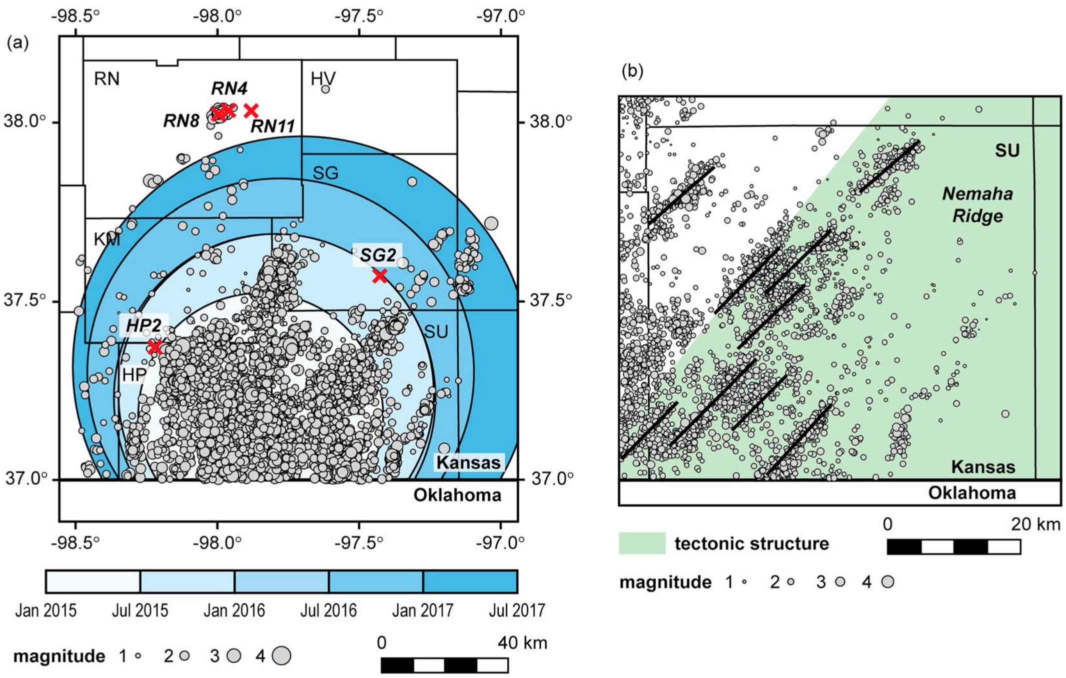

Figure 3. (a) Nearly 7,000 earthquakes were recorded by the KGS seismic network in Harper (HP), Sumner (SU), Sedgwick (SG), and Reno (RN) counties from January 2015 through June 2017. The shaded blue circles represent the standard distance calculated at 6 month intervals. The red crosses indicate locations of Class I wells with bottomhole pressure measurements. (b) Close up of earthquakes recorded in Sumner County (shown in Figure 3a) with interpreted earthquake lineaments (black lines) relative to the Nemaha Ridge (green).

comparisons between different wells, pressure was normalized relative to the baseline pressure in each well (measured in 2002, or first reported bottomhole pressure).

Initially, bottomhole pressures were relatively consistent with small annual fluctuations (~0.05 MPa) or gradational changes. Beginning in 2012, a large increase in bottomhole pressure was observed at a Class I facility in northwest Harper County (well HP2, Figure 3), with pressure rising more than 0.4 MPa by 2016 (Figure 4a). A negligible amount of fluid is disposed of at this facility. Likewise, Class II saltwater disposal wells within 20 km of this facility had been injecting at historically low rates (3,600 bbl/d or less, on average). It is therefore highly unlikely that local injection practices are responsible for the abrupt increase in formation pressure and associated seismic activity. Rather, the marked rise in fluid pressure strongly correlates with the dramatic increase in high-volume saltwater disposal 20 km or more to the south.

The nearest Class I well to the Harper County Class I facility is located in Sedgwick County near an area where seismic activity has recently advanced (well SG2, Figure 3). The bottomhole pressure trend measured at this well is very similar to the Harper County trend. A steady rise in pressure began in 2012 and increased about 0.3 MPa by 2016 (Figure 4b). Unlike the Harper County facility, there are several disposal wells within 2 km of this Sedgwick County facility, three of which inject at rates of about 10,000 bbl/d on average. However, it is critical to note that local injection rates in both Class I wells and Class II saltwater disposal wells within 20 km have been consistent for more than a decade and have even declined slightly in recent years.

Several Class I facilities are located within 10 km of the northernmost earthquake swarm in Reno County (Figure 3). The two facilities closest to these earthquakes inject at low rates, ranging from about 200 to 4,000 bbl/d. The facility 10 km to the east of the swarm has two wells injecting at rates of more than 20,000 bbl/d. Although the combined annual injection volume in both Class I wells and Class II saltwater disposal wells within 20 km of the earthquake swarm is a relatively large amount of fluid, injection rates in this area have been consistent for nearly a decade. Bottomhole pressures measured in a well at the Class I facility closest to the earthquake swarm (RN8) increased about 0.2 MPa in the last few years (Figure 4c). Despite vastly different disposal volumes, nearly identical bottomhole pressure trends were measured in wells at the two other Class I facilities (wells RN4 and RN11, Data Set S3). This strongly supports the suggestion that local injection is not the primary driver of rising fluid pressures in northern Reno County. Furthermore,

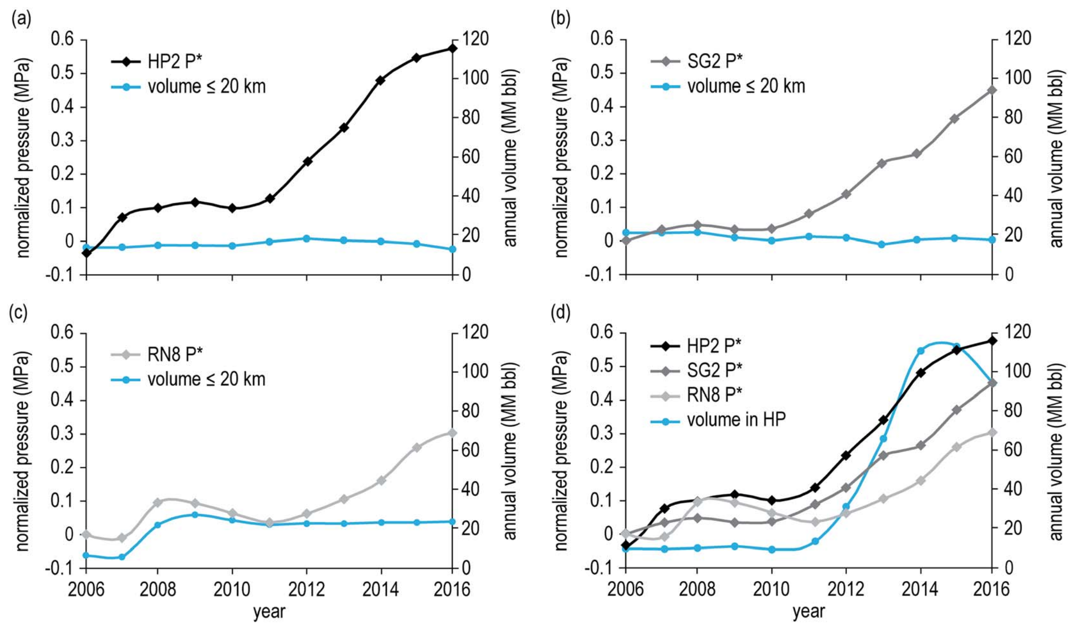

Figure 4. Normalized bottomhole pressure (P*) measured in Class I wells in (a) Harper County, (b) Sedgwick County, and (c) Reno County, and annual volume of fluid injected in wells located within 20 km (blue). (d) Normalized bottomhole pressures shown in Figures 4a–4c relative to the combined annual injection volume of disposal wells in Harper County (blue).

the progression of earthquakes toward these high-rate injection wells is counterintuitive to the expectation that the onset of induced earthquakes would occur in proximity to high-volume wells and seismicity would advance with pressure diffusion away from the causal wells.

5. Discussion

The observed rise in bottomhole pressures in Harper, Sedgwick, and Reno counties does not appear to correlate with local (less than 20 km) injection volumes. This is a crucial observation because currently the largest

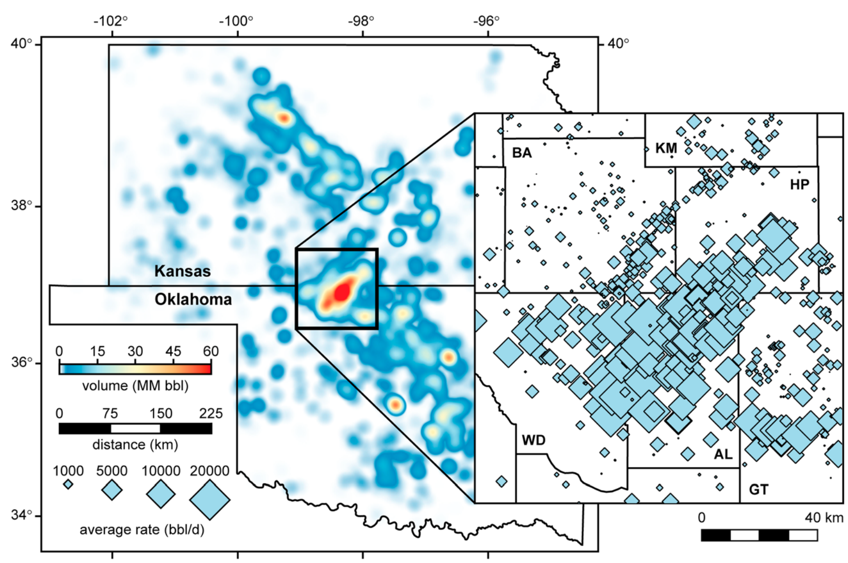

Figure 5. Map of combined injection volumes in Class II saltwater disposal wells and Class I wells in Kansas and Class II saltwater disposal wells in Oklahoma reported in 2015. The distribution is based on injection volume per square kilometer using the kernel density function with a 20 km search radius. Inset: wells near the Kansas-Oklahoma border (diamonds) sized relative to the average daily injection rate in 2015.

reported distance between the onset of an induced seismic swarm (and thus critically elevated pore fluid pressure) and the nearest causal well(s) is about 20 km (Keranen et al., 2014; King et al., 2014; Yeck et al., 2016). Elevated Arbuckle Group fluid pressure is most prominent to the south, diminishes to the north and northeast, and closely tracks the rise in saltwater disposal near the Kansas-Oklahoma border (Figure 4d). Combined with the gradual northward progression of earthquake swarms, this strongly suggests that high-volume saltwater disposal near the border contributed to inducing earthquakes as far as 90 km away.

Although our analysis focuses on earthquakes and fluid injection in Kansas, it should be noted that a spatially dense group of high-volume Class II saltwater disposal wells operates across an ~3500 km^2 area (about the size of two counties) that spans both sides of the Kansas-Oklahoma border (Figure 5). In 2015, 47 high-volume wells (with injection rates of 10,000 bbl/d or more) operated within this area and were separated by an average distance of only 4 km. The total volume of fluid injected in this area in 2015 is equivalent to over 100 wells operating at a rate of 10,000 bbl/d. Considering most published induced seismicity studies involved at most a few high-volume wells injecting at about this rate (Ake et al., 2005; Deichmann & Giardini, 2009; Healy et al., 1968; Hornbach et al., 2015; Horton, 2012), the volume of fluid injected near the southern Kansas border is unprecedented. Observing elevated pore pressure 90 km from the causal wells, while unexpected, should not be surprising given the extraordinary volume of injected fluid.

Earthquakes in southern Kansas progressed to the north and northeast away from the causal high-volume saltwater disposal wells with very different migration patterns and rates. In Sumner County, earthquakes followed a distinct northeastern progression along linear trends that are subparallel to the Nemaha Ridge (Figure 3b), a prominent post-Mississippian uplift structure (Jewett, 1951). The Nemaha Ridge has a history of natural earthquakes (Hildebrand et al., 1988), and therefore, some faults are suitably oriented for reactivation relative to the preexisting crustal stress field. The progression of earthquakes following northeast trends strongly suggests migration of fluid and pressure diffusion along fault zones associated with the Nemaha Ridge. Because critically stressed faults are often permeable (Townsend & Zoback, 2000), these faults may serve as preferential pathways for fluid flow. To the north, earthquakes progressed through Kingman and Reno counties as either brief clusters or single earthquakes with as much as 10 km aseismic gaps between sparse events. No earthquakes larger than the respective detection thresholds of regional networks operating in and around Kansas (about *M* 2 to *M* 3 or larger) were recorded in these counties during nearly 40 years of monitoring (NEIC, 2017; Steeples et al., 1987, 1990). Therefore, faults in this area were likely not in a state of critical stress and, thus, had a higher threshold for earthquake triggering. The northernmost earthquake swarm (the most active in Reno County, with 19 *M* 2 or larger earthquakes) is located within 10 km of historically consistent high-volume injection operations. Although pore pressure increases from local fluid injection alone were not sufficient to induce a recorded earthquake prior to 2016, effective stress is locally reduced and the critical threshold for earthquake triggering is likely lower than surrounding areas. The directional disparity in earthquake migration patterns highlights the role of the preexisting stress field in earthquake triggering, in terms of both crustal stress and effective stress.

6. Conclusions

In the years following the onset of high-volume saltwater disposal near the Kansas-Oklahoma border, earthquakes migrated from initial swarm locations near high-volume wells to as far as 90 km away. Seismic activity progressed to the northeast away from the southern Kansas border along trends consistent with prominent regional basement structures, suggesting fluid migration and pressure diffusion along permeable fault zones away from high-volume injection areas. A disparity in earthquake migration patterns suggests largely aseismic pressure diffusion to the north, except where faults are suitably oriented for reactivation relative to the preexisting crustal stress field or where effective stress is locally reduced from nearby fluid injection. Bottomhole pressure measurements in wells that terminate in the Arbuckle Group reveal a pattern of regionally elevated fluid pressure that is most prominent to the south and diminishes to the north and northeast. Changes in fluid pressure do not correlate with local injection volumes, but rather appear to be in response to high-volume saltwater disposal near and south of the Kansas-Oklahoma border. The combination of regionally elevated fluid pressure, gradual northward progression of earthquakes away from the initial dense swarm locations, and lack of commensurate changes in local injection volumes strongly suggests that the observed pressure increases are predominantly influenced by increases in high-volume injection to the south. Pressure diffusion as far as 90 km from the causal high-volume wells is likely the primary contributor to rising fluid pressures that have induced earthquakes in surrounding areas where the effective stress is locally reduced from nearby historically consistent injection operations.

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