The 2013–2016 Induced Earthquakes in Harper and Sumner Counties, Southern Kansas

by Justin L. Rubinstein, William L. Ellsworth, and Sara L. Dougherty

Abstract We examine the first four years (2013–2016) of the ongoing seismicity in southern Kansas using high-precision locations derived from a local seismometer network. The earthquakes occur almost exclusively in the shallow crystalline basement, below the wastewater injection horizon of the Arbuckle Group at the base of the sedimentary section. Multiple lines of evidence lead us to conclude that disposal of wastewater from the production of oil and gas by deep injection is the probable cause for the surge of seismicity that began in 2013. First, the seismicity correlates in space and time with the injection. We observe increases in seismicity subsequent to increases in injection and decreases in seismicity in response to decreases in injection. Second, the earthquake-rate change is statistically improbable to be of natural origin. From 1974 through the time of the injection increase in 2012, no $M_L$ 4 or larger earthquakes occurred in the study area, while six occurred between 2012 and 2016. The probability of this rate change occurring randomly is $\sim 0.16\%$. Third, the other potential industrial drivers of seismicity (hydraulic fracturing and oil production) do not correlate in space or time with seismicity. Local geological conditions are important in determining whether injection operations will induce seismicity, as shown by absence of seismicity near the largest injection operations in the southwest portion of our study area. In addition to local operations, the presence of seismicity 10+ km from large injection wells indicates that regional injection operations also need to be considered to understand the effects of injection on seismicity.

Electronic Supplement: Tables of seismic stations used, and earthquake catalogs and figures showing oil and gas operational histories and their relationship to seismicity.

Introduction

Beginning in 2009, the central United States experienced an unprecedented surge in seismicity (Ellsworth, 2013; Ellsworth et al., 2015). This surge included earthquakes in New Mexico and Colorado (Barnhart et al., 2014; Rubinstein et al., 2014), Texas (Frohlich et al., 2016), Arkansas (Horton, 2012), Ohio (Skoumal et al., 2015), Kansas (Buchanan, 2015; Nolte et al., 2017b; Trugman et al., 2017), and Oklahoma (Walsh and Zoback, 2015). The vast majority of this increase, including the two largest earthquakes ($M$ 5.8 Pawnee earthquake, Yeck et al., 2017, and $M$ 5.7 Prague earthquake, Keranen et al., 2013), occurred in Oklahoma. This increase in seismicity is believed to be caused by the rapid development of unconventional oil and gas fields in the central United States and the associated deep underground injection of fluids (Ellsworth, 2013; Rubinstein and Mahani, 2015). Fluid injection into basinal aquifers, or directly into the crystalline basement, can increase fluid pressures and reduce the frictional resistance to failure on well-oriented faults (Hubbert and Rubey, 1959; Healy et al., 1968), which is believed to be the primary mechanism for causing the dramatic increase in seismicity. Given that damaging earthquakes are occurring as part of the increased seismicity, for example, the 2016 Pawnee earthquake (Yeck et al., 2017), the 2011 $M$ 5.3 Trinidad earthquake (Rubinstein et al., 2014), and the 2016 $M$ 5.0 Cushing earthquake (Taylor et al., 2017), there is a need to understand the probability of future earthquakes and their potential impact. To this end, the U.S. Geological Survey (USGS) has begun to develop methods to estimate earthquake hazard from induced earthquakes (Petersen et al., 2015) and has released 1-yr hazard forecasts for both 2016 and 2017 (Petersen et al., 2016a,b, 2017).

The seismicity in Kansas, during our study duration of 2013–2016, represents the second highest statewide
earthquake rate in the central United States. Between January 2013 and December 2016, 127 $M_{3+}$ earthquakes occurred in Kansas. This accounts for $\sim 5\%$ of the seismicity in the central United States and $\sim 40\%$ of the central U.S. seismicity outside of Oklahoma. In this article, we explore the seismicity in southern Kansas and its relationship to oil and gas operations. Using a local seismographic network deployed by the USGS in March 2014 that spans 40 km north–south and 55 km east–west with up to 16 stations, we are able to observe the seismicity with more clarity and down to smaller magnitudes than in other regions experiencing similar earthquake-rate increases. With this network, we examine basic statistical properties of the recorded earthquakes, as well as the spatiotemporal evolution of the seismicity. Comparing locations and timing of seismicity relative to different oil and gas operations indicates that wastewater disposal is the cause of the seismicity in the region, and hydraulic fracturing operations and oil/gas production are not. We also explore the relationship between the seismicity and effects of economics and regulation on wastewater disposal volumes.

Geologic Setting

Kansas is located on an extension of the stable continental craton (Merriam, 1963) and has been since Precambrian times. Deformation rates are very low, and the thickness of the sedimentary cover over the Precambrian basement ranges from 120 to 1900 m (Merriam, 1963). There are two dominant geological structures in Kansas, the Nemaha Ridge/Humboldt fault system and the central Kansas uplift (Fig. 1). The central Kansas uplift (not shown) is $\sim 100$ km east–west, and runs northwest along the eastern border of the Mississippi Limestone Play, with its southern terminus near 38° N. The color version of this figure is available only in the electronic edition.
Our study area is located in a geologic province known as the Sedgwick basin (Schoewe, 1949). The Sedgwick basin is bounded by the Nemaha anticline on the east, the Pratt anticline on the west, and there is a saddle between it and the Salina basin to the north. Surface rocks are sedimentary and are of Permian age and younger (Bayne, 1960; Walters, 1961).

There are three key strata for this study: the Mississippian Formation (the source rock for the petroleum and produced water), the Arbuckle Group at the base of the sedimentary section (the group into which wastewater is injected), and the Precambrian basement (the metamorphic and igneous rocks in which earthquakes are occurring).

Within our study area, reported depths of production wells in the Mississippian range between depths of 1350 and 1650 m. The production zone of the Mississippian is typically ∼15 m thick (Evans and Newell, 2013). The Maquoketa Shale, the Viola Group, and the Simpson Group lie between the Mississippian and Arbuckle Group, separating them by ∼100 m (Merriam, 1963; Carr et al., 1986). They are thought to serve as a seal that prevents the upward flow of fluid injected into the Arbuckle.

The injection zone in the Arbuckle Group ranges between 300 and 350 m thick and lies unconformably on the Precambrian basement, where the earthquakes are occurring (Carr et al., 1986).

The Arbuckle-basement contact is at ∼1700 m below land surface. Multiple lines of evidence suggest that there is hydraulic communication across this boundary, including the production of oil from fractured Precambrian rock on the central Kansas uplift (Walters, 1953), an extensive joint system that connects the Arbuckle to the basement (Walters, 1958), the observation of multiple faults that cross from the Arbuckle into the basement in central Sumner County (Schwab, 2016; Schwab et al., 2017), and the occurrence of seismicity in the basement that is believed to be induced by increased fluid pressure there due to injection in the Arbuckle in Oklahoma (e.g., Keranen et al., 2014). The basement rocks of Kansas are primarily composed of igneous and metamorphic rocks: granite, schist, and quartzite (Merriam, 1963).

Statewide Seismicity in Kansas (1867–Present)

The focus of this article is on the seismicity in southern Kansas, specifically the region of intense hydrocarbon development of the Mississippi Limestone Play within Harper and Sumner counties (Fig. 1). To put the seismicity in that region in context, we discuss seismicity across the entire state. In the Southern Kansas Seismicity section, details on the seismicity in that specific region will be discussed.

Historical Seismicity in Kansas (1867–1972)

A history of earthquakes in Kansas going back to 1867 was originally compiled by Merriam (1956) and has since been updated by DuBois and Wilson (1978). Merriam (1956) noted that the first earthquakes historically felt in Kansas did not actually occur in the state but were the 1811 and 1812 New Madrid, Missouri, earthquakes.

From 1867 to 1972, a total of 28 felt earthquakes in Kansas were identified by DuBois and Wilson (1978), with an additional two earthquakes in 1871 and 1879 identified in Steeples et al. (1990) (Fig. 1). Docekal (1970) documented many of these same earthquakes and an additional 11 events. Nine of these were aftershocks of the 7 January 1906 earthquake. Several of the earthquakes documented above lie on or near the Nemaha ridge in the vicinity of Manhattan, Kansas (Steeples et al., 1979). The two largest historical earthquakes to have occurred in Kansas were the 1867 and 1906 earthquakes near Manhattan, Kansas. Maximum modified Mercalli intensities (MMI) of VII–VIII and VII were reported for these earthquakes, respectively. A magnitude of 5.1 has been assigned to the 1867 earthquake, based on felt reports (Stover and Coffman, 1993), and there is evidence that there have been multiple prehistorical M>5 earthquakes in the vicinity of Manhattan (Niemi et al., 2004). In the years 1867–1972, an additional three earthquakes in Kansas caused MMI VI shaking.

Instrumentally Located Seismicity (1973–2012)

In the 40 yrs between 1973 and 2012, the USGS Advanced National Seismic System (ANSS) Comprehensive Catalog (ComCat) identified 29 earthquakes in Kansas, 15 of which were magnitude 3 or larger. We estimate magnitude of completeness during this time period using a catalog that contains the whole of Kansas and Nebraska, eastern Colorado, and parts of southwestern Iowa and northwestern Arkansas. We find M_c to be 3.4, using the maximum curvature method (Wiemer and Wyss, 2000), with an upward adjustment of 0.2 magnitude units because the method has been shown to underestimate M_c by this amount (Woessner and Wiemer, 2005). We note that the M_c in Colorado was estimated to be between 3.5 and 3.8 in approximately the same time period with similar station density and more earthquakes (Rubinstein et al., 2014), making the estimate of M_c in Colorado more reliable. Hence, it is possible that the M_c in Kansas is higher than 3.4.

The largest group of seismicity reported in ComCat is located in northwest-central Kansas (19 of 30 earthquakes) near Palco (Fig. 1). With the exception of three earthquakes that occurred over a period of 10 yrs in a cluster south of the Kansas–Nebraska border, the rest of the seismicity during this time period is scattered around the state.

It is notable that a significant percentage of the instrumentally located seismicity in Kansas identified in ComCat is suspected of being induced. The seismicity near Palco from 1986 to 1992 (12 of the 19 earthquakes that occurred near Palco) have been interpreted to be induced by saltwater disposal (Armbruster et al., 1989; J. Armbruster, personal comm., 2016). This includes the two largest earthquakes to occur during the time period (M 3.8 and 4.0 in 1989). Little research has been done on the seven earthquakes in the area since 1993, so we cannot draw any con-
Since late 2013, the earthquake rate in Kansas has dramatically risen. From the start of 2013 through the end of 2016, 127 $M \geq 3$ earthquakes occurred in Kansas. Seven of these earthquakes occurred outside southern Kansas, and of the remaining 120 earthquakes, 115 lie in the adjoining Harper and Sumner counties of south-central Kansas (Fig. 1). Examining a catalog developed by the Kansas Geological Survey (Miller et al., 2016; Peterie et al., 2016), seismicity can be found in a few more regions, but the vast majority of seismicity still lies in Harper and Sumner counties. The seismicity outside Harper and Sumner counties has not been carefully studied, so no conclusions on the relationship between hydrocarbon activities and this seismicity can be drawn. In this article, we detail the case for the 115 $M \geq 3$+ earthquakes in Harper and Sumner counties being induced, which leaves 12 $M \geq 3$+ earthquakes outside of Harper and Sumner counties that could be natural. This would represent an increase in the seismicity rate relative to the earlier catalog but not a statistically improbable one. More detail on the seismicity in Harper and Sumner counties is provided in the Southern Kansas Seismicity section.

Data and Data Processing

In response to the increased seismicity in southern Kansas, the USGS deployed the Southern Kansas Seismic Network beginning in mid-March 2014. The network initially consisted of five “NetQuake” accelerometer stations. The footprint of the first iteration of the network was ~20 km on a side. The network has since been expanded. In its current configuration, 15 stations all have accelerometers, and 13 have co-located broadband sensors as well. The network stretches ~40 km north–south and 55 km east–west (Fig. 2). Waveform data from the USGS seismic network are available from Incorporated Research Institutions for Seismology under the network codes GS and NQ.

In addition to the USGS stations, we use data from other nearby seismic networks, including the Oklahoma Geological Survey network and the central and eastern United States Network. Names and locations of all stations used in this study are listed in Table S1 (available in the electronic supplement to this article).

With this set of stations, we manually analyzed 6845 earthquakes between 21 March 2014 and 31 December 2016. This represents all the events with automatic magnitudes of 1.8 and higher that had automatic locations within the study-area boundaries. It also includes some events outside the study area and/or with automatic magnitudes smaller than 1.8.

Recent Seismicity (2013–Present)

Since late 2013, the earthquake rate in Kansas has dramatically risen. From the start of 2013 through the end of 2013, the earthquake rate in Kansas has dramatically risen. From the start of 2013 through the end of
than 1.8. The seismograms are processed using the ANSS Quake Monitoring System, with local magnitudes and locations computed with HYPOINVERSE (Klein, 2002).

All of the processing uses a 1D velocity model, with station corrections that were determined from 453 earthquakes that occurred between November 2014 and February 2015 using VELEST (Kissling et al., 1994) (© Fig. S1). The starting model was based on a combination of the velocity model used by the Oklahoma Geological Survey for Oklahoma (A. Holland, personal comm., 2014) and velocity logs from three boreholes in the area.

Solutions for earthquakes that were manually reviewed and within the study area that meet quality and magnitude criteria ($M \geq 1.5$, closest station within 20 km, maximum root mean square (rms) residual 0.1, maximum magnitude residual of 0.3, a minimum of eight phases used in computing location, a minimum of four stations used in computing magnitude) are submitted to the National Earthquake Information Center via PDL and are included as part of ComCat and the PDE (Preliminary Determination of Epicenters). Smaller earthquakes that meet these criteria are used in some of the analysis in this work.

Using the same procedure described above for the state of Kansas, we compute the magnitude of completeness in our study area. For the time period July 2014–December 2016, we compute an $M_c$ of 1.9. We chose this time period because the network was largely complete in July 2014. For the seismicity in the study area prior to this, the magnitude of completeness should be considered to be 3.4, the value computed for the statewide magnitude of completeness.

To enhance the earthquake locations, we apply the GrowClust earthquake relocation algorithm (Trugman and Shearer, 2017), which refines the locations of the seismicity and provides location uncertainties. This program uses a hybrid hierarchical clustering and relocation algorithm to provide stable relocation results for large-scale catalogs with multiple discrete clusters. It takes differential travel times and cross-correlation values for sets of event pairs observed at common stations as its fundamental input. We identify event pairs by selecting a maximum of 500 neighboring events located within 4 km distance of a particular earthquake, with recordings at a minimum of eight common stations. This produces 541,577 event pairs for 5093 earthquakes that meet the criteria. We perform time-domain wave cross correlation of these event pairs for a 0.8 s window around the relevant catalog phase pick ($\pm 0.4$ s for $P$ wave and $\pm 0.2/0.6$ s for $S$ wave), with the waveform data low-pass filtered at 15 Hz. We use only those event pairs with a minimum of eight differential times with cross-correlation values greater than or equal to 0.70 as input for the GrowClust algorithm. This input consists of 90,514 event pairs with 901,139 differential times/cross-correlation values. A maximum station distance of 80 km and a maximum rms differential time residual for a proposed cluster merger to be allowed of 0.2 s are selected for GrowClust parameterization. With the described input and parameter selections, GrowClust successfully relocates 4187 events with 1σ horizontal and vertical location uncertainties of 200 and 420 m, respectively. The median depth for this relocated seismicity is 5.03 km, with 74% of earthquakes located between 3.5 and 6.5 km depth. Unless otherwise indicated, the full earthquake catalog (relocated combined with events not relocated) is being analyzed.

Southern Kansas Seismicity

We focus our study on earthquakes lying within the box bounded by 37° N, 37.35° N, 98.1° W, and 97.45° W. We have chosen this region because it is where the largest increase in seismicity has been observed, and this is the region in which the USGS temporary seismic network offers the best coverage of earthquakes. A total of 3871 earthquakes from the relocated catalog fall within this region. Although we are concerned with the seismicity in this region as a whole, we examine the seismicity as subdivided into five zones (zones 1–5) (Fig. 2) and as the seismicity outside of these zones within the box. These zones were originally defined by the Kansas Corporation Commission (KCC) as “areas of seismic concern,” to which injection rules were applied (KCC, 2015) beginning in March 2015. These zones were selected to encompass a high percentage of the seismicity that occurred in this area.

Seismicity Prior to 2013

The background earthquake rate in our study area was very low prior to 2013. Prior to 1973, we are unaware of any evidence for earthquakes in the study area (Steeples et al., 1990), and there is evidence of only one earthquake in the area from 1973 to 2012. This $M_D$ 2.0 earthquake occurred on 31 December 1986 in the southwest portion of our study area (Fig. 2), during a period of enhanced detection capability from 1977 to 1989 when the University of Kansas operated a denser network (Steeples et al., 1987, 1990).

Seismicity 2013–2016

Starting in late 2013, the earthquake rate increased in our study area (Fig. 3). Of particular note are six $M_L$ 4+ earthquakes: $M_L$ 4.6 (4.3) October 2014 in zone 1, $M_L$ 5.2 (M 4.9) November 2014 in zone 5, $M_L$ 4.2 November 2014 in zone 2, $M_L$ 4.0 April 2015 in zone 3, $M_L$ 4.1 (M 4.1) June 2015 in zone 1, and $M_L$ 4.1 November 2015 in zone 4. There have also been 121 $M$ 3+ earthquakes in this same region since 2013. The 12 November 2014 $M$ 4.9 Milan earthquake is discussed at greater length in Choy et al. (2016).

Spatial Distribution of the Seismicity. Most of the seismicity in the study area takes place within zones 1–5. Of the 1073 $M$ 2+ earthquakes that occurred from July 2014 to December 2016, 879 (82%) were located within one of the defined earthquake zones. Similarly, 86 (92%) of the 93 $M$ 3 and larger earthquakes in the study area occurred within the earthquake zones. We find that 95% of the moment release

J. L. Rubinstein, W. L. Ellsworth, and S. L. Dougherty
Given that the largest magnitude earthquake observed outside these zones was $M_{L} 3.5$, it is reasonable to surmise that all of the seismicity lies in the basement ($\sigma$ depth uncertainties of 420 m). Much of the seismicity defines short (2–3 km) fault structures that trend west-northwest or east-northeast (Fig. 2). In some cases, we can identify multiple en echelon short faults (e.g., in the southern portion of zone 2). Some short fault segments in the southeast portion of zone 3 may form a continuous structure, but gaps in the seismicity prevent us from making this conclusion with certainty. The longest continuous structure that we can identify with the seismicity begins in the vicinity of the Arbuckle fault at 1.7 km depth, and 90% lies between 2.4 and 7.3 km depth.

Depth Distribution of Earthquakes. Seismicity in our study area occurs primarily in the crystalline basement. Less than 2% of the seismicity in the relocated earthquake catalog lies above our interpreted basement–Arbuckle boundary at 1.7 km depth, and 90% lies between 2.4 and 7.3 km depth. Given 1σ depth uncertainties of 420 m, it is reasonable to surmise that all of the seismicity lies in the basement (Fig. S2). Schoenball and Ellsworth (2017) reached the same conclusion in their study of southern Kansas seismicity.

Faults Revealed by Planar Distributions of Seismicity. The relocated earthquake catalog shows many fault structures. Most of these faults strike to the north-northeast. It also hosted the M 4.9 Milan earthquake, which was a strike-slip event. Slightly more than half of the earthquakes in the study area have strike-slip focal mechanisms, although there is some variability, with some regions more dominated by normal-faulting mechanisms (Fig. 4). The difference in faulting styles may be explained by variability in fault structure.

Although much of the seismicity is occurring on what appear to be planar faults, a significant percentage of the seismicity appears in clusters that have no clear structure in map view (e.g., the northern parts of zones 1 and 2). Schoenball and Ellsworth (2017) also relocated southern Kansas seismicity and found that some of these clusters are composed of orthogonal normal faults that appear diffuse in map view.

Temporal Variability in Earthquake Rates. The first earthquakes that were documented in our study region occurred in 2013, two in September ($mB_{Lg} 2.4$ and 2.9) and a third in December ($M_{L} 3.8$). All of these earthquakes occurred in zone 3. The next earthquakes in the catalog were reported in February 2014, when three $M_{L} 3$ occurred, followed by four $M_{L} 3$ in March 2014 (Fig. 3b). During this period, the seismicity began to spread beyond zone 3, and by the time of the next $M_{L} 3+$ earthquake in July 2014, seismicity spread throughout much of the study region.

At least one $M_{L} 3+$ earthquake occurred in the study area each month for the next 16 months (through November 2015). Since October 2015, $M_{L} 3$ events have been intermittent. The rate of $M_{L} 2+$ earthquakes remained high until it significantly dropped in January 2016 and remained lower than the particularly elevated period of September 2014–December 2015 (Fig. 3b).

The earthquake rates both inside and outside of the earthquake zones follow the same general behavior, with an increase in early 2014, a peak in earthquake rates in early-to-mid 2015, and a decline at the end of 2015 (Fig. 3c). When there are spikes in earthquake rates in individual zones, they are commonly, but not always, associated with larger earthquakes (e.g., the M 4.9 Milan event that occurred on 12 November 2014 in zone 5).

The seismicity in the zones was highest during the initial stages of our study period. From January 2014 through July 2015, 94% of the 812 total $M_{L} 2+$ earthquakes in the study area occurred in these zones. The seismicity rate in these zones declined significantly, beginning in August 2015. From August 2015 through the end of 2016, only 57% of the

---

**Figure 3.** (a) Count of Southern Kansas Seismic Network stations operational through time. (b) Monthly earthquake rates in study area from ANSS ComCat (January 2013–22 March 2014) and this study (23 March 2014–December 2016). Earthquake catalogs may be incomplete below $M_{L} 3.4$ prior to July 2014. Catalog (July 2014–December 2016) is complete at $M_{L} 1.9$. (c) Cumulative earthquake counts by earthquake zones and seismicity outside of these zones within the study area. The color version of this figure is available only in the electronic edition.
352 M 2+ earthquakes in the study area occurred in the designated zones (Fig. 5).

With the exception of the period of August 2015–November 2015, seismicity in the areas outside the zones appears to remain relatively constant, with a median earthquake rate of six M 2+ earthquakes per month from December 2015 to December 2016. The spike in seismicity outside the zones from August 2015 to November 2015 had earthquake rates ranging from 17 to 26 M 2+ earthquakes per month, for a total of 79 earthquakes. Most of this surge comes from two swarms of seismicity in the southeast portion of the study area. These swarms had 43 and 9 earthquakes from August to November 2015 and 7 and 2, respectively, outside these time periods.

Focal Mechanisms and Stress. For the 3871 earthquakes in our relocated catalog that are in the study area, we use the HASH algorithm (Hardebeck and Shearer, 2002) to compute focal mechanisms. Input comes from manually picked P-wave polarities and takeoff angles determined from TauP (Crotwell et al., 1999), given the velocity model shown in Figure S1. We require a minimum of eight picks and a maximum azimuthal gap of 90°. Of the earthquakes that fit these criteria, 150 earthquakes have a HASH focal-mechanism quality of A or B. Of the A and B quality mechanisms, 59% of the earthquakes have predominantly strike-slip mechanisms, 31% predominantly normal, and 9% predominantly reverse mechanisms, according to the criteria set out by Kagan (2005) (Fig. 4a). The nodal planes for the mechanisms are largely consistent with the structures delineated by the relocated seismicity (Fig. 4b).

From the A and B quality focal mechanisms, we compute the local stress field using MSATSI (Martínez-Garzón et al., 2014), which iteratively inverts for the stress field based on SATSI (Hardebeck and Michael, 2006) and other techniques (Lund and Townend, 2007; Vavrycuk, 2014). The preferred stress field has σ2 as near-vertical (dip 79°), and σ1 and σ3 are near-horizontal, striking at ∼N74°E and S16°E, respectively. The best-fitting R-value is 0.34, which indicates a significant preference for strike-slip faulting and that σ1 is significantly larger than σ2. The mean misfit angle is ∼35°, so, given a focal mechanism uncertainty of ∼44°, we are unable to document possible heterogeneity in the stress field (Michael, 1991). Other authors inverted for the stress field in southern Kansas using drilling-induced tensile fractures (Schwab et al., 2017) and focal mechanisms (Alt and Zoback, 2017; Schwab et al., 2017) and found similar orientations of SHmax. Schwab et al. (2017) infer

---

**Figure 4.** (a) Ternary diagram of T and B axis plunges determined from focal mechanisms (Frohlich, 1992) for 150 earthquakes for which high-quality solutions could be computed. Diagram was generated with FMC (Álvarez-Gómez, 2014) using criteria set forth by Kagan (2005). (b) Map of earthquake locations from the relocated catalog developed by this study (dots) and focal mechanisms for the 150 earthquakes that had high-quality mechanisms. Note that many focal mechanisms overlie each other. Large focal mechanisms are shown for M 4+ earthquakes for which USGS moment tensors are available. From west to east, these are 2 October 2014 ML 4.6 (M 4.3), 5 June 2015 ML 4.1 (M 4.1), and 12 November 2014 ML 5.3 (M 4.9) earthquakes. The orientation of the regional stress field is shown with arrows. The color version of this figure is available only in the electronic edition.
a strike-slip dominated system, but Alt and Zoback (2017) infer a normal-faulting regime. The Alt and Zoback (2017) stress estimate was derived from a limited number of focal mechanisms, which may explain the difference in our assessments of the stress field.

We also search for temporal and spatial variability in the stress field. We examine the stress field as determined by the seismicity in the individual years 2014, 2015, and 2016 and find no statistically significant variability in stress orientations. Similarly, we find no significant variability when examining three periods of seismicity containing 50 earthquakes each. We also find no statistically significant variation in the stress field when comparing the two regions of our study area with the largest seismicity rates (in the northwest and in the southwest; Fig. 4b).

Magnitude–Frequency Statistics. Using a conservative estimate of magnitude of completeness of $M_L = 2$ and a catalog starting in July 2014, we use the Tinti and Mulargia (1987) formulation for computing $b$-value. We note that, although this method is appropriate for small data sets like the one we are analyzing, it underestimates the uncertainty (Marzocchi and Sandri, 2003). The entire region has a $b$-value of 1.06, with an uncertainty of 0.03 using 1073 earthquakes of $M \geq 2$, i.e., relatively indistinguishable from 1. Examining the $b$-value with time, we determine that quarterly $b$-values in 2014 and 2015 ranged between 0.92 and 0.98. Hence, with uncertainty they are indistinguishable (Fig. 6a). The earthquake rate in 2016 was too low to compute reliable quarterly estimates of $b$-value, so we compute it over the entire year. We find a $b$-value of 1.26 in 2016, which is statistically distinct from the other time periods.

It is likely that the temporal variability in the $b$-value results from spatial variability in the $b$-value coupled with spatially varying earthquake rates. Examining the seismicity zone-by-zone, we find that the $b$-values are all within 1 standard deviation of 0.93, with the exception of zone 4, which has a $b$-value of 0.76 (Fig. 6b). Outside of the zones, $b$ is 1.23. Throughout the study period, the $b$ outside of the zones is well above 1. Given that the percentage of the seismicity outside of the zones in the latter half of 2015 and 2016 increases (Fig. 5), this switch is the probable source of the temporal variability in the $b$-value. The $b$-value outside of the zones is likely higher than it is within the earthquake zones because its $M_{\text{max}} (3.5)$ is lower than in the zones, all of which have $M_{\text{max}} \geq 4.0$. That said, the slope of the Gutenberg–Richter distribution is notably steeper between $M = 0$ and 3.
for the seismicity outside the zones relative to that within the
zones (Fig. 6b), implying a higher $b$-value. The findings that
the $b$-value is the lowest inside the earthquake zones, which
are also roughly the areas of highest injection, are in contrast
to the findings of Bachmann et al. (2012), who observe a
decrease in $b$ both with increasing time since the start of
injection and increasing distance from the injection point.

Industrial Activity

Oil and gas operations began in 1915 in Sumner County
(Walters, 1961) and in 1950 in Harper County (Bayne,
1960). By the late 1950s, over 1 million barrels of oil and 1
billion cubic feet of natural gas were being produced annu-
ally in both Harper and Sumner counties (see Fig. S3). Produc-
tion of both oil and gas was primarily from the Missis-
sippi Limestone, although there was also production in the
Kansas City and Viola Formations (Bayne, 1960; Walters,
1961). Oil production declined steeply in the late
1960s and continued to slowly decline in both counties
through 2010. Gas production in Harper and Sumner
counties remained relatively constant between the late 1950s
and 2011. Beginning in 2011, oil and gas production began
to increase in Harper County, continually increasing through
2015, while remaining steady in Sumner. The increase in
production corresponds to renewed interest in the Missis-
sippi Limestone Play, due to the improved extraction capa-
bilities afforded by extended-reach horizontal drilling and
the rising price of oil (Evans and Newell, 2013). This rise
was followed by a decrease in oil and gas production in
2016 subsequent to the drop in prices at the end of 2014.

The Mississippi Limestone yields copious volumes of
formation water along with petroleum. This produced water
is typically disposed by injection into saltwater disposal wells.
Wastewater disposal in the study area is typically into the Ar-
buckle Group, a laterally extensive aquifer covering most
of the state, primarily composed of dolomite (Carr et al.,
1986). The Arbuckle lies directly on the Precambrian basement.
Basement tectonics and regional uplift events likely created
fractures and faults that increased permeability of the Ar-
buckle Formation. Studies of 3D seismic data from the nearby
Wellington field show multiple faults that extend from the Ar-
buckle Group into the basement (Schwab et al., 2017).

Wastewater Disposal

In this study, we examine wastewater disposal within
0.1° of the seismic study region. We choose this distance
range because most injection-induced earthquake sequences
occur within several kilometers of injection operations
(National Research Council, 2013; Rubinstein and Mahani,
2015). We have compiled monthly injection volumes for the
years 2012–2016 and have annual injection volumes for the
years 1995–2011 (data sources discussed in Data and
Resources). From 1995 to 2011, annual injection rates were
low, ranging between 10 and 20 million barrels injected per
year across the entire study area (Fig. S4). Injection began
to increase in the study area in 2012, doubling to over 36
million barrels per year in 2012 and reaching a high of over
100 million barrels in 2014 (Fig. 7). Carefully examining in-
jection data starting in 2012 gives us 20 months of injection
data prior to seismicity commencing. We also limit our
analysis from 2012 onward to wells that injected at least
50,000 barrels in one or more month(s) during 2012–2016
because increased injection rate has been linked to an in-
creased probability of inducing earthquakes (e.g., Frohlich,
2012; Weingarten et al., 2015). Wells that injected at least
50,000 barrels in one month represent 85%–90% of the
annually injected volumes from 2012 to 2016.

Injection principally occurs in the southwestern portion
of the study area (Fig. 8). This area is home to all of the
highest total volume wells and wells with the highest

---

**Figure 7.** Earthquake rate per month in study area, injected vol-
ume for all wells within 0.1° of study area, and total injected volume
for wells within KCC specified zones for January 2012–December
2016. The color version of this figure is available only in the elec-
tronic edition.

**Figure 8.** Total injected volume and seismicity from relocated
earthquake catalog only. Only earthquakes located within study area
(long dashed line) are shown (dots). Injection volumes within short
shorted rectangle are complete; volumes outside this area may be in-
complete. Total injection volumes are computed in bins that are
0.05° × 0.05° (~5.6 km north–south, 4.4 km east–west). The color
version of this figure is available only in the electronic edition.
monthly rates. The first high-rate injection wells in the study area were also located here (Fig. 9).

Throughout the study area, injection appears to have increased steadily until the end of 2014, when significant decreases in injection were observed (Fig. 7). The drop in injection corresponds with the price of oil, which dropped from ~$100 per barrel in August 2014 to ~$50 per barrel in January 2015. The location of the decreases in injection correlates with the five zones that fell under rules from the KCC mandating reduced injection, which started to be phased-in in 29 March 2015 (KCC, 2015) (Fig. 9). Some wells just outside these zones saw corresponding increases in injection, but this is at least partially due to changes in production operations in the field (R. Hoffman, personal comm., 2017).

Injection was at its highest in the five zones from July 2014 to December 2014, averaging 5 million barrels/month. Injection began declining in January 2015, dropping to 3.8 million barrels/month in March 2015 (Fig. 7). Since the full force of the rules went into place in July 2015, injection in the five zones has dropped by ~50%, ranging between 1.8 and 2.7 million barrels/month from July 2015 to December 2016. It is probable that the injection decrease was a combination of both economic and regulatory forces because the injection decline began before the rules took effect, and the injection decreases correlate in space with the region affected by the rules.

An additional set of rules issued by the KCC in August 2016 required reduced injection across a much broader part of southern Kansas (KCC, 2016). We have not identified any change in injection by the end of 2016.

**Relationship between Industrial Activities and Seismicity**

As noted above, nearly all of the seismicity occurs within the crystalline basement. This implies that perturbations to fault stability imparted by any anthropogenic source are transferred from the formation in which the human activity is occurring (Mississippian if production or hydraulic fracturing, Arbuckle if saltwater disposal) to the crystalline basement. In the case of fluid-pressure-induced stress changes, this would require fluid pathways through which the fluid pressure could travel. Using downhole pore-pressure measurements and time-dependent seismic anisotropy observations, Nolte et al., (2017b) demonstrated that there was a significant increase in pore pressures in the Arbuckle in the study area and in the Wellington field.

**Production and Earthquakes**

Production of oil and gas does not appear to be directly causing seismicity in the study area. Examining the produc-

---

**Figure 9.** Panels showing total injected volume and relocated seismicity plotted by six-month period. Seismicity is overlain on preceding six months of injection. Symbols and lines are as in Figure 8. The color version of this figure is available only in the electronic edition.
tion data available from the KCC, we find that oil and gas production remained fairly steady from 1995 through 2011, at which point it began to increase, more than doubling by 2013. This change in production precedes the increase in seismicity by 2 yrs, suggesting that production is not directly related to the earthquakes (see Fig. S5). Additionally, we find a spatial anticorrelation between the locations of production wells and seismicity (see Fig. S6). Given that we expect that production-induced seismicity will locate close to production wells (McGarr et al., 2002), this is further evidence that production is likely not the primary cause of the seismicity. The lack of reverse-faulting mechanisms (14 of the 150 computed) also suggests that production is not the cause of seismicity because production most frequently induces reverse-faulting earthquakes (McGarr et al., 2002).

Hydraulic Fracturing and Earthquakes

We find that hydraulic fracturing operations in the area are not statistically correlated with the seismicity. We expect hydraulic-fracturing-induced earthquakes to occur within days of the stimulation (Kanamori and Hauksson, 1992; Green et al., 2012; Holland, 2013; Skoumal et al., 2015; Atkinson et al., 2016) and within a kilometer of the well (Clarke et al., 2014; Friberg et al., 2014). There are exceptions to this rule, as hydraulic-fracturing-induced earthquakes have been observed to occur up to three months after stimulation has been completed (Bao and Eaton, 2016), but there is little evidence that earthquakes are induced at distances much greater than 1 km.

We use the FracFocus database to identify hydraulic fracturing stimulations. Most of the stimulations completed in the study area occurred between 2012 and September 2014, yet nearly all of the seismicity has occurred since September 2014 (see Fig. S7). The delay between most of the stimulations and most of the earthquakes implies that hydraulic fracturing is likely not causing the earthquakes. The locations of the stimulations and the locations of the earthquakes are nearly anticorrelated, again implying that hydraulic fracturing is not causing these earthquakes (see Fig. S8). If we examine all of the earthquakes and search for stimulations that were located within 2 km of an earthquake that occurred sometime between the start of the stimulation and two days after it ended, we find only 0.19% of our earthquakes are potentially induced by hydraulic fracturing. Using a bootstrap analysis (Efron, 1979), we randomize the timing of the injection operations (and maintain their locations), and we find an expectation that 0.07% ± 0.04% (1σ) of the earthquakes would randomly be associated with hydraulic fracturing. Hence, there appears to be a very small triggering effect of hydraulic fracturing on seismicity in the area (0.12% equates to six earthquakes of the over 4800 earthquakes analyzed). We also conduct the same analysis using a 30-day window and 2 km limit, which yields 1.1% of earthquakes associated with hydraulic fracturing, but a random reshuffling would produce 0.92% ± 0.13% (1σ) of earthquakes that would be randomly associated with hydraulic fracturing. Using this definition of hydraulic-fracturing-induced seismicity, the observations lie within 2σ bounds of the observations being random.

Carbon Dioxide Sequestration and Earthquakes

Approxiately 1 km to the east of the study area, there is a carbon dioxide sequestration pilot project in the Wellington field (Y. Holubnyak, W. Watney, et al., 2017). Active injection lasted ~5½ months from 9 January 2016 to 21 June 2016, during which ~20,000 metric tons of supercritical CO₂ were injected into the Arbuckle. Assuming that liquid CO₂ is being injected, which has a density of ~1 kg/L, this would mean that ~120,000 barrels of CO₂ were injected over these 5½ months. We have four reasons to believe that this CO₂ injection did very little to contribute to any of the seismicity in the area: (1) the injection rate of CO₂ (~22,000 barrels per month) and total injected volume is much lower than many of the wastewater disposal wells in the study area, making it less likely to have induced the seismicity than the wastewater disposal; (2) the CO₂ well is located far from most of the seismicity in our study area; (3) most of the seismicity in our study area occurred before injection began at the CO₂ test site; and (4) there appears to be no appreciable change in the seismicity in the area immediately surrounding the CO₂ test site during the time of injection (Y. Holubnyak, L. Watney, et al., 2017; Nolte et al., 2017a).

Wastewater Disposal and Earthquakes

There is a clear temporal correlation between increased wastewater injection operations and seismicity (Fig. 7). The monthly rate of M ≥ 2 earthquakes appears to lag behind the monthly, regional injection rate by 2–6 months (Fig. 9 and Fig. S9).

In addition to the 2–6-month lag time between injection rate and the seismicity rate, we note that there was a significant increase in injection for 2 yrs in our study area (2012–late 2013) before any significant seismicity occurred (Fig. 7). The majority of the injection during these 2 yrs was occurring in the southwestern portion of the study area, a region that has not produced a significant number of earthquakes. We posit that the lack of notable seismicity associated with this increase is either due to a lack of fluid pathways to the basement or due to the absence of faults that are close to failure. An alternative explanation for the absence of seismicity is that the hydrologic system is capable of accepting up to a few million barrels per month in this region before earthquakes would occur. Langenbruch and Zoback (2016) offered this hypothesis to explain a similar delay in seismicity observed in Oklahoma. We prefer the first explanation because it explains the spatial variability of seismicity that we observe and does not assume a purely regional earthquake response. Undoubtedly, the pressures observed are some combination of the local and regional effects of wells, but the second hypothesis neglects any local fluid-pressure
There has been a dramatic increase in seismicity in southern Kansas that began in 2013, an area with little evidence of seismicity adjacent to high-rate wells cannot be explained by deviated injection wells because none of the wells that we consider are deviated.

Summary and Conclusions

There have been several notable exceptions to the correlation between high injection rates and seismicity. First, we find that high seismicity rates and magnitudes do not necessarily mean that there is high-rate injection nearby. The seismicity in the eastern portion of the study area (near zones 4 and 5 and to the east of them; −97.75 and eastward) does not occur near areas of particularly high total injected volume (max = 4.4 million barrels in a 0.05° × 0.05° region) or maximum monthly injection rate (max = 210,000 barrels per month in a 0.05° × 0.05° region) versus 57.3 million barrels and 1.5 million barrels per month across the study area. This seismicity in the east, that is 10 km or more from the largest injectors, includes the largest earthquake in the region, the M 4.9 Milan earthquake (Choy et al., 2016).

We also find that high-rate/high-cumulative volume injection does not necessarily equate with high rates of seismicity. For example, the highest injection rates in the area occur in a 0.25° × 0.1° region in the southwestern portion of our study area that extends westward outside the study area (Fig. 8). This region accounts for ~40% of the total fluid injected between 2012 and 2016. The three highest cumulative injection volume wells also lie in this region (Macy, Wrigely, and Shelby). They injected 22–28 million barrels each from 2012 to 2016 (Fig. 10). The next largest total volume injector in the study area injected 16.4 million barrels during the same time period. Although injection rates and total volumes are very high in this area, seismicity is largely absent. The only exception is some seismicity at its eastern edge, which may be related to the larger trend of seismicity that is adjacent to other areas of significant injection. We should note, though, that there are three sets of twinned wells in the middle of the study area: Jill 1 and 2, Stacey 1 and 2, and Ethan John 1 and 2 that are comparable in total volume and to the highest-rate wells in the southwest (32, 31, and 25 million barrels, respectively, injected between 2012 and 2016) (Fig. 10). Twinned wells are wells that are drilled from the same pad in different directions or to different depths in the Arbuckle Group to increase the volume of water injected at a single surface facility. All of the high-cumulative volume, twinned wells have seismicity within 2 km.

In general, the areas of highest total injection and highest-rate injection wells are at least 5 km away from cataloged seismicity. In the areas where seismicity is most active, large wells can be as close as 2 km from the earthquakes (horizontally), but we do not see seismicity any closer. The accuracy of our earthquake locations is sufficient to resolve this absence of seismicity close to the wells, and therefore this absence of seismicity is not an artifact. The absence of seismicity adjacent to high-rate wells cannot be explained by deviated injection wells because none of the wells that we consider are deviated.
previously documented seismicity (only one documented $M \geq 2.0$ earthquake during 1867–2012). Over 1000 $M \geq 2.0$ and larger earthquakes occurred between 2013 and 2016. Although moderate-magnitude earthquakes have occurred in other parts of the state, none are known in this area in the past 150 yrs. The earthquake rate in southern Kansas peaked in 2015 with 51 $M \geq 3$ earthquakes. Most of these earthquakes occurred in Harper County, but earthquakes in smaller numbers also occurred in neighboring counties. The largest earthquake that occurred since 2013 in southern Kansas, the $M = 4.9$ Milan earthquake (Choy et al., 2016), was located in adjacent Sumner County. The seismicity in Kansas is also contiguous with the ongoing surge in seismicity in Oklahoma (Ellsworth et al., 2015; Walsh and Zoback, 2015; Langenbruch and Zoback, 2016).

Aside from the dramatic earthquake-rate change, the overall magnitude–frequency statistics do not differ from natural earthquakes. Specifically, the $b$-value is close to 1 and does not show statistically significant temporal variations. Spatial variations in $b$ do exist, but these likely reflect variability in fault structures. Focal mechanisms and the activated faults are also consistent with the regional tectonic stress field. Both strike-slip and normal-faulting focal mechanisms were observed on faults that trend either north–northeast or north–northwest, yielding a maximum principal stress oriented slightly north of east.

Three principal lines of evidence suggest that the seismicity is induced by wastewater injection into the Arbuckle Group at the base of the sedimentary section.

1. The rate change we observe beginning in 2013 is highly improbable as a random variation of the pre-2013 seismicity rate. Following the method described in Rubinstein et al. (2014) and McNamara et al. (2015), we find that the observed earthquake-rate change would only occur randomly 0.17% of the time using the rate derived from the earthquake catalog from 1974 to 2016, with a conservative magnitude of completeness threshold of 4 and a change point in 2012 when injection began to increase in the region.

2. The earthquake occurrence history is consistent with wastewater injection operations in the area. We observe that there is a spatial and temporal correlation with the increase and subsequent decrease in seismicity and wastewater disposal operations.

3. The other potential industrial drivers to the seismicity (hydraulic fracturing and oil production) are not viable causes of the seismicity because they do not spatially or temporally correlate with the seismicity.

It appears that both local and regional wastewater injection operations influence where and when earthquakes occur, as well as their frequency of occurrence. In the case where regional operations dominate the seismicity (i.e., the nearest high-rate injection wells are located 10 or more kilometers away), the seismicity continues long after injection has slowed at the closest wells. In contrast, seismicity close to high-rate wells subsides shortly after injection decreases. We infer that the fluid pressures inducing the earthquakes near the well decline rapidly, but the fluid pressures remain elevated at greater distances for months. This slowly diffusing pressure perturbation would likely result in a slowly declining earthquake rate. Although we focus on effective normal stress reduction by fluid-pressure elevation as the main factor responsible for inducing the earthquakes, we acknowledge the potential contribution of poroelastic stresses (Segall and Lu, 2015; Chang and Segall, 2016; Barbour et al., 2017).

In addition to the areas where there is seismicity without nearby high-rate injection wells, there are high-rate injection wells with no nearby seismicity. Nearly half of the total injection occurs in the southwest corner of the study area, yet there is little seismicity there. The absence of cataloged seismicity in this area implies that high-rate injection alone is not the only condition necessary to induce earthquakes, but additional factors are needed. A similar observation of large injector wells and a lack of nearby earthquakes was noted by Yeck et al. (2016) in an area of northern Oklahoma located immediately to the southwest of our study area, suggesting this is a regional effect. An absence of faults that are appropriately oriented in the local stress field, low absolute differential stress levels, and/or a lack of fluid-pressure pathways from the injection formation to faults in the crystalline basement could explain the notable lack of seismicity in the southwestern corner of the area.

The seismicity in Kansas behaved very similarly to that in Oklahoma. In both locations, seismicity increased following a number of years of increased injection. Once seismicity started, the seismicity appeared to lag behind injection rates by somewhere between two and six months in Kansas and two and five months in Oklahoma (Langenbruch and Zoback, 2016). Seismicity has also declined recently in both regions, likely caused by declines in injection driven by economic and regulatory decisions. Given that the seismicity in Oklahoma has waned, but three of the four largest recorded earthquakes in that region (all $M \geq 5$) occurred in 2016, we cannot rule out the possibility that moderate magnitude earthquakes could still occur in Kansas.

In summary, the spatial and temporal correlation between increases and decreases in injection and corresponding changes in seismicity strongly supports the conclusion that the earthquakes are the consequence of wastewater disposal by injection into the Arbuckle group. Declining rates of seismicity since 2016 reflects the impact of declining injection rates caused by both economic and regulatory factors. The question remains, however, whether injection can be reduced such that the hydrogeologic system re-establishes its long-term equilibrium with capacity to accept some wastewater without inducing earthquakes.

Data and Resources

Waveforms used in this study were recorded by the following seismic networks: the Southern Kansas Seismic
Network (U.S. Geological Survey [USGS]), the Oklahoma Seismic Network (Oklahoma Geological Survey [OGS]), and the central and eastern United States Seismic Network (CEUSN). All waveform data are available from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center under network codes: GS, NQ, N4, and OK. A list of all stations and networks can be found in Table S1. The local seismic network catalog (before relocation) is available as part of Comprehensive Catalog (ComCat) for all \( M \geq 1.5 \) earthquakes within the study region, subject to quality-control criteria. A catalog of the calculated focal mechanisms is found in Table S2. The relocated earthquake catalog and earthquakes that were not relocated are found in Tables S3 and S4, respectively. Injection data from Kansas are collected by the Kansas Corporation Commission (KCC) and distributed online or in scans of paper records through the Kansas Geological Survey (KGS) website: http://www.kgs.ku.edu/Magellan/Qualified/fluid.html (last accessed May 2017) and the Kansas Open Records Act Request from the KCC (form at http://kcc.ks.gov/kora/, last accessed February 2018). Monthly injection data from Oklahoma are made available by the Oklahoma Corporation Commission Oil and Gas Database at http://www.occeweb.com/og/ogdatafiles2.htm (last accessed May 2017). Hydraulic fracturing data came from FracFocus available at http://fracfocus.org (last accessed May 2017). Authors will also share injection data if requested.

Acknowledgments

This work would not have happened without the deployment of seismic instruments and ongoing semi-real-time analysis of the data coming from southern Kansas. Seismic deployments and network operations require countless hours of support staff. The authors gratefully acknowledge the following people who were involved in field deployments and servicing of instruments in the field: Jemile Erdem, Fabia Terra, Steve Walter, Jim Smith, Jonah Merritt, Adria McClain, Don Moehring, Bryant Platt, Steve Ploetz, and James Allan. The following team members were invaluable in maintaining back-end operations of the network, software, and input into the Advanced National Seismic System (ANSS) catalog: Lynn Dietz, Lind Gee, Paul Friberg, Allan Walter, Harley Benz, Paul Earle, Jim Luetgert, Fred Klein, David Mason, and David Ketchum. The authors thank the National Earthquake Information Center (NEIC) duty seismologists for maintaining a real-time catalog in southern Kansas, Fabia Terra, Dan Langerman, Nick Ogas, Steve Walter, and Jemile Erdem were all critical in maintaining the earthquake catalog, picking earthquakes, and conducting quality control. The authors also would like to thank Andy Barbour, Jack Norbeck, Tandis Bidgoli, Rall Walsh, Patricia Martinez-Garon, and Brittany Russo for their assistance in obtaining wastewater disposal and hydraulic fracturing data. Aren Crandall-Bear’s help was critical for digitizing old earthquake catalogs. Rex Buchanan, Tandis Bidgoli, and Lynn Watney of the Kansas Geological Survey were excellent partners and were highly valuable for coordination and cooperation in research. The authors also thank Ryan Hoffman of the Kansas Corporation Commission (KCC), who was readily available to help us in understanding operations in Kansas. The authors gratefully acknowledge Mike Tate and Mike Cochran of the Kansas Department of Health and Environment, who were also available to help us understand underground injection operations in Kansas. Jeanne Hardebeck, Rob Skoumal, and Art McGarr provided insightful reviews on an earlier version of this article. The authors thank Heather DeShon and Cliff Frohlich for their thoughtful reviews of this work. William Ellsworth was supported by the Stanford Center for Induced and Triggered Seismicity. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References


The 2013–2016 Induced Earthquakes in Harper and Sumner Counties, Southern Kansas

689


U.S. Geological Survey
345 Middlefield Road, MS-977
Menlo Park, California 94025
jrubinstein@usgs.gov

(J.L.R.)

Department of Geophysics
Stanford University
395 Panama Mall
Stanford, California 94305

(W.L.E.)

U.S. Geological Survey
525 S. Wilson Avenue
Pasadena, California 91106

(S.I.D.)

Manuscript received 24 July 2017;
Published Online 20 February 2018