Seismicity Observed at Seismograph Station RC01 Located near Bushton, Kansas: July 1 to December 31, 2016

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Executive Summary

In the past three years, Kansas has generally experienced a two-orders-of-magnitude increase in the rate of seismic activity across the state. The vast majority of these earthquakes have been confined to a half-dozen counties in the south-central part of the state (Peterie et al., 2016c). This uptick in seismicity is generally coincident with the increase in oil and gas production since 2012 (KGS, 2017) and the associated increased volumes of produced formation water disposed of into deep aquifers. Fluid injection in some geologic settings has induced earthquakes (e.g., Healy et al., 1968; Horton, 2012). The strong spatial and temporal correlation between disposed fluids, injection well locations and disposal depths, and earthquake epicenters suggests a link between regulated fluid disposal into deep aquifers and the recent (since 2013) elevated seismic activity measured in south-central Kansas. This surge in seismicity has similar characteristics to recent, well-documented increases in felt earthquakes in Oklahoma and Texas that have been correlated with increases in permitted waste fluid injection volumes (Walsh and Zoback, 2015; Hornbach et al., 2015).

Accurate recording and analysis of background seismicity well below felt levels is an industry-accepted practice for identifying and evaluating the potential effects subsurface injection might have on natural balances and to help avoid any unintended consequences of waste fluid injection. To obtain a cursory awareness of the background seismicity near Bushton, Kansas, and to determine the utility and practicality of single station observations, the Kansas Geological Survey (KGS) deployed a single temporary monitoring station (RC01) that began operation on August 20, 2015. The station operation has been fully funded by the KGS and in continuous operation within the designed signal-to-noise ratio and sensitivity ranges since that time and has provided a 99% continuous data stream.

From July 1 to December 31, 2016, 63 seismic events with characteristics consistent with local microearthquakes were located within 20 km of station RC01. More than one-third of these events occurred in December, with two microearthquake sequences that are uniquely clustered in space and time. These two sequences include a total of 11 events that occurred within a 24-hour period beginning at 12:10 p.m. CST, December 17. The magnitudes are M less than 1 and occur at epicentral distances of 4–5 km and 8–10 km, respectively, from RC01. Based on reported daily injection volumes in Bushton disposal wells WWDW#3, WWDW#4, WWDW#5, and WWDW#6 from August 2015 to December 2016 (ONEOK, 2016), at this time there does not appear to be a direct correlation with injection activities and the observed microearthquake sequences. In general, the seismicity in this area remains very low energy with two earthquakes of M less than 1 per week, on average, and only one M 1 or greater earthquake detected in the last six-month period. Although the recurrence of events with M less than 1 increased relative to the prior year, short-term fluctuations in seismicity are common and to be expected under natural conditions.

Bottomhole pressure and static fluid levels in the Bushton disposal wells appear to have risen in recent years (Murta, 2016a, 2016b, 2016c, and 2016d). Between 2007 and 2016, the bottomhole pressure measured in WWDW#3 increased by 30 psi. Model and case studies of induced seismicity suggest that pressure perturbations ranging from 2 to 30 psi could be enough to initiate slip on critically stressed faults (Keranen et al., 2014; Hornbach et al., 2015). Although there is no clear evidence that microseismicity near RC01 has been influenced by local or regional injection activities, it cannot be definitively ruled out at this early stage. Continued monitoring will be crucial to provide insight into the duration and nature of the recent uptick in low-magnitude events before possible causes can be assessed. Because disposal of waste fluid is not restricted to WWDW#3, WWDW#4, WWDW#5, and WWDW#6 within 20 km of RC01, it would be prudent to request and track injection volumes and pressures for other Class I and Class II wells within the influence radius of disposal wells WWDW#3, WWDW#4, WWDW#5, and WWDW#6.

Introduction

The state of Kansas has a history of relatively low seismic activity, with only one earthquake of magnitude (M) 3 or greater occurring approximately every two to three years, based on the last nearly 40 years of recording by the Kansas Geological Survey (KGS) and U.S. Geological Survey (USGS) (Steeples et al., 1987; Steeples et al., 1990; NEIC, 2017). Beginning in 2013, more than 100 earthquakes of M 3 or greater were detected in Kansas, most of which occurred in a two-county area in south-central Kansas with very little historic seismic activity (Figure 1). This two-orders-of-magnitude increase in seismicity lagged a significant and unprecedented increase in disposal of produced formation water into deep and fractured Paleozoic aquifers (e.g., the Arbuckle Group) by one to two years (Figure 2). Disposal in geologic units
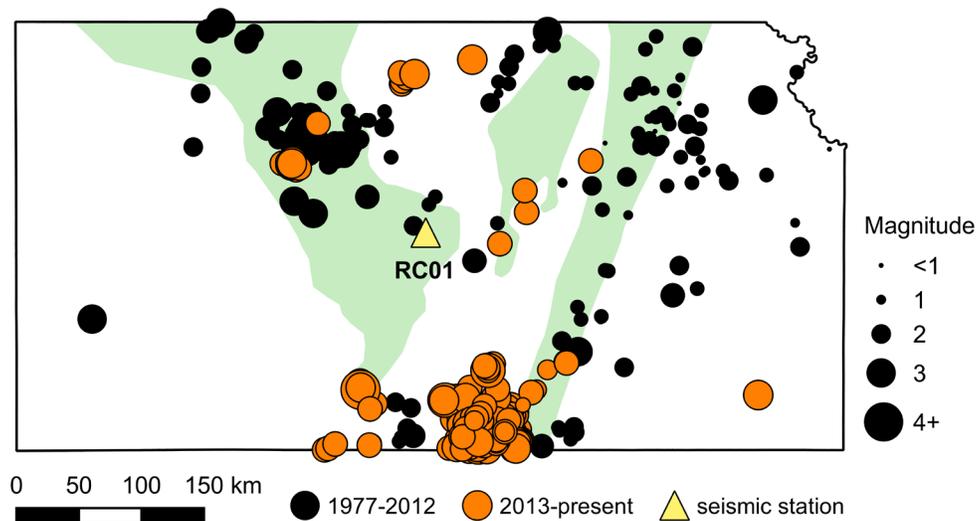
Figure 1. Historic earthquakes (black) and recent earthquakes (orange) superimposed on the prominent uplift structures in Kansas (green). Station RC01 (yellow triangle) is located near the center of the state.
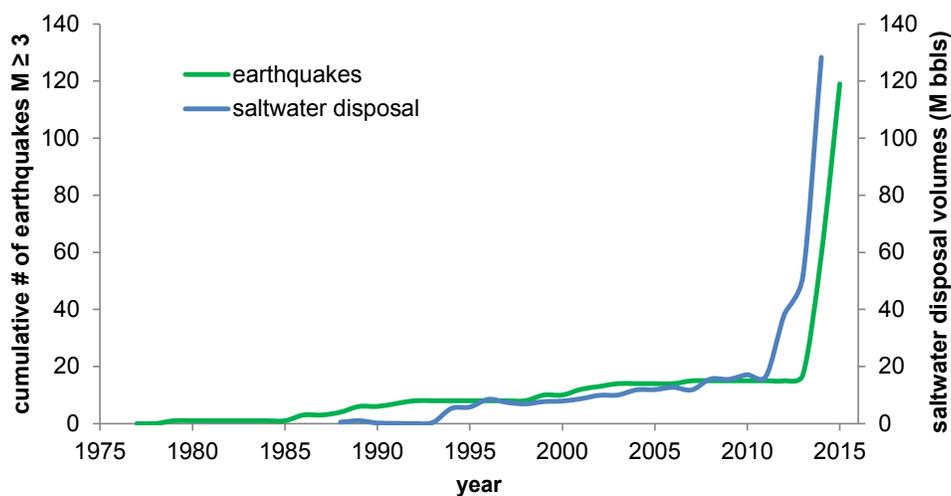
Figure 2. Annual saltwater disposal (SWD) volumes in Harper and Sumner counties (blue), provided by the Kansas Corporation Commission, and cumulative number of earthquakes with M 2.5 or greater in Kansas (green).

2

that are hydraulically connected to the crystalline basement may allow fluid transmission to basement rocks (Ellsworth, 2013; Walsh and Zoback, 2015). The strong spatial and temporal correlation between this increase in disposed fluid volumes, injection well locations and injection interval, and earthquake epicenters suggests recent seismic activity may be induced as a result of the cumulative volumes and locations of injection points. This surge in seismicity is similar to recent, well-documented increases seen in Oklahoma (Walsh and Zoback, 2015; Keranen et al., 2014) and Texas (Frohlich et al., 2011; Hornbach et al., 2015), where significant increases in volumes of waste fluid injection have also been noted.

For decades, it has been known that fluid disposal into deep aquifers can induce seismic activity (Nicholson and Wesson, 1990). The first widely accepted and confirmed case of induced seismicity occurred in the 1960s at Rocky Mountain Arsenal near Denver, Colorado. Wastewater disposal in a deep well caused more than 1,500 earthquakes in six years, the largest of which—originally estimated as a magnitude 5.0 to 5.5—occurred more than a year after injection was terminated (Healy et al., 1968). Fluid injection raises pore pressure within the injection interval, which is in turn translated to any fault or fracture in hydraulic communication with the injection interval. Increased pore pressure reduces the effective stress (i.e., the frictional resistance related to clamping force) on the fault (Hubbert and Rubey, 1959), increasing the potential for a fault plane to experience slip and an earthquake to occur (Nicholson and Wesson, 1990).

Many confirmed or suspected cases of induced seismicity have attempted to directly link seismic activity to fluid injection in a single nearby well (e.g., Seeber et al., 2004; Ake et al., 2005; Frohlich et al., 2011). Recently published research in *Science* (Weingarten et al., 2015) and *Science Advances* (Walsh and Zoback, 2015) statistically relates large instantaneous and/or cumulative volumes of wastewater injected into near-basement aquifers as drivers for inducing earthquakes 8 km or more from the injection point (Healy et al., 1968; Ake et al., 2005; Keranen et al., 2014). The sensitivity or tendency of a seismically susceptible area to produce earthquakes from injected fluid depends on many factors, including permeability within the injection interval, proximity to critically stressed basement faults, connectivity between injection interval and basement rocks, and volume of injected fluid per square mile.

With the strong correlation between recent increased volumes/rates of injected wastewater and seismicity comes concern that any changes to existing or new injection programs could increase the number and/or magnitude of felt earthquakes. The keys to maintaining historical levels of seismicity in areas with existing or planned deep fluid disposal well fields include avoiding areas with critically stressed faults, minimizing chances for fluid connectivity to basement rocks, and establishing sustainable fluid volumes/rates that will not impact background seismicity. Sustainable fluid volumes and rates depend on the properties of the permitted intervals and pore pressures along fault planes. Determining those levels is best done through analysis/understanding of historical injection practices and active monitoring of local seismicity, both before and during injection. Abnormally elevated seismicity within several kilometers of the injection site that is sustained over extended periods of time and that correlates with changes in local injection habits is a strong indicator that injected fluids are inducing or have induced or triggered earthquakes.

Several case studies from the central interior of the United States provide insight into the onset of injection-induced/influenced seismicity. In south-central Kansas, M 3 or larger earthquakes (capable of being felt by the local population) followed an unprecedented increase in saltwater disposal rates in this region by approximately two years (Figure 2). Delays ranging

from months to years were similarly observed in Oklahoma (Walsh and Zoback, 2015) and Arkansas (Horton, 2012). In a controlled experiment in Paradox Valley, Colorado, a local seismic network detected the first microearthquake (M 0 to less than 2.5) more than three months after continuous pumping at sustained rates and pressures began, and the first felt earthquake one year after that (Ake et al., 2005). Although there may be a delay ranging from months to years, local seismic monitoring is key to early detection of elevated seismicity (relative to historic/ natural recurrence) associated with fluid injection practices.

To better understand the nature and patterns of background seismicity near Bushton, Kansas, the KGS deployed a temporary, three-component seismic monitoring station (RC01) on August 20, 2015. Key to confident discrimination of local microearthquakes and accurate interpretations of earthquake arrival patterns on these data was a pre-processing step designed to attenuate seismic "noise" from regional or distant earthquakes and nearby cultural activity. Single-station style analysis of compressional (P) and shear (S) wave arrivals and their duration provides an approximate distance from RC01 to the potential local microearthquake and an estimate of magnitude. With only a single station within the sensitivity range of these micro-earthquakes, distance and magnitudes are all that can be determined for M less than 1 earth-quakes. A study of an earthquake swarm near Jones, Oklahoma, found that this swarm was induced primarily by four high-volume injection wells, and the onset of induced seismicity occurred within 20 km of these wells (Keranen et al., 2014). To date, this is the greatest distance reported in the refereed literature for high-volume injection wells to influence pore pressures along fault surfaces sufficiently and induce an earthquake. Therefore, analysis on RC01 focuses on earthquakes within 20 km of the station.

During the first 10 months of monitoring from August 2015 to June 2016, 58 seismic events that have characteristics consistent with local (within 20 km) earthquakes of M 1 or less were recorded at RC01 (Peterie et al., 2016a; Peterie et al., 2016b). Epicentral distances of many of the observed events are consistent with a pair of earthquakes (M 2.0 and M 1.8) recorded during the 1980s, which are a part of the historical record (Steeples et al., 1987). This observa-tion is consistent with the notion that seismic events that have been observed near RC01 since operation began in August 2015 are (1) within the range of magnitudes measured for earthquakes in the historical record and (2) consistent with continued movement on critically stressed faults or fractures. The overall magnitude and rate of seismicity was low (relative to areas within the high seismicity zones in south-central Kansas), averaging only one to two earthquakes per week with M less than 1 and one M 1 every two months. In this report, we present observations made during an additional six months of monitoring that supplements previous reports (Peterie et al., 2016a; Peterie et al., 2016b). Additionally, a brief assessment of fluid injection trends is provided for wells located less than 1.5 km from RC01.

Regional Geology and Historic Earthquakes

There are three prominent geologic structures associated with known basement faults and historic earthquakes in Kansas. The Midcontinent Geophysical Anomaly (MGA) is the largest gravity anomaly in North America and is caused by a thick sequence of mafic igneous rocks formed during major late Precambrian rifting (Ocola and Meyer, 1973). It is bounded by laterally expansive faults (Serpa et al., 1984). The Nemaha Ridge is one of the most prominent crustal features in the midcontinent, extending across the state in a northeast-southwest direction. The Nemaha Ridge formed during a post-Mississippian uplift (Jewett, 1951). A system of normal and reverse faults on the eastern margin of the Nemaha Ridge (Merriam, 1963) forms the

Humboldt Fault Zone. Wrench faults with a northwest-southeast trend intersect the Nemaha Ridge and represent pre-Phanerozoic crustal extension associated with the Midcontinent Rift System (Gerhard, 2004). The Central Kansas Uplift and its associated faults and folds formed during the post-Mississippian (Merriam, 1963) and may also be influenced by the earlier Mid-continent Rift System.

To characterize seismicity and evaluate seismic risk in eastern Kansas, eastern Nebraska, and westernmost segments of Iowa and Missouri, the 15-station Kansas-Nebraska Network was established and operated by the KGS from 1977 to 1989 with funding from the U.S. Nuclear Regulatory Commission and the U.S. Army Corps of Engineers. During the network's 13 years of operation, more than 170 earthquakes were located in Kansas with duration magnitudes ranging from 0.5 to 4.0. Beginning in the 1990s, only the two regional seismic stations operated by the USGS were present in Kansas. From 1990 to 2012, the National Earthquake Information Center (NEIC) reported 19 earthquakes in Kansas ranging from M 2.2 to 3.5. The majority of earthquakes located by the seismic networks in place from 1977 to 2012 are related to faults associated with the three major uplift features (Figure 1). These findings suggest that natural movement due to regional crustal stress on existing faults and fractures associated with prominent geologic structures is the source of recorded earthquakes in Kansas.

Station RC01 is located northeast of Bushton, Kansas, along the eastern margin of the Central Kansas Uplift (Figure 3). The axis of the Ellsworth anticline, an early Pennsylvanian fold that may be associated with nearby faults or fractures, runs northeast through west-central Rice County (Jewett, 1951). Three earthquakes detected by the Kansas-Nebraska Network between 1981 and 1983 were located within 55 km of RC01 (Steeples et al., 1987). The closest was a M 2.0 that occurred 11 km northwest of RC01 on September 7, 1983. These earthquakes most likely occurred naturally as a result of movement on faults or fractures attributed to the Central Kansas Uplift or associated secondary geologic features. This suggests there are basement faults near RC01 optimally oriented with the regional stress field that could potentially be seismically sensitive to fluid injection in geologic intervals with hydraulic connection to basement rocks.
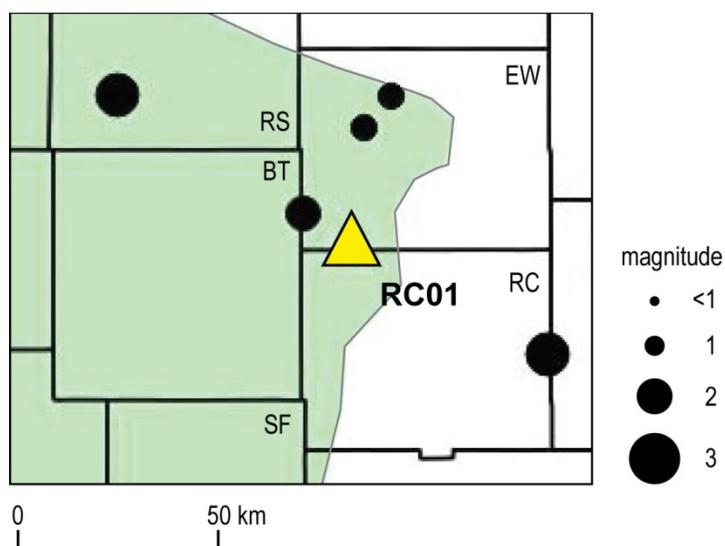

Figure 3. Station RC01 (yellow triangle) is located on the eastern margin of the Central Kansas Uplift (green). Five natural earthquakes (black) ranging from M 1.7 to 2.7 were recorded in this area from 1981 to 1983.

Earthquake Monitoring and Data Analysis

Temporary seismic monitoring station RC01 was installed near Bushton on August 20, 2015 (Figure 4a). Approximate GPS coordinates of RC01 are 38°32.406' N, 98°22.079' W at 541 m elevation. The sensor is a three-component Guralp CMG-6T force feedback seismometer with a flat response from 1 to 100 Hz. The seismometer is installed on top of a concrete pad approximately 1 m below ground surface in a temporary vault. The horizontal components are aligned north and east. Gravel was placed in the floor of the vault surrounding the concrete pad to facilitate drainage of any excess groundwater. A 20-gallon bucket was inverted and placed over the sensor and then buried with filled dirt.

A solar panel, cellular antenna, GPS antenna, and equipment box are mounted to a steel pole located 3 m from the vault (Figure 4b). Inside the equipment box are two deep cycle marine batteries, a charge controller, cellular modem, and digitizer connected to the seismometer via a buried sensor cable. Three-component seismic data are sampled at 100 samples per second and continuously transmitted in real time via cellular telemetry to a server at the KGS. Since installation, station RC01 has been operating within the designed signal-to-noise ratio and sensitivity ranges with a 99% continuous data stream.
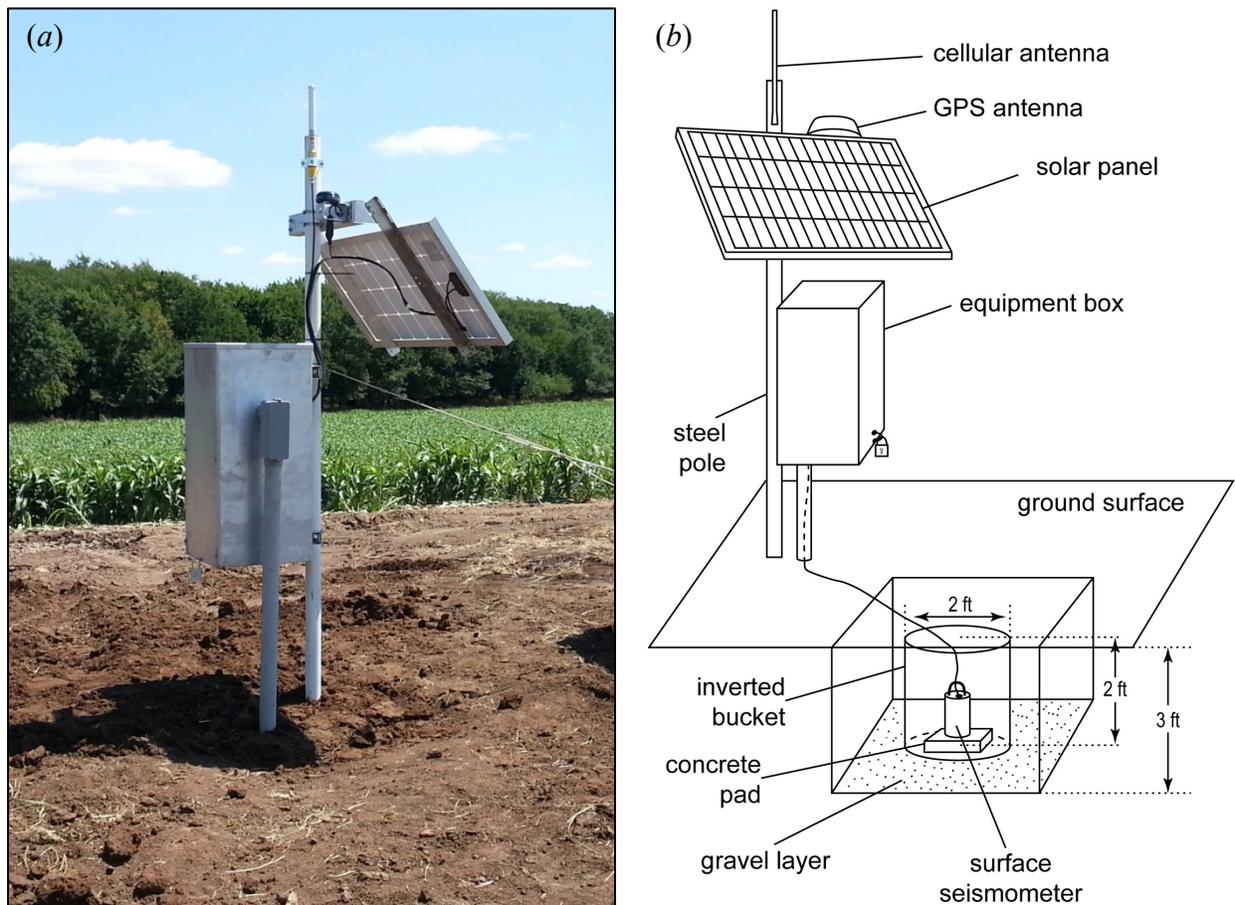
Figure 4. (*a*) Seismic station RC01 installed near Bushton, Kansas. (*b*) Diagram illustrating a temporary seismic monitoring station.

Compressional and shear waves are generated when a fault plane slips and an earthquake occurs. These waves travel at different but predictable speeds and arrive at seismic monitoring stations at different times that depend on depth of earthquake, distance from earthquake to recording station, and rock properties. The S-wave velocity (v_s) is slower than the P-wave velocity (v_p) and, therefore, the S-wave arrives later than the P-wave. The distance (d) of the earthquake from the seismic station is directly related to the difference in time between the P- and S-waves (Δt):

$$d = C\Delta t ,\tag{1}$$

where C is a scaling factor directly related to crustal velocities:

$$C = \left(\frac{v_p v_s}{v_p - v_s}\right) .\tag{2}$$

Using the crustal velocity model developed for the state of Kansas (Steeples et al., 1987) from the surface to a depth of 5 km, the scaling factor C is approximately 7.3 km/s.

Locating the epicenter of an earthquake requires detecting P- or S-waves at three or more stations. For small local events that are only recorded on a single station, the epicenter location cannot be uniquely determined. Rather, the epicenter exists somewhere on a circle centered on the seismic station with radius equal to the calculated distance to the earthquake epicenter (Figure 5). The duration magnitude (Mc) of an earthquake is calculated from the coda—the time (t_c) from the arrival time of the P-wave until the energy is approximately equal to background noise (Lawson, 1978):

$$Mc = 1.86 \log(t_c) - 1.49 .\tag{3}$$
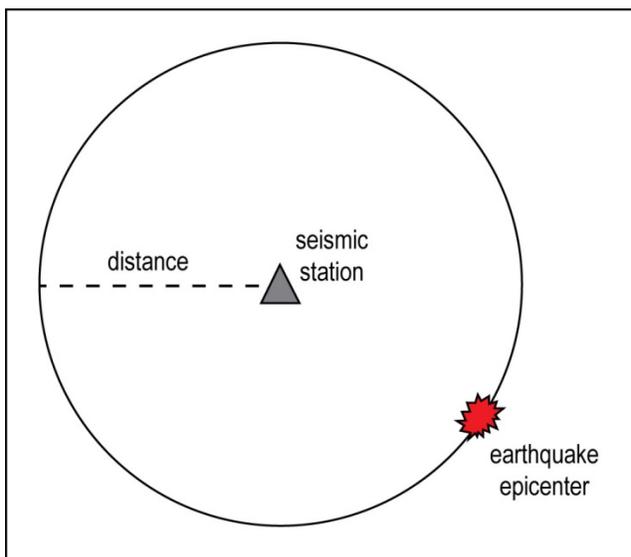
Figure 5. The epicenter of an earthquake exists somewhere on a circle centered on the seismic station with radius equal to the calculated epicentral distance.

Small local earthquakes can be discriminated from distant earthquakes and some types of seismic noise based on distinct arrival of seismic phases associated with earthquakes (P, S, surface, and coda waves) and/or spectral characteristics. Local earthquakes have distinct wave-forms and phases with short P-S arrival time differences (Figure 6) and generally have a higher dominant frequency than distant earthquakes. Data from RC01 were analyzed using the Seisan earthquake processing software package. A 15-25 Hz passband filter was applied to the contin-uous waveform data to attenuate low-frequency noise and regional or distant earthquakes. Seis-mic events evident within this passband were inspected for apparent P- and S-waves to discrim-inate events that were clearly non-earthquake. For events with earthquake-like characteristics, apparent P- and S-wave arrival and coda times were recorded and the distance from RC01 and magnitude were estimated using equations 1–3.

Observations at RC01 from July 1 to December 31, 2016

Dozens of seismic events are recorded each day at RC01, the overwhelming majority being earthquakes with M 1.5 or greater from south-central Kansas and northern Oklahoma. A great deal of effort and meticulous attention to detail go into discriminating small, local earth-quakes from these more distant regional events based on their very short P-S arrival time differ-ence and higher dominant frequencies. From July 1 to December 31, 2016, 63 possible earth-quakes were recorded at RC01 with epicentral distances of less than 20 km from RC01 (Table 1). Magnitudes of these events ranged from -1.5 to 1.3. This range is at least an order of magnitude lower than what is generally felt by people close to the epicenter (about M 2.5 or greater).

A very significant observation and one that plays into the need for longer term monitoring is that more than one-third (23) of the 63 earthquakes detected during this six-month monitoring period within 20 km of RC01 occurred in December 2016. The number of events observed within this influence zone during December 2016 is more than double the number observed in any single month since monitoring began in 2015. Half of the December events occurred within a 24-hour period beginning at 18:10 UTC (12:10 p.m. local time) on Decem-ber 17. The events recorded during that 24-hour period are grouped in two spatial clusters with epicentral distances of 4–5 km and 8–10 km, respectively. This much separation clearly segre-gates them into two unique microearthquake sequences with magnitudes ranging from -0.4 to 0.5. Although these events are very low energy, the spatial and temporal clustering is a depar-ture from what has been previously observed around RC01.

Short-term fluctuations in microearthquake recurrence are expected and commonly observed under purely natural influences. To begin to investigate whether there is a direct correlation between the December microearthquake sequences and fluid injection in nearby UIC Class I disposal wells, daily disposal volumes were obtained for WWDW#3, WWDW#4, WWDW#5, and WWDW#6 for a period beginning in August 2015 (Figure 7) (ONEOK, 2016). The only perturbation observed in injected fluid volume was an increase during July 2016 to more than double the volume injected during any single month since monitoring began. Fluid injection was throttled back to a lower, more historical rate by August 2016. If there is a correlation between injection practices and microearthquakes within a 20 km range of influence around RC01, it is not evident over the period covered by these data. With continued earthquake recording, fluid injection reporting, and analysis of current and additional historical injection data—the lag between increased injection and induced seismicity can be as much as two years (Langenbruch and Zoback, 2016)—a strong case could be made for suggesting there does not appear to be a direct correlation between the microearthquake sequences and injection activities around RC01.
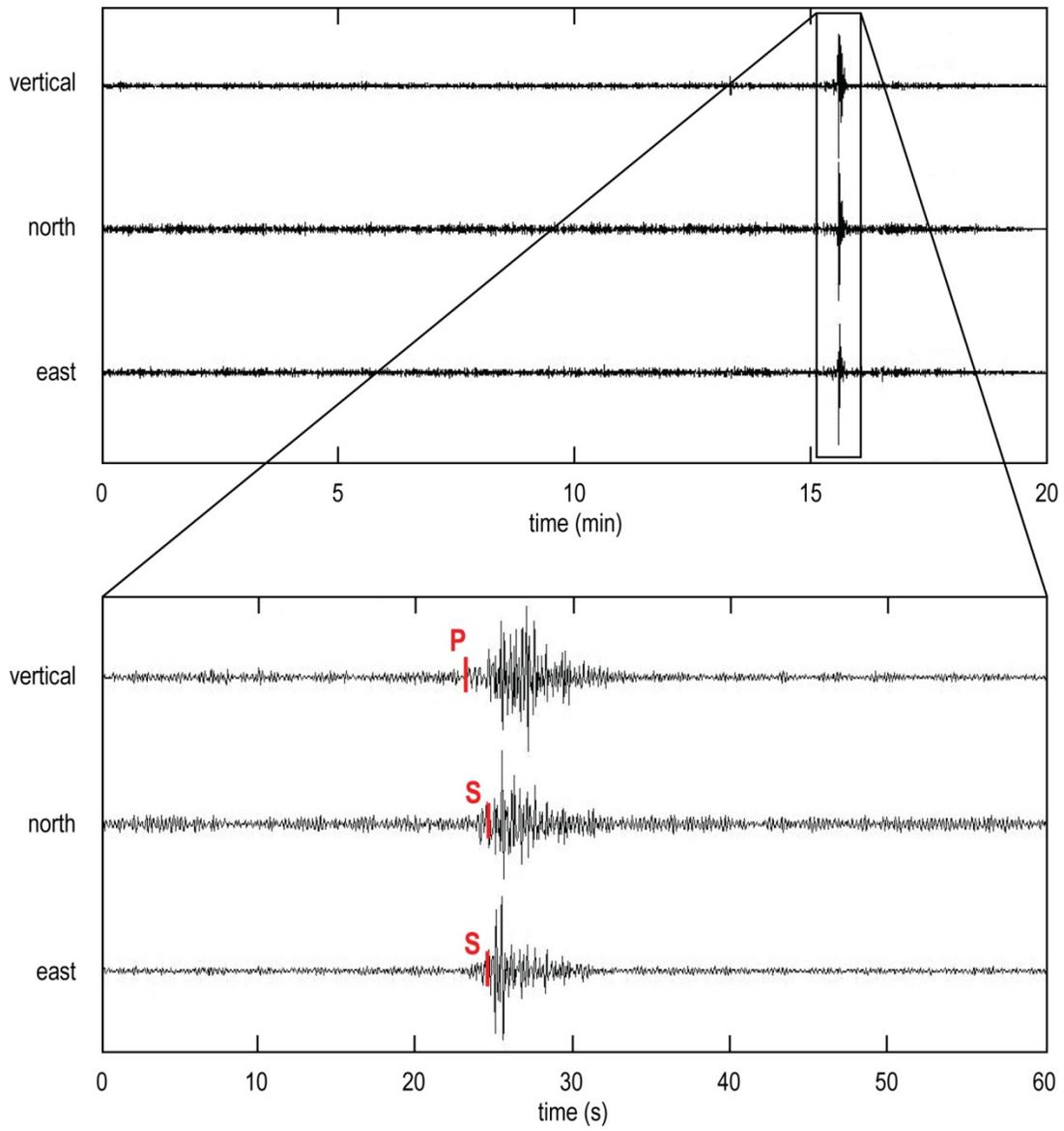
Figure 6. Seismogram of a possible local earthquake detected at station RC01.

Table 1. Possible earthquakes detected within 20 km of RC01 from July 1 to December 31, 2016.

| time (UTC)	distance (km)	magnitude	time (UTC)	distance (km)	magnitude
2016-07-01 11:41	12.1	0.0	2016-11-09 00:40	16.8	0.6
2016-07-03 07:20	6.4	-0.6	2016-11-10 09:48	6.9	-0.4
2016-07-16 03:34	3.2	-0.9	2016-11-14 08:13	4.2	-0.4
2016-07-29 05:02	4.8	-0.6	2016-11-15 03:15	17.7	0.6
2016-08-05 02:15	4.3	-0.4	2016-11-17 09:19	5.5	0.4
2016-08-05 05:04	12.8	0.5	2016-11-19 23:35	10.8	0.0
2016-08-15 06:05	3.9	-0.4	2016-11-20 09:53	6.4	-0.2
2016-08-21 04:38	3.8	-1.5	2016-11-30 15:12	16.0	0.8
2016-08-25 19:38	2.0	0.7	2016-12-06 12:55	6.0	0.1
2016-08-31 07:02	5.2	-0.4	2016-12-06 23:28	7.6	0.6
2016-09-06 07:51	7.1	-0.2	2016-12-15 13:53	6.3	-0.4
2016-09-14 06:53	11.8	-0.2	2016-12-16 13:05	14.7	0.5
2016-09-16 10:15	7.0	-0.4	2016-12-17 18:10	4.4	-0.4
2016-09-18 13:14	13.6	0.6	2016-12-18 04:24	4.7	0.2
2016-09-21 00:49	6.3	-0.6	2016-12-18 04:39	4.4	0.0
2016-09-24 10:50	14.4	0.5	2016-12-18 04:44	4.3	0.3
2016-09-26 01:57	3.9	-0.6	2016-12-18 07:44	10.2	0.1
2016-09-29 10:01	3.9	-0.9	2016-12-18 08:26	3.9	0.1
2016-09-29 10:28	2.9	-0.6	2016-12-18 10:11	5.5	0.4
2016-09-29 12:20	14.5	1.3	2016-12-18 10:18	7.9	0.1
2016-10-02 12:45	6.1	0.2	2016-12-18 12:07	9.6	0.0
2016-10-09 23:48	18.3	0.4	2016-12-18 12:07	4.8	0.0
2016-10-11 23:37	10.9	0.7	2016-12-18 13:04	10.0	0.5
2016-10-12 04:48	5.1	-0.2	2016-12-20 23:24	2.7	-0.2
2016-10-15 00:48	15.7	0.8	2016-12-22 09:05	4.4	-0.2
2016-10-20 04:05	6.3	0.0	2016-12-22 09:06	12.5	0.5
2016-10-21 11:48	8.2	-0.2	2016-12-22 09:50	11.0	0.7
2016-10-23 02:40	5.4	0.1	2016-12-22 09:50	10.9	0.6
2016-10-23 08:10	6.5	0.1	2016-12-23 04:46	8.6	0.3
2016-11-05 03:40	10.8	0.5	2016-12-23 12:24	16.3	0.4
2016-11-05 08:50	7.6	0.3	2016-12-25 08:33	7.7	0.6
2016-11-05 08:51	12.3	0.4			
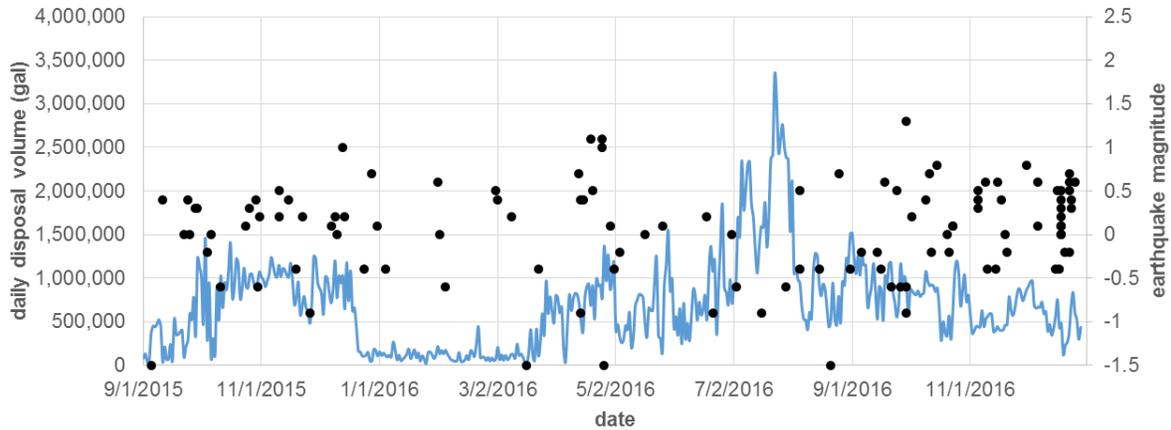
Figure 7. Total daily volume of injected fluid in WWDW#3, WWDW#4, WWDW#5, and WWDW#6 (blue line) and magnitude of microearthquakes (black dots).

Bottomhole pressure (P*) and static fluid level measured annually in the Bushton disposal wells provide insight into the long-term fluid trends within the injection interval (the Arbuckle formation). The static fluid level has increased in recent years (Figure 8) and the available data indicates that bottomhole pressure in WWDW#3 increased between 2007 and 2015 (Figure 9) (Murta, 2016a). These observations are consistent with other regional Arbuckle disposal wells in central and south-central Kansas (Dave Newell, personal communication). Between 2007 and 2016, bottomhole pressure in WWDW#3 increased by 30 psi. Recent model and case studies of induced seismicity suggest that pressure changes ranging from 2 to 30 psi could be enough to initiate slip on critically stressed faults and, therefore, produce earthquakes (Keranen et al., 2014; Hornbach et al., 2015). These measured, regional increases in bottomhole pressures are not directly related to activities in proximity to RC01 but are likely a cumulative effect of historical, regional injection practices.
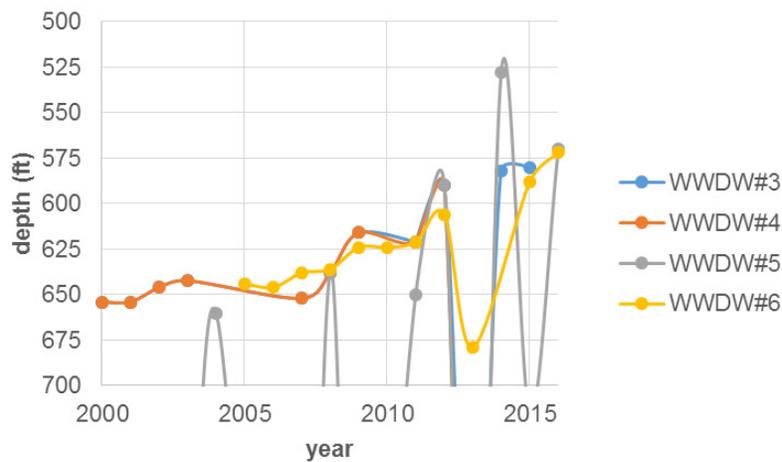
Figure 8. Depth to the static fluid in the Bushton disposal wells.

11
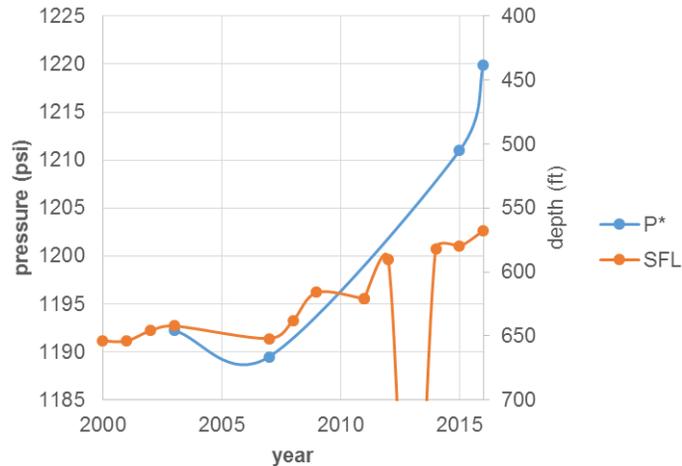
Figure 9. Bottomhole pressure (blue) and static fluid level (orange) in WWDW#3.

Preliminary Interpretation

Consistent with previous observations, seismicity near RC01 continues at a low recurrence rate and with low energy, with two earthquakes of M less than 1 per week, on average, and only one M 1 earthquake detected in the last six-month period. Although the recurrence of earthquakes with M less than 1 increased during December, short-term fluctuations in both natural and induced seismicity can be expected in areas with critically stressed faults and elevated pore fluid pressures. While there is no direct correlation with daily injection operations in the Bushton disposal wells and low energy seismicity, it cannot be definitively ruled out at this early stage. Other case studies from the central interior of the United States suggest a delay of months to years can be expected between changes in injection practices (e.g., rate, volume, pressure) and abnormally elevated seismicity (e.g., Ake et al., 2005; Langenbruch and Zoback, 2016). The period of this delay depends on a variety of site-dependent factors ultimately related to the time for fluid (and associated pressure perturbation) to reach a critically stressed fault.

The increase in microearthquakes in December began 4–5 months after a relatively large but temporary increase in fluid disposal volumes in July 2016. This spike in seismicity (rate of earthquakes increased but at historically consistent magnitudes) in December is noteworthy and justifies continued monitoring, but at this point in the analysis does not appear to be directly related to the increased disposal in July. Enhanced study of historical (prior to the start of operation of RC01) fluid practices and any future changes in fluid operations will allow strong conclusions to be made regarding the likelihood of a relationship between seismicity and fluid injection near RC01. Continued monitoring in 2017 will be crucial for providing insight into the duration and nature of the recent uptick in low-magnitude events before possible causes can be assessed.

Conclusions

Very small earthquakes are ubiquitous and expected almost anywhere a seismic monitoring station is installed. Bushton, Kansas, is no exception. From July 1 to December 31, 2016, 63 seismic events with the characteristics of local microearthquakes occurred within 20 km of seismic monitoring station RC01. In December, the rate of earthquakes approximately doubled, with two unique sequences totaling 11 events observed within a 24-hour period beginning on

December 17. Although there is no direct correlation with these or any microearthquakes within 20 km of RC01 and daily injection activities within 1.5 km, it cannot be definitively ruled out at this early stage. Seismicity near RC01 continues to be low energy with an average of two M less than 1 earthquakes per week and only one M 1 or larger earthquake detected in the last six-month period. Although the recurrence of events with M less than 1 spiked during December, it is not unusual to observe short-term fluctuations in natural as well as induced seismicity in areas potentially influenced by deep fluid injection. Continued monitoring will be crucial to provide insight into the duration and nature of the recent uptick in low-magnitude events before possible causes can be assessed and "normal" background seismicity levels can be established for this area.

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