Baseline Seismicity Observed at Seismograph Station RC01 Located near Bushton, Kansas

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Executive Summary

In the past two years, Kansas has experienced a two-orders-of-magnitude increase in the rate of seismic activity in general across the state, with the vast majority confined to a half-dozen counties in the south-central part of the state. The observed elevated seismicity is generally coincident with a rise in oil and gas production since 2012 and associated disposal of produced formation water. Fluid injection in some 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 depths, and earthquake epicenters suggests a reasonable link between regulated, underground fluid disposal into deep aquifers and the recent elevated seismic activity measured in south-central Kansas. This surge in seismicity is similar in nature to recent, well-documented increases in felt earthquakes in Oklahoma and Texas, where notable increases in waste fluid injection volumes have also been documented.

An underlying requirement to begin understanding and quantifying the potential effects subsurface injection might have, and to help avoid any unintended consequences of waste fluid injection, is the accurate recording and analysis of background seismicity levels across a statistically meaningful length of time and within an area potentially affected by local injection. To obtain a cursory awareness of the background seismicity near Bushton, Kansas, the Kansas Geological Survey deployed a single temporary monitoring station (RC01) that began operation on August 20, 2015. The station has been in continuous operation within the designed signal-to-noise ratio and sensitivity ranges since that time and has provided a 100% continuous data stream.

RC01 is a relatively quiet station with intermittent low levels of surface noise (cultural and ambient). The station is sufficiently sensitive that it can detect earthquakes as small as M 1.5 from distances up to 100 km away. This level of sensitivity is consistent with the standards the Kansas Geological Survey requires for a permanent station. From August 20 to December 31, 2015, thirty-three seismic events with characteristics consistent with local earthquakes were detected within 20 km of station RC01. One-third of these events occurred 11-15 km from the station; this is consistent with the epicentral distance of a M 2.0 earthquake recorded in 1983 (Steeples et al., 1987). This correlation supports the notion that these events are small local earthquakes, with continued movement on critically stressed faults or fractures. In general, the seismicity in this area is very low with one to two M <1 earthquakes observed per week, on average, and only two possible M 1 earthquakes observed in the initial four months of baseline monitoring.

Monitoring beyond the few months reported on here will be critical to ensuring an accurate estimate of recursion relationships and the cycle time on an earthquake with sufficient magnitude to be felt. Secondarily, continued recording at this station will help enhance the earthquake catalog, will contribute to a more accurate understanding of earthquake recurrence, and will be beneficial for early detection and, thus, mitigation of any elevated seismicity associated with changes to existing or start-up of new injection programs.

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., 1990; NEIC webpage). Beginning in 2013, 104 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 (Figure 2) into deep and fractured Paleozoic aquifers by one to two years. In many places, disposal practices allow fluid direct access to basement rocks. The strong spatial and temporal correlation between this increase in disposed fluid volumes, injection well

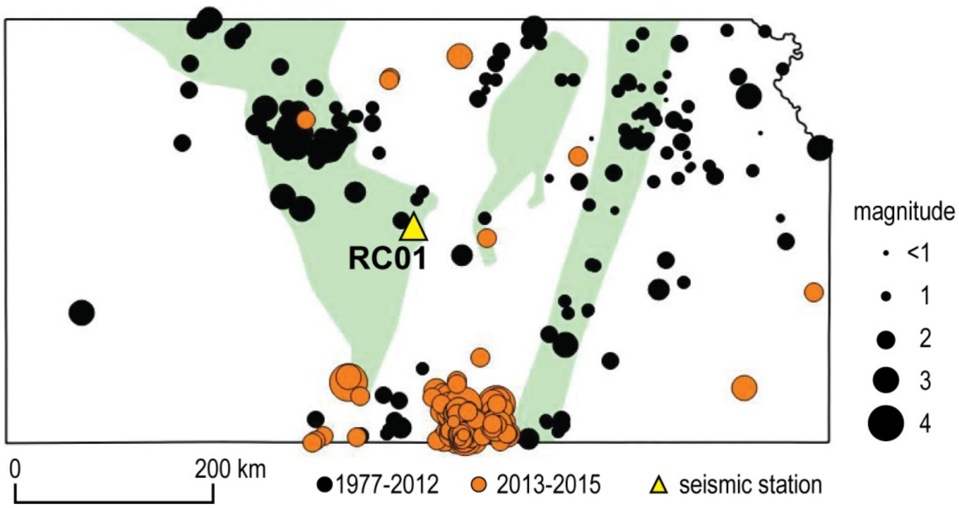

Figure 1. Historic earthquakes (black) and recent earthquakes (orange) superimposed on the prominent geologic structures in Kansas (green). Station RC01 (yellow triangle) is located near the center of the state.

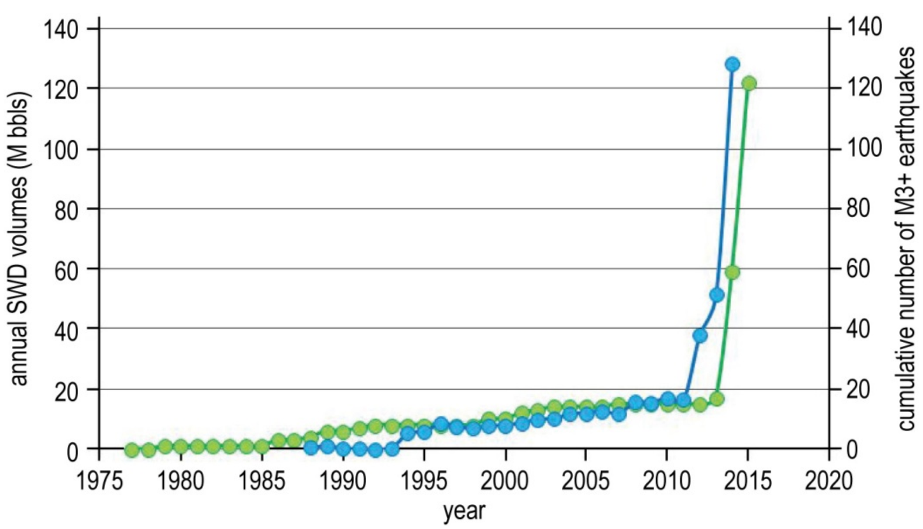

Figure 2. Annual saltwater disposal (SWD) volumes in Harper and Sumner counties (blue) and cumulative number of earthquakes with magnitude 3.0 or greater in Kansas (green).

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 over 1500 earthquakes in six years, the largest of which—originally estimated as a magnitude 5.0 to 5.5—occurred over a year after injection was terminated (Healy et al., 1968). Fluid injection raises pore pressure within the injection interval and at 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* and *Science Advances* (Weingarten et al., 2015; Walsh and Zoback, 2015) statistically relate large instantaneous and/or cumulative volumes of wastewater injected into near-basement aquifers as drivers for inducing earthquakes as much as 20 km from the injection point. 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 of course volume of injected fluid per square mile.

With the strong correlation between recent increased volumes/rates of injected waste water and seismicity comes concern that any changes to existing or start-up of 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 are 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.

To obtain a cursory awareness of the background seismicity near Bushton, Kansas, the KGS deployed a temporary, three-component seismic monitoring station (RC01) on August 20, 2015. In this report, we present findings from four months of baseline recording. Data are preprocessed to attenuate seismic "noise" from regional or distant earthquakes and nearby cultural activity, allowing discrimination of possible local microearthquakes ($M < 2$). Single-station analysis of compressional- (P) and shear- (S) wave arrivals and the coda time will provide approximate distance from RC01 and magnitude of possible local earthquakes. Analysis will focus on earthquakes within 20 km of the station. Twenty kilometers is the largest distance between an induced earthquake epicenter relative to a suspected high-volume injection well reported in refereed literature (Keranen et al., 2014).

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, 176 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, nineteen earthquakes were reported in Kansas by the National Earthquake Information Center (NEIC) with an average magnitude of 2.9. 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 natural movement due to regional crustal stress on existing faults and fractures associated with prominent geologic structures are 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 and with hydraulic connection to basement rocks.

Monitoring Station Installation

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

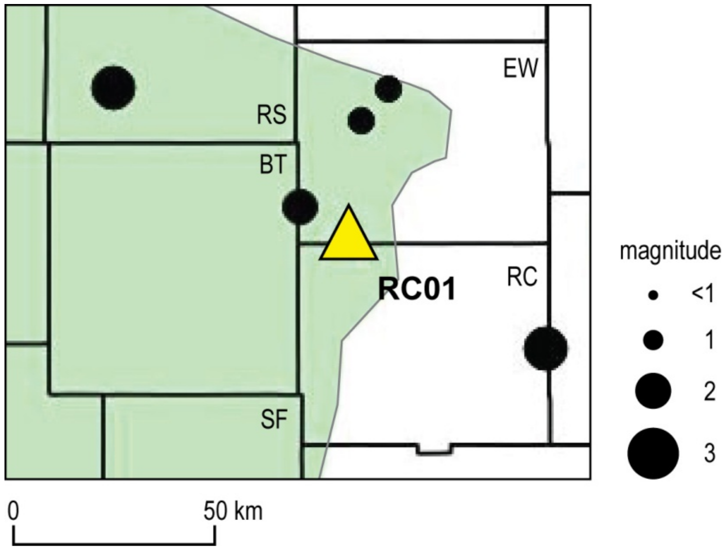

Figure 3. Station RC01 (yellow triangle) is located on the eastern margin of the Central Kansas Uplift (green). Five natural earthquakes (black) ranging from M 1.7 to 2.7 were recorded in this area from 1981 to 1983.

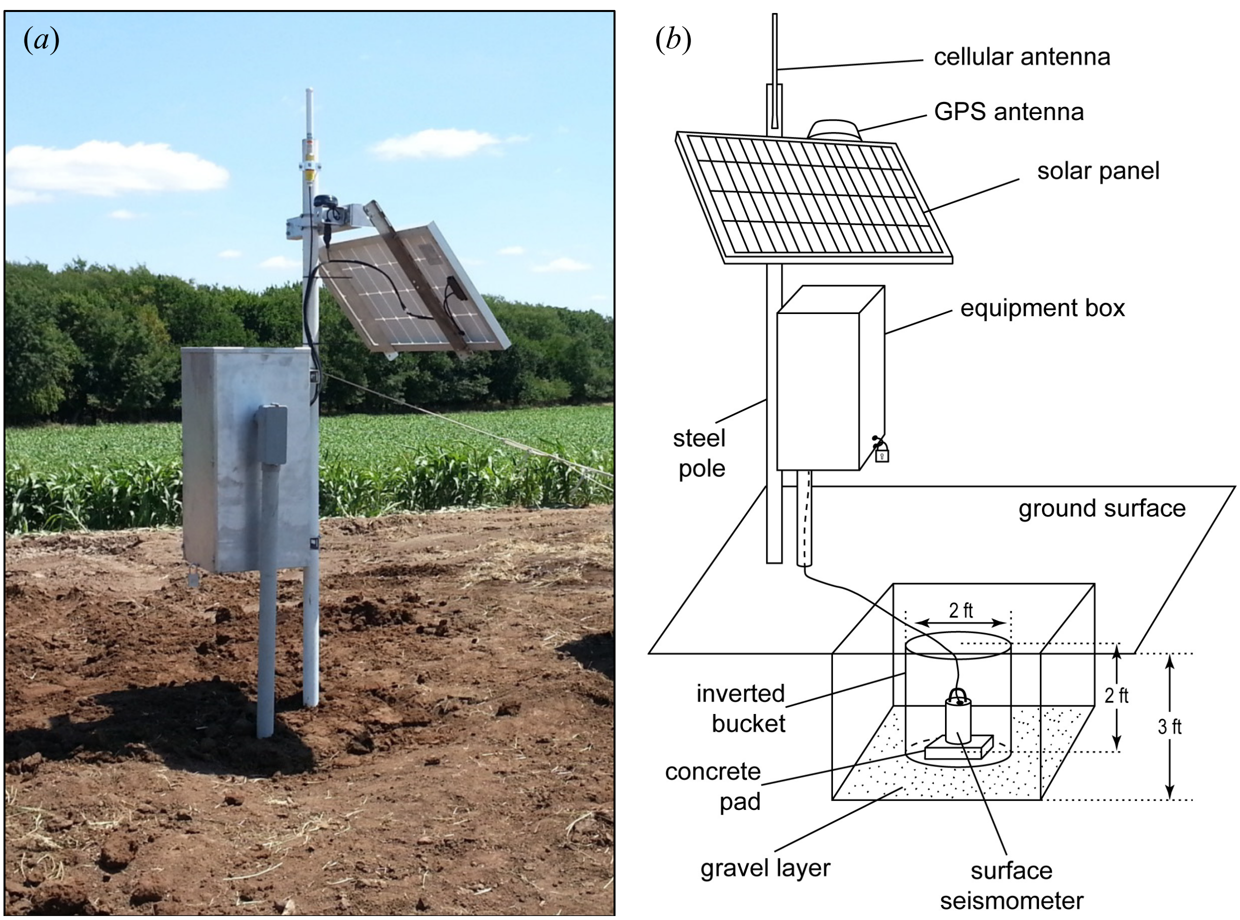

Figure 4. (*a*) Seismic station RC01 installed near Bushton, Kansas. (*b*) Diagram illustrating a temporary seismic monitoring station.

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 real-time via cellular telemetry to a server at KGS. Since installation, station RC01 has been operating within the designed signal-to-noise ratio and sensitivity ranges with a 100% continuous data stream.

Seismic Event Analysis

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 (Figure 5). 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 6). 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 et al., 1978):

$$Mc = 1.86\log(t_c) - 1.49\,. \tag{3}$$

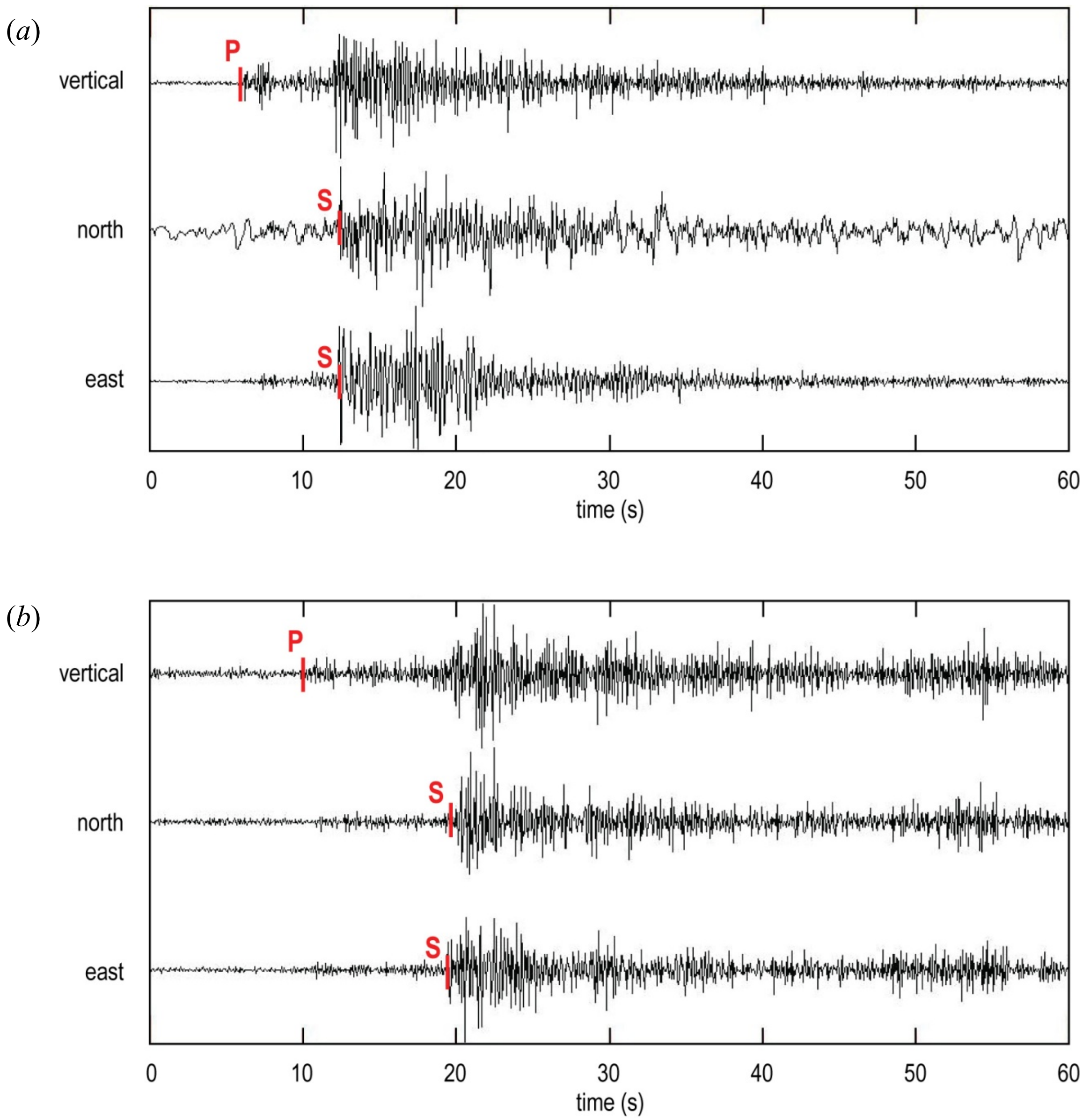

Figure 5. P-wave and S-wave arrival times marked on the seismograms of an earthquake at a distance of (*a*) 50 km and (*b*) 70 km.

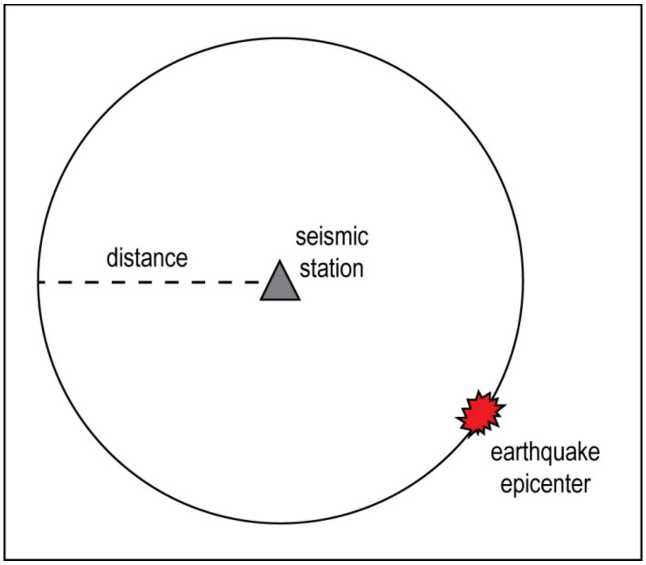

Figure 6. The epicenter of an earthquake exists somewhere on a circle centered on the seismic station with radius equal to the calculated epicentral distance.

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. Seismic noise often has sporadic arrivals, inconsistent amplitudes, and lacks distinct earthquake phases (Figure 7). Local earthquakes have distinct phases and waveforms 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 continuous waveform data to attenuate low-frequency noise and regional or distant earthquakes. Seismic events evident within this passband were inspected for apparent P- and S-waves to discriminate 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.

Example of methodology used from confident earthquake energy recorded at Station SG01

Local earthquakes that are too small to locate are frequently observed at stations in the south-central Kansas network, operated by the KGS. Several such events were observed at station SG01 both before and after larger earthquakes. For example, 16 local earthquakes (e.g., Figure 8) were observed during the first week of October 2015 (Table 1). These events are low magnitude, ranging from less than M 0 to M 0.6, and occur 7-20 km from the station. Plotting each event as a circle with radius equal to the earthquake distance indicates the general pattern of seismicity. Although this kind of analysis does not provide mapped earthquake locations, it does provide general information about the seismicity (size, distance, recurrence) and is consistent with epicenters of larger earthquakes located by the regional network (Figure 9).

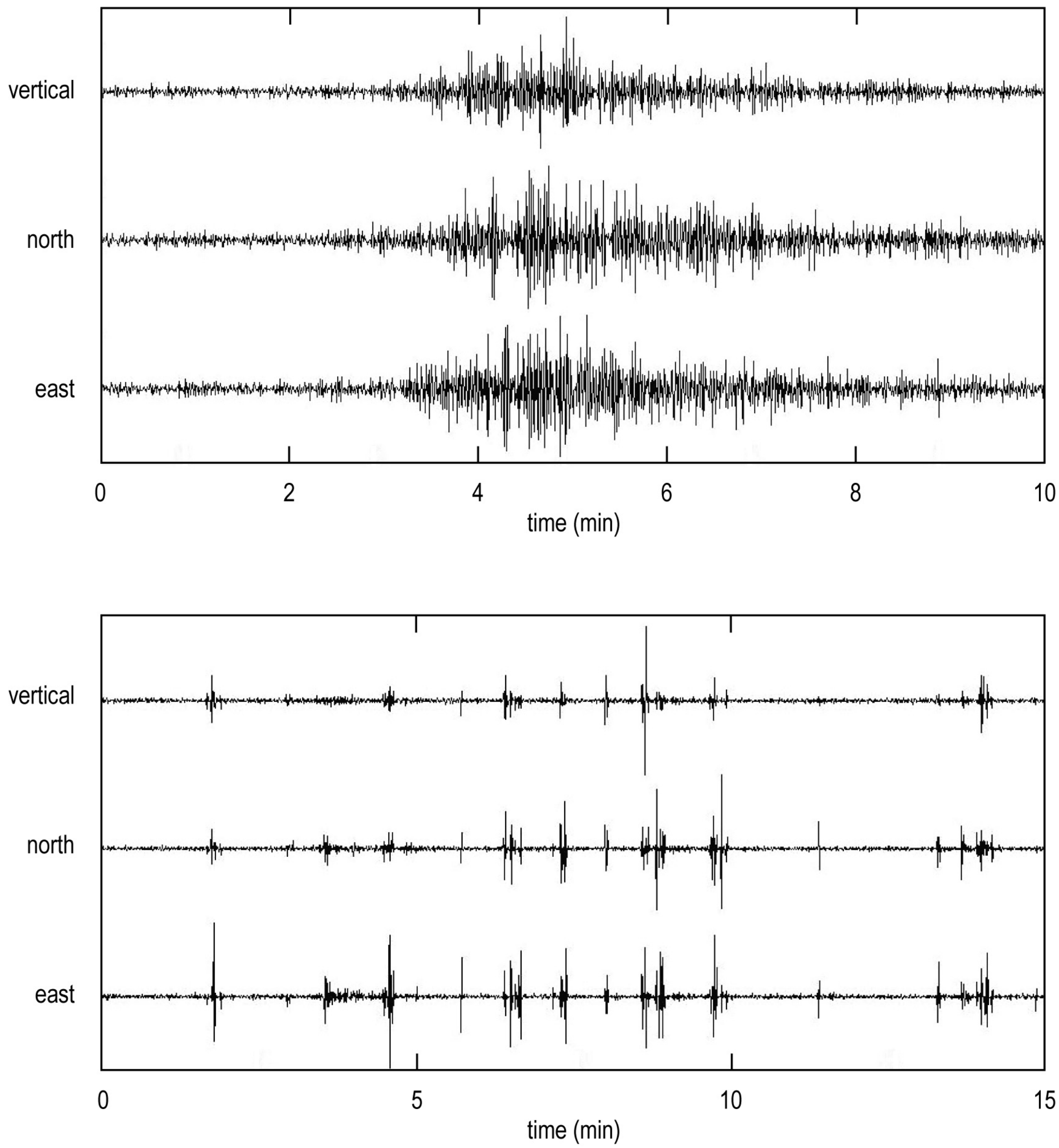

Figure 7. Seismograms with examples of seismic noise recorded by stations in the south-central Kansas temporary network.

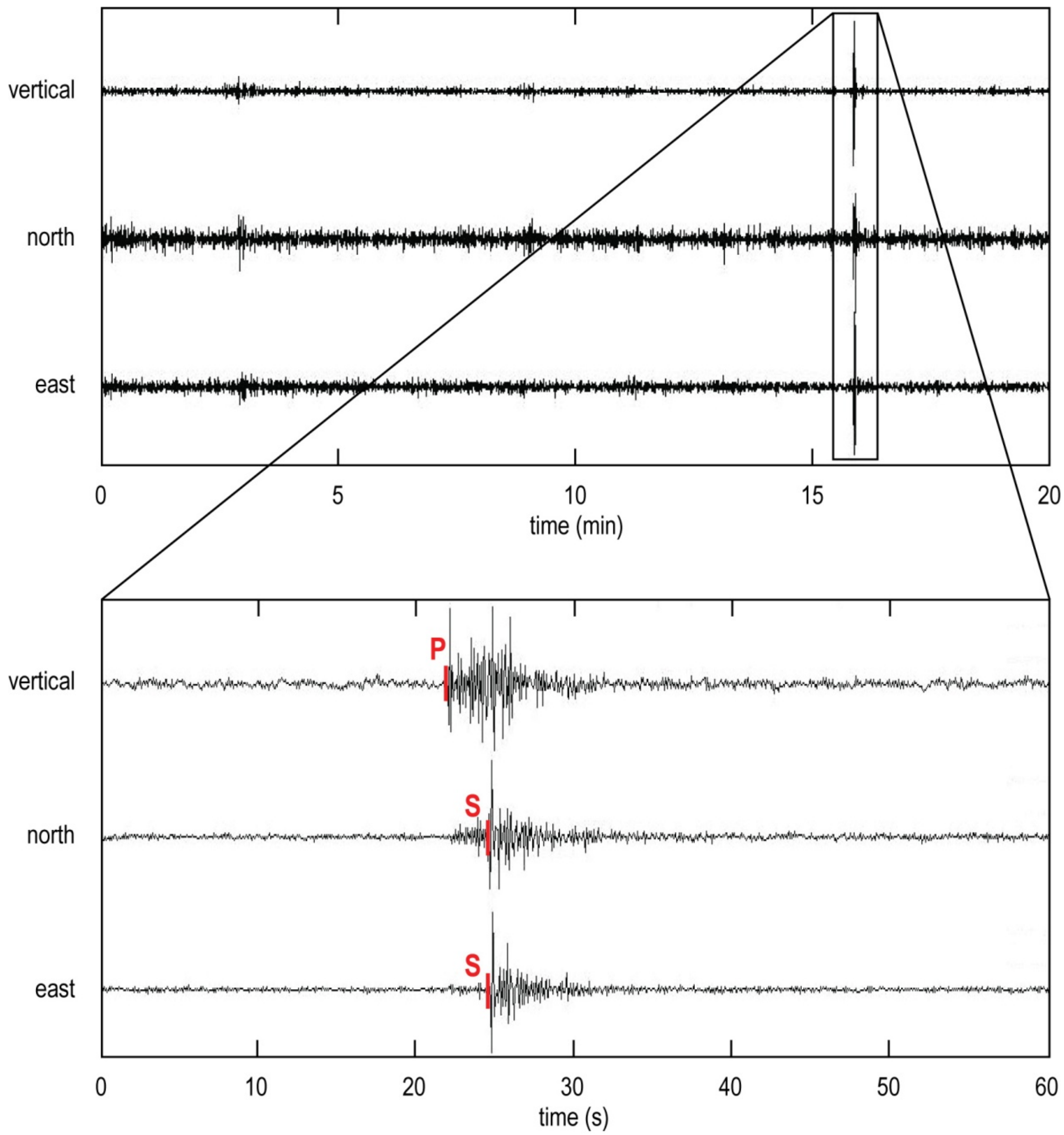

Figure 8. Seismogram of a local earthquake recorded at station SG01 in the south-central Kansas network.

Table 1. Local earthquakes observed at station SG01 the first week of October 2015.

time (UTC)	distance (km)	magnitude	time (UTC)	distance (km)	magnitude
10/1/15 0:51	6.6	-0.9	10/4/15 9:26	14.6	0.0
10/1/15 0:00	10.9	0.6	10/4/15 13:25	14.6	0.0
10/1/15 1:59	10.2	0.0	10/6/15 6:06	18.2	0.1
10/1/15 3:10	14.6	-0.1	10/6/15 6:21	16.0	0.1
10/1/15 17:04	14.6	0.2	10/6/15 6:41	14.6	0.0
10/3/15 1:12	10.9	0.0	10/6/15 13:19	15.3	0.0
10/3/15 12:48	10.2	-0.4	10/6/15 18:04	13.8	0.2
10/3/15 15:43	8.7	0.3	10/7/15 7:54	15.3	0.1

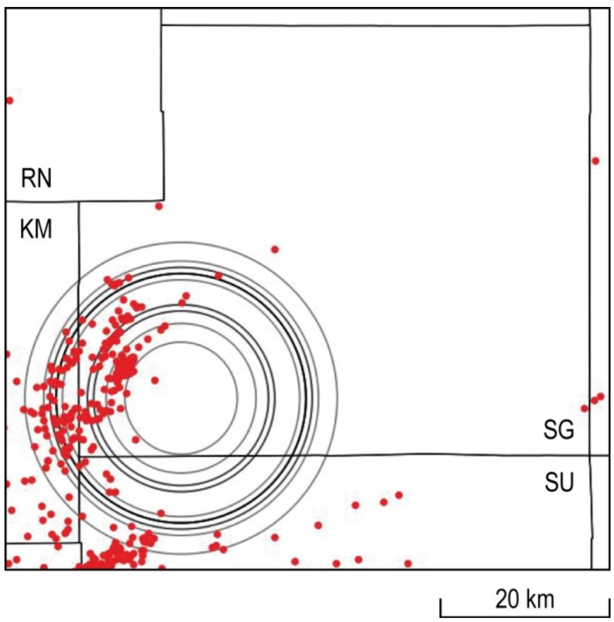

Figure 9. Epicentral distances of local earthquakes (open circles) detected at SG01 are, in general, consistent with epicenters of larger earthquakes located by the south-central Kansas network in 2015 (red dots).

Baseline Observations at RC01

RC01 is a relatively quiet station with intermittent surface noise (cultural and ambient). The station has shown high sensitivity to M 1.5 earthquakes at distances up to 100 km away. These are criteria that are consistent with the standards and sensitivity required for a permanent station in Kansas. Seismic events are observed daily, the majority of which are earthquakes M 1.5+ from south-central Kansas and northern Oklahoma. Small, local earthquakes (e.g., Figure 10) are discriminated from these more distant regional events based on their short P-S arrival time difference and higher dominant frequencies.

From August 20 to December 31, 2015, thirty-three possible earthquakes were detected within 20 km of RC01 (Figure 11, Table 2). Magnitudes of these events range from -1.5 to 1.0, well below what are generally felt (typically M 2.5 or greater). With only one station, local earthquakes cannot be discriminated from nearby cultural noise with complete certainty. However, these events have characteristics—distinct arrivals of P- and S-waves and high dominant frequency—that are consistent with possible local earthquakes.

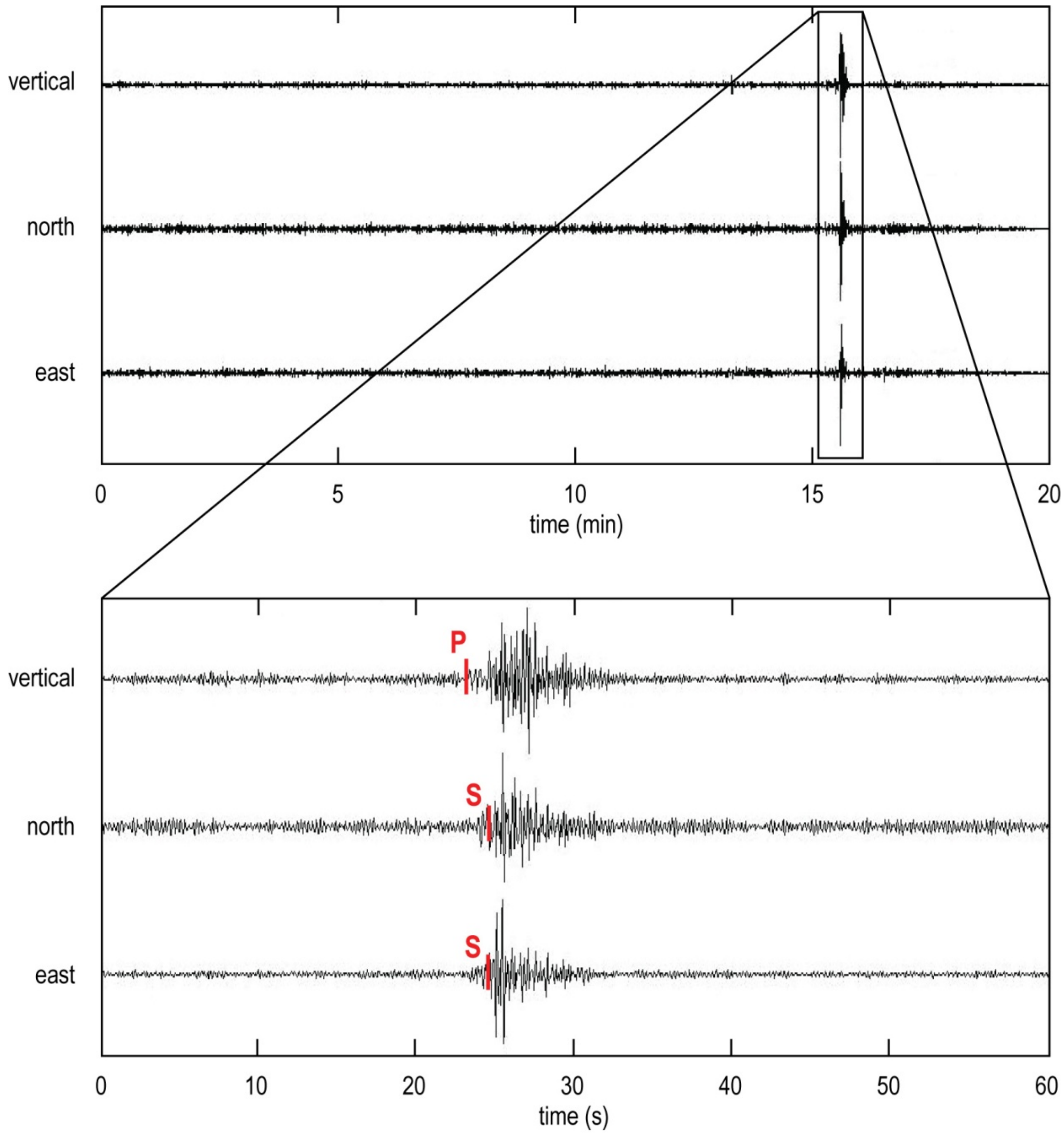

Figure 10. Seismogram of a possible local earthquake detected at station RC01.

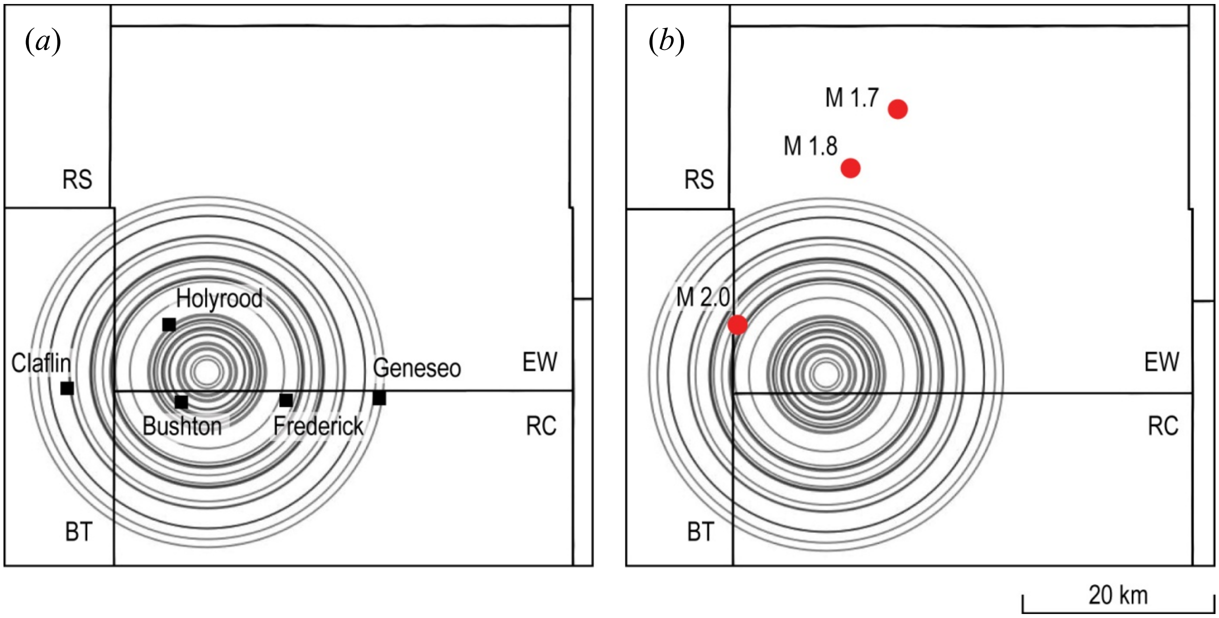

Figure 11. Epicentral distances for possible local earthquakes (open circles) detected at RC01 relative to (*a*) nearby population centers and (*b*) epicenters of historic earthquakes (red).

Table 2. Possible earthquakes detected within 20 km of station RC01.

time (UTC)	distance (km)	magnitude	time (UTC)	distance (km)	magnitude
8/20/15 21:13	17.4	1.0	10/30/15 0:40	2.5	-0.6
8/29/15 11:47	5.9	-0.2	10/31/15 0:57	12.4	0.2
8/31/15 11:18	4.9	-0.6	11/10/15 11:55	10.5	0.5
8/31/15 18:38	4.2	0.0	11/10/15 17:23	10.7	0.2
9/5/15 7:38	3.1	-1.5	11/15/15 23:37	18.6	0.4
9/11/15 1:08	14.4	0.4	11/19/15 8:26	10.5	-0.4
9/22/15 12:46	5.0	0.0	11/22/15 11:20	12.7	0.2
9/24/15 12:05	11.5	0.4	11/26/15 15:52	4.1	-0.9
9/25/15 12:05	6.5	0.0	12/7/15 3:24	12.9	0.1
9/28/15 0:35	5.5	0.3	12/9/15 13:29	15.1	0.2
9/29/15 1:06	19.5	0.3	12/10/15 23:07	1.4	0.0
10/4/15 6:54	3.3	-0.2	12/13/15 1:31	8.5	1.0
10/6/15 4:56	2.7	0.0	12/14/15 23:12	17.4	0.2
10/11/15 1:51	4.7	-0.6	12/24/15 22:55	5.8	-0.4
10/24/15 8:21	10.1	0.1	12/28/15 21:49	15.2	0.7
10/26/15 9:26	6.3	0.3	12/31/15 11:07	1.8	0.1
10/29/15 13:01	12.8	0.4			

Preliminary Interpretation

The seismic events observed near RC01 fall within three spatial groupings at approximately 4 km, 11 km, and 17 km from the station. These distances roughly coincide with nearby small incorporated towns (population <1000) (Figure 11a). If some of the seismic events were associated with industrial, agricultural, or other cultural activities in or near these population centers, it is likely there would be a bias in the time of day these events occur. Seismic events related to cultural activities are, in general, more likely to occur during daylight hours, while passive geologic processes are equally likely to occur day or night. Fewer than half of the events observed at RC01 occur between 7 AM and 7 PM local time. Although this does not definitively confirm that these seismic events are passive geologic processes, the timing does not suggest cultural activity.

Events located approximately 11 km from RC01 are consistent with the epicenter of a M 2.0 earthquake that occurred on September 7, 1983 (Figure 11b). This correlation supports the notion that the observed 11 km seismic events may be associated with movement on nearby critically stressed faults or fractures. If these events are earthquakes, fault slip is low-energy (very small segment of fault plane experienced relative movement), probably began prior to industrial operations, and likely is natural. No large or damaging earthquakes have been observed in this area since instrumented monitoring began 38 years ago and, therefore, the frequency of such events is at present too small to be known. In general, the seismicity in this area is very low with one to two M <1 earthquakes observed per week, on average, and only two possible M 1 earthquakes observed in the initial four months of baseline monitoring.

The timing of the M 0.1 event on December 31, 2015, at 11:07 universal time coordinated (UTC) is coincident with the arrival of the surface wave generated by a distant earthquake—a M 5.7 with epicenter located off the coast of Nicaragua (NEIC webpage) (Figure 12). The stress perturbations caused by passing seismic waves (generally surface waves) from a moderate to large distant earthquake can trigger slip and, thus, an earthquake on a local stressed fault. This phenomenon is known as remote or dynamic triggering and is generally associated with natural seismicity (Freed, 2005; Hill and Prejean, 2007; Velasco et al., 2008). Several studies indicate that distant earthquakes can trigger local microearthquake activity (Hill et al., 1993; Stark and Davis, 1996; Jiang et al., 2010) with magnitudes as small as M 0 (Aiken and Peng, 2014). Given the coincident origin time of the local event on December 31, 2015, and the arrival of the surface wave from the Nicaragua earthquake, this event was most likely remotely triggered and further supports natural, low-energy movement on a critically stressed fault near RC01.

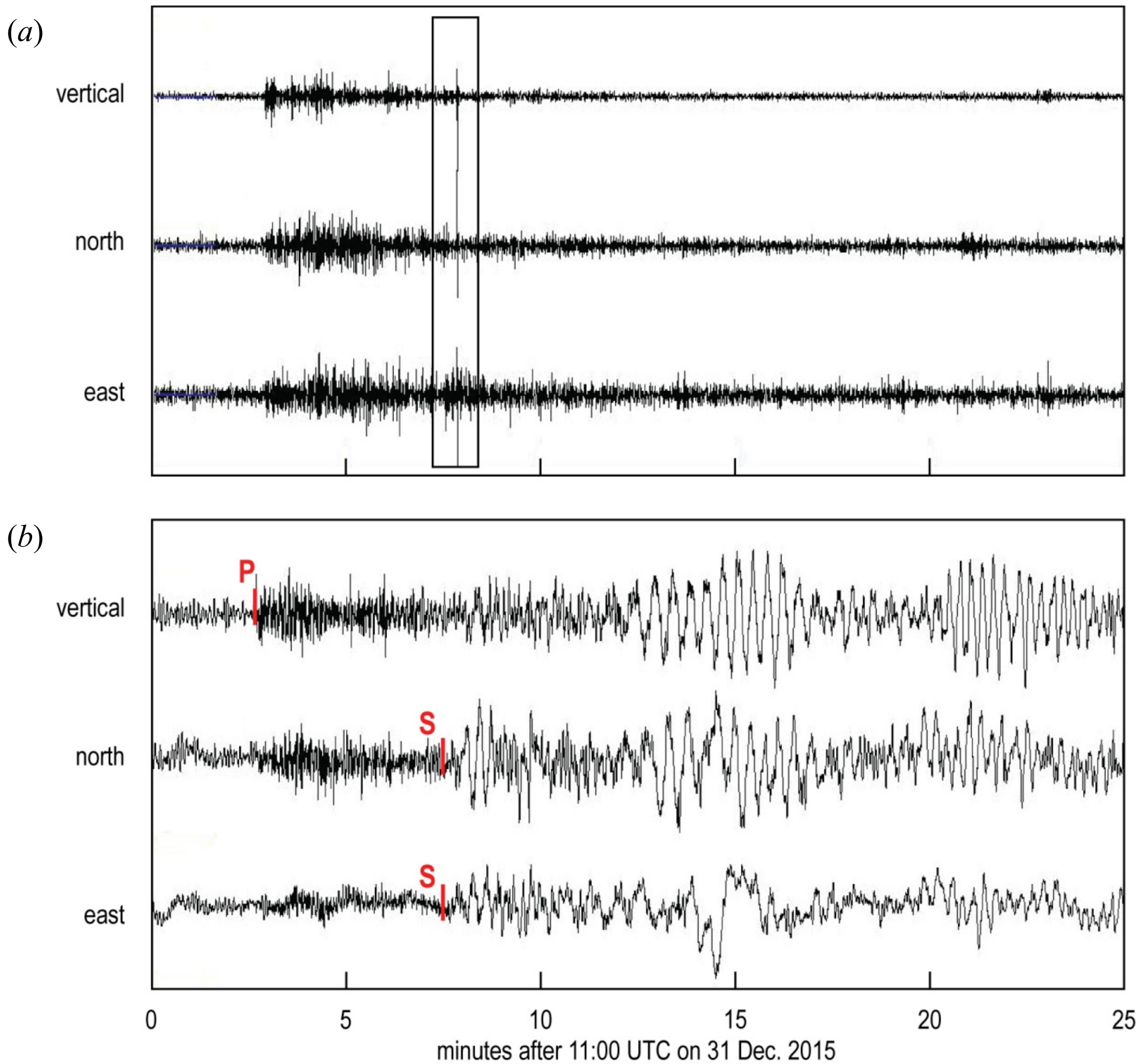

Figure 12. Seismogram of (*a*) a local earthquake (black box) observed at station RC01 on December 31, 2015, at 11:07 UTC and (*b*) a M 5.7 earthquake from Nicaragua recorded by a broadband sensor operated by the USGS in south-central Kansas.

Conclusions

Very small earthquakes are ubiquitous and expected to be observed almost anywhere a seismic monitoring station is installed—Bushton, Kansas, is no exception. During four months of recording, 33 seismic events originated within 20 km of station RC01 and had characteristics consistent with local earthquakes. Approximately one-third of these events have an epicentral distance of 11-15 km from the station, which is consistent with the epicentral distance of a M 2.0 earthquake recorded northwest of RC01 in 1983. One event was apparently triggered by stress perturbations from the surface wave generated by a M 5.7 earthquake in Nicaragua. These observations/correlations support the notion that these events are small local earthquakes and are indicative of natural movement on critically stressed basement faults or fractures in this area. In general, the seismicity in this area is low, with only two possible M 1 earthquakes observed in the initial four months of baseline monitoring. Continued monitoring will enhance establishment of earthquake trends (if there are any), contribute to a more accurate understanding of earthquake recurrence, and be beneficial for early detection and, thus, mitigation of any abnormally elevated seismicity associated with changes to existing or start-up of new injection programs.

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