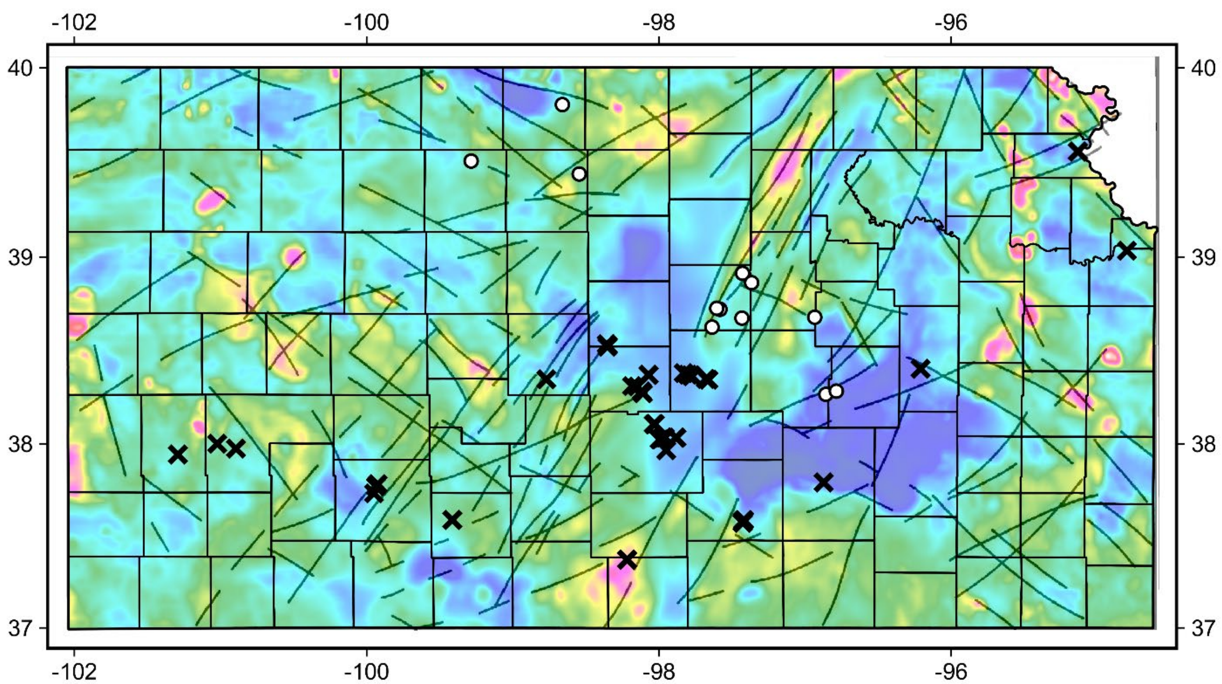
Consortium to Study Trends in Seismicity



July 1, 2024 – June 30, 2025

Draft Annual Report by
Rex Buchanan, Shelby Peterie, and Rick Miller

Kansas Geological Survey Open-file Report 2026-35

Cover Figure Caption: Earthquakes (white) located using CSTS stations that otherwise would have not been located by any other seismic network overlaying the state aeromagnetic map in color. Correlated with structural trends, the earthquakes provide insight into the stress conditions and relative stability of both unmapped faults and faults interpreted geologic and geophysical datasets.

Kansas Geological Survey
Consortium to Study Trends in Seismicity

2024-2025 Draft Annual Report

NOTICE: This annual report was released in draft to Consortium members on October 23, 2025, and will be subject to further review and comment by Consortium members until April 23, 2026. The KGS is then allowed an additional three months to revise the draft report and distribute the final annual report.

 This study was conducted in complete compliance with ASTM Guide D7128-05. All data, interpretations, and opinions expressed or implied in this report and associated study are reasonably accurate and in accordance with generally accepted scientific standards.

CONSORTIUM TO STUDY TRENDS IN SEISMICITY
KANSAS GEOLOGICAL SURVEY
Fourth Quarter / Annual Report
July 1, 2024 – June 30, 2025

INTRODUCTION

The Kansas Geological Survey's Consortium to Study Trends in Seismicity (CSTS) is a public-private project aimed at studying trends in seismicity in Kansas. The consortium focuses on areas where public and private entities benefit from high-sensitivity seismic monitoring and scientifically supported projections. Seismicity increased significantly in Kansas and the midcontinent around 2013, leading to a need to better define and understand earthquake activity, particularly as it relates to subsurface fluid disposal. The CSTS oversees the operation of a seismic network that records and allows accurate location, and magnitude estimates of seismicity for felt earthquakes and particularly for microseismic events that are hundreds of times smaller than can be routinely identified with previous regional seismic networks. Understanding current micro-trends in seismicity and establishing a data-driven awareness of potential factors affecting seismicity should help with industry response, guide governmental oversight, and inform public opinion.

The CSTS is operated by the Kansas Geological Survey (KGS), a research and service division of the University of Kansas with a long history of studying the state's subsurface and seismic issues. Current members of the CSTS are from the state's Underground Injection Control Class I disposal well community (Class I wells are used for disposal of municipal and industrial waste and regulated by the Kansas Department of Health and Environment [KDHE]). Membership in the CSTS is voluntary and open to any industry partner. The CSTS objective is identifying and understanding seismicity at magnitudes down to zero in proximity to member facilities. The CSTS works to establish baseline or background seismicity near those facilities, provide a scientific basis for differentiating natural from induced seismicity, and predict future earthquake occurrences. Confidence in distinguishing natural from induced earthquake trends and predicting future occurrences is greatly enhanced through extended monitoring periods relying on stations near earthquake epicenters.

The following report describes the eighth year of CSTS activities, including a discussion of membership status; network station installation and operation; earthquakes recorded and identified, and earthquake alerts provided to members; web page development; other activities, especially involving publications, presentations, and meeting attendance; and plans for the coming year. Three quarterly reports were provided to members after the Consortium's annual meeting in August 2025. This current report includes summaries of seismicity and CSTS activities in both the past quarter (April, May, and June of 2025) and for the past 12 months.

STATUS OF MEMBERS

The CSTS was established with a two-tier membership system. For Tier 1 members the CSTS provides equipment, installation, and monitoring of a seismograph station; maintains a catalog of seismic events, updated weekly, with a goal of providing e-mail alerts within 24 hours or less of any earthquakes greater than magnitude 2 within 30 miles of a facility; provides quarterly updates on monitoring findings; and hosts an annual meeting at which results from the past year are discussed and plans formulated for the coming year. Tier 2 members have access to information related to the general seismicity being studied by the CSTS and can attend the annual meeting, but do not have the right to vote at that meeting or use the reports while still under confidential status. The CSTS currently has twelve Tier 1 members.

STATUS OF NETWORK

The CSTS seismic network currently consists of twelve stations in Ellsworth, Rice, McPherson, Reno, Kiowa, Sedgwick, Butler, Johnson, and Atchison counties, Kansas (Figure 1, Appendix A). Waveforms for these stations are available for Tier 1 members on the seismic network page of the CSTS website. For each of those locations, ambient noise tests were completed to establish background noise levels. Those tests identified noise from nearby highways, trains, pump jacks, and other facilities that might interfere with earthquake analysis. Stations were relocated when initially deployed in places where noise and vibrations interfered with station response characteristics above a pre-determined threshold as determined by a site-specific ambient noise test. Many of the existing sites are in cemeteries, on government property, or in remote locations where noise levels are measured and determined to be low and likely to remain low. In all cases, KGS has obtained written agreements with landowners of each station's location.

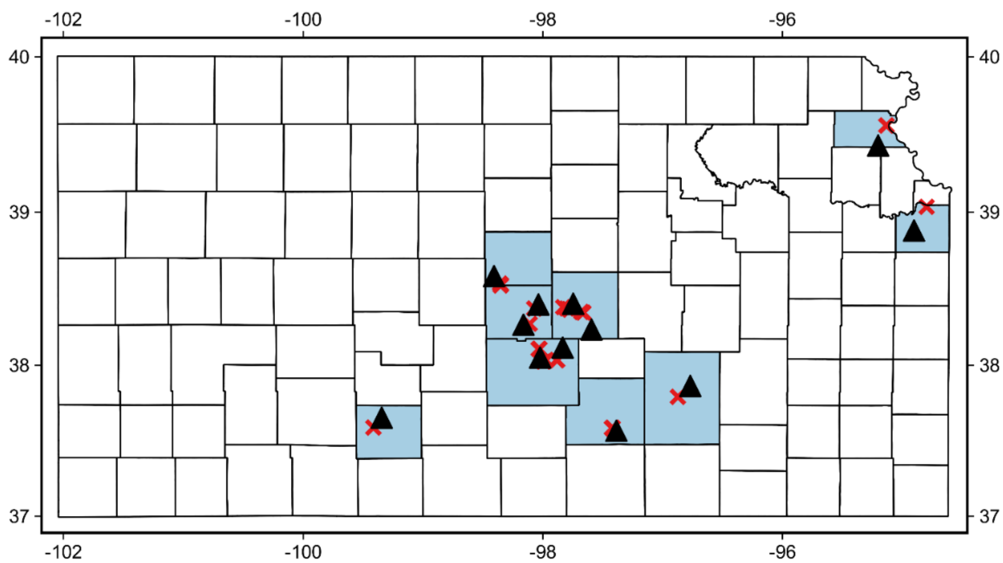


Figure 1. Earthquake stations (black triangles) with member facilities (red X) provide high sensitivity coverage with the potential to identify earthquakes with magnitudes below 0 within 20 miles of each facility.

Each station consists of a seismic sensor that includes a shallowly buried seismometer embedded in a concrete platform atop a gravel layer and a digitizer (Figure 2). Ground motion detected by the seismometer is transmitted back to KGS offices in Lawrence real-time via a cellular modem. That communication system is powered by a solar panel that charges two deep-cycle marine batteries. The footprint for each station is approximately 10 feet by 10 feet. The stations operated over the last year within designated operational sensitivity and signal-to-noise ratio.

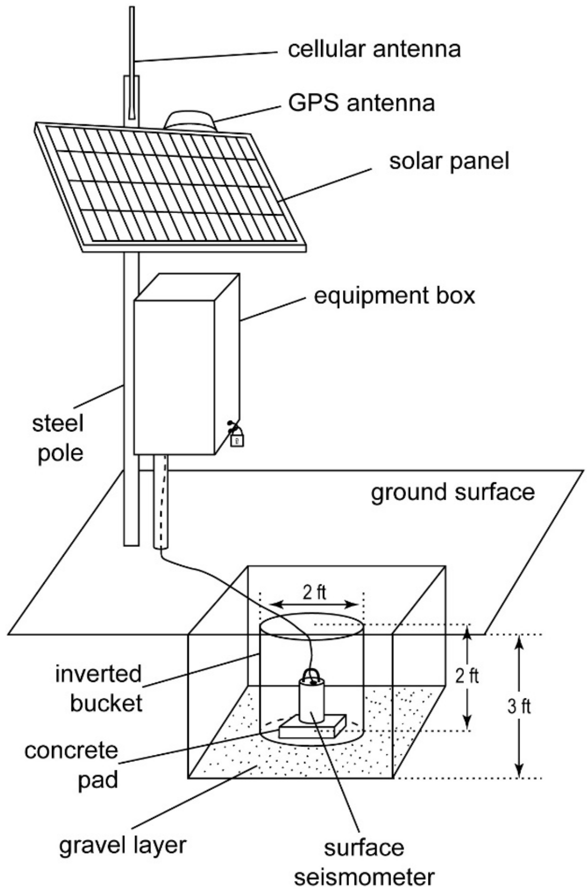


Figure 2. Diagram illustrating a temporary seismic installation.

EARTHQUAKE ALERTS, CATALOG

Earthquakes with a magnitude of 2 or larger represent a threshold above which energy levels provide highly confident automatic analysis for feeds coming from a network as dense as the CSTS network and especially in conjunction with the KGS regional and subregional networks. It is therefore reasonable to provide accurate epicenter locations using automated picking routines for each event down to M 2, with results available within minutes of the fault rupture and release of energy. KGS staff notify CSTS members of a M 2 or larger earthquake within 30 miles of Tier 1 member wells. Earthquakes below magnitude 2.5 are generally considered below felt levels. Earthquakes with magnitudes down to 1 can be located with confidence in areas where at least three CSTS stations are within 50 miles of each other. There were 35 earthquake alerts from July 2024 through June 2025 (Table 1), similar to the 2023-2024 reporting year. The majority of this year's alerts (80%) occurred in Saline County, where seismicity dramatically increased in 2021 but has since tapered off to lower (but still elevated) rates, as discussed in later sections.

ORIGIN TIME (UTC)	LATITUDE	LONGITUDE	MAGNITUDE	COUNTY
2024-07-12 01:54:41	38.67992	-97.63522	2.7	Saline
2024-07-27 08:01:22	38.69237	-97.56776	2.7	Saline
2024-07-27 13:02:39	38.68139	-97.56293	2.4	Saline
2024-07-28 11:53:04	38.68802	-97.52949	2.4	Saline
2024-07-29 18:00:34	38.68012	-97.56241	2.1	Saline
2024-07-29 23:45:28	37.72850	-98.00090	2.3	Kingman
2024-08-02 07:19:14	38.68232	-97.52088	2.1	Saline
2024-08-07 11:44:16	38.68713	-97.51862	2.5	Saline
2024-08-12 00:30:41	38.67510	-97.63432	2.8	Saline
2024-08-13 12:14:40	38.67892	-97.62263	2.1	Saline
2024-08-28 23:19:57	38.73585	-97.62466	2.5	Saline
2024-10-20 10:52:05	37.73217	-97.97984	2.2	Kingman
2024-10-23 08:38:39	38.68421	-97.52319	2.1	Saline
2024-12-08 11:44:14	38.67987	-97.51499	2.4	Saline
2024-12-09 09:05:09	38.68095	-97.53741	2.1	Saline
2024-12-31 10:14:00	38.67247	-97.64304	2.5	Saline
2025-01-16 04:53:18	38.67532	-97.64236	2.5	Saline
2025-02-11 23:53:55	38.67089	-97.63527	2.8	Saline
2025-02-17 09:07:53	38.67365	-97.65429	2.5	Saline
2025-03-09 17:36:45	38.68754	-97.57330	2.5	Saline
2025-03-10 19:11:50	38.67060	-97.65065	3.0	Saline
2025-03-18 02:25:42	37.29005	-99.71953	2.3	Clark
2025-03-24 20:57:04	37.40431	-97.76451	2.1	Sumner
2025-03-24 23:28:46	37.40384	-97.76222	2.1	Sumner
2025-03-25 00:40:50	37.40644	-97.77085	2.1	Sumner
2025-03-25 03:22:20	37.40762	-97.75298	2.8	Sumner
2025-03-26 23:37:25	38.64741	-97.65163	2.7	Saline
2025-03-27 05:43:04	38.67032	-97.63553	2.3	Saline
2025-03-27 05:46:51	38.67040	-97.63664	2.1	Saline
2025-03-30 06:28:05	38.68023	-97.51192	2.3	Saline
2025-04-17 10:23:00	38.67694	-97.53288	2.4	Saline
2025-06-24 04:31:00	38.67493	-97.62528	2.2	Saline
2025-06-25 04:55:00	38.64254	-97.47723	2.2	Saline
2025-06-25 05:22:00	38.64937	-97.47247	2.2	Saline
2025-06-25 08:47:00	38.63144	-97.47174	2.9	Saline

Table 1. M 2 or larger earthquakes recorded from July 2024 through June 2025 with epicenters located within 30 mi of member wells.

INTERESTING OBSERVATIONS AND SIGNIFICANT TRENDS

Regional Seismicity (M 2 or larger)

During the past year, 292 earthquakes magnitude (M) 2 or larger were recorded in Kansas (Figure 3). This is a more than 30% increase in the number of events of this size compared to the 2023-2024 reporting year, ending the years-long trend of consistent gradual decline. The majority of earthquakes either occurred in parts of the state where historic earthquakes, occurred along prominent basement structures, or where earthquakes were recorded in recent years. Notable exceptions are two sequences of earthquakes in Graham and Mitchell counties. Although M 2 or larger earthquakes have been reported previously in both counties, prior seismicity was relatively isolated and low magnitude. Active sequences with the largest earthquakes ever reported in these counties occurred this year, with four M 3 or larger in both counties.

South-Central Kansas (Sedgwick Basin)

Only about 5% of the regional-scale earthquakes (M 2 or larger) recorded by the KGS network occurred in south-central Kansas (Figure 4). In Harper and Sumner counties, 13 M 2 or larger earthquakes were recorded from July 2024 to June 2025, about the same as the previous reporting period and an overall decrease of 99% relative to 2015. During that same period (2015 to present), injection volumes from Class I and Class II wells in Harper County decreased nearly 80%. From 2015 to 2018, earthquakes migrated from the highly active zones of seismicity in Harper and Sumner counties progressively farther along structural trends into surrounding counties, including Sedgwick, western Butler, Kingman, and Reno counties. Earthquakes along these trends are most likely induced, triggered by elevated pore pressure that effectively reduced frictional resistance along critically stressed basement faults. Notable sequences of earthquakes within clusters near Hutchinson in 2019-2020 and Wichita in 2020-2021 may have been influenced by nearby Class I and/or Class II injection operations. Seismicity continues to occur at significantly lower rates this year within this zone of measured elevated pressures, with only one M 1.4 near Wichita and no earthquakes near Hutchinson.

Pratt Anticline

West of the Sedgwick Basin, elevated pore pressure was likely the cause of a significant increase in seismic activity in Barber, Comanche, and surrounding counties in 2015-2018. Earthquakes have continued to occur near the Pratt Anticline since that time, but at a much lower rate. Only one regional-scale earthquake occurred in this area during the past year (Figure 5), noteworthy because 244 M 2 or larger earthquakes were recorded here in 2015-2018, an average of more than 60 events of this size per year. The large reduction in seismicity over the past four years is consistent with a drop in reported injection volumes and stabilizing formation pressures across the region.

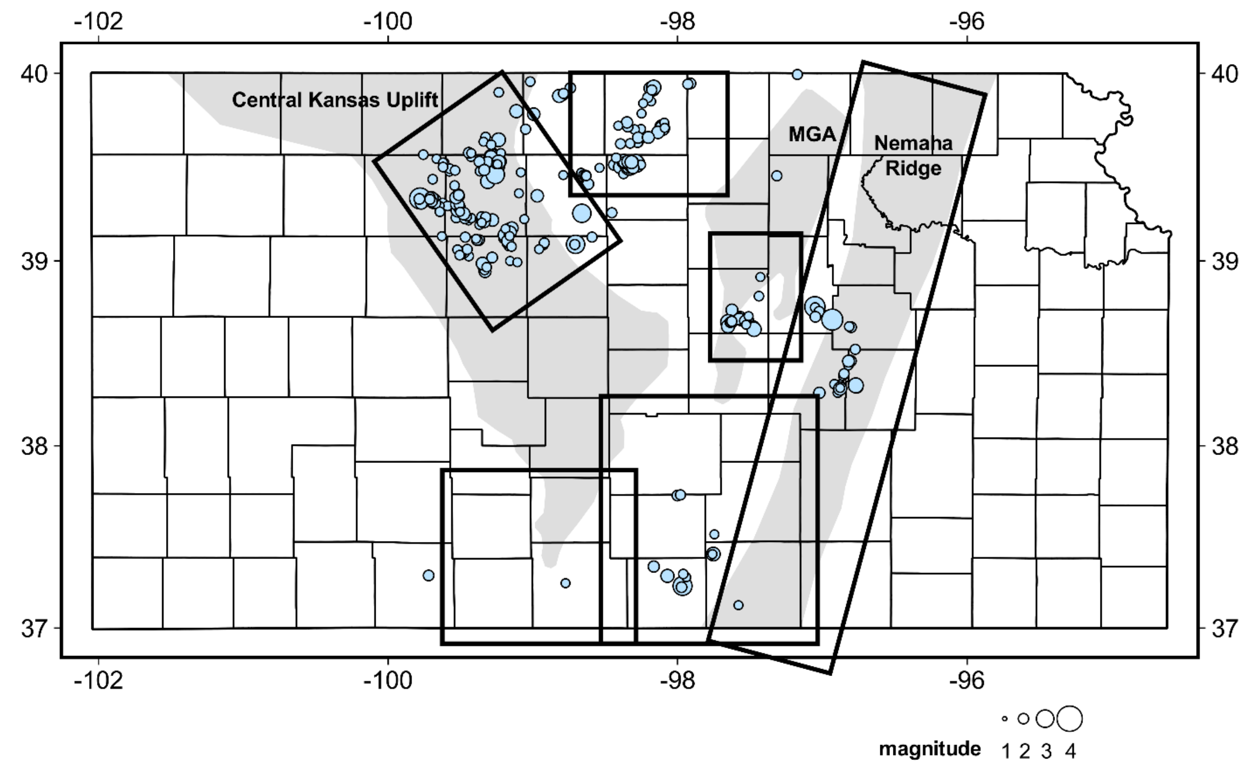


Figure 3. M 2 or larger earthquakes recorded in Kansas by the KGS seismic network from July 2024 through June 2025 (blue) superimposed on the prominent basement structures (gray). Black boxes indicate areas discussed in this section.

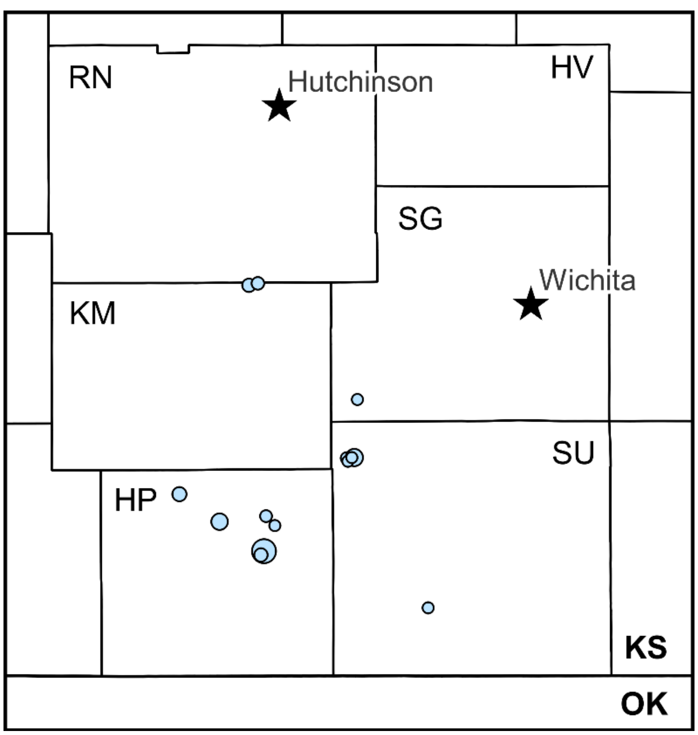


Figure 4. M 2 or larger earthquakes recorded in south-central Kansas from July 2024 through June 2025.

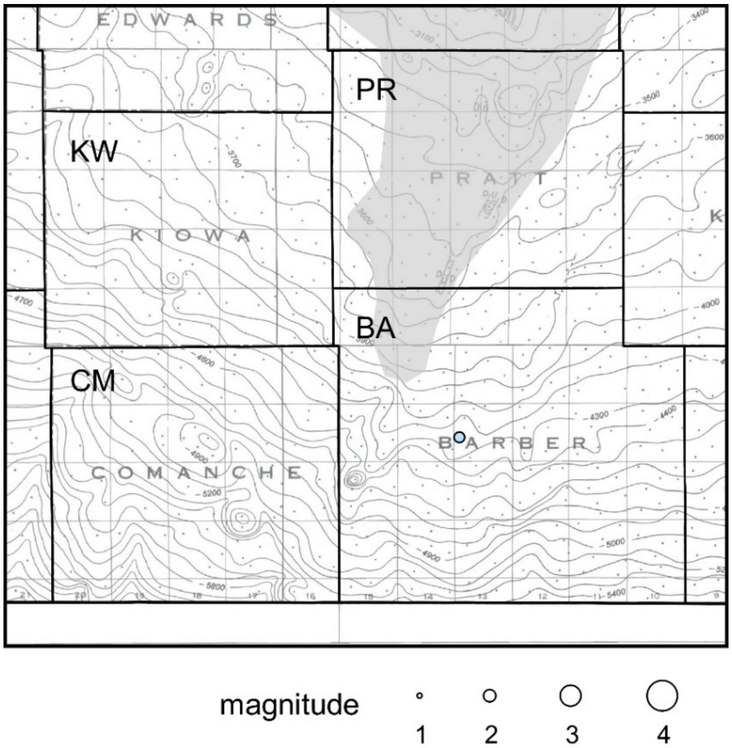


Figure 5. M 2 or larger earthquakes recorded in Kiowa, Pratt, Barber, and Comanche counties July 2024 through June 2025 superimposed on Precambrian structural contours (from Cole, 1976). The interpreted Pratt Anticline is shown in gray.

Central Kansas Uplift

One hundred thirty-eight M 2 or larger earthquakes were recorded in areas affected by the Central Kansas Uplift, nearly double the number reported last year (Figure 6). Seven M 3 or larger earthquakes occurred in Graham, Osborne, and Rooks counties. The Graham County cluster with four M 3 or larger events is particularly notable because only two earthquakes of this size were recorded here since monitoring began in 1977. In the late 1980s, two earthquake clusters in Rooks and neighboring counties strongly correlated with nearby saltwater disposal operations and were suspected to have been induced (Armbruster et al., 1989). Several notable clusters of earthquakes have occurred in and around the Central Kansas Uplift in recent years. The spatial extent of the seismically active area migrated to greater distances over time, most notably from west to east across Russell County and continues to persist at generally low magnitudes (M less than 2). Although reliable pressure measurements are not available from wells that penetrate the full thickness of the Arbuckle Group (as in central and south-central Kansas), the persistent seismicity and progression of earthquakes is not behavior normally expected for natural seismicity and, thus, earthquakes in this area may be induced.

North-Central Kansas (Salina Basin)

Seventy-six M 2 or larger earthquakes were recorded in Smith, Jewell, and neighboring counties (Figure 7), more than double the previous reporting year. The most notable cluster occurred in northwest Mitchell County near the Waconda Lake dam west of Glen Elder. More than three dozen earthquakes occurred there, including four M 3 or larger events. This is significant because Mitchell County experienced no documented seismicity prior to 2016. Several periods of seismicity have occurred in the Salina Basin, peaking about every few years (Figure 7b). Three M 3 or larger earthquakes occurred between 1928 and 2017, averaging one earthquake of this size every 44 years. Since 2017, more than three dozen M 3 or larger earthquakes occurred in Jewell County, averaging one earthquake of this size every 4-5 months. This significant increase in recurrence rate is not expected for natural earthquakes. At this time, the trigger for these earthquakes remains unclear, but they appear to be coincident with lineaments interpreted on aeromagnetic data.

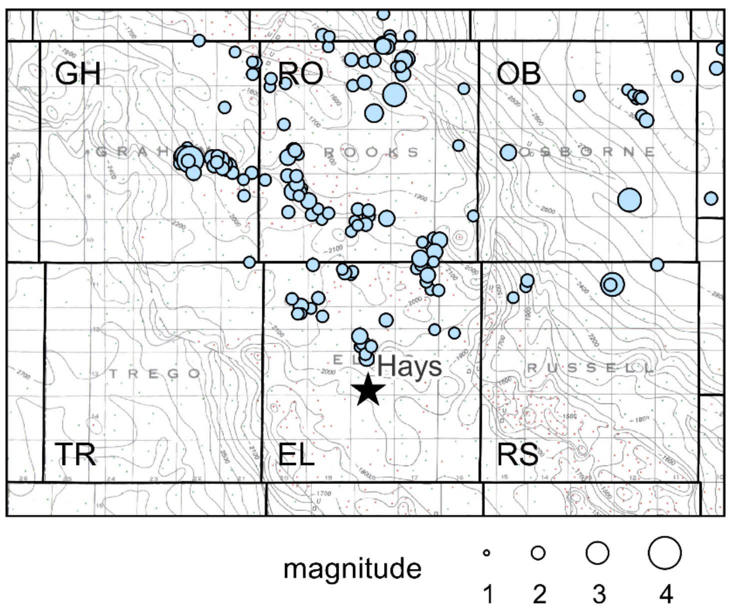
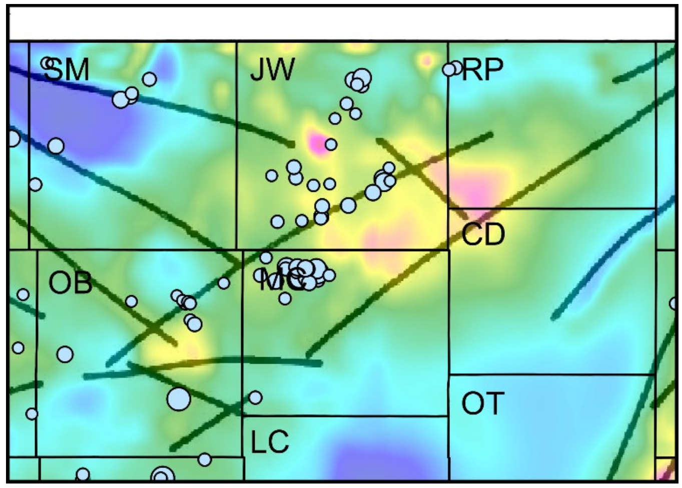


Figure 6. M 2 or larger earthquakes recorded near the Central Kansas Uplift from July 2024 through June 2025.

(a)



(b)

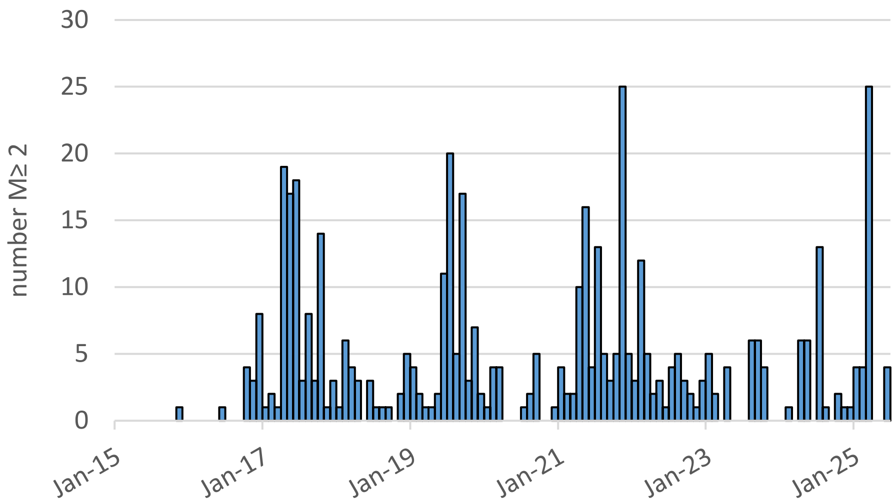


Figure 7. (a) M 2 or larger earthquakes recorded in the Salina Basin from July 2024 through June 2025 superimposed on the aeromagnetic map (Xia et al., 1995) and interpreted magnetic lineaments (Yarger, 1983). (b) Monthly number of M 2 or larger earthquakes recorded by the KGS network in the Salina Basin.

Midcontinent Geophysical Anomaly

The Midcontinent Geophysical Anomaly (MGA), the largest positive gravity anomaly in North America, is interpreted as the result of a thick sequence of mafic igneous rocks that formed during major late Precambrian rifting as part of the Midcontinent Rift System (MRS). Two ongoing clusters of earthquakes have been recorded along the southeastern margin of the MGA since the KGS network was installed in 2015. There were 62 M 2 or larger earthquakes this year, similar to the previous year but significantly less than the 192 earthquakes from July 2021 to June 2022 (Figure 8). A new cluster of earthquakes emerged in Ottawa County in 2022. The largest event in this cluster to date was an M 4.3 that occurred on November 11, 2023. Ottawa County had no historic seismicity and only sparse, low-magnitude earthquakes beginning in 2020. These earthquakes are likely occurring on faults associated with the MGA, but the cause of these earthquakes is unclear. Given the rise in formation pressure in the Arbuckle Group and hydraulically connected basement faults, it seems likely that increased pressure has propagated from south-central Kansas along faults associated with the MRS.

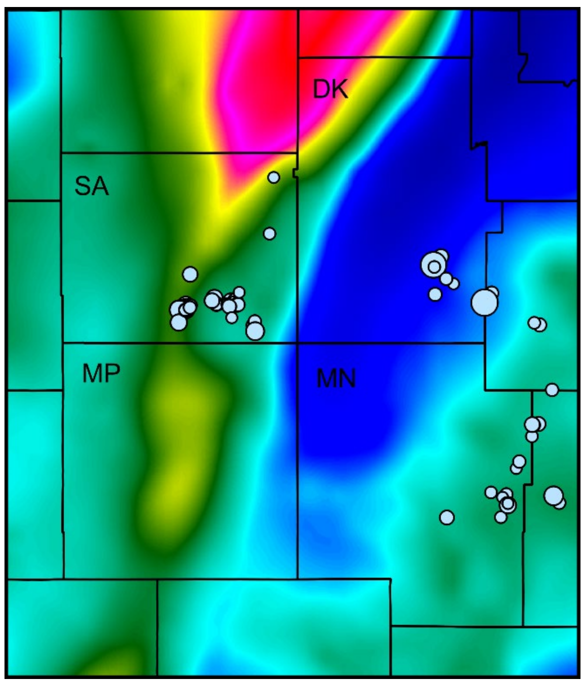


Figure 8. M 2 or larger earthquakes recorded near the Midcontinent Geophysical Anomaly from July 2024 through June 2025 superimposed on the gravity anomaly map of Kansas (Xia et al., 1995).

Nemaha Ridge

The Nemaha Ridge is one of the most prominent crustal features in Kansas, extending across the state with a northeast-southwest orientation. The Nemaha Ridge formed during post-Mississippian uplift of Precambrian age granite. A system of normal and reverse faults on the eastern margin of the Nemaha Ridge forms the Humboldt Fault Zone. Transform faults with a northwest-southeast trend intersecting the Nemaha Ridge represent a pre-Phanerozoic crustal extension associated with the Midcontinent Rift System. Dozens of historic earthquakes have been felt or recorded along the Nemaha Ridge, including an estimated M 5.2 near Wamego in 1867.

Eighteen M 2 or larger earthquakes were recorded during this reporting period along the Nemaha Ridge ranging from Pottawatomie County to Marion County (Figure 9), similar to previous years. More than half of these events occurred in a cluster along the Marion–Chase County line, with one M 3 or larger event this year. The rate of M 3 or larger earthquakes in this area in recent years has been unusual relative to more than a decade of monitoring in the 1970s and 80s. The primary trigger for these events is unclear, but the sustained increase in seismic activity is not consistent with a natural temporal fluctuation in the seismicity rate.

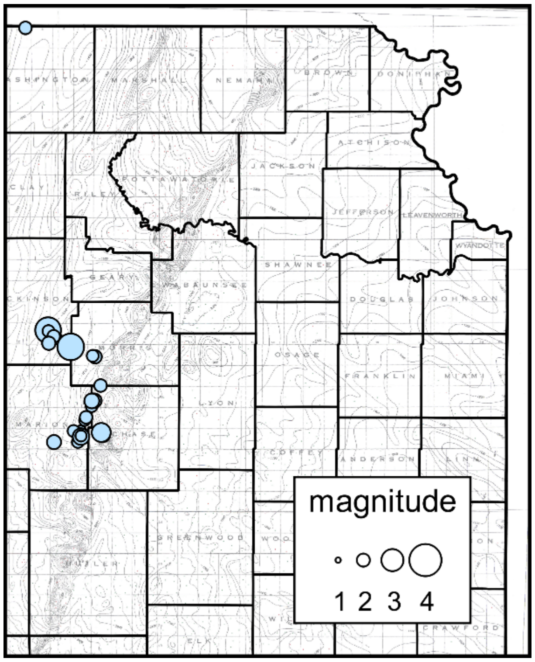


Figure 9. M 2 or larger earthquakes recorded along the Nemaha Ridge from July 2024 through June 2025 superimposed on Precambrian structural contours (from Cole, 1976).

Local Seismicity within 20 mi of Member Wells

Together with regional scale felt events, analysis of events well below M 2 greatly improves our ability to interpret earthquakes relative to structures and evaluate possible causal factors. Sub M 2 events provide opportunities to forecast seismicity once the recursion relationship in specific areas can be accurately calculated for the current pressure regime. During the past year, 387 microearthquakes (M less than 2) were recorded by the KGS seismic network (with enhanced sensitivity and improved location accuracy possible with the addition of CSTS stations) (Figure 10). Similar to regional scale earthquakes, microearthquakes have continued to decline in overall numbers since the peak in 2015. Microearthquakes make up more than 50% of the events logged in the earthquake catalog last year. Of the entire catalog at all magnitudes, only 14 earthquakes (the fewest since recording began) were mapped within 20 mi of Tier 1 member wells (Appendix B).

Uniquely locating the epicenter of an earthquake requires detecting P- and/or S-waves at three or more stations. Subnetwork events are defined as earthquakes (typically with magnitudes less than M 1) that are only recorded on a single or at most two station(s) and therefore, the epicenter location cannot be determined uniquely. Rather, the epicenter exists somewhere on a circle centered on the seismic station with radius equal to the calculated distance to the earthquake epicenter. The magnitude of a subnetwork event is estimated from the coda, or duration—the time from the first P-wave arrival until the energy is approximately equal to or drops below the noise floor at that time and station (background noise usually based on pre-event noise levels). Eighteen subnetwork events were recorded at CSTS stations (Appendix C), a significant decrease from previous years. The majority of these subnetwork events are low-energy microearthquakes that provide valuable insight into the relative stability and stress conditions of faults in proximity to earthquake stations and, thus, member facilities.

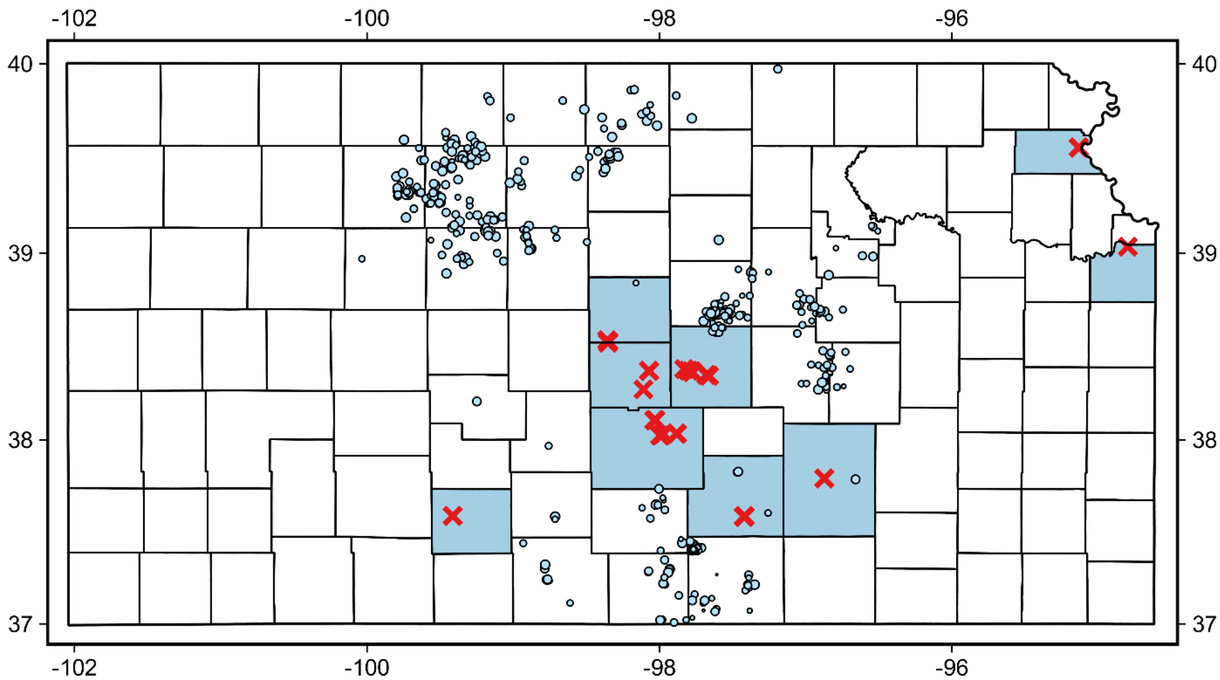


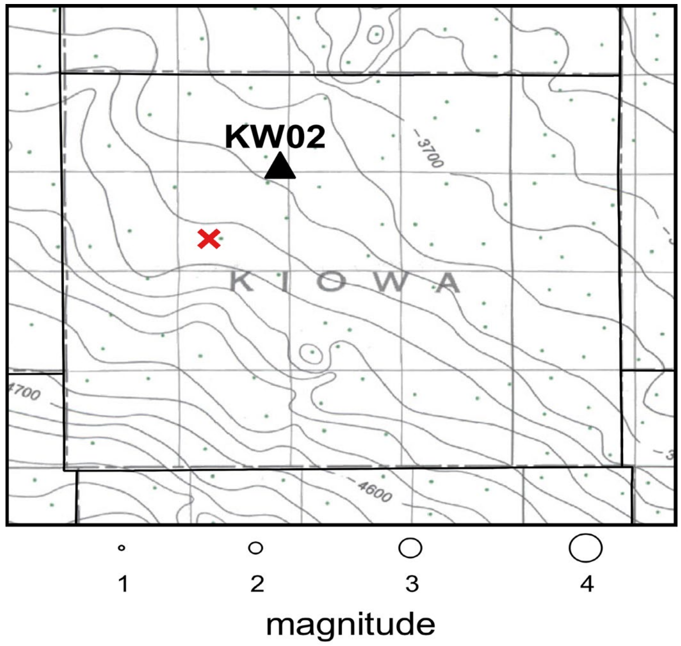
Figure 10. Microearthquakes (M less than 2) recorded in Kansas by the KGS seismic network from July 2024 through June 2025. Blue shading indicates counties with CSTS member wells (red X's).

In this section, seismicity at all magnitudes (including both uniquely located events and subnetwork events) and relevant basement structures are evaluated in each of the nine counties with Tier 1 member facilities.

Kiowa County

Similar to previous years, no earthquakes were mapped within 20 miles of the Kiowa County member well and no subnetwork events were detected (Figure 11). The closest earthquake was a M 2.3 about 25 mi away in neighboring Clark County. The low number of earthquakes in Kiowa County is consistent with the overall stabilizing of pressures in south-central Kansas as observed in Harper, Sedgwick, and Kiowa county wells.

(a)



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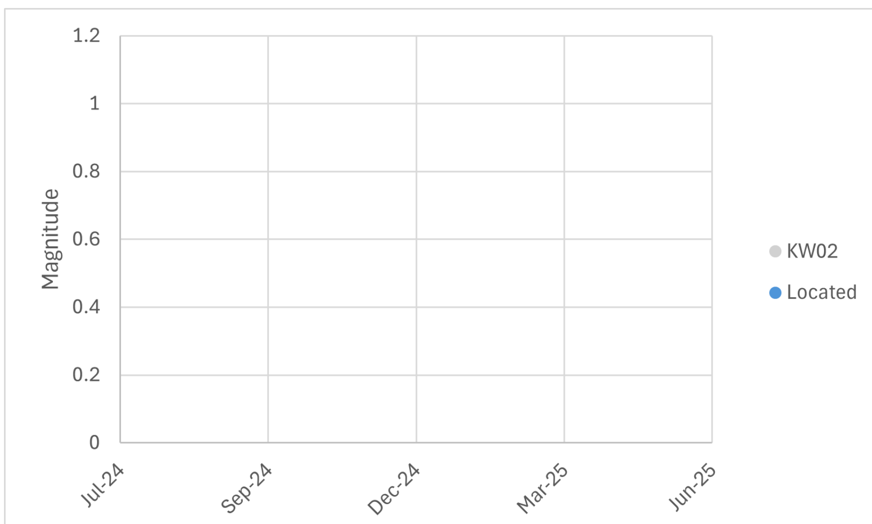


Figure 11. (a) Earthquakes recorded in Kiowa County from July 2024 through June 2025 superimposed on Precambrian structural contours (from Cole, 1976) and inferred Pratt Anticline at the southern end of the Central Kansas Uplift (gray). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. (b) Scatter plot of mapped and subnetwork events recorded within 12 mi of CSTS stations.

Rice and Ellsworth Counties

No earthquakes were recorded within 20 mi of the member wells in Rice and Ellsworth counties (Figure 12a). The closest events were a M 1.3 in northern Ellsworth County about 24 mi from wells at the Ellsworth–Rice county line and a M 1.9 in Saline County more than 25 mi from wells in Rice County. Twelve subnetwork events were recorded at stations RC03 and none at RC02 and EW01 (Figure 12c), which is slightly lower than the long-term average at these stations. Most of these events likely represent low-amplitude natural movement on faults associated with Geneseo Uplift, an eastern lobe of the Central Kansas Uplift and the predominant basement structure in Rice County (Berendsen and Blair, 1986). An elevated number of subnetwork events in 2020-2021 were likely precursors to a M 2.9 earthquake on June 28, 2022. Although these events were likely the result of natural crustal stress, it indicates that this area has active faults that may be susceptible to induced seismicity. Although Arbuckle formation pressures in this area remain elevated, pressures are either stabilizing or show early signs of declining.

(a)

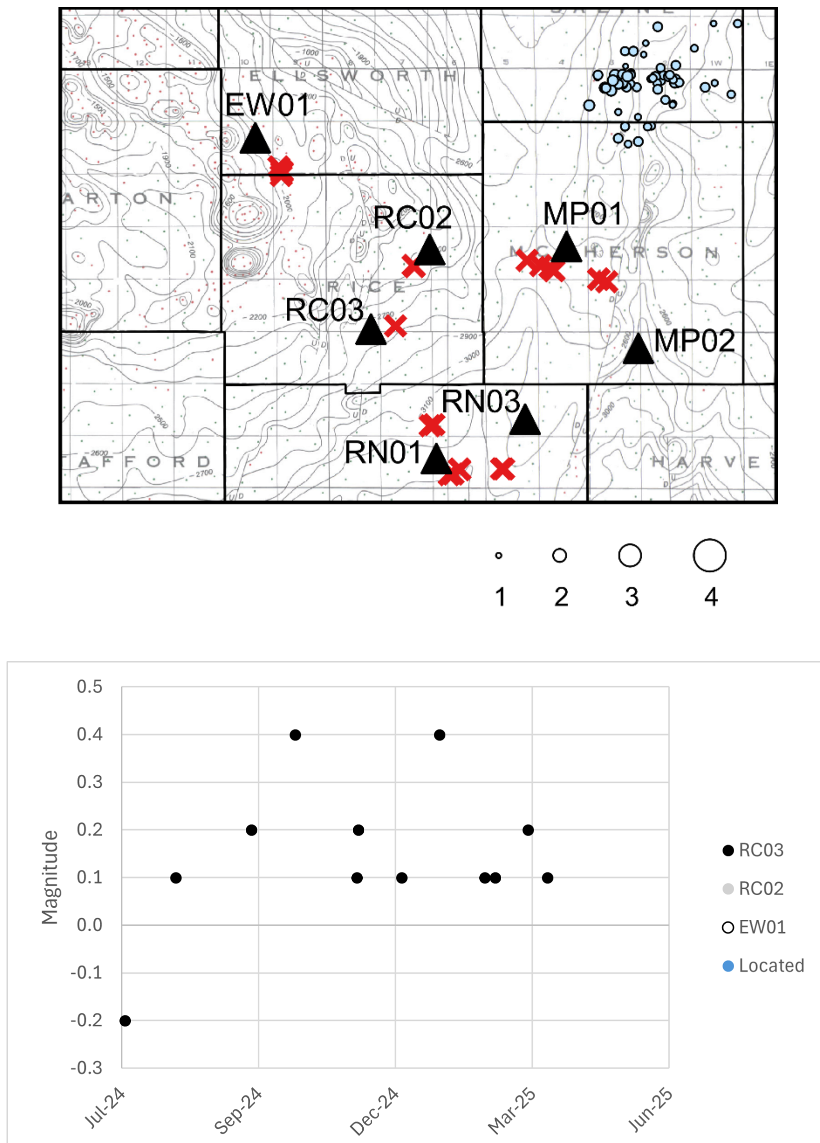


Figure 12. (a) Earthquakes near Rice and Ellsworth counties from July 2024 through June 2025 superimposed on Arbuckle Group structural contours (from Berendsen and Blair, 1986). CSTS member well and station in the CSTS network are indicated by a red X and black triangle, respectively. Scatter plot of earthquakes (blue) recorded within 20 mi of member wells in Rice and Ellsworth counties, subnetwork events recorded within 12 mi of CSTS stations at RC03 (black), RC02 (gray), and EW01 (white).

McPherson County

Seismic activity within 20 km of member wells in McPherson County was primarily concentrated near the McPherson–Saline County line (Figure 13). These events occur near the eastern margin of the Midcontinent Geophysical Anomaly (MGA), along and east of the Salina Fault in Saline County. Seismicity in this area has been ongoing since installation of the KGS seismic network in 2015 with about 100 M 2 or larger earthquakes cataloged from 2015-2020. Seismic activity increased dramatically in 2021 with 146 M 2 or larger earthquakes, including three M 4 or larger. Given the lack of recorded earthquakes in Saline County prior to 2015, the probability of such a dramatic change in seismicity is extremely low for natural earthquakes. Arbuckle Group formation pressures measured in McPherson County have been steadily rising since 2014 and are currently about 30-40 psi greater than historic pressures (Figure 14). The rise in pressure appears to be related to pressure diffusion from high-volume disposal near the southern Kansas border along high-permeability fractures in the granite basement. Although there are no pressure measurements for the Arbuckle or basement in Saline County, it is reasonable to assume pressures have risen here as well.

Historically, seismicity within 20 mi of McPherson County member wells is extremely sparse and persistent seismicity in this area would not be expected. To date, only a few earthquakes have occurred in McPherson County outside of the cluster at the northern county line. Low-rate, low-magnitude seismicity has occurred east of the Voshell Anticline. Five microearthquakes occurred at the same location in 2019 and early 2021, indicating the presence of a seismically active fault. In November 2021, a M 2.2 earthquake occurred in the southeast corner of the county 11 mi or more from member wells. An earthquake of this size subsequently occurring is not surprising based on recurrence rates of natural earthquakes. In the absence of other influences (e.g., pressure changes from injection operations), earthquakes are likely to continue at this location at similar rates and magnitudes.

Station MP01 is bounded to the west and east by northeast trending faults mapped in Precambrian and/or Arbuckle Group rocks associated with the Midcontinent Rift System. One M -0.2 subnetwork event was recorded at MP01 (Figure 13b). The epicentral distance of about 7 mi is roughly consistent with the location of a M 2.6 earthquake that occurred on November 3, 2014. The average rate of subnetwork events is typically about a dozen events per year. The decrease in microearthquakes in this area is consistent with the overall decrease in seismicity statewide.

Two subnetwork events were recorded at station MP02 with magnitudes ranging from -0.4 to 1.0 (Figure 13b). These events occurred at epicentral distances ranging from 8 to 11 mi. The rate of subnetwork events at MP02 is generally higher than other stations with about two dozen per year, but the rate has declined significantly in the last three years. MP02 is bounded to the west by a system of faults associated with the Voshell Anticline, to the southeast by the Halstead Fault, and is surrounded by several anticlinal and synclinal structures. The grouping of mapped earthquakes in the southeast corner of the county (described above) is about 6 mi from MP02. Therefore, it is likely these events are occurring on seismically active structures responsible for the larger mapped earthquakes.

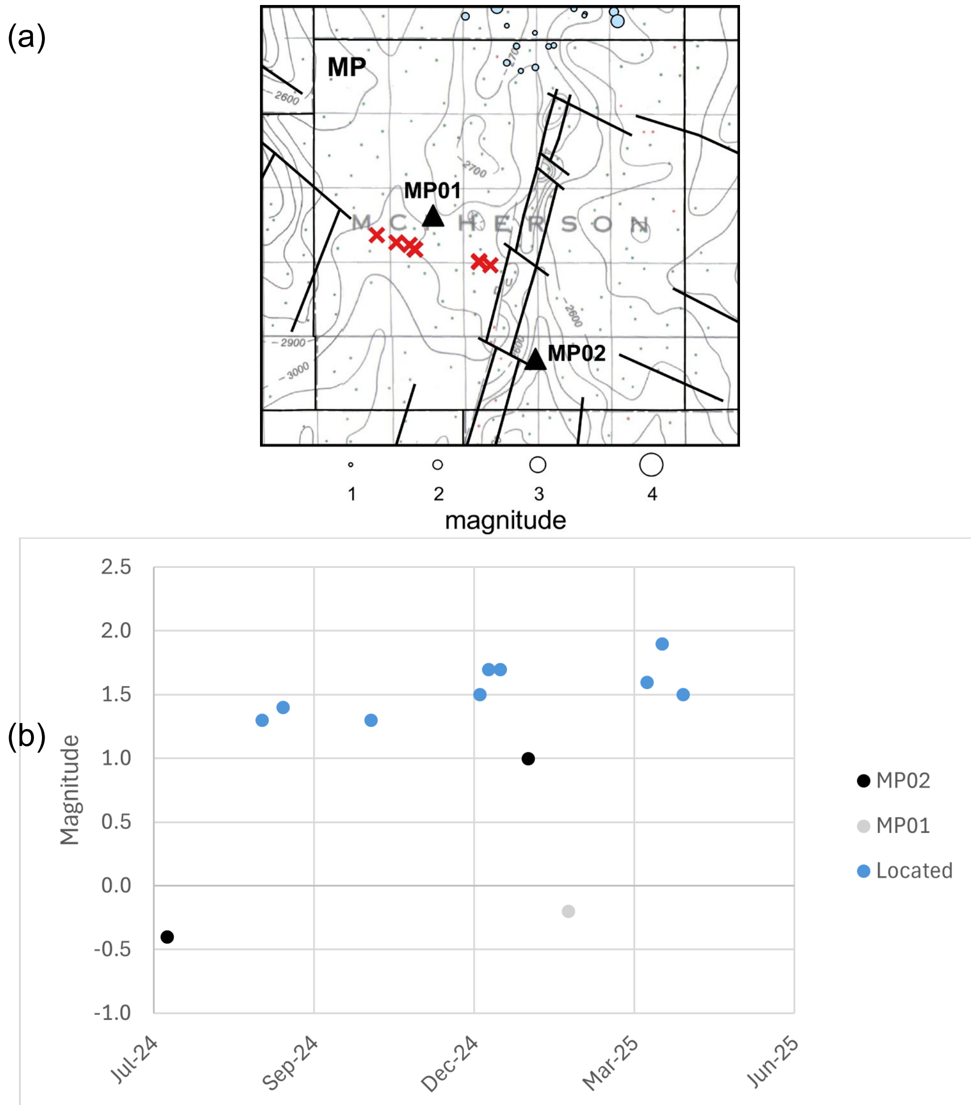


Figure 13. (a) Earthquakes recorded in McPherson County from July 2024 through June 2025 superimposed on Arbuckle Group structural contours (from Berendsen and Blair, 1986). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. Scatter plot of earthquakes (blue) recorded within 20 mi of member wells in McPherson County, subnetwork events recorded within 12 mi of CSTS stations at MP02 (black) and MP01 (gray).

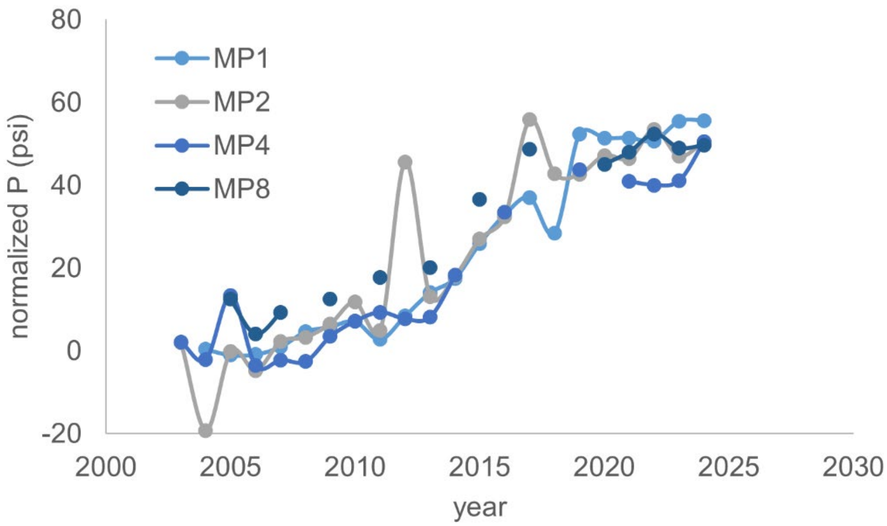


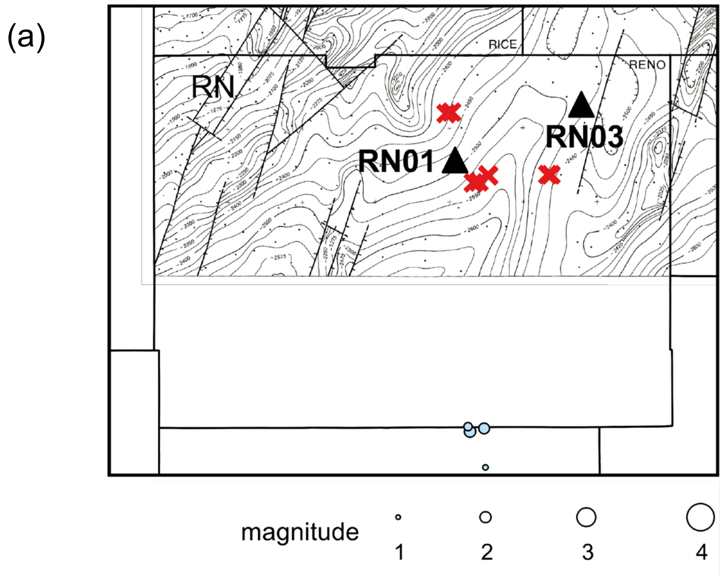
Figure 14. Change in formation pressure relative to historic values in Class I wells in McPherson County.

Reno County

Only one earthquake was recorded in Reno County (Figure 15a), a M 1.8 microearthquake located in a small cluster at the Reno–Kingman County line. Notably, for the third year in a row, no earthquakes were recorded in the Hutchinson cluster. This is a remarkable decrease in seismic activity, considering that hundreds of earthquakes were recorded in Reno County since 2015, the majority of which were near South Hutchinson. The decrease in seismicity is consistent with stabilizing pore pressures measured during 2022. Injection volumes remained relatively consistent in Reno County over the last decade while total volumes dropped across most of the state.

Station RN01 is located 2-3 mi northwest of the Hutchinson earthquakes. Only one M 0.2 subnetwork event was recorded at RN01 (Figure 15b). This is a substantial decrease from the more than 400 subnetwork events/year average from 2017-2021 and is consistent with the overall drop in earthquake rates in the Hutchinson cluster since January 2020. The estimated epicentral distance of these subnetwork events is about 5 mi. Although this is slightly larger than the 2.8 mi distance to the center of the mapped Hutchinson earthquakes, these microearthquakes almost certainly originate from the same fault or set of faults. The epicentral distance was calculated assuming a fixed earthquake depth of 3 mi, a common assumption used to locate earthquakes in the midcontinental U.S. Earthquakes likely occur on faults within the shallow Precambrian basement, which is at a depth of about 1 mi in this part of Reno County. Recalculating the epicentral distance using a depth of 1 mi results in an average distance of 3 mi, consistent with the location of the swarm of earthquakes located by the KGS regional seismic network. These events provide confidence in the suggestion that the Hutchinson earthquakes are occurring in the shallow basement.

Zero subnetwork events were recorded at station RN03. Although the Hutchinson Fault runs NE-SW through the northeast corner of Reno County and east of the City of Hutchinson, no mapped earthquakes have been recorded along that fault since monitoring began in 2017.



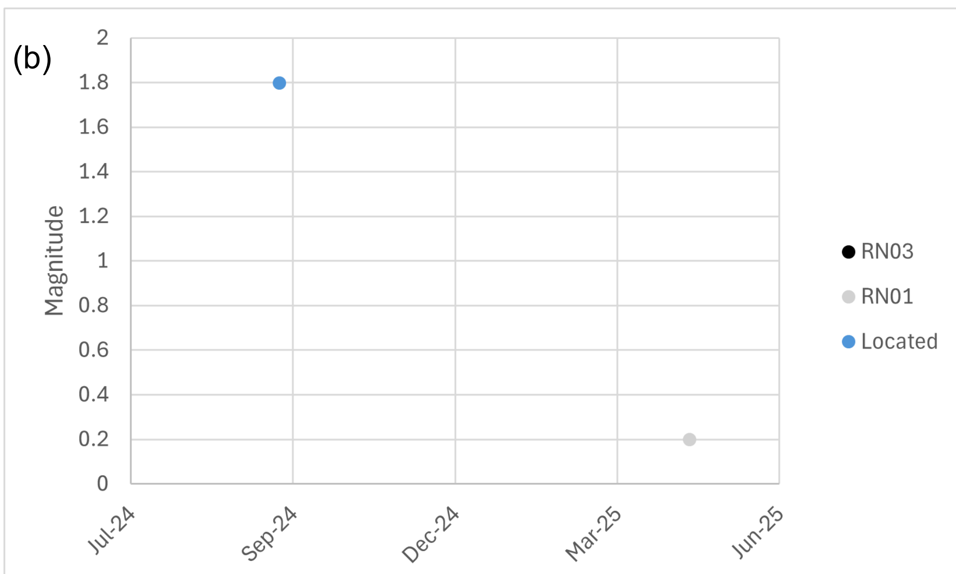
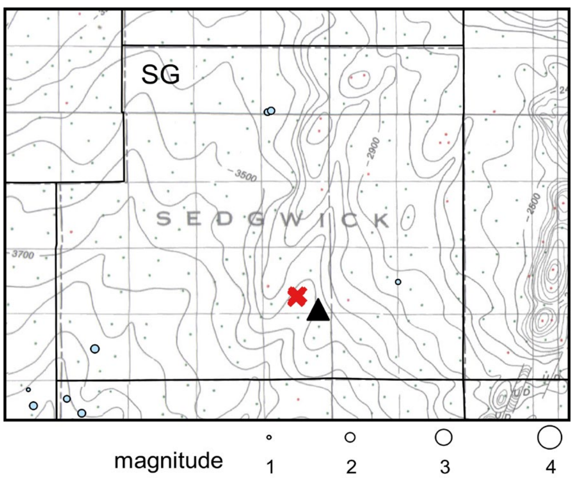


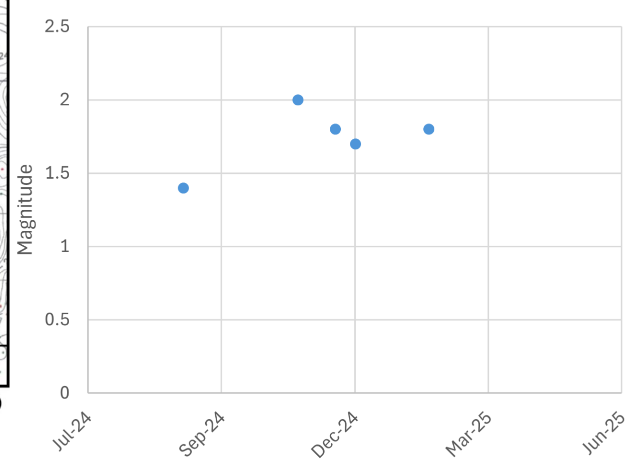
Figure 15. (a) Earthquakes recorded in Reno County from July 2024 through June 2025 superimposed on Arbuckle structural contours (from Berendsen and Blair, 1986). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. (b) Scatter plot of earthquakes (blue) recorded within 20 mi of member wells in Reno County; subnetwork events recorded within 12 mi of CSTS stations at RN03 (black) and RN01 (gray).

Sedgwick County

In 2020-2021, a cluster of nearly 150 earthquakes occurred in east Wichita, including multiple distinct sequences with 25 M 2 and 11 M 3 earthquakes. Unlike prior earthquakes near Wichita, the events had an abrupt onset and increased energy release from November 26 to December 30, 2020. Given the stabilizing and possibly decreasing formation pressures in Sedgwick County, these earthquakes were unexpected. This year, no earthquakes were recorded in the Wichita cluster, and only sparse seismic activity was recorded in and around Sedgwick County. In past years, subnetwork events have been recorded at station SG02, occurring at epicentral distances within 5 mi of the station (about the same distance as a group of nearby Class I wells). Subnetwork events were likely occurring on faults associated with the Valley Center anticline. This year, no subnetwork events were recorded (Figure 16b), consistent with the overall decline in seismicity in Sedgwick County and the south-central Kansas region. While formation pressures in this area remain elevated well above historic levels, earthquakes will likely persist at low rates and magnitudes and seismically active structures will continue to be sensitive to pressure fluctuations (e.g., from local Class I and II well injection operations).



(a)



(b)

Figure 16. (a) Earthquakes recorded in Sedgwick County from July 2024 through June 2025, superimposed on Arbuckle Group structural contours (from Berendsen and Blair, 1986). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. (b) Scatter plot of earthquakes (blue) recorded within 20 mi of member wells and subnetwork events (gray) recorded within 12 mi of CSTS stations.

Butler County

One M 1.7 earthquake was mapped within 20 mi of the Butler County member well this year (Figure 17). Butler County has a history of natural seismicity along faults associated with Nemaha Ridge. The majority of earthquakes recorded in Butler County since 2015 occurred as part of foreshock-aftershock sequences at the Butler–Sedgwick County line near the towns of Andover and Rose Hill. These earthquake clusters were active from 2016-2019 and continued at low rates through early 2024 and appeared to be a result of progression of seismicity along northeast trends through Sumner and Sedgwick counties. Other less active earthquake clusters and a few sparse earthquakes have been recorded elsewhere in the county, likely representing natural seismicity. This year, only one M 0.1 subnetwork event was recorded at station BU02. Although this represents a notable decrease from previous years, this observation is consistent with the overall decrease in seismicity in the region.

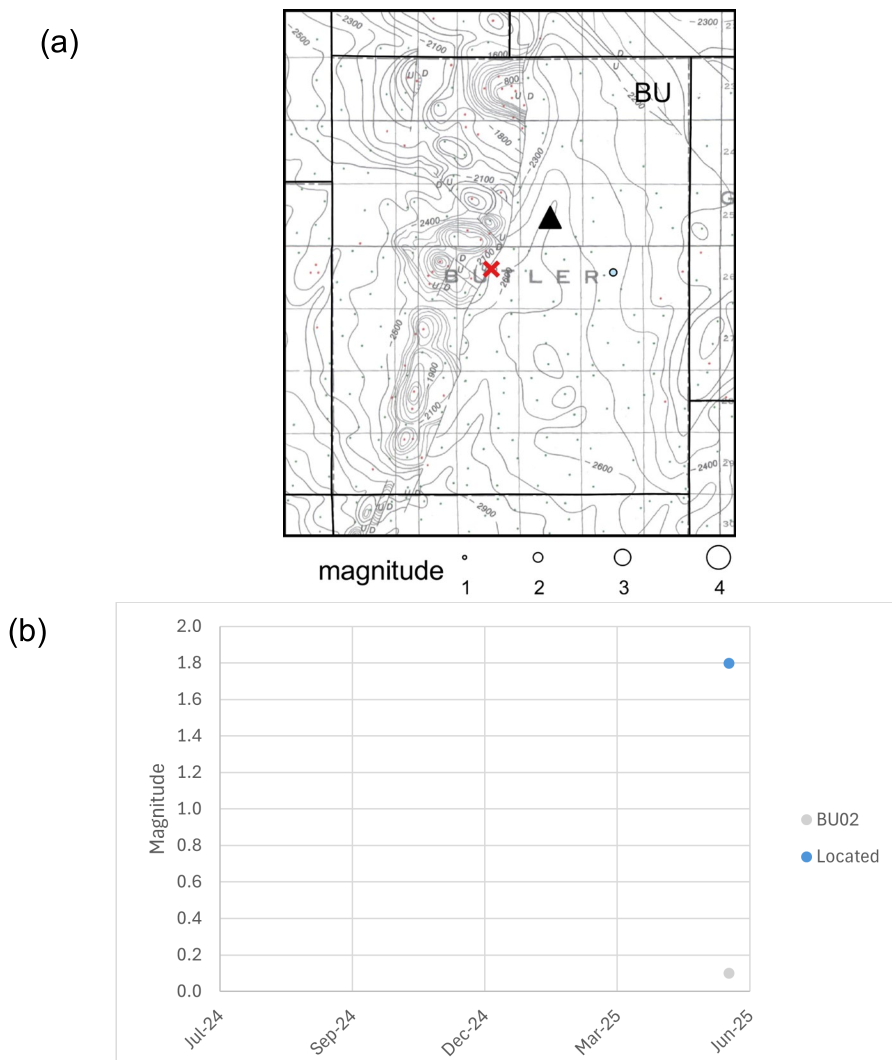
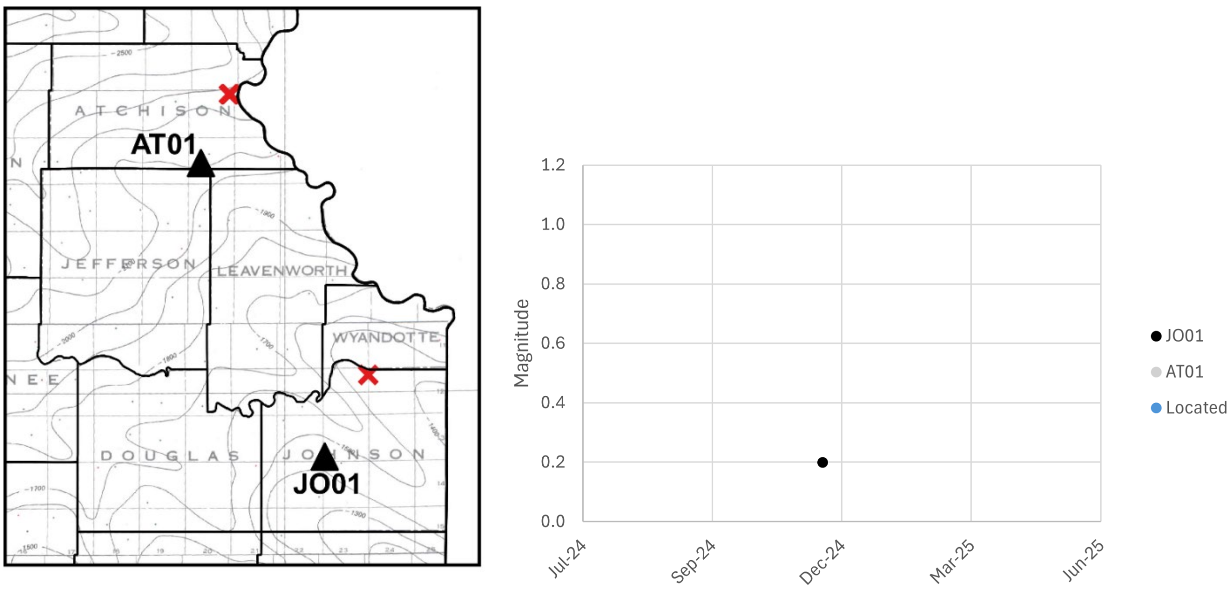


Figure 17. (a) Earthquakes recorded in Butler County from July 2024 through June 2025 superimposed on Arbuckle Group structural contours (from Berendsen and Blair, 1986). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. (b) Scatter plot of earthquakes (blue) recorded within 20 mi of member wells and subnetwork events (gray) recorded within 12 mi of CSTS stations.

Johnson and Atchison Counties

Although there are no mapped faults in this area (known as the Forest City Basin), contours of the top of the Precambrian suggest a NW–SE structural grain consistent with the Central Missouri Tectonic Zone to the east. This area has a history of felt seismicity dating back to 1897, with M 3 and 3.1 earthquakes recorded in Wyandotte and Atchison counties, respectively. Therefore, isolated earthquakes of this size are expected to occur here occasionally at a relatively low rate. No earthquakes were mapped this year within 20 mi of the Johnson County member well or in Doniphan County north of the Atchison County member well (Figure 18a). No subnetwork events were recorded at station AT01 and only one was recorded at station JO01 at an epicentral distance of about 9 mi (Figure 18b). A very low earthquake rate is unsurprising given the stable tectonic regime and limited number of historic earthquakes recorded in this area.



(a) (b)

Figure 18. (a) Earthquakes recorded in Johnson and Atchison counties from July 2024 through June 2025 superimposed on Arbuckle Group structural contours (from Berendsen and Blair, 1986). CSTS member wells and stations in the CSTS network are indicated by a red X and black triangle, respectively. (b) Scatter plot of earthquakes (blue) recorded within 20 mi of member wells in Johnson and Atchison counties and subnetwork events recorded within 12 mi of CSTS stations JO01 (black) and AT01 (gray).

DISCUSSION

The Arbuckle Group is a multi-use aquifer that, at depths greater than 4,000 ft, serves as the injection zone for thousands of Underground Injection Control (UIC) wells in Kansas and neighboring Oklahoma. Widespread seismic activity across central Oklahoma and south-central Kansas since 2012 is primarily attributed to elevated pore pressures along critically stressed faults in the hydraulically connected basement rock underlying the Arbuckle Group. As injection volumes in south-central Kansas have decreased over the past several years, pressures in south-central Kansas began to stabilize in 2016 and the earthquake rate likewise began levelling off (Figures 19 and 20). In 2024 (the most current year with complete pressure data), pore pressures within the Arbuckle Group (and thus, the basement which is hydraulically connected) remain elevated at levels above the earthquake triggering threshold defined as pre-2012 pressure levels but appear to be gradually declining in some areas while still increasing slightly in others (Figure 21). Based on recent trends, earthquakes will likely persist along established trends as crustal stresses continue to load near-critical faults properly aligned with the stress field before returning to near-natural rates within the next ~5 years.

Injection practices that produce even small local pressure fluctuations or pulses may contribute to anthropogenically triggered earthquakes on nearby faults in areas where formation pressures remain elevated. Large and/or abrupt changes in injection volumes that appeared benign prior to 2015 may contribute to seismicity now. Fluctuations in injection volumes over short time spans have likely been at least partially responsible for some earthquakes triggered in the Hutchinson and Wichita areas in recent years. When possible, large or abrupt changes in injection volume should be avoided in favor of gradual step-up or step-down to minimize pressure perturbation that could trigger earthquakes on critically stressed faults.

Injection within the Arbuckle Group has altered the regional fluid pressure regime at depths three to four times the injection depth through hydrologic connectivity provided by a complex system of fractures and faults from within the Arbuckle to well into the Precambrian granites. Because permeability in granite is fracture- and fault-controlled, local and regional fracture and fault systems present at the Paleozoic/Precambrian surface become the transport mechanism responsible for localized elevated stresses. Migration of the pressure field that instigates fault movement below the basal contact of the Paleozoic is primarily controlled by the alignment, permeability, and connectivity of fracture systems within the upper two to four miles of Precambrian rocks (principally granite). This scenario explains the general migration of earthquake epicenters into areas with little or no injection and makes it reasonable to suggest general trends and clusters active for months to years or longer are strongly influenced by regional injection volumes, as appears to be the case in Saline County.

More than half of the earthquake cataloged this year occurred in north-central Kansas along the Central Kansas Uplift and Salina Basin. Trego and Smith counties experienced a large uptick in seismicity in 2016; seismicity has remained active and migrated into surrounding counties since that time. The earthquake rates and migration are not consistent with patterns expected for natural seismicity. The spatial density of disposal volumes (bbls/sq mi) in the Arbuckle is higher at the Rooks–Ellis County line (RO–EL) than anywhere else in Kansas. In fact, the spatial density is double that of Harper County in 2015 when disposal rates were at their peak. The argument could be made that, because the Arbuckle is also produced along the Central Kansas Uplift, extraction offsets the effects of fluid disposal. However, this is an oversimplification. As reported for induced seismicity case studies from West Texas, pore pressure is locally reduced near production wells and locally elevated near disposal wells (Dvory and Zoback, 2021; Ge et al., 2022). Production and disposal will not result in a net zero pressure change where there is a spatial discrepancy between injection and extraction. Although there are no representative pore pressure measurements in the Arbuckle or Precambrian basement from this area, it is reasonable to expect pressure to be elevated. As in south-central Kansas, pressure diffusion and poroelastic stress change is likely the source of earthquakes in Rooks and surrounding counties.

Although only a few faults have been mapped in north-central Kansas, magnetic lineaments suggest NE–SW trending faults in the Salina Basin associated with the Midcontinent

Rift System. Seismicity occurred near a magnetic lineament that extends across Osborne and Jewell counties, suggesting this feature may be a hydraulically conductive fault that served as a pathway for pressure diffusion away from the spatially dense disposal volumes near the Rooks–Ellis County line. With little to no historic earthquakes in the Salina Basin, a potential source of increased pore pressure and pathway for pressure diffusion, and the west-to-east progression of seismic activity, fluid movement along this pathway appears to be the most likely scenario to account for the dramatic and otherwise unexpected increase in seismicity. In this way, earthquakes in the Salina Basin are analogous to the Saline County earthquakes, where pressure diffusion along hydraulically conductive faults associated with the MRS triggered earthquakes on the eastern margin of the Midcontinent Geophysical Anomaly.

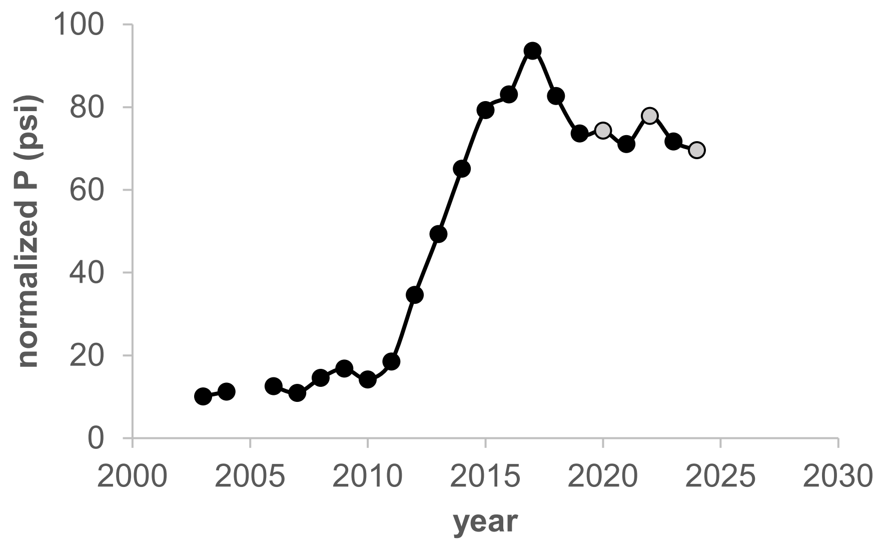


Figure 19. Arbuckle Group pore pressure reported for the Class I facility in Harper County.

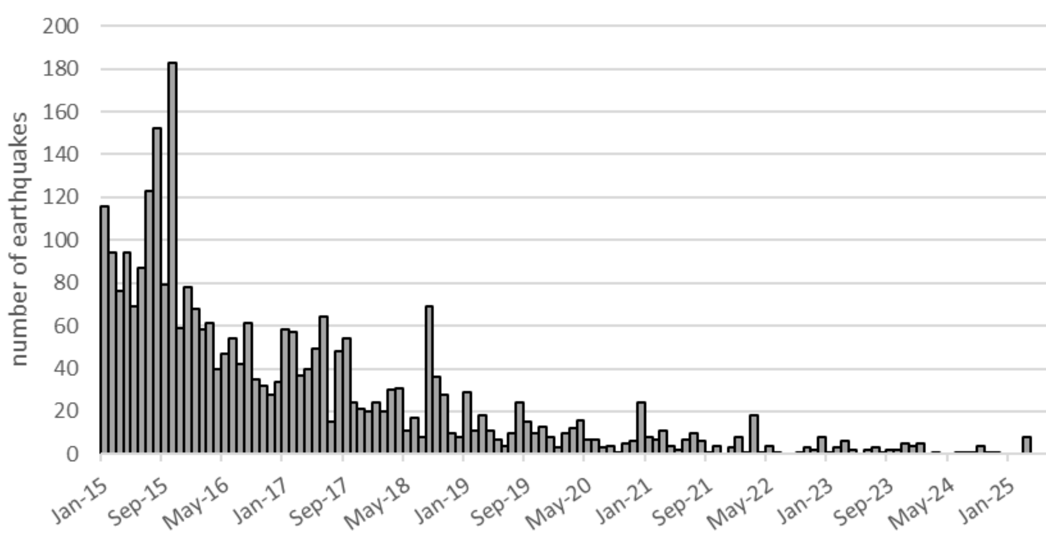


Figure 20. Monthly number of earthquakes M 2 or larger in south-central Kansas.

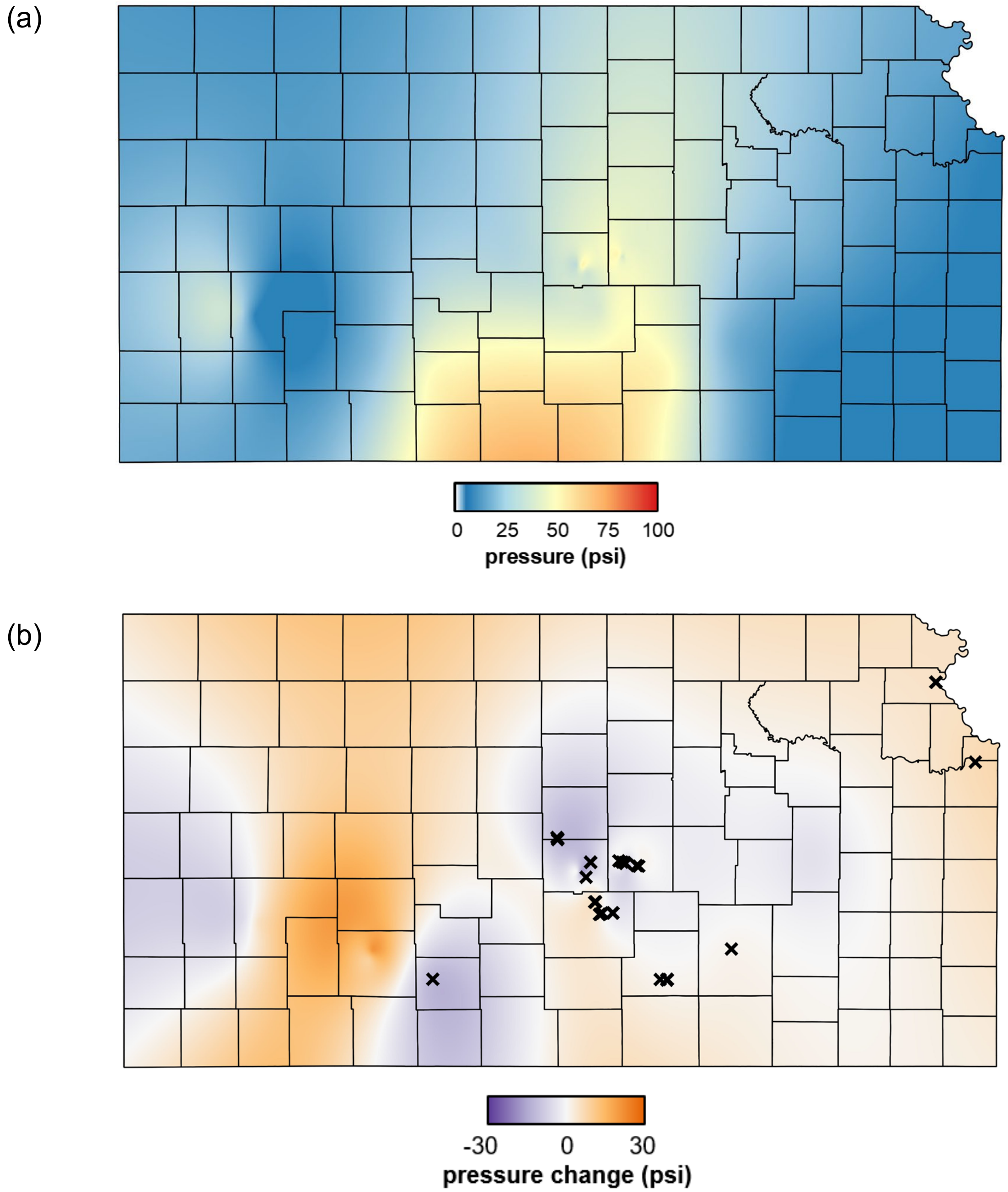


Figure 21. (a) Change in Arbuckle Group pore pressure in 2023 (relative to baseline pressures reported in 2002, or earliest available report thereafter). (b) Change in Arbuckle Group pore pressure from 2022 to 2023. Black Xs indicate Tier 1 member wells.

WEB PAGE CONTENT

The CSTS web page (http://www.kgs.ku.edu/Geophysics/CSTS/index.html) is operated by the KGS. It includes links to information about meetings, publications, network updates, and seismic updates (for Tier 1 members) and information about the seismic network for Tier 2 members. It includes semi-annual newsletters about earthquake activity, along with access to a comprehensive catalog of events, including time, location, magnitude, and the Seismic Action Score (based on evaluation criteria developed by the State's Induced Seismicity Task Force) for each event. The website also includes a series of pictures and accounts of the installation process and gives a feel for the environment and footprint of each consortium station. Currently at least one station has been installed within 20 miles of every Tier 1 member's well (Figure A-0, Appendix A). A short discussion and set of pictures are posted on the website documenting the installation process.

Beginning in 2021, the Publications section of the webpage includes a detailed overview of recent publications that may be relevant to Consortium members (https://www.kgs.ku.edu/Geophysics/CSTS/Group/recent_lit.html, Appendix D). For each paper, we provide three key points highlighting the primary findings, a summary (paraphrased from the published abstract, in most cases), and a link to the full paper on the publisher's webpage. This section of the webpage will continue to be updated as new relevant papers are published. In time, we hope to provide detailed overviews for past induced seismicity publications as well.

OTHER ACTIVITIES

The Consortium continues to hold its quarterly meetings remotely and plans for that to continue. The annual meeting returned to an in-person format in 2022 and was hosted in August 2025 by Oneok in Hutchinson, Kansas. The agenda for that meeting is included below.

2025 Annual Meeting
Tuesday, July 29, 2025 – 9 a.m.
Strataca 3650 E Avenue G, Hutchinson KS 67501

9:00 a.m. **Registration and breakfast**
10:00 a.m. **Welcome and Introductions**
Rex Buchanan, Kansas Geological Survey
10:15 a.m. **Quarterly and 10-year seismic update** –
Shelby Peterie, Kansas Geological Survey
11:15 a.m. **Arbuckle Update**
Rick Miller, Kansas Geological Survey
11:45 a.m. **KDHE Update**
KDHE

Noon **Lunch**
1:00 p.m. **Consortium Future Direction** – all
1:30 p.m. **Other Business** – all
2:00 p.m. **Tour of Strataca**

PLANS

Over the next decade milestone products we plan to provide to CSTS member, beyond routine microearthquake and Arbuckle injection monitoring and analysis, will include generalized mapping of active fault plains greater than 3 km deep in basement (where no drill bit has gone in), enhanced data streams with the addition of 3 to 6 wells explicitly designed and installed to monitor Arbuckle fluids in spatially under sampled areas, update the state's Seismic Action Plan to benefit from the last decade of monitoring and to consider the possibility that CCUS and critical mineral mining in the Arbuckle could be coming to Kansas, and integrate earthquake epicenters with faults/lineaments in basement interpreted from statewide aeromagnetic and gravity data and derivatives.

Recent earthquake activity in northcentral and northwestern Kansas has elevated to unexpected levels based on recursion relationships developed from historical seismicity. Unexpected earthquake activity in this region has been suggested to be induced as a result of disposal of wastewater. With no apparent local increase in disposal volumes, this is another location that lends itself to the concept of fluid movement through deep fractures until contact is made with critically stressed faults in basement rocks.

Fluid pressure buildup along critically stressed faults resulting from fluid transported tens to hundreds of kilometers away through basement fracture systems could trigger unexpected earthquake swarms. Once wastewater is injected into the Arbuckle it undergoes uncontrolled flow driven by head pressures and guided by permeability. Once fluid finds an exit out of the Arbuckle (fault, fracture, karst, etc.) it can move along the surface of basement until encountering a highly permeable fault or fracture where it percolates downward into basement rock. Considering basement rock (normally igneous or metamorphic) has zero permeability, once fluid enters a high permeability basement fracture system, pressure drives fluid horizontally and vertically through these relatively narrow high permeability corridors. If contact is made with critically stressed faults extending miles into the Precambrian rocks and pore pressure increases beyond the triggering threshold, displacement along the fault plane is possible.

Use of large-scale geophysical data with lineaments interpreted that represent basement structures can be used to help identify potential major fracture/faults capable of guiding fluid movement in the basement rocks. Comparing reported injection volumes at locations along these basement lineaments and in proximity to interpreted faults in the lower Paleozoic could provide insights into potential catalysts for earthquakes suspected to be induced.

Temporary monitoring with modular seismographs designed to help identify fluid movement within the Arbuckle in proximity to selected member injection wells will be considered as an experiment. By locating microearthquake clusters (clouds) at magnitudes well below measurable with our current network resulting from increased pore pressure along flow paths, we hope to better understand the movement of fluid away from the injection point of the well bore. This information would allow study of near-field migration patterns and identify localized preferential flow directions.

A variety of outcomes significant to operations at CSTS member's facilities could result from the various studies identified for future research using CSTS network waveforms. These plans for future investigations and products are based on what we have learned about the subsurface by integrating the State earthquake network, CSTS network, and basic geologic, engineering, and geophysical principles mixed with curiosity and innovation.

CONCLUSION

The Consortium continues to monitor felt and micro-seismic activity with a high rate of station performance. The number of recorded earthquakes in south-central Kansas continued to drop, while statewide earthquake numbers of M2 events increased, largely because of activity in Saline County. Seismicity does continue to expand into areas where it has not previously been documented, as evidenced by the M 3 or larger events in Graham, Rooks, and Mitchell counties. But much of that increase is outside of the areas in proximity to Consortium member wells. The Consortium continues to monitor seismic activity with an eye toward identifying areas where micro-seismic activity may indicate a future increase in earthquakes, including the possibility of larger magnitude events.

Sufficient data have been acquired to allow enhanced confidence in both predicting locations and magnitudes of future felt events and to monitor impacts of various changes in injection well operations. High level of confidence has become a reality over the last half dozen years as both past measurements and current measurements are beginning to establish patterns and predictable responses. With future research into mapping fluid pathways from injection points and preferential flow within basement rocks will have increasingly more direct impact on consortium members' operational planning.

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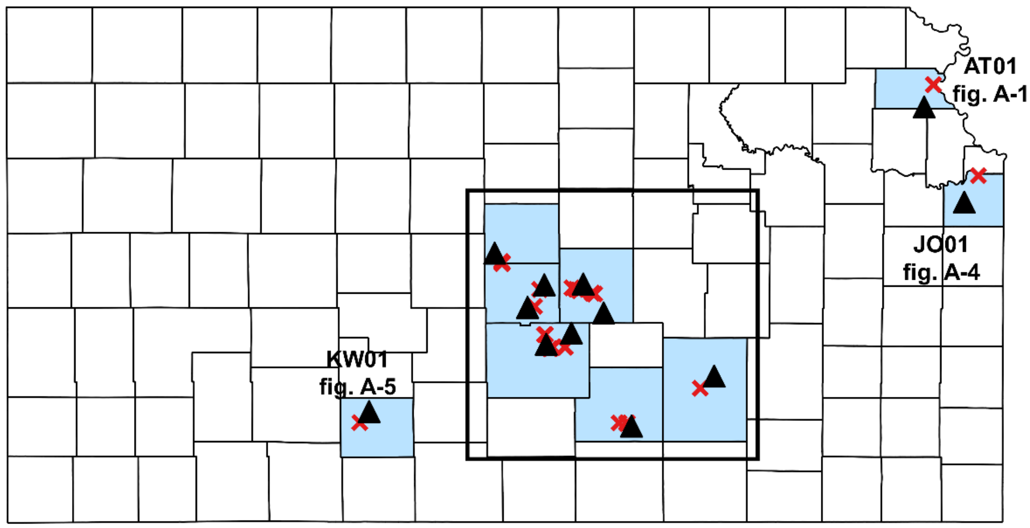
Appendix A: CSTS Station Locations, Pictures, and Descriptions



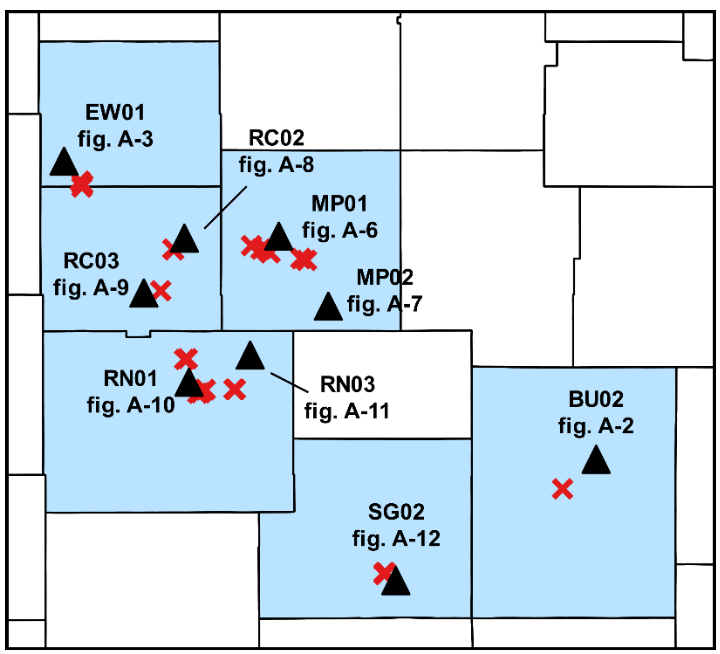


Figure A-0. Base map for pictures of equipment configuration at each station included in this appendix. Top figure is State of Kansas with the bottom figure enlargement of black box in upper figure. Black triangles are earthquake stations and red Xs are each member's injection facility location(s).

Figure A-1. AT01 is located in the Spring Hill Cemetery in southern Atchison County. This station is in a pasture near the El Dorado Lake about 2 mi from US Highway 59.

Figure A-2. BU02 is located in the El Dorado State Park in northern Butler County. This station is in a pasture near the El Dorado Lake about 4 mi from Interstate 35.

Figure A-3. EW01 is located in southwestern Ellsworth County near the city of Holyrood. The station is in a cemetery about 1 mi from highway Kansas Highway 156.

Figure A-4. JO01 is located on the grounds of the Olathe Prairie Center in Johnson County about 4 mi west of Kansas Highway 10. There is light traffic around the station and two rock quarries within about 5 mi.

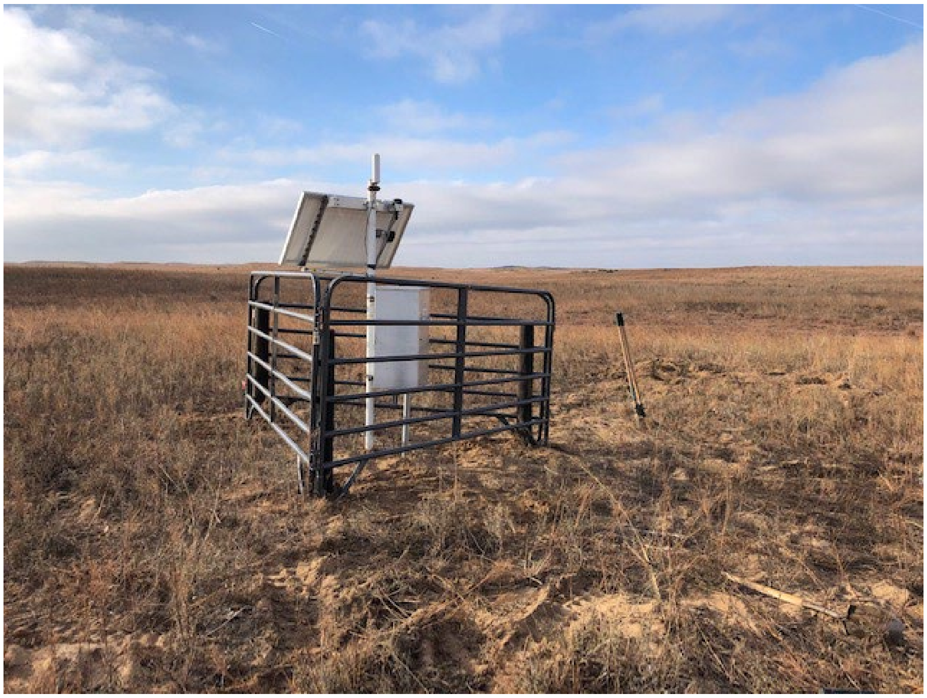


Figure A-5. KW02 is located in northern Kiowa County in a pasture located between Mullinville and Greensburg more than 1 mi from the railroad and highway.

Figure A-6. MP01 is located in the McPherson Valley Wetlands Wildlife Area in McPherson County. The station is northwest of Conway about 2 mi from US Highway 56.

Figure A-7. MP02 is located in south-central McPherson County southeast of McPherson. The station is in a pasture on the grounds of a local church about 3 mi from Interstate 135.

Figure A-8. RC02 is located in eastern Rice County near the city of Little River. This station is installed in a pasture more than 1 mi from US Highway 56 and Kansas Highway 46.

Figure A-9. RC03 is located in Rice County between Lyons and Sterling. This station is installed in a pasture about 2 mi from highway Kansas Highway 96 and is near a small landing strip.

Figure A-10. RN01 is located in Reno County west of Hutchison. This station is installed in a cemetery about 2 mi from Kansas Highway 14.

Figure A-11. RN03 is located in Reno County northeast of Hutchison in Sand Hills State Park. It is installed about 2.5 mi from Kansas Highway 61.

Figure A-12. SG02 is located in Sedgwick County south of Wichita. This station is on the grounds of a local church about 3 mi from Interstate 35 and US Highway 81 and 2 mi from two sets of railroad tracks to the west and east.

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Appendix B: CSTS Earthquake Catalog

This catalog includes all earthquakes that were uniquely located, and within 20 miles of a consortium member facility from July 1, 2024, to June 30, 2025.

Origin Time (UTC)	Latitude	Longitude	Magnitude	County
2024-08-31 09:25:03	38.61772	-97.59500	1.3	Saline
2024-09-04 00:03:05	37.60360	-97.25786	1.4	Sedgwick
2024-09-12 08:38:05	38.57302	-97.61598	1.4	McPherson
2024-11-01 11:09:58	38.62608	-97.63688	1.3	Saline
2024-11-21 04:13:32	37.51590	-97.74564	2.0	Sedgwick
2024-12-16 09:58:27	37.41408	-97.71423	1.8	Sumner
2024-12-30 08:16:50	37.82569	-97.46776	1.7	Sedgwick
2025-01-02 02:34:28	38.60299	-97.56691	1.5	McPherson
2025-01-07 06:15:34	38.57716	-97.59435	1.7	McPherson
2025-01-13 14:23:41	38.58249	-97.63700	1.7	McPherson
2025-02-18 09:46:27	37.82748	-97.46212	1.8	Sedgwick
2025-04-07 00:37:00	38.60210	-97.62248	1.6	McPherson
2025-04-15 14:55:00	38.63710	-97.69862	1.9	Saline
2025-04-27 10:30:00	38.60181	-97.57465	1.5	McPherson
2025-06-15 13:59:00	37.78612	-96.65935	1.8	Butler

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Appendix C: Subnetwork Events Catalog

Subnetwork events recorded from July 1, 2024, to June 30, 2025, with epicentral distance within 12 miles of member wells. Epicentral distance is the estimated distance from the earthquake epicenter to the seismic station where it was recorded.

Station	Origin Time (UTC)	Distance (mi)	Magnitude
RC03	2024-07-03 02:28:48	7.3	-0.2
MP02	2024-07-08 11:53:28	7.9	-0.4
RC03	2024-08-06 02:23:34	9.7	0.1
RC03	2024-09-25 03:57:43	7.0	0.2
RC03	2024-10-24 10:23:02	7.9	0.4
RC03	2024-12-04 07:29:24	8.9	0.1
RC03	2024-12-05 06:21:51	10.8	0.2
JO01	2024-12-16 05:36:07	9.0	0.2
RC03	2025-01-03 03:26:33	7.3	0.1
RC03	2025-01-28 07:02:43	8.8	0.4
MP02	2025-01-29 16:34:39	11.2	1.0
MP01	2025-02-21 11:29:09	7.0	-0.2
RC03	2025-02-27 08:03:09	7.6	0.1
RC03	2025-03-06 11:02:29	9.1	0.1
RC03	2025-03-28 02:22:42	6.5	0.2
RC03	2025-04-10 01:59:02	10.1	0.1
RN01	2025-05-10 06:54:14	5.3	0.2
BU02	2025-06-15 13:59:11	7.6	0.1

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Appendix D: Literature Review

Separating Injection-Driven and Earthquake-Driven Induced Seismicity by Combining a Fully Coupled Poroelastic Model With Interpretable Machine Learning

Hill et al. (2024), *Geophysical Research Letters*
https://doi.org/10.1029/2024GL109802

Key Points

- Thousands of earthquakes have occurred within 25 km of the Paradox Valley Unit (PVU), a deep brine disposal well since operation began in 1991.
- Machine learning was used to determine that only ~20% of events were directly triggered by pressure/stress from injection, while the rest are a result of earthquake interactions.
- Implications for risk assessment/management: injection induced earthquakes can be controlled through injection best practices.

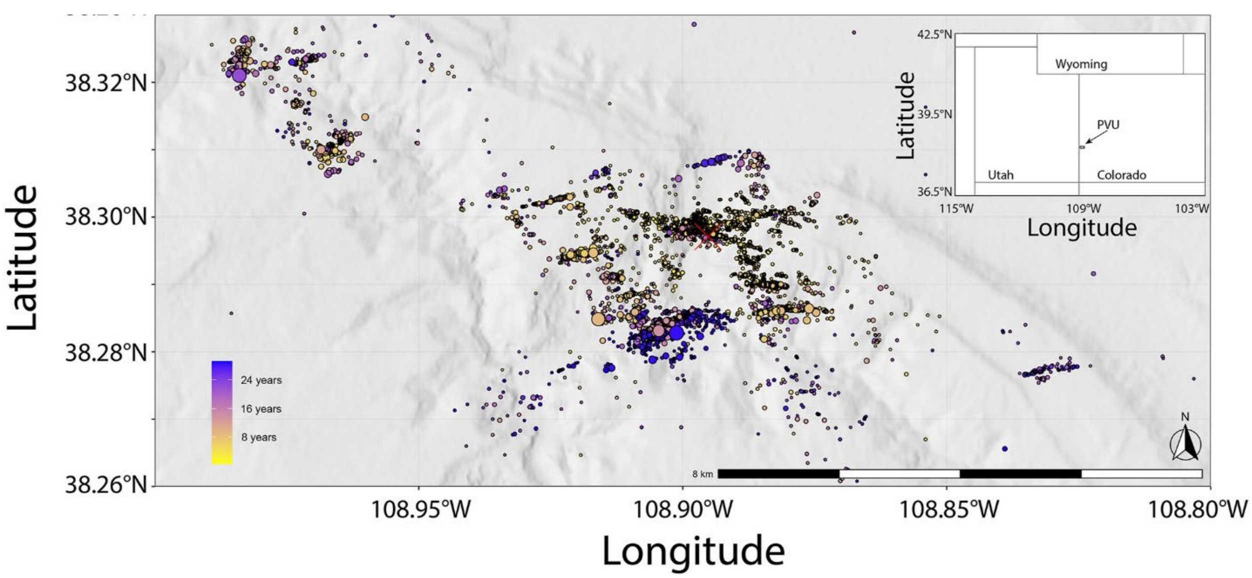

Figure D-1. Temporal evolution of seismicity near the Paradox Valley Unit, CO (PVU) well (denoted by the red 'X').

Mitigation and Optimization of Induced Seismicity Using Physics-Based Forecasting

Hill et al. (2024), *JGR Solid Earth*
https://doi.org/10.1029/2024JB028759

Key Points

- Thousands of earthquakes have occurred in the Raton Basin where coal-bed methane production and wastewater disposal began in 1994, included a M 5.3 event.
- Following the machine-learning based classification method in the previous paper (Separating Injection-Driven and Earthquake-Driven Induced Seismicity…), it was determined that induced seismicity in the Raton Bason is primarily injection-driven.
- Physics-based and statistical models were used to develop an optimization framework to proactively reduce earthquake potential while maximizing fluid injection.

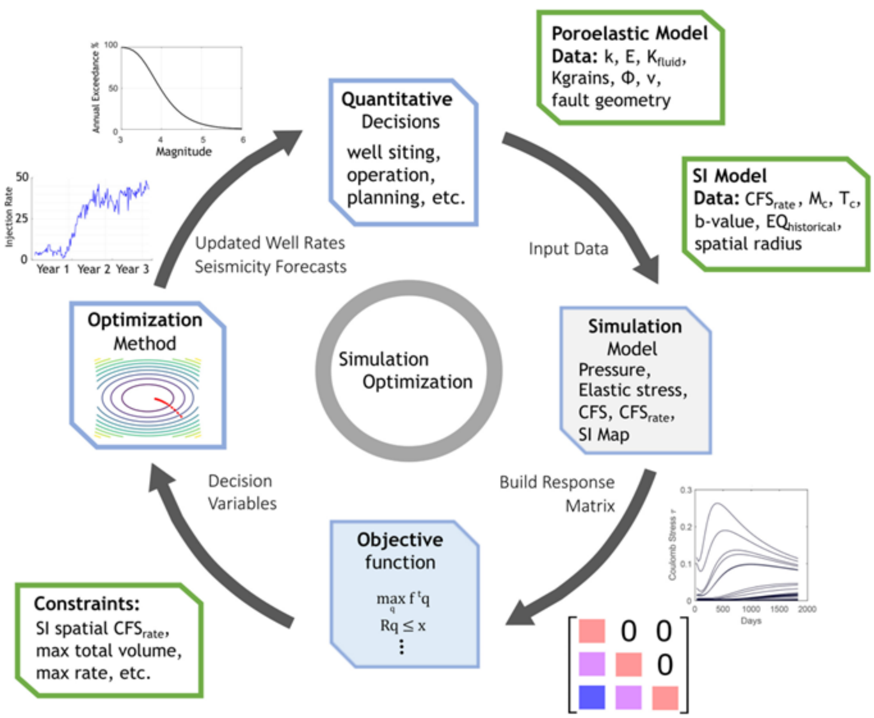

Figure D-2. Simulation Optimization Schematic. Beginning at the top, operations consider quantitative decisions in well placement and operation prior to injection. By developing a numerical model and SI map from current injection, a simulation model is built. The simulation model is used to build a response matrix which through linear programming solves a desired objective function (maximize the fluid injected). Additional constraints further inform the optimization which arrives at informed injection rates and spatial earthquake probability maps to then advise future operation practices.