Supplemental Material for

Evidence for Far-Field Wastewater Disposal Causing Recent Increases in Seismicity in Central and Northern Kansas

S. L. Fasola[1,+,*], M. R. Brudzinski[2], and N. M. Jackson[1]

[1]Department of Geology, University of Kansas, Lawrence, KS, United States
[2]Department of Geology and Environmental Earth Science, Miami University, Oxford, OH, United States
[+]Now at the Cascadia Region Earthquake Science Center, Eugene, OR, United States
[*]Corresponding author: sfasola@uoregon.edu

S1. Methods

S1.1 Template Matching

Seismic data for broadband (N4 R32B, GS KS28, US KSU1, US CBKS) and short-period (KS JLK) stations were band-pass filtered between 3 and 10 Hz and 1 and 45 Hz, respectively. KGS catalog earthquakes and ComCat earthquakes not already in the KGS catalog from 2000 to 2022 in the regions surrounding M≥4 earthquakes were used as templates. The ComCat and KGS catalogs both had a M_C 2.75 for 2000 to 2013 when station coverage was sparser and a M_C 1.85 and M_C 1.95, respectively, for 2014 to 2022 when station coverage improved. M_C was determined using the maximum curvature algorithm (Wiemer and Wyss, 2000). For the regional stations (N4 R32B, US CBKS, US KSU1), we used a template length of 30 s starting ~5 s before the P-wave on the vertical component and ~5 s before the S-wave on the horizontal components, which was determined to be an optimal length for regional template matching (Skoumal et al., 2014). For the local stations (GS KS28, KS JLK), we used a shorter template length of 15 s starting ~5 s before the P-wave on the vertical component and ~5 s before the S-wave on the horizontal components. The phase arrival times were estimated using the IRIS DMC (now EarthScope Consortium) traveltime web services (https://service.iris.edu/irisws/traveltime/1/) and iasp91 velocity model. Since we used a single station for template matching for each region, we employed a high correlation coefficient threshold of 0.5. This means that the total number of detections we presented in this study is a minimum number as we may have missed true positive events with lower correlation coefficients. We verified the similarity of matches by plotting matched waveforms (Supplemental Figure S2). Since KS JLK had a few substantial gaps in recording, Jewell County matches from KS JLK and US CBKS were combined and duplicates were removed.

Magnitudes of the matched earthquakes were estimated as in Schaff and Richards (2014) by comparing the unnormalized correlation coefficients of the events to the cataloged magnitude of its matched template. The estimation is given as:

$$\delta mag = \log_{10}[\max(x \star y)/(x \cdot x)]$$

in which ★and · represent cross-correlation and dot product, x and y are the cataloged template earthquake and a matched event, respectively. Due to the poor spatial coverage of seismic stations at the time of this study in northern and central Kansas, locations of matched events were not determined. Therefore, matched events were assigned the location of the best matched template.

S.1.2 Class II wells and Manual Inspection

An extensive effort was put forth to clean up the Kansas Class II fluid injection database of SWD wells and identify wells injecting into or below the Arbuckle. For a given well, the reported injection zone would vary from year to year with generally more consistency after 2015, making it difficult to know the true injection zone. In addition, if wells were plugged back, the plug back depth is not easily available to confirm a shallower injection zone as manual inspection of each completion report would be needed. Due to the lesser likelihood of EOR wells generating seismicity and the sheer number of EOR wells compared to SWD wells in Kansas (~16,300 vs. 6,800 wells), our focus was on SWD wells. While the Arbuckle typically overlies the Precambrian basement (Franseen et al., 2004), in some locations the Arbuckle is underlain by the Cambrian Reagan sandstone (in some places referred to as Basal Sand) or Granite Wash, a Cambrian sand unit resting on the Precambrian basement but not directly associated with the overlying Reagan sandstone (Merriam, 1963; McElroy and Kaesler, 1965). Therefore, in this study we use the term 'Arbuckle' in a general sense to refer to the Arbuckle and all underlying units down to the Precambrian basement.

In order to determine if a well was injecting into the Arbuckle, we cross-checked the most recent reported injection interval of a well in the Kansas Class II fluid injection database (https://www.kgs.ku.edu/PRS/Ora_Archive/KS_UIC_archive.zip) with the reported formation from completion reports in the Kansas Master List of Wells (https://www.kgs.ku.edu/PRS/Ora_Archive/ks_wells.zip). The difference between these two databases compiled by the KGS is that the Kansas Class II fluid injection database is derived from Annual Reports which includes monthly and annual injection volumes and the injection zone while the Kansas Master List of Wells is a database of well-header information for all oil and gas wells in Kansas which includes the 'formation at total rotary depth' and 'producing formation typed in from completion form or from lease production data'. SWD wells that listed the Arbuckle or an underlying unit in both databases were deemed an Arbuckle well. For all other SWD wells, we cross-checked the depth of the well with the depth to the top of the Arbuckle in the nearest well in the KGS database of tops picked (https://www.kgs.ku.edu/PRS/Ora_Archive/ks_tops.zip). If the well was within 5 km spatially and at least 25 ft below the top of the Arbuckle in the nearest well in the KGS tops database, then the injection interval of that well was listed as Arbuckle. The completion reports of the remaining wells with a depth below the top of the Arbuckle (i.e., wells within 5 km and less than 25 ft and wells more than 5 km) were manually checked to confirm an injection interval (https://www.kgs.ku.edu/Magellan/Qualified/index.html). If the completion reports were not available, then Casing Mechanical Integrity Tests were used if available to confirm if well was injecting into the Arbuckle or an underlying unit. Similarly, wells within 5 km but within 25 ft above the top of the Arbuckle were spot-checked. We note that this method is not specifying if the well is in fact injecting into the Arbuckle or into a lower unit. Since we use the term 'Arbuckle' in this study to refer to the Arbuckle group and all intervals below the Arbuckle, we did not find it necessary to distinguish.

We removed duplicated lines where in some cases annual reports appeared to be submitted or entered twice. Monthly injection volumes for Class II wells are incomplete prior to 2015 as the KCC switched to requiring digital reporting in 2015 (personal communication with the KGS). Therefore, we used annual volumes prior to 2015 and monthly volumes after 2015. Thus, we only checked for typos in monthly volumes after 2015. By this we mean monthly volumes that were one or more orders of magnitude larger than the other months of the given and adjacent years. For these monthly volumes, annual injection reports available on the KGS website were checked for a submitted "Corrected" annual report and adjustments were made accordingly. Average WD monthly injection volumes reported in this study were calculated for 2015 to 2022.

The corrected catalog of SWD wells we determined to be injecting into the Arbuckle or underlying units is provided in the Supplemental Material (Dataset S4). This catalog is still likely an incomplete list of Arbuckle wells as the total depth of the well was used when comparing with the top of the Arbuckle thus not accounting for if the well was plugged back and tops picked are derived from various sources and not necessarily confirmed by the KGS. Therefore, volumes reported in this study serve as an approximation.

References Only in Supplement

McElroy, M. N., and Kaesler, R. (1965). Application of factor analysis to the Upper Cambrian Reagan Sandstone of central and northwest Kansas. *Compass*, *42*(3), 188-201.

Merriam, D.F. (1963). *The geologic history of Kansas*, Kansas Geological Survey Bulletin, Vol. 162, http://www.kgs.ku.edu/Publications/Bulletins/162/index.html.

Skoumal, R. J., Brudzinski, M. R., Currie, B. S., and Levy, J. (2014). Optimizing multi-station earthquake template matching through re-examination of the Youngstown, Ohio, sequence. *Earth and Planetary Science Letters*, *405*, 274-280. DOI: 10.1016/j.epsl.2014.08.033

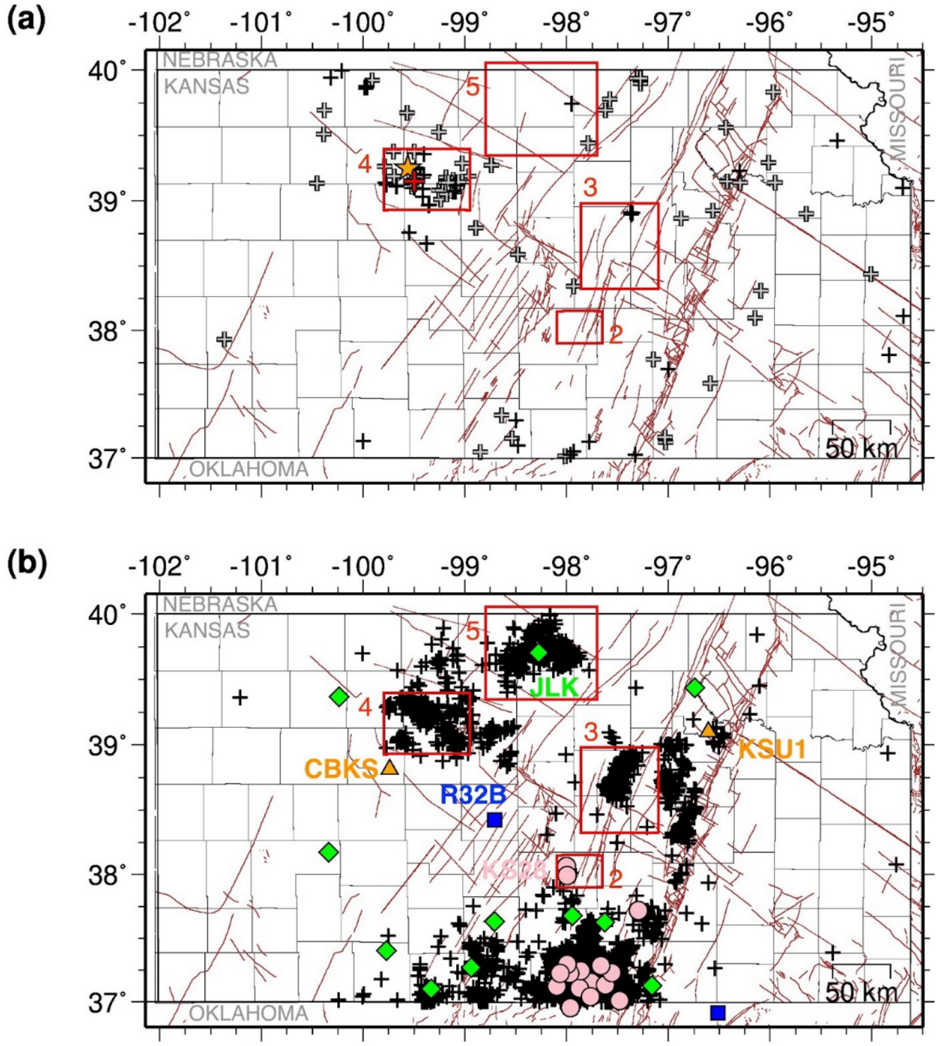

Figure S1. (a) Map of historical earthquakes (M≥2) in Kansas from 1977 to 1989 (Steeples et al., 1990; gray crosses) and 1990 to 2013 (ComCat; black crosses). Red cross is the likely WD-induced 1989 M 4.0 earthquake near the town of Palco (orange star). Red boxes mark the four focus regions in this study corresponding to Figures 2-5. (b) Map of seismic stations operating or installed after 2014 and in operation for longer than 3 years. Networks include Kansas Geological Survey Network (KS; green diamonds); Central and Eastern US Network (N4; blue squares); US Geological Survey Network (GS; pink circles); US National Seismic Network (US; orange triangles). Stations are labeled if they were used for template matching. KGS and ComCat earthquakes (M≥2) from 2014 to 2022 are shown (black crosses).

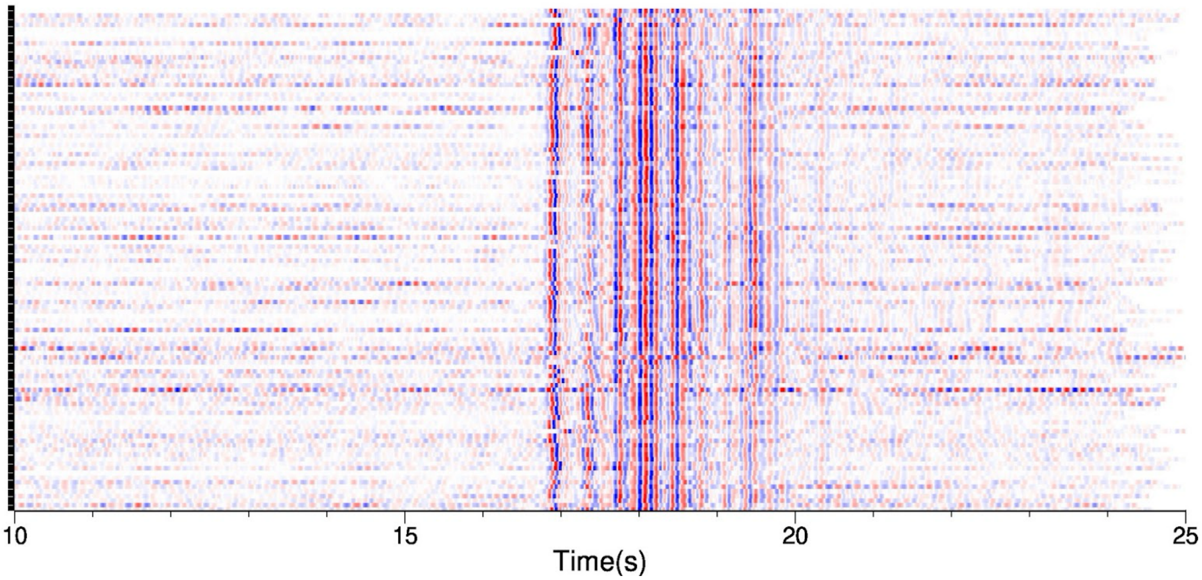

Figure S2. Gridded waveform plot of matched events from an example template earthquake in Hutchinson, KS to show similarity of waveforms. Waveforms are plotted on the vertical component of GS KS28.

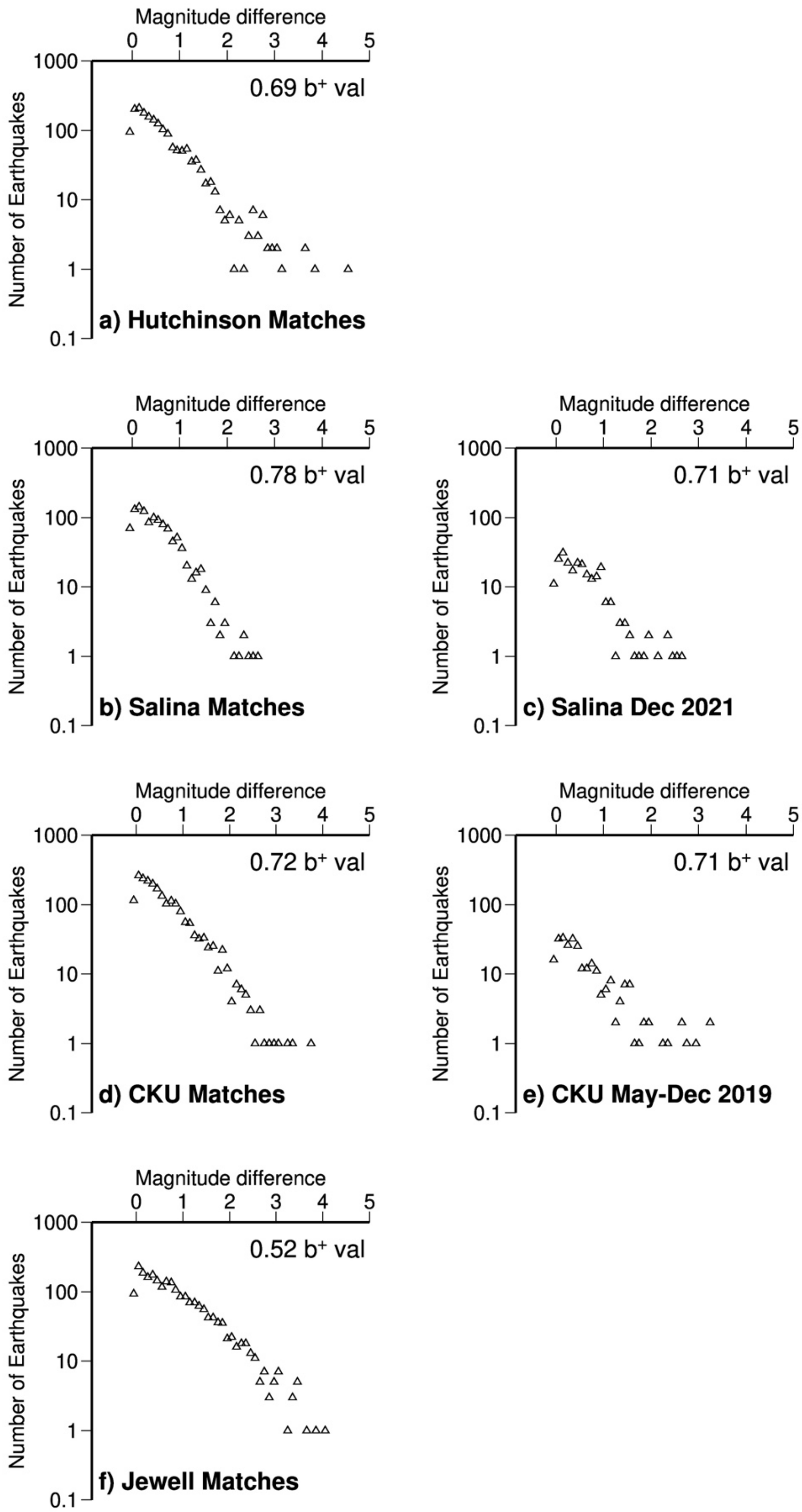

Figure S3. Frequency magnitude difference distributions with b-value calculated via the b-positive method (b^+ val). Triangles represent cumulative number of earthquakes. Matched events for (a) Hutchinson (Figure 2b). (b) Salina (Figure 3b). (c) Salina during the December 2021 swarm (Figure 3c). (d) CKU (Figure 4b). (e) CKU during the May-December 2019 swarm (Figure 4c). (f) Jewell County and surrounding region (Figure 5b).

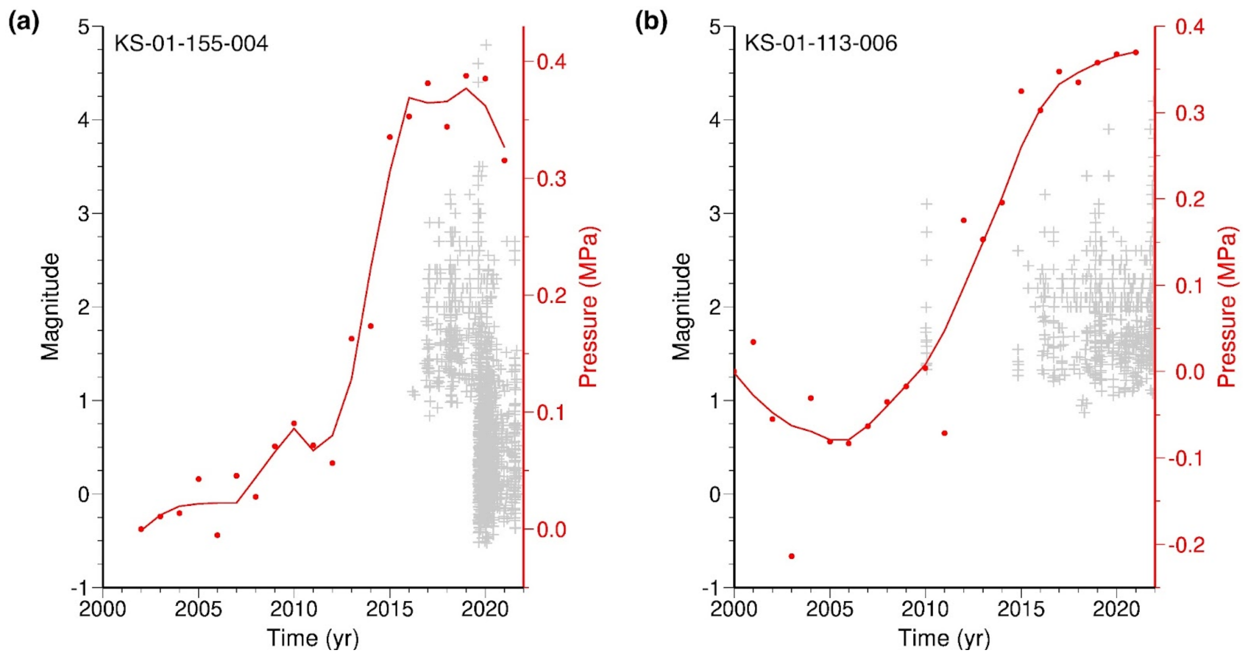

Figure S4. Relative pressure from Class I well annual fall-off tests (red circles) and magnitudes of KGS, ComCat, and matched earthquakes (gray crosses). Pressure is relative to the pressure in 2000 or the first data point. Pressure data for 2000 to 2017 is from Ansari et al. (2019) while data for 2018 to 2021 is new data from the KDHE. Red line is the pressure trend determined using locally weighted regression. The pressure trend is used to determine the annual change in pressure shown in Figures 2d and 3e. (a) Class I well KS-01-155-004 (RN4) and Hutchinson seismicity. (b) Class I well KS-01-113-006 (MP6) and Salina seismicity.

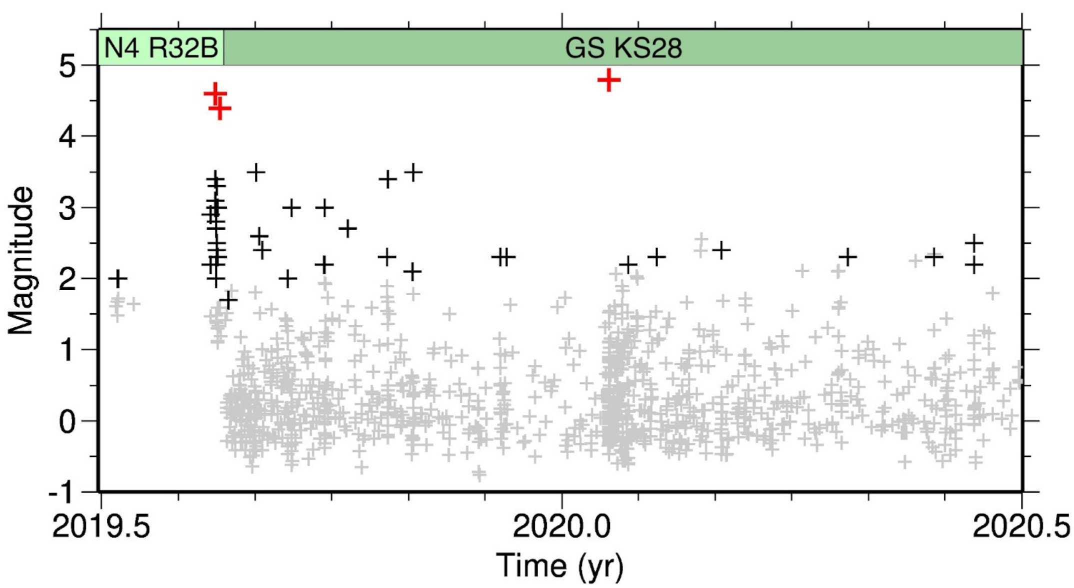

Figure S5. Magnitude-time plot for the three M≥4 earthquakes (red crosses) in Hutchinson, KS. Template earthquakes (M<4) are shown in black while the matched events are shown in gray. Bars at top of plot denote timing of stations used for template matching.

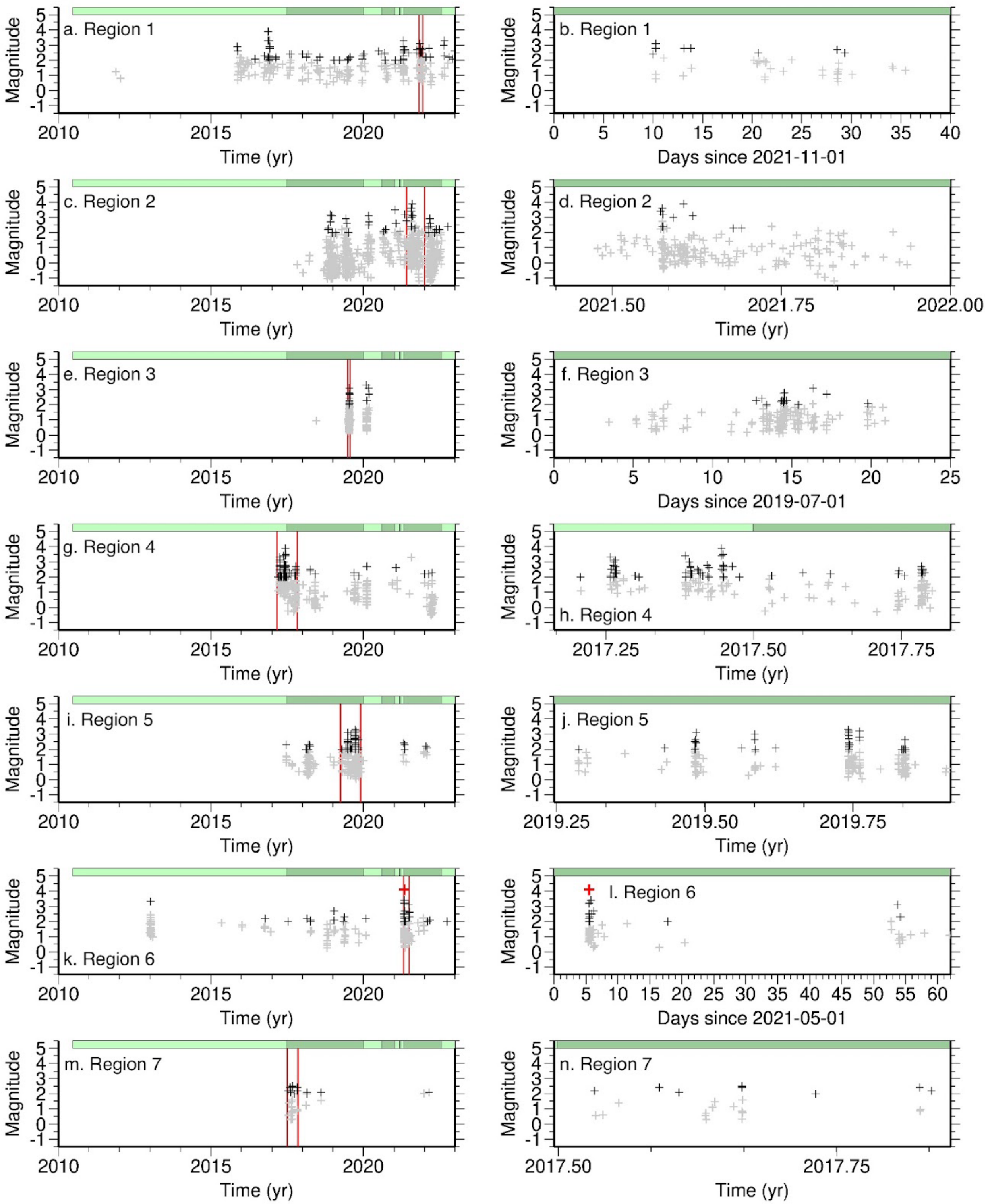

Figure S6. (a) Magnitude-Time plot for earthquakes in Region 1 in Jewell county with template earthquakes as black crosses and matched events as gray crosses. Bars at top of plot mark timing of stations used for template matching (US CBKS: light green; KS JLK: dark green). Red box denotes timing in (b). (b) Magnitude-Time plot of zoomed-in view of increased seismicity. (c-d) Region 2. (e-f) Region 3. (g-h) Region 4. (i-j) Region 5. (k-l) Region 6. (m-n) Region 7.

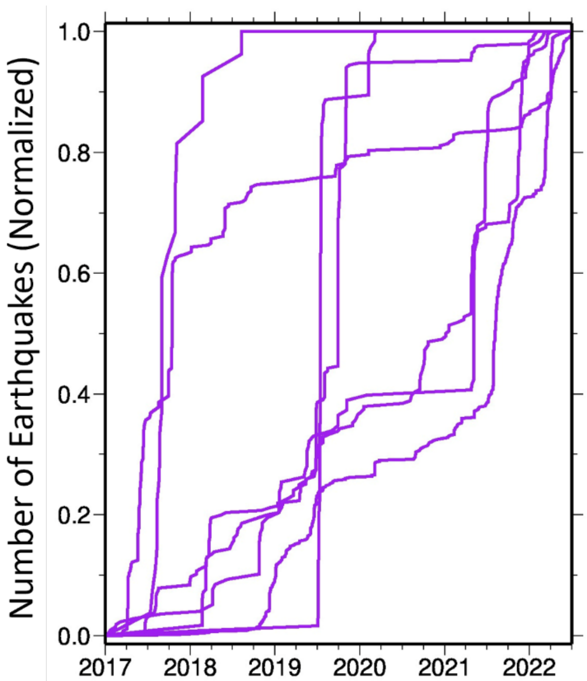

Figure S7. Cumulative number of earthquakes identified over time in Jewell County divided into the 7 geographical bins. Clustering in time is present in each of the geographic clusters.

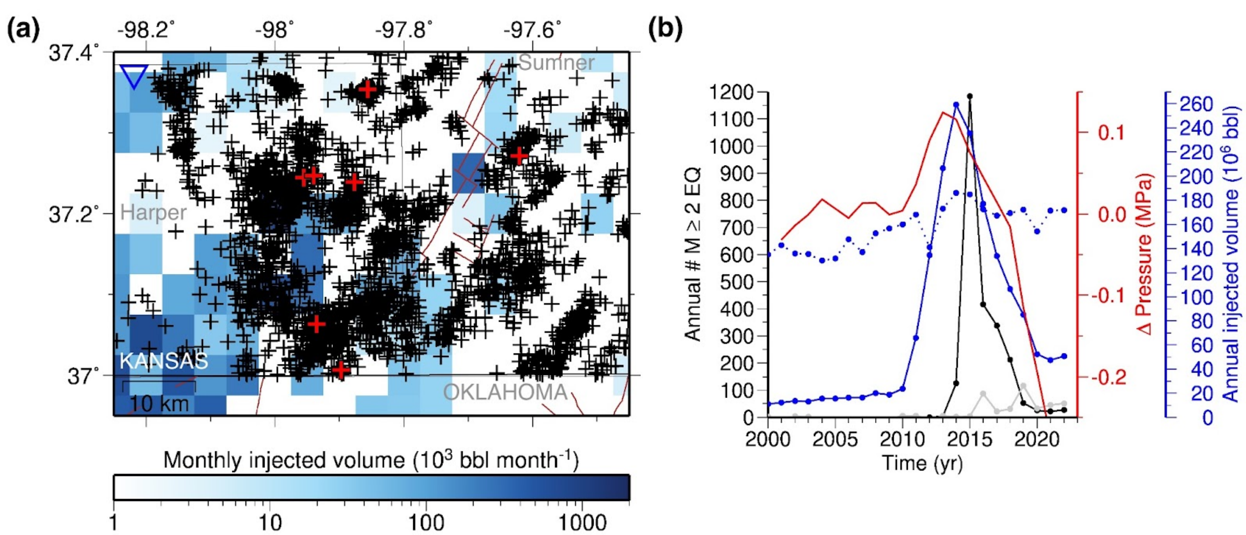

Figure S8. Harper-Sumner seismicity and WD. (a) Map of earthquakes (crosses, red if M≥4) and average monthly injection volume for Arbuckle WD wells from 2015-2022 computed in bins that are 0.05°×0.05°. Blue inverted triangle marks location of Class I well KS-01-077-002 (HP2). Counties (gray) are labeled. (b) Annual rates of injected volume for WD wells within 0.1˚ of the map boundary (solid blue) and M≥2 earthquakes (solid black). For comparison, CKU annual volumes (dotted blue) and earthquakes (solid gray) from Figure 4e are shown. Note both regions are the same size. Red line shows the change in pressure per year at Class I well HP2.

Data S1 (separate file)

Dataset including all earthquakes detected with template matching.

Data S2 (separate file)

Compiled injection volume data for Class I wells from 2000-2022 (See Data and Resources for sources of data). Note there is a '0' in the MONTH column if only annual volumes are available. STATUS lists if the well is ACTIVE or PLUGGED.

Data S3 (separate file)

Compiled pressure data (MPa) from Class I well fall off tests. Dataset includes pressures for 2000 to 2017 as in Ansari et al. (2019) and for 2017 to 2021 available upon request from the KDHE.

Data S4 (separate file)

Injection volume data for Class II SWD wells injecting into the Arbuckle and underlying units from 2000-2022 (See Data and Resources for sources of data and Supporting Text S1 for description of updates to the dataset). Note there is a '0' in the MONTH column if only annual volumes are available. WELL_TYPE lists either 'SWD' if the well is active or 'SWD-P&A' if the well is plugged and abandoned.