# KGS Earthquake Products for CSTS Members, Regulators, and the Public

**Shelby Peterie**, Rick Miller, Juliana Gonzales, Carl Gonzales, Erik Knippel

*Kansas Geological Survey*

Fourth Annual CSTS Meeting

August 5, 2021

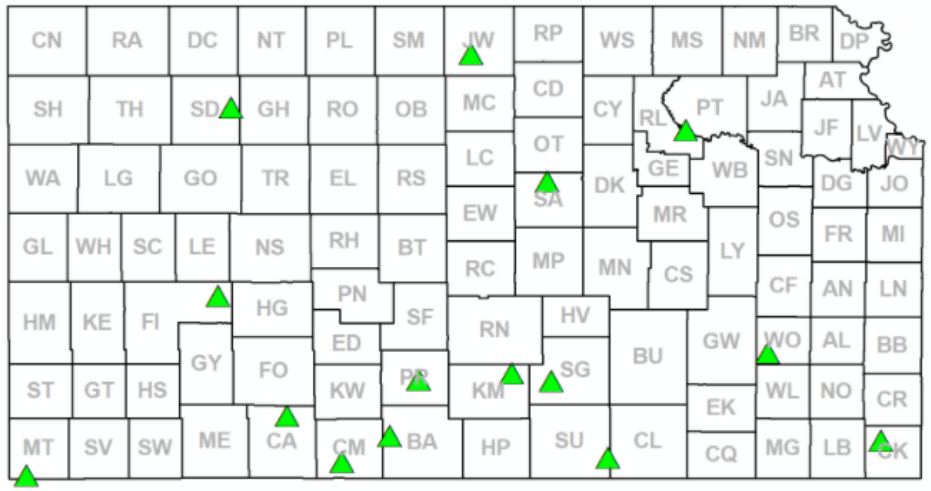
McPherson, KS

# Earthquake Product Access

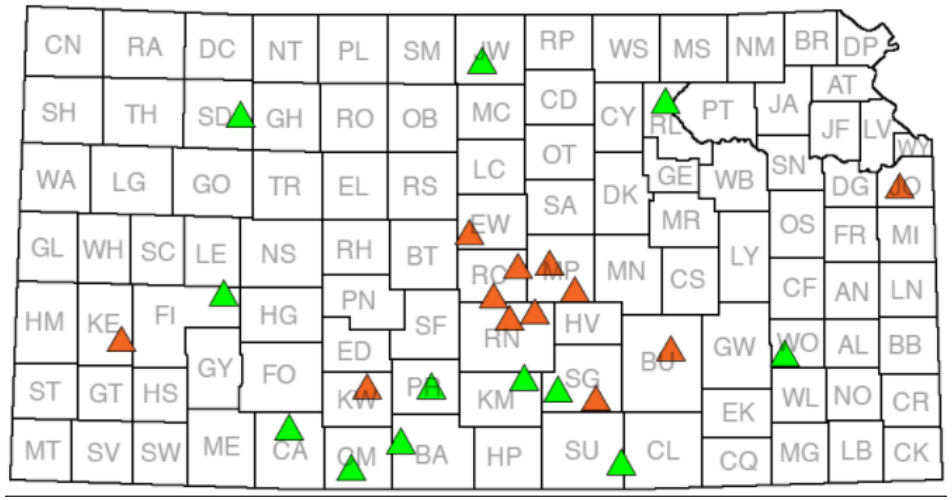
| Product | Public | KCC/KDHE | CSTS |
|---|---|---|---|
| seismograms | KGS network (14) | KGS network (14) | KGS & CSTS networks (25) |
| catalog | M 2+ restricted | M 1.8+ restricted | all M unrestricted |
| earthquake viewer | basic map | basic map | mapper |
| mapper | *disposal wells*<br>*public catalog*<br>*no downloads* | disposal wells<br>KCC/KDHE catalog<br>limited downloads | disposal wells<br>full catalog<br>full downloads |
| real-time alerts | *M 2.5+ statewide* | *M 2.5+ statewide* | M 2+ within 30 mi |
| CSTS reports | none | annual | annual – Tier 1&2<br>quarterly – Tier 1 |

# Network Map

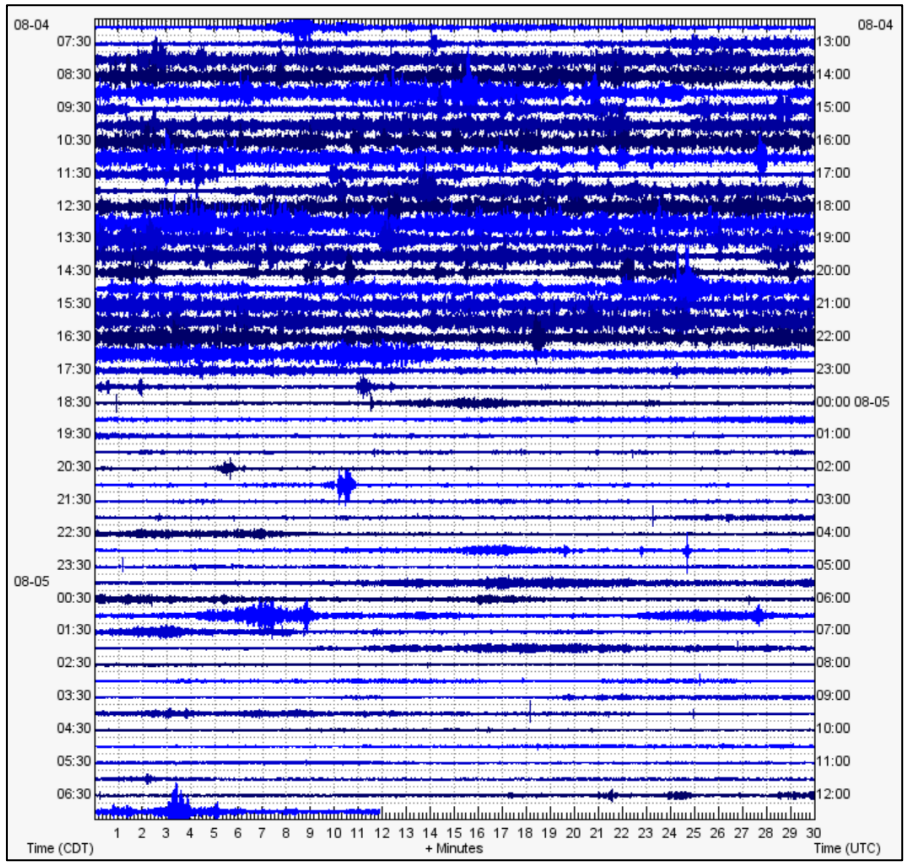
## KGS Website

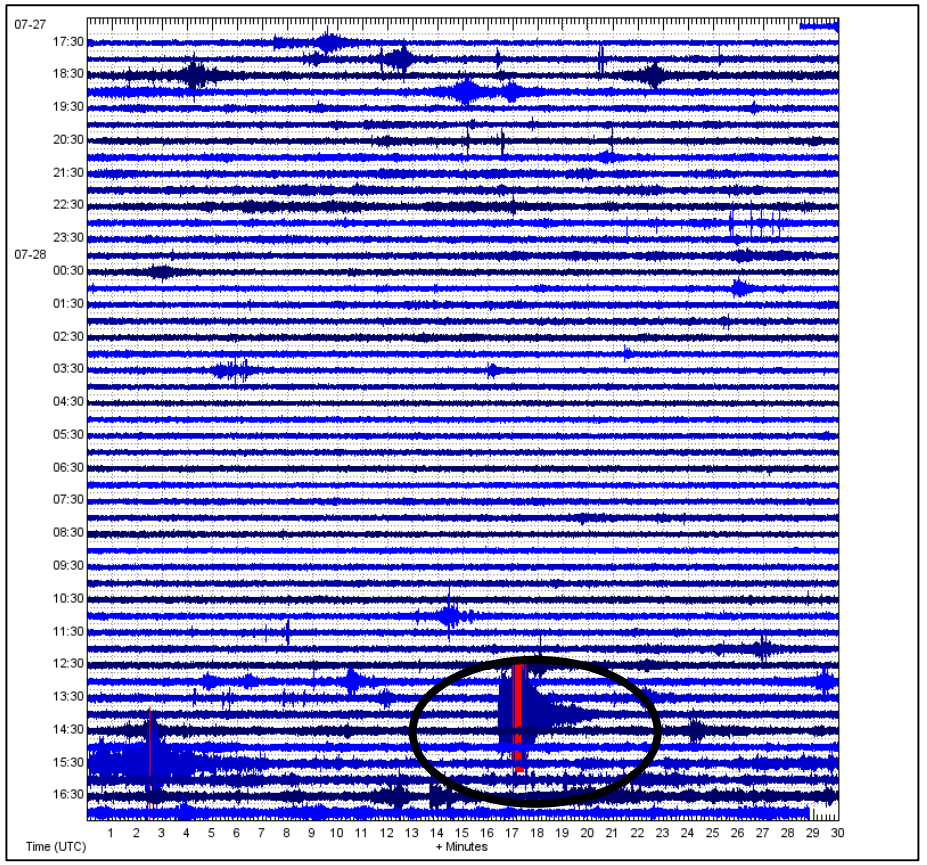



## CSTS Website (Tier 1)



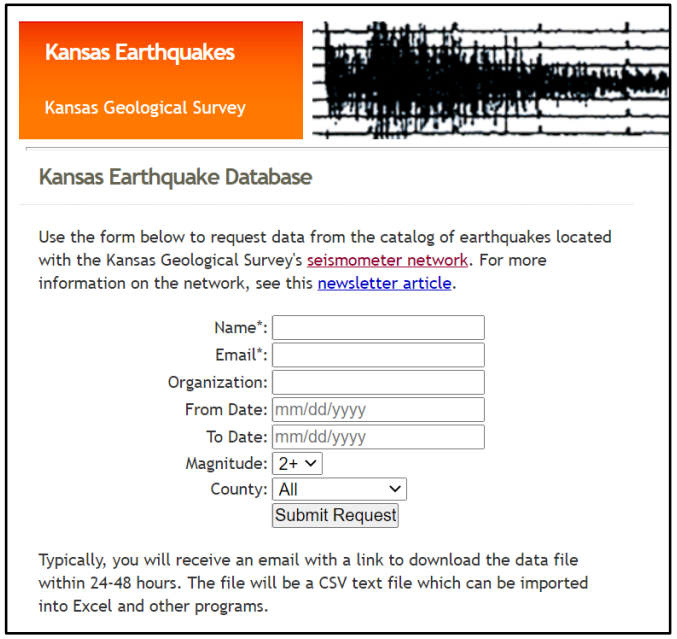
# Seismograms



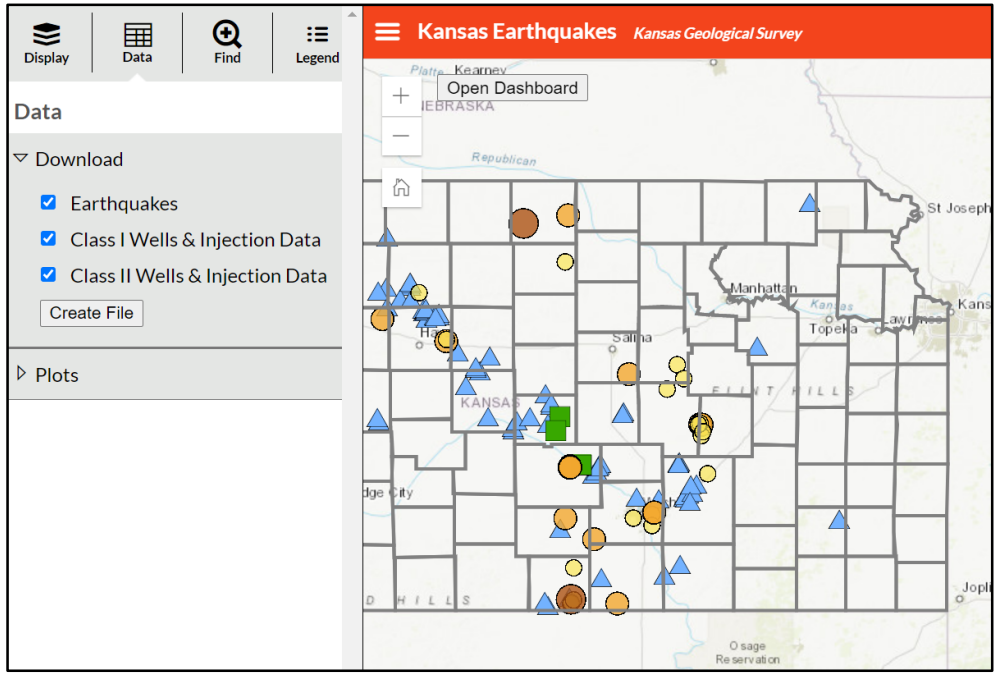



# Catalog

## Public, KCC/KDHE




## CSTS

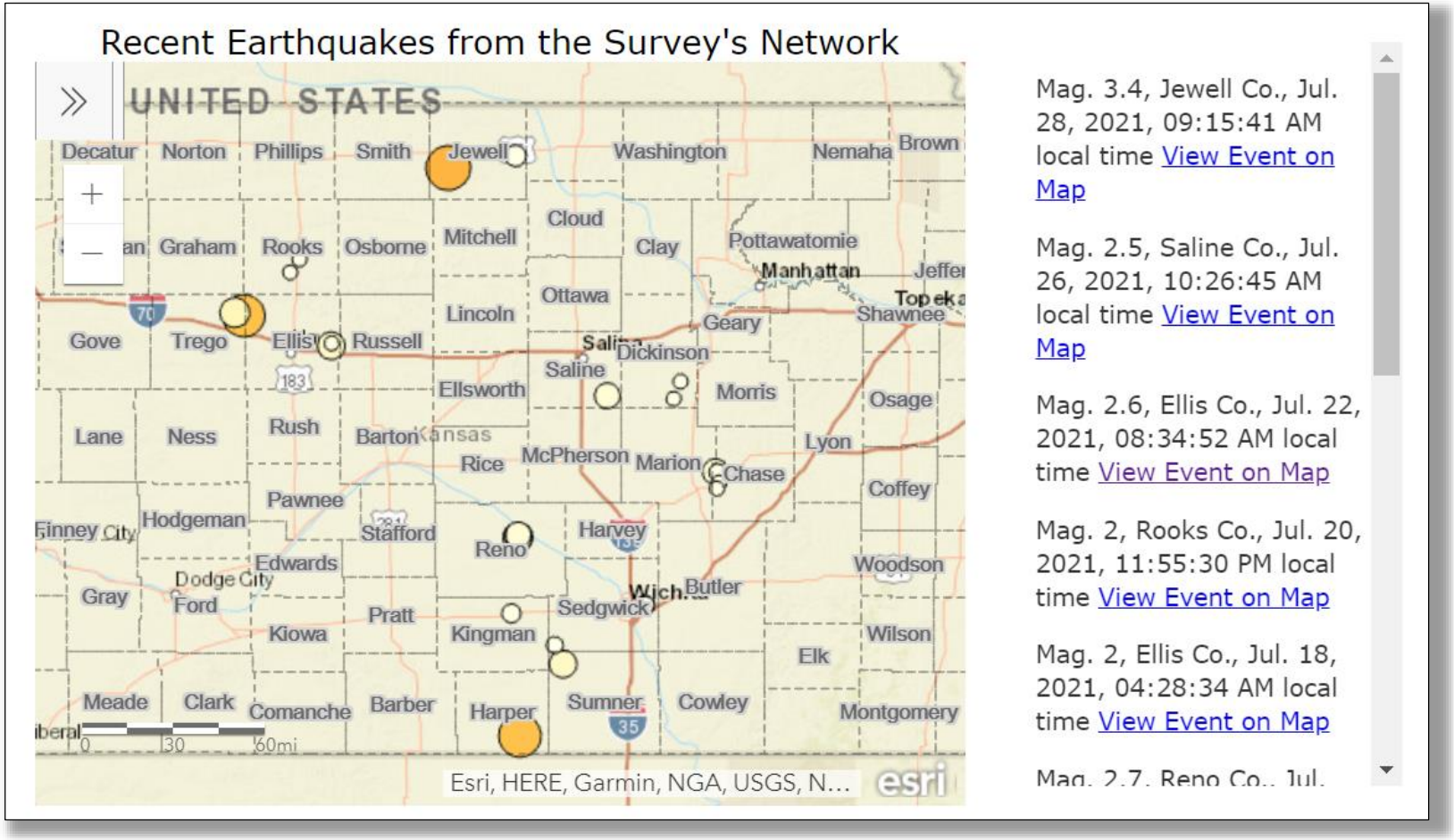



- Download via mapper
  - all magnitudes
  - no restrictions

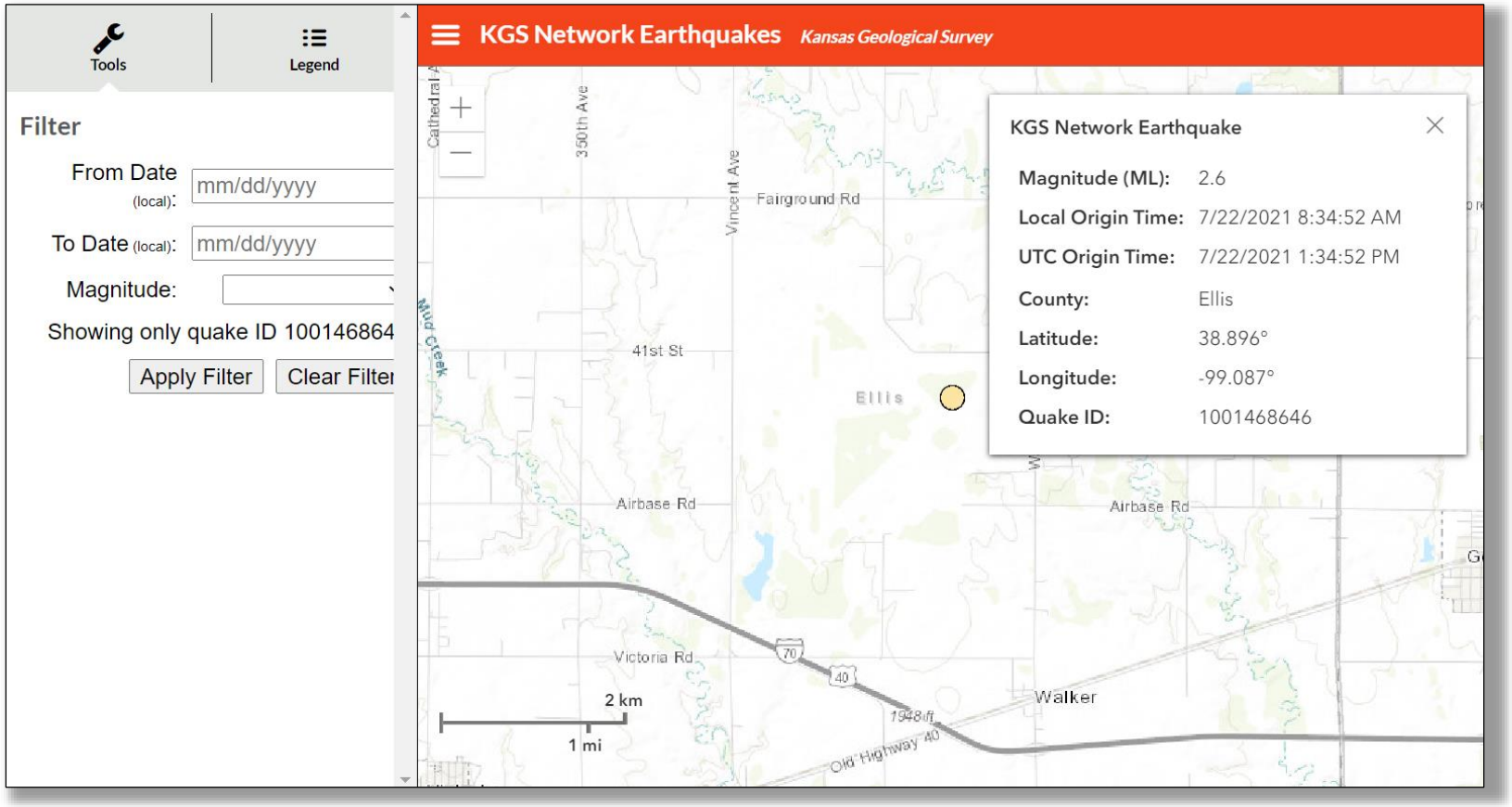
# Catalog Requests

| ORGANIZATION | COUNTY | FROMDATE | TODATE | MAG | REQUEST_DATE | DATE_COMPLETED | REQ_ID | STATUS |
|---|---|---|---|---|---|---|---|---|
| | Sedgwick | 01.01.2010 00:00:00 | 21.07.2021 00:00:00 | 2 | 21.07.2021 09:25:29 | 21.07.2021 10:17:41 | 581 | approved |
| | all | 01.01.2021 00:00:00 | 14.07.2021 00:00:00 | 2 | 19.07.2021 09:33:04 | 19.07.2021 09:33:44 | 562 | approved |
| | all | 21.06.2021 00:00:00 | 27.06.2021 00:00:00 | 2 | 19.07.2021 09:02:52 | 19.07.2021 09:33:36 | 561 | approved |
| | Reno | | | 2 | 17.07.2021 07:15:10 | 17.07.2021 08:09:06 | 541 | approved |
| Emporia State University | all | 01.01.2016 00:00:00 | 01.12.2021 00:00:00 | 2 | 14.07.2021 13:28:27 | 14.07.2021 13:30:45 | 521 | approved |
| Emporia State University | all | 01.01.2016 00:00:00 | 01.12.2021 00:00:00 | 2 | 12.07.2021 14:49:14 | 12.07.2021 14:54:57 | 501 | approved |
| | all | 01.06.2021 00:00:00 | 12.07.2021 00:00:00 | 2 | 12.07.2021 12:36:05 | 12.07.2021 14:55:12 | 481 | approved |
| Regional Development Association | Lyon | 01.01.2011 00:00:00 | 01.06.2021 00:00:00 | 2 | 12.07.2021 10:24:36 | 12.07.2021 11:01:34 | 461 | approved |
| Regional Development Association of East Central Kansas | Lyon | 01.06.2010 00:00:00 | 01.06.2021 00:00:00 | 2 | 09.07.2021 14:02:33 | 09.07.2021 17:21:10 | 441 | approved |
| DPTMS-Fort Riley | Geary | 07.06.2020 00:00:00 | 07.06.2021 00:00:00 | 2 | 07.07.2021 13:45:03 | 07.07.2021 13:45:27 | 422 | approved |
| DPTMS- Fort Riley | Riley | 01.06.2020 00:00:00 | 07.06.2021 00:00:00 | 2 | 07.07.2021 13:44:13 | 07.07.2021 13:45:21 | 421 | approved |
| State Farm Insurance | Sedgwick | 01.01.2021 00:00:00 | 01.06.2021 00:00:00 | 2 | 06.07.2021 17:33:28 | 06.07.2021 17:39:40 | 401 | approved |
| | Sedgwick | 15.06.2021 00:00:00 | 05.07.2021 00:00:00 | 2 | 05.07.2021 10:04:37 | 05.07.2021 10:17:58 | 381 | approved |
| | Harvey | 01.06.2021 00:00:00 | | 2 | 30.06.2021 15:28:43 | 30.06.2021 15:33:37 | 361 | approved |
| | Sumner | 19.06.2021 00:00:00 | 20.06.2021 00:00:00 | 2 | 29.06.2021 15:14:21 | 30.06.2021 15:15:11 | 341 | approved |
| Terracon | Allen | 09.07.2010 00:00:00 | 09.07.2020 00:00:00 | 2 | 28.06.2021 15:42:48 | 28.06.2021 15:43:17 | 321 | approved |
| Seoul National University | all | 25.06.2021 00:00:00 | 31.08.2021 00:00:00 | 2 | 24.06.2021 20:01:06 | 24.06.2021 20:04:48 | 301 | approved |
| | Riley | 01.01.1980 00:00:00 | 30.03.2021 00:00:00 | 2.5 | 12.06.2021 08:31:05 | 12.06.2021 08:41:35 | 281 | approved |
| | all | 01.01.2020 00:00:00 | 31.12.2021 00:00:00 | 2.5 | 10.06.2021 11:59:48 | 11.06.2021 06:51:13 | 261 | approved |
| | all | 01.01.2020 00:00:00 | 05.06.2021 00:00:00 | 2.5 | 06.06.2021 08:39:57 | 06.06.2021 09:04:40 | 221 | approved |

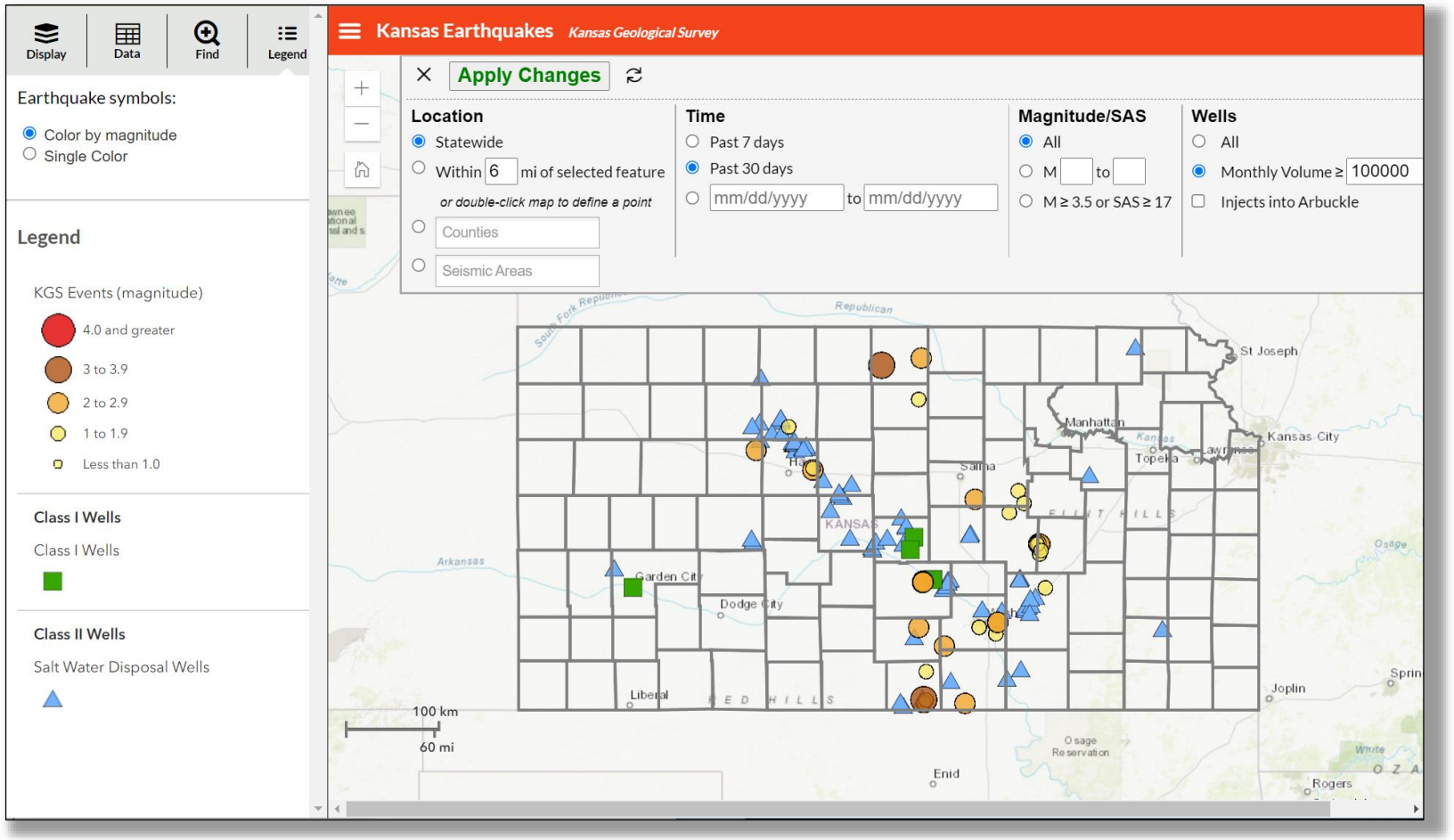
# KGS Website: Recent Earthquake Feed



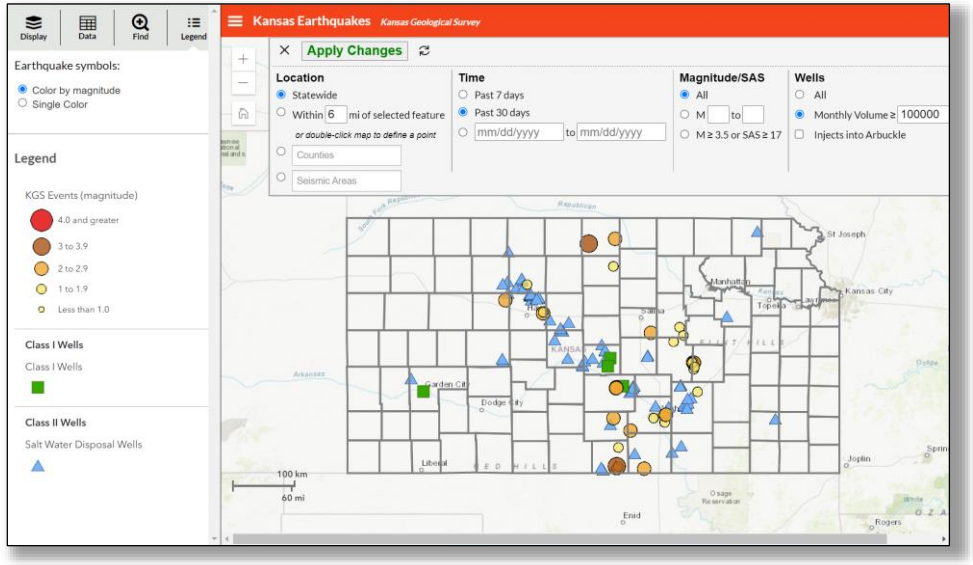
# KGS Website: Basic Interactive Map



# CSTS: Full Interactive Mapper



# Interactive Mapper




- CSTS
  - magnitudes: all
  - downloads
    - earthquakes
    - injection volumes
- KCC/KDHE (beta testing)
  - magnitudes: M 1.8+
  - downloads
    - injection volumes
- Public (coming soon)
  - magnitudes: M 2+
  - downloads
    - none
    - earthquakes: download request
    - injection volumes: KGS website

# Real-Time Alerts

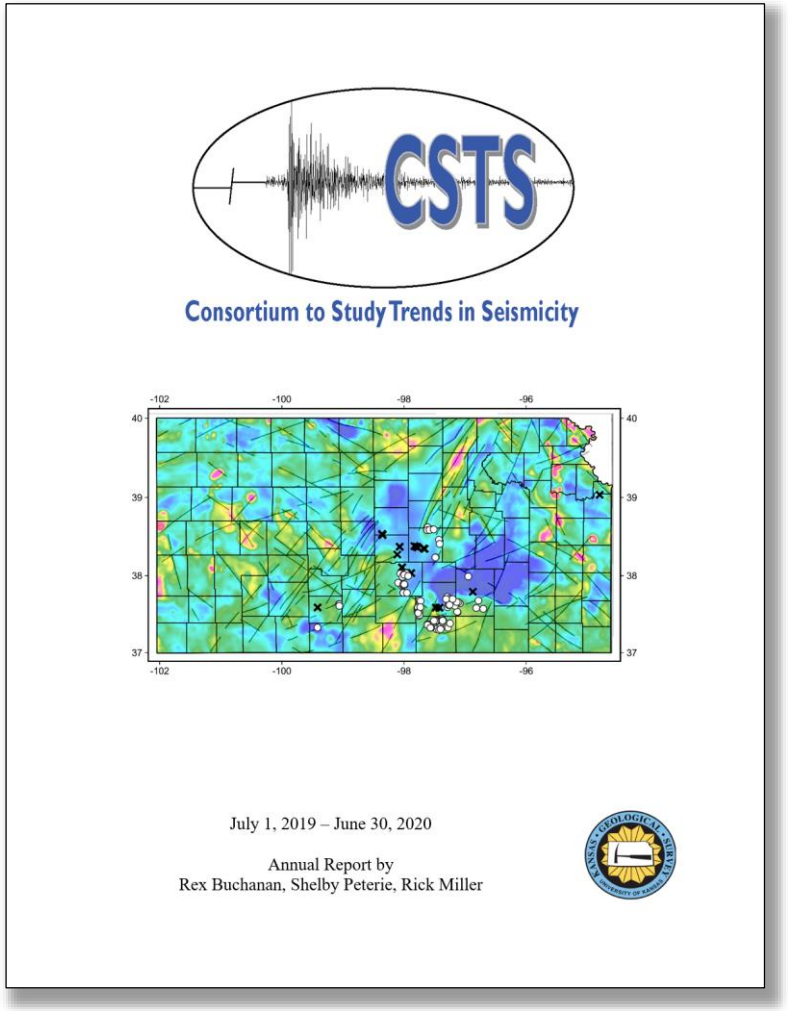
**Magnitude 2.5**
**Saline County**
View with mapper
Note: it may take time to load

Latitude: 38.666
Longitude: -97.457
Origin Time (UTC): 07-26-2021 15:26:45
Local Time: JULY 26, 2021 at 10:26:45 AM
Quake ID: 1001468685

| Miles | Well | Permit |
|---|---|---|
| 24.8 | CHS Refinery #3 | KS-01-113-010 |
| 24.9 | CHS Refinery #2 | KS-01-113-009 |
| 25.0 | CHS Refinery #1 | KS-01-113-008 |
| 27.0 | Williams (Conway East) #1 | KS-01-113-003 |
| 27.0 | Williams (Conway East) #2 | KS-01-113-004 |
| 27.2 | CHS Conway #1 | KS-01-113-002 |
| 27.6 | ONEOK (Conway) #2 | KS-01-113-006 |
| 28.3 | Williams (Conway West) #1 | KS-01-113-001 |

- CSTS
  - M 2+
  - within 30 mi of well
- KCC/KDHE
  - Seismic action plan: SAS alerts
  - USGS events
- Public
  - currently: none
  - real-time feed
  - beta testing
    - M 2.5+
    - statewide

# CSTS Reports




- Consortium members
  - Tier 1
    - Quarterly reports
    - Annual reports
  - Tier 2
    - Annual reports
- KDHE
  - Annual meeting attendance
  - No hardcopy
- KCC, Public
  - None
  - research in progress

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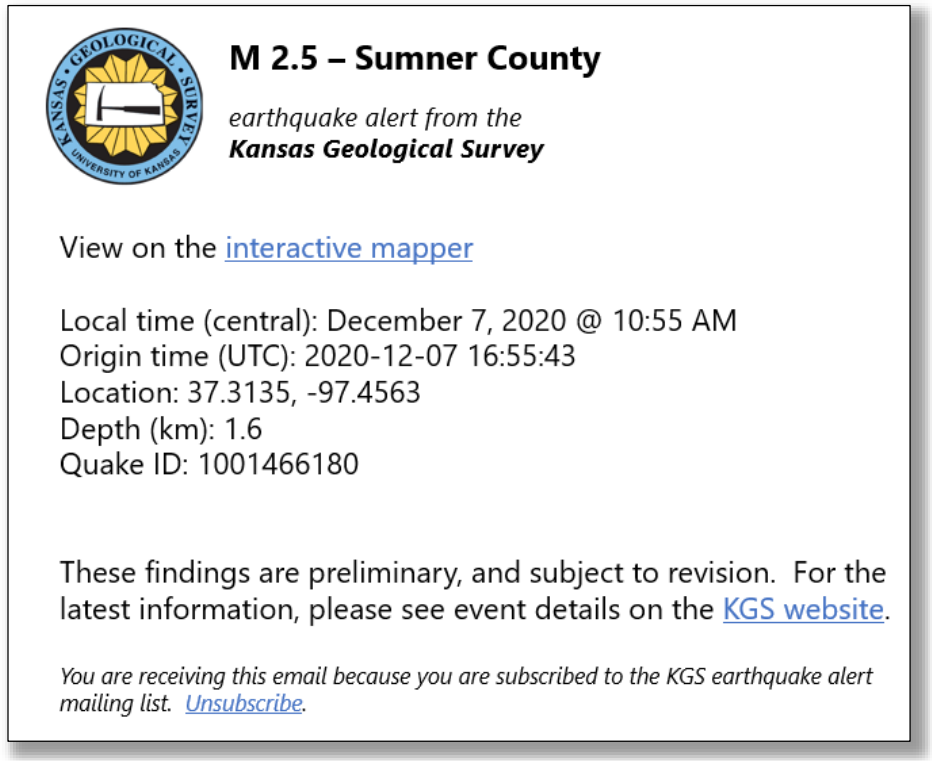
# Future Products



**M 2.5 – Sumner County**

*earthquake alert from the*
***Kansas Geological Survey***

View on the interactive mapper

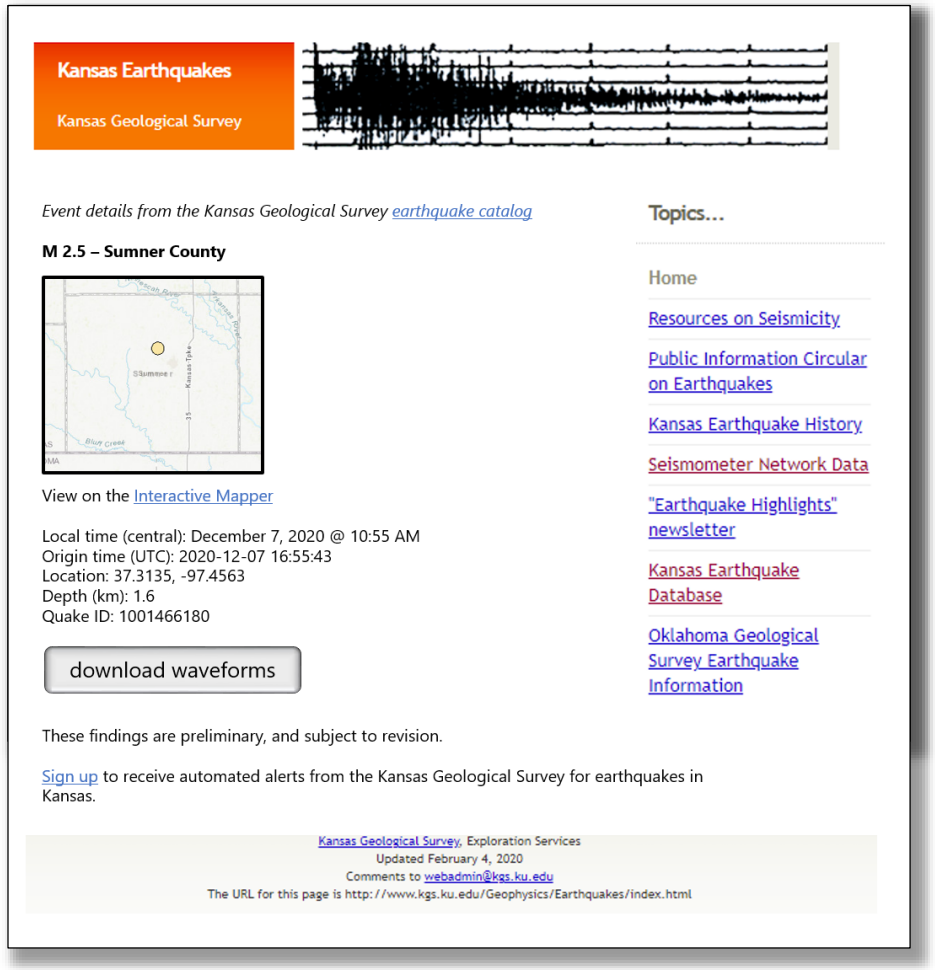
Local time (central): December 7, 2020 @ 10:55 AM
Origin time (UTC): 2020-12-07 16:55:43
Location: 37.3135, -97.4563
Depth (km): 1.6
Quake ID: 1001466180

These findings are preliminary, and subject to revision. For the latest information, please see event details on the KGS website.

*You are receiving this email because you are subscribed to the KGS earthquake alert mailing list. Unsubscribe.*

- Alerts
  - Public, KCC/KDHE
  - M 2.5+
- Event webpages
  - Waveform downloads
  - Did you feel it?
- Alerts: embedded maps
- Induced seismicity publications
  - recent, relevant past papers
  - plain language summaries

# Future Products

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# Future Products

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB017327

**Key Points:**
- The tidal response of the Arbuckle reservoir in Oklahoma is inconsistent with confined, radial flow and shows evidence of leakage
- Time series show additional signals unrelated to tides and atmospheric pressure, including a robust teleseismic response and long-term trends
- Fluid pressure in the Arbuckle is steadily increasing, presumably related to high volume wastewater disposal

**Supporting Information:**
- Supporting Information S1
- Data Set S1
- Data Set S2

**Correspondence to:**
A. J. Barbour,
abarbour@usgs.gov

**Citation:**
Barbour, A. J., Xue, L., Roeloffs, E., & Rubinstein, J. L. (2019). Leakage and increasing fluid pressure detected in Oklahoma's wastewater disposal reservoir. *Journal of Geophysical Research: Solid Earth, 124*, 2896–2919. https://doi.org/10.1029/2019JB017327

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Accepted article online 1 MAR 2019
Published online 22 MAR 2019



## Leakage and Increasing Fluid Pressure Detected in Oklahoma's Wastewater Disposal Reservoir

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[1]U. S. Geological Survey, Menlo Park, CA, USA, [2]Berkeley Seismological Laboratory, Berkeley, CA, USA

**Abstract** The Arbuckle Group is the principal reservoir used for wastewater disposal in Oklahoma. In Osage County—a seismically quiet part of the state—continuous measurements of fluid pressure reveal that pressure in the reservoir is increasing by at least 5 kPa annually and sometimes at a much higher rate. Tidal analysis reveals that fluid level changes lead the local strain tides, with no apparent influence from transient permeability changes; this indicates a response that is inconsistent with flow in a radially extensive, confined reservoir. We investigate whether this is due to vertical flow to the water table, vertical flow within the Arbuckle, or local distortions from fractures. While none of these alternative models can fully explain both the observed tidal phases and amplitude ratios, the observed response to teleseismic waves supports a mechanism related to leakage rather than fracture effects. At this location fluid influx associated with wastewater disposal is offset by migration into surrounding layers, which include the Precambrian basement below. Thus, our findings suggest the need to monitor for changes in the induced seismicity hazard, while pore pressures increase in a leaky disposal reservoir.

**Plain Language Summary** There is consensus among earthquake scientists that subsurface fluid pressure changes are the principal cause of the manmade (or "induced") earthquakes occurring in Oklahoma and around the globe. This is because greater fluid pressures reduce the clamping pressure that would otherwise prevent a fault from having an earthquake. The leading cause of pressure changes on faults in Oklahoma is the disposal of wastewater related to production of oil and natural gas. Disposing of wastewater is generally done by pumping fluid down boreholes into deep, highly permeable reservoirs, like the Arbuckle. One way for scientists to measure water pressure changes is by lowering specially designed instruments down unused wastewater disposal wells. The paper presents continuous measurements of fluid pressure at an Arbuckle well located in Osage County, Oklahoma. Our findings show an overall trend of fluid pressures increasing over time. The only conceivable source of this increase is due to the injection of wastewater. Furthermore, our findings show evidence that fluids are leaking out of the reservoir at a significant rate.

### 1. Introduction

In parts of the central United States and elsewhere, seismicity rates have increased because of wastewater disposal. Injection-induced earthquakes (Ellsworth, 2013) are traditionally considered to be the result of a reduction in effective normal stress through an increase in pore pressure, but in practice, this has been difficult to establish unambiguously as a causal mechanism, except in few cases (e.g., Raleigh et al., 1976). For example, seismicity patterns in Oklahoma are affected by the distribution of wastewater injection (Goebel et al., 2017) and changes in the rate of wastewater injection (Barbour et al., 2017) but also include a significant proportion of events induced by high-pressure reservoir stimulation (Skoumal et al., 2018). So it remains of critical importance to understand how interactions between injection and reservoir response impact pore pressure diffusion, poroelastic stress changes, and flow patterns, because of the implications for fault slip at seismogenic depths (e.g., Chang & Segall, 2016, 2017; Zhang et al., 2013), seismicity rates (Dieterich et al., 2015; Llenos & Michael, 2013; Segall & Lu, 2015), and, ultimately, seismic hazard (Langenbruch et al., 2018; Langenbruch & Zoback, 2016; Petersen et al., 2017; Norbeck & Rubinstein, 2018; Zhai & Shirzaei, 2018).

Wastewater disposal is active across Oklahoma and largely in the Arbuckle Group. Thus, a major outstanding issue related to seismicity there is why induced earthquakes do not occur everywhere (Figure 1) even though the state of stress in the crust appears to be nearly homogenous (e.g., Alt & Zoback, 2017). The



- Alerts
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  - M 2.5+
- Event webpages
  - Waveform downloads
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- Induced seismicity publications
  - recent, relevant past papers
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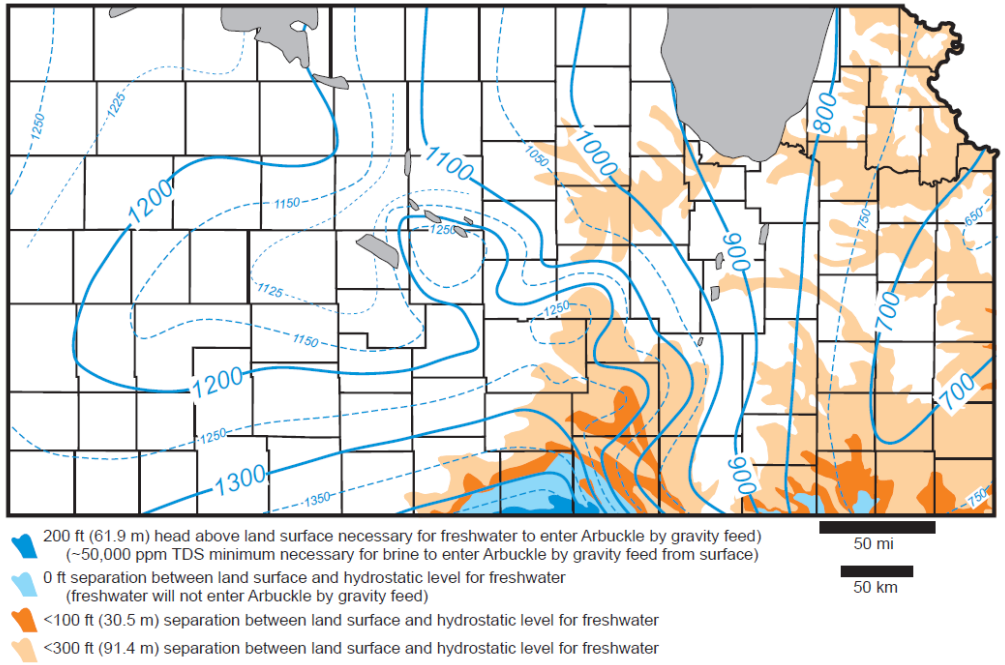
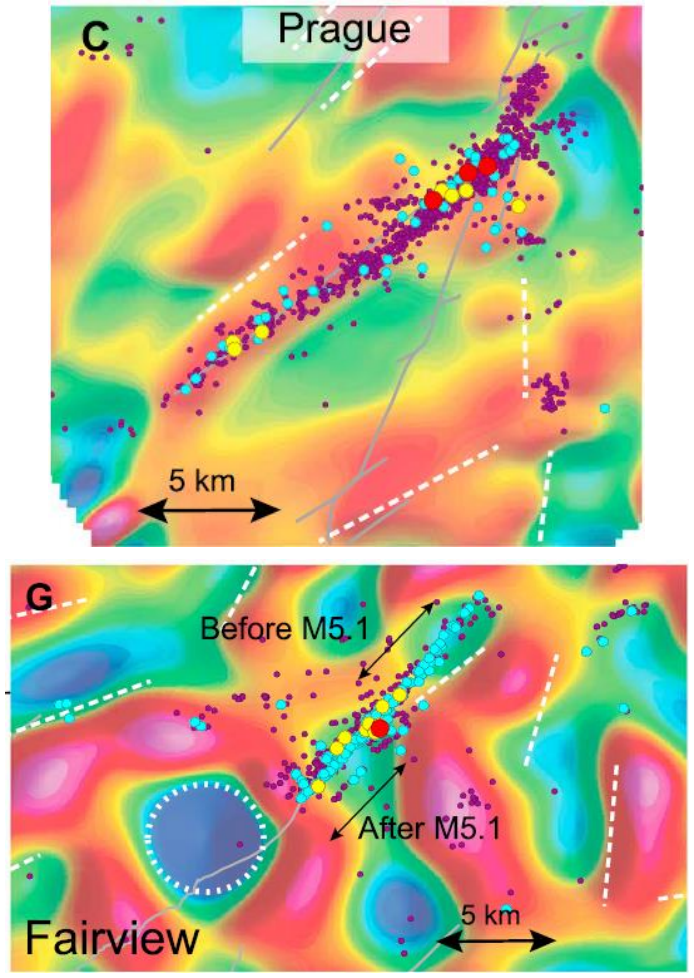
# Review of Recent Publications

# KGS Authors



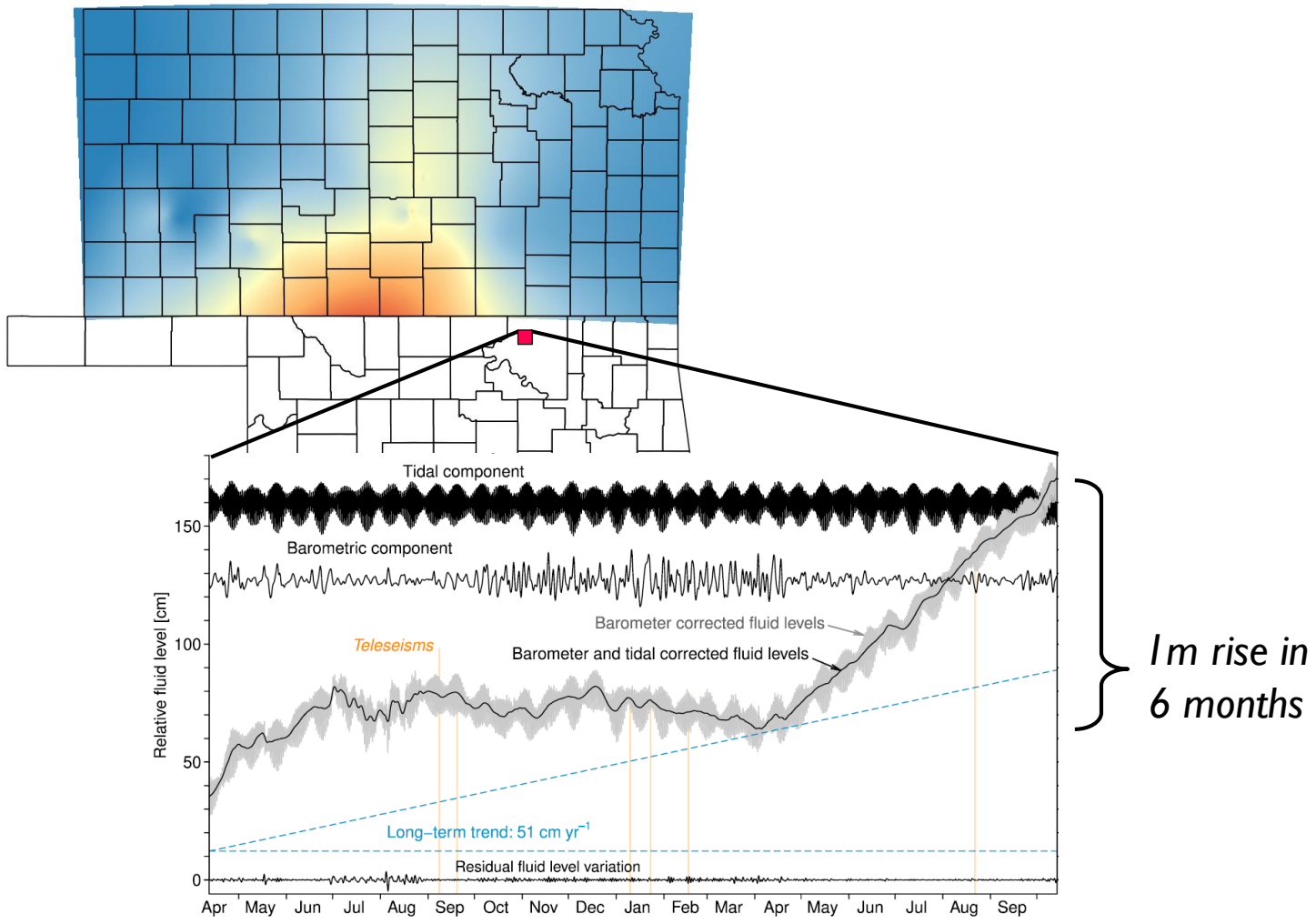

- Newell et al. (2020)
  - Diminishing Depth to Water in Cambrian-Ordovician Arbuckle Group Disposal Wells in Kansas, *Midcontinent Geoscience*
- Peterie et al. (2020)
  - Comment on "Accelerated Fill-Up of the Arbuckle Group Aquifer and Links to U.S. Midcontinent Seismicity" by Ansari et al. (2019), *Journal of Geophysical Research*
- Peterie et al. (2020)
  - Potential factors contributing to induced seismicity near Hutchinson, Kansas, *SEG Expanded Abstracts*

# Shah and Crain (2018)




- **Aeromagnetic Data Reveal Potential Seismogenic Basement Faults in the Induced Seismicity Setting of Oklahoma**
- OK earthquake sequences aligned with aeromagnetic lineaments
- Limited correlation with mapped faults suggests significant structural differences between the crystalline basement and sedimentary cover
- Faults being activated have not been significantly active for millions of years.
- Intrusions locally inhibit induced seismicity due to fault termination or changes in permeability

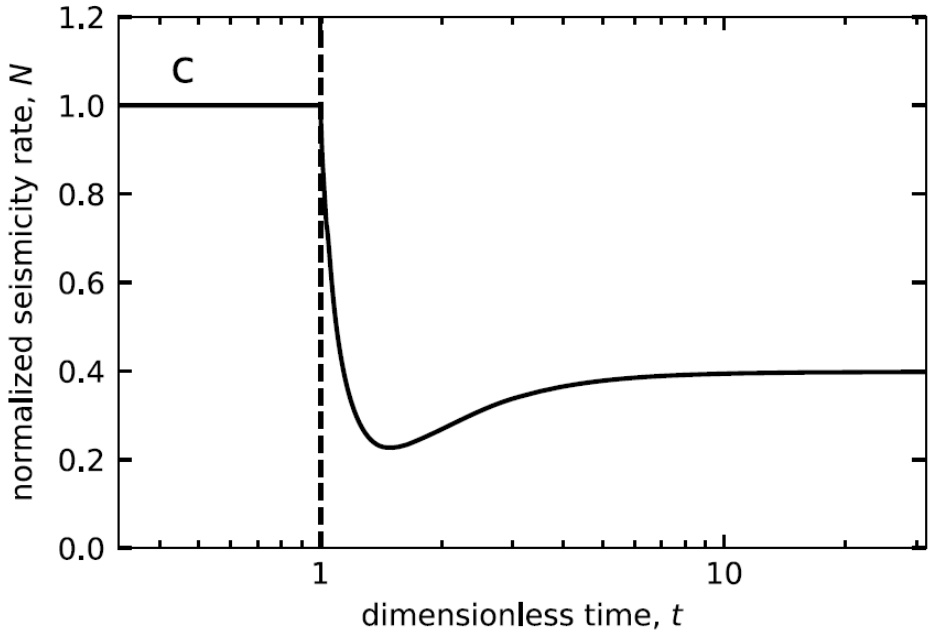
# Barbour et al. (2019)




*1 m rise in 6 months*

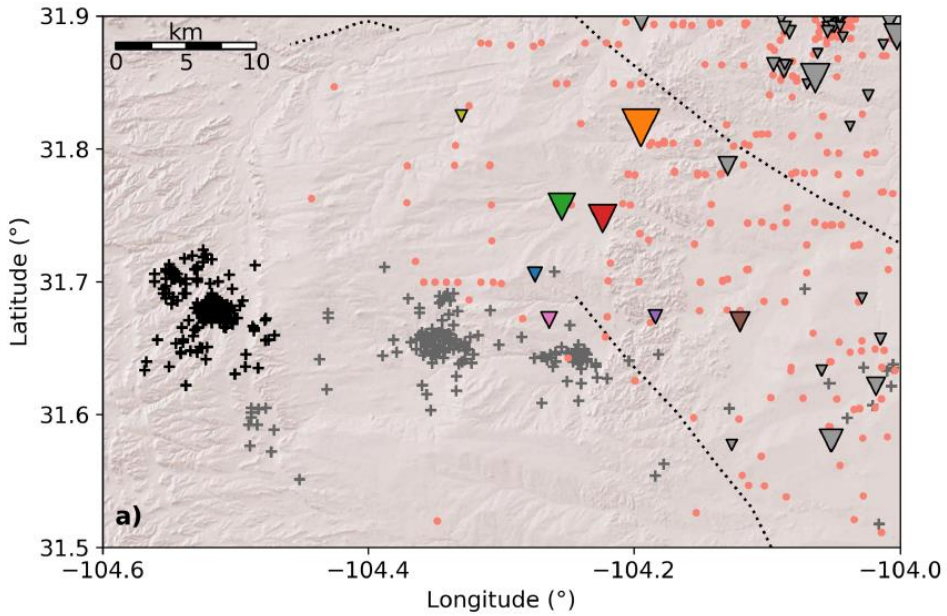
- **Leakage and Increasing Fluid Pressure Detected in Oklahoma's Wastewater Disposal Reservoir**
- Inactive Class II disposal well
- Teleseismic response to invert for properties, suggests leaky reservoir
- "Fluid pressure in the Arbuckle is steadily increasing, presumably related to high volume wastewater disposal"
- Flow in outpaces leakage

# Dempsey and Riffault (2019)



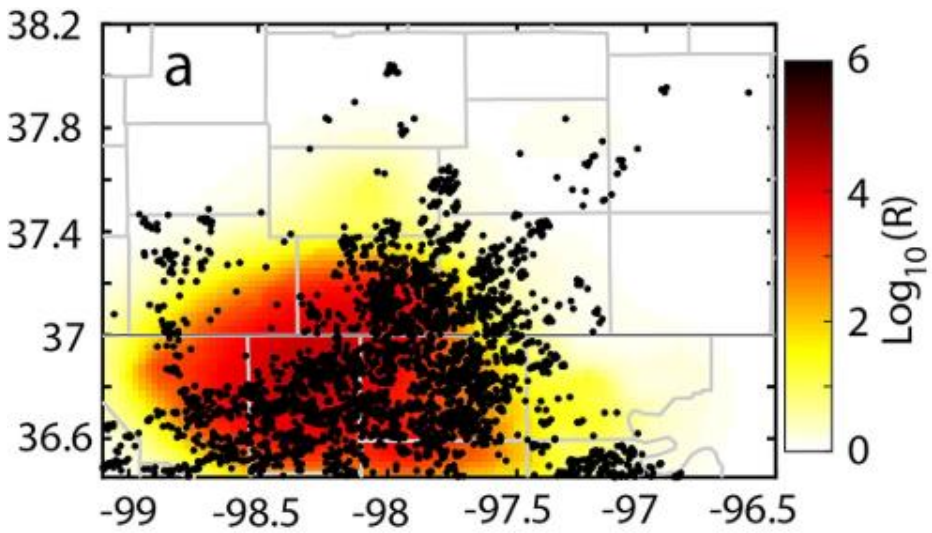

- **Response of Induced Seismicity to Injection Rate Reduction: Models of Delay, Decay, Quiescence, Recovery, and Oklahoma**
- Modeling to predict possible outcomes of injection rate reductions in Oklahoma
- Reaffirms regional pressure "plume"
  - single well-based approaches will not be successful for mitigating wastewater induced seismicity
- Depending on critical pressure, may experience "quiescent" period then rebound
  - early estimates shortly after volume reduction may not represent long term earthquake rate

# Skoumal et al. (2020)



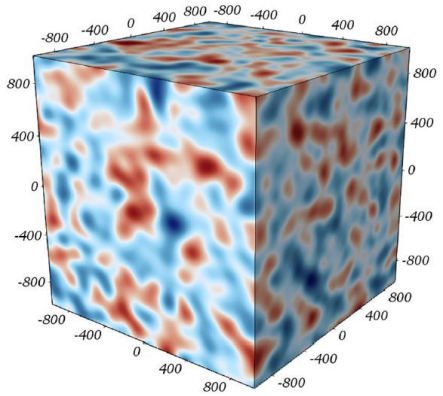

- **Induced Seismicity in the Delaware Basin, Texas**
- West Texas case study
  - Bone Spring and Wolfcamp formations
  - order of magnitude increase in rate
  - majority induced by SWD
- Westernmost cluster
  - ~3%
  - 25 km nearest
  - >30 km from high-rate wells
- Reaffirms far-field effects

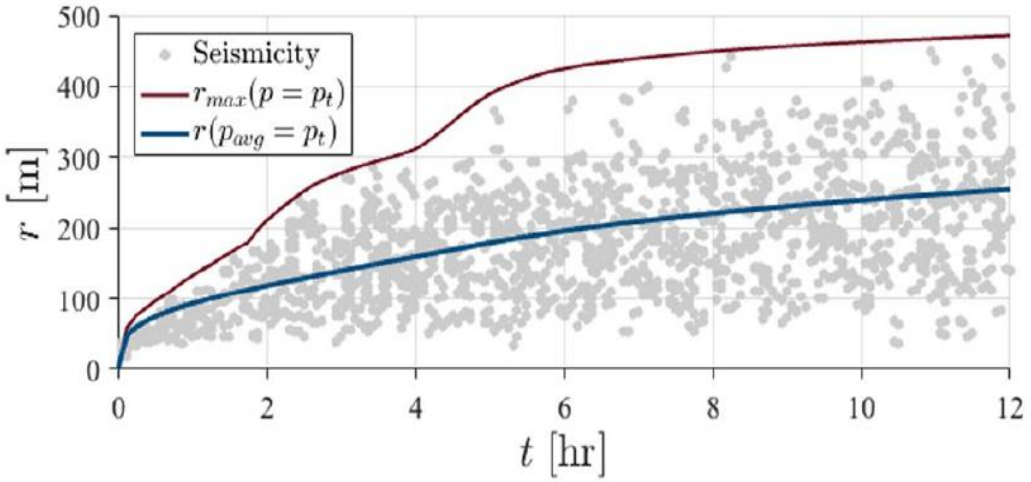
# Zhai et al. (2020)




- **Elevated Seismic Hazard in Kansas Due to High-Volume Injections in Oklahoma**
- Methods
  - Poroelastic modeling
  - Seismic hazard
- Conclusions
  - injection in Oklahoma caused 3x increase in Kansas seismicity
- Implications
  - Confirms regional pressure influence
  - Significant distance from injection point

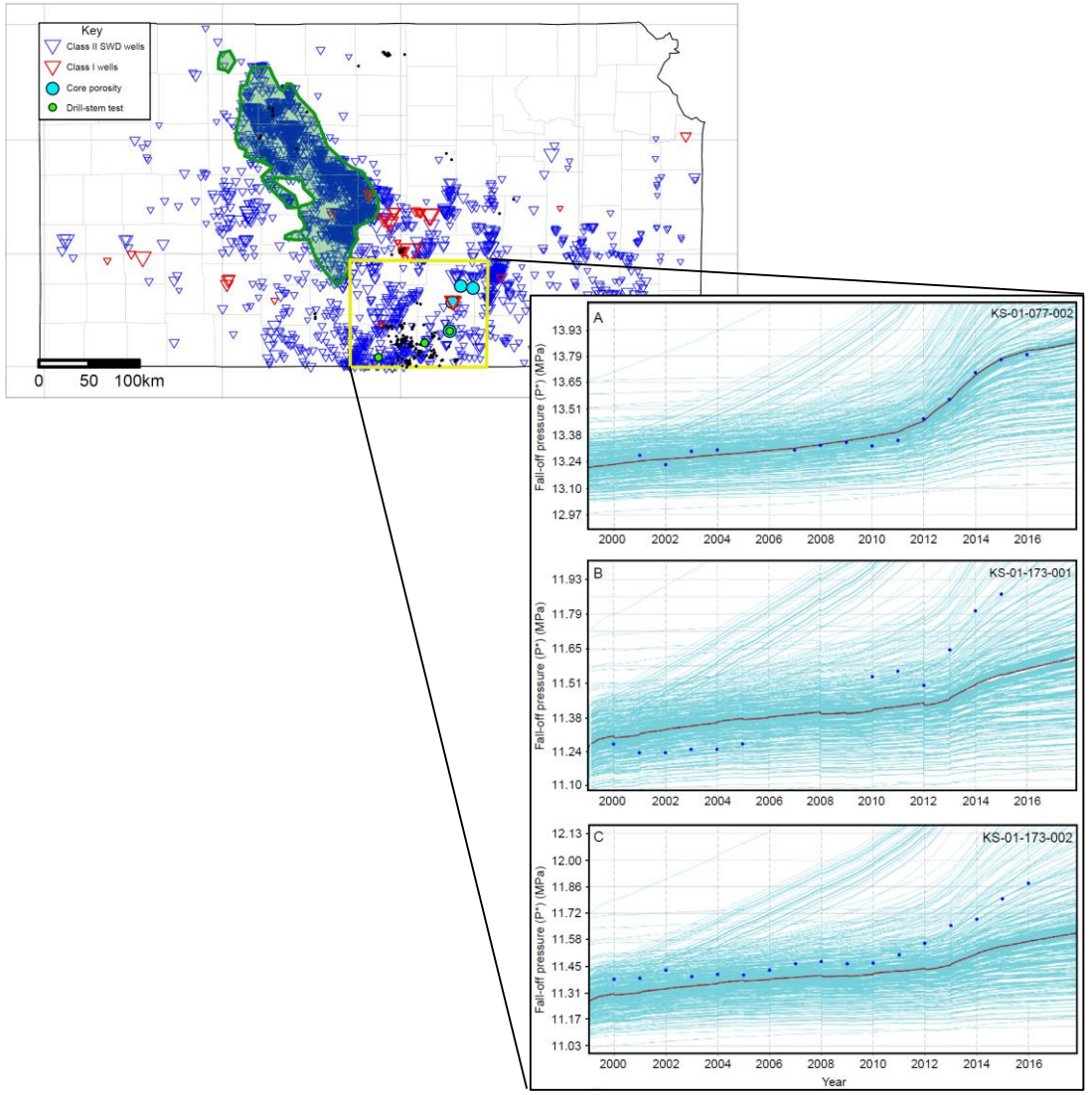
# Haggenson and Rajaram (2021)






- Distinction between seismic diffusivity and effective diffusivity
- Seismicity controlled by high-permeability pathways
- Seismic diffusivity may be an order of magnitude greater
- Earthquakes propagate more rapidly than matrix permeability would predict

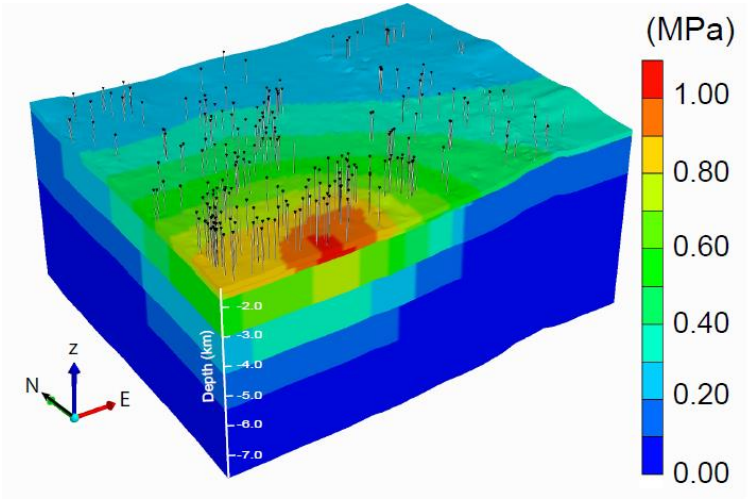
# Ansari et al. (2021)




- Model pressure in south-central KS
  - detailed geologic model
  - Class I and II volumes
  - Class I PFO for "pressure history matching"
  - invert for basement/Arbuckle properties
- Limitations/drawbacks
  - uncoupled: neglects poroelastic effects
  - neglects OK injection
  - only 3 Class I wells
  - results inconsistent with observations
- Conclusions
  - basement/Arbuckle model
  - pressure rate controls local seismicity rate
    - regulate wells < 30 km

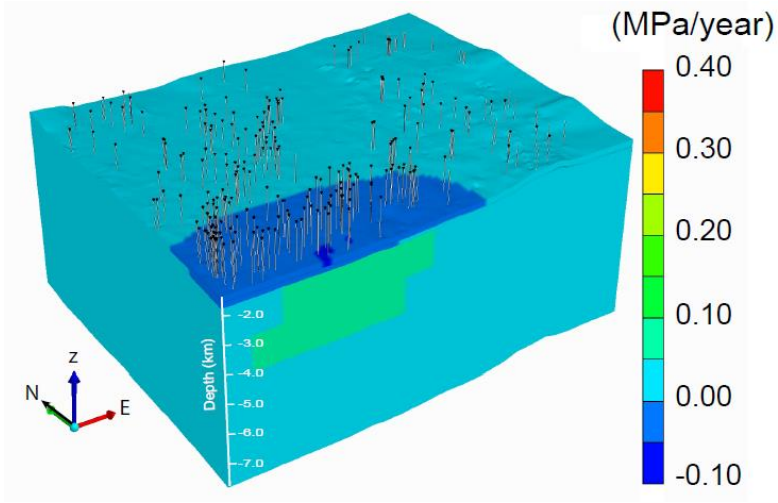
# Ansari et al. (2021)

*2016 pressure*




regional pressure increase across entire 118 x 152 km model

*2016 pressure change (from 2015)*




contradicts observed pressures

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August 5, 2021

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