Navigating earthquake hazards in the intraplate: the last decade as a guide for the next decade

    

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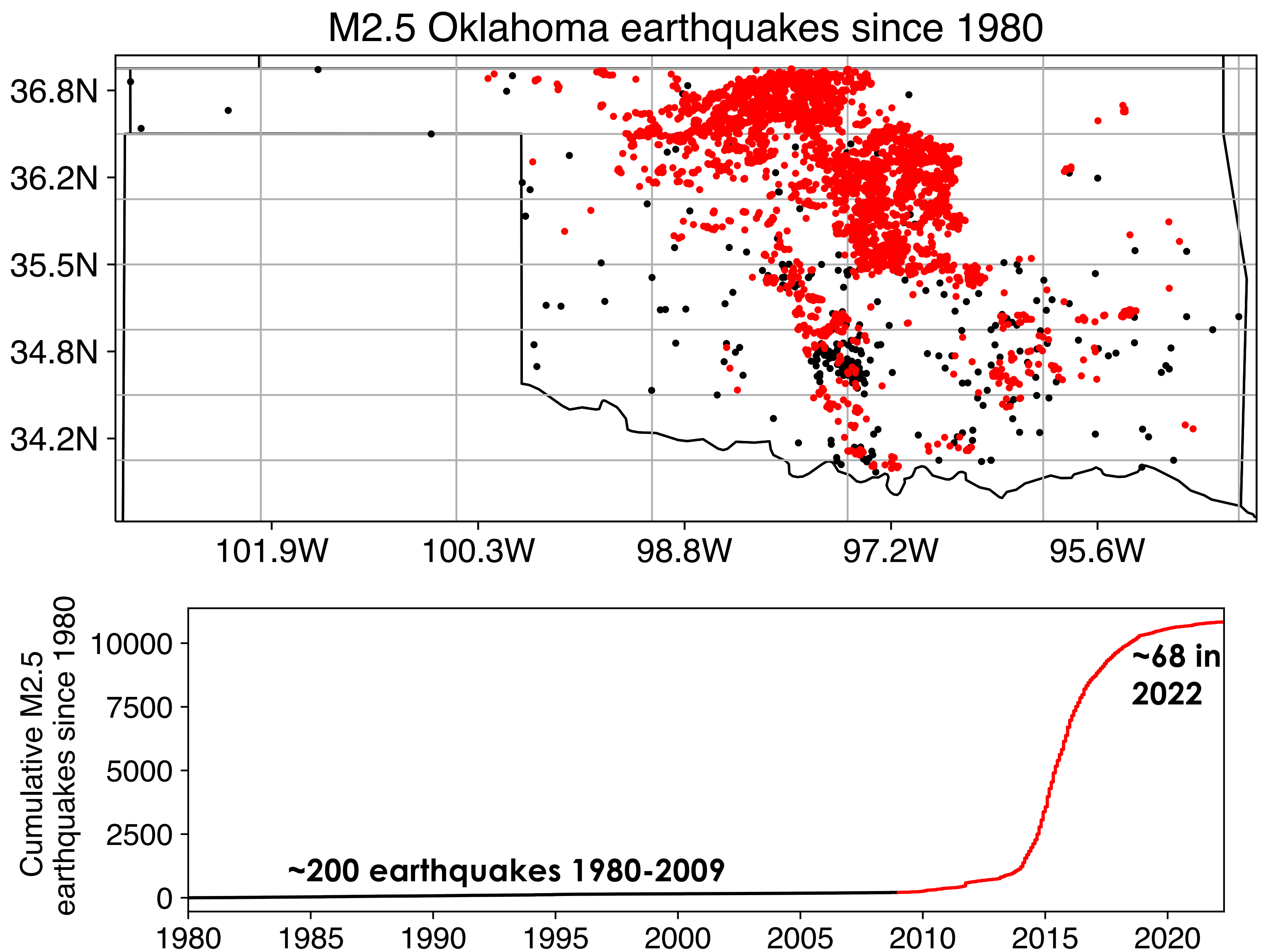
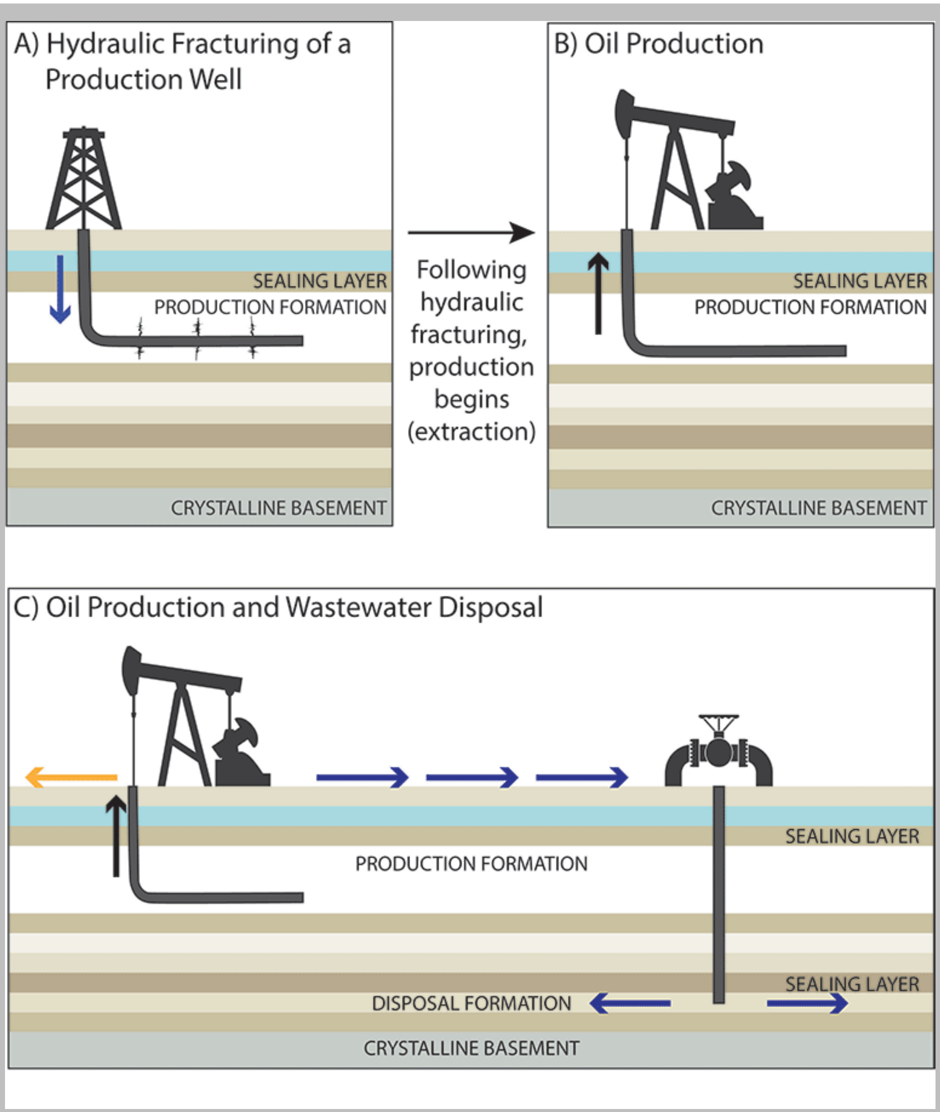
Keys to successful regional implementation of geostorage

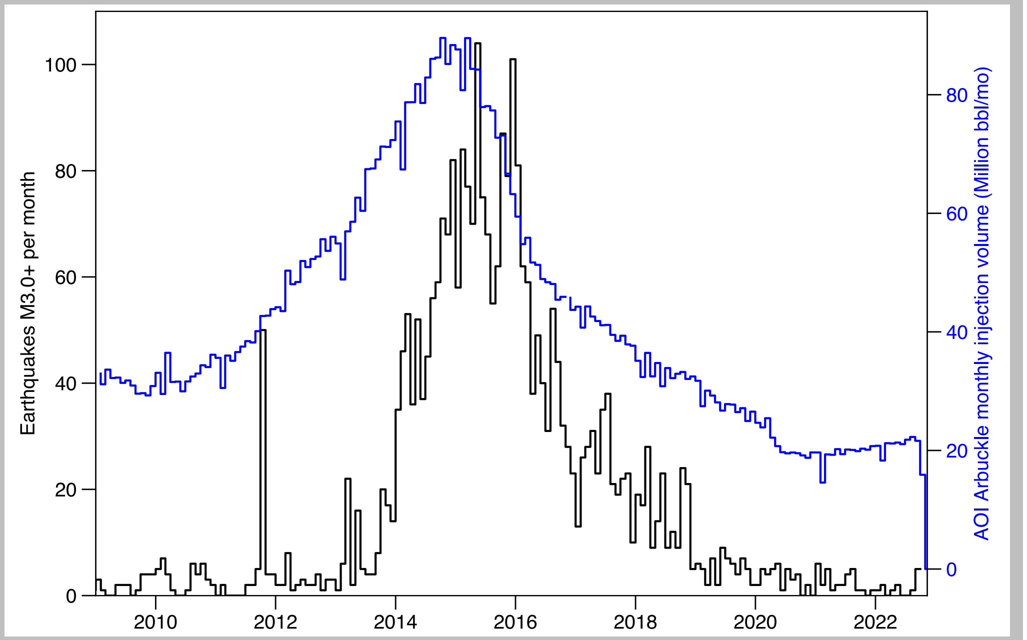
- Site planning to identify faults and good storage zones
- Expect that seismicity will occur
- Invest in monitoring earthquakes and pressure – hardware, software, and workforces
- Mitigate seismicity when it occurs


M2.5 Oklahoma earthquakes since 1980
36.8N
36.2N
35.5N
34.8N
34.2N
101.9W
100.3W
98.8W
97.2W
95.6W
Cumulative M2.5 earthquakes since 1980
10000
7500
5000
2500
0
1980
1985
1990
1995
2000
2005
2010
2015
2020
~200 earthquakes 1980-2009
~68 in 2022

- November 2011 – Magnitude 5.7 near Prague, OK
- September 2016 – Magnitude 5.8 near Pawnee, OK
- November 2016 – Magnitude 5.0 near Cushing, OK

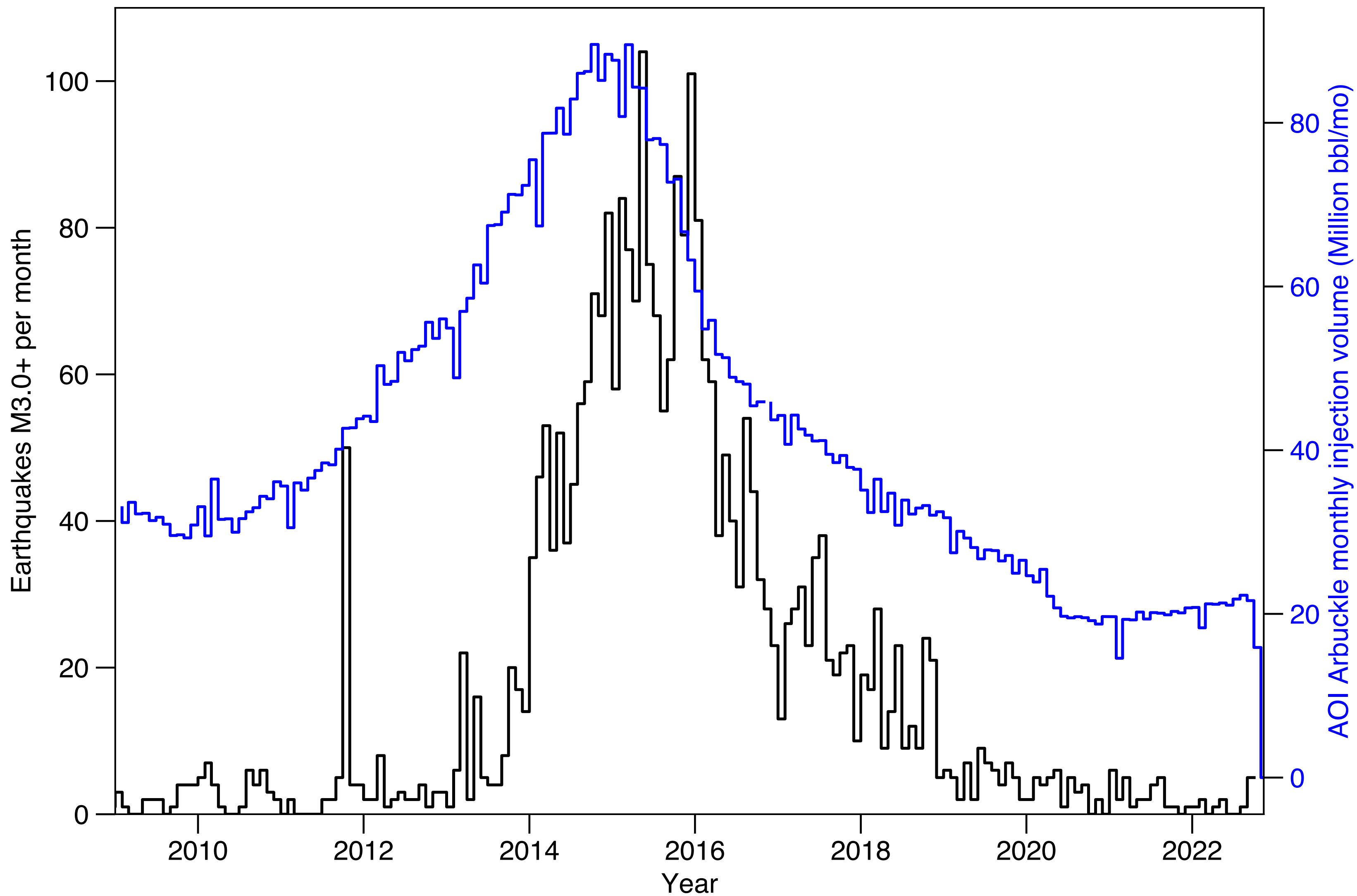
Unconventional production





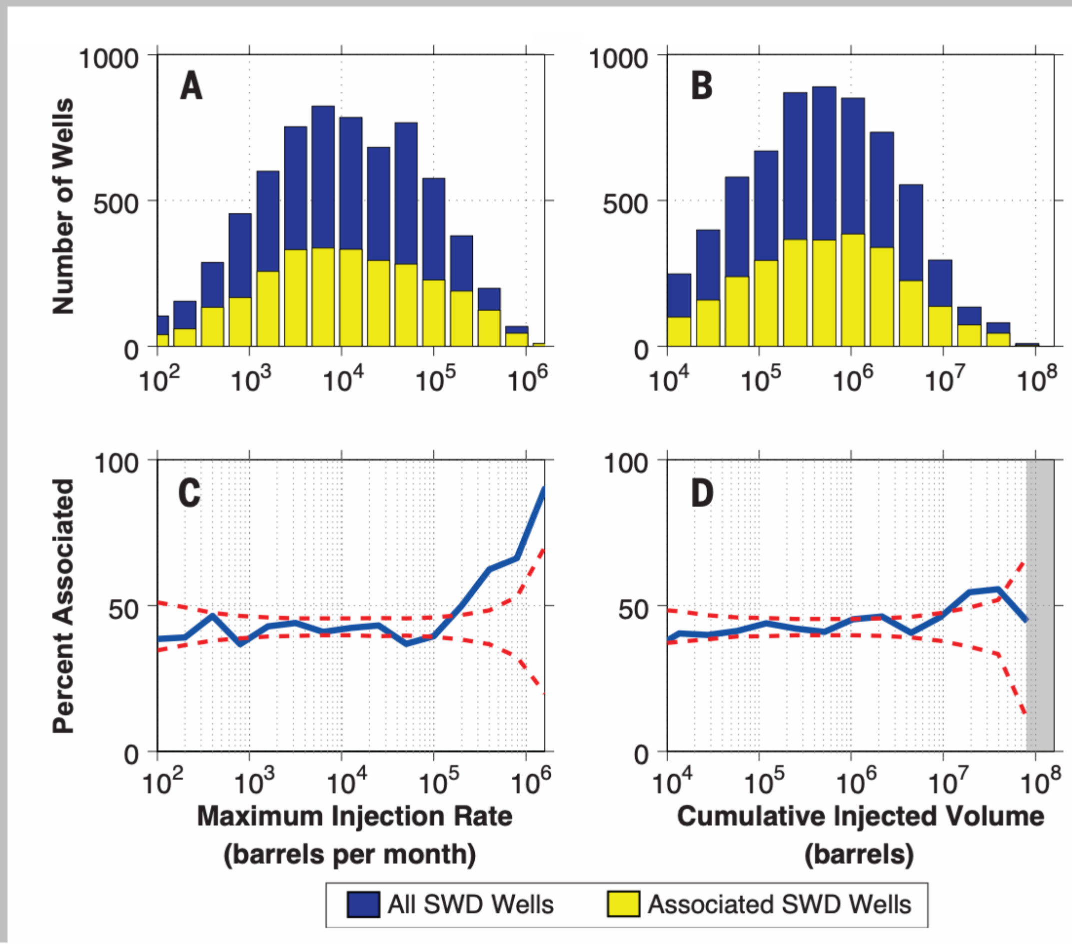
Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015

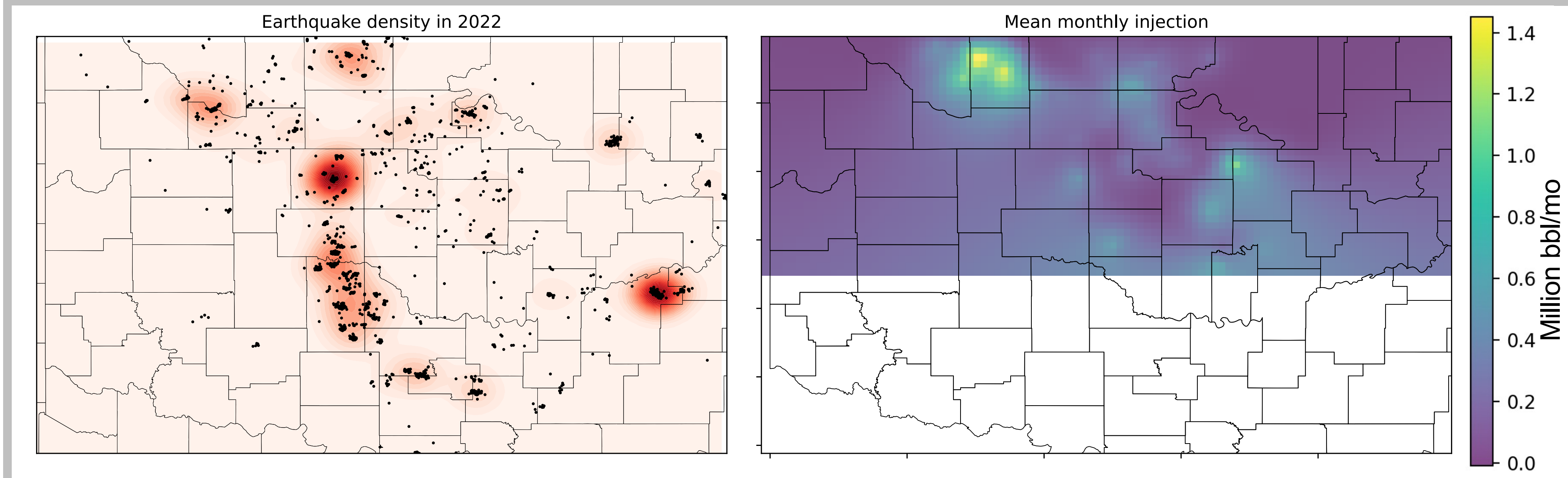


Earthquakes M3.0+ per month
AOI Arbuckle monthly injection volume (Million bbl/mo)
Year
0
20
40
60
80
100
0
20
40
60
80
2010
2012
2014
2016
2018
2020
2022

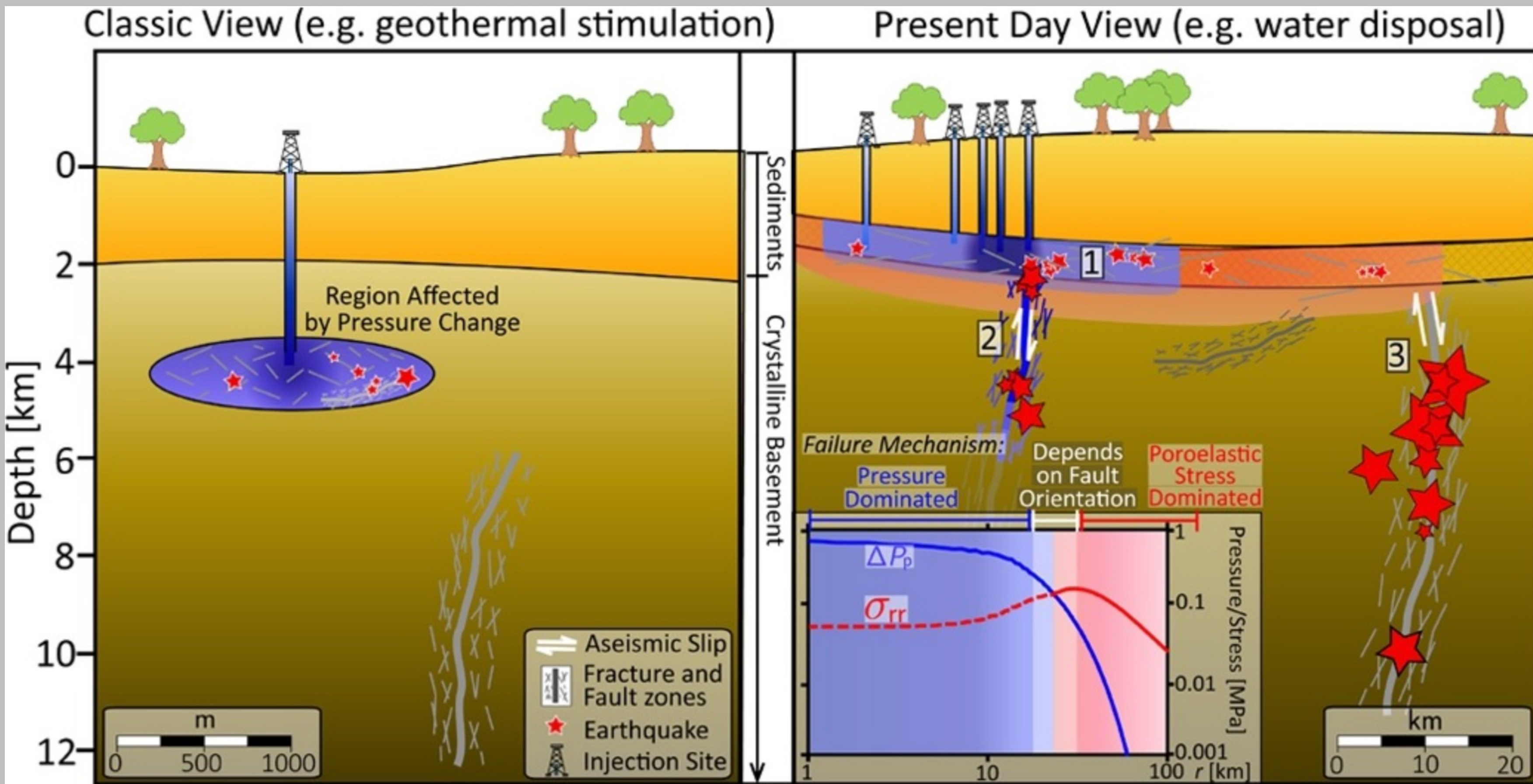
Meta-analysis suggests that high volume injection tends to produce earthquakes



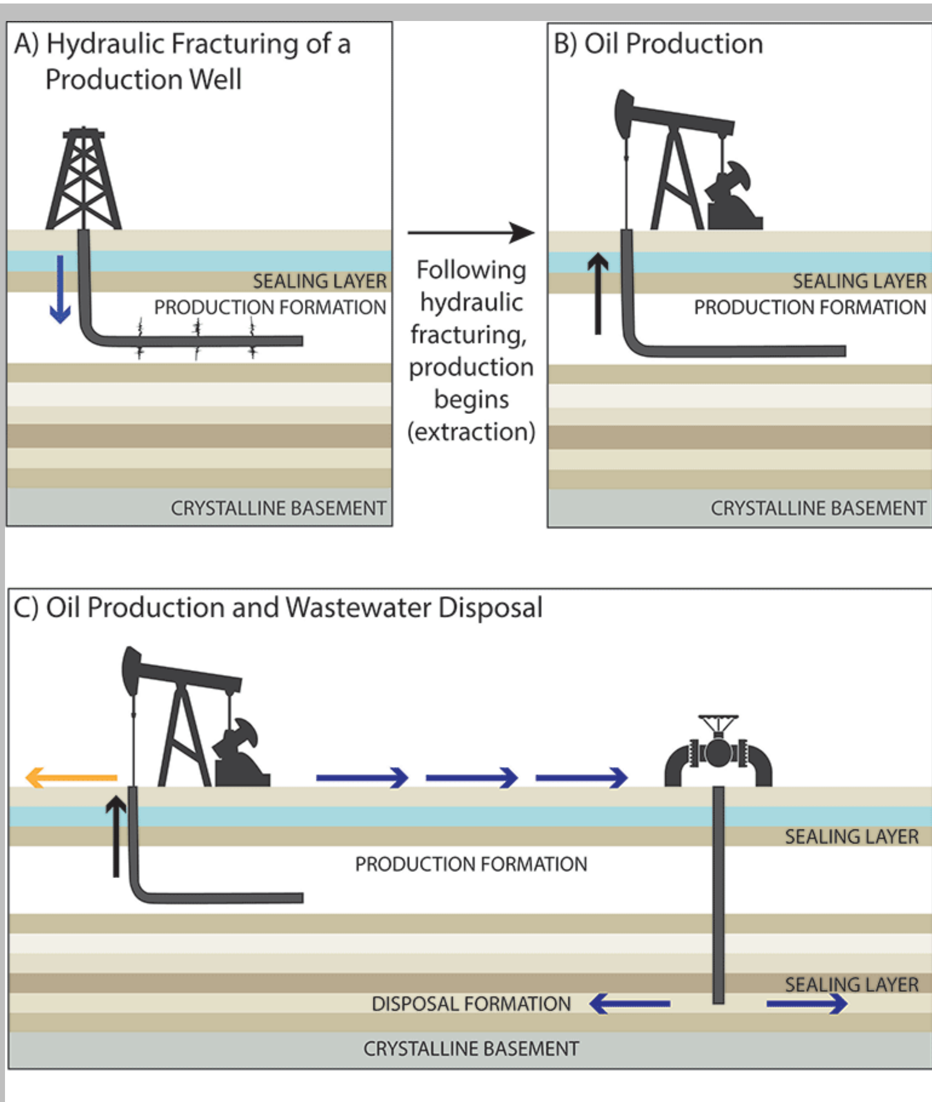
Weingarten et al., 2015



Earthquake density in 2022
Mean monthly injection
Million bbl/mo
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0



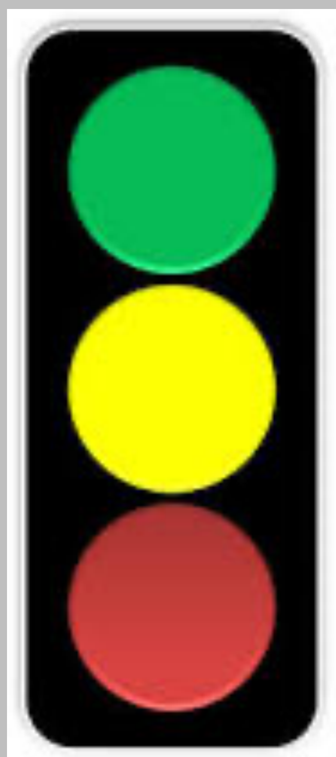
Goebel et al., 2017



Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015

Oklahoma Corporation Commission Protocol for earthquakes associated with well completions (issued Dec 20, 2016, since updated, with more updates likely)



SUMMARY OF WELL COMPLETION SEISMICITY GUIDANCE

Terms: Oil and Gas Conservation Division (OGCD)
Oklahoma Geological Survey (OGS)

Action following anomalous seismic activity within 1.25 miles of hydraulic fracturing operations:

- **If magnitude, as determined by the OGS, is greater than or equal to 2.5M:**
  - **OGCD contacts designated representative for the operator with active completion operations within a 2 km radius of located seismic events.**
  - **Implementation of the operator's internal mitigation practices commences.**
  - **Operation continues.**

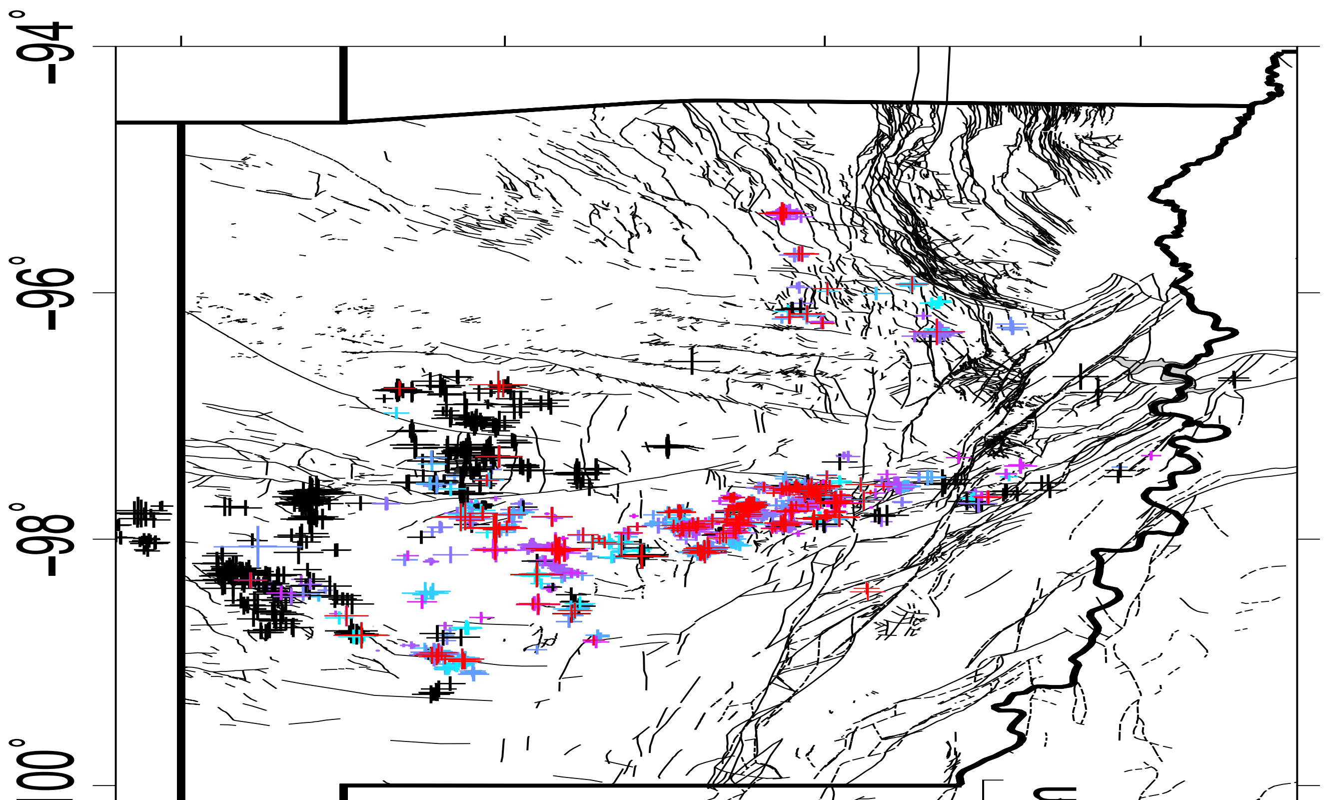
- **If magnitude is greater than or equal to 3.0M:**
  - **Operator initiates a pause of operations for no less than 6 hours.**
  - **Technical conference/call held between the OGCD staff and operator about operator mitigation practices.**
  - **Upon agreement between operator and OGCD regarding mitigation practices and reduced seismic activity, operator permitted to resume with revised completion procedure.**

- **If magnitude is greater than or equal to 3.5M:**
  - **Operator suspends operations**
  - **In-person technical conference held with OGCD staff and operator to examine whether operation can resume with changes.**

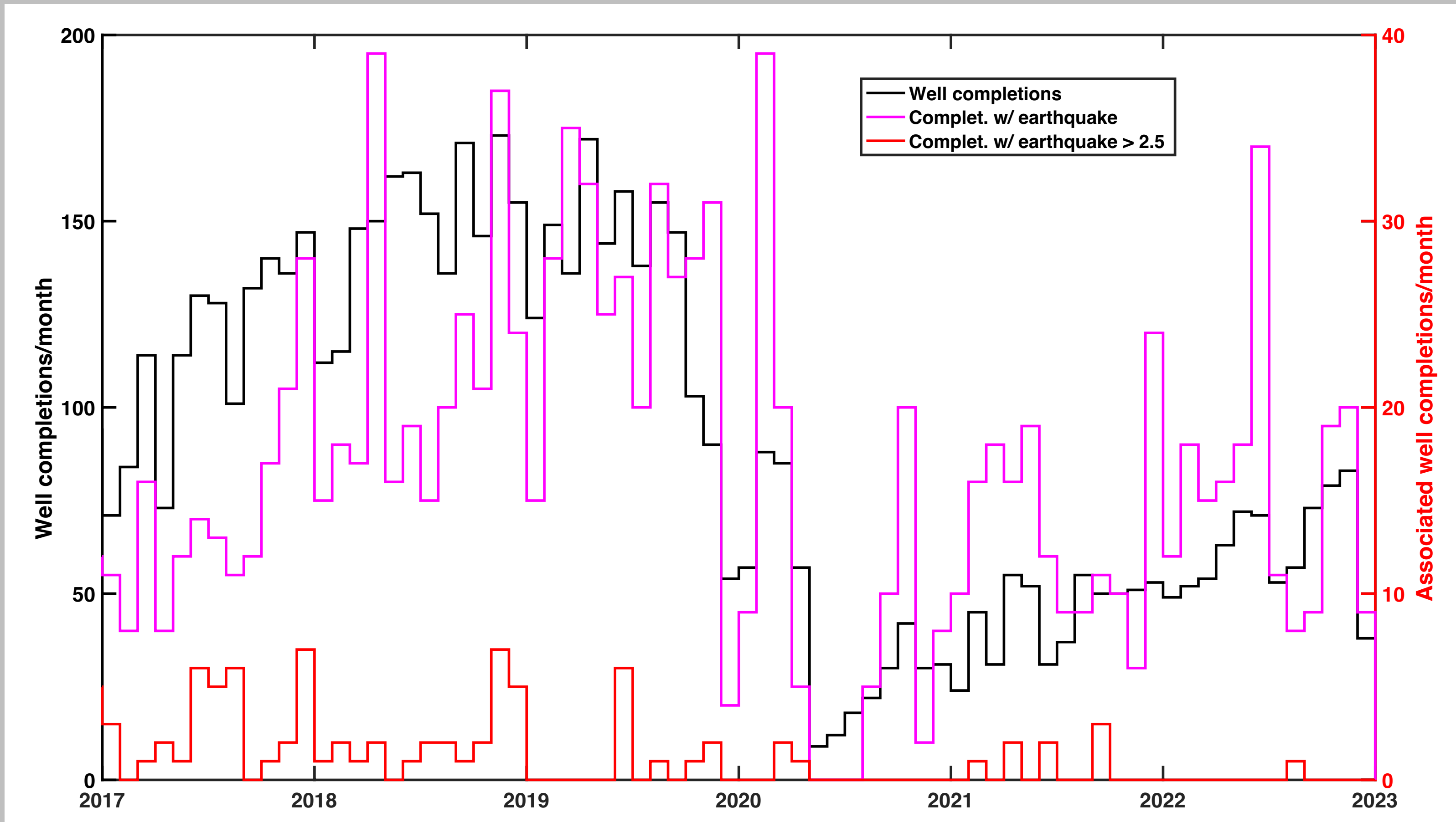
M2.0

M2.5

M3.0



HF-associated activity (red DYFI events)



HF-associated activity through time

Lessons from mitigating induced seismicity

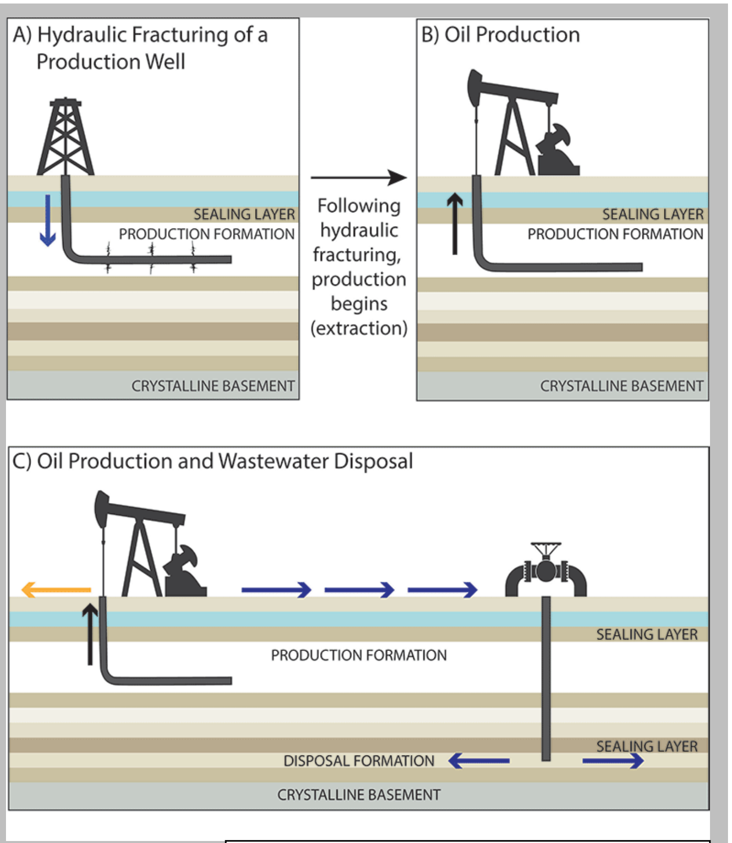
High volume disposal more likely seismicity (Weingarten et al., 2015; Walsh and Zoback, 2016)

Proximity to faults (Darold and Holland, 2015; Alt and Zoback, 2017) and basement (Hincks et al., 2018)

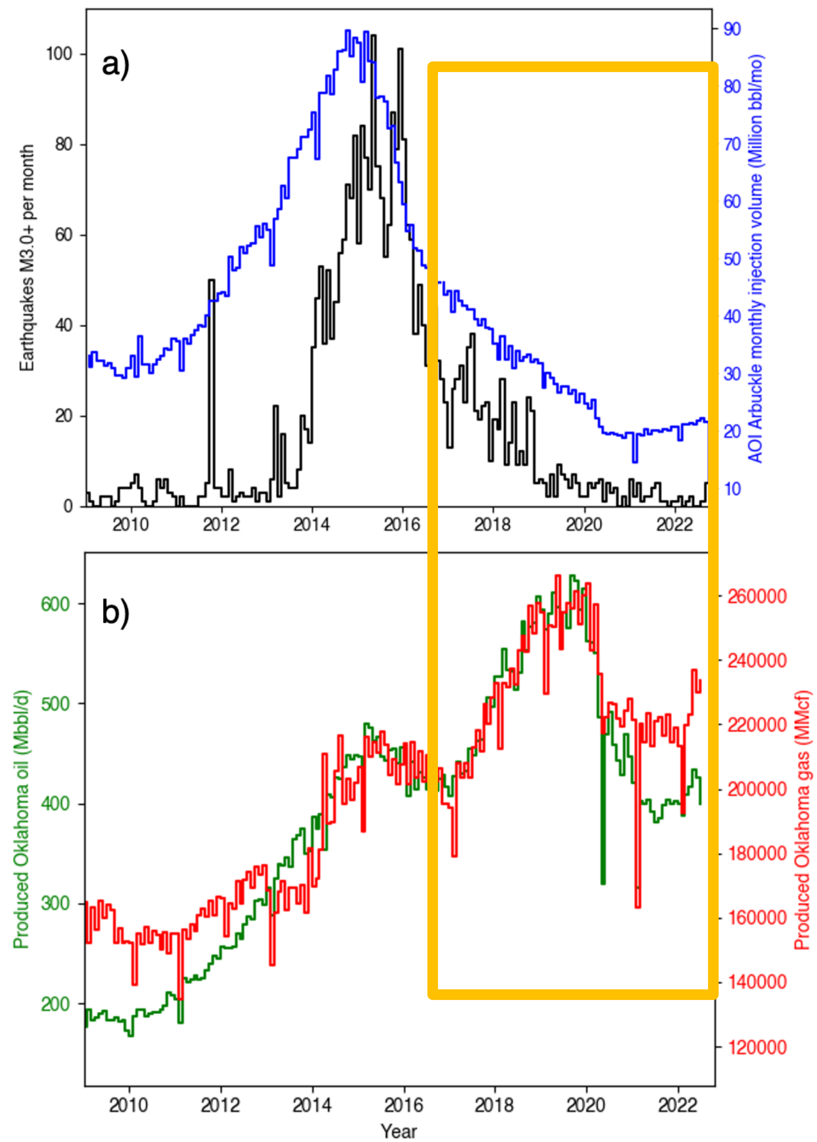
Rapid shut-in reduces aftershock activity by plausibly reducing poroelastic stress (Goebel et al., 2019)

Long-term regional reduction in wastewater disposal (since 2015) in Arbuckle driven by market and regulatory factors

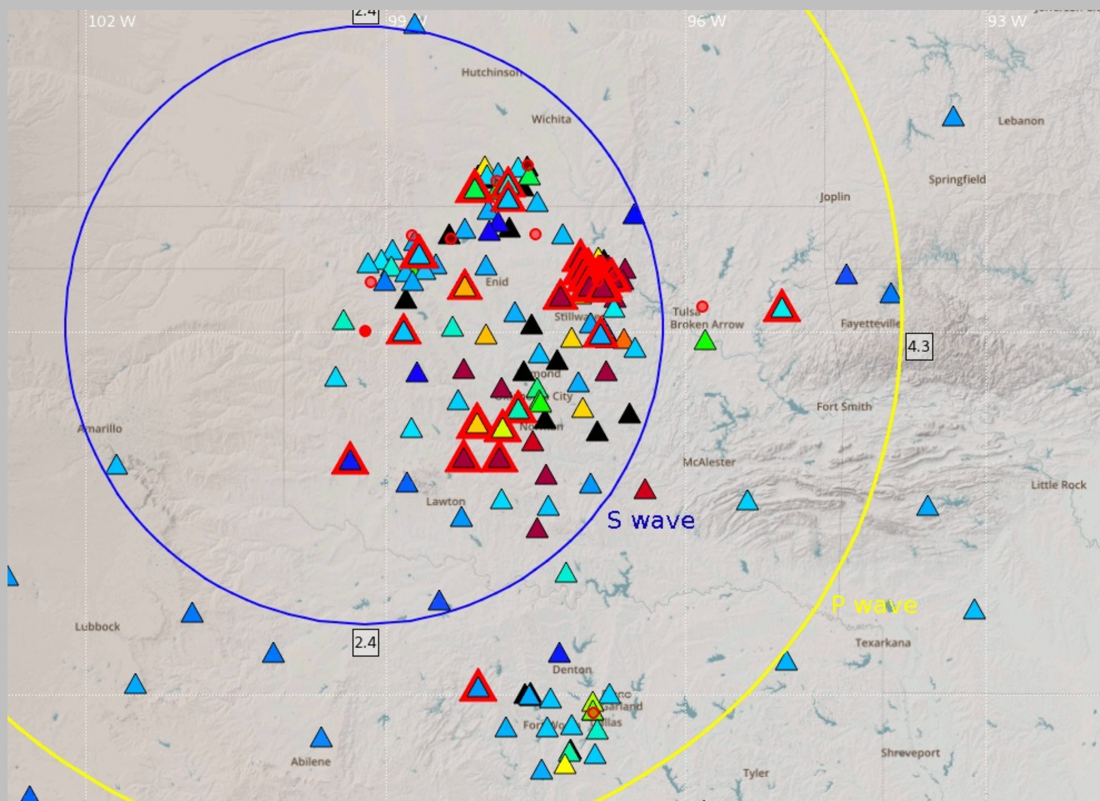
Traffic light effective in disincentivizing well completions producing felt seismicity



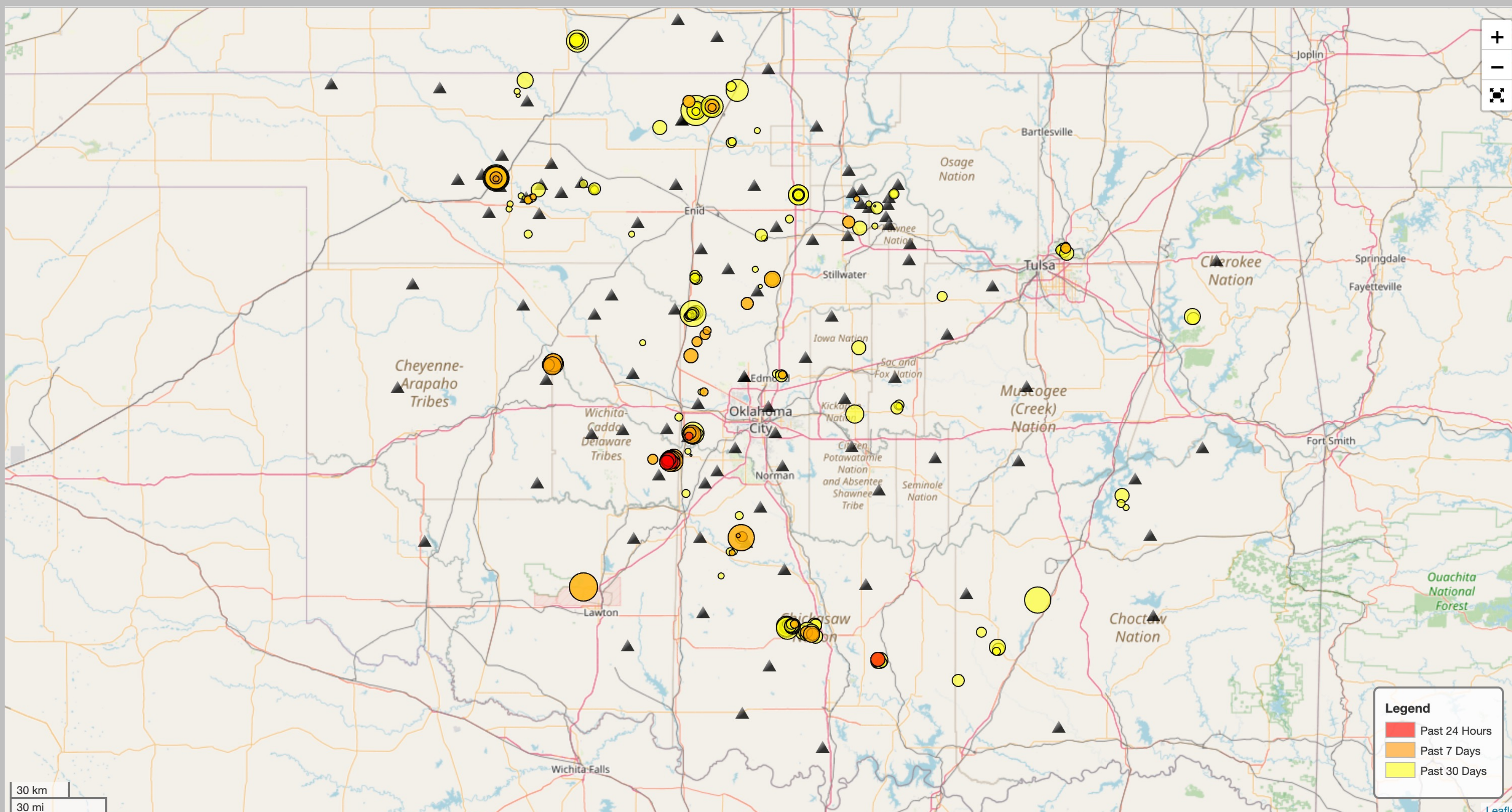
Rubinstein and Mahani, 2015



Production increases significantly, during the window of heightened regulatory scrutiny/rules, without larger damaging earthquakes

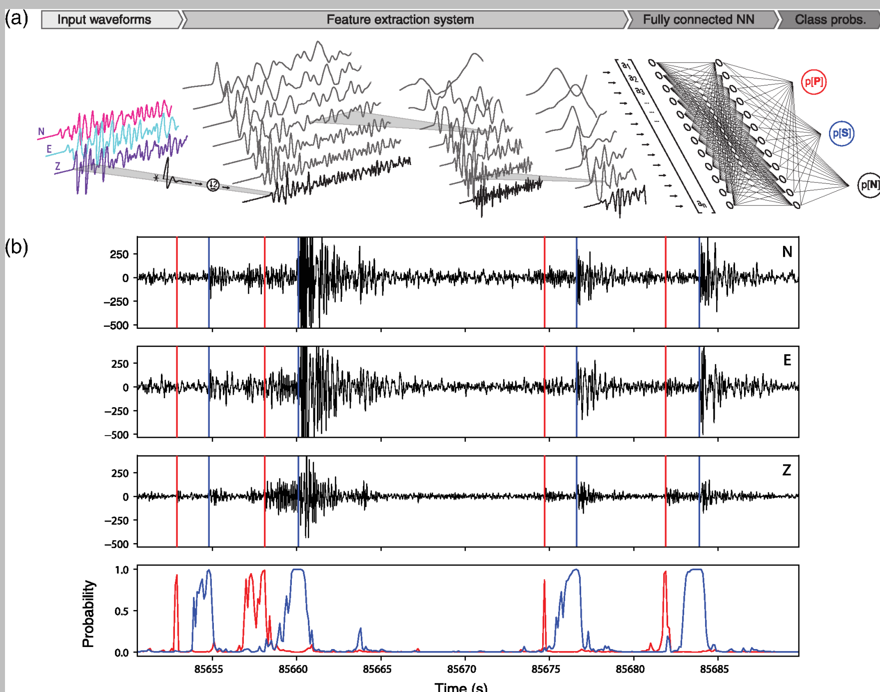

102 W
96 W
93 W
2.4
Hutchinson
Wichita
Lebanon
Springfield
Joplin
Enid
Tulsa
Broken Arrow
4.3
Fort Smith
Amarillo
McAlester
Little Rock
Lawton
S wave
Lubbock
P wave
2.4
Texarkana
Denton
Shreveport
Abilene
Tyler

ogs.ou.edu for products, **rtserve.ou.edu** for real-time seedlink buffer



~15-20 earthquakes/day

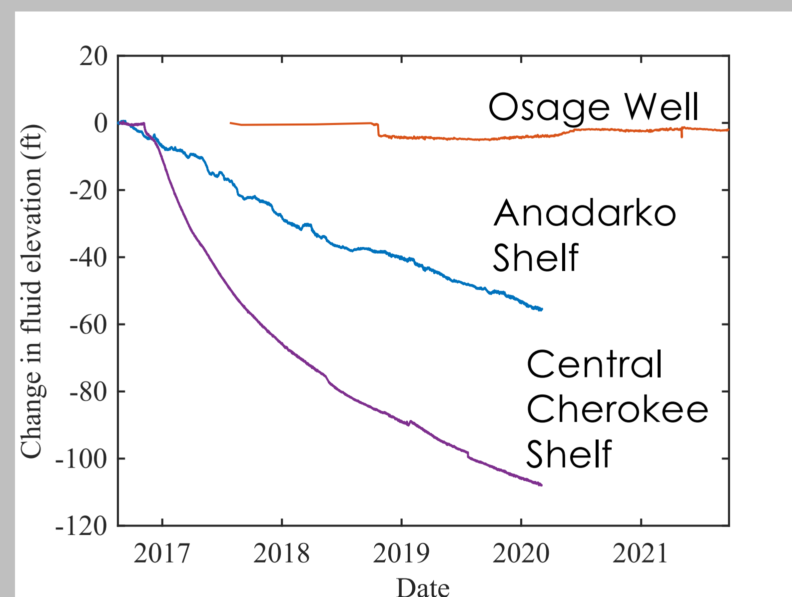
Machine learning

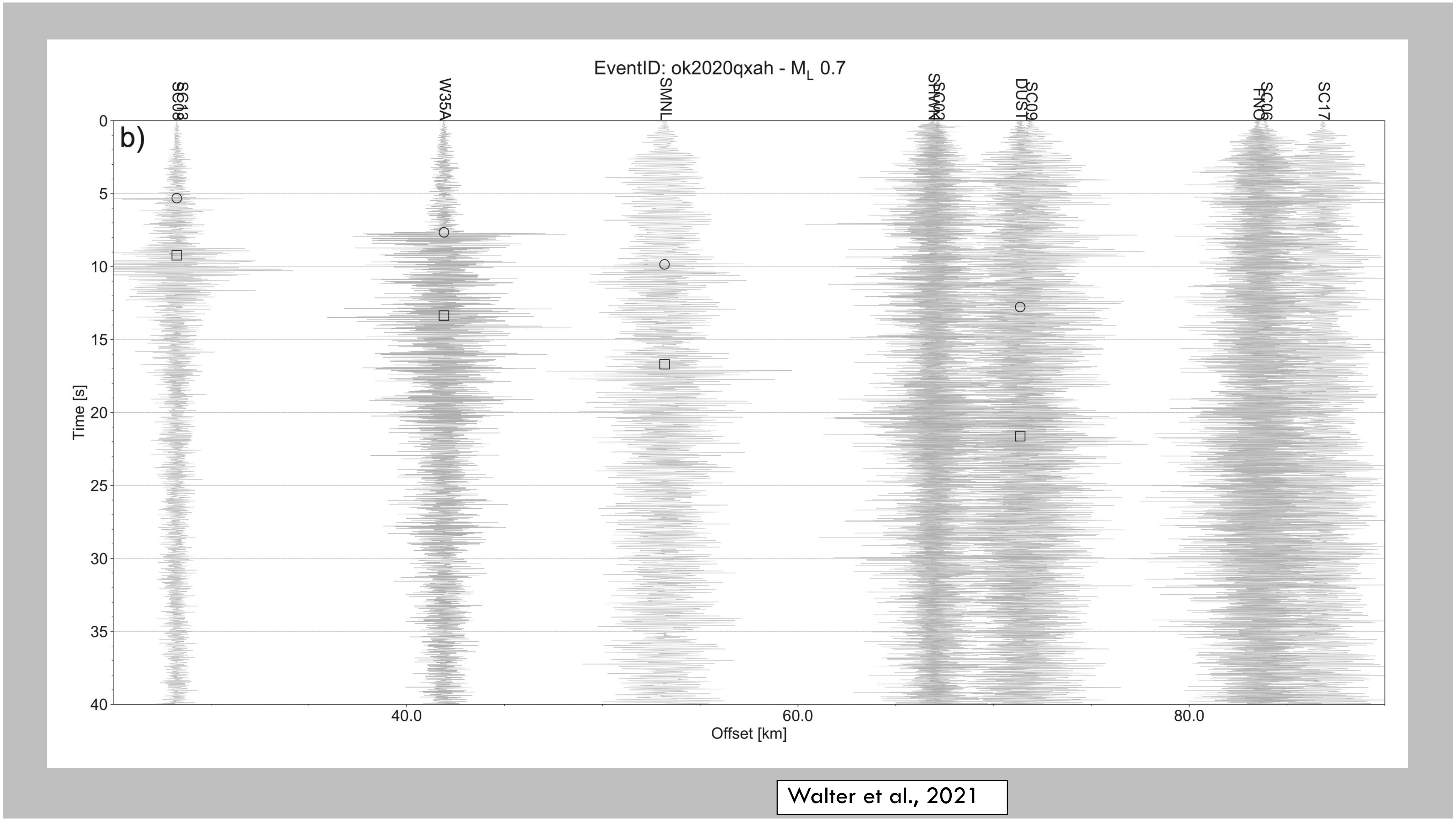


Ross et al., 2018; Kong et al., 2019

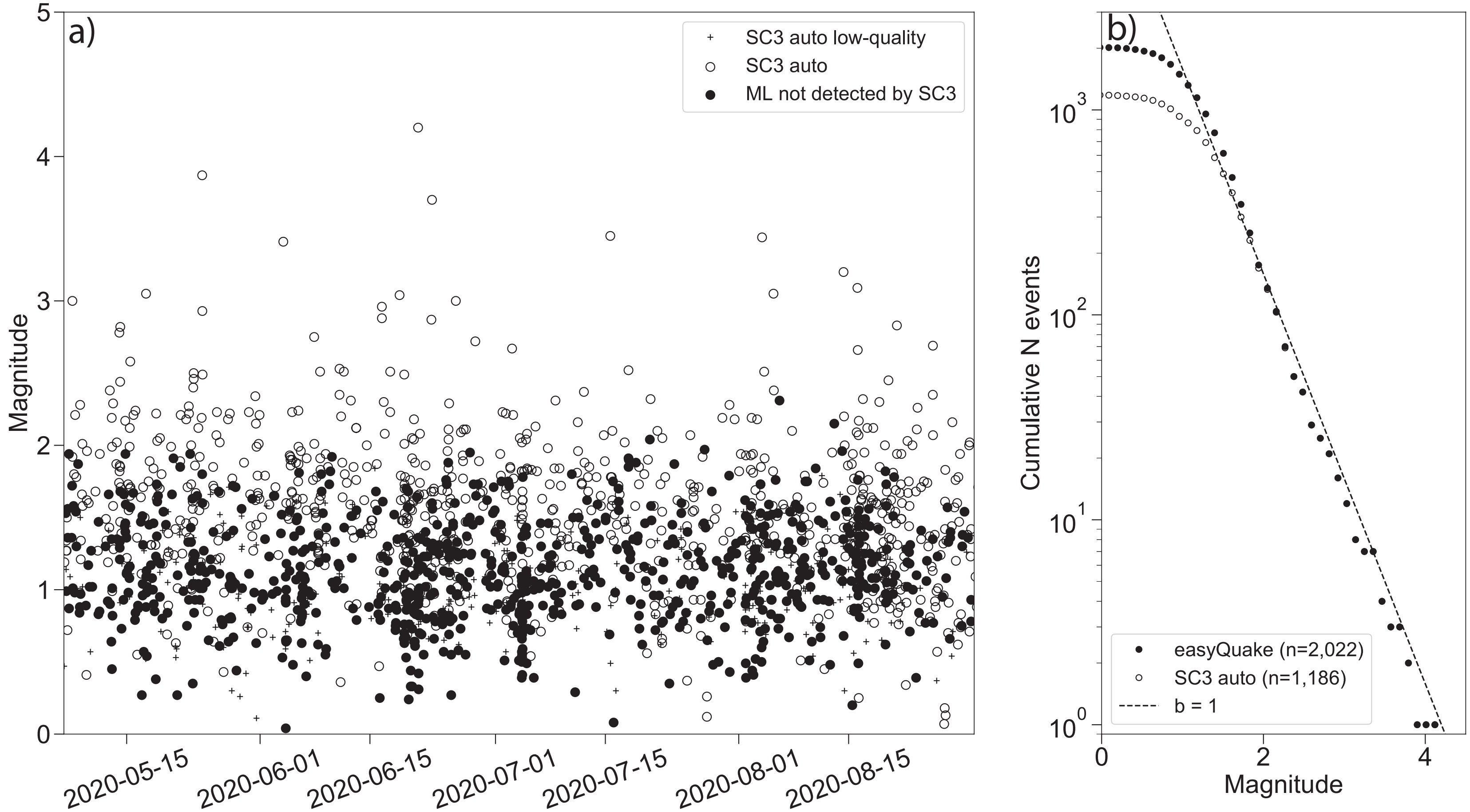
+ Large-N sensors

+ In-situ measurements



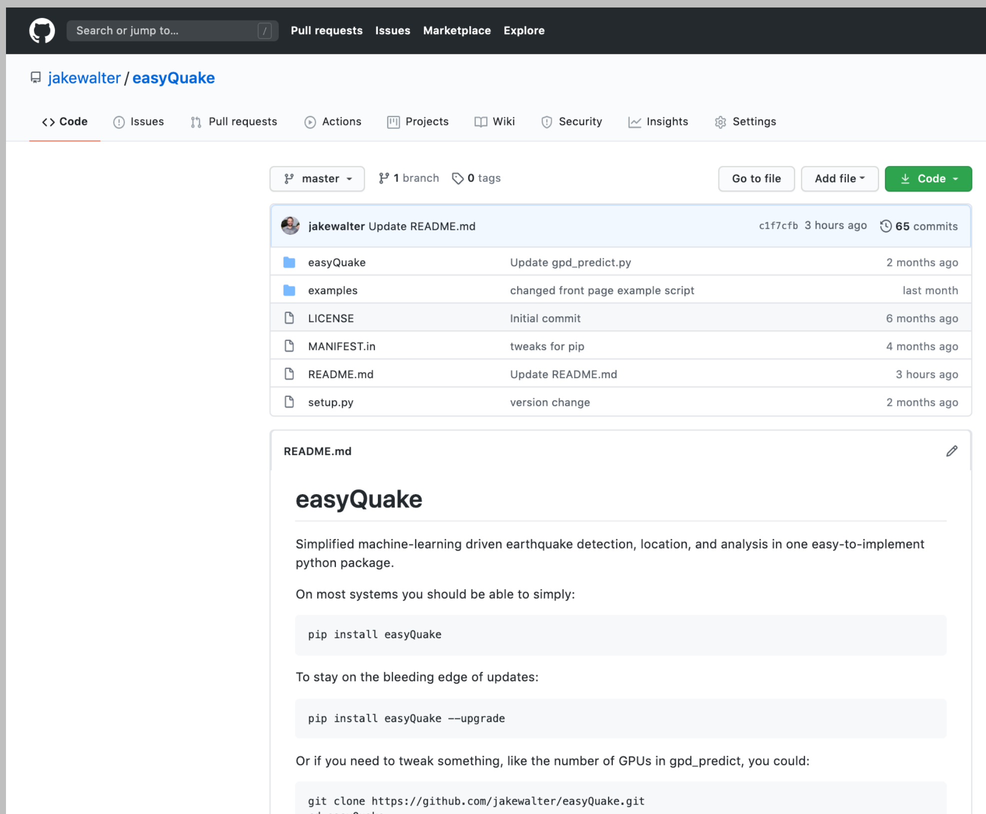

EventID: ok2020qxah - M L 0.7
b)
SC08
SC18
W35A
SMNL
SPWN
SC02
DUST
SC09
FNO
SC06
SC17
Time [s]
0
5
10
15
20
25
30
35
40
40.0
60.0
80.0
Offset [km]
Walter et al., 2021

Machine-learning/AI to find smaller earthquakes



Walter et al., 2021

https://github.com/jakewalter/easyQuake

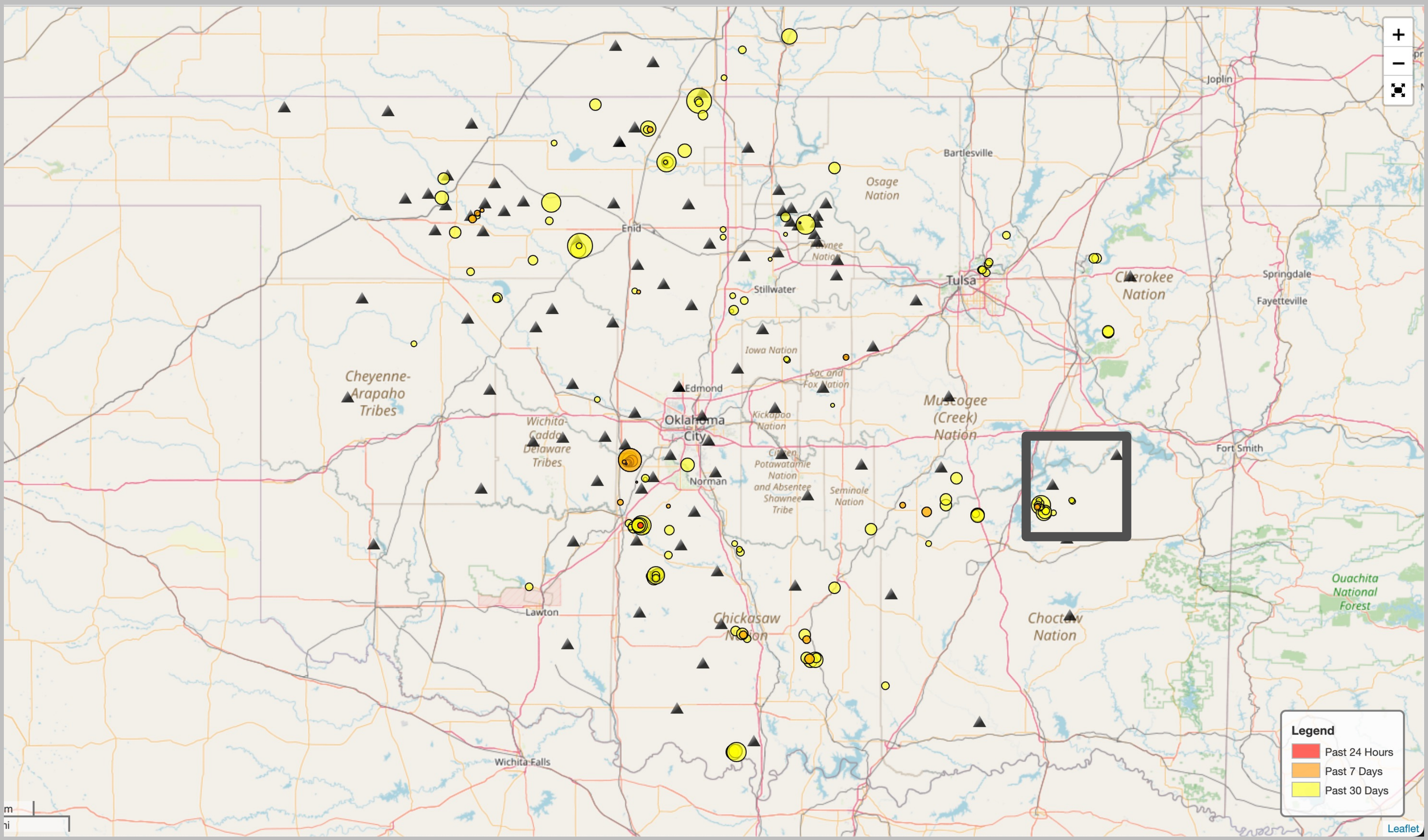



```
conda create -n easyquake python=3.7 anaconda
conda activate easyquake
conda install tensorflow-gpu==2.1
conda install keras
conda install obspy -c conda-forge
pip install easyQuake
```

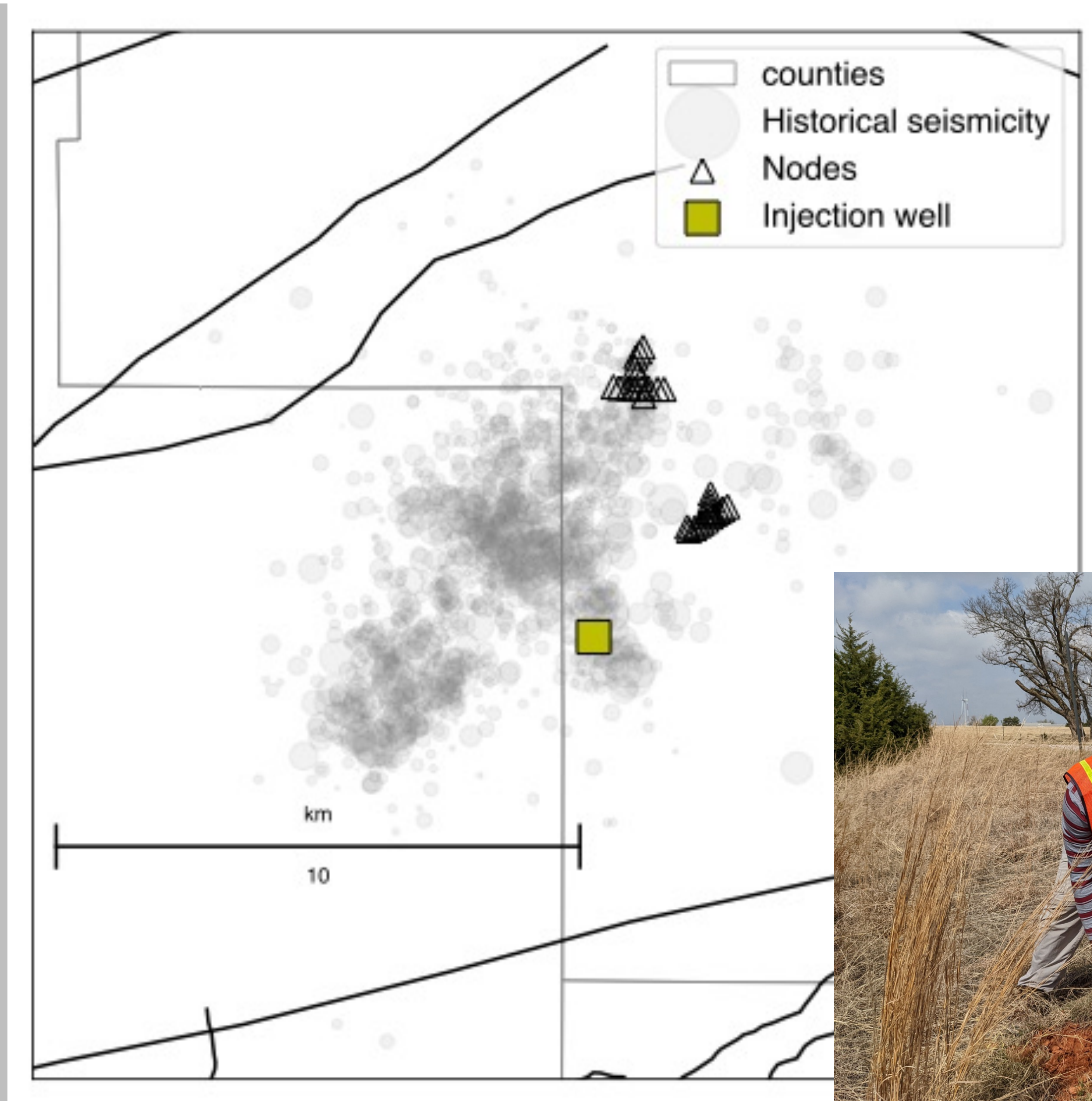
Email me: jwalter@ou.edu

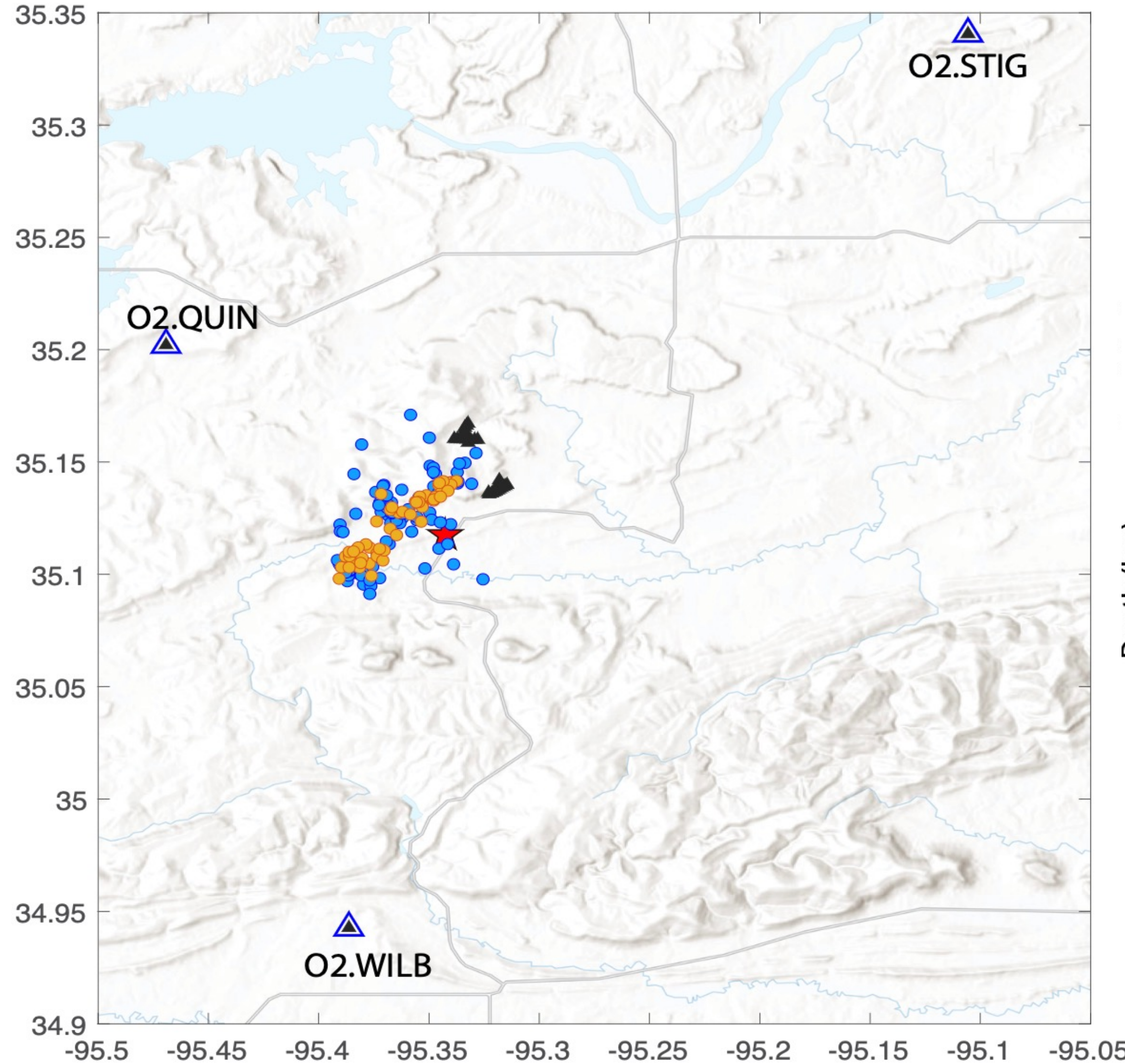
Walter, J. I., P. Ogwari, A. Thiel, F. Ferrer, and I. Woelfel (2021), easyQuake: Putting machine learning to work for your regional seismic network or local earthquake study, *Seismological Research Letters*, https://doi.org/10.1785/0220200226.

Future: near real-time and expanding modularity (new pickers, direct hypoDD or HASH functionality rather than just producing outputs, plotting, statistics)



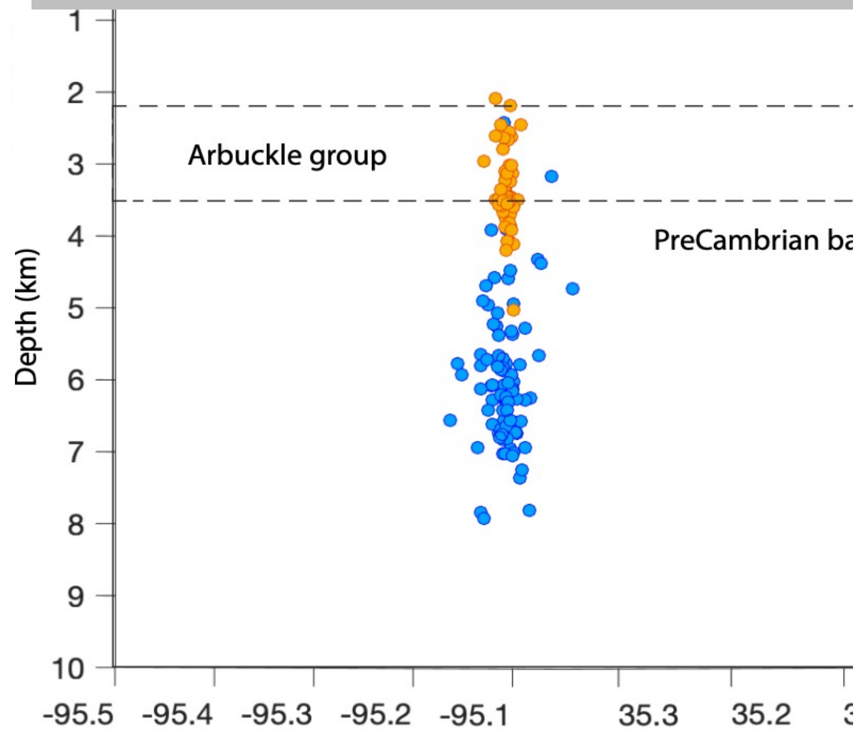
Legend
Past 24 Hours
Past 7 Days
Past 30 Days
Oklahoma City
Tulsa
Edmond
Norman
Enid
Stillwater
Lawton
Wichita Falls
Bartlesville
Joplin
Springdale
Fayetteville
Fort Smith
Osage Nation
Cheyenne-Arapaho Tribes
Wichita-Caddo-Delaware Tribes
Iowa Nation
Sac and Fox Nation
Kickapoo Nation
Citizen Potawatomie Nation and Absentee Shawnee Tribe
Seminole Nation
Muscogee (Creek) Nation
Cherokee Nation
Chickasaw Nation
Choctaw Nation
Ouachita National Forest
Leaflet

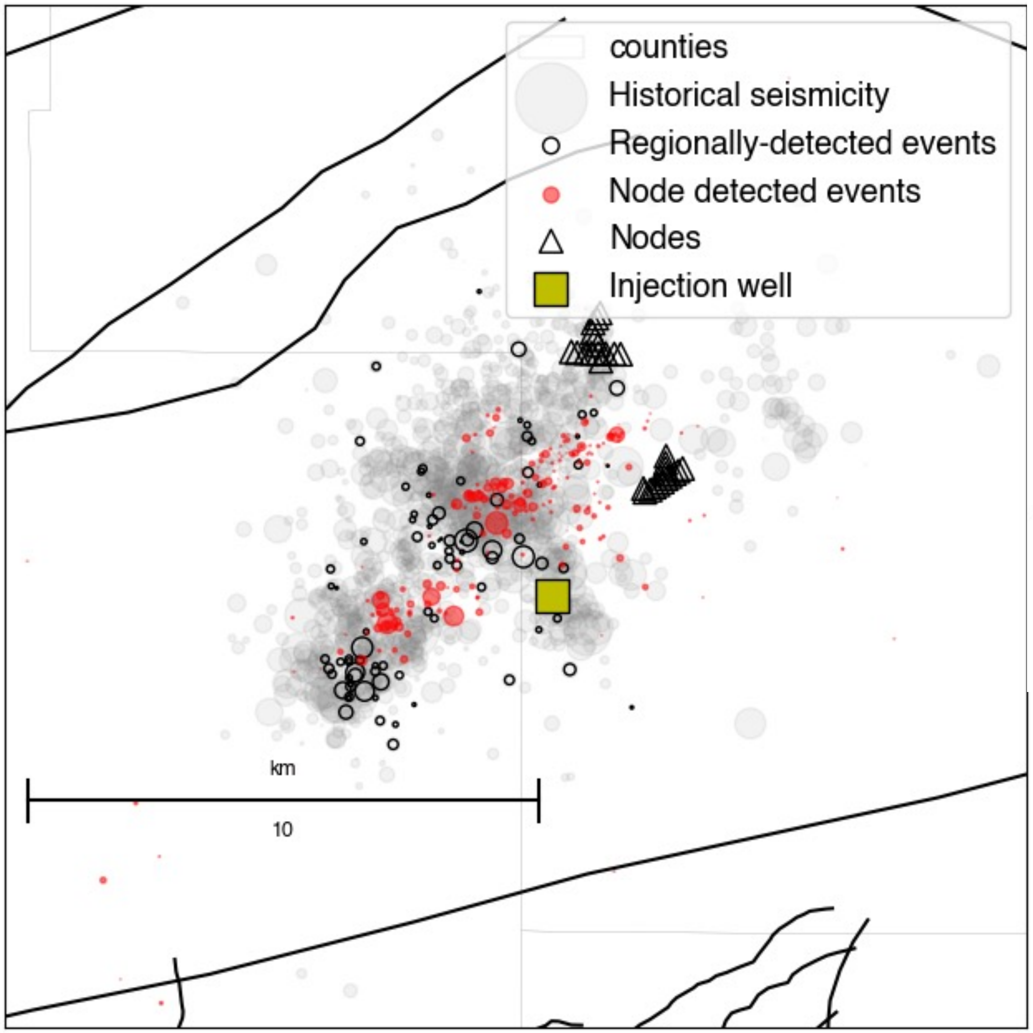

counties
Historical seismicity
Nodes
Injection well
km
10

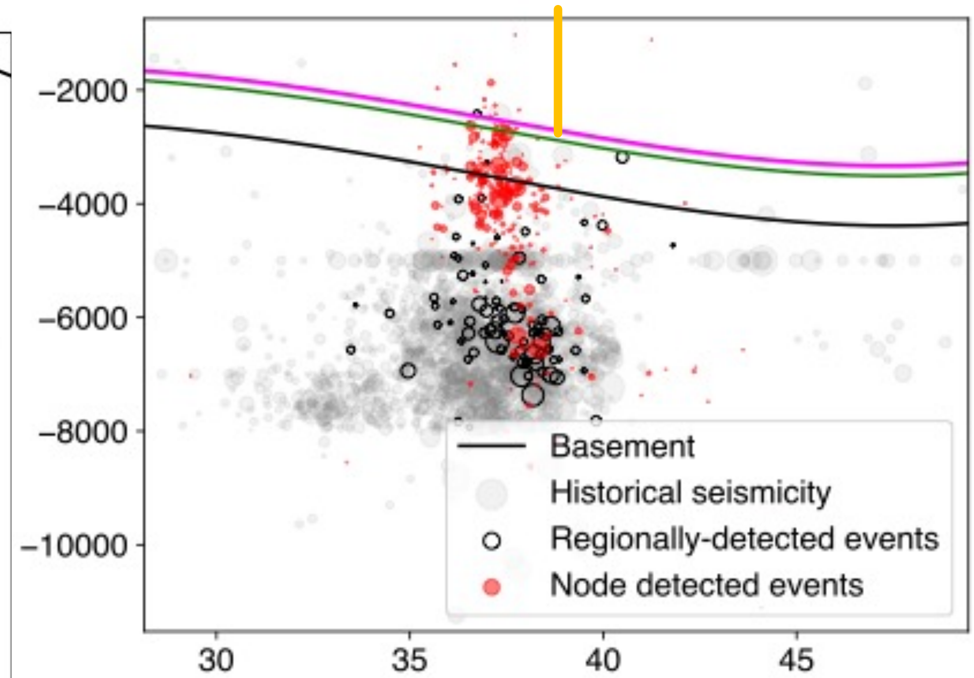



Add the picks from nodes as though they are part of the network

Paul Ogwari



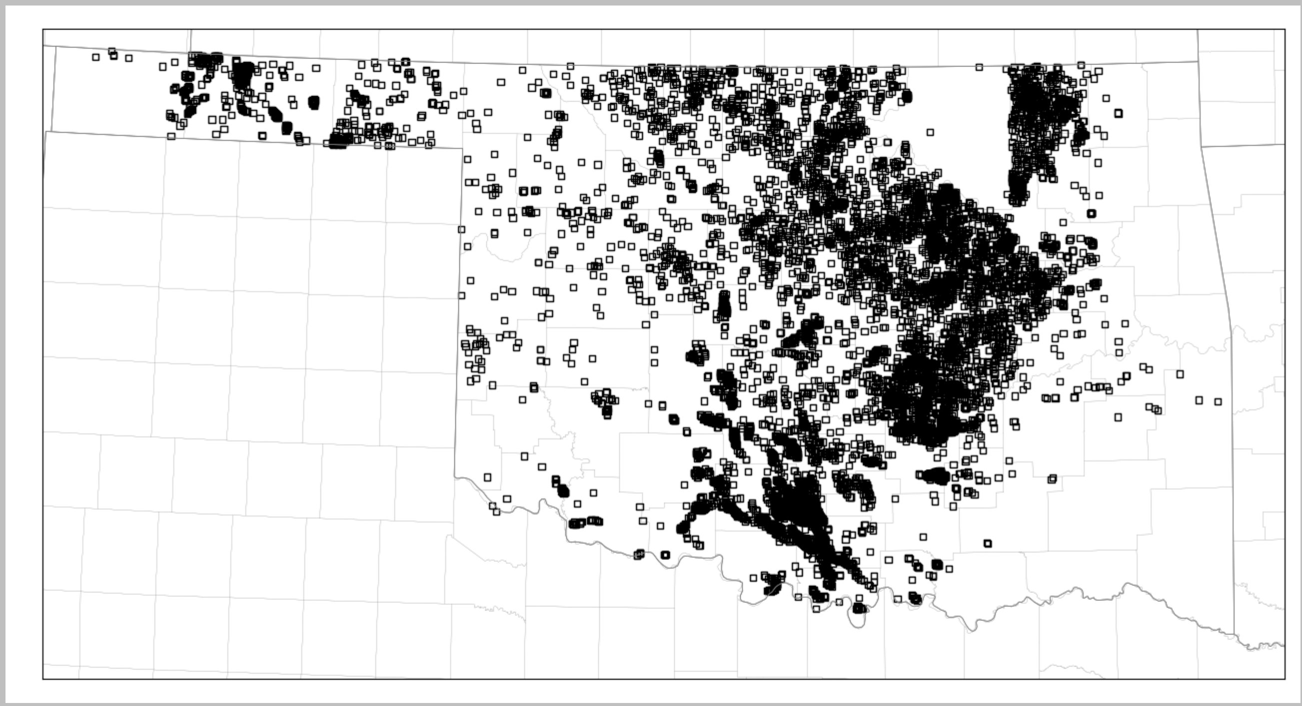




Combining ML-assisted event detection and node deployment for close-up view

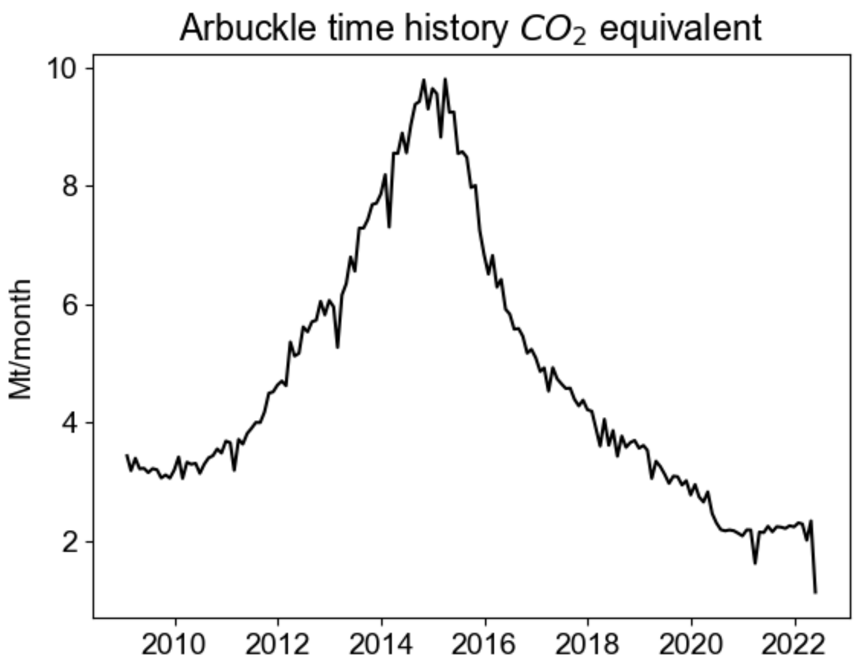
- **M3.7 in 2019 led to brief shut-in of disposal well During node deployment we detected 500+ earthquakes, while real-time network detected 89**

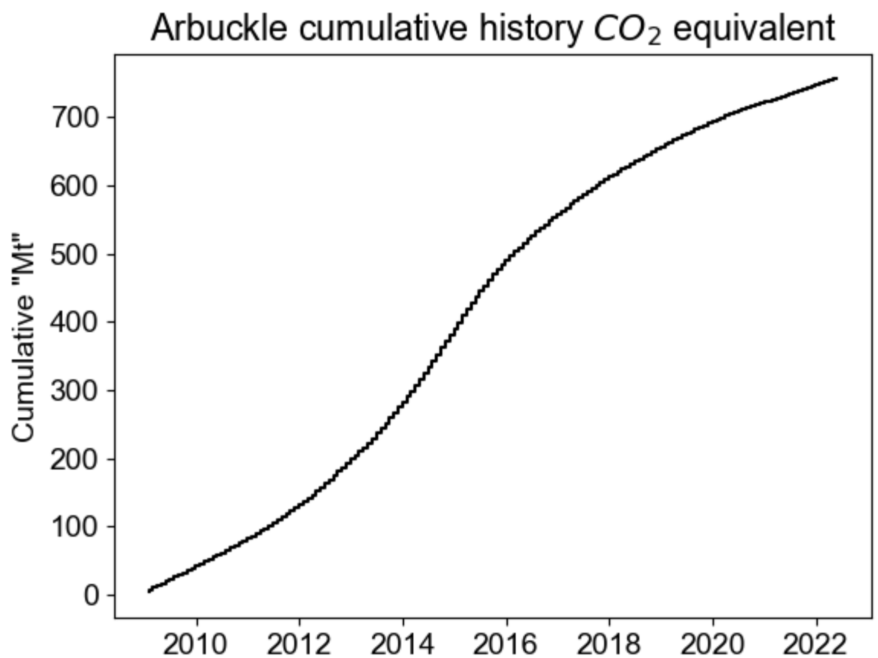
~14,000 Class II wells within the Oklahoma Corporation Commission Underground Injection Control program



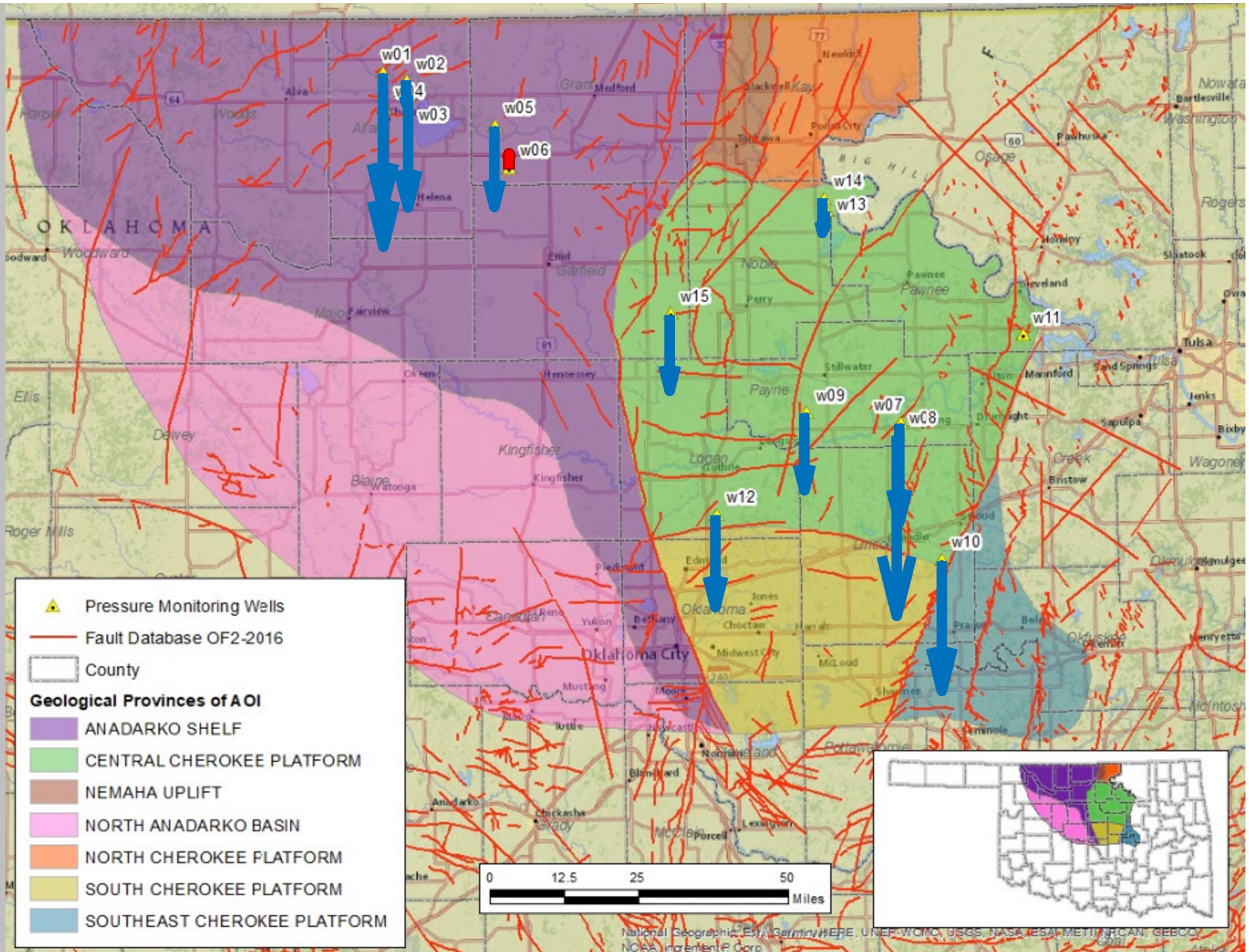
Long-term carbon storage needs to be broadly distributed with a regional approach to risk

Thought experiment supercritical CO_2 is 700 kg/m^3



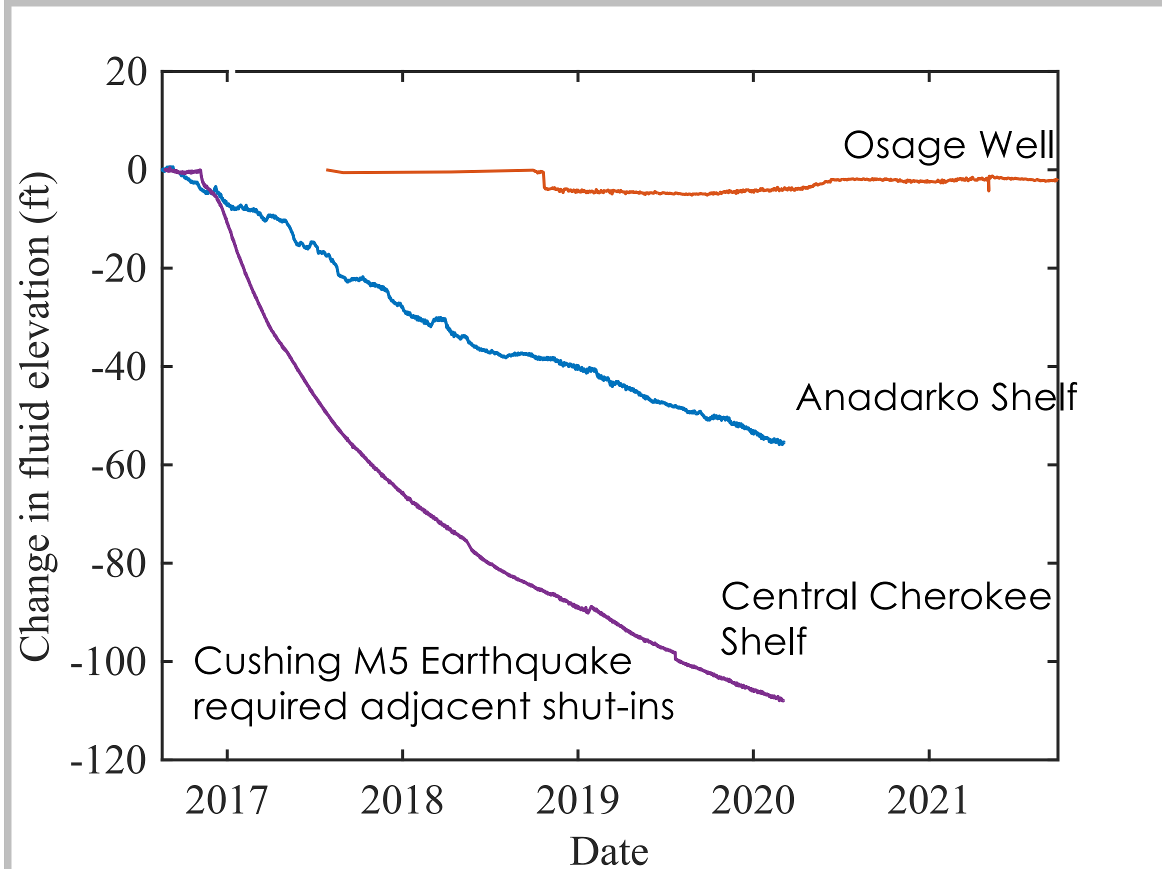


~ 5 $GtCO_2$/yr USA emissions

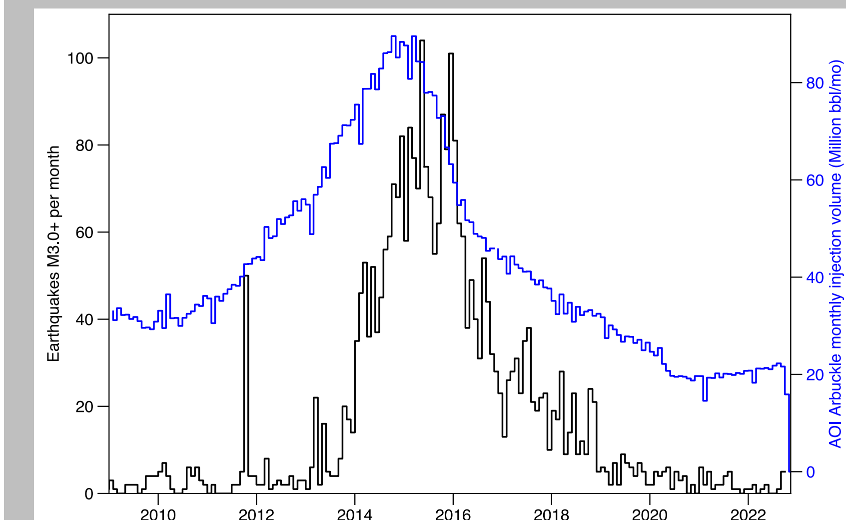


Pressure Monitoring Wells
Fault Database OF2-2016
County
Geological Provinces of AOI
ANADARKO SHELF
CENTRAL CHEROKEE PLATFORM
NEMAHA UPLIFT
NORTH ANADARKO BASIN
NORTH CHEROKEE PLATFORM
SOUTH CHEROKEE PLATFORM
SOUTHEAST CHEROKEE PLATFORM
w01
w02
w03
w05
w06
w07
w08
w09
w10
w11
w12
w13
w14
w15
0
12.5
25
50
Miles
OKLAHOMA
Oklahoma City
Tulsa
Enid
Stillwater
National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Change in fluid elevation



Comparison of regional well responses



Lessons ~~from~~ for mitigating ~~wastewater disposal seismicity hydraulic-fracture triggered~~ seismicity from long-term carbon storage/EOR or hydrogen storage

Volume – long-term operation and large volumes

Geology and faults – planning operations to avoid large faults that are oriented for slip; FSP is not effective for planning purposes during permitting

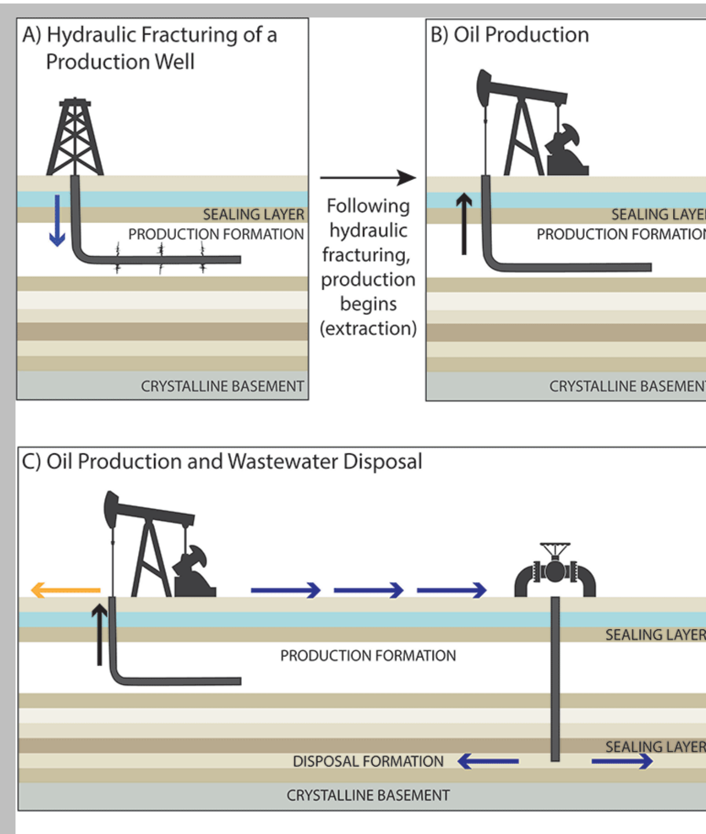
Rapid mitigation – traffic light pauses or disposal shut-in may be effective on hours to days timescales

Clear industry/public agency communication channels and proactive planning can keep the social license to operate intact. When events happen, a clear understanding of the “reaction” (mitigation)

Clear need for comprehensive borehole and surface monitoring by trusted (public) agencies

Emerging technology and techniques

Additional thoughts? – jwalter@ou.edu



Rubinstein and Mahani, 2015