Lessons learned from a decade of disposal-induced Oklahoma seismicity for future regional approaches to gigaton-scale carbon storage

Jake Walter

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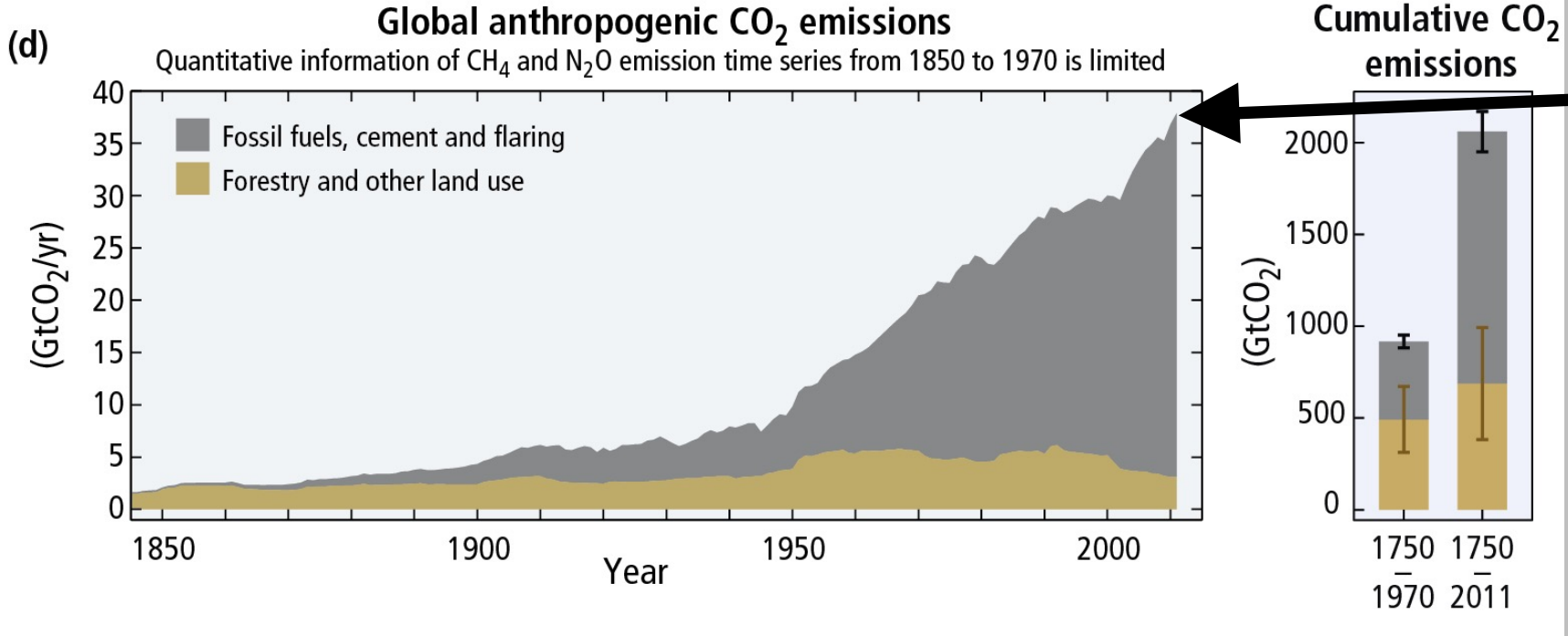
Emissions



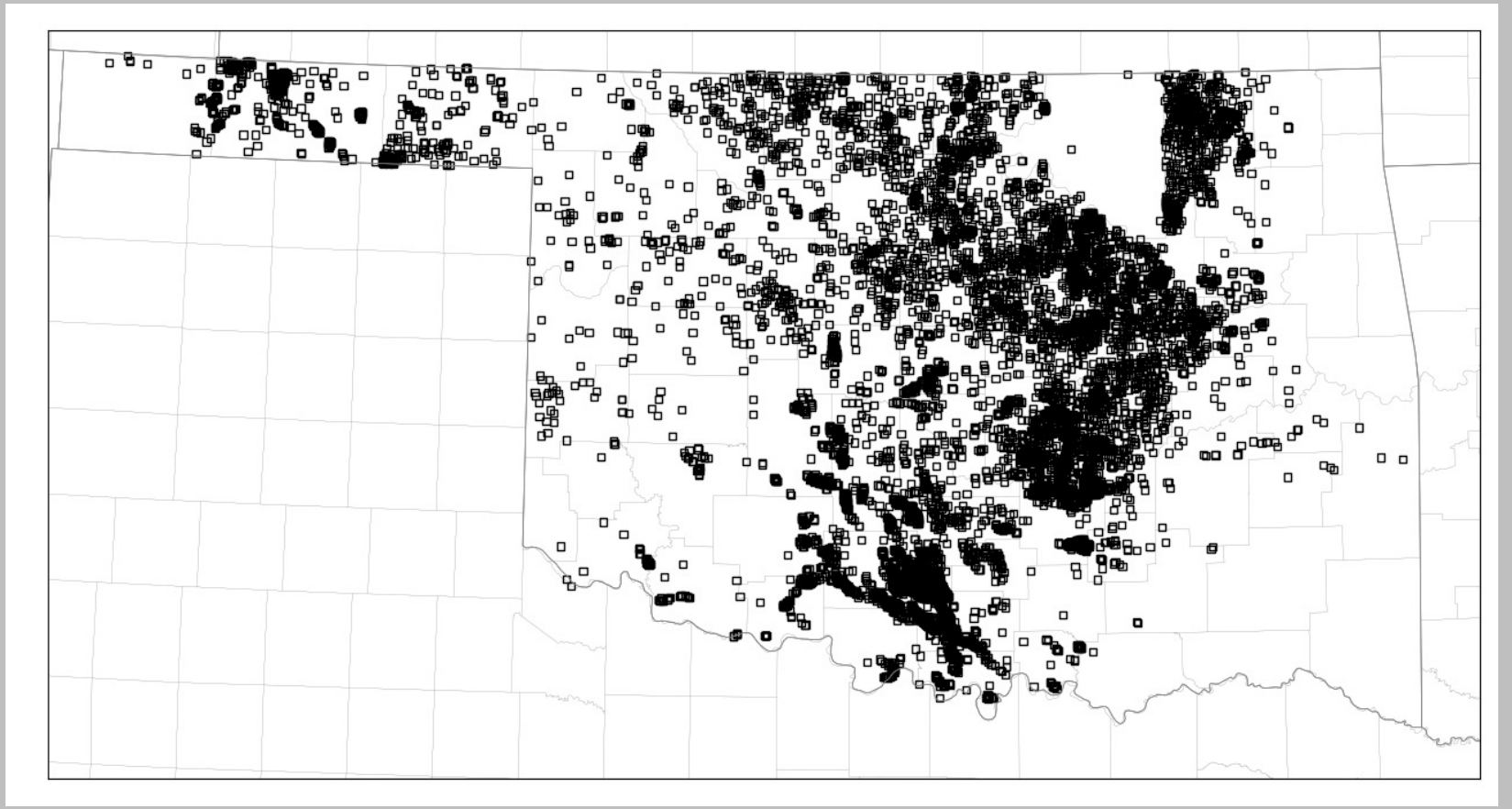
~ 40 $GtCO_2$/yr World

~ 5 $GtCO_2$/yr USA

2015 National Academies Climate Intervention report – "*Recommendation 2: The committee recommends research and development investment to* ***improve methods of carbon dioxide removal and disposal at scales that would have a global impact on reducing greenhouse warming****, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring*"

Decatur, Illinois – 1 Mt over 3 years at a cost of $200 million

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



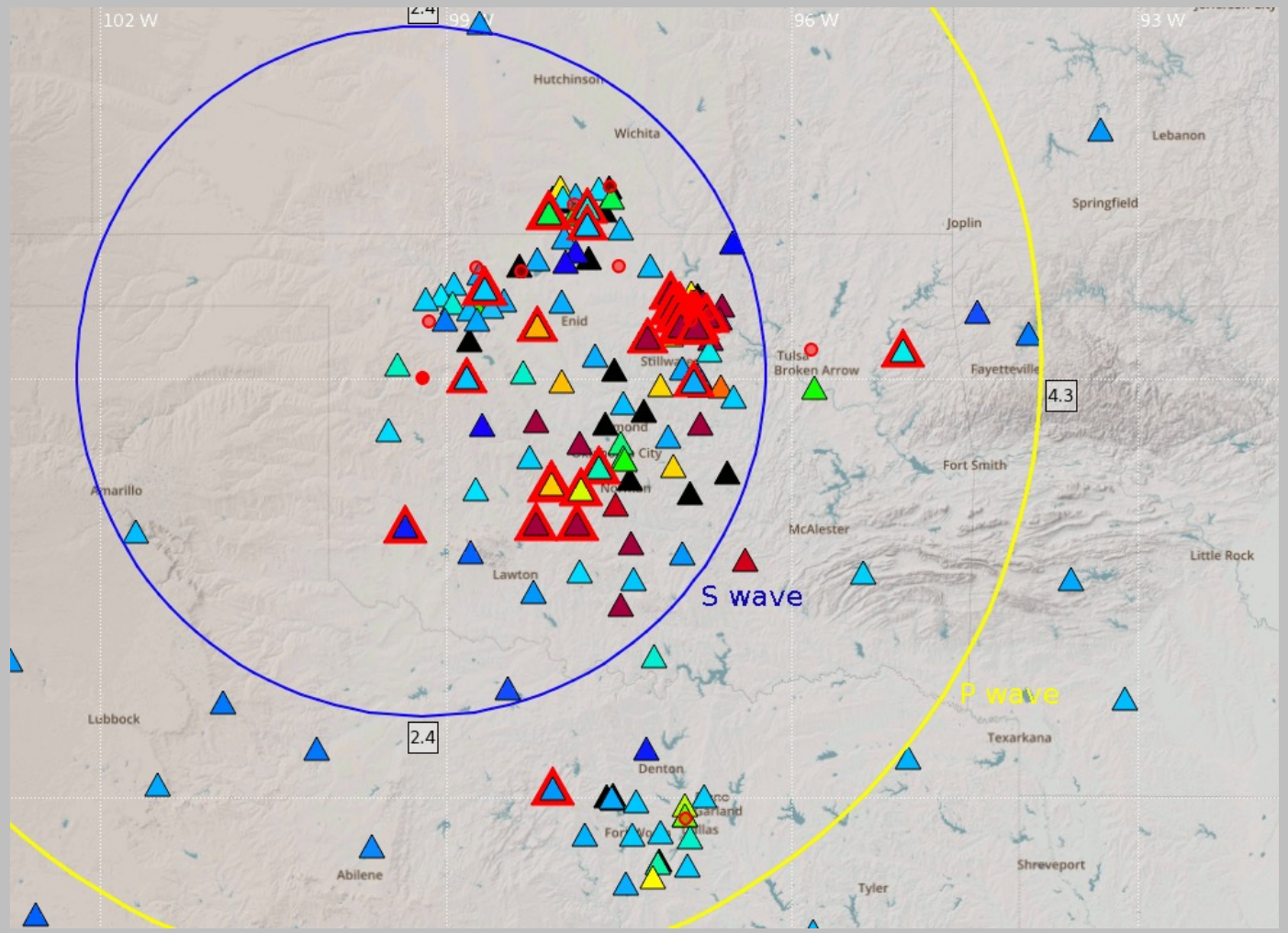
Long-term carbon storage needs to be broadly distributed with a regional approach to risk

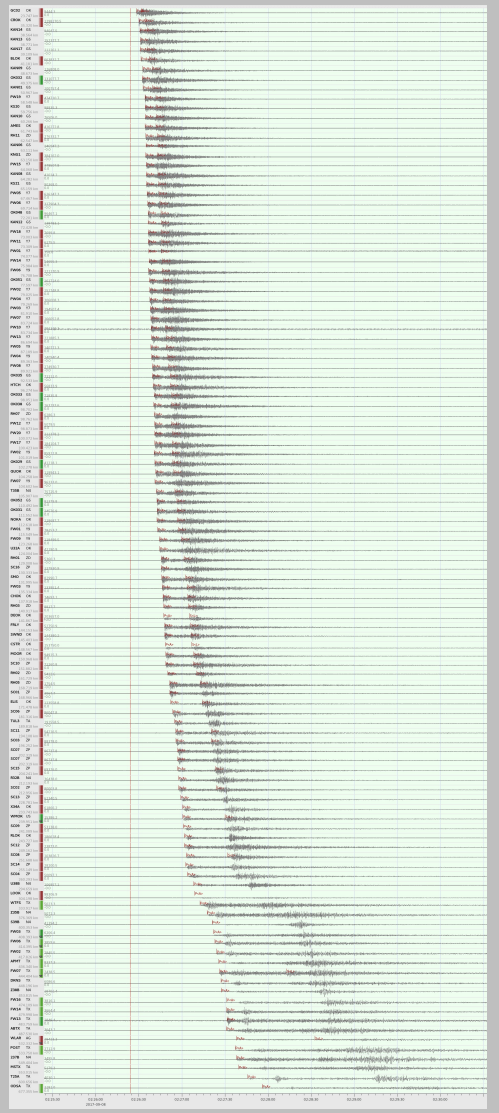
Leverage new technologies in hardware and software



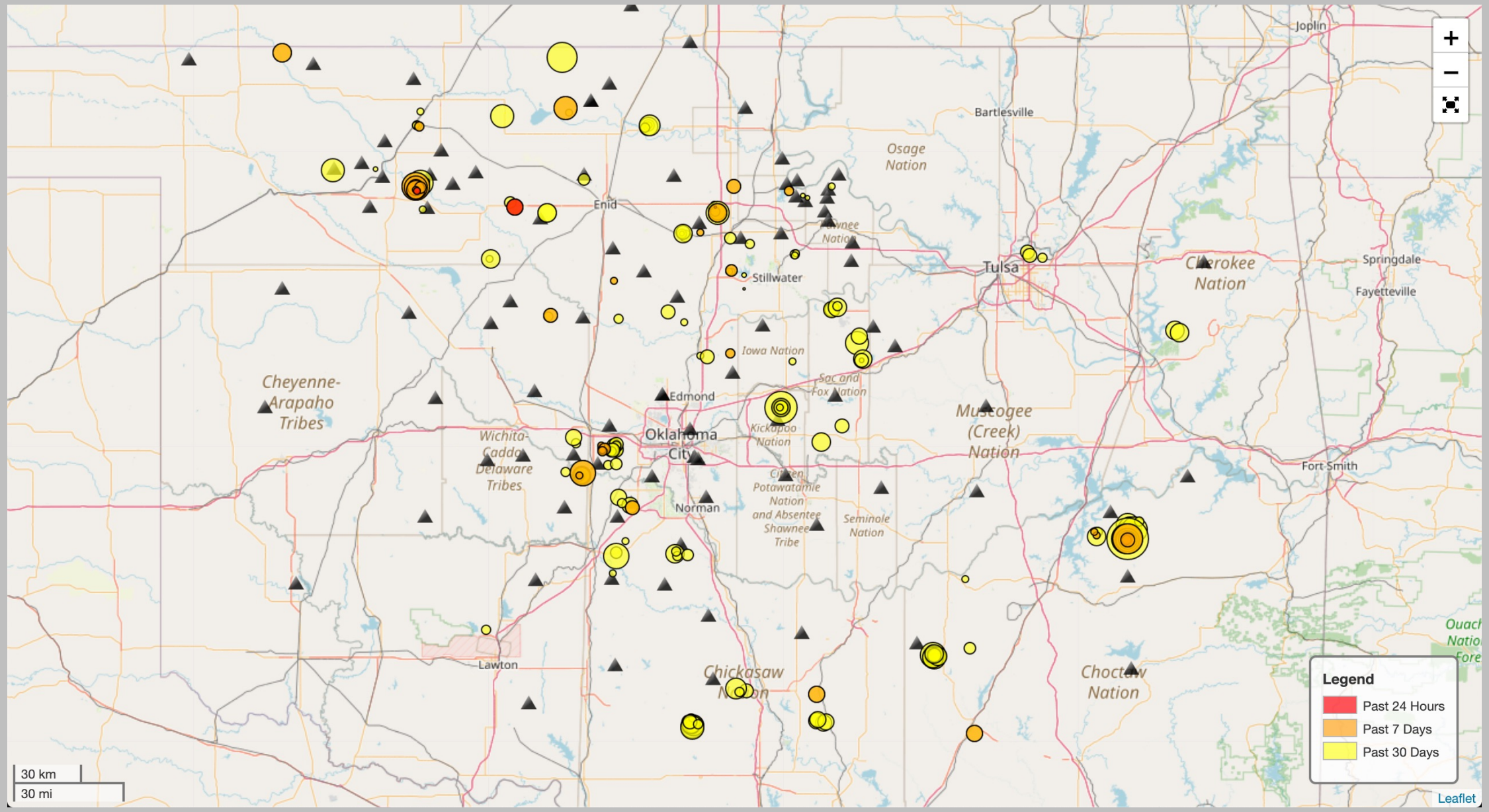


Jake Walter, Ph.D. – State Seismologist
Paul Ogwari, Ph.D. – Geophysicist
Fernando Ferrer – Lead Analyst/Metadata
Andrew Thiel – Analyst/Outreach/Field
Isaac Woelfel – Field Technician


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

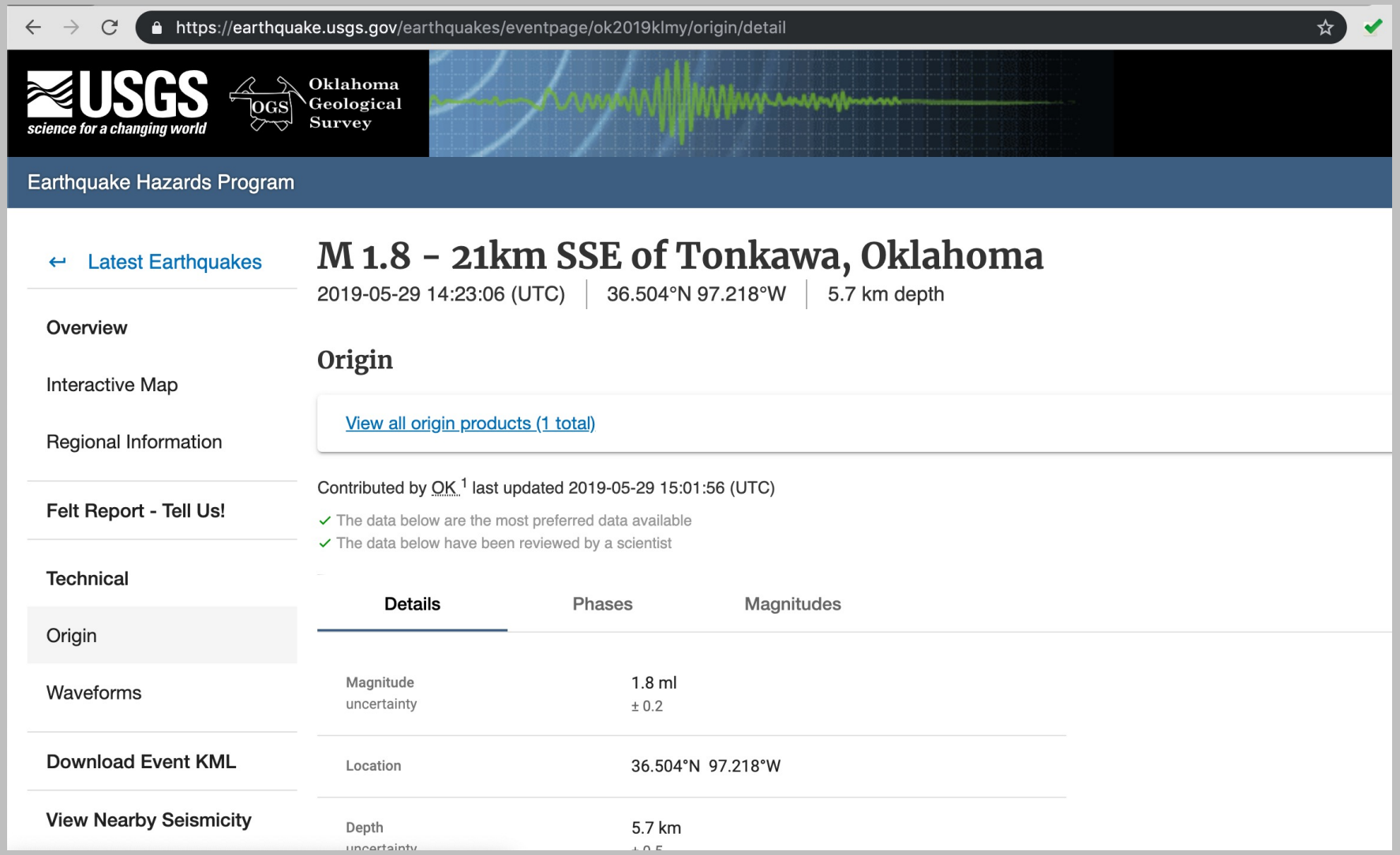


ogs.ou.edu for products, **rtserve.ou.edu** for real-time seedlink buffer



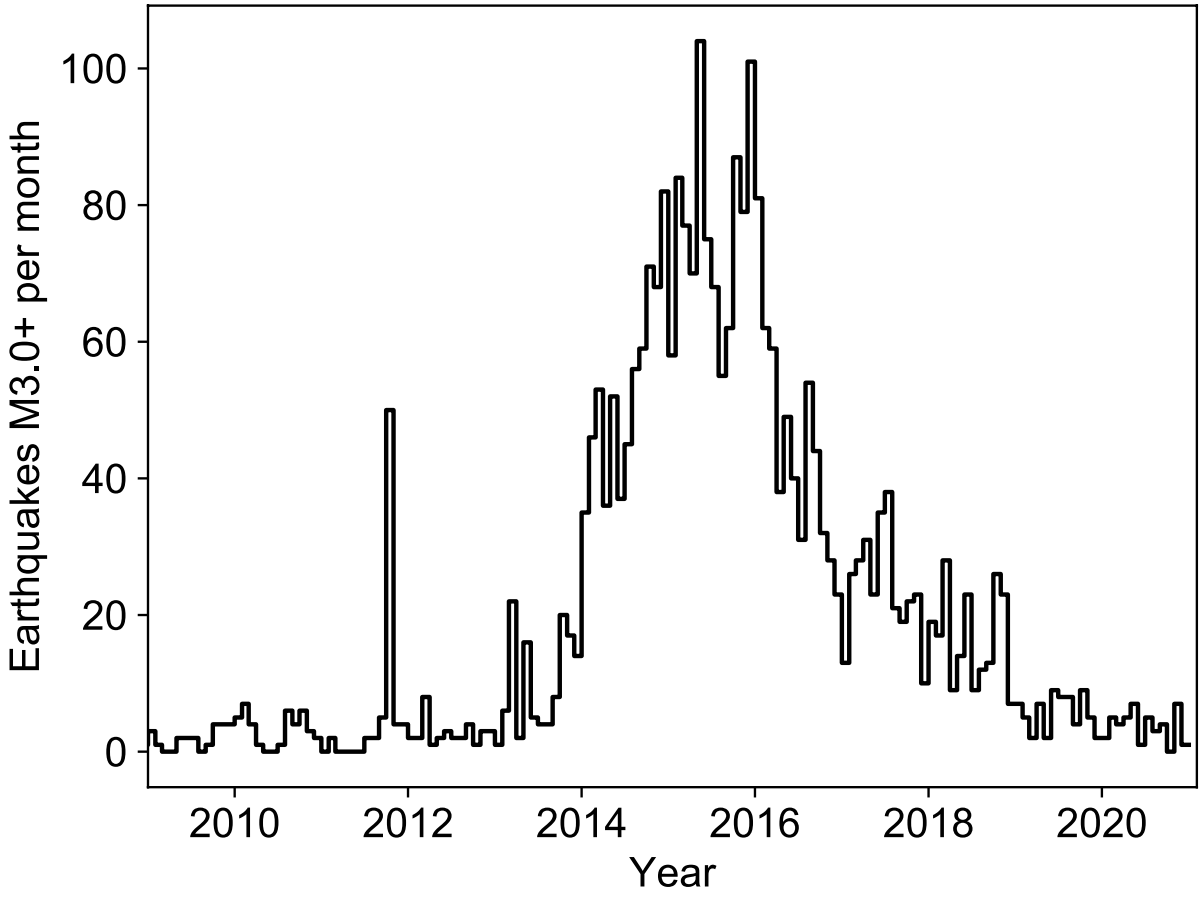
~15-20 earthquakes/day

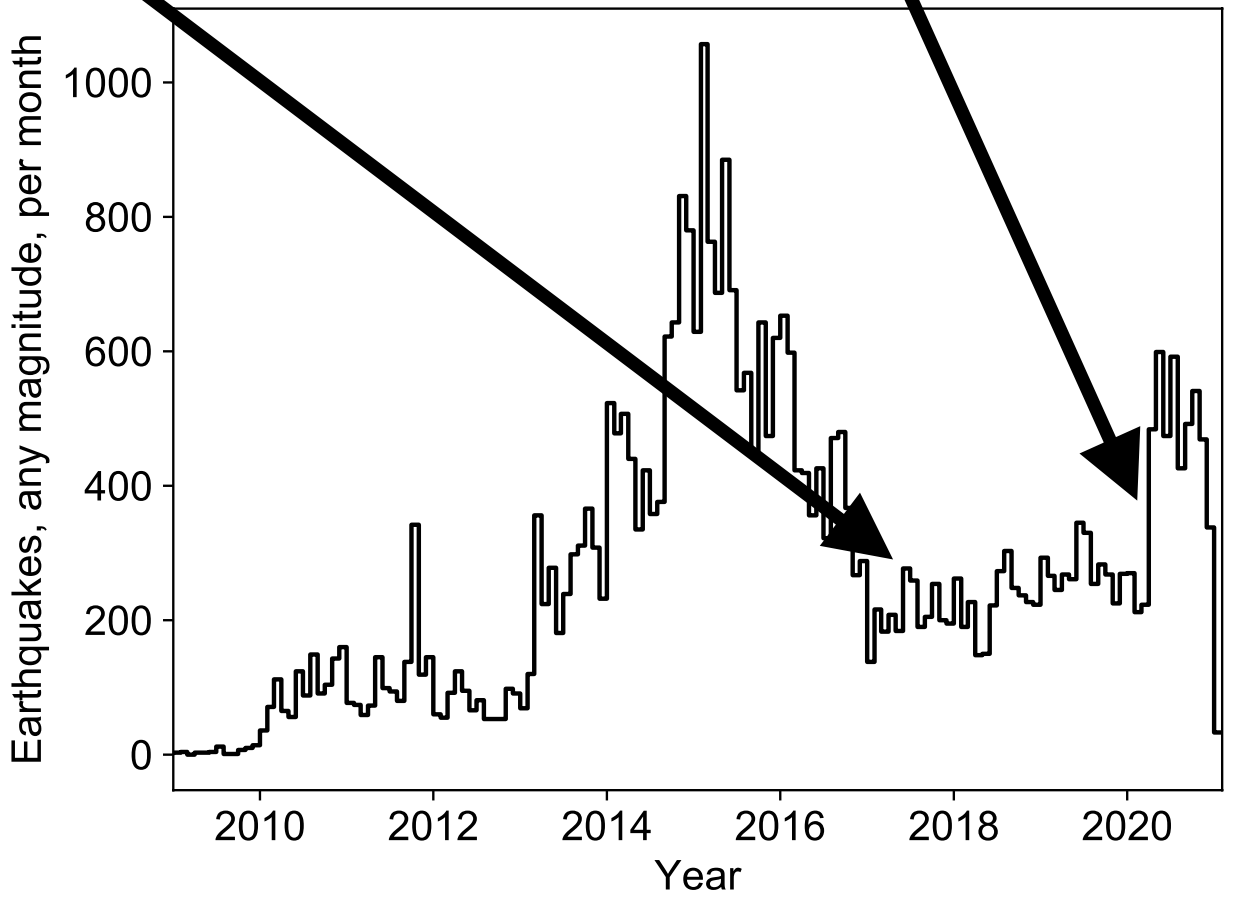
As of May 29, 2019 - OGS is the authoritative regional network in the state, so USGS published are reported by OGS



Improved monitoring software

easyQuake





Summary – full turnkey earthquake catalog tool, including FDSN waveform download and QuakeML event file creation

1. Detect – Choose machine-learning picker, either the generalized phase detector (Ross et al., 2018) or EQTransformer (Mousavi et al., 2020)

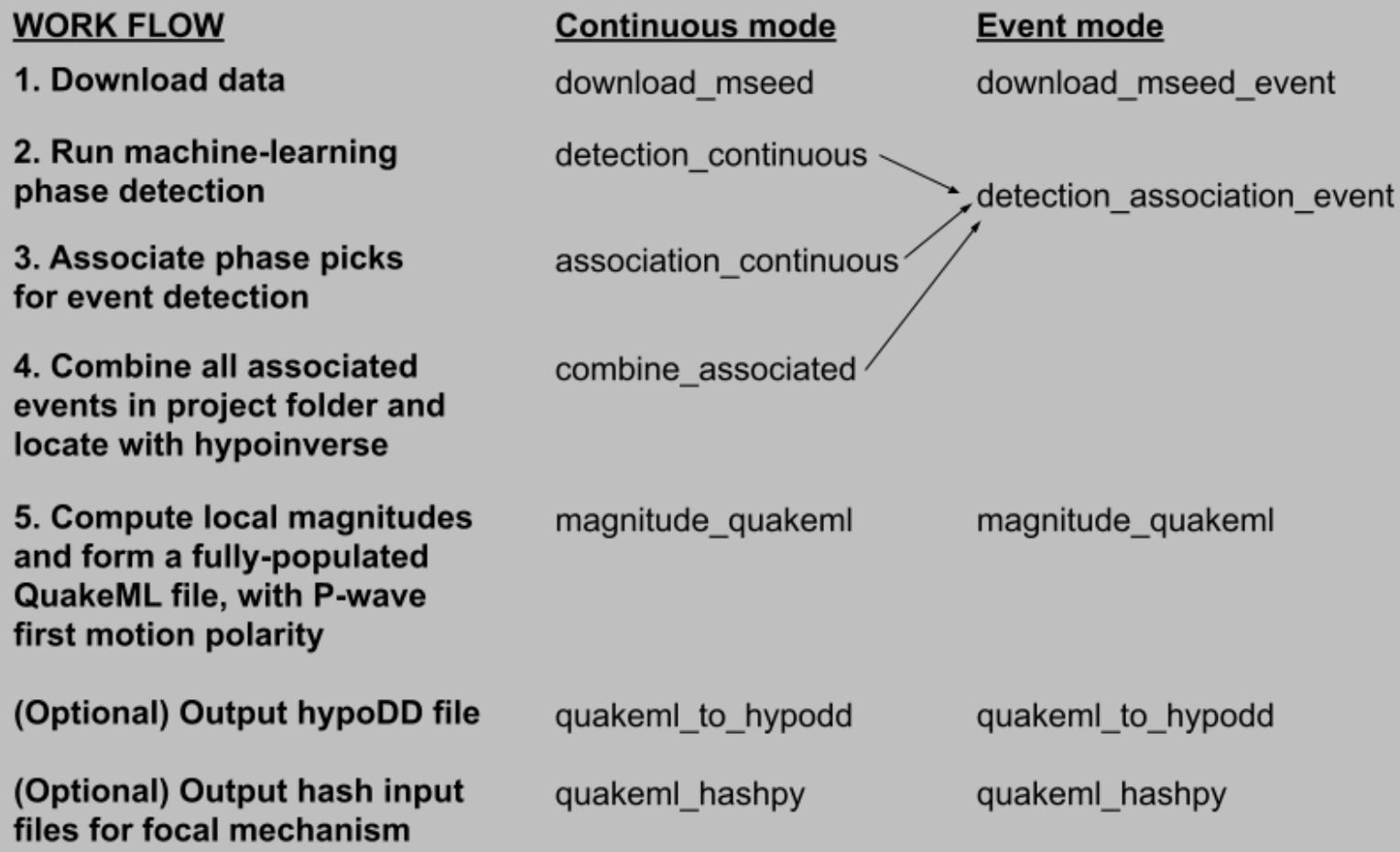
2. Associate and locate - Modified PhasePApy 1D associator (Chen and Holland, 2016)

3. Magnitude - Compute preliminary magnitude

4. Full QuakeML file event files

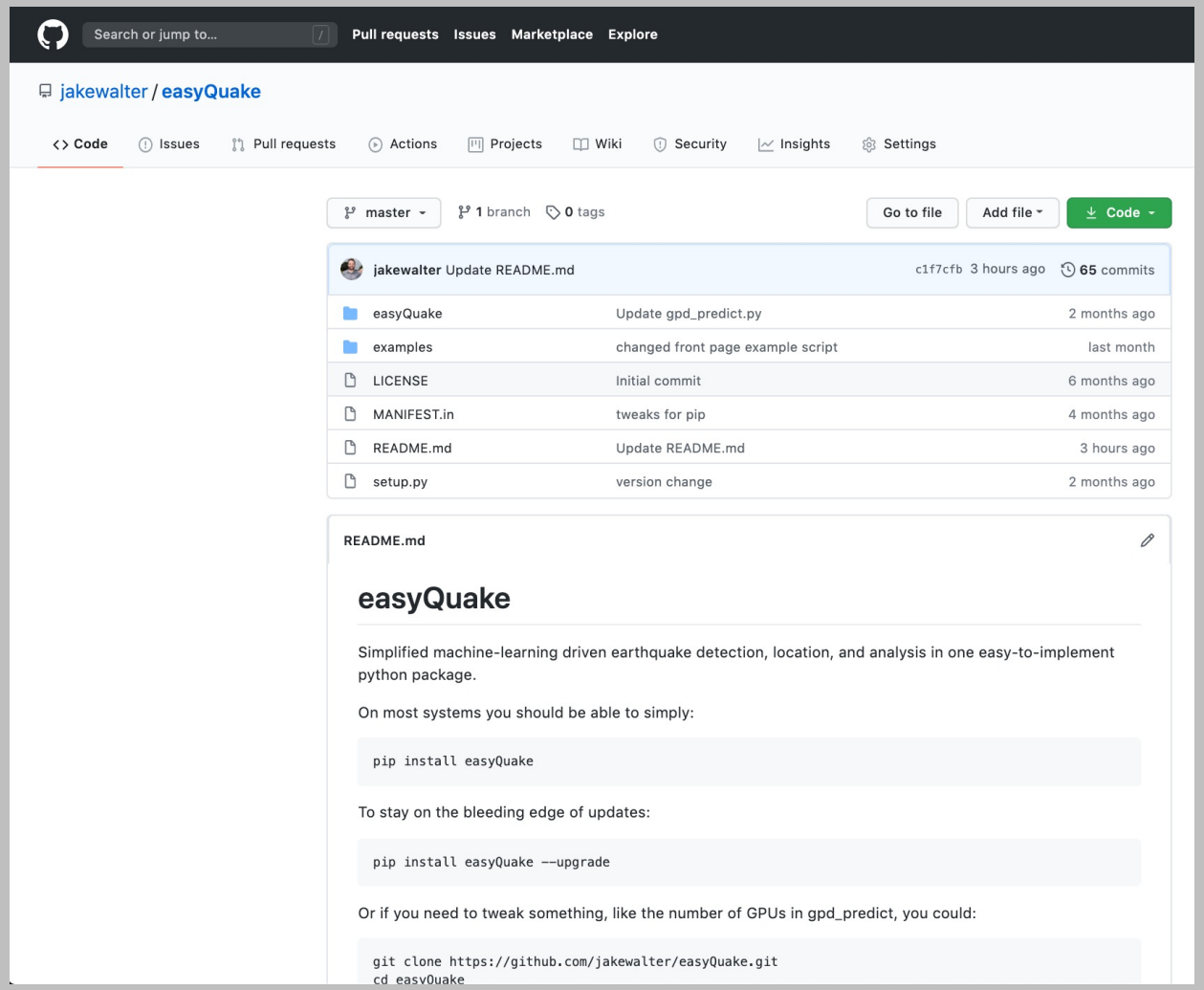
5. Input it into SeiscomP system for analyst review or output various file formats for relocation or focal mechanism determination

easyQuake python package



Can be run on data collected already or direct it to download data from FDSN servers

https://github.com/jakewalter/easyQuake



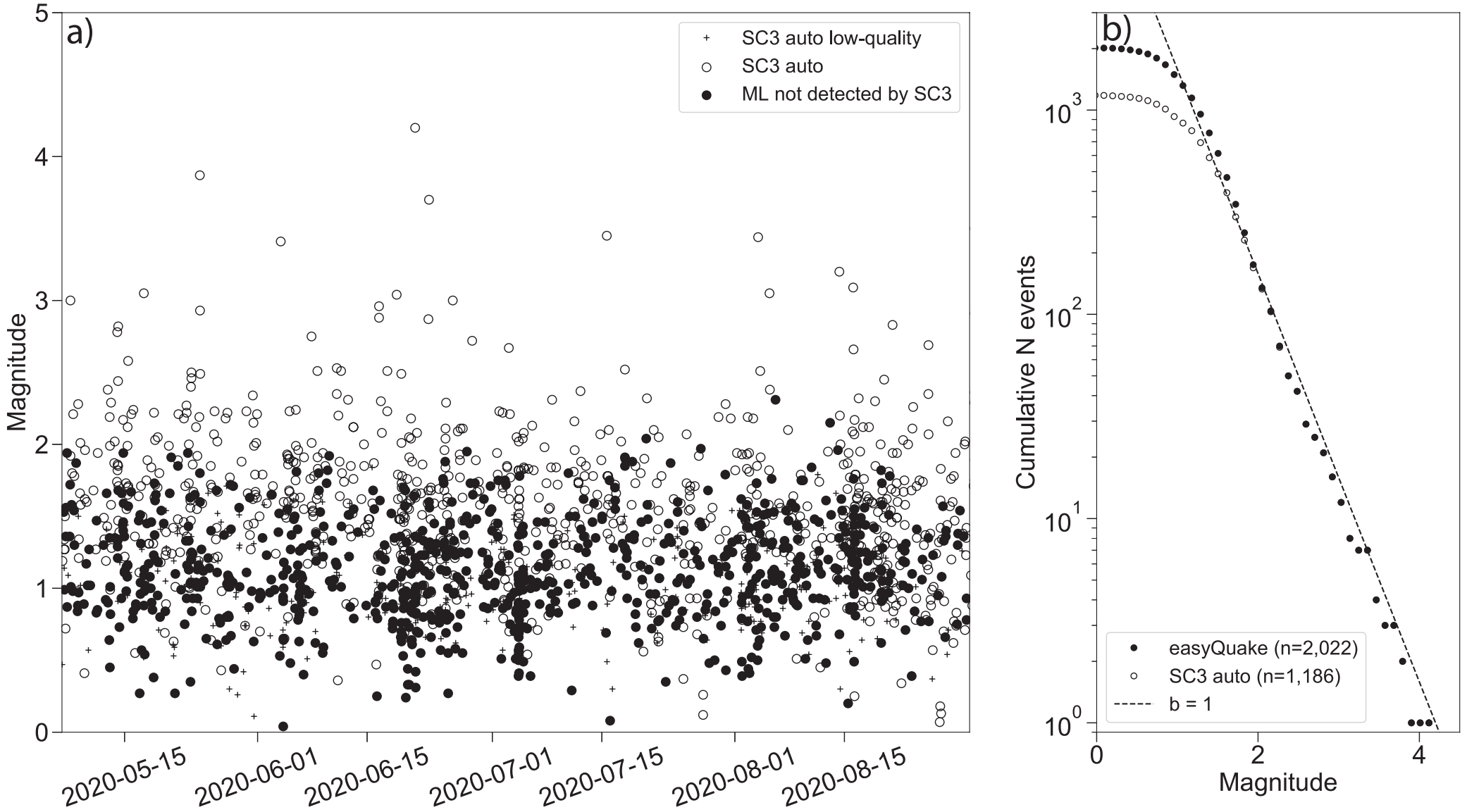

```
conda create -n easyquake python=3.7 anaconda
conda activate easyquake
conda install tensorflow-gpu==2.1
conda install keras
conda install obspy -c conda-forge
pip install easyQuake
```

Email me: jwalter@ou.edu

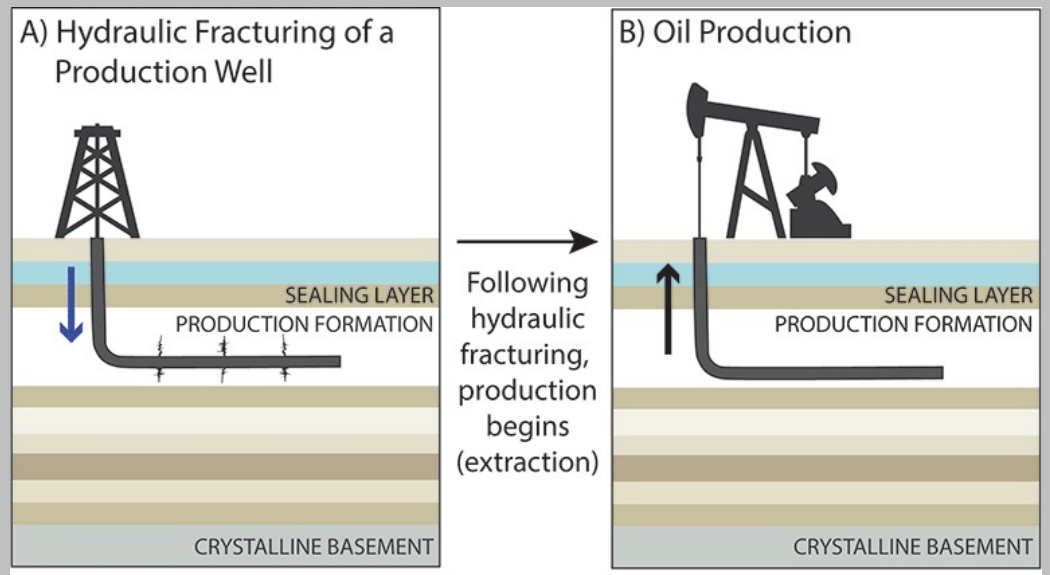
Walter, J. I., P. Ogwari, A. Thiel, F. Ferrer, and I. Woelfel (2021), easyQuake: Putting machine learning to work for your regional seismic network or local earthquake study, *Seismological Research Letters*, https://doi.org/10.1785/0220200226.

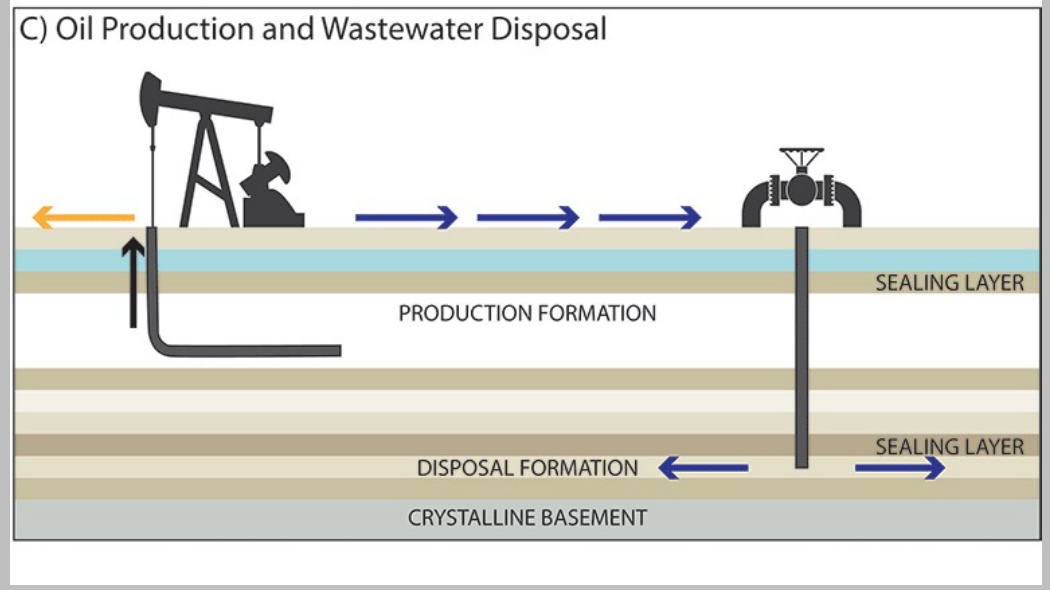
Future: near real-time and expanding modularity (new pickers, direct hypoDD or HASH functionality rather than just producing outputs, plotting, statistics)

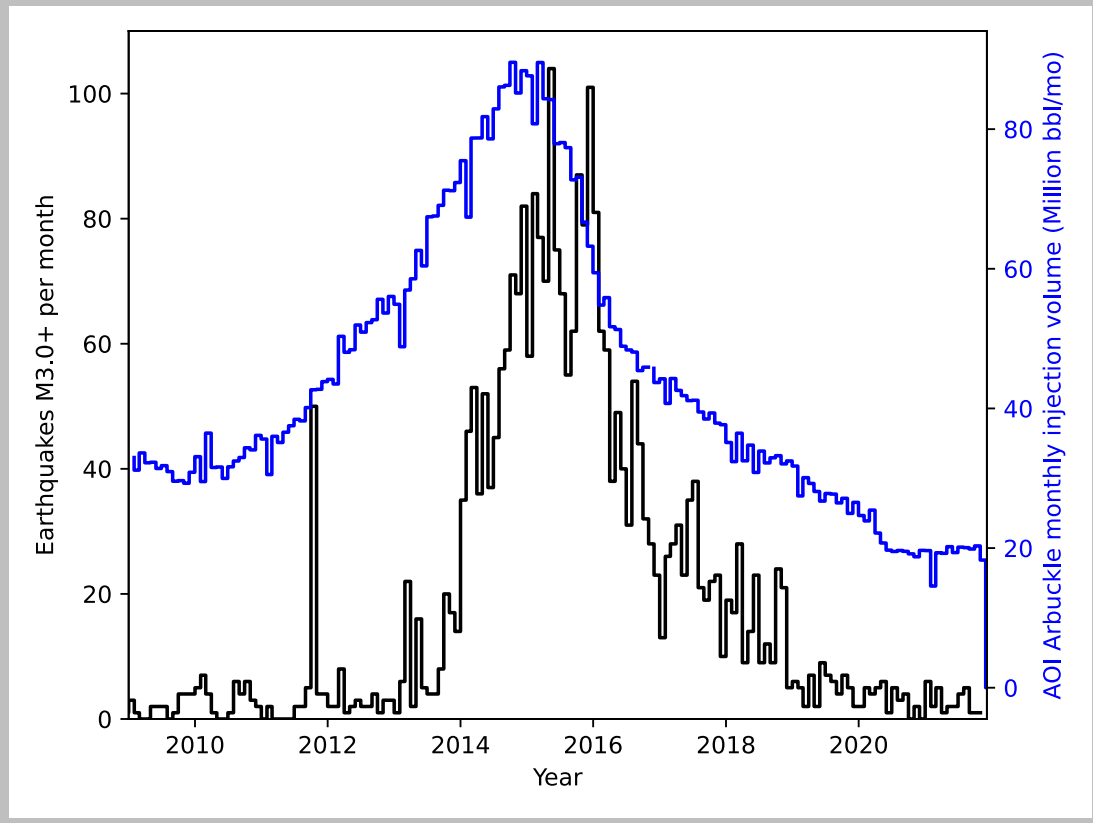
Machine-learning/AI to find smaller earthquakes



Walter et al., 2021

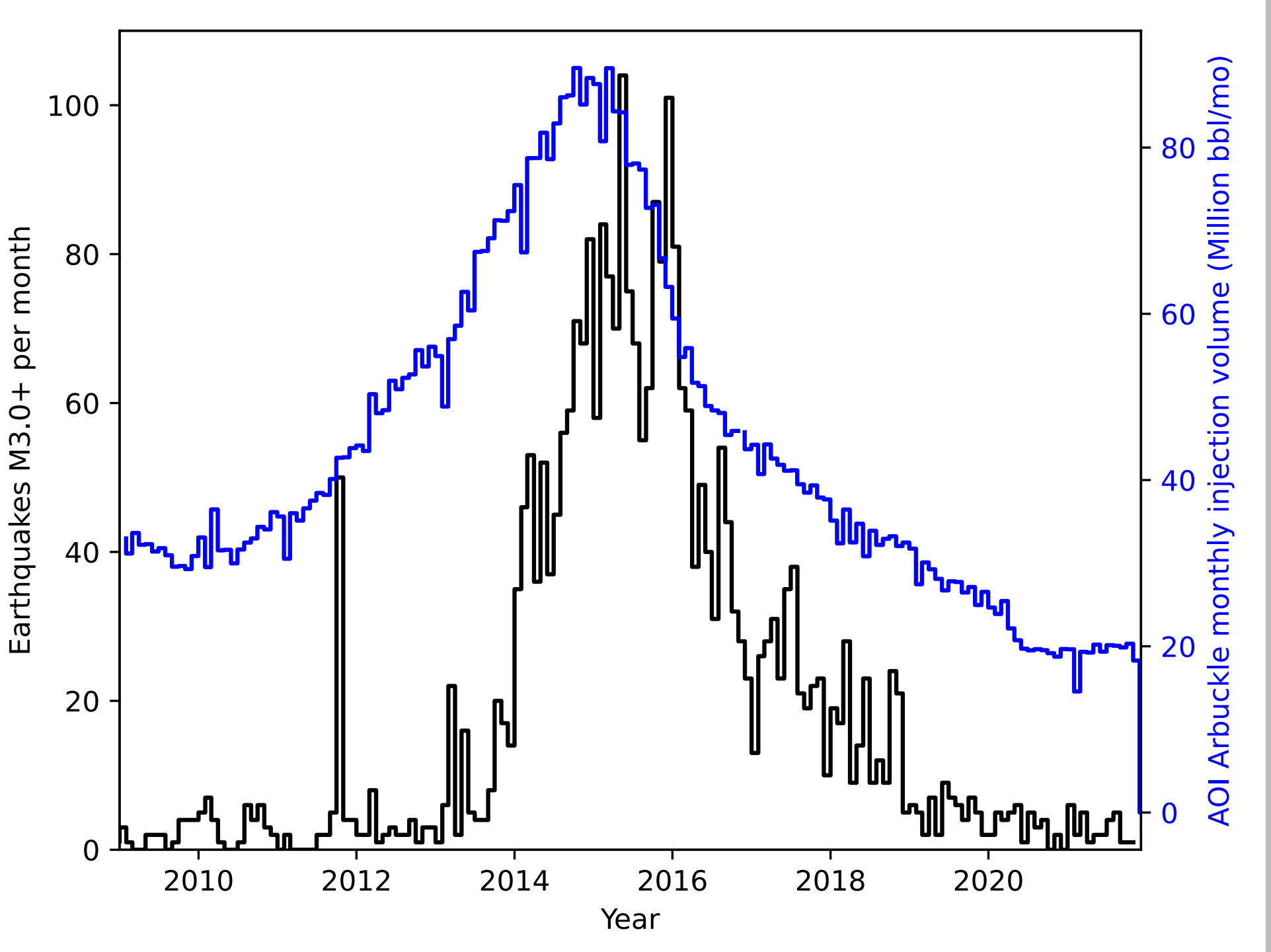






Arbuckle Group in Oklahoma

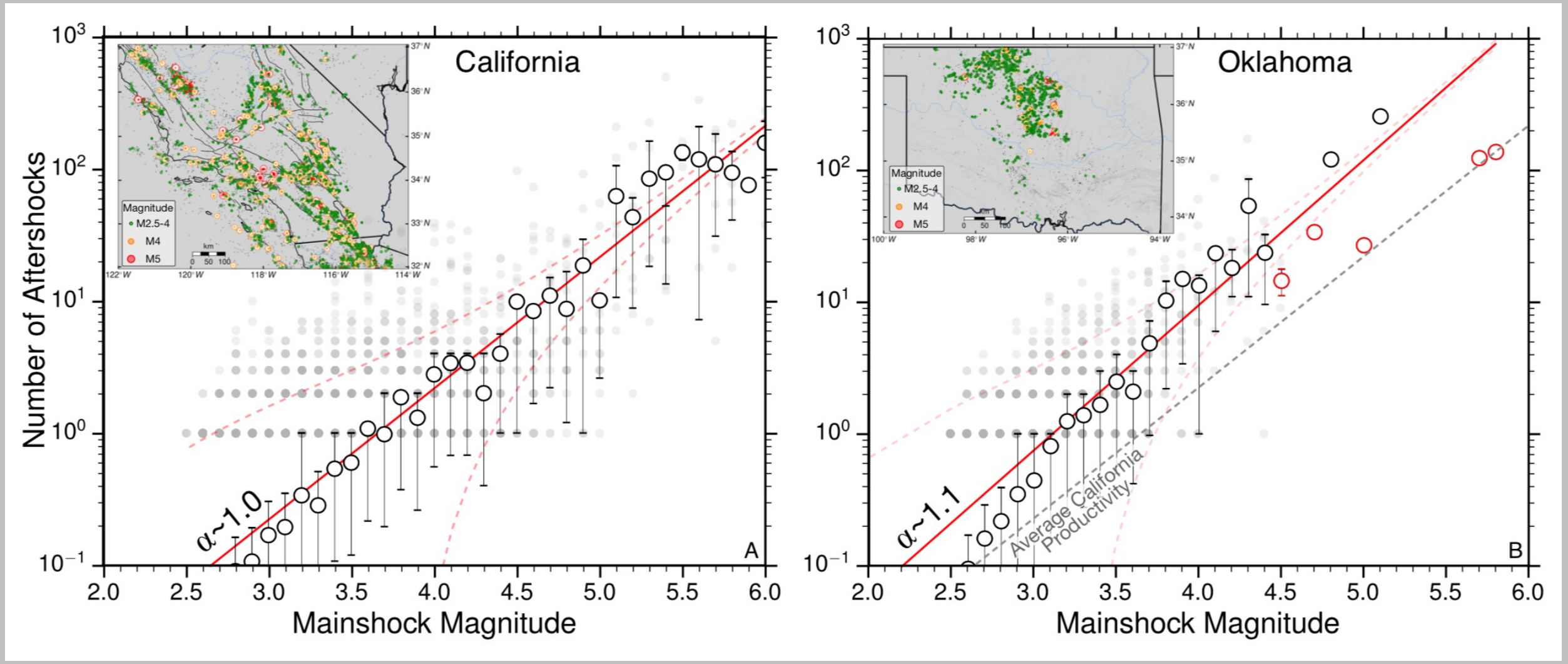
Rubinstein and Mahani, 2015



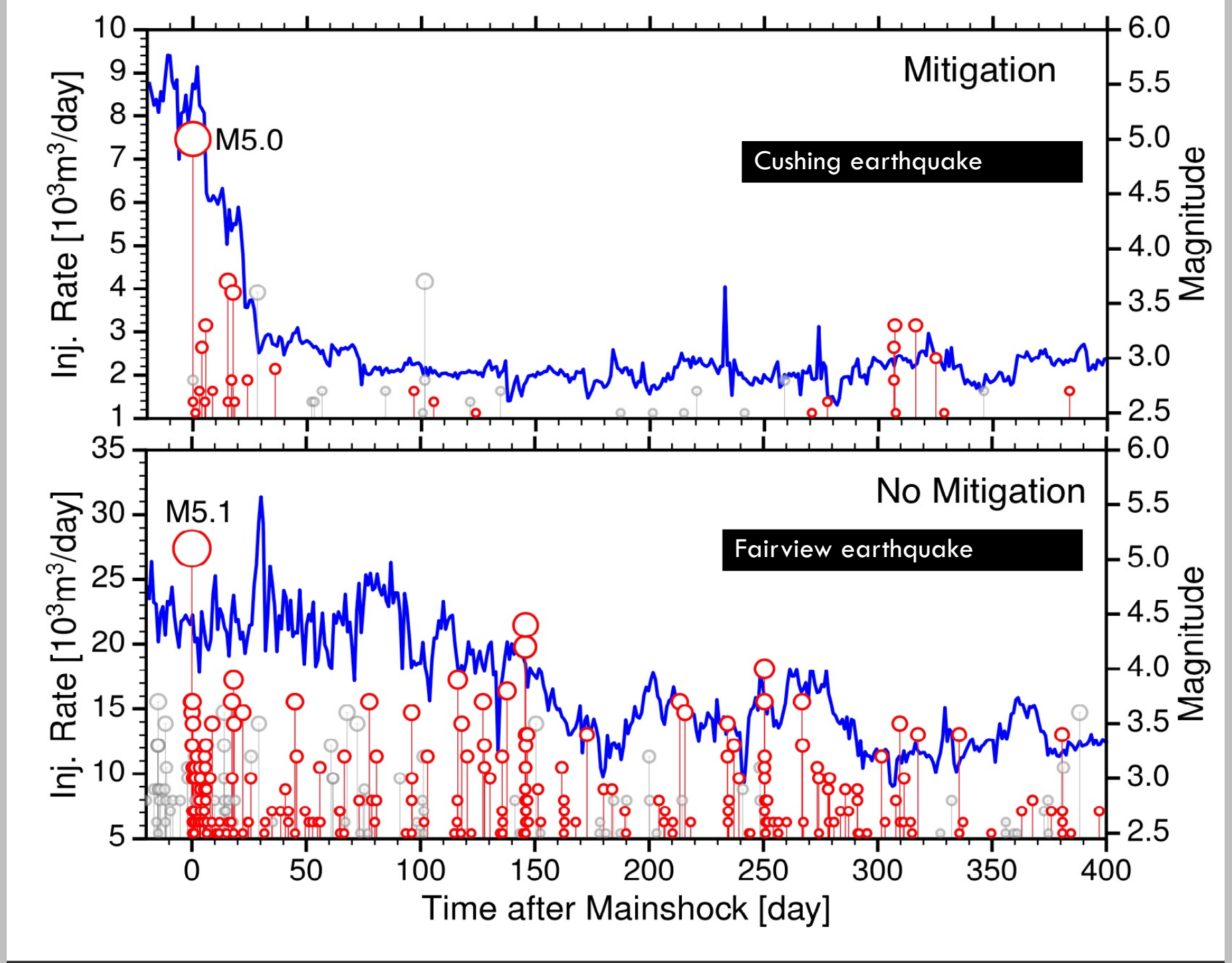
Walter et al., 2020

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


OKLAHOMA EARTHQUAKES
OCC: SHUTTING DOWN WELLS, REDUCING VOLUME
THE LATEST
FOX 23 NEWS
5:01
62°



Goebel et al., 2019


Mitigation
M5.0
Cushing earthquake
No Mitigation
M5.1
Fairview earthquake
Inj. Rate [10³m³/day]
Magnitude
Time after Mainshock [day]
0
50
100
150
200
250
300
350
400

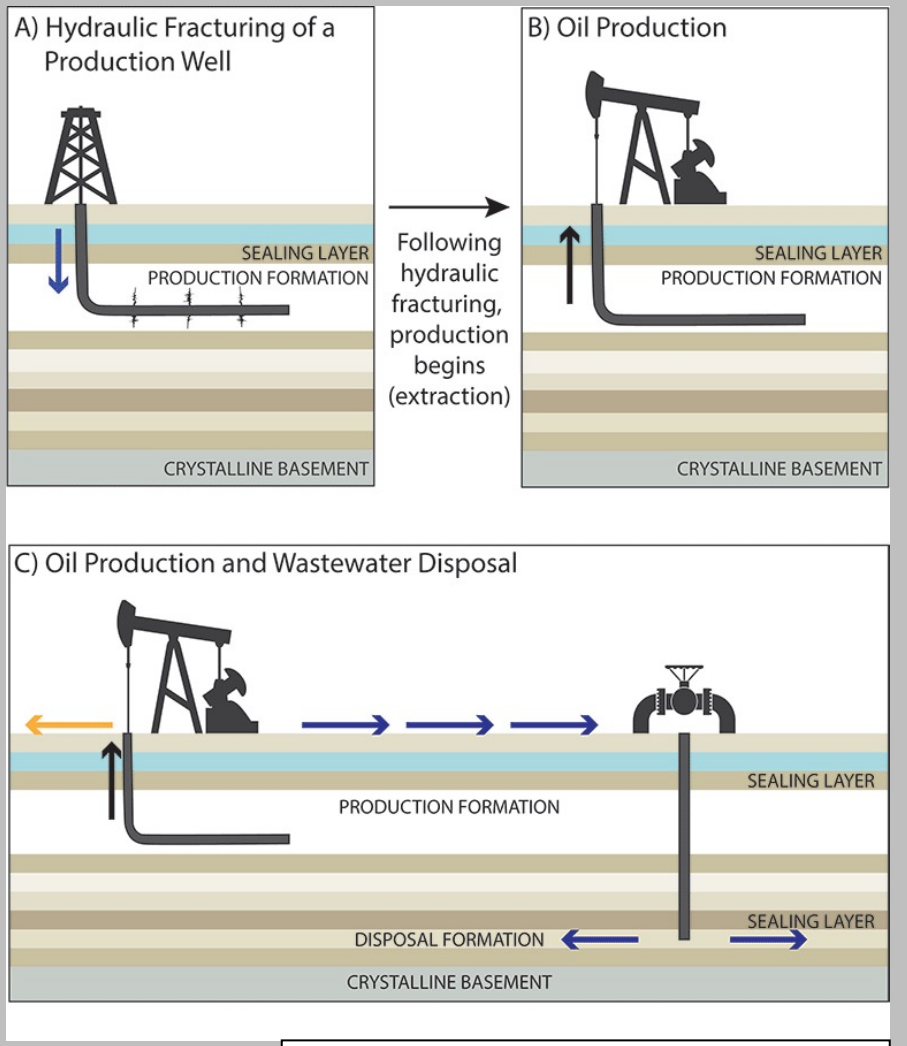
Lessons from mitigating wastewater disposal seismicity

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)

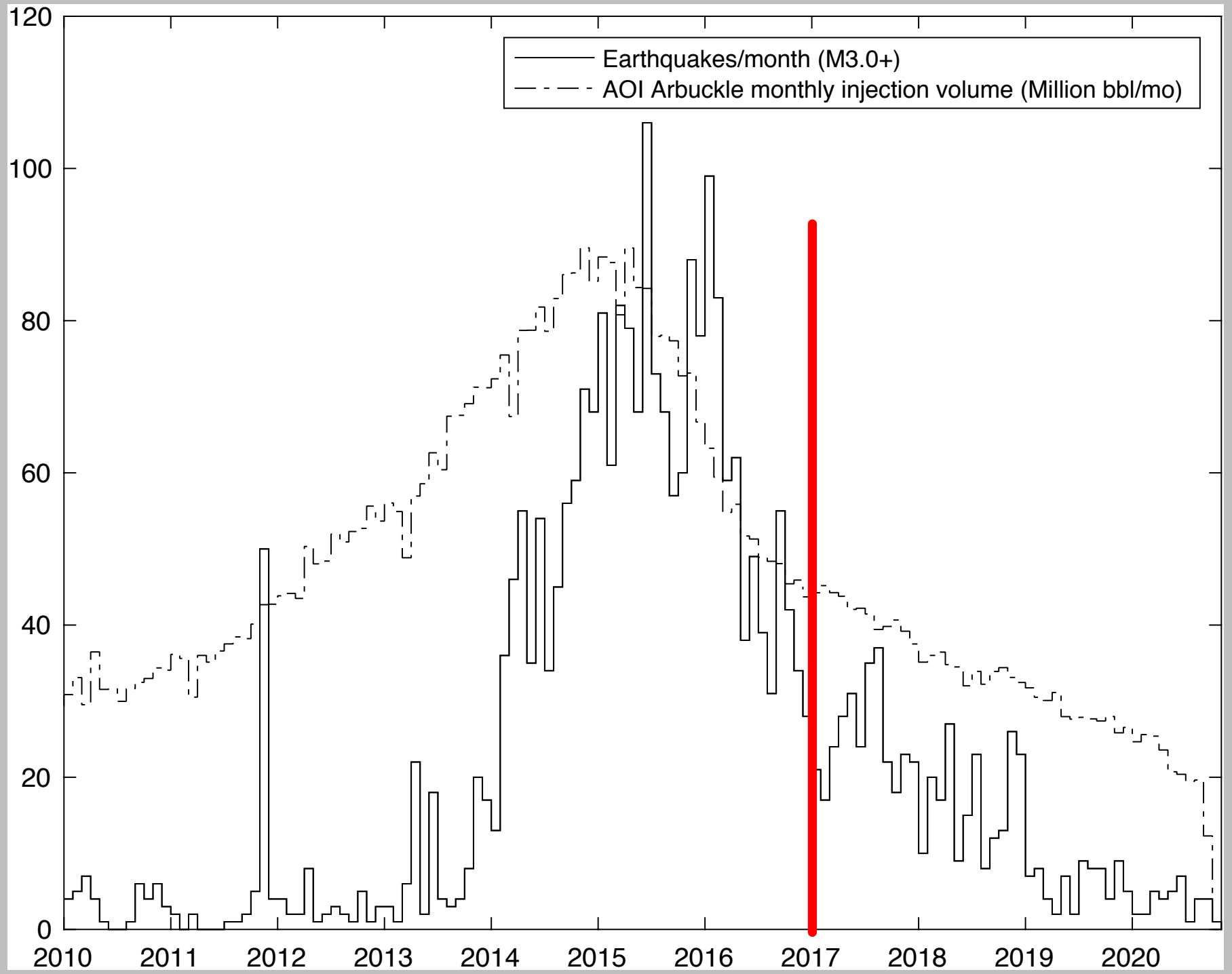
Long-term regional reduction in wastewater disposal in Arbuckle driven by market and regulatory factors



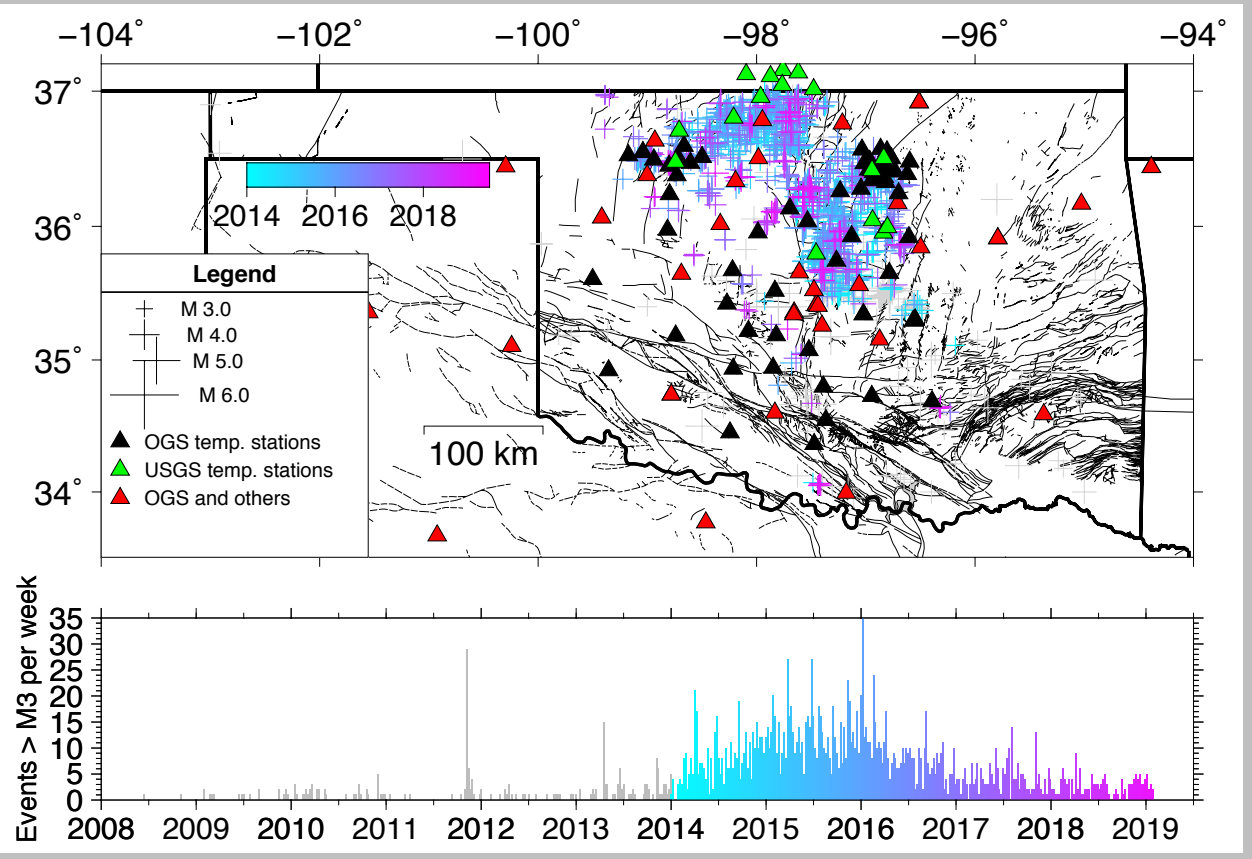
Rubinstein and Mahani, 2015

Holland, 2013 – HF triggered seismicity in S Oklahoma

Skoumal et al., 2018 – results from this paper were available in 2016 suggesting HF triggered seismicity common across wide swath of SCOOP/STACK

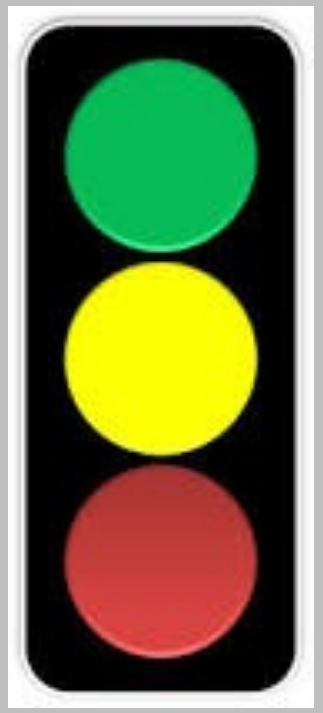


Oklahoma Geological Survey



Oklahoma Corporation Commission

Oklahoma Corporation Commission Protocol for earthquakes associated with well completions, as tracked by their FracNotice (issued Dec 20, 2016, since updated)



SUMMARY OF WELL COMPLETION SEISMICITY GUIDANCE

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

M2.0

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.**

M2.5

- **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.**

M3.0

- **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.**

Data caveats for OGS analysis for HF association

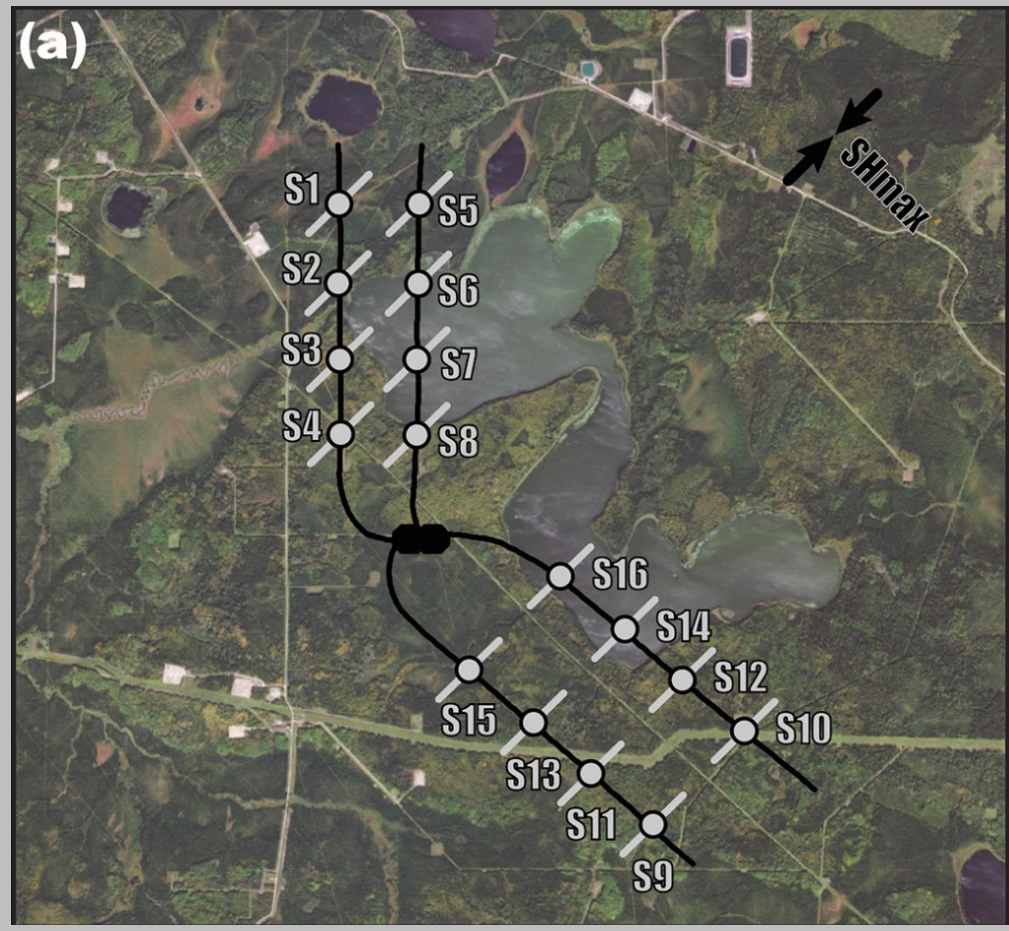
OCC FracNotice (since Dec 2016) began requiring operators to provide at least 48 hours notice of HF completion and intended duration, # of stages, volumes

OCC uses OGS real-time catalog to determine their own spatial/temporal association according to the directive

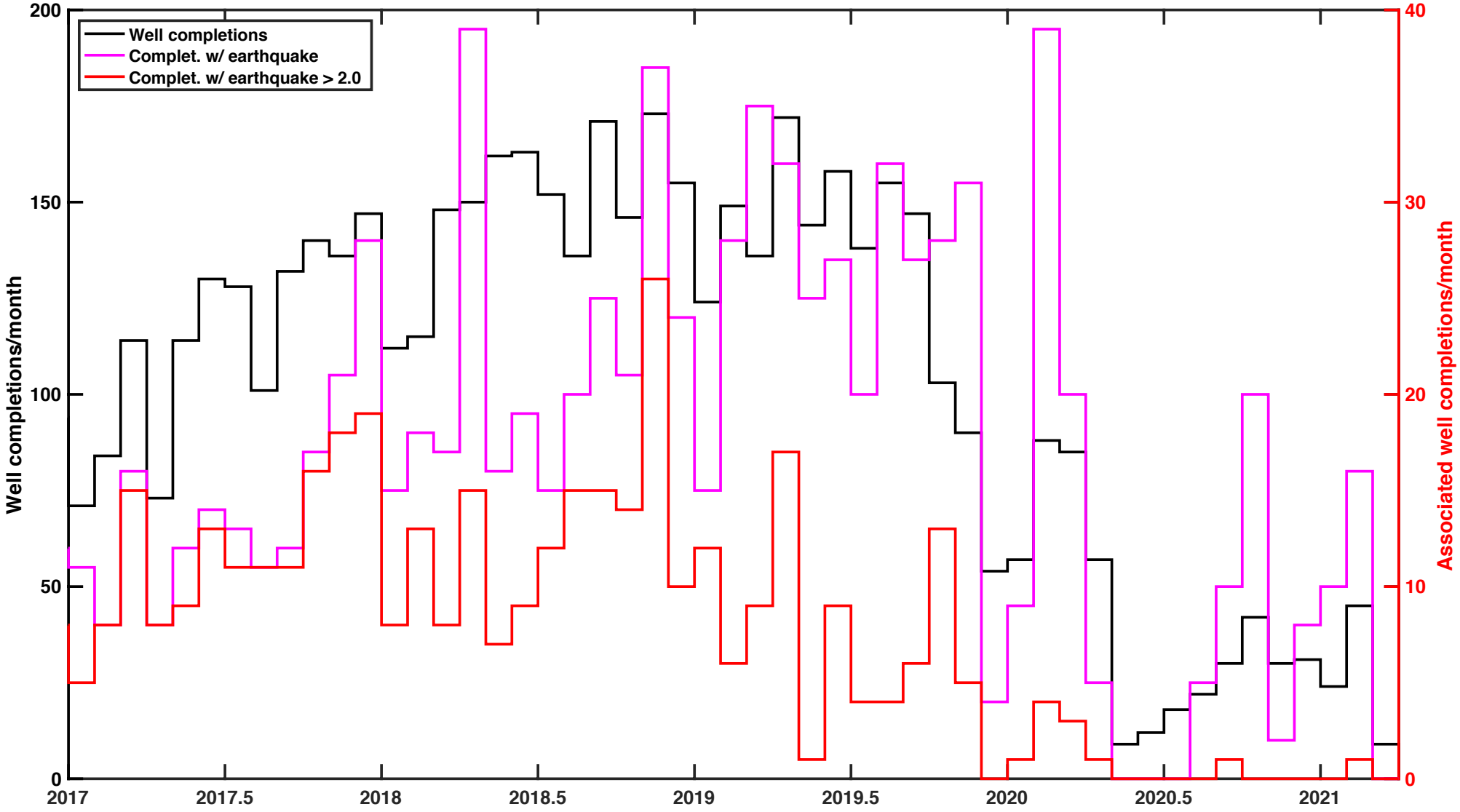
OGS expanded the network into western and southwestern Oklahoma in late 2016/early 2017

OGS participates in technical conferences with OCC on occasion or investigates specific case studies

OGS does not have access to real-time denser private networks in the area



Schultz et al., 2020

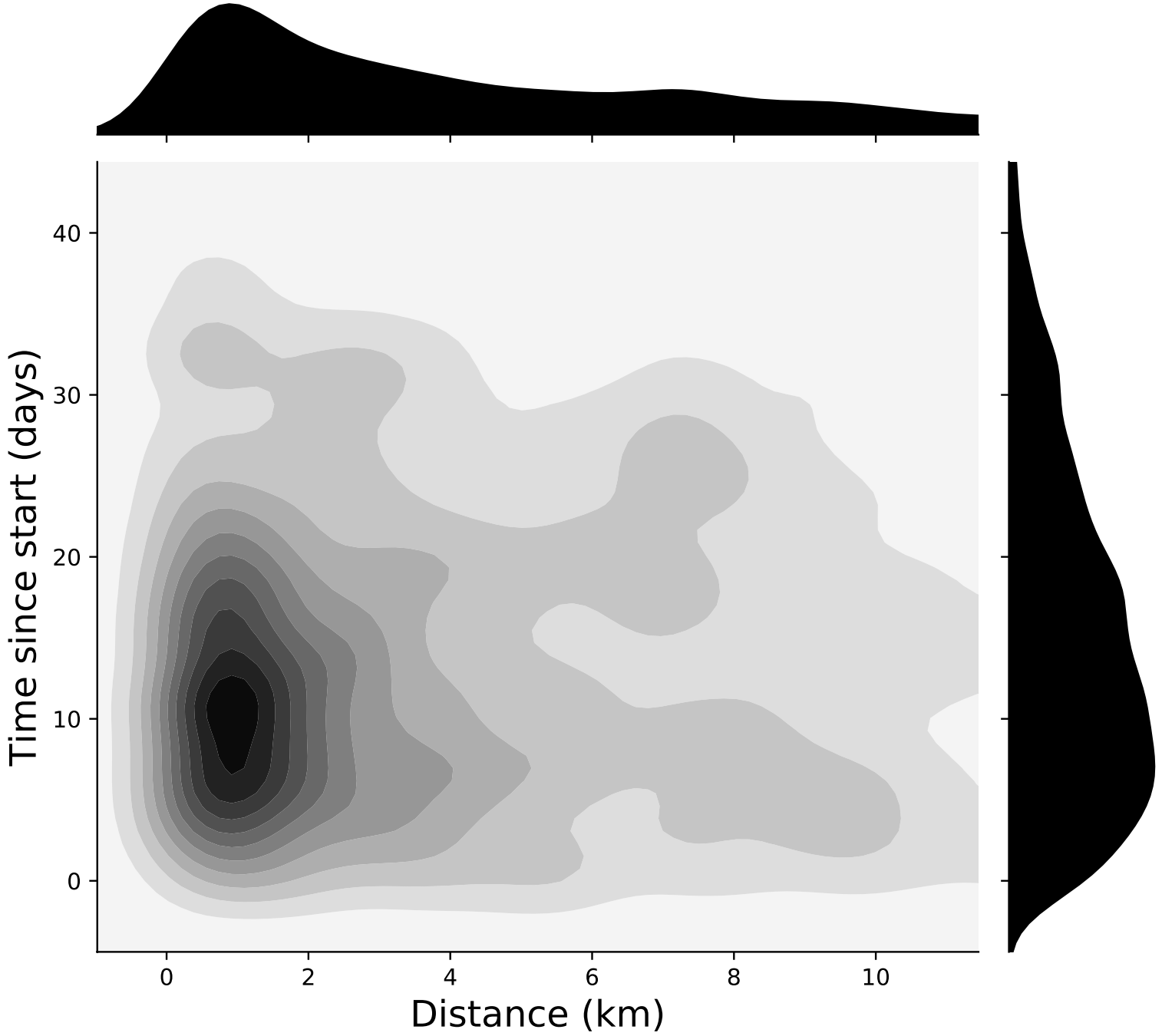


Black
HF wells

Pink line
All quakes

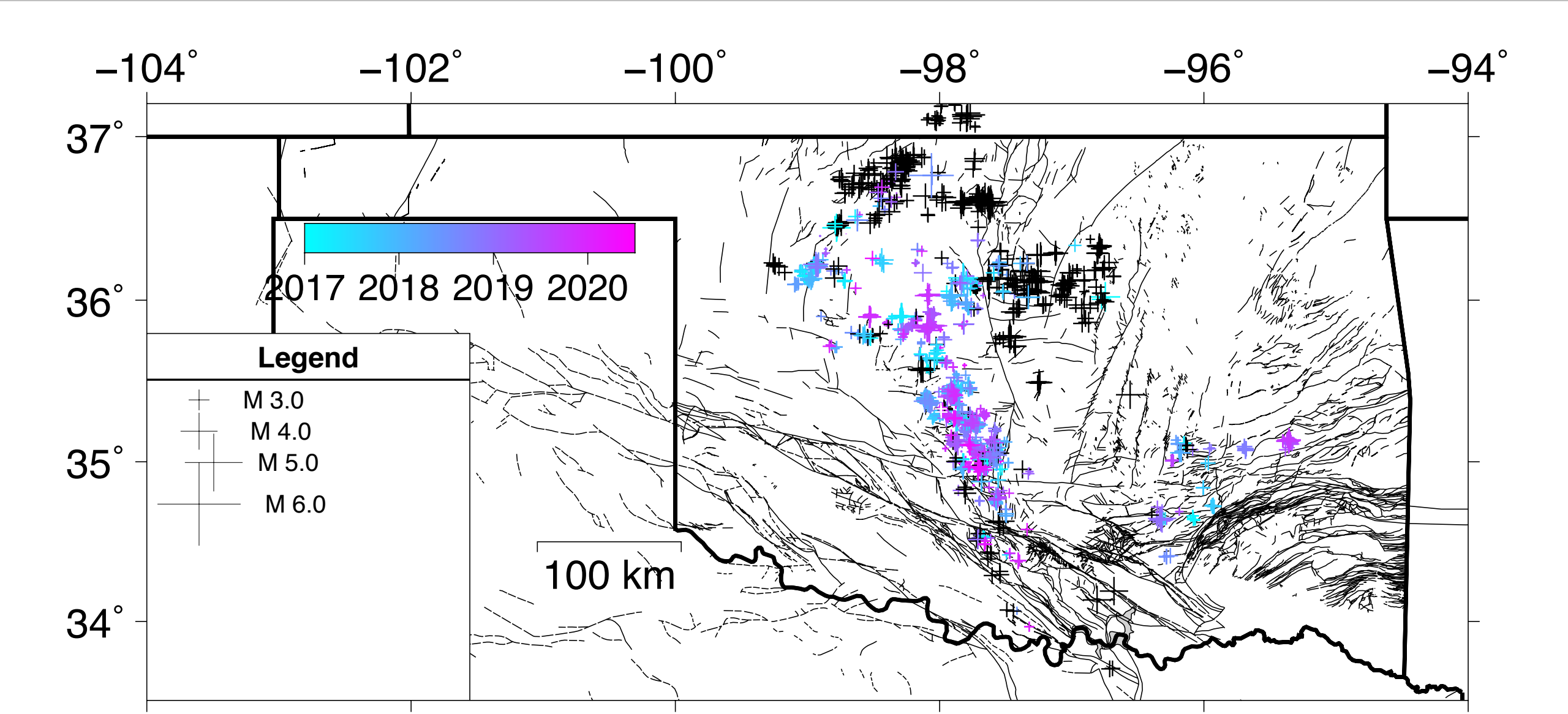
Red line
M2.0+

Monthly HF and HF-associated activity

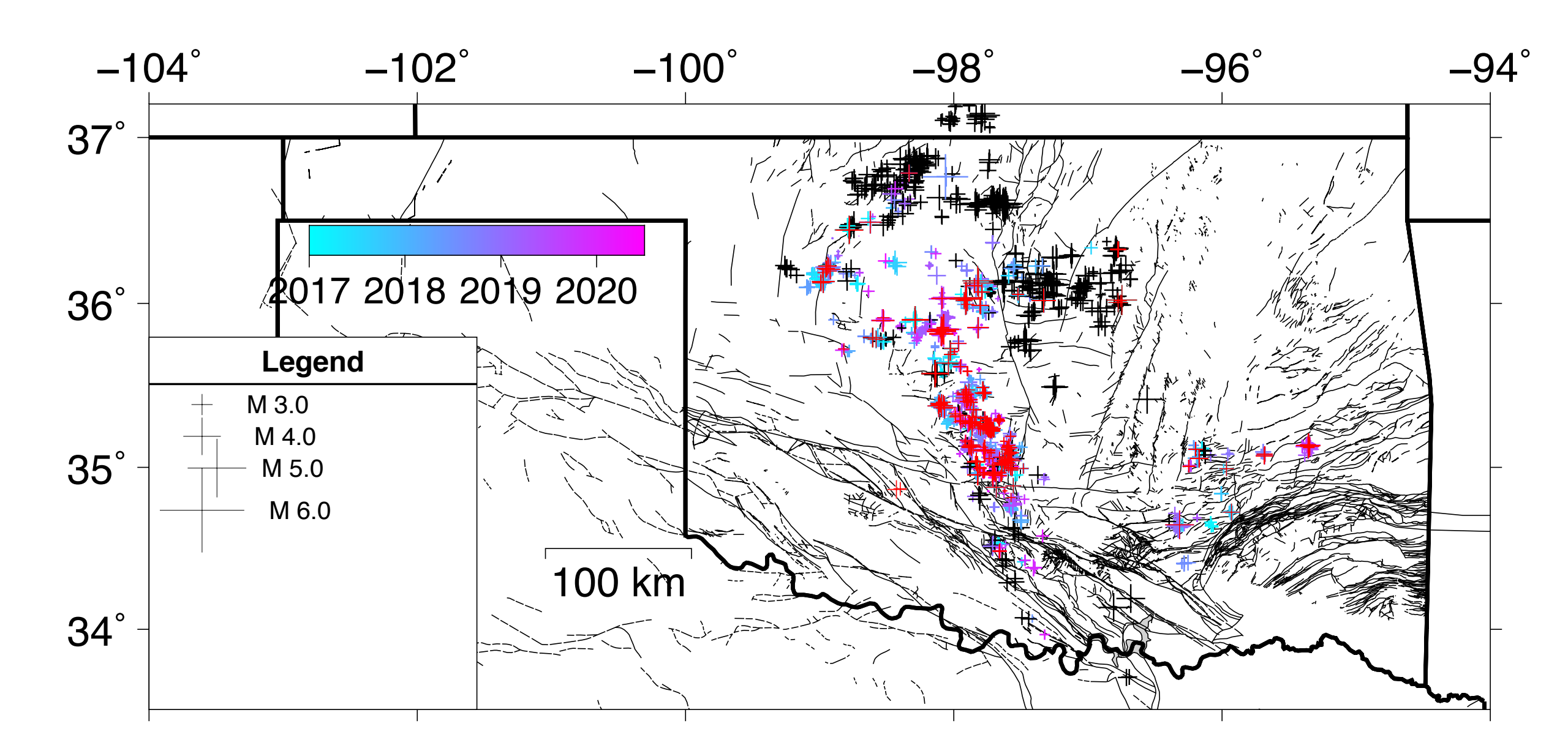


Time and radial distance of seismicity during HF with 20 day buffer afterwards

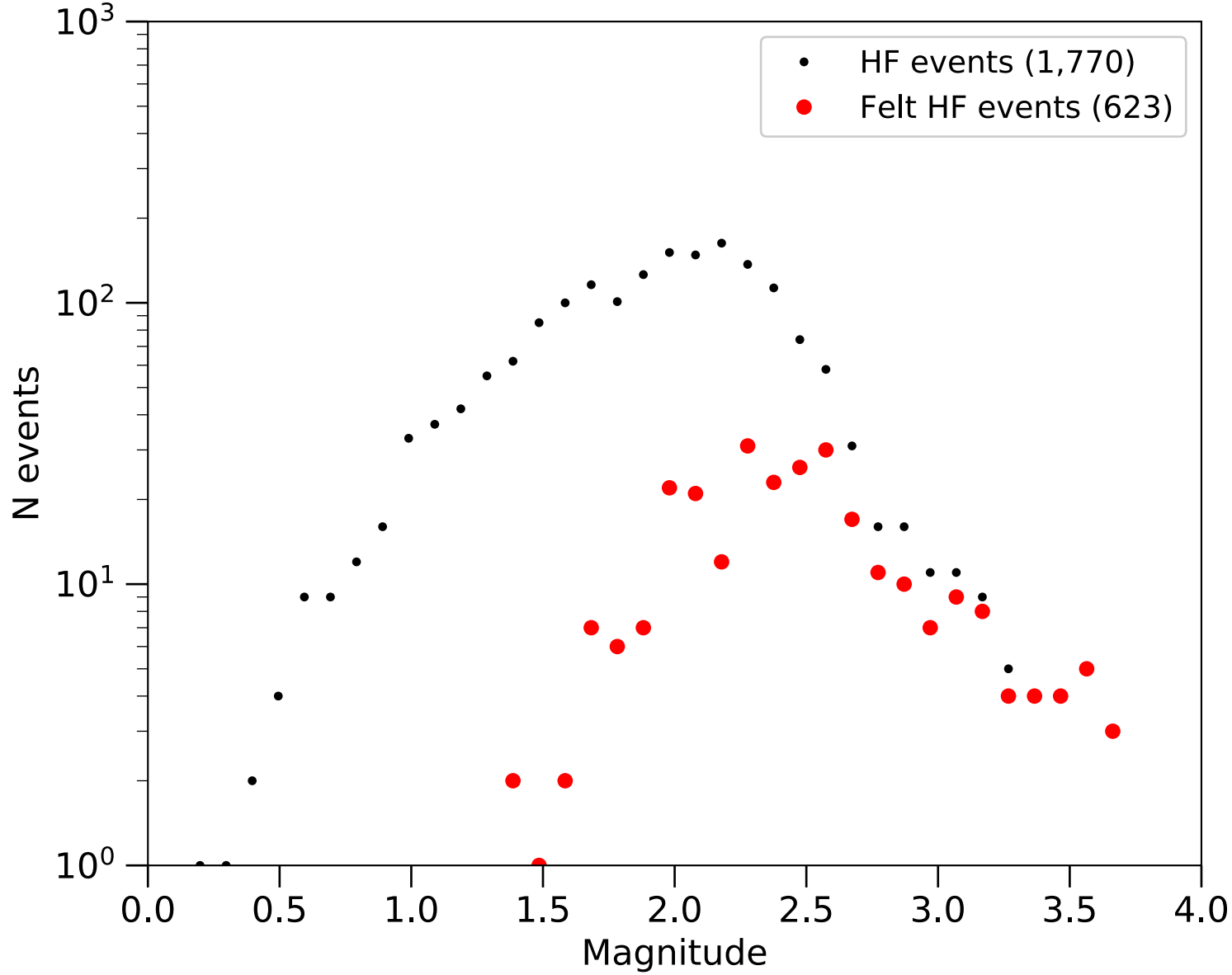
4 km and 20 days is a conservative estimate

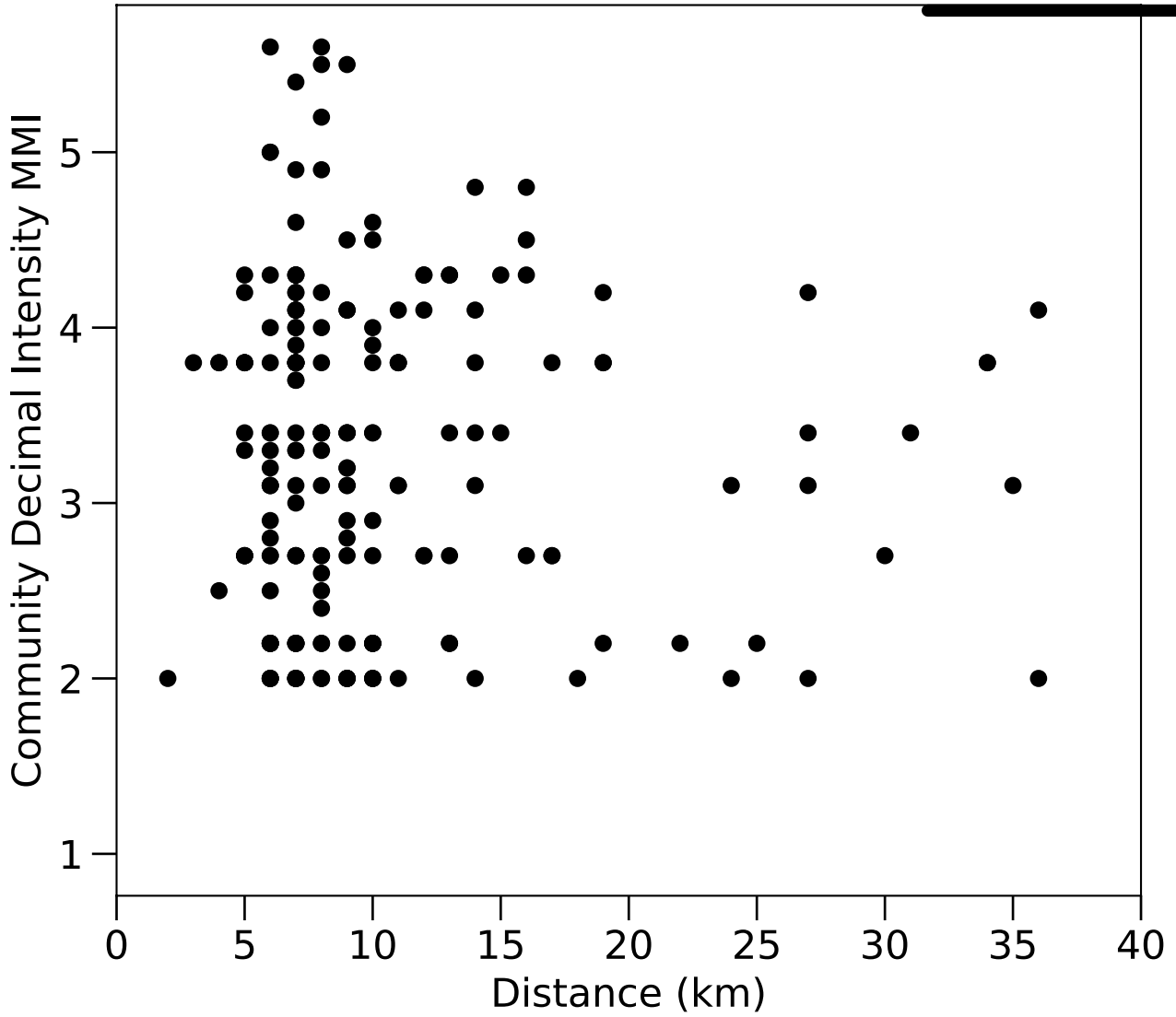


HF-associated activity

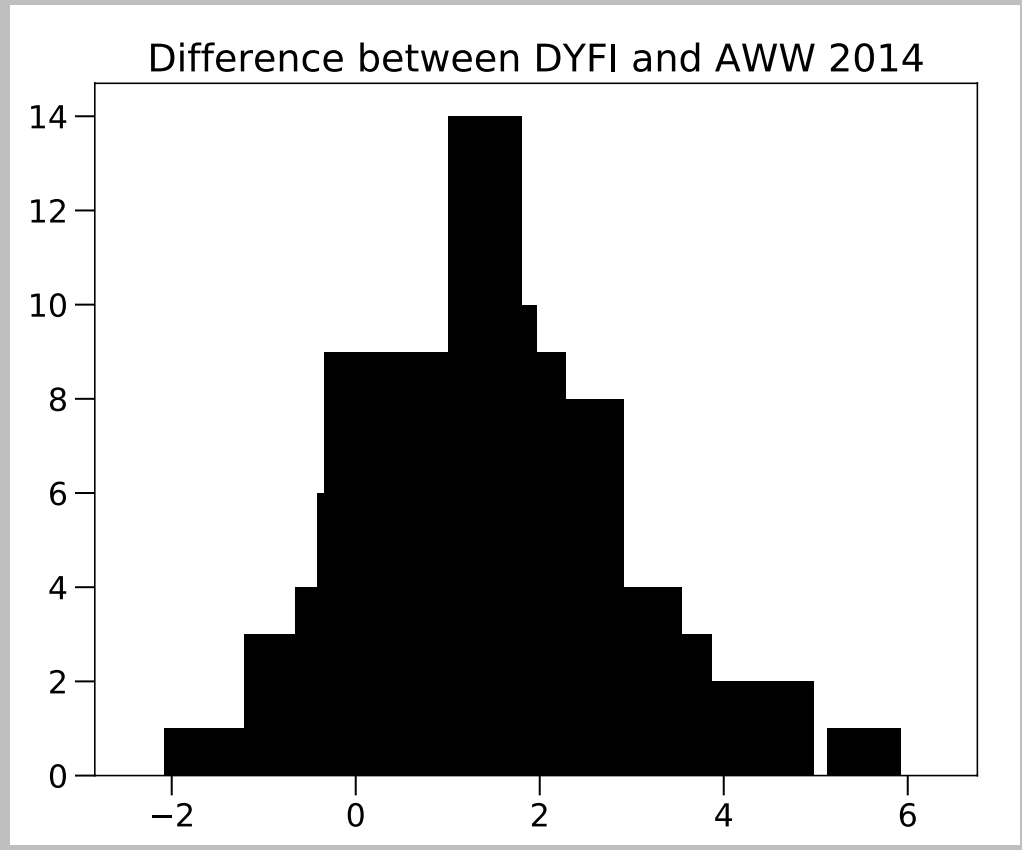


HF-associated activity (red DYFI or “felt” events)


HF events (1,770)
Felt HF events (623)
N events
Magnitude
10^3
10^2
10^1
10^0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0



Light damage threshold



Simple spatio-temporal association at 4 km and 20 days in time

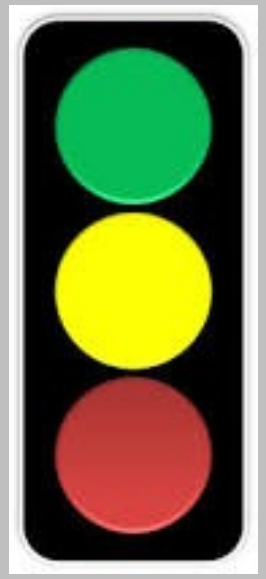
Out of 5,404 completions since Oct 2016:

515 fracs or about 9% associated with earthquake of any size

194 fracs were associated with a felt event (from DYFI) or about 4%

Largest earthquake(s) M3.6

Interesting anecdotes: Potential damage from a M3.2 HF-triggered earthquake and felt reports from M1.8 earthquakes



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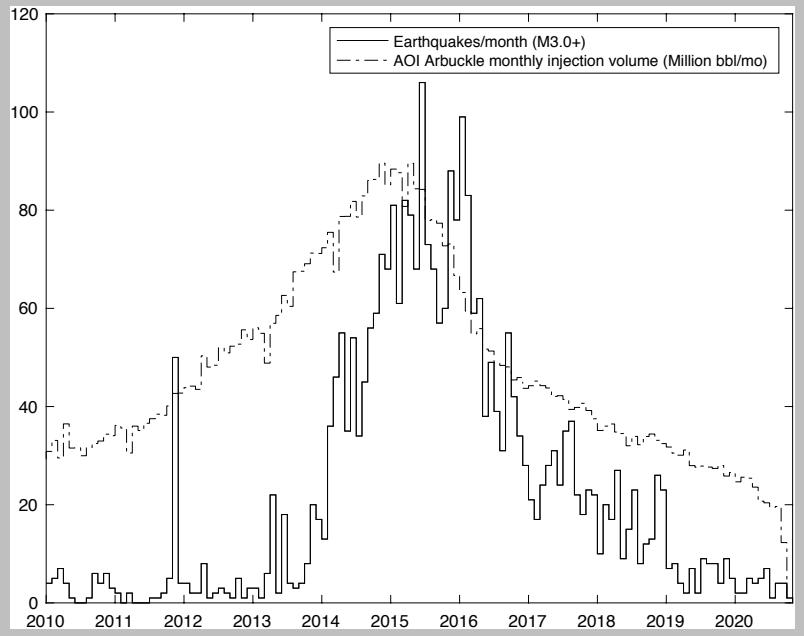
Hydraulic fracturing – injection occurs over days, mitigation on hours



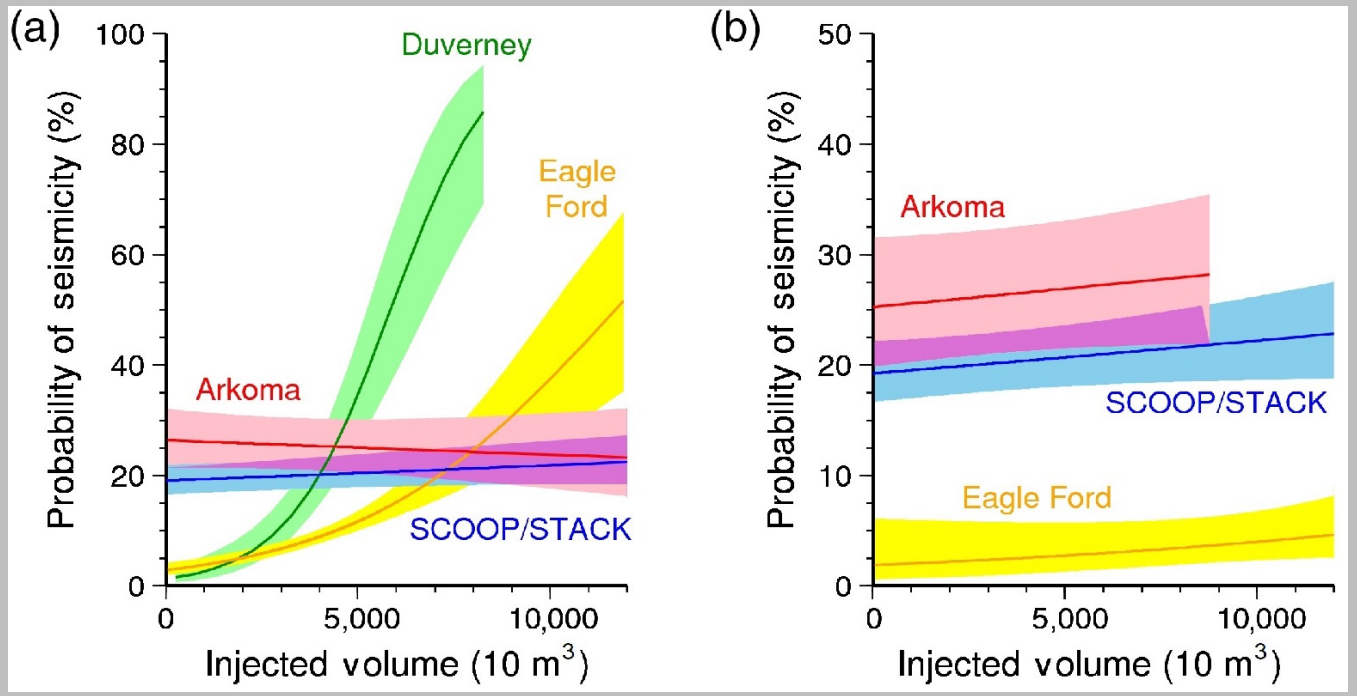
Wastewater injection - injection for several years, mitigation for several years?

Rapid mitigation appears to successfully reduce aftershock productivity

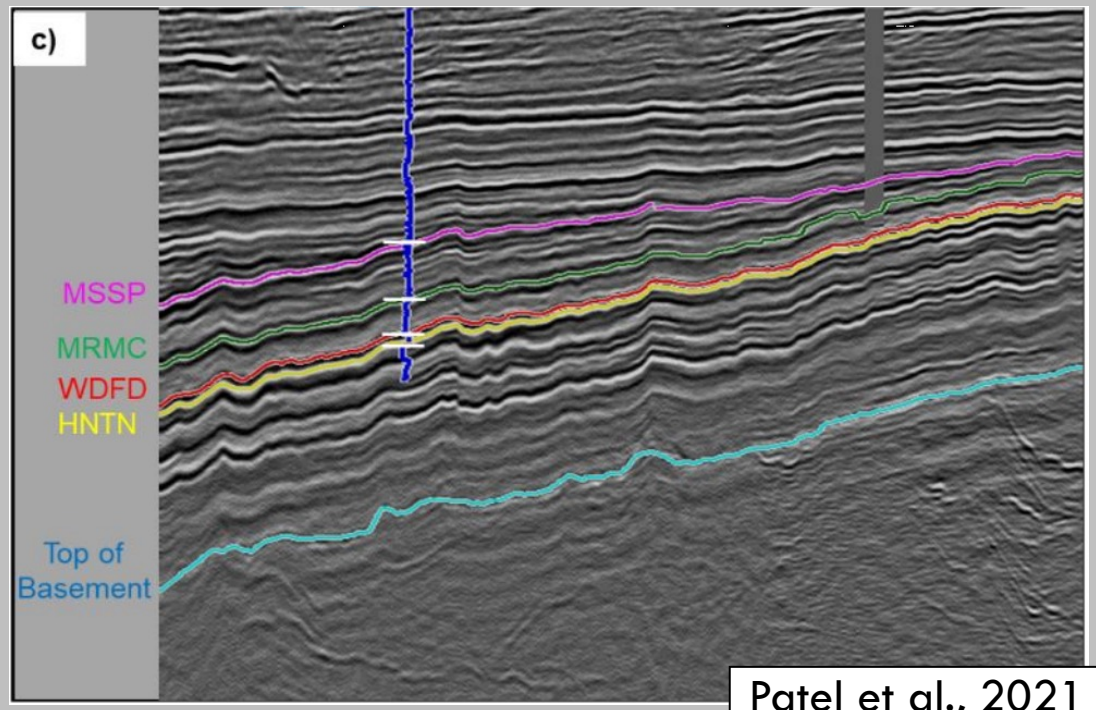
Causal factors?

No strong dependence upon volume

Geology?



Ries et al., 2020



Patel et al., 2021

Swetal Patel's recently published work from 3D seismic attributes suggests basement structures extend into the sedimentary column

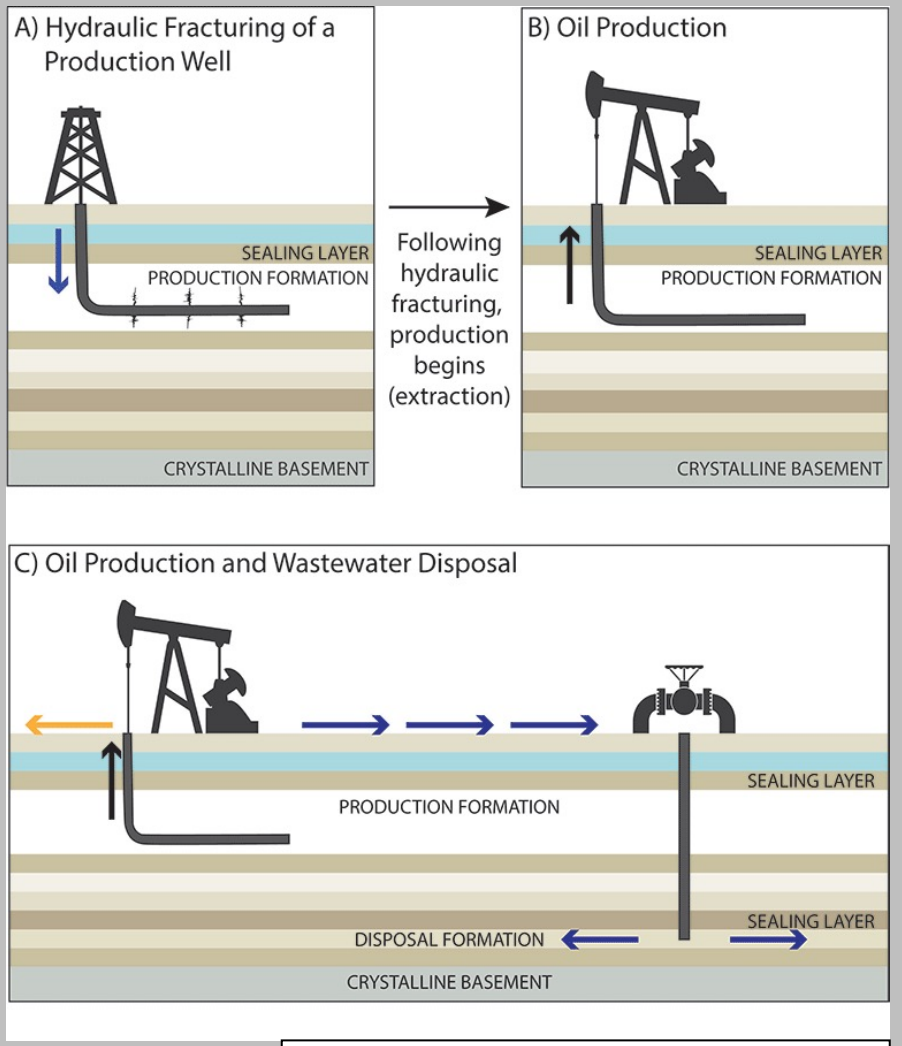
Lessons ~~from~~ for mitigating ~~wastewater disposal seismicity~~ hydraulic-fracture triggered seismicity

Volume - No clear dependence on volume (Ries et al., 2020)

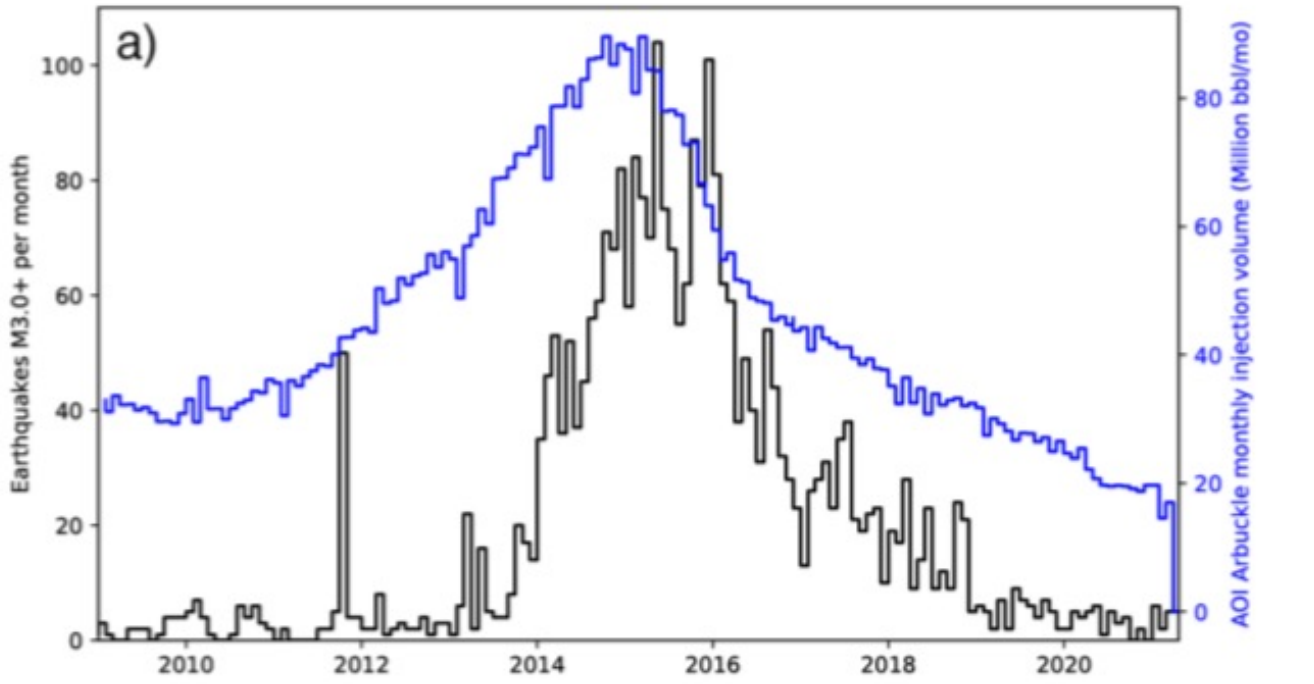
Geology and faults – Seismogenic structures visible in seismic attributes, though subtle (Patel et al., 2021)

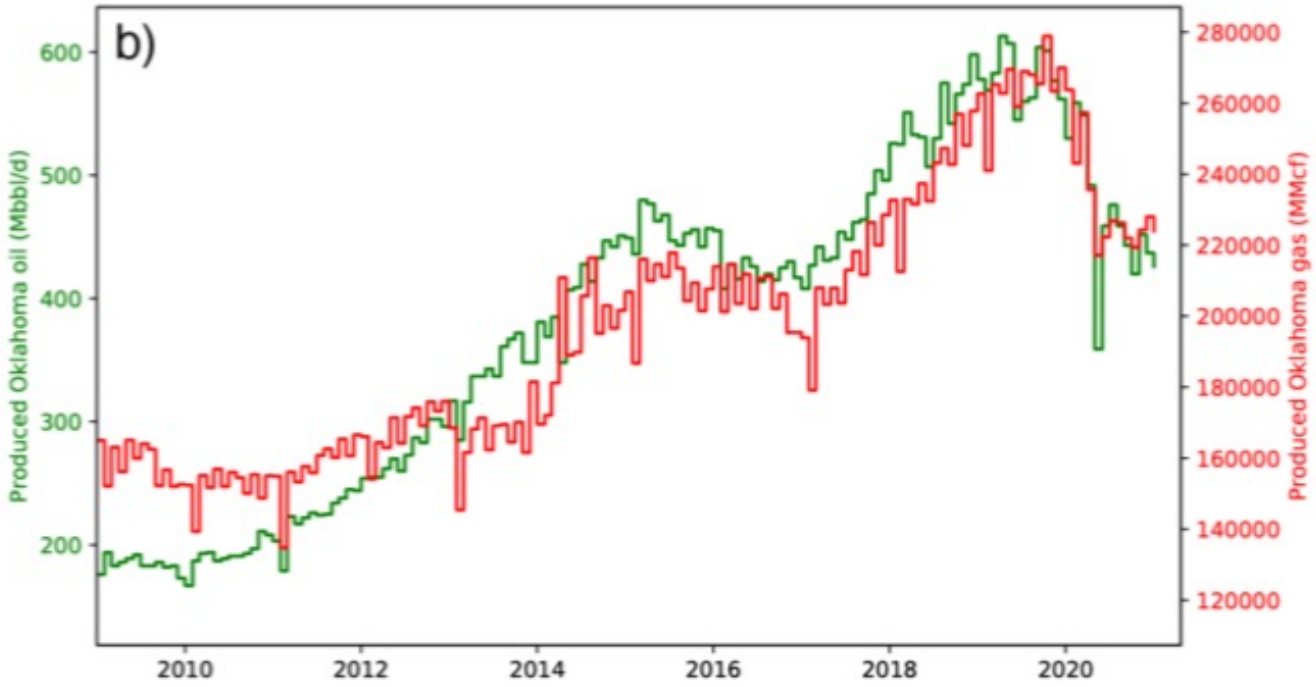
Rapid mitigation – traffic light pauses seem effective in reducing damaging events, operators report anecdotal success at implementing traffic light approaches set at 1 magnitude unit below the regulatory one

Safety conscious proactive approach seems to have led to Oklahoma increasing production of both oil and gas relative to 2014/2015 production levels, without the accompanying damaging earthquakes during that past time period



Rubinstein and Mahani, 2015





Large earthquakes are rare, but have incurred ~$10 million damage total (claims paid in Oklahoma), likely an underestimate of actual damage

($74 million in gross production taxes collected in September 2019)

OGS Fact Sheet No. 1
Geological Carbon Management in Oklahoma

The Oklahoma Geological Survey
November, 2021

- Requests for more insight into Carbon Capture in Oklahoma. OGS produced this fact sheet starting a new series (though there have been previous OGS fact sheets);
- Envisaged CO_2 trapping in regard to the storage estimates for OK geology;
- Primer on some of the jargon
- Available for download now: **ogs.ou.edu**

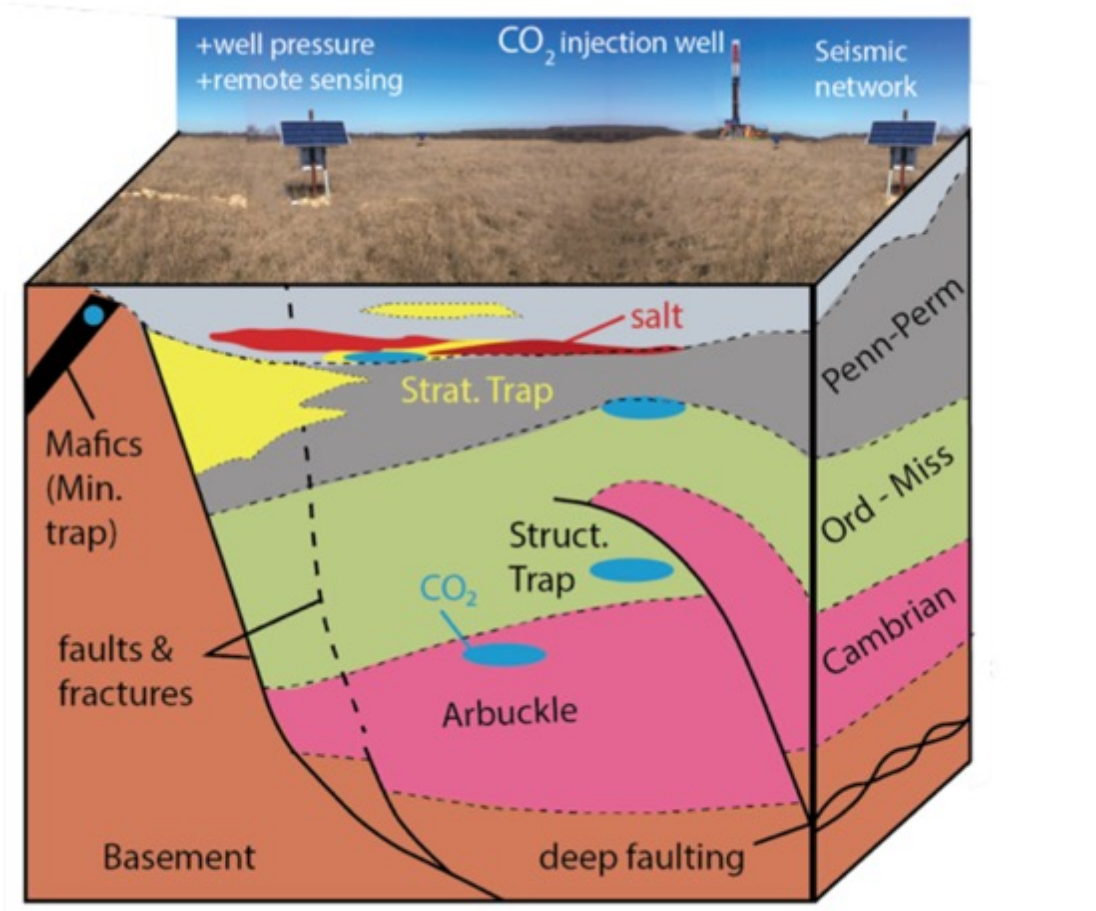
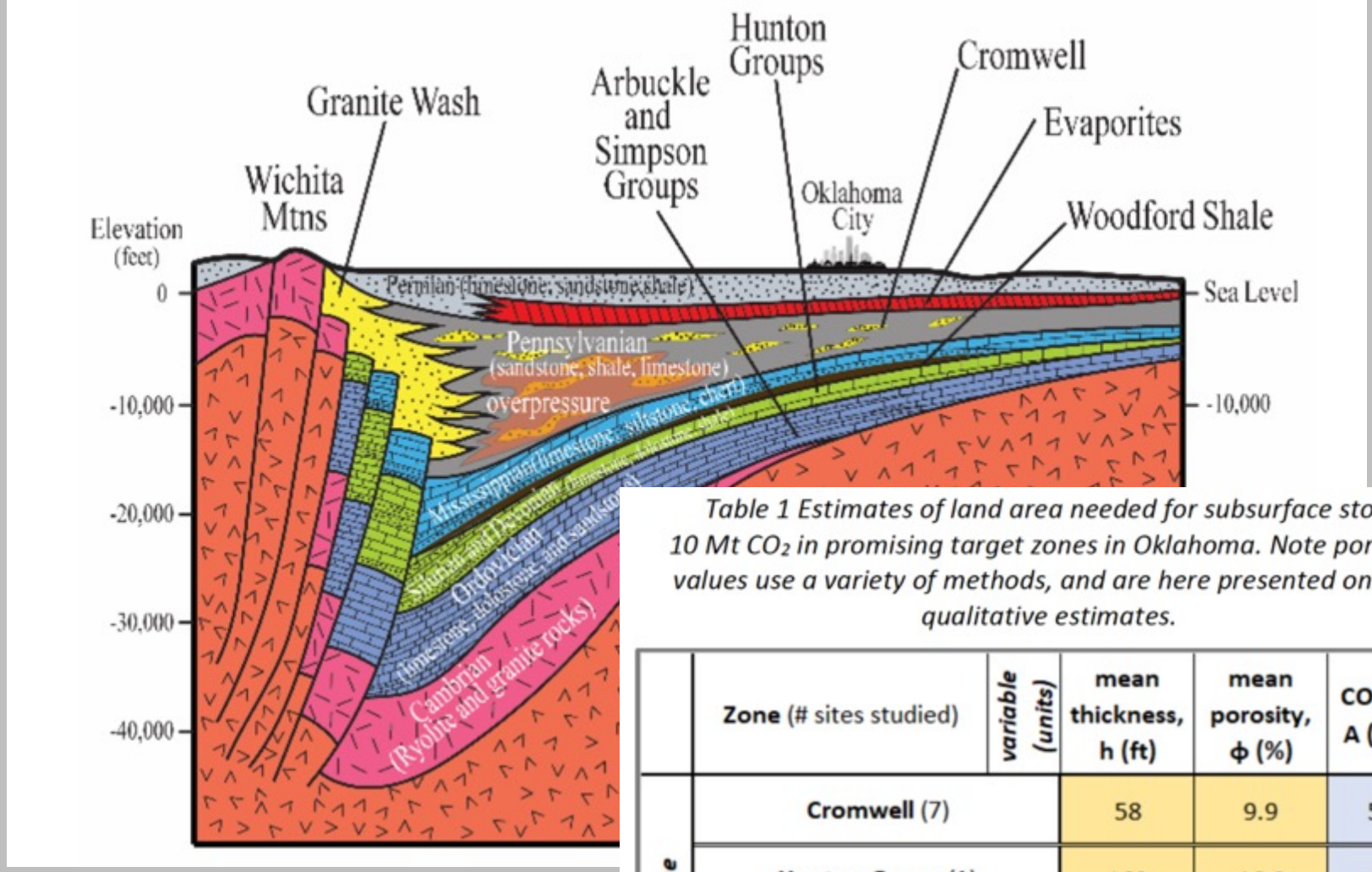


Figure 1. Schematic of carbon management targets in Oklahoma.



Fact sheet quick estimate for 10 Mt storage areas for a few targets: Arbuckle continues to offer high storativity

Table 1 Estimates of land area needed for subsurface storage of 10 Mt CO_2 in promising target zones in Oklahoma. Note porosity values use a variety of methods, and are here presented only as qualitative estimates.

	Zone (# sites studied)	variable (units)	mean thickness, h (ft)	mean porosity, ϕ (%)	CO_2 area, A (acres)
Geological Zone	**Cromwell** (7)		58	9.9	5491
	Hunton Group (1)		160	16.0	1230
	Simpson Group (7)		147	10.7	2002
	Arbuckle (2)		432	7.1	1026
	Mafic or Precambrian (2)		1080	3.0	972
	mean value from OGS geological studies				
	calculated footprint required for storage of 10 Mt CO_2				

Heterogeneous state geology with numerous EOR-CCUS opportunities, as well as large CCS opportunities

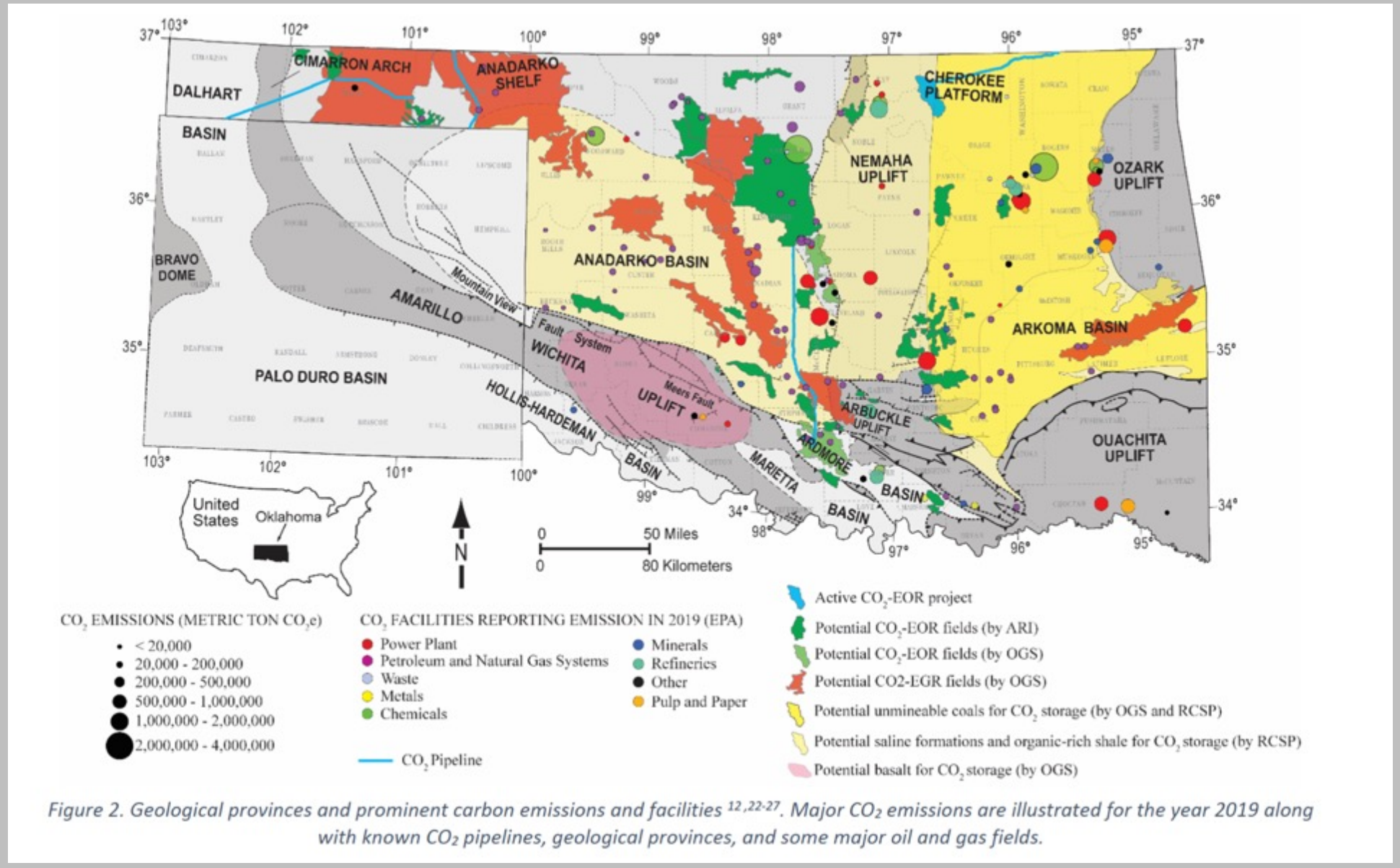
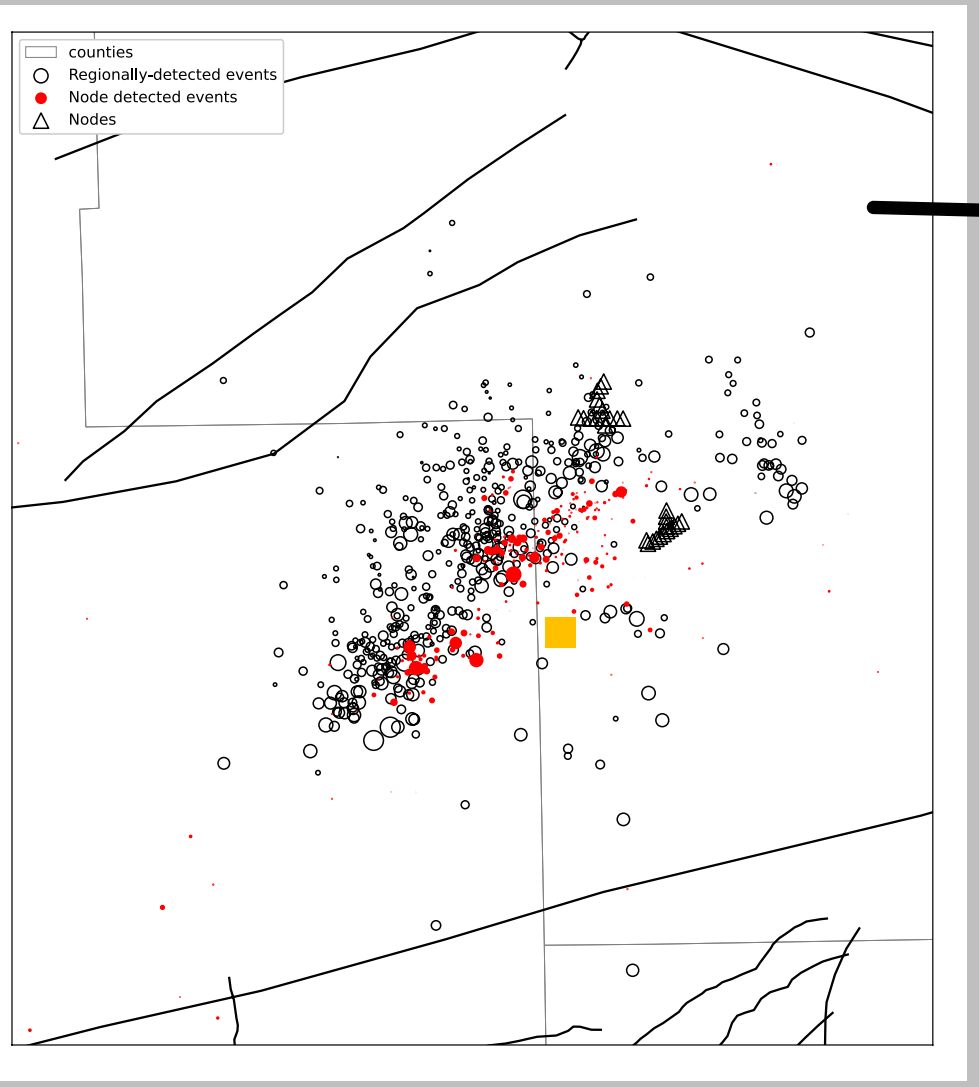
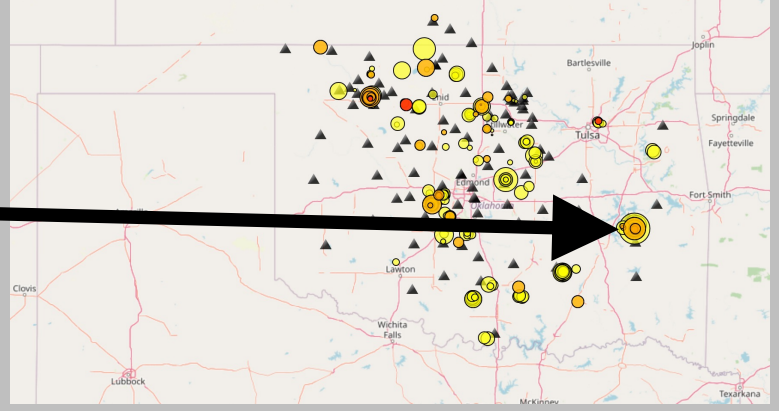
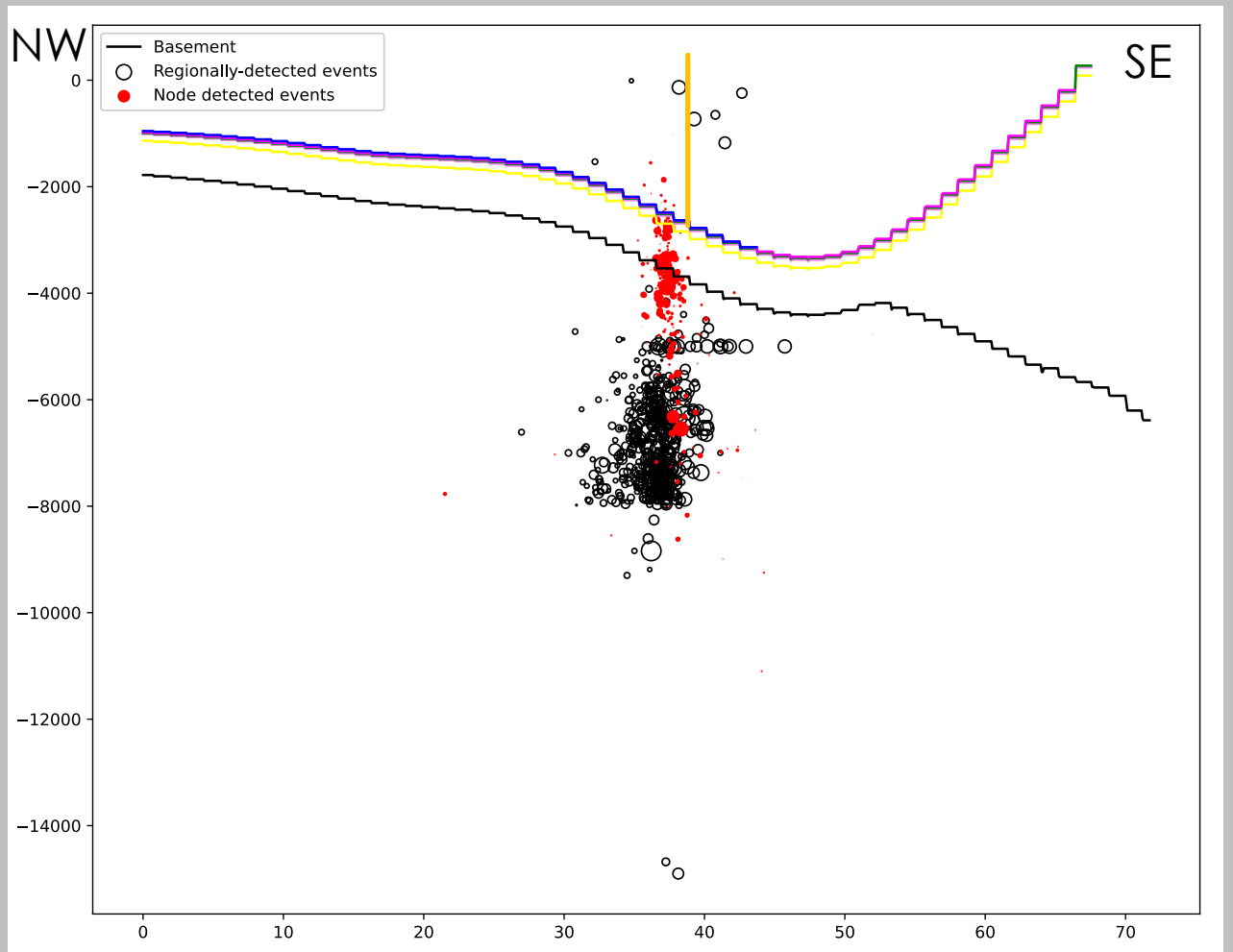


Figure 2. Geological provinces and prominent carbon emissions and facilities [12,22-27]. Major CO_2 emissions are illustrated for the year 2019 along with known CO_2 pipelines, geological provinces, and some major oil and gas fields.







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

- M3.7 in 2019 led to brief shut-in of disposal well and ~1,000 OGS-detected earthquakes since then
- During node deployment we detected 500+ earthquakes, while real-time network detected 89

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

Volume – Probably dependent upon over long-term operation and large volumes

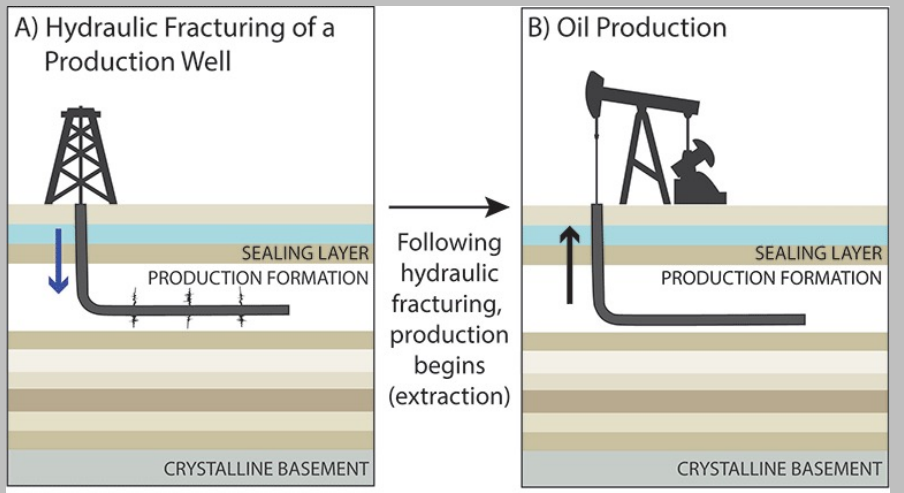
Geology and faults – planning operations to avoid large faults that are oriented for slip; FSP is not effective for planning purposes during permitting

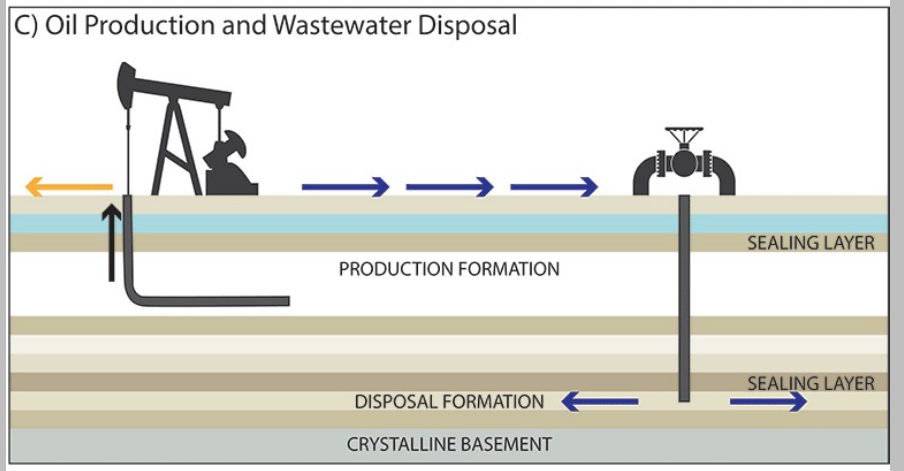
Rapid mitigation – traffic light pauses or disposal shut-in may be effective on hours to days timescales

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

Additional thoughts? – jwalter@ou.edu





Rubinstein and Mahani, 2015