Regional Induced Seismicity Collaborative (RISC) Workshop

Induced Seismicity: What has changed and what is important for decision making?

RISC Members
Lily Horne – TX Bureau of Economic Geology
Rex Buchanan – KS Geological Survey
Paul Ogwari – OK Geological Survey
Mairi Litherland – NM Bureau of Geology and Mineral Resources
Scott Ausbrooks – AR Geological Survey

Regulatory Community
Paul Dubois – TX Railroad Commission
Jim Marlatt – OK Corp Commission

Groundwater Protection Council Annual Forum, Salt Lake City, UT

June 23, 2022 (3:30 – 5:00 pm MST)

RISC
Regional Induced Seismicity Collaborative

Regional Induced Seismicity Collaborative (RISC)

RISC was created 4 years ago to address a common problem in regional-scale geosciences: how can research groups at different institutions better collaborate to avoid data gaps and overlaps, and to improve communication of ideas and technical approaches?

Goals

- To better understand recent seismicity and the injection-related data that the states collect, synthesize, and make available to the public.
- To understand how data are used by regulators in their decisions related to SWD wells and how emergent seismogenic regions have impacted the decision-making process.
- To find commonalities and differences between approaches used to mitigate seismicity and risk.

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Paul Ogwari – OK Geological Survey
Mairi Litherland – NM Bureau of Geology and Mineral Resources
Martha Kopper – AR Geological Survey

Regulatory Community

Paul Dubois – TX Railroad Commission
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RISC Homepage: https://www.beg.utexas.edu/risc

RISC Member Activities: https://www.beg.utexas.edu/risc-research

RISC Workshops and Meetings: https://www.beg.utexas.edu/risc-workshops-meetings

We gratefully acknowledge funding for RISC from the U.S. Department of Energy, National Energy Technology Laboratory, through a contract with the Groundwater Protection Council.

Arkansas Geological Survey (AGS)

Technical lead – Martha Kopper, martha.kopper@arkansas.gov

Lead Principal Investigator – Scott Ausbrooks, scott.ausbrooks@arkansas.gov

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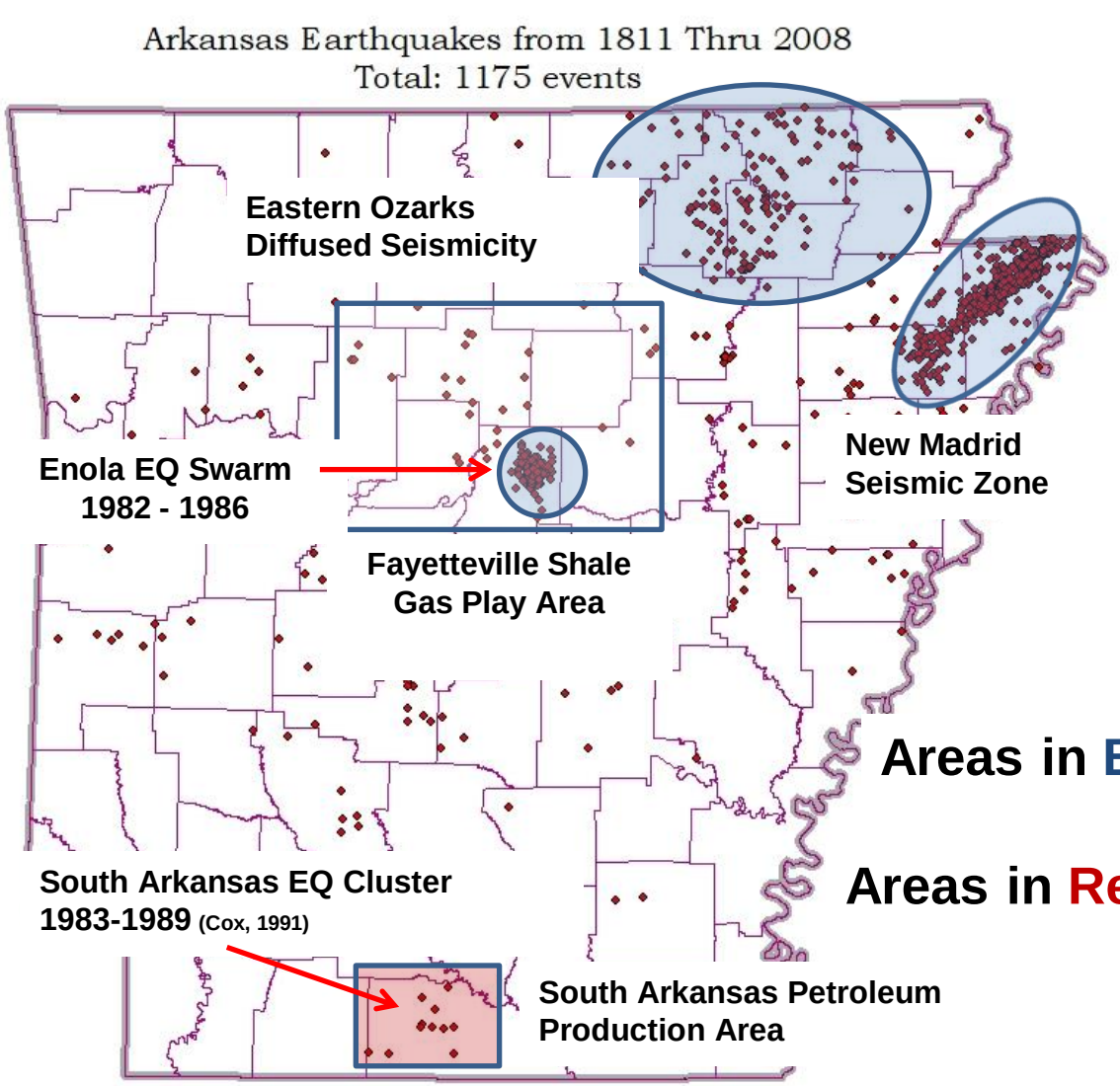
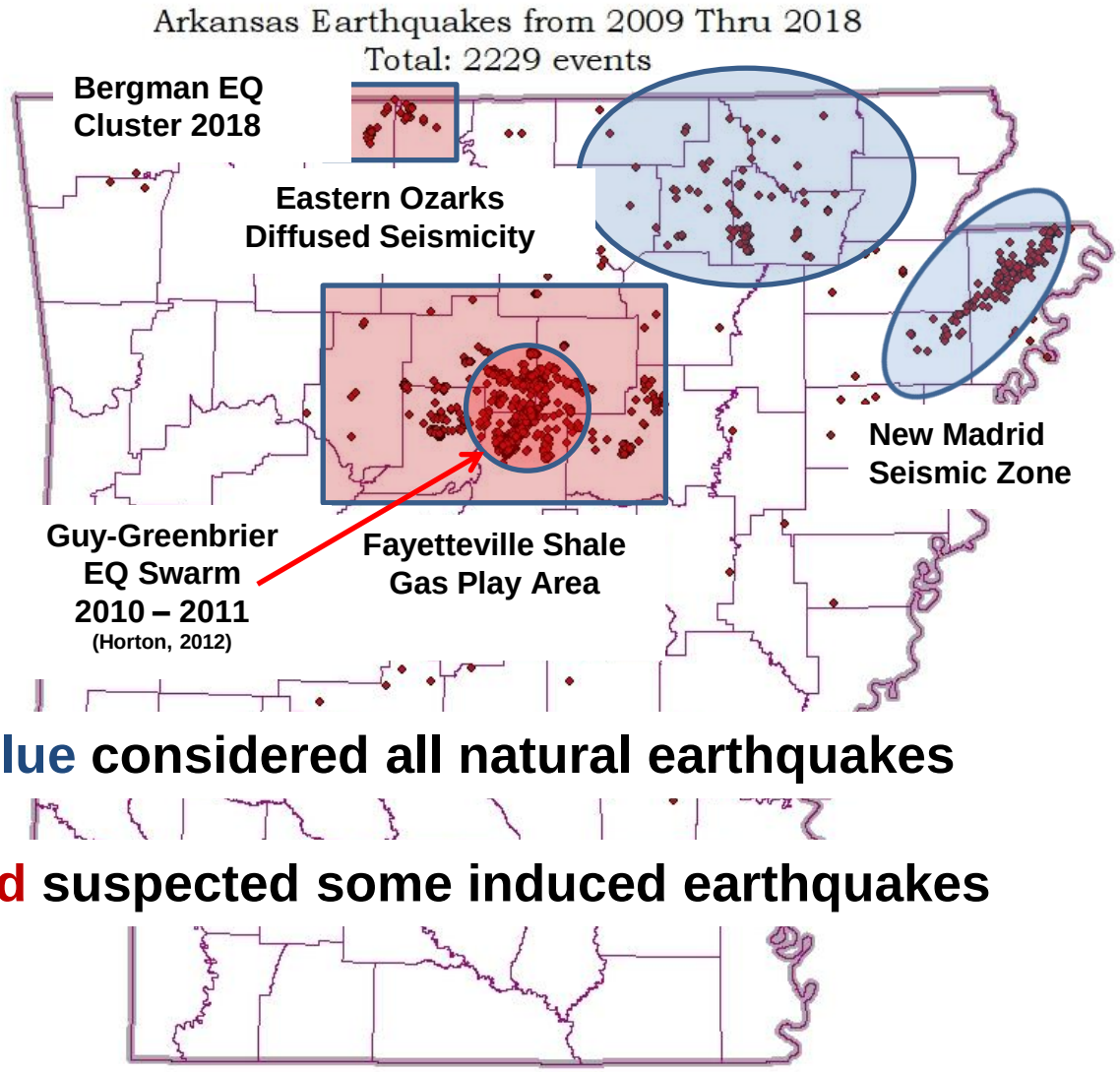
Seismicity in Arkansas





Areas in Blue considered all natural earthquakes

Areas in Red suspected some induced earthquakes

Guy-Greenbrier EQ Swarm 2010 – 2011 Summary

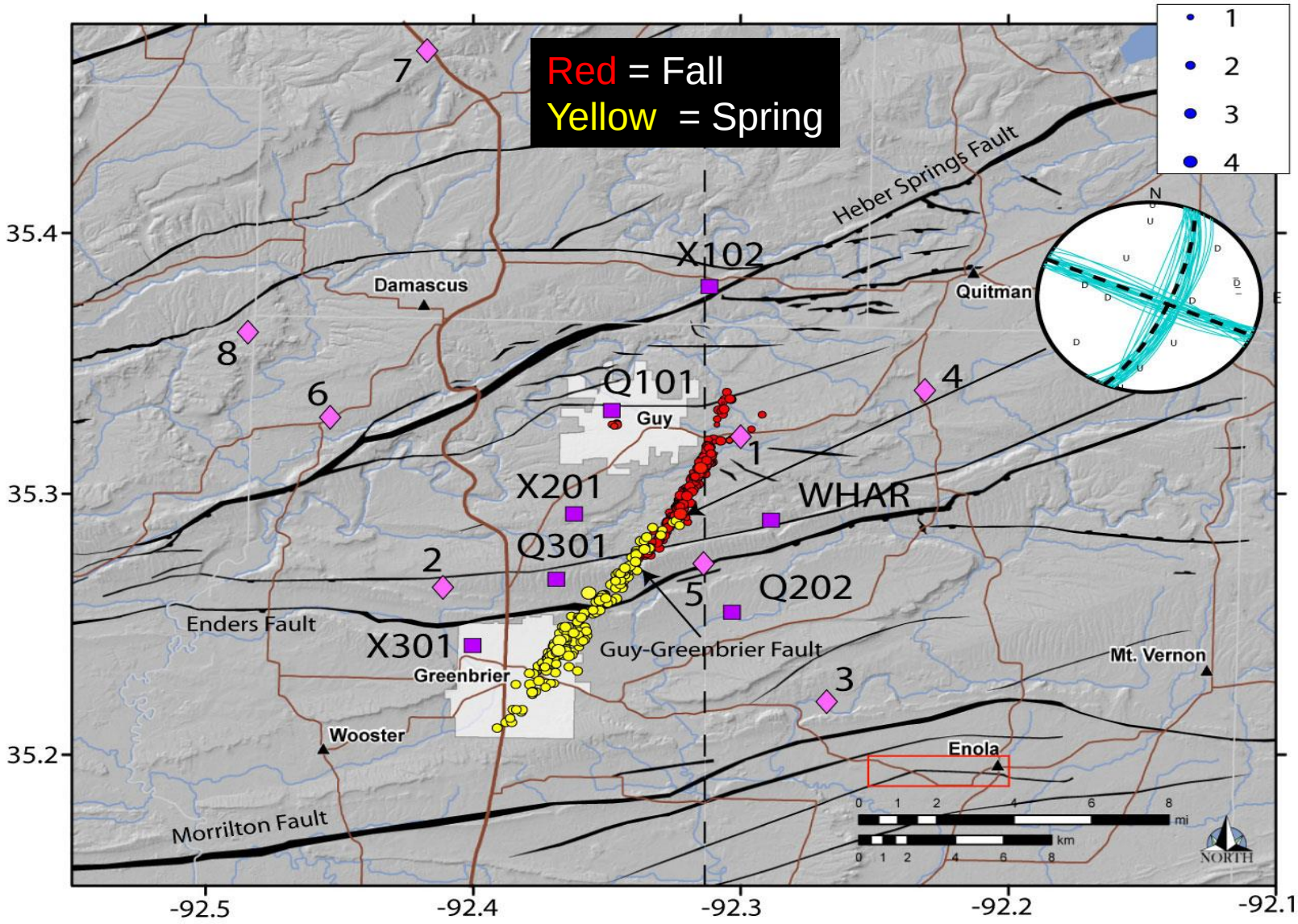
- The Guy-Greenbrier fault, was a previously unknown fault, illuminated by over **1,300 earthquakes (M≤4.7)** that occurred from the Fall of 2010 to Spring of 2011.

- A plausible hydraulic connection exists between the injection depths at a waste-disposal wells and the nearby Guy-Greenbrier Fault.

- One of the primary concerns at the height of the seismicity was that the fault was theoretically capable of producing a potentially damaging --- M5.6 – 6.0 earthquake.

- Given the spatial and temporal correlation between the UIC wells and activity on the fault, it would be an extraordinary coincidence if the earthquakes were not triggered by fluid injection.

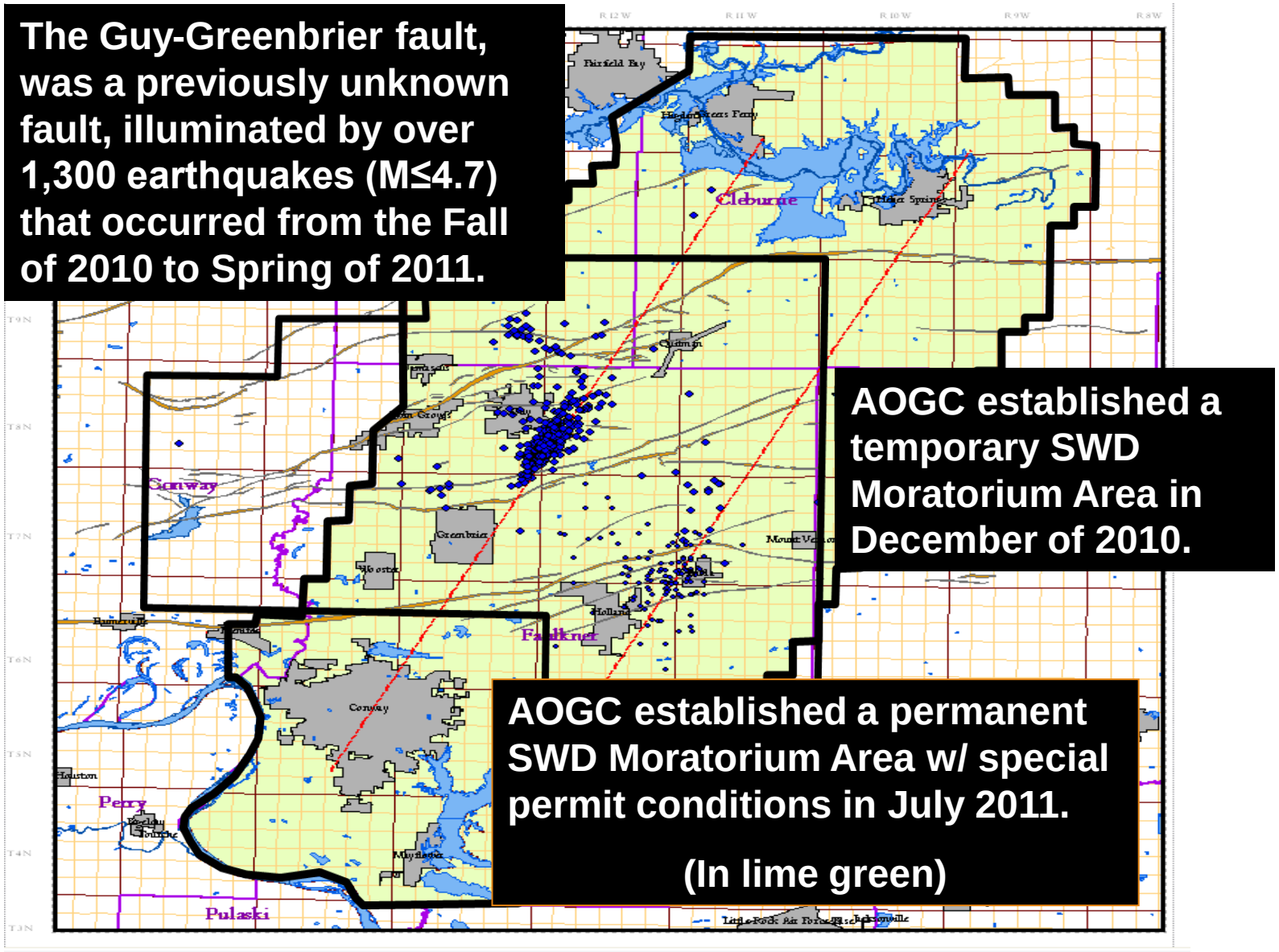
Guy-Greenbrier EQ Swarm 2010 – 2011 Seismicity



- In late summer of 2010, seismic activity began to occur in the Guy area of north-central Arkansas. Due to this increase in seismic activity, formal consultation between the AOGC, AGS and CERI began in early Fall of 2010. The seismic activity ramped up significantly in October and November of 2010.
- In December of 2010 the AOGC ordered a moratorium on drilling of new disposal wells in vicinity of Guy-Greenbrier area and required 7 existing disposal wells to report injection data on an hourly basis for a 6-month study period until July 2011.
- After an initial drop-off in seismic activity during January of 2010, a significant increase of seismicity was observed in the last two weeks of February culminating in a M4.7 earthquake on Sunday night February 28, 2011.

Guy-Greenbrier EQ Swarm Regulatory Response

The Guy-Greenbrier fault, was a previously unknown fault, illuminated by over 1,300 earthquakes (M≤4.7) that occurred from the Fall of 2010 to Spring of 2011.



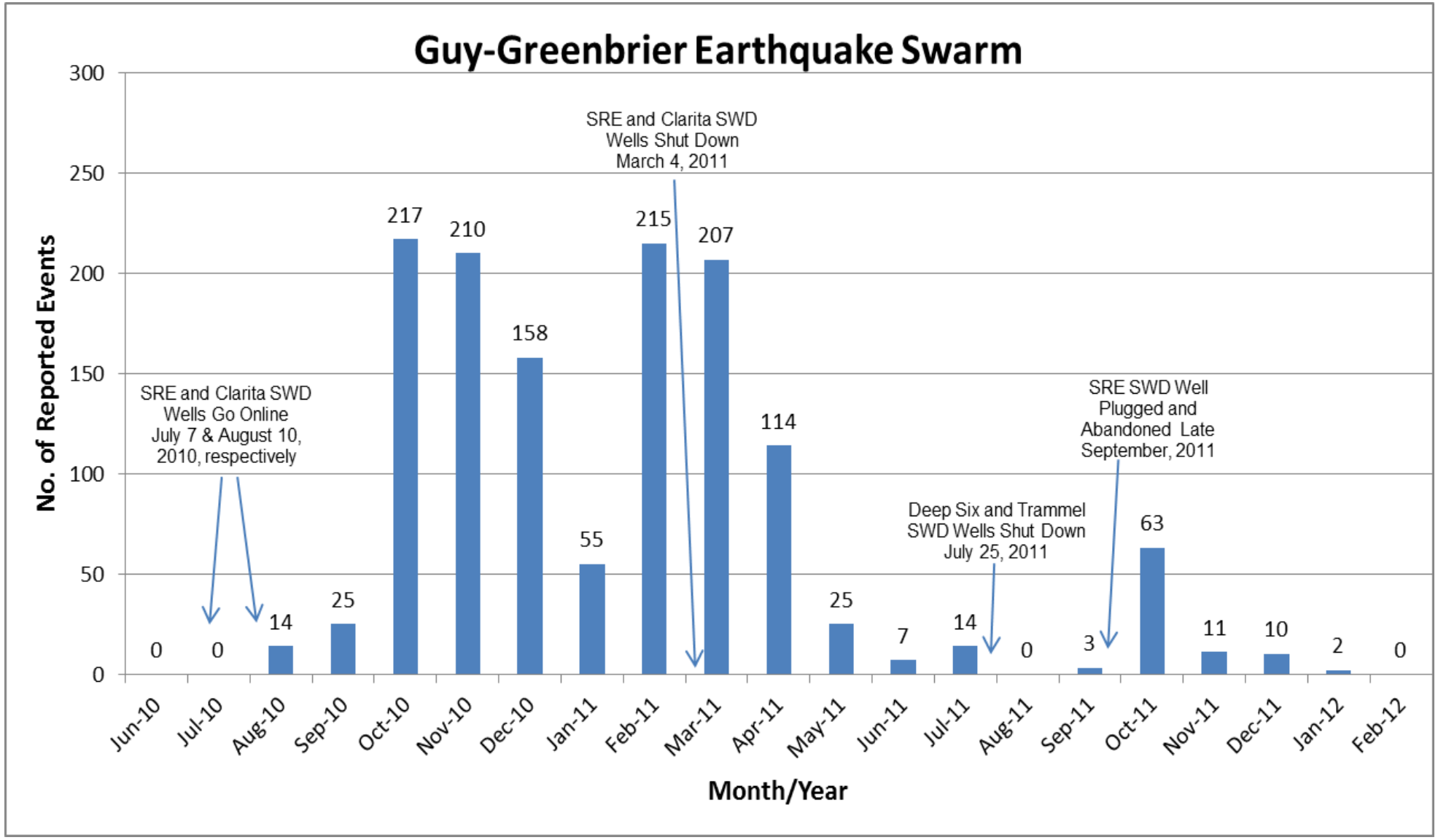
AOGC established a temporary SWD Moratorium Area in December of 2010.

AOGC established a permanent SWD Moratorium Area w/ special permit conditions in July 2011.

(In lime green)

- During the week after the M4.7 event, disposal well operators of three of the SWDs closest to the Guy-Greenbrier seismic activity agreed to voluntarily shut down.
- By Friday afternoon on March 04, 2011, the AOGC formally ordered the temporary cessation of the three disposal operations in the Guy-Greenbrier area while the fourth well (Deep-Six Moore Estate) was allowed to continued to operate until the six-month study was completed in June of 2011.
- At the AOGC hearing in July of 2011, the AOGC established a permanent moratorium and ordered all remaining SWDs in the area to cease operation.

Guy-Greenbrier EQ Swarm Timeline



Number of events per year:

2010 = 624
2011 = 724
2012 = 8
2013 = 2
Total: 1,358 (>M1.0)

~ 200 = M≥2.5
~ 40 = M≥3.0
4 = M≥4.0

General Rule H-1 Disposal Well Permit Seismic Requirements

Outside Moratorium Area in Fayetteville Shale Production Area

- Disposal wells not permitted within 1 mile of regional fault (defined) and within 5 miles of deep fault (defined)
- Disposal well spacing established based on stratigraphic depth of disposal zone (1/2 to 5 mile spacing)
- Information on faults required to be submitted with permit application. Director may request additional information if necessary
- Permitted wells required to submit daily injection rate and pressure information

Future Items:

- Modification of the Permanent Moratorium Area
- Proposed *Traffic Light Monitoring System*...

What Have We Learned?... Ten years later…

- The **Guy-Greenbrier EQ Swarm** suggested that tight injection zone with low primary porosity/permeability between the grains will pressure up the injection reservoir/aquifer quickly. Most likely the pressure front will take the path of least resistance via orthogonal joints and fractures (secondary porosity/permeability), suggesting a plausible hydraulic pressure connectivity between the well(s) and the fault(s).
- The **Guy-Greenbrier EQ Swarm** suggested a plausible hydraulic pressure connectivity between the well(s) and the fault(s) via missing confining units and the orthogonal joint sets and fractures thus increasing the pore pressure in the fault zone. This results in a change in the Mohr-Coulomb criterion --- resulting in movement.
- The **Guy-Greenbrier EQ Swarm** suggested that earthquakes are more likely to occur on faults that are critically stressed (near failure) and are favorably oriented to the regional stress.
- The **Guy-Greenbrier EQ Swarm study** suggested that multiple SWDs in close proximity and injecting into the same interval(s) may have a multiplier effect.
- The **Greenbrier EQ Cluster** indicated that cross-correlation (template matching) is an important tool for future induced seismicity studies.

Sources, Contributors & References

Sources:

Arkansas Geological Survey

Arkansas Oil and Gas Commission

Center for Earthquake Research and Information, University of Memphis

El Dorado News Times

Contributors:

Steve Horton, Ph.D., CERI at University of Memphis

Larry Bengal, Arkansas Oil & Gas Commission

Randel Cox, Ph.D., University of Memphis

References:

Cox, R. T., 1991, Possible triggering of earthquakes by underground waste disposal in El Dorado, Arkansas area; Seismological Research Letters, V. 62, N. 2, p. 113-122.

Horton, S. H., and Ausbrooks, S. M., 2010, Are recent earthquakes near Greenbrier, Arkansas induced by waste-water injection?, Seismological Society of America, SSA Annual Meeting of 2010, poster, 1 page.

Horton, S. H., 2012, *Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential or damaging earthquake;* Seismological Research Letters, V. 83, N. 2, p. 250-260.

Johnston, A., et al, 1982, The Central Arkansas earthquake swarm: Tennessee Earthquake Information Center (TEIC -Now CERI) Special Report # 8, parts 1, 2.

Oklahoma Geological Survey (OGS)
University of Oklahoma

Technical Lead – Paul Ogwari, pogwari@ou.edu

Lead Principal Investigator – Jake Walter, jwalter@ou.edu

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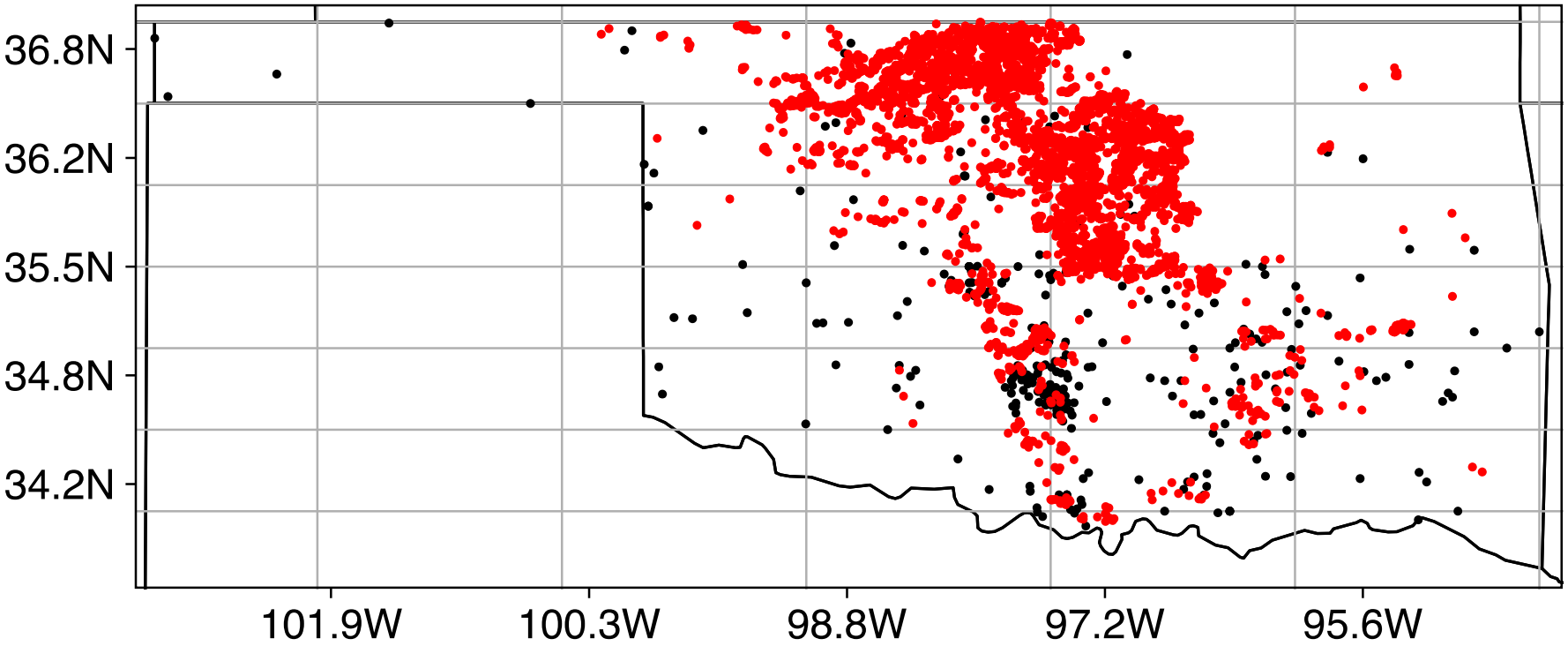
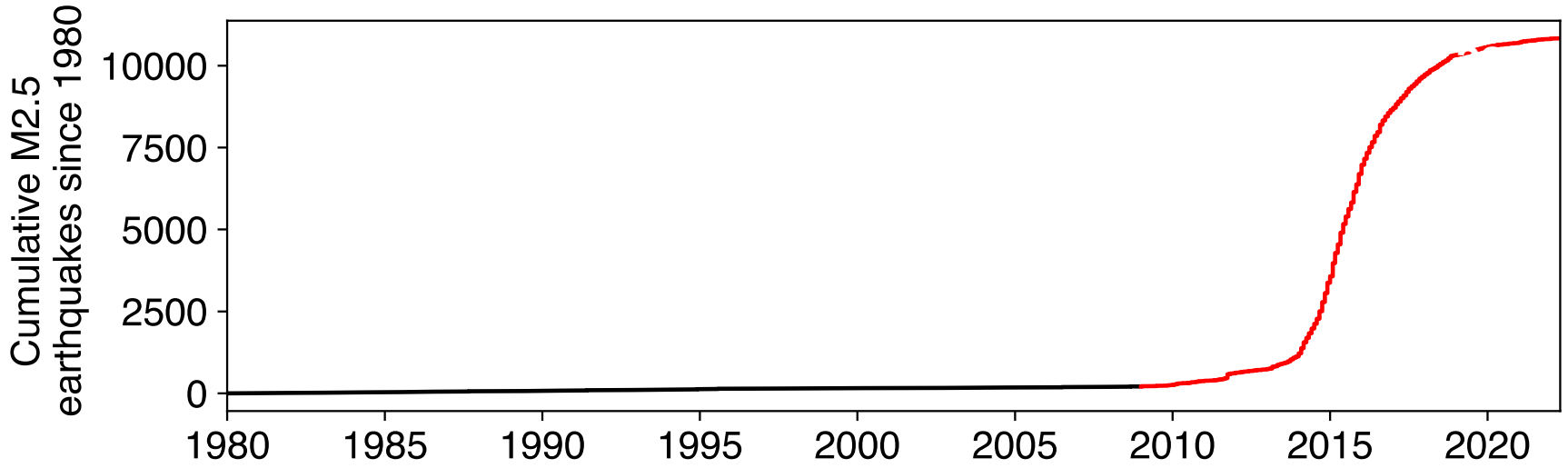
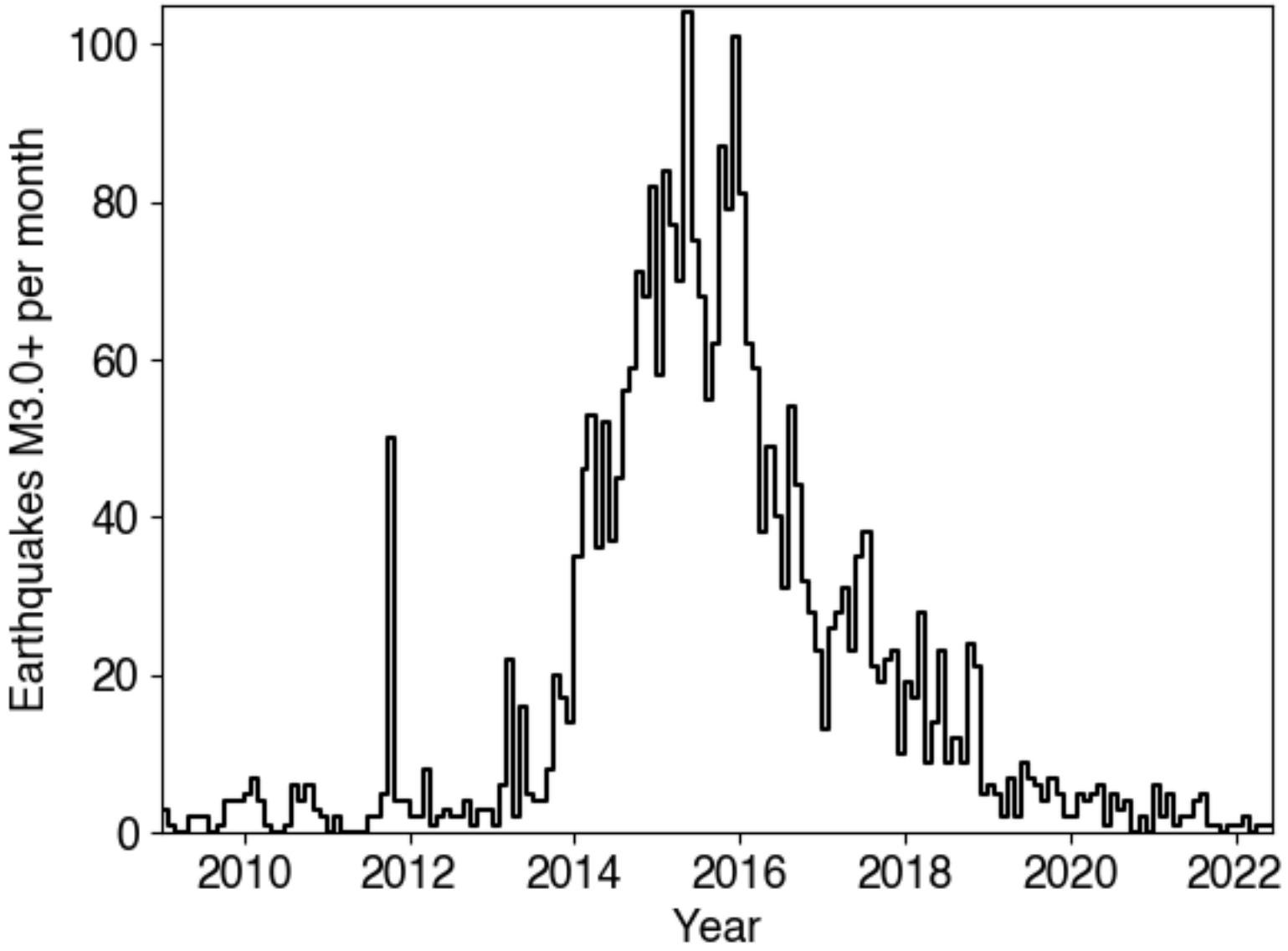
Regional Induced Seismicity Collaborative

M2.5 Oklahoma earthquakes since 1980

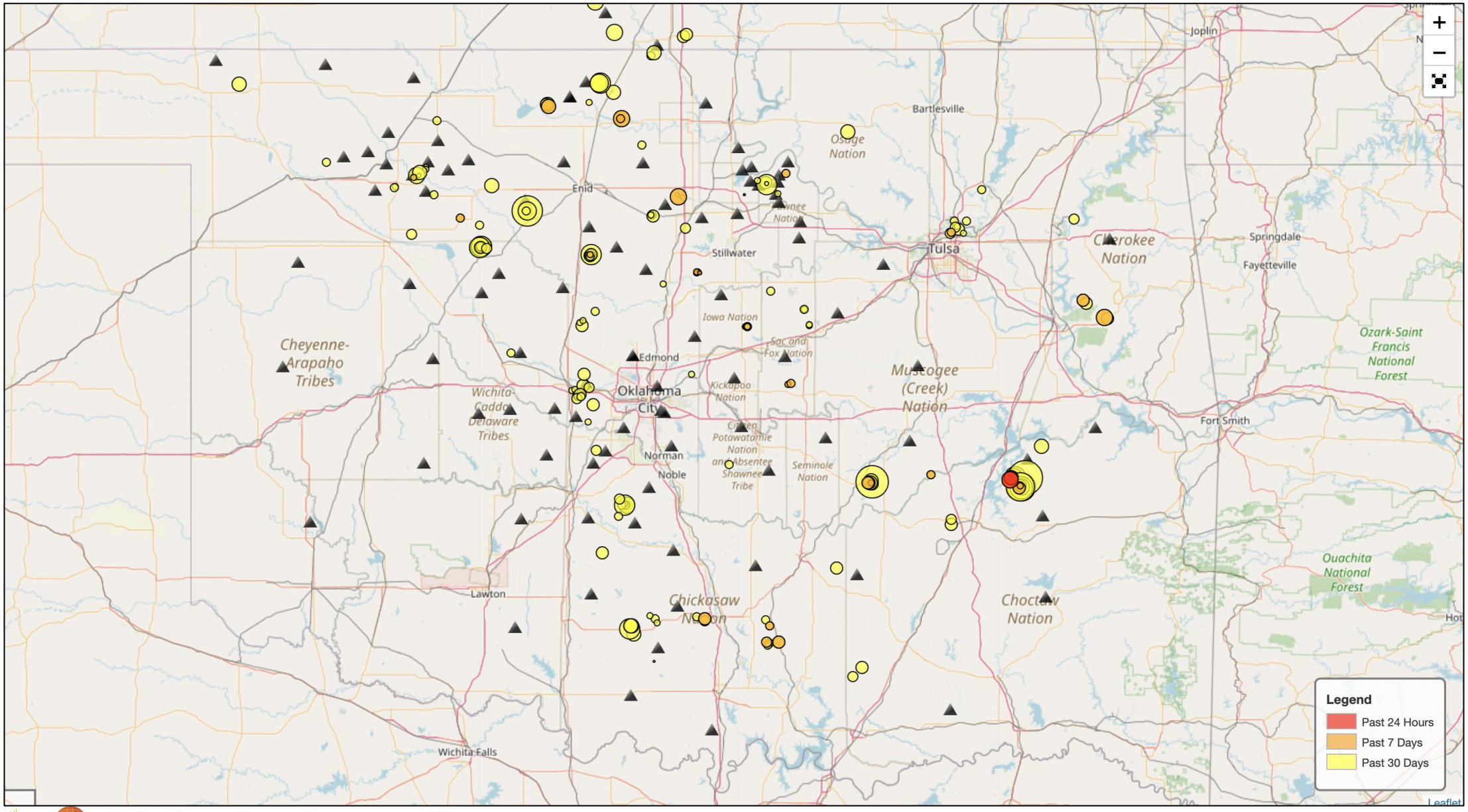




M3.0+ Oklahoma earthquake rate



OGS seismic network: OK & O2

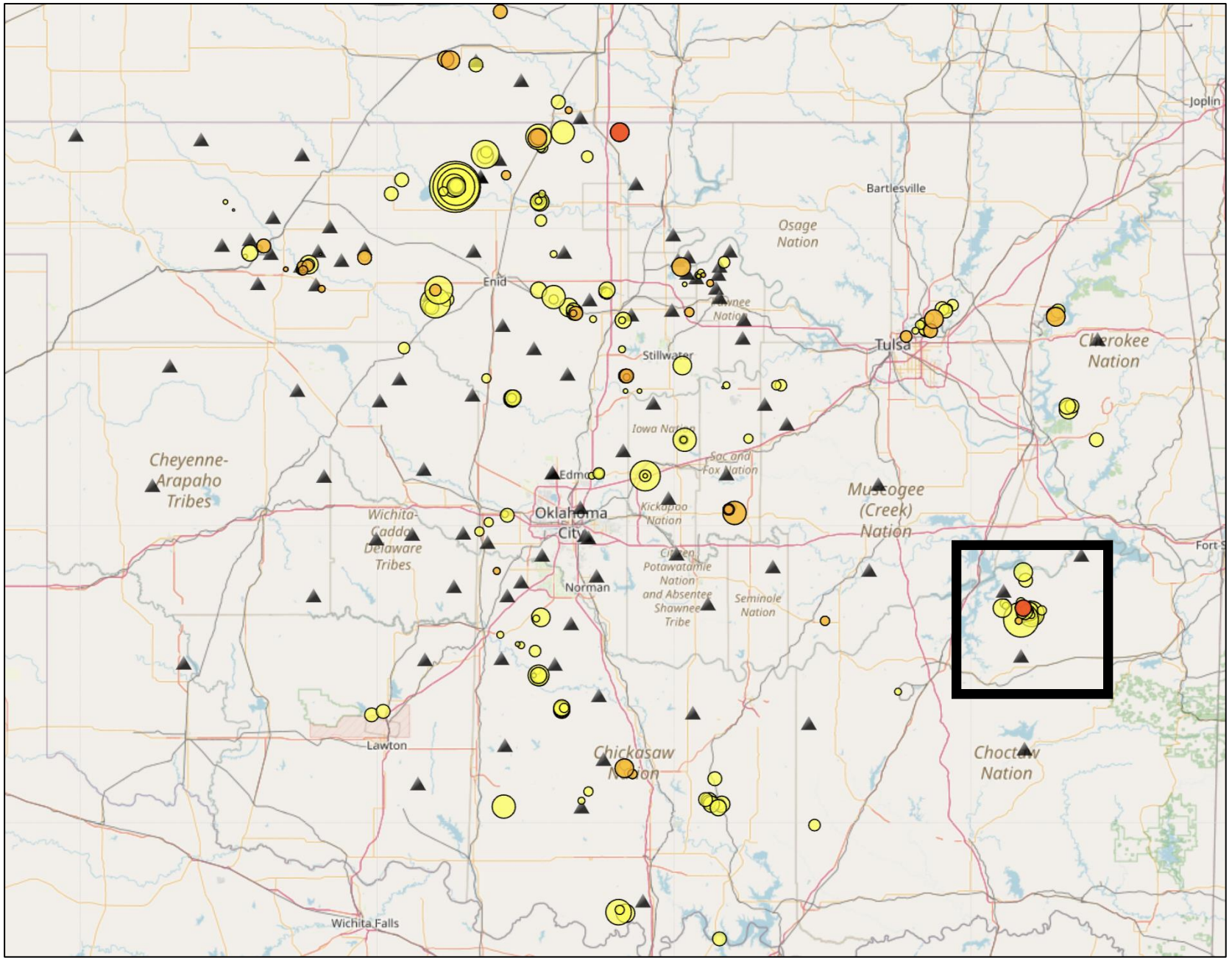


RISC Regional Induced Seismicity Collaborative

Node deployments

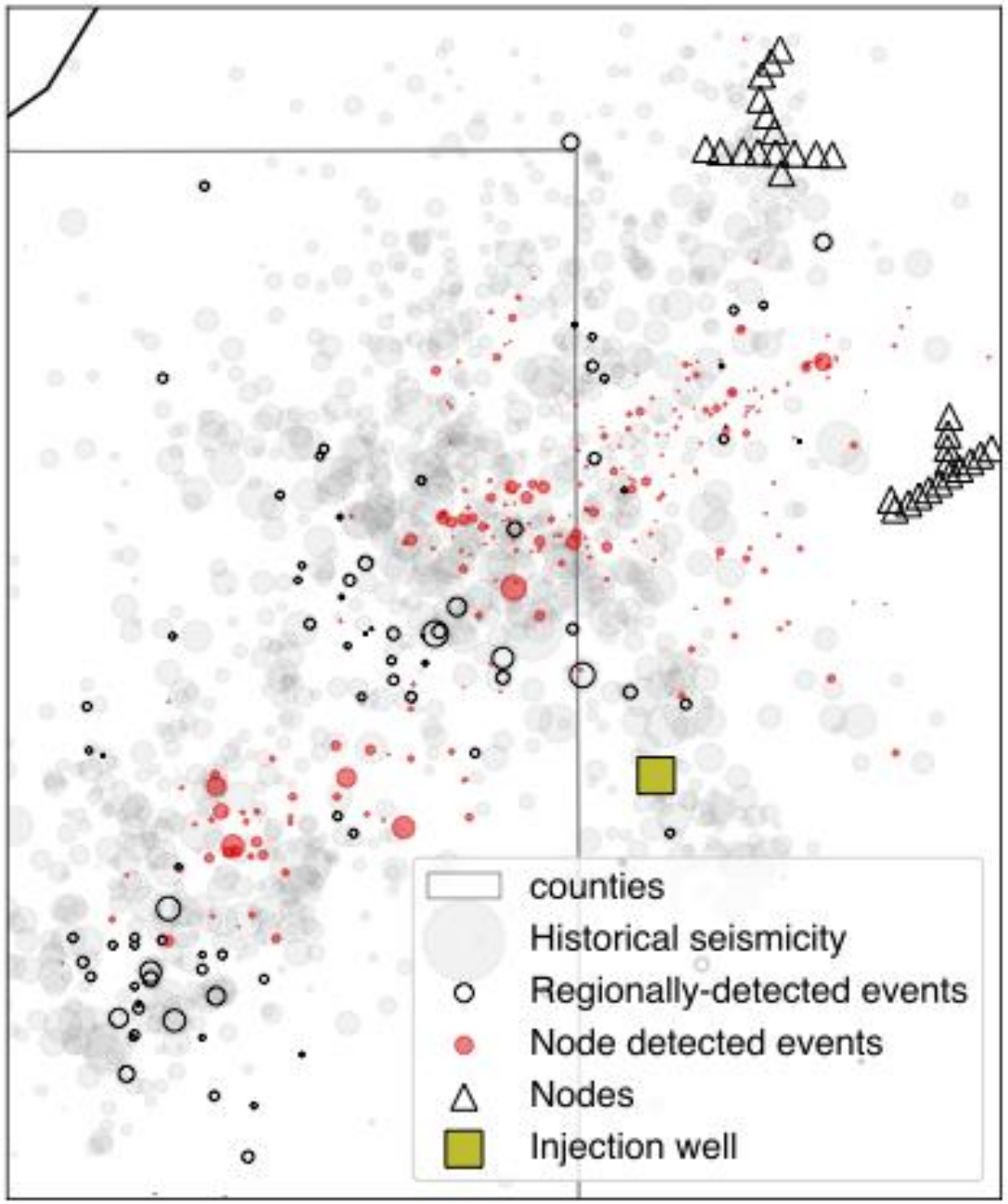
In addition to routine network operations, we have pioneered utilizing 3-component nodes available from OU – regions of interest identified in our bi-weekly calls with OCC

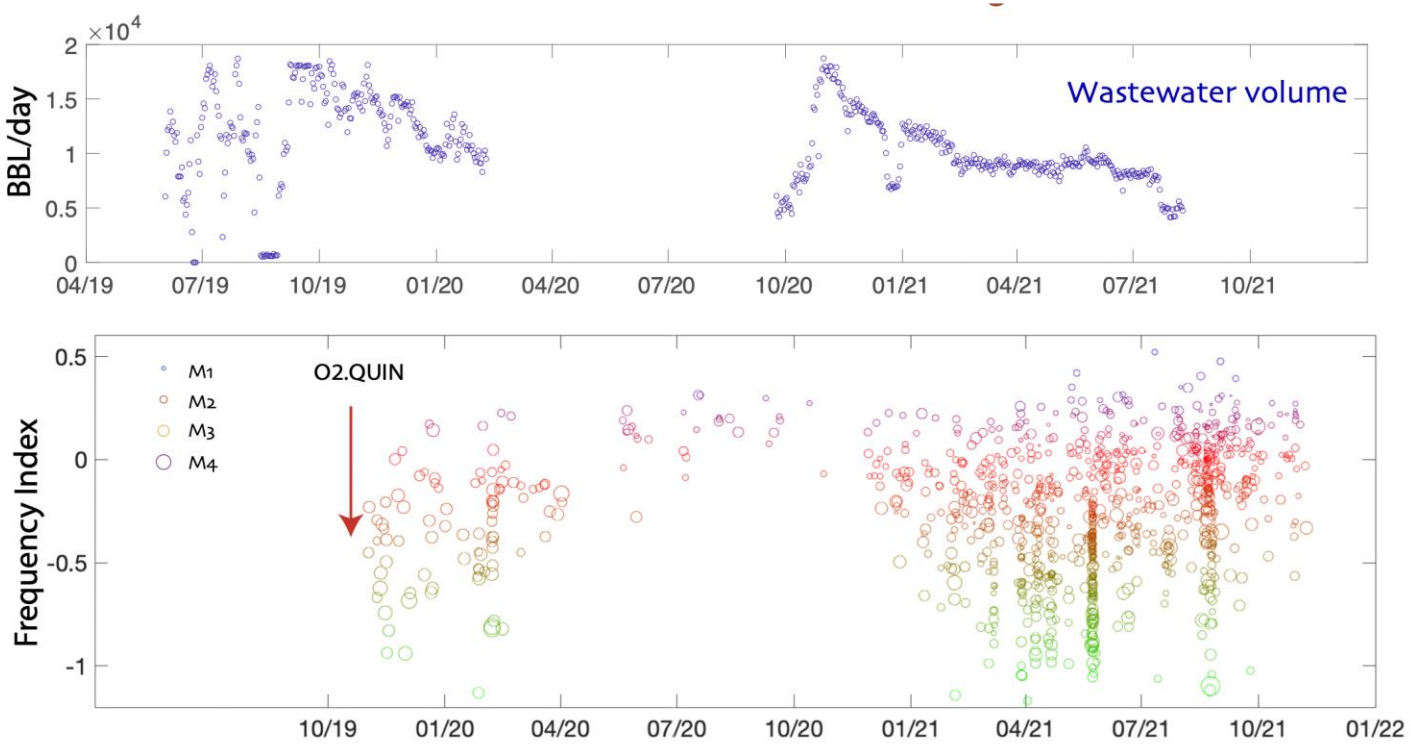
- 90 nodes that can be deployed for a period of ~4 weeks
- Data collected and then processed after the 4 weeks
- Apply easyQuake – our machine-learning software to detect small events



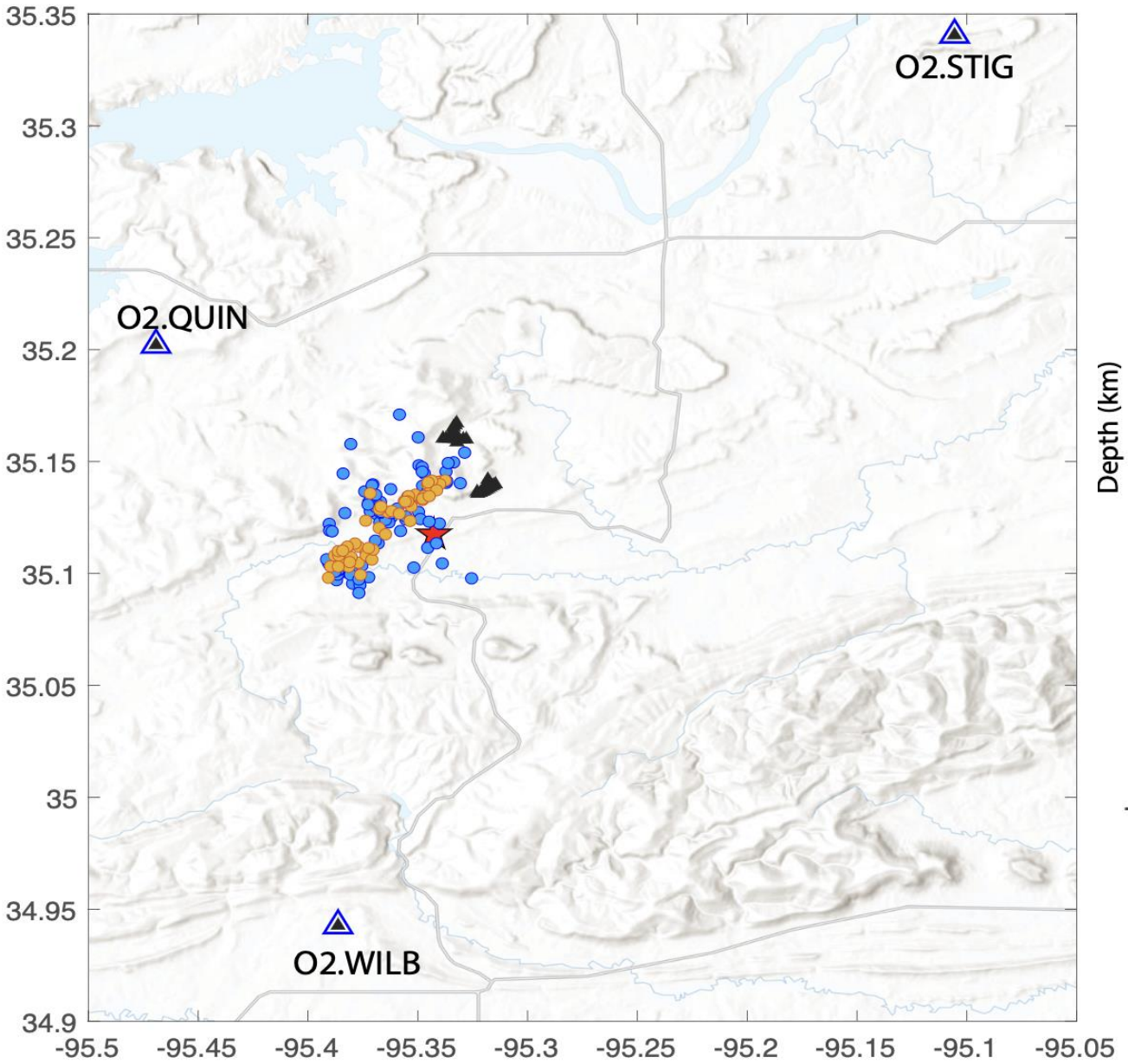
Case study:

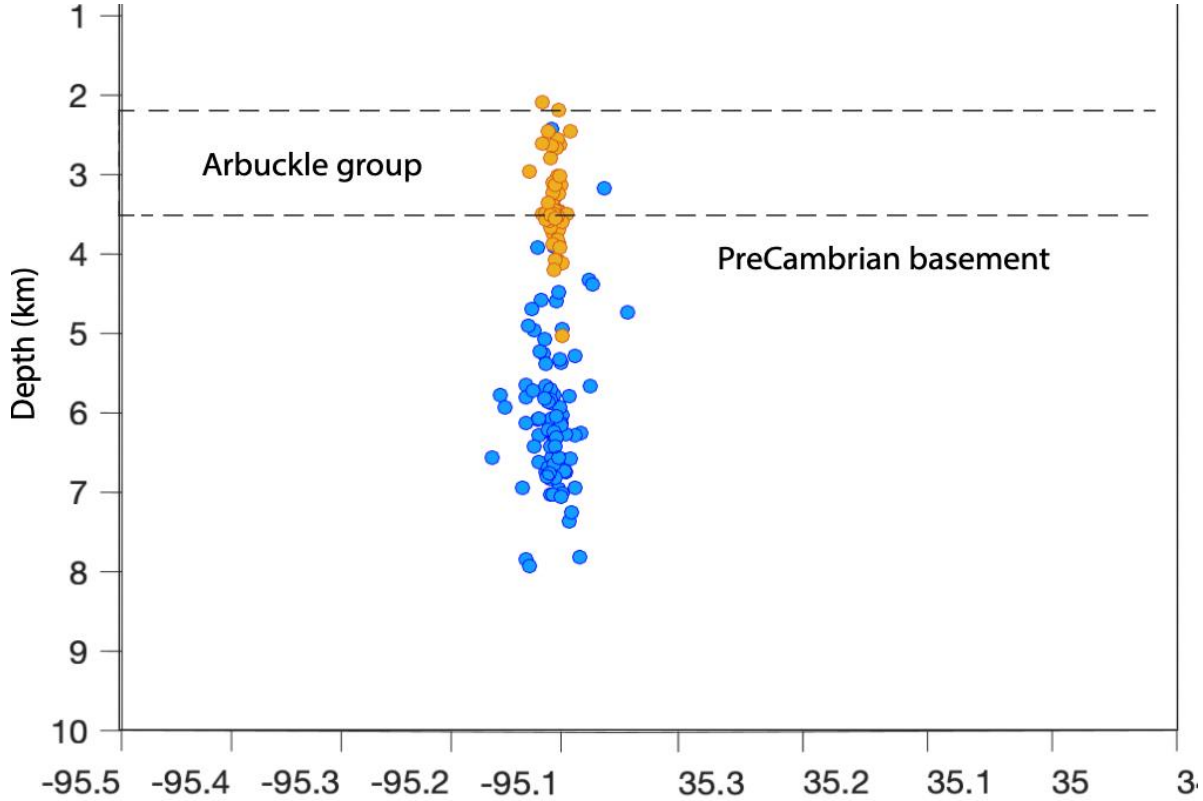
Quinton OK



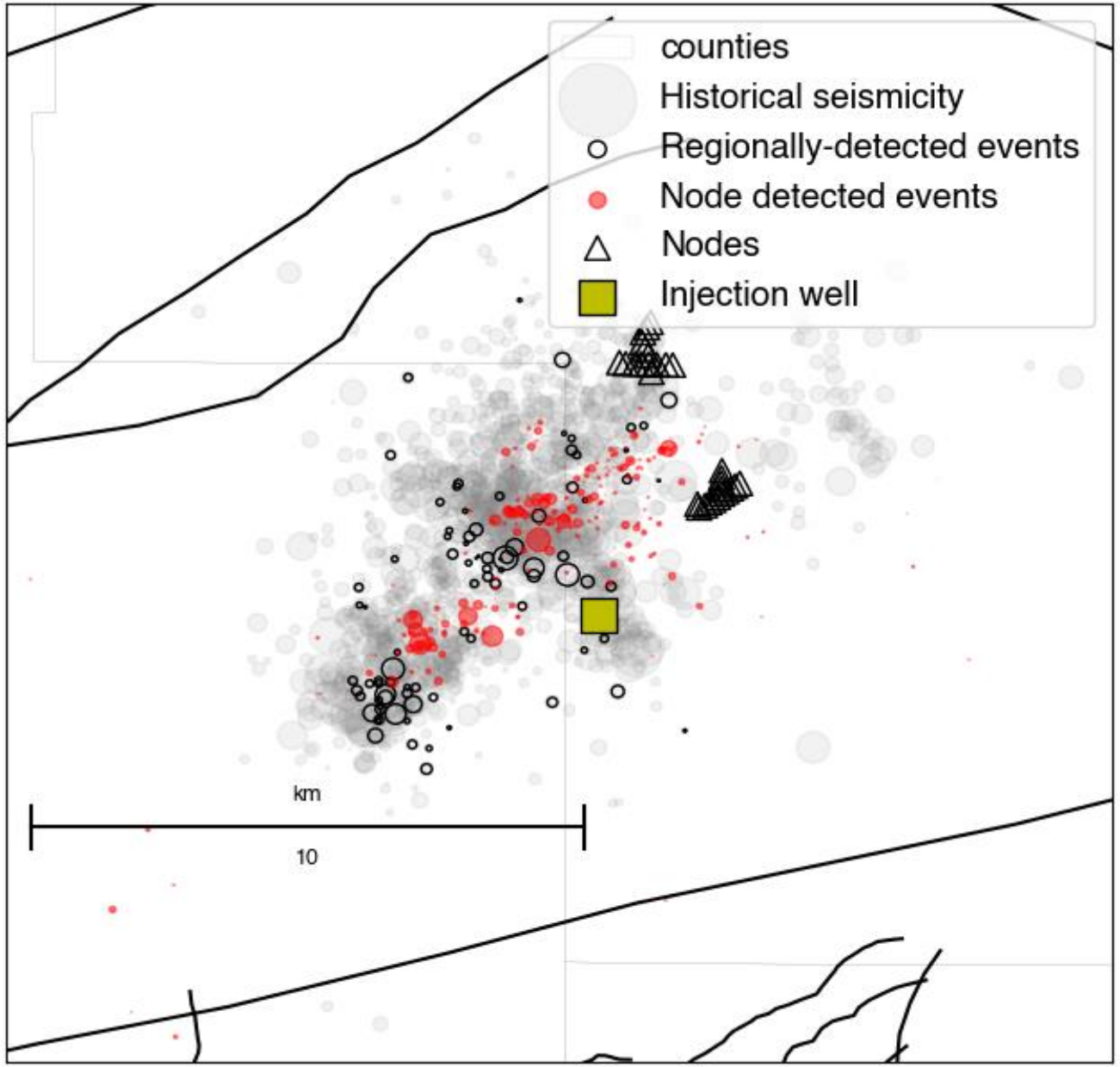


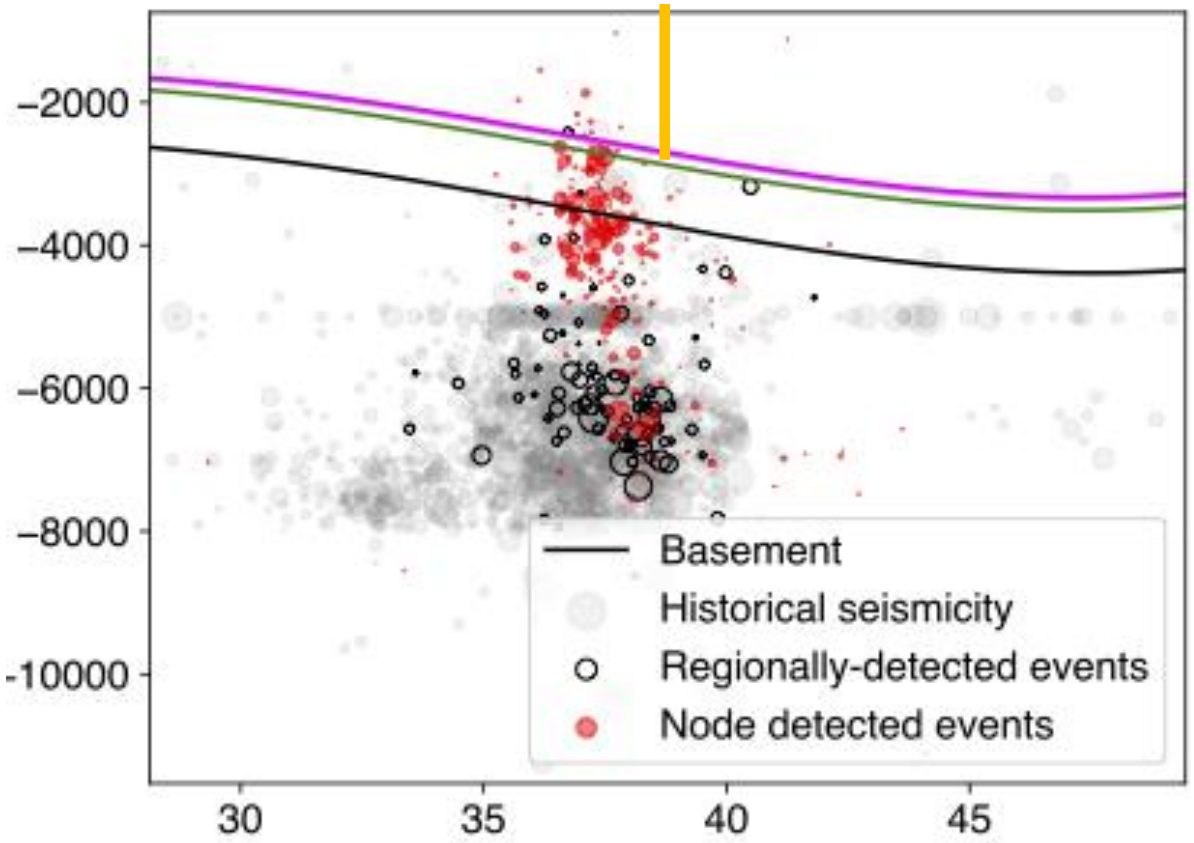
- **Wide damage zone**
- **Complex earthquake physics**


O2.STIG
O2.QUIN
O2.WILB
35.35
35.3
35.25
35.2
35.15
35.1
35.05
35
34.95
34.9
-95.5
-95.45
-95.4
-95.35
-95.3
-95.25
-95.2
-95.15
-95.1
-95.05


Arbuckle group
PreCambrian basement
Depth (km)
1
2
3
4
5
6
7
8
9
10
-95.5
-95.4
-95.3
-95.2
-95.1
35.3
35.2
35.1
35

Independently detect events with easyQuake using only the nodes





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**

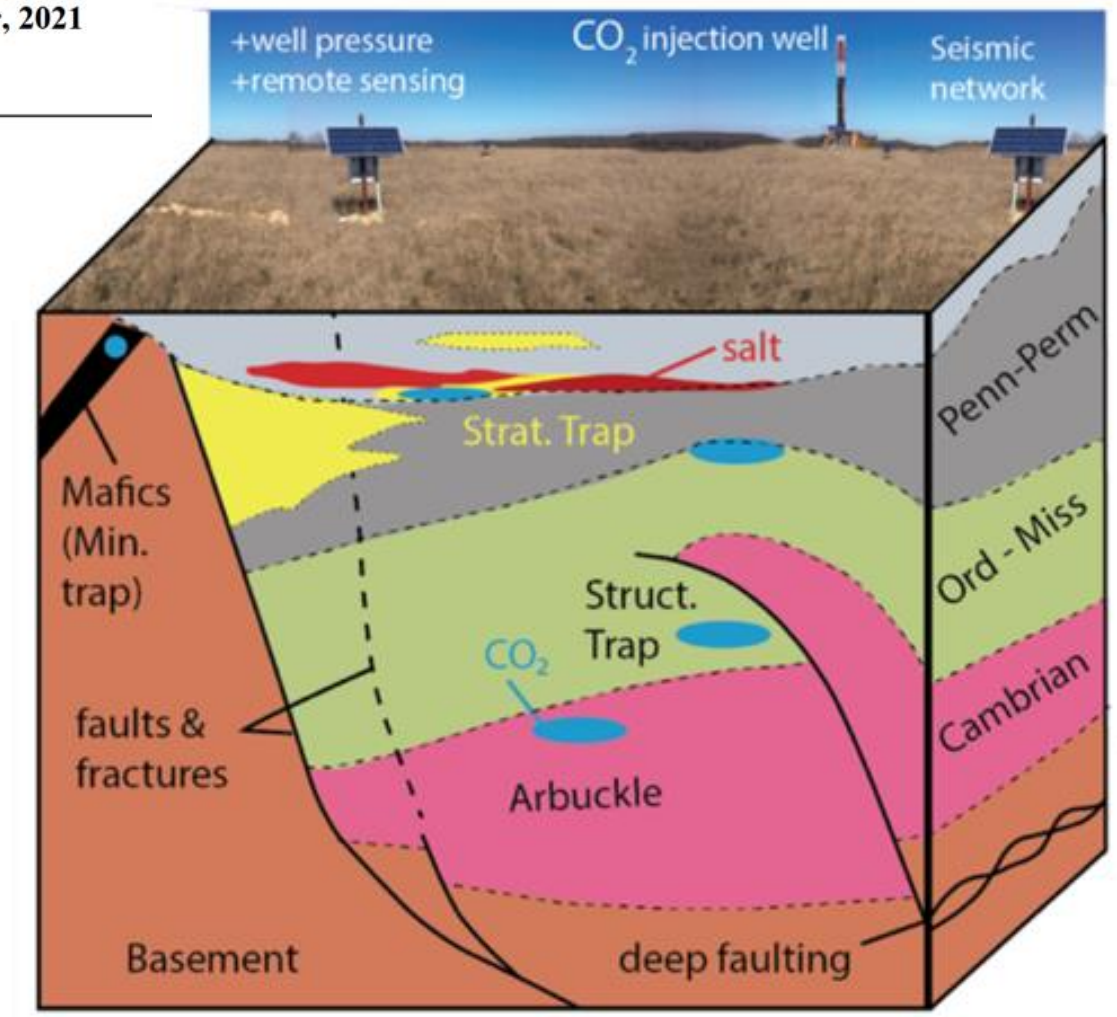


Figure 1. Schematic of carbon management targets in Oklahoma.

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

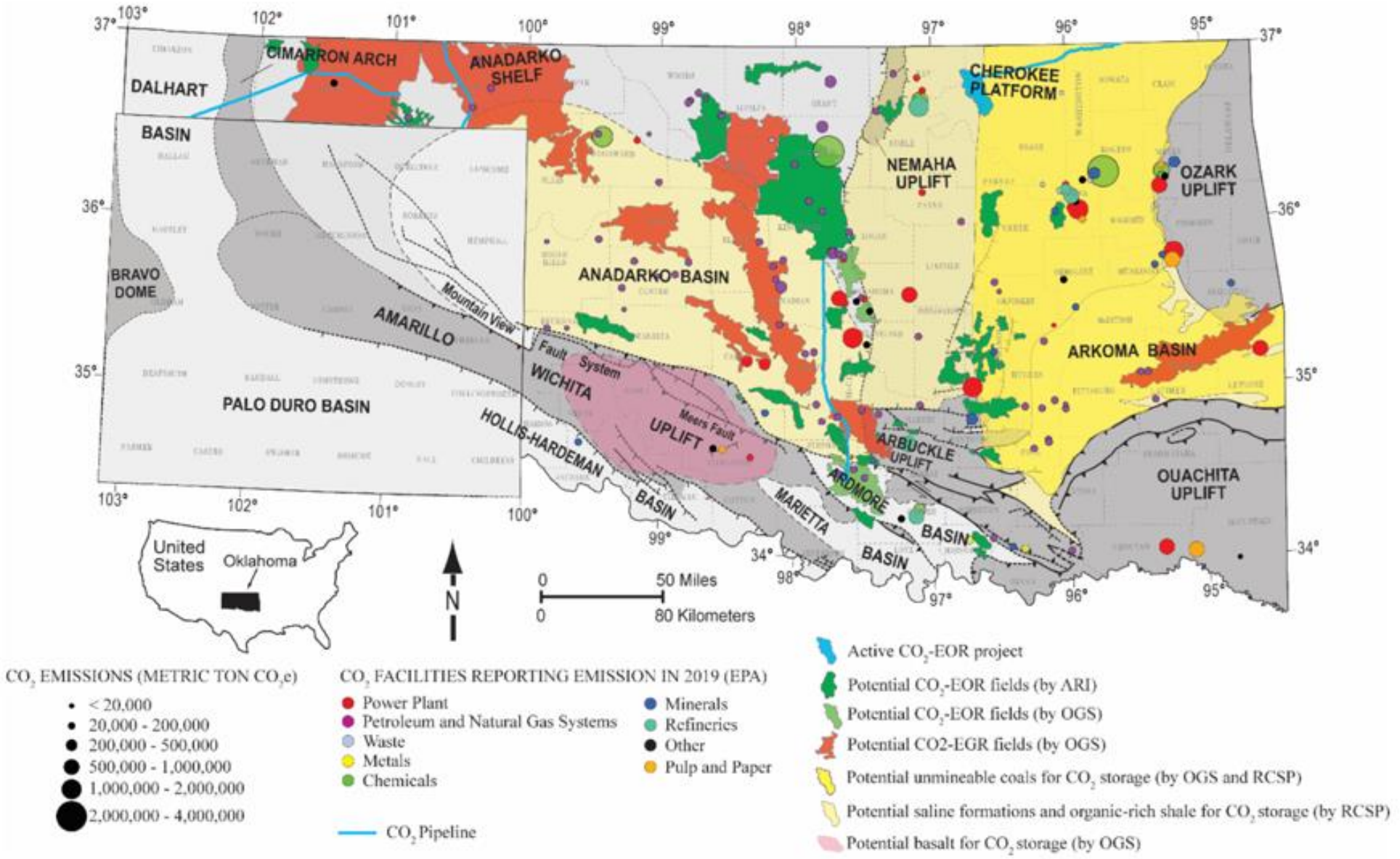
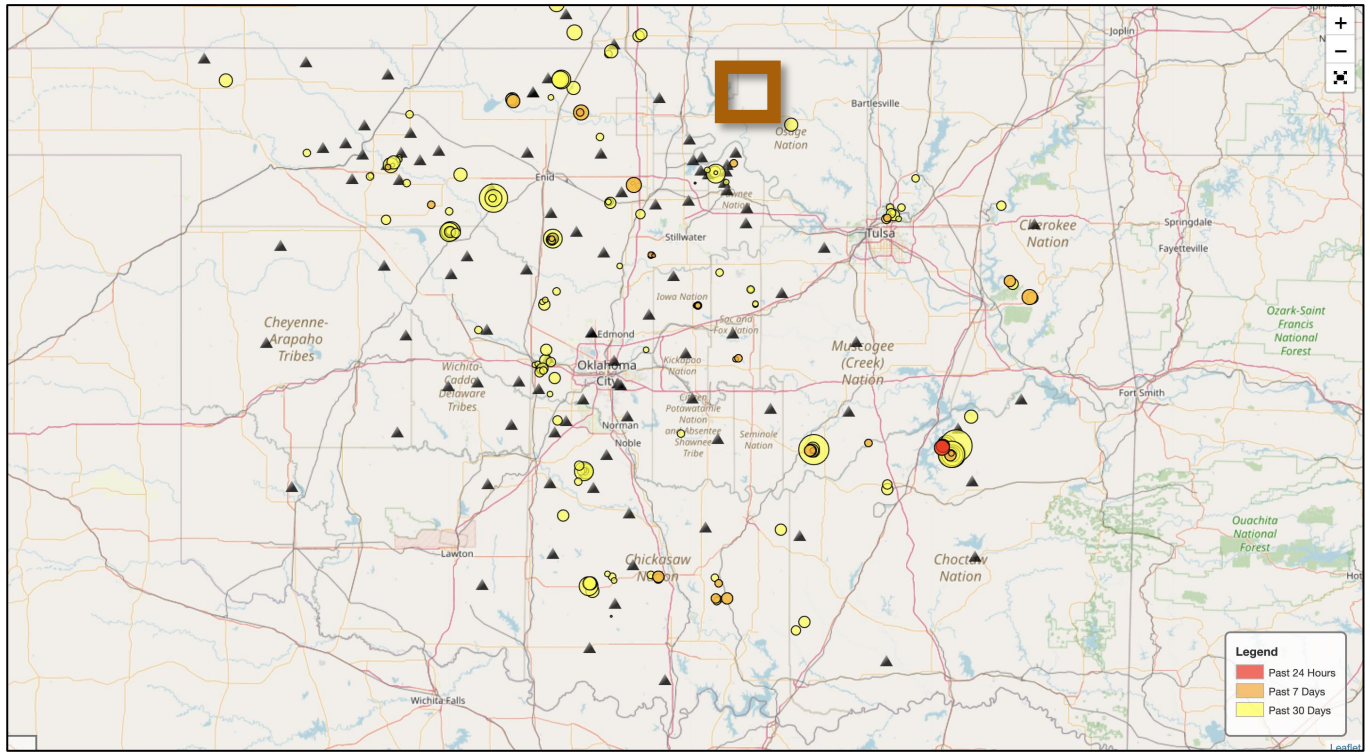
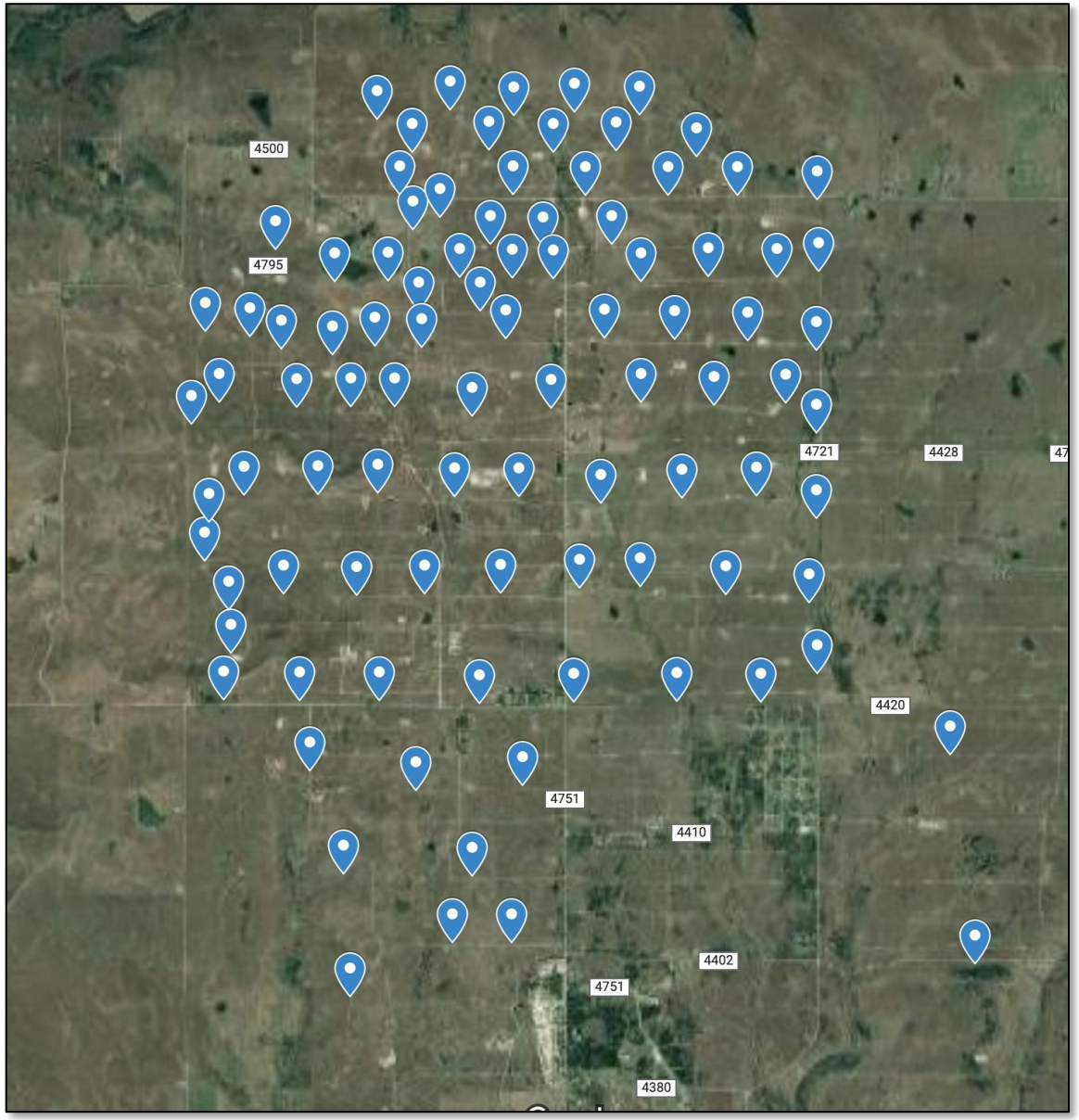


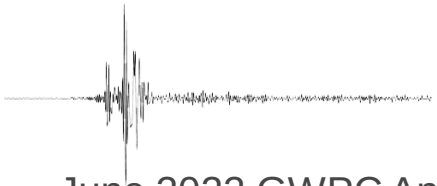
Figure 2. Geological provinces and prominent carbon emissions and facilities [12,22-27]. Major CO_2 emissions are illustrated for the year 2019 along with known CO_2 pipelines, geological provinces, and some major oil and gas fields.

North Burbank Unit

90+ node deployment starting last week to attempt to detect any ambient seismicity from ongoing CO_2 flood and Arbuckle disposal





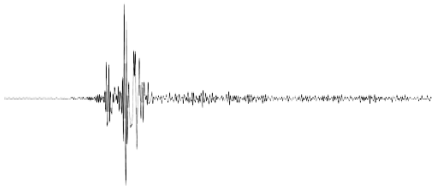


June 2022 GWPC Annual Meeting, Salt Lake City

Updating the Response to Induced Seismicity

Jim Marlatt – Special Projects Manager
Induced Seismicity Department
Oil and Gas Conservation Division
Oklahoma Corporation Commission

OKLAHOMA



Induced Seismicity Mandate:

(1) Mitigate the risk of induced seismicity in Oklahoma related to O&G activity[a]

(2) Ensure the collection and integrity of O&G data submitted to and maintained by the Oklahoma Oil and Gas Conservation Division

(3) Emergency response authority: "For purposes of immediately responding to emergency situations…within its jurisdiction, the Corporation Commission may take whatever action is necessary, without notice and hearing,…to promptly respond to an emergency." Title 17, Sec.52 D.

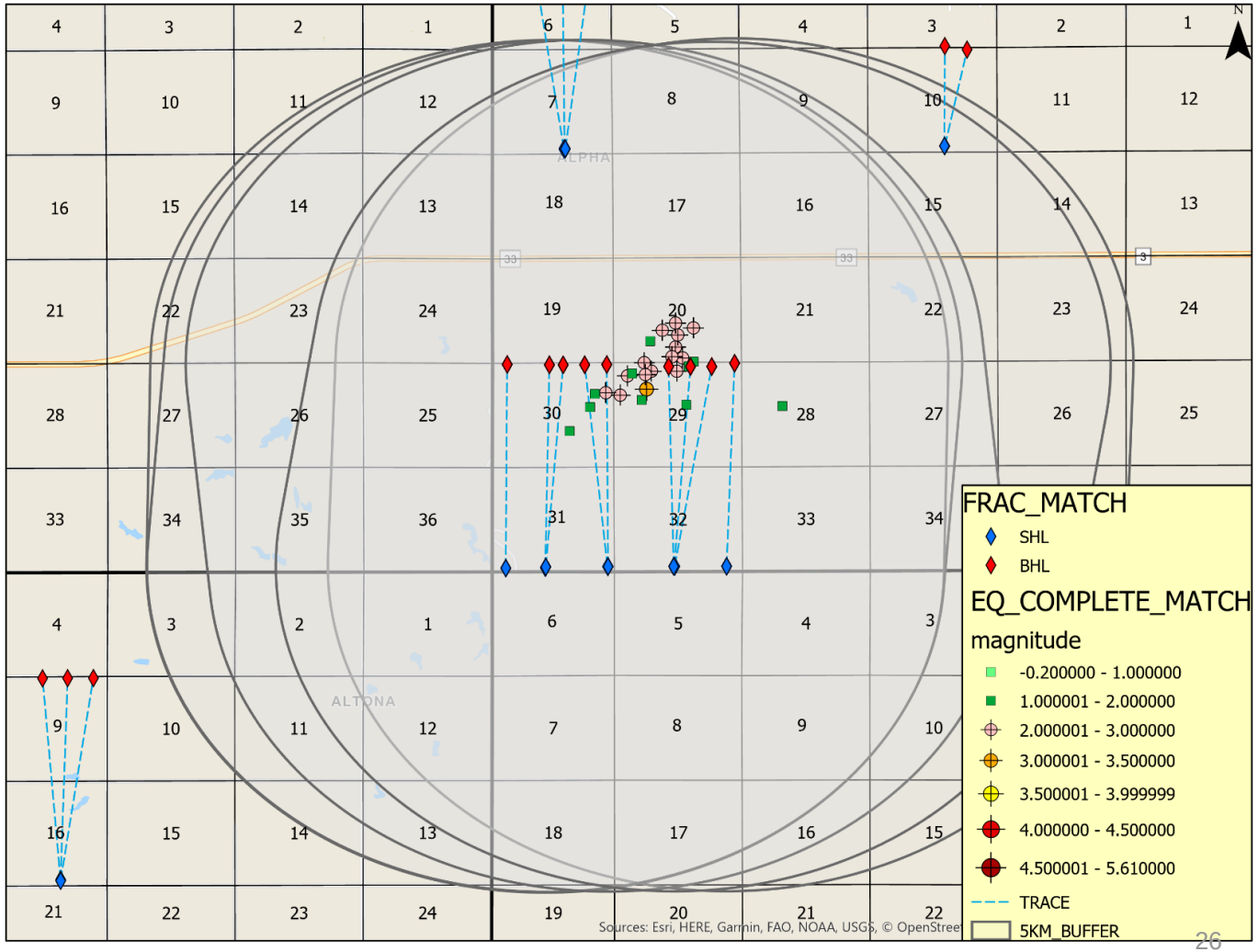
a. 17 O.S. Sec. 52, 52 O.S. Sec. 139(D) (1) and OAC 10-5-7(g) Shutdown or other action

Possible Sources Of Induced Seismicity

- Deep Water Injection
  - Far-field reactivation of "old" basement faults
- Well Completions
  - Near-field reactivation of younger sedimentary fault segments (hydraulic connections and near-instantaneous pore pressure influence)

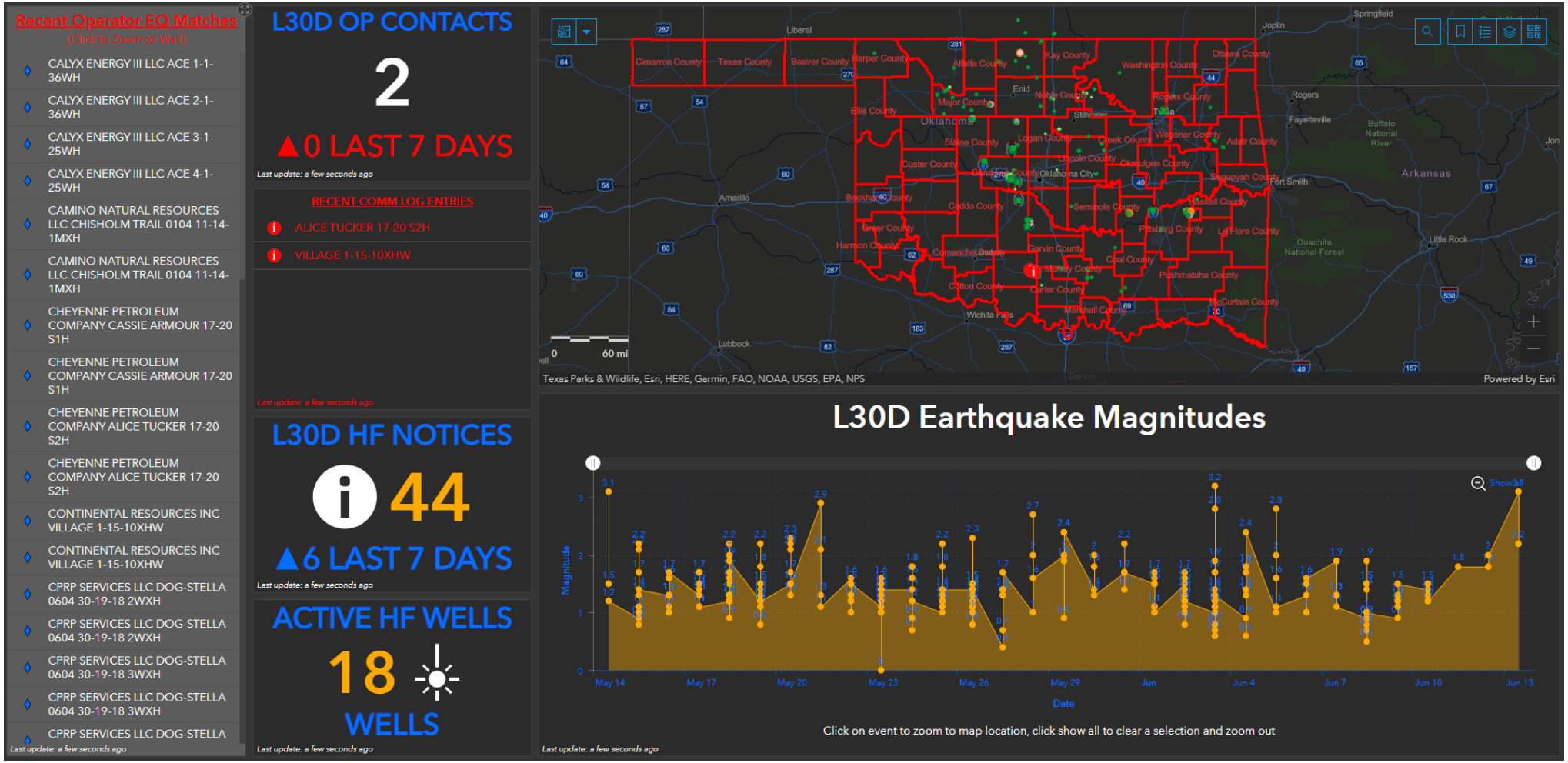
Well-Seismic Match Model GIS Output

- Frac-Match models run every 15 minutes throughout the day with 5-minute updated OGS earthquake data
- Matches are automatically added to reports and to map layers
- Staff review matches, determine if protocol levels were exceeded, contact associated operators



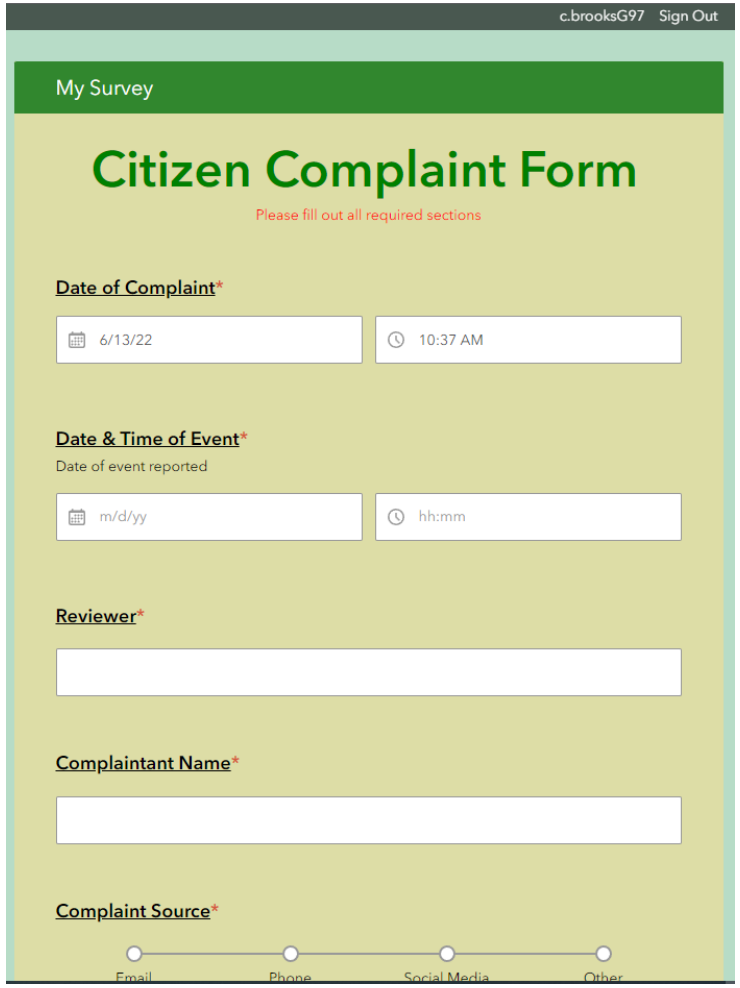
Frac Notice Match Update

Well completion and spatiotemporal seismic event correlation – June 2022



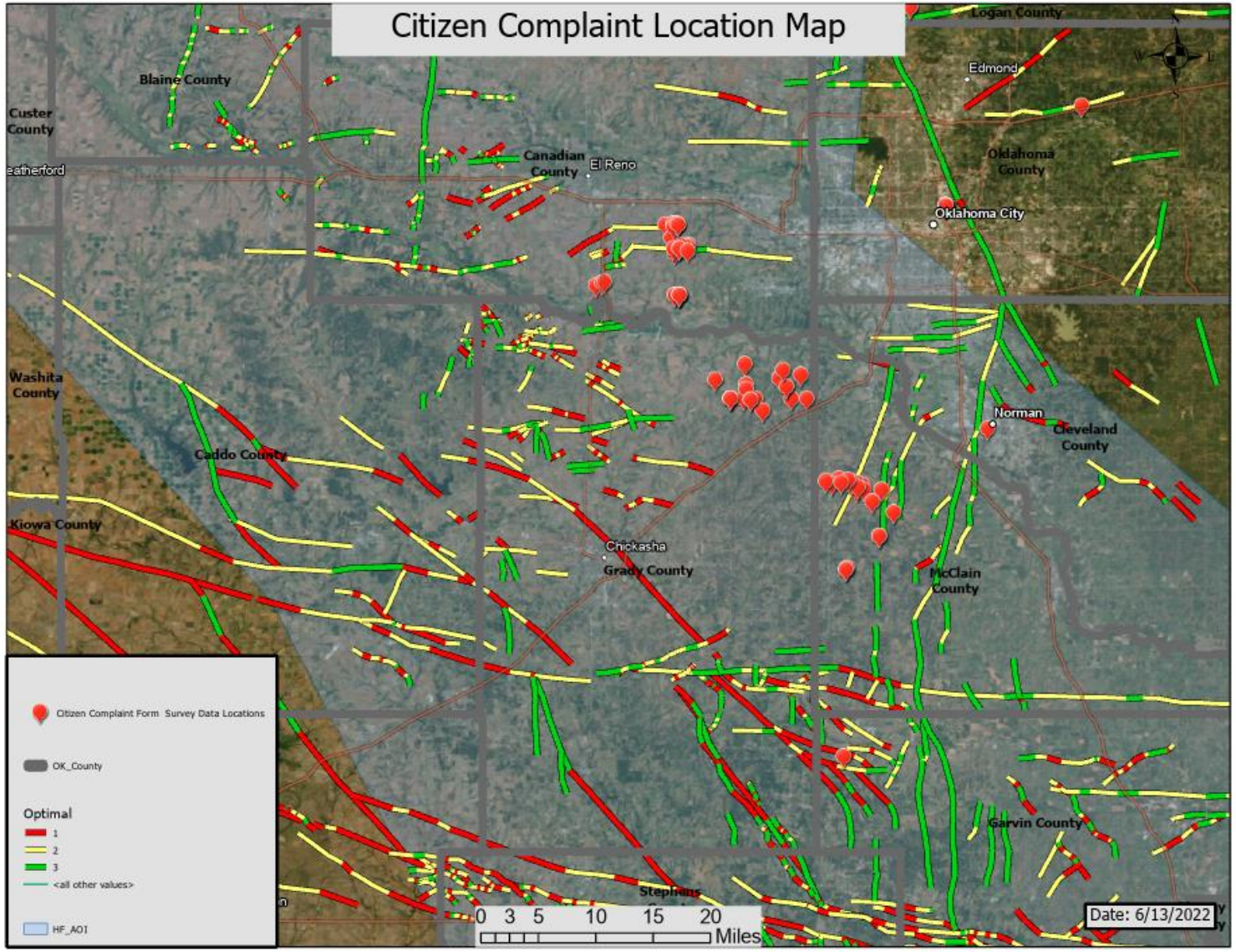
https://occokc.maps.arcgis.com/apps/dashboards/f5574d9dd14b4f679e0090e841990e9d

Citizen Complaint Form and Response

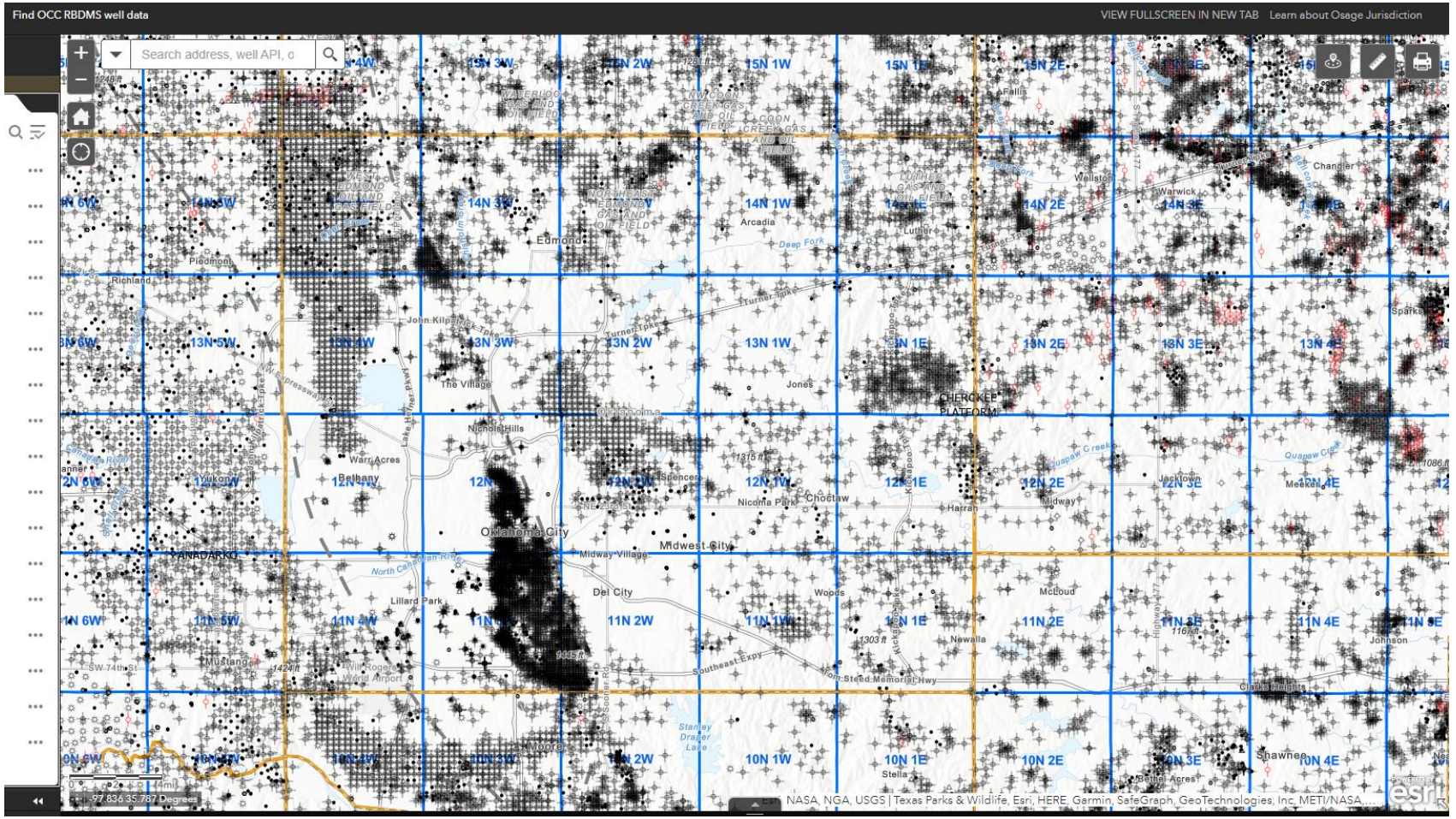


- Smart ESRI form for Citizen Complaints and felt reports created in 2019 and expanded in early 2022
- Public Information Office receives complaints. Inquires about willingness to have follow-up call to collect details
- ISD follows up with complainants to document details about seismicity and record felt data in database for researchers

Citizen Complaints

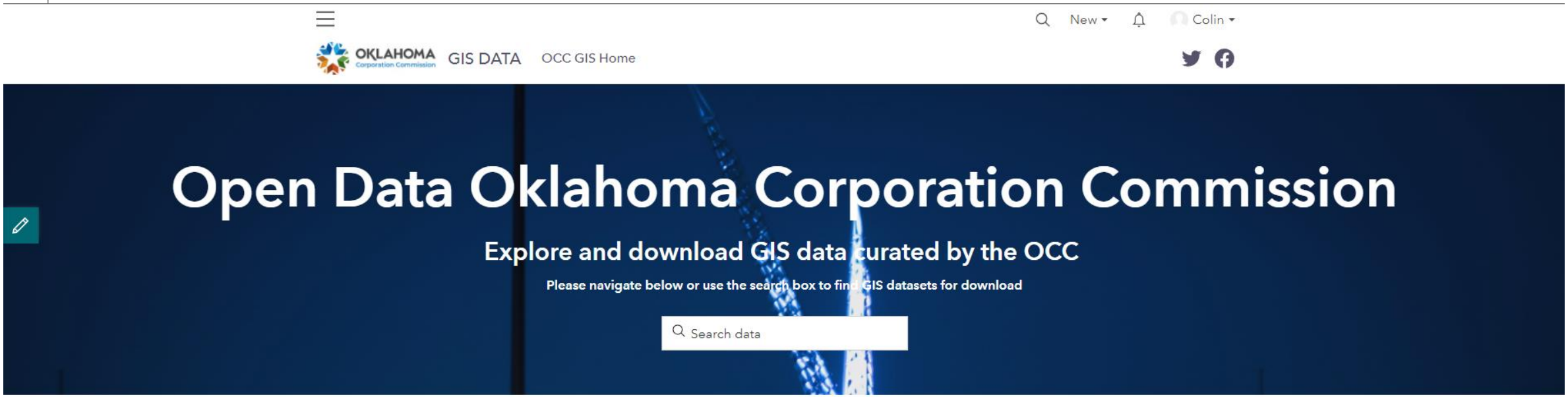


OCC WELL DATA FINDER APP

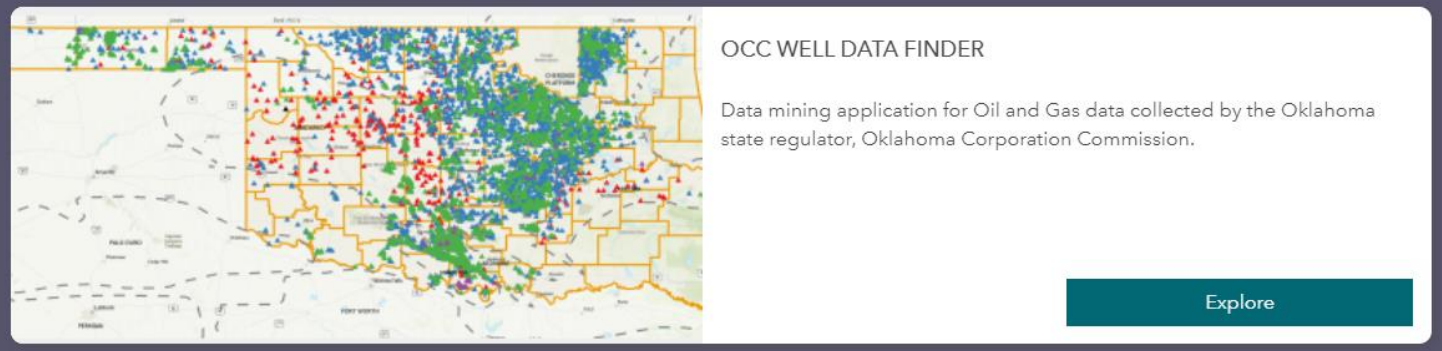


https://gis.occ.ok.gov/portal/apps/webappviewer/index.html?id=ba9b8612132f4106be6e3553dc0b827b

Open Data Portal



OCC WEBAPPS



https://gisdata-occokc.opendata.arcgis.com/

2.0+ Earthquake Update

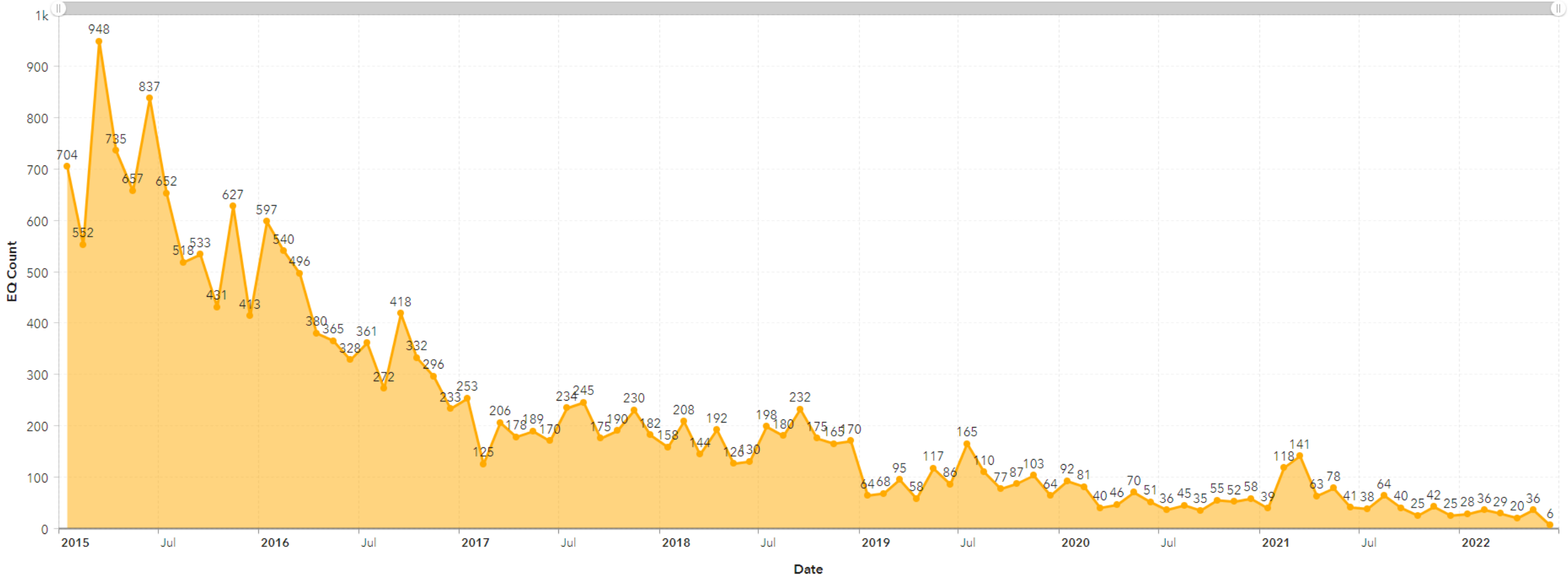
OCC Daily Earthquake Update

Use year selector or magnitude threshold (right) to filter data

Earthquake Magnitude T...
2+

Year Selection: 2015-2022 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022

Earthquake Counts OGS Catalog

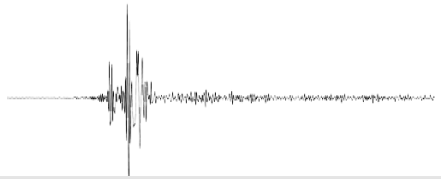


Please use the tabs at the bottom of the page to navigate to different data panels. At the far right you will find a list of FAQs under About This Dashboard

Last update: a minute ago

Earthquake Chart (Line) | Earthquake Chart (Bar) | 2.7+ Earthquakes by Year | 3.0+ Earthquakes by Year | 2.7+ Daily EQ Rates By Year | 3.0+ Daily EQ Rates By Year | OGS Earthquake Map | About This Dashboard

2.7+ Daily Earthquake Rates



OCC Daily Earthquake Update

Use year selector or magnitude threshold (right) to filter data

Earthquake Magnitude T...
2+

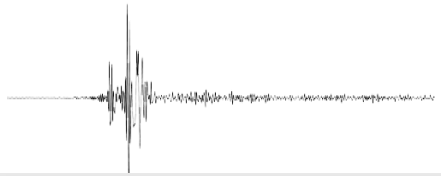
Year Selection: 2015-2022 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022

2015 Avg Rate	2016 Avg Rate	2017 Avg Rate	2018 Avg Rate
5.397	3.611	1.699	1.151
Per Day	Per Day	Per Day	Per Day
Last update: a minute ago	*Last update: a minute ago*	*Last update: a minute ago*	*Last update: a minute ago*

2019 Avg Rate	2020 Avg Rate	2021 Avg Rate	2022 Avg Rate
0.441	0.288	0.216	0.152
Per Day	Per Day	Per Day	Per Day
Last update: a minute ago	*Last update: a minute ago*	*Last update: a minute ago*	*Last update: a few seconds ago*

Earthquake Chart (Line) | Earthquake Chart (Bar) | 2.7+ Earthquakes by Year | 3.0+ Earthquakes by Year | 2.7+ Daily EQ Rates By Year | 3.0+ Daily EQ Rates By Year | OGS Earthquake Map | About This Dashboard

3.0+ Daily Earthquake Rates



OCC Daily Earthquake Update

Use year selector or magnitude threshold (right) to filter data

Earthquake Magnitude T...
2+

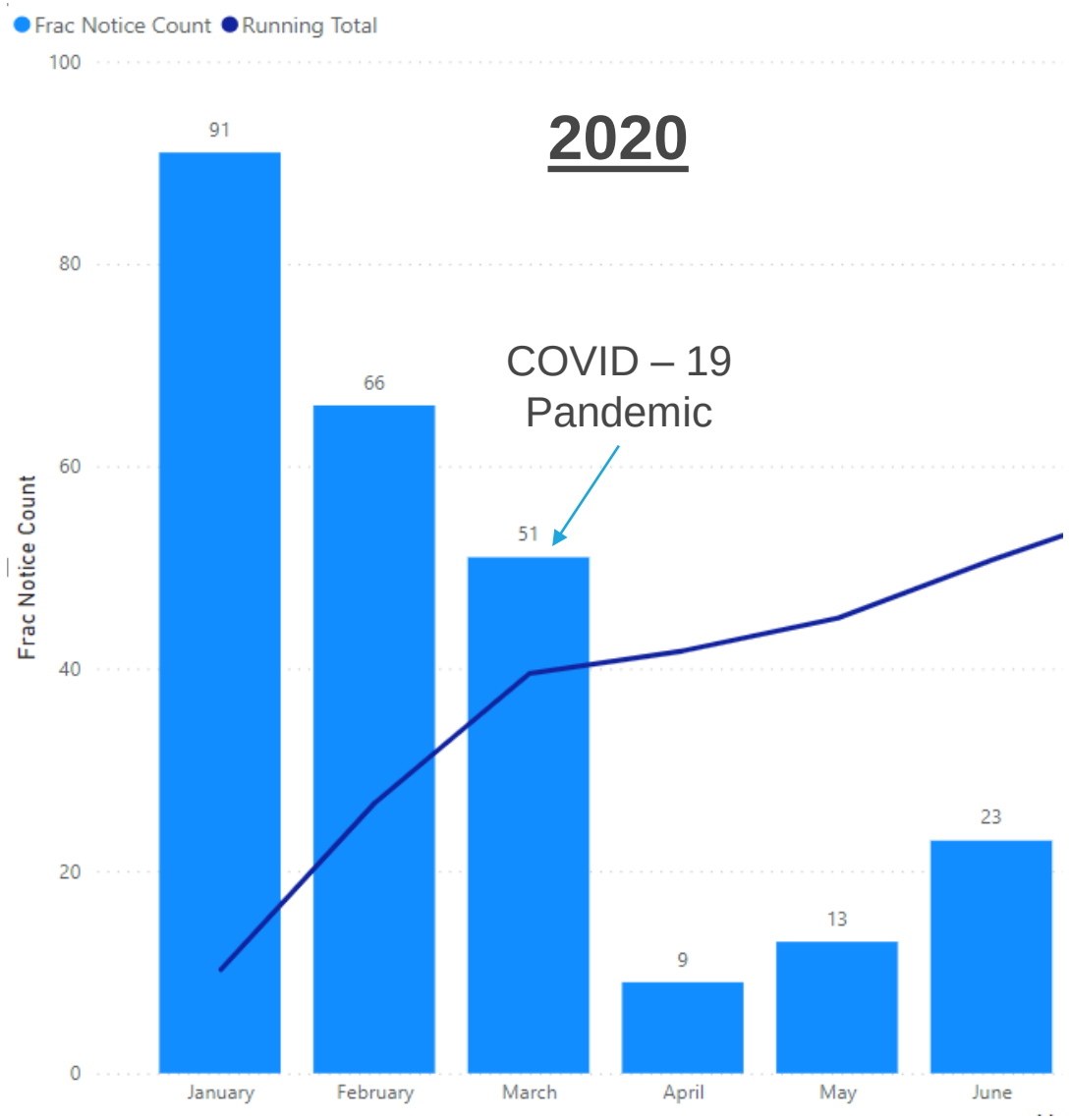
Year Selection: 2015-2022 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022

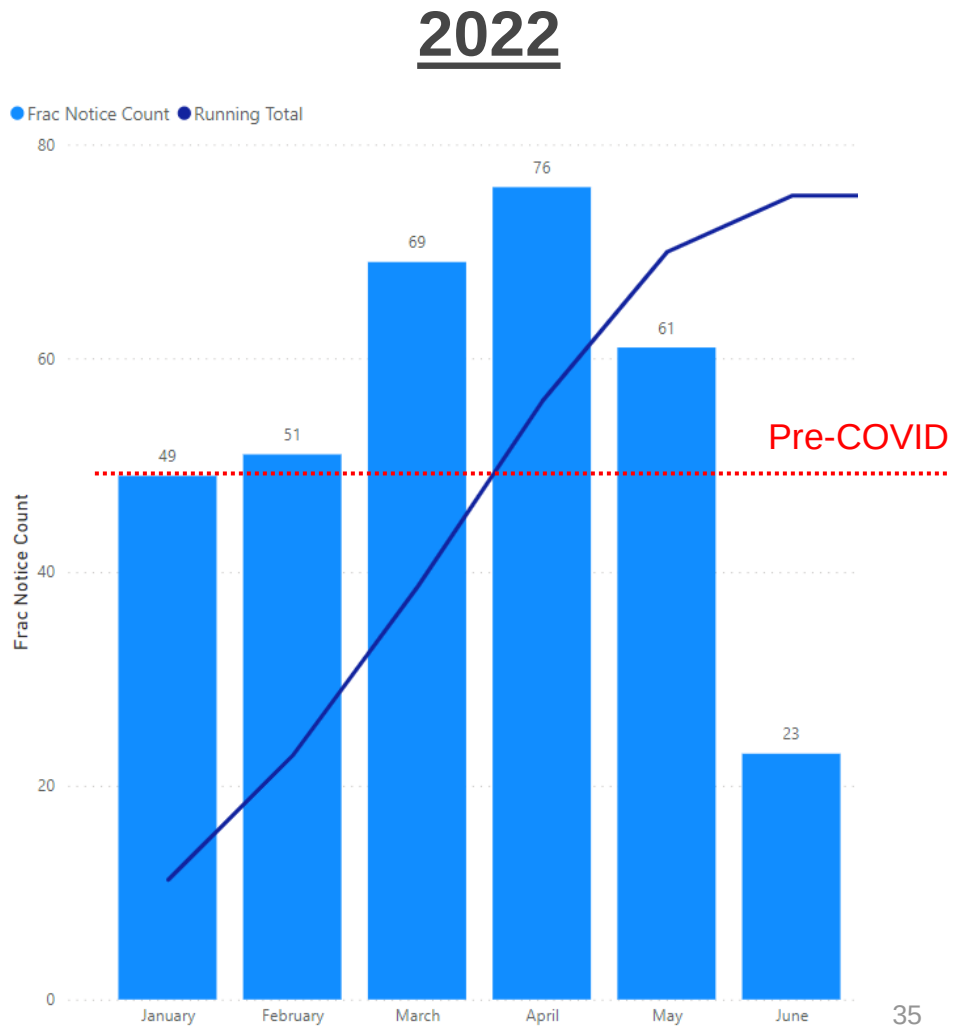
2015 Avg Rate	2016 Avg Rate	2017 Avg Rate	2018 Avg Rate
2.468	1.696	0.827	0.556
Per Day	Per Day	Per Day	Per Day
Last update: 2 minutes ago	*Last update: 2 minutes ago*	*Last update: 2 minutes ago*	*Last update: 2 minutes ago*

2019 Avg Rate	2020 Avg Rate	2021 Avg Rate	2022 Avg Rate
0.2	0.123	0.104	0.043
Per Day	Per Day	Per Day	Per Day
Last update: 2 minutes ago	*Last update: 2 minutes ago*	*Last update: 2 minutes ago*	*Last update: 2 minutes ago*

Earthquake Chart (Line) | Earthquake Chart (Bar) | 2.7+ Earthquakes by Year | 3.0+ Earthquakes by Year | 2.7+ Daily EQ Rates By Year | 3.0+ Daily EQ Rates By Year | OGS Earthquake Map | About This Dashboard

Frac Notice Trends





INFORMATION SHARING

- BIWEEKLY MEETINGS WITH THE OKLAHOMA GEOLOGICAL SURVEY TO DISCUSS ONGOING ISSUES, UPCOMING AREAS OF CONCERN, CURRENT PROJECTS
- COORDINATING COUNCIL ON INDUCED SEISMICITY – OKLAHOMA SECRETARY OF ENERGY AND ENVIRONMENT
- INDUSTRY, RESEARCHER AND AGENCY MEETINGS, TRAININGS, WORKSHOPS, AND CONFERENCES

WEB TOOLS

- RESPONSE TO OKLAHOMA EARTHQUAKES
- OCC DAILY EARTHQUAKE UPDATE
- WELL COMPLETION SEISMICITY PROTOCOLS
- OCC WELL DATA FINDER

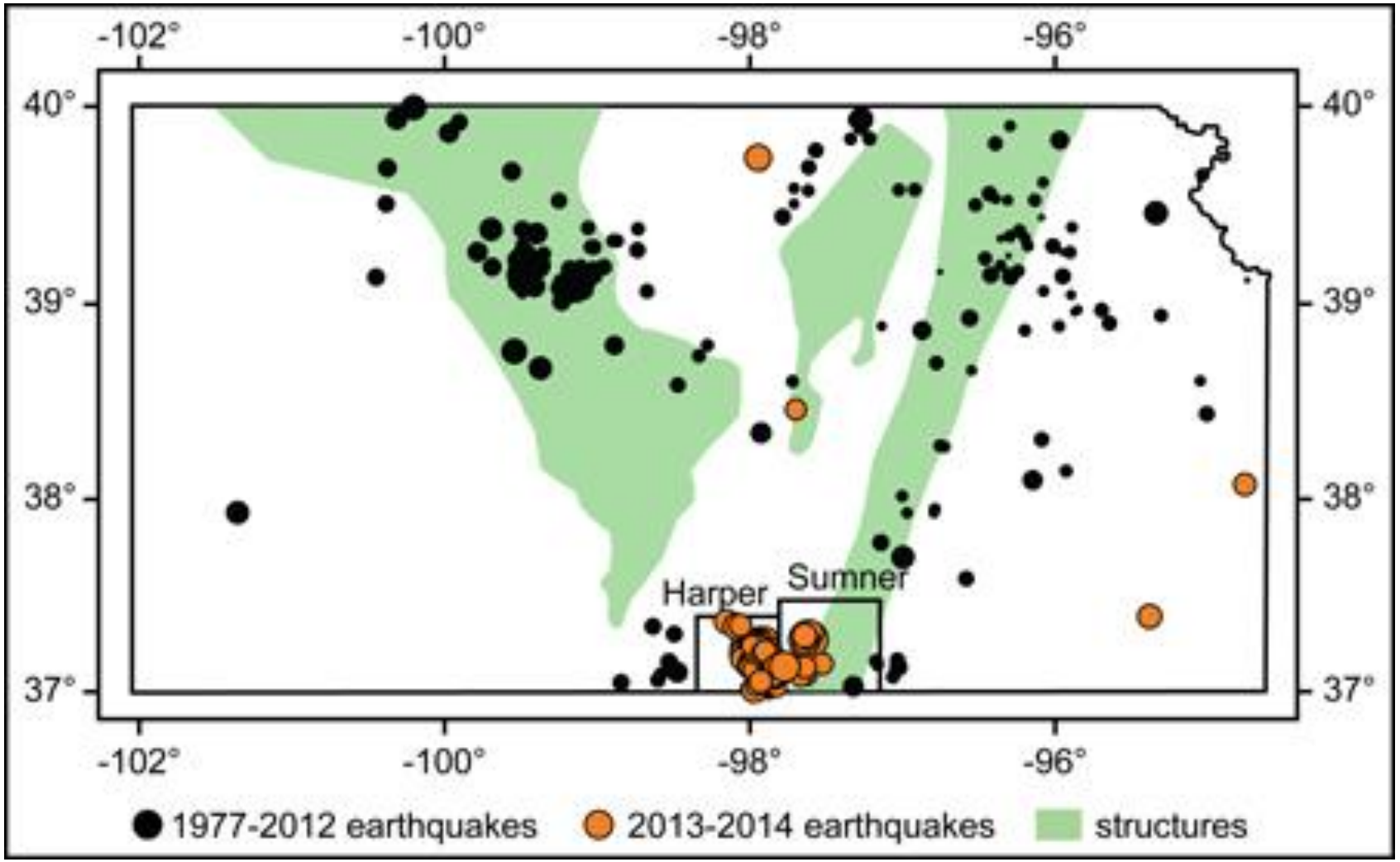
Kansas Geological Survey (KGS)
University of Kansas

Technical Lead – Rex Buchanan, rex@ksg.ku.edu

Lead Principal Investigator – Rolfe Mandel, mandel@ku.edu

RISC
Regional Induced Seismicity Collaborative

Kansas Earthquakes, 1977 – 2014



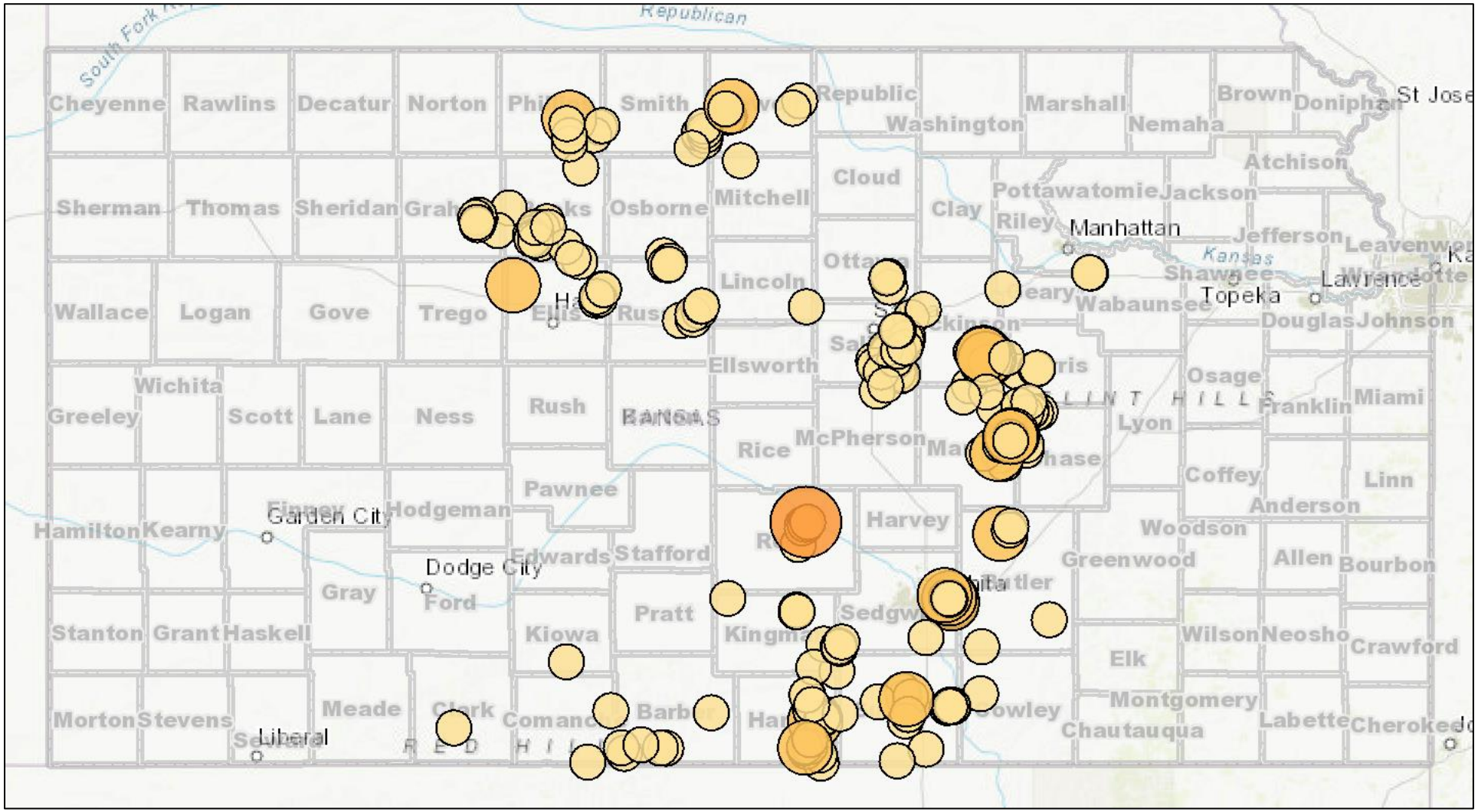
Peterie, S. L., Miller, R. D., Buchanan, R., and DeArmond, B. (2018), Fluid injection wells can have a wide seismic reach, Eos, 99, https://doi.org/10.1029/2018EO096199. Published on 17 April 2018.

South-Central Kansas Earthquakes, 2014

2014 Earthquakes – U.S. Geological Survey

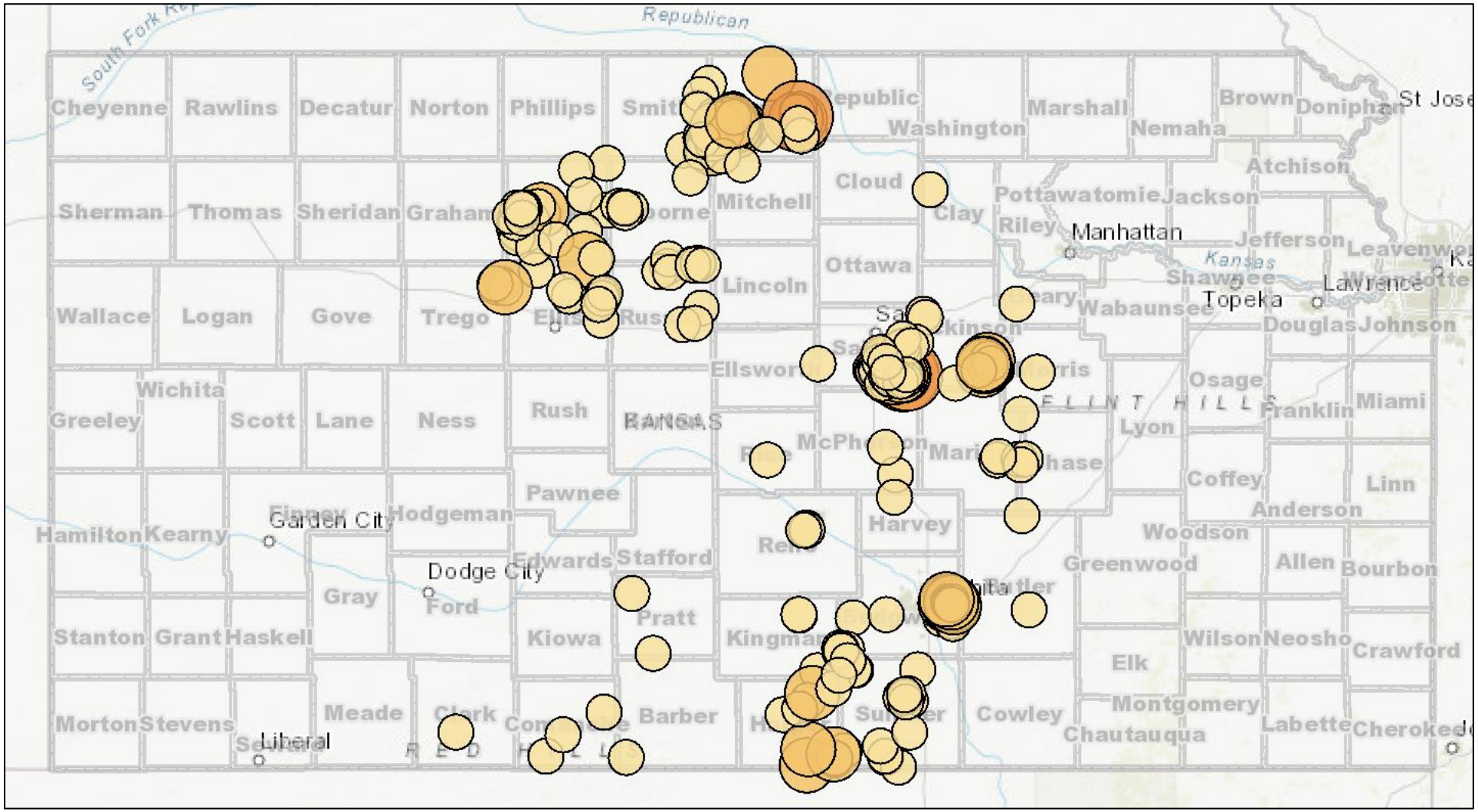
Kansas Earthquakes (M2.0 and larger), 2020

Kansas Geological Survey Interactive Mapper

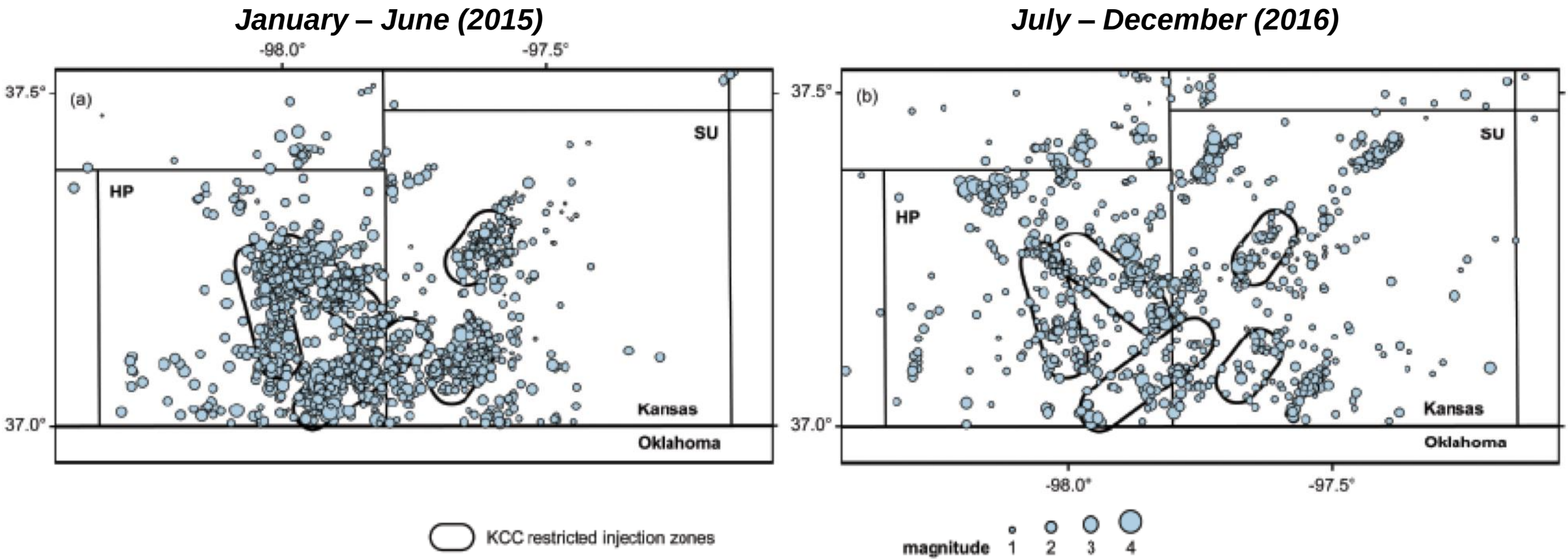


Kansas Earthquakes (M2.0 and larger), 2021

Kansas Geological Survey Interactive Mapper

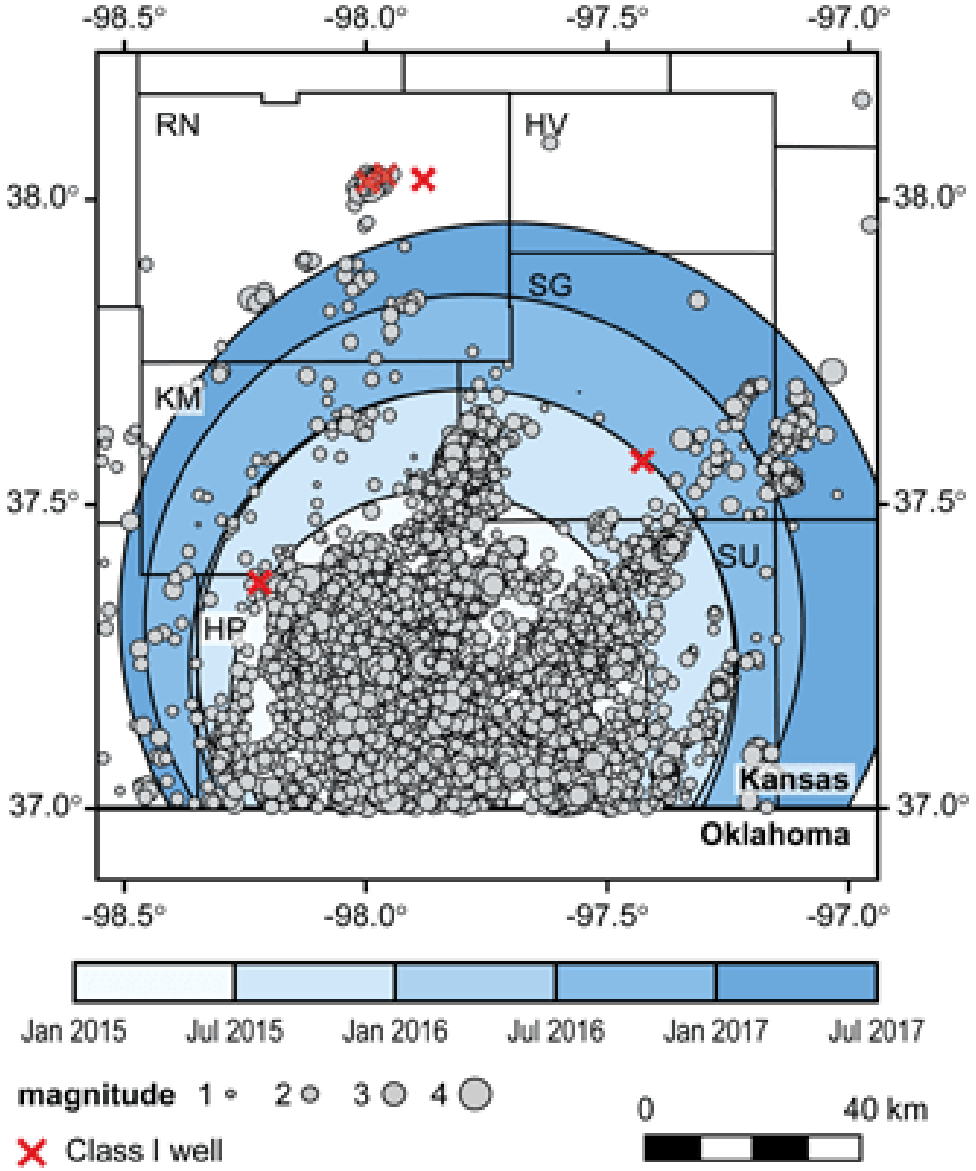


Harper/Sumner counties, Kansas, Earthquakes /KCC order zones



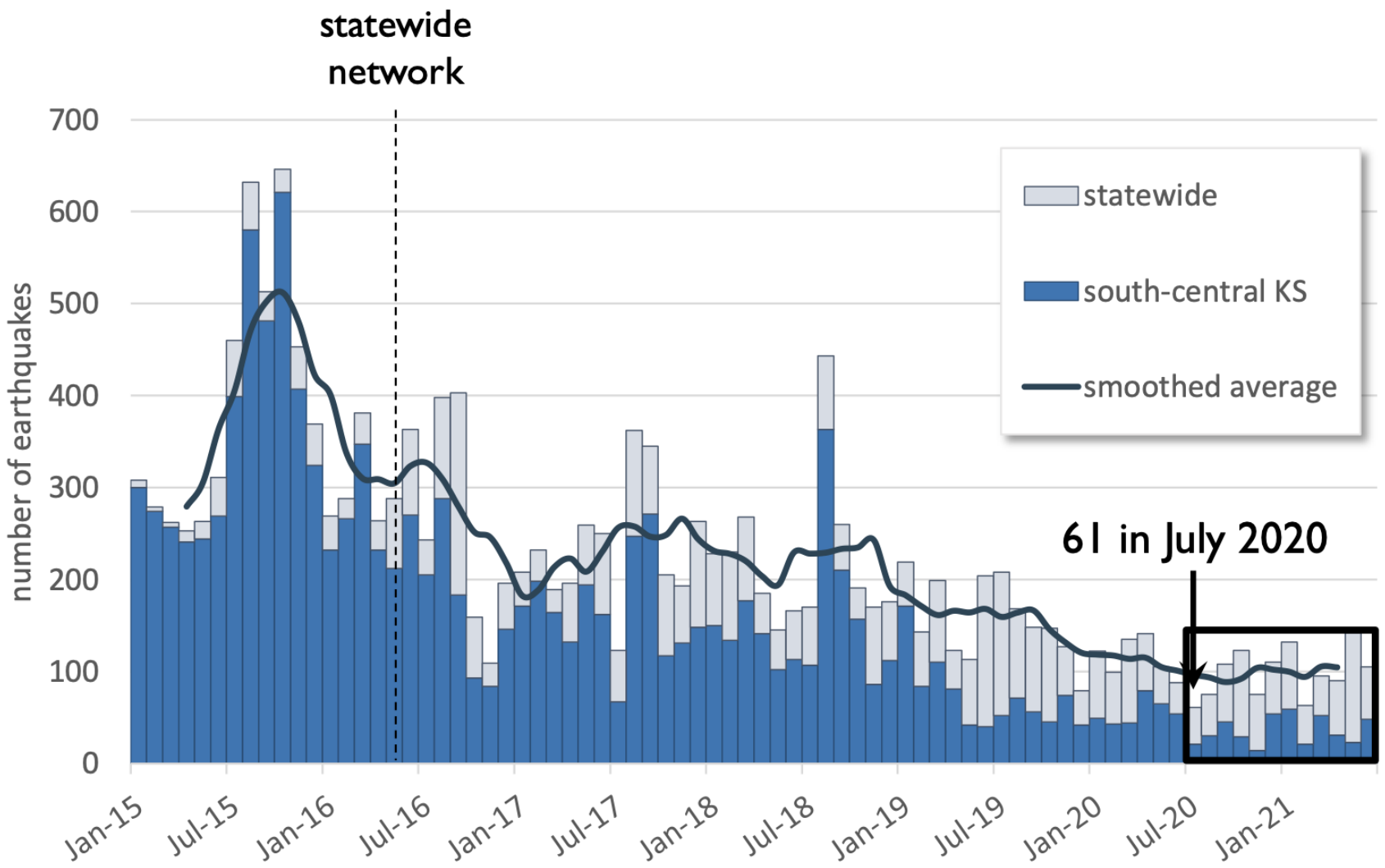
Peterie, S. L., Miller, R. D., Buchanan, R., and DeArmond, B. (2018), Fluid injection wells can have a wide seismic reach, Eos, 99, https://doi.org/10.1029/2018EO096199. Published on 17 April 2018.

South-Central Kansas Earthquakes, 2015 – 2017



Peterie, S. L., Miller, R. D., Buchanan, R., and DeArmond, B. (2018), Fluid injection wells can have a wide seismic reach, Eos, 99, https://doi.org/10.1029/2018EO096199. Published on 17 April 2018.

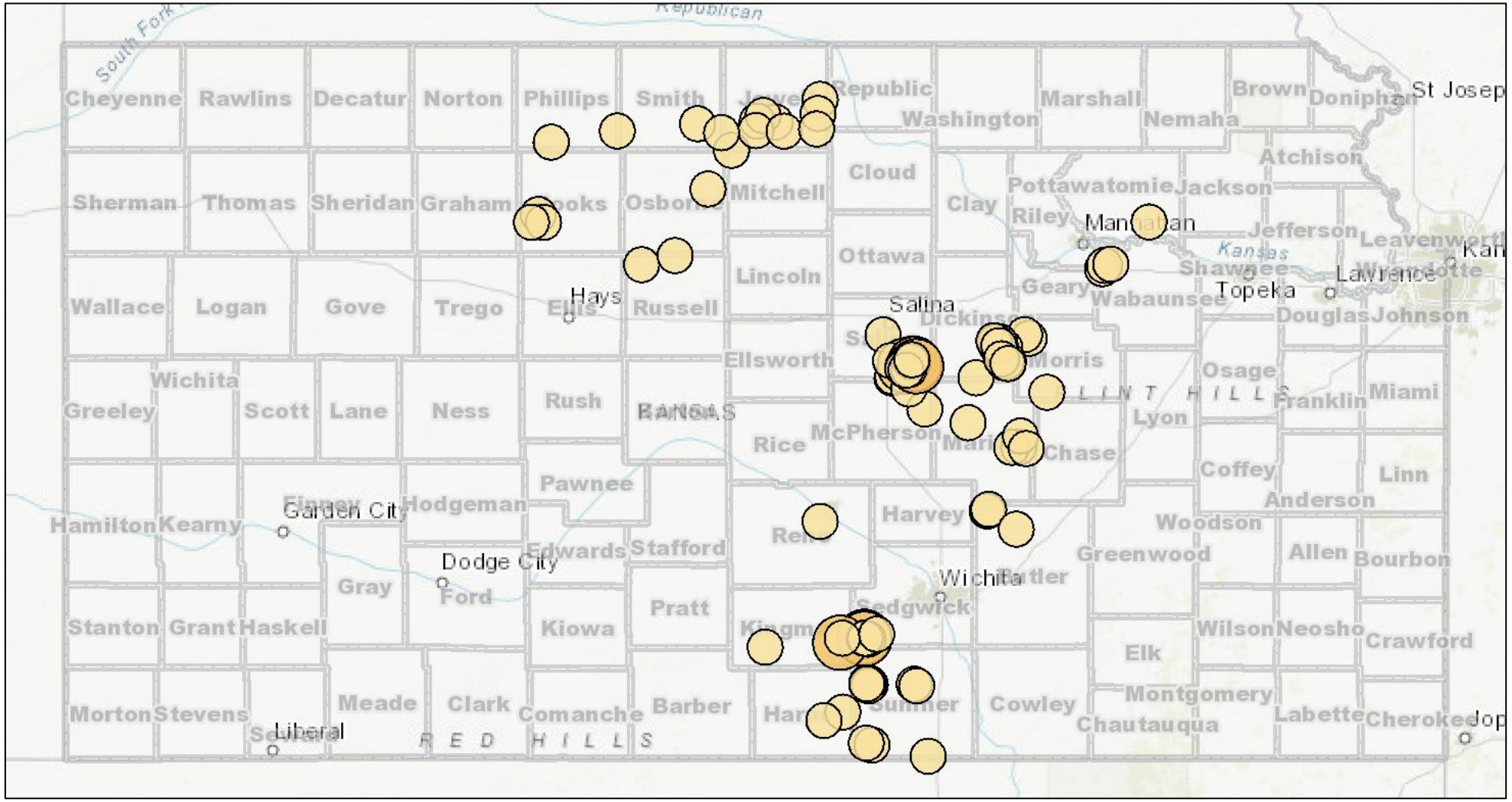
Monthly Kansas earthquakes, 2015-2021: Kansas Geological Survey



RISC Regional Induced Seismicity Collaborative

Kansas Earthquakes (M 2.0 and greater), January – June 2022

Kansas Geological Survey Interactive Mapper



New Mexico Bureau of Geology and Mineral Resources (NMBGMR), New Mexico Tech

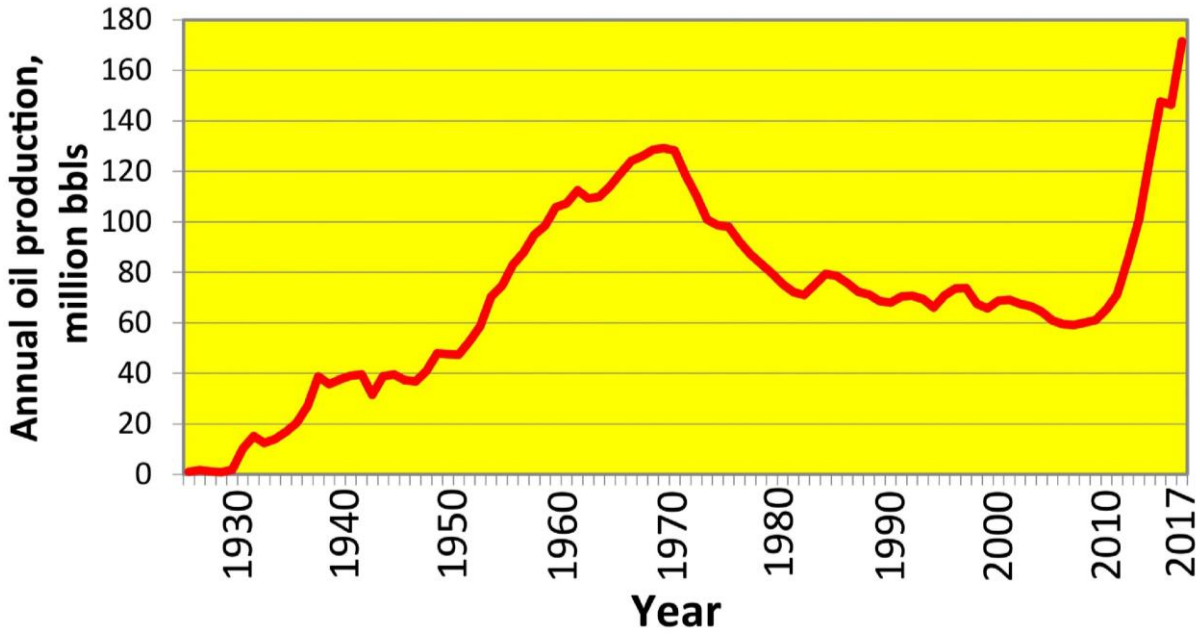
Technical Lead – Mairi Litherland, mairi.litherland@nmt.edu

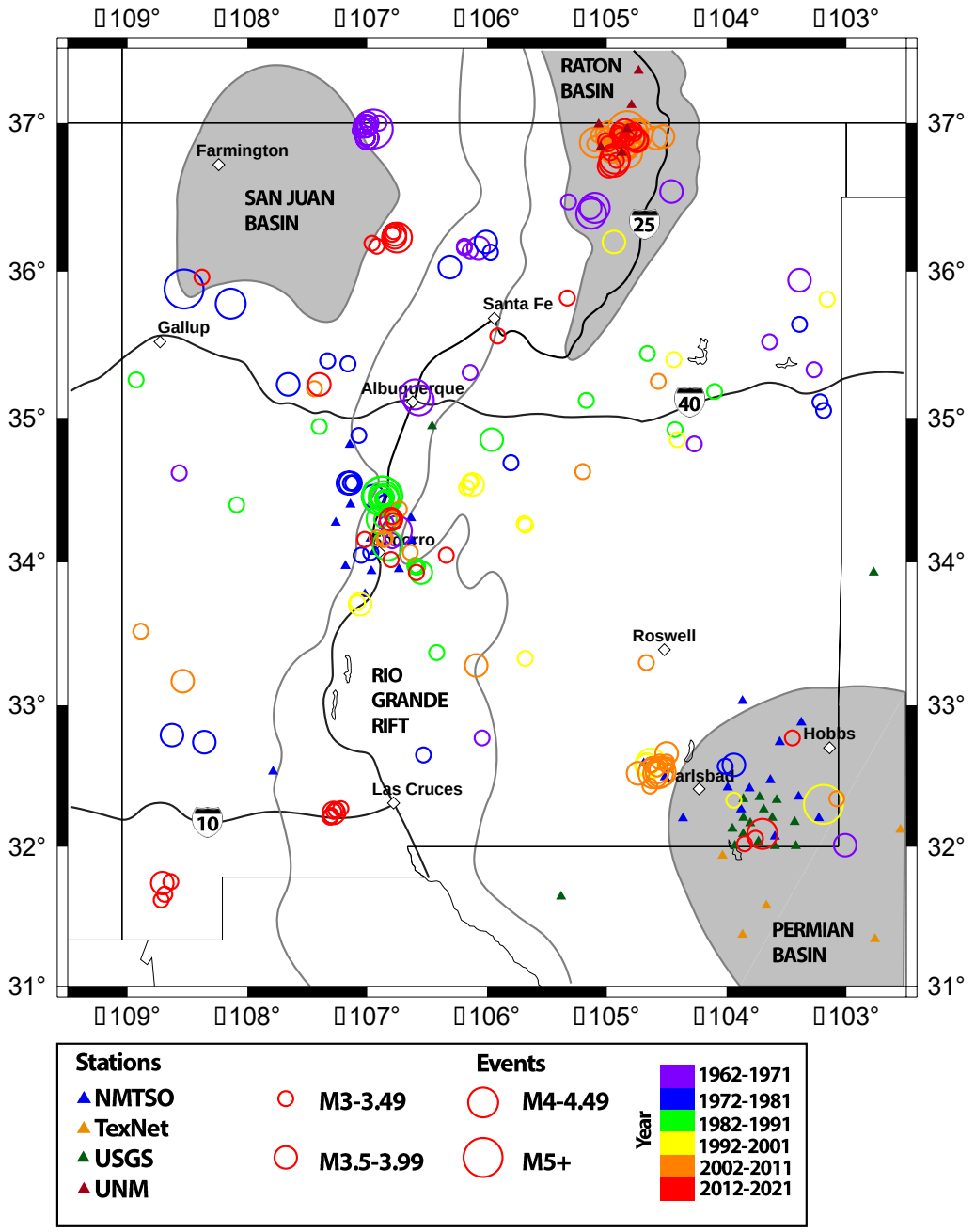
Lead Principal Investigator – Mike Timmons, mike.timmons@nmt.edu

RISC
Regional Induced Seismicity Collaborative

Induced seismicity in New Mexico

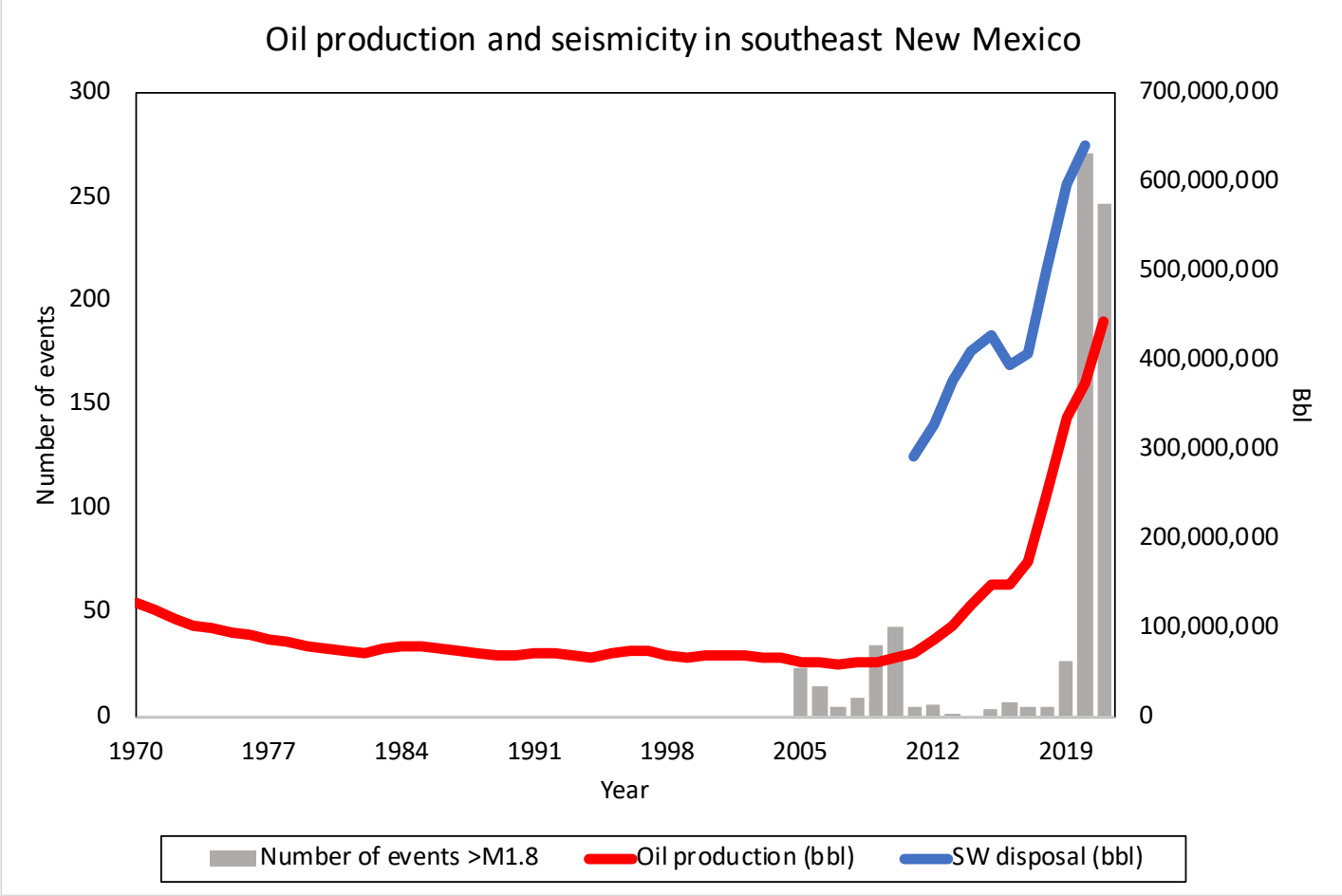
- Oil and gas production in NM has increased significantly over past decade
- Majority occurring in Delaware Basin in SE NM
- Raton basin has extraction from coal-bed methane deposits

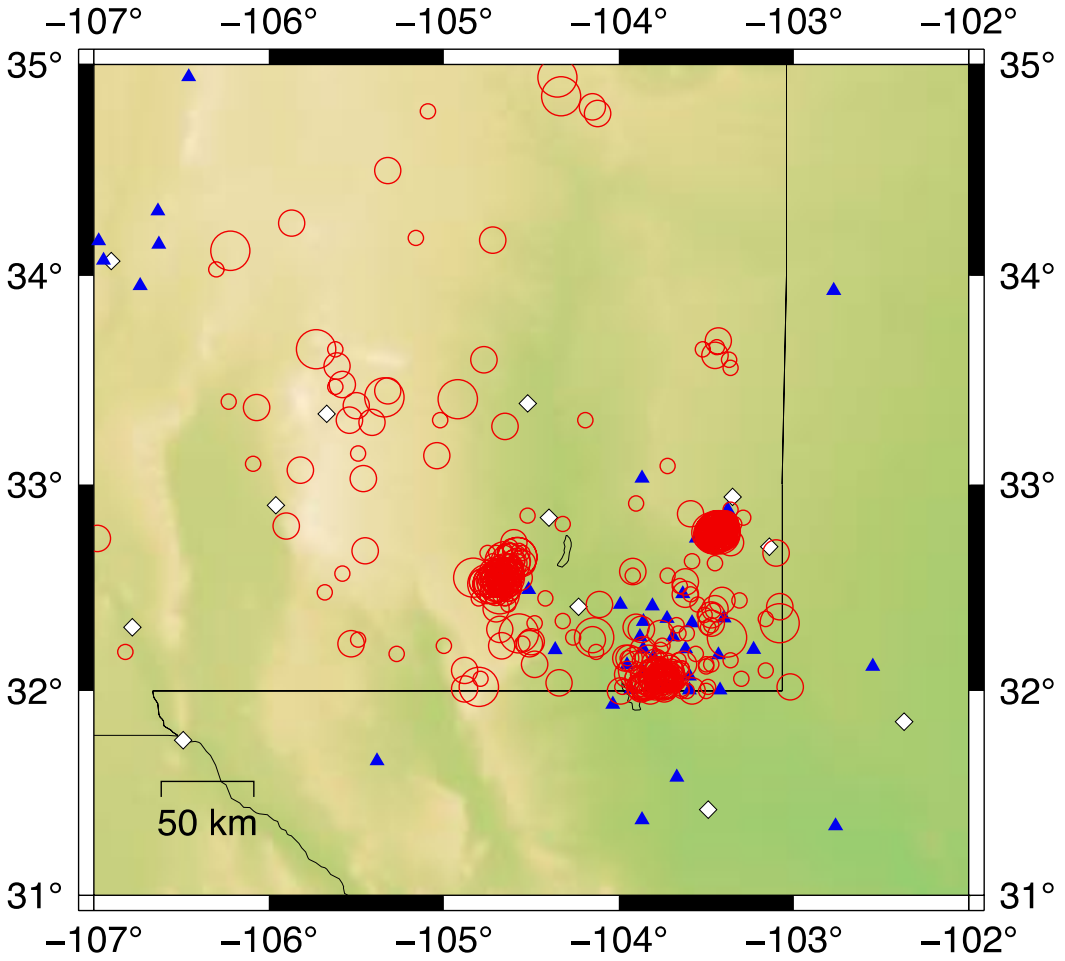




RISC Regional Induced Seismicity Collaborative

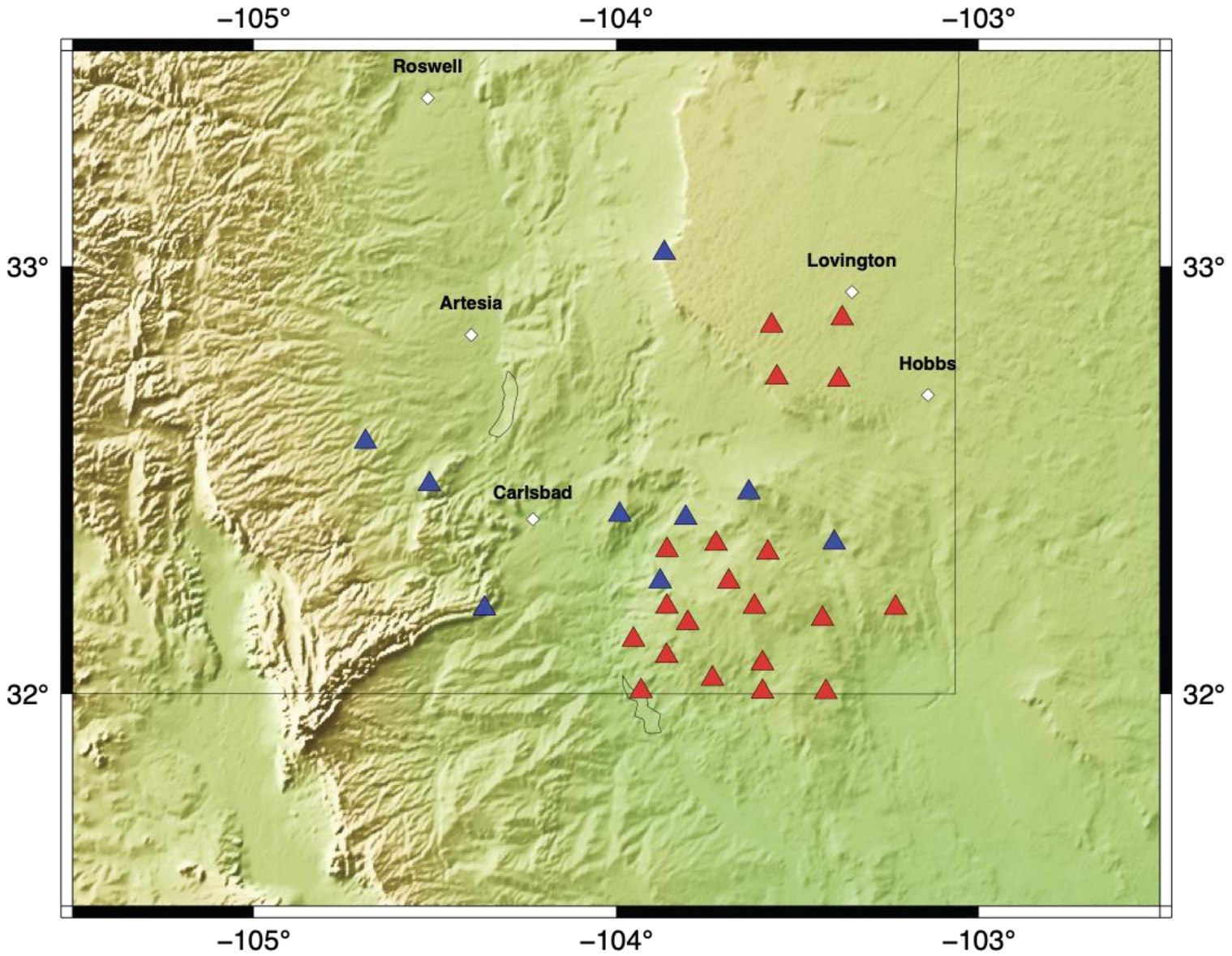
Induced seismicity in the Delaware Basin





Map of earthquakes larger than M1.8 recorded by the NMTSO in southeastern New Mexico from 2005-2021

Expanding seismic monitoring in New Mexico



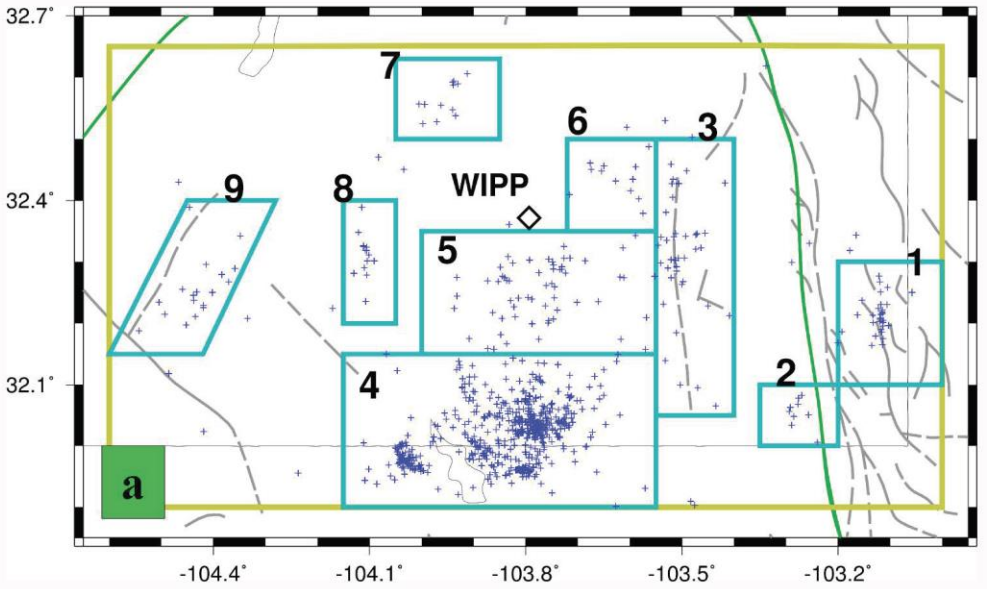
18 new 3-component broadband stations added in SE NM since late 2019

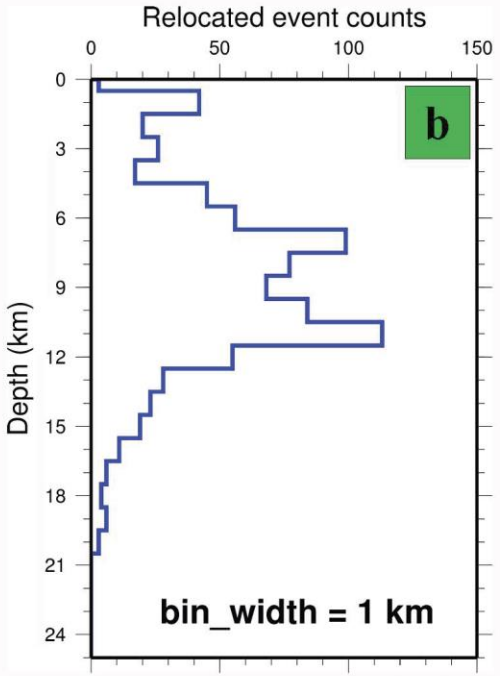
- 4 NMTSO stations
- 14 USGS stations

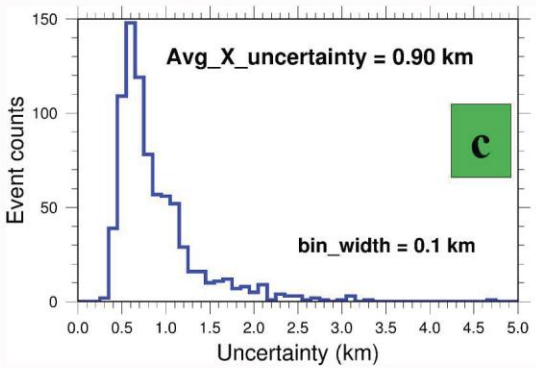
RISC Regional Induced Seismicity Collaborative

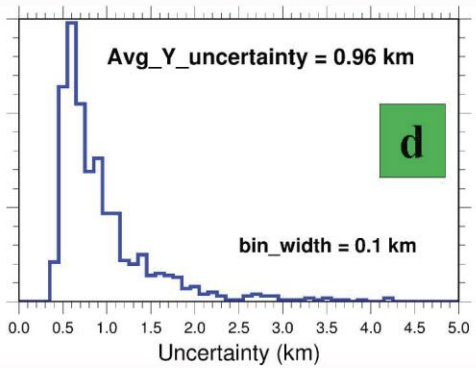
Improving historical seismic catalog

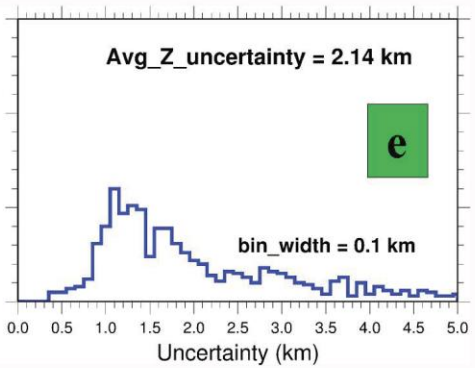
Earthquake relocation



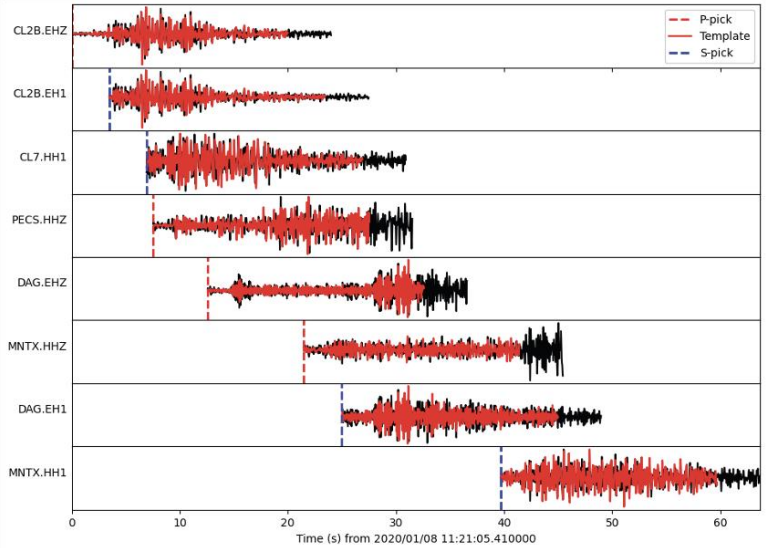




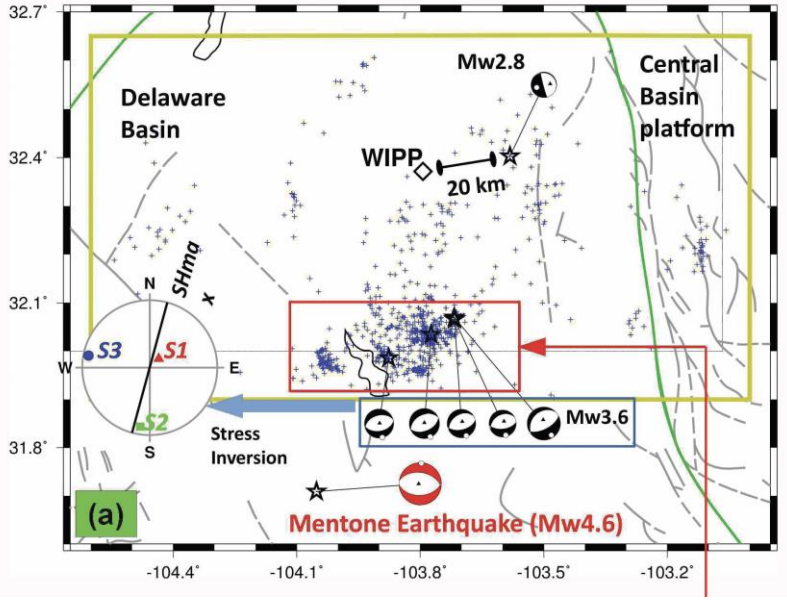




Template matching

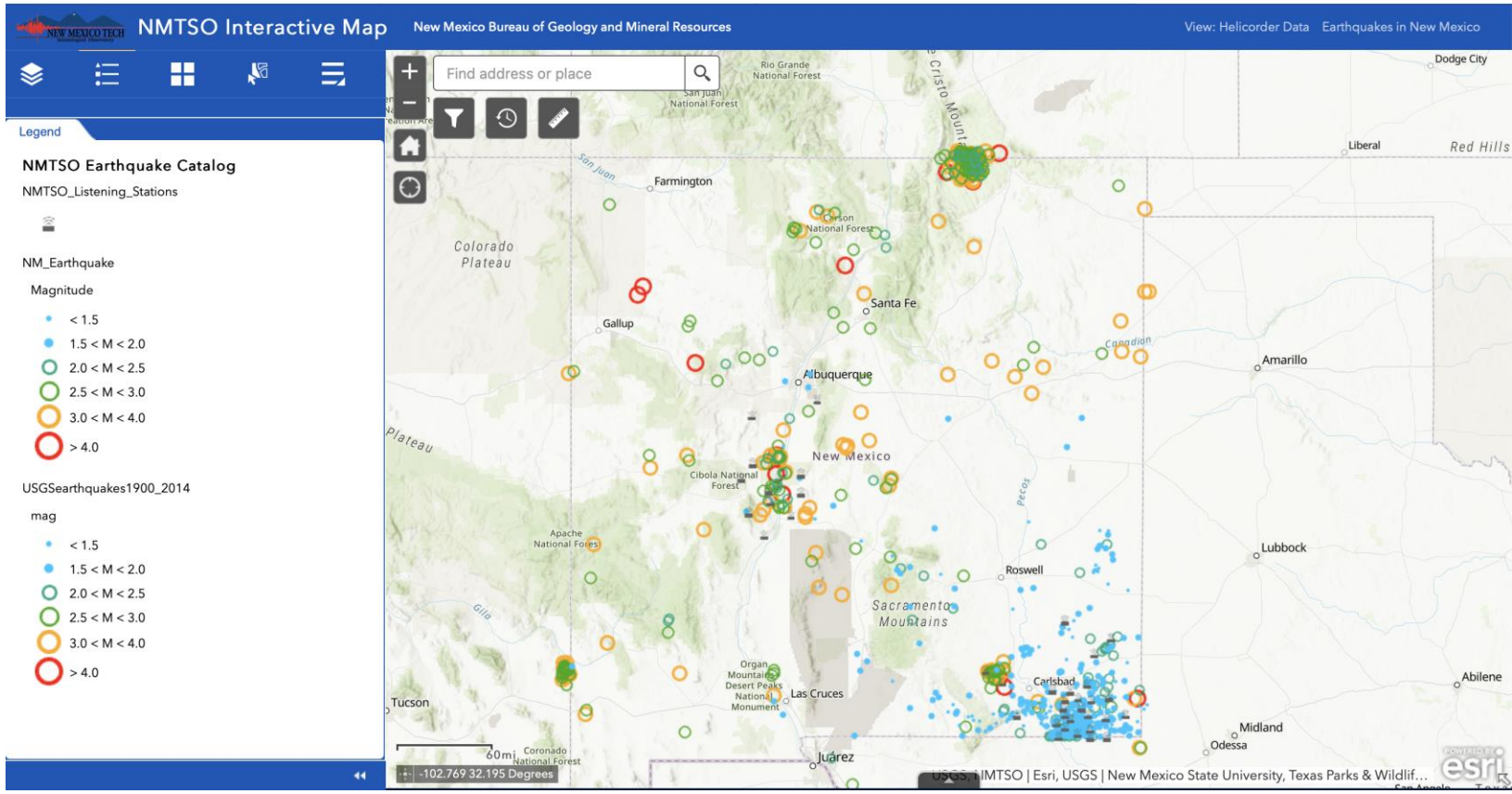


Moment tensor inversion



Real-time detection

- Began using Seiscomp for earthquake location in mid-2022
- Using machine learning algorithm to improve earthquake detection
- Rolling out new website to make event locations easily accessible to public, regulators, and industry



New Seismic Response Protocol

Oil Conservation Division
Energy, Minerals and Natural Resources Department
State of New Mexico

Seismicity Response Protocol (rev. date November 23, 2021)

Category 1: Seismicity Response Protocol:

Effective when Two M2.5 Events Occur Within 30 Days and Within a 10 mile Radius

Within 10 Miles

Monitoring & Reporting Protocols

- Weekly reporting of daily injection volumes and average daily surface pressure
  - Reporting in addition to C-115 reporting, on form provided by OCD
  - Digitally measure injection volume and pressure. The Data must be recorded on an hourly basis at a minimum. Operator shall archive digital injection data and deliver upon request
- Operators must provide an analysis identifying the perforated injection interval and formation tops.
- Operator must monitor seismicity (magnitude >~M2.5 for 10 miles around well using USGS/NMTSO data)
  - Operators shall share monitor data with OCD when requested
- Additional requirements may be added if determined appropriate by the OCD.

Category 2: Seismicity Response Protocol:

Effective with one M3.0+ Event

M3.0+ event

All Category 1 Monitoring & Reporting protocols, and

- 50% rate reduction within 0-3 miles
- 25% reduction between 3-6 miles
- Reductions to rate should start immediately and be completed within a week
- Notify OCD of pertinent information within 24 hours or next business day, whichever is latest, of an event using the OCD form.

M3.5+ event

All Category 1 Monitoring & Reporting protocols, and

- Shut in at 0-3 miles
- 50% rate reduction at 3-6 miles
- 25% rate reduction at 6-10 miles
- Reductions to rate should start immediately and be completed within a week
- Notify OCD of pertinent information within 24 hours or next business day, whichever is latest, of an event using the OCD form.

- **All rates should be reduced from the previous 6-month daily average of active injection days**
- **Notifications should be made to the OCD by submitting to the OCD Permitting within 24 hours of receiving monitoring data of a seismic event within 10 miles of its facility.**
- **Such notification can be based on private or public seismic network data; however, final actions will be determined by USGS data concerning magnitude and location. All distances in this document are based on determined Epicenter.**
- **Pertinent information will be submitted to the OCD by an OCD form which is in development and will be submitted to the OCD via OCD.Engineer@state.nm.us**
- **OCD my reduce or eliminate disposal volumes within the curtailment radii above, at its sole discretion, if after 6 months no M3.0 events have occurred within 10 mi. of the original triggering event and/or OCD approves an operator/industry response plan within the response radii.**

Bureau of Economic Geology (BEG)
University of Texas at Austin

Lead Principal Investigator – Lily Horne, lily.horne@beg.utexas.edu

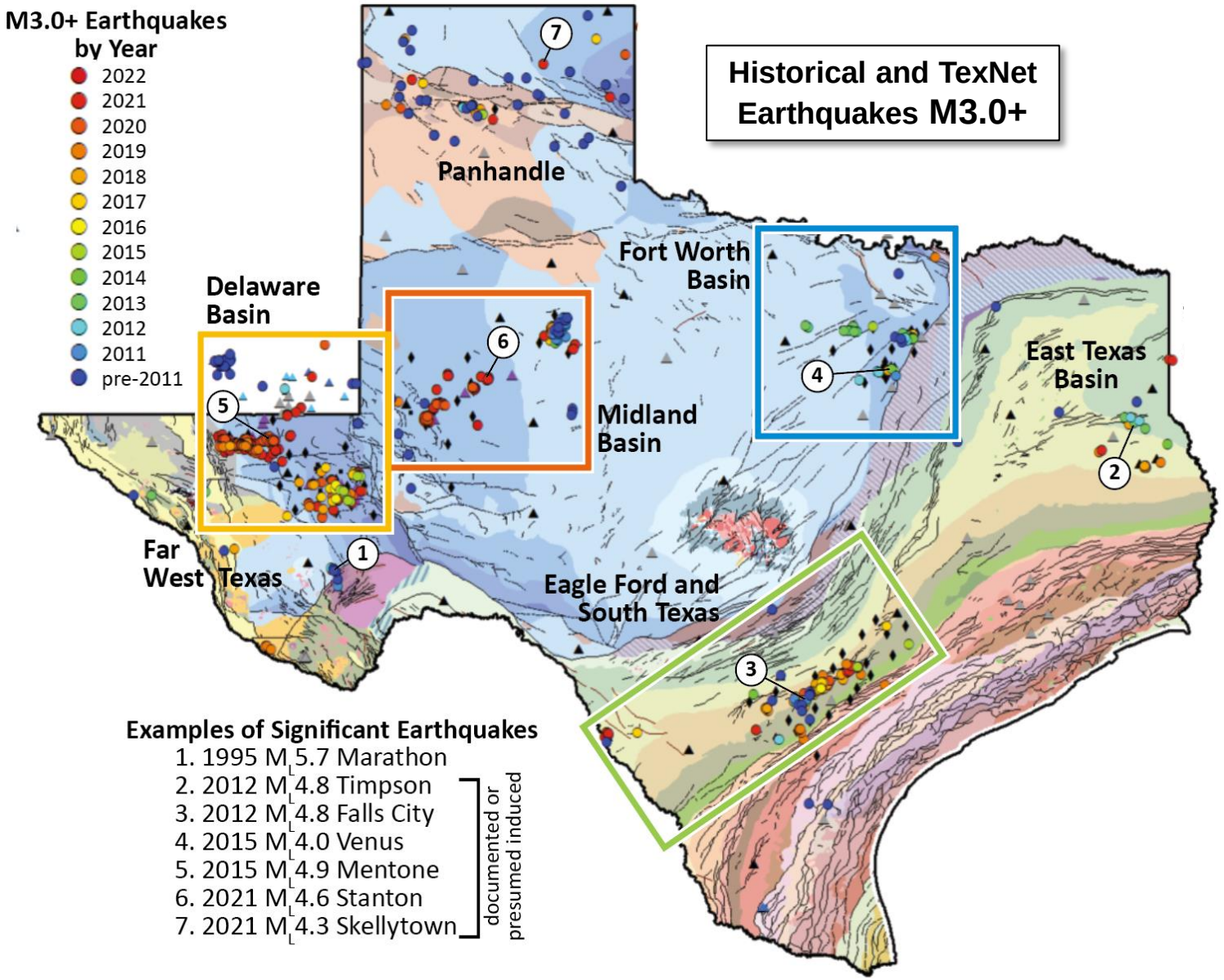
Contributors & Mentors:

Michael Young, michael.young@beg.utexas.edu

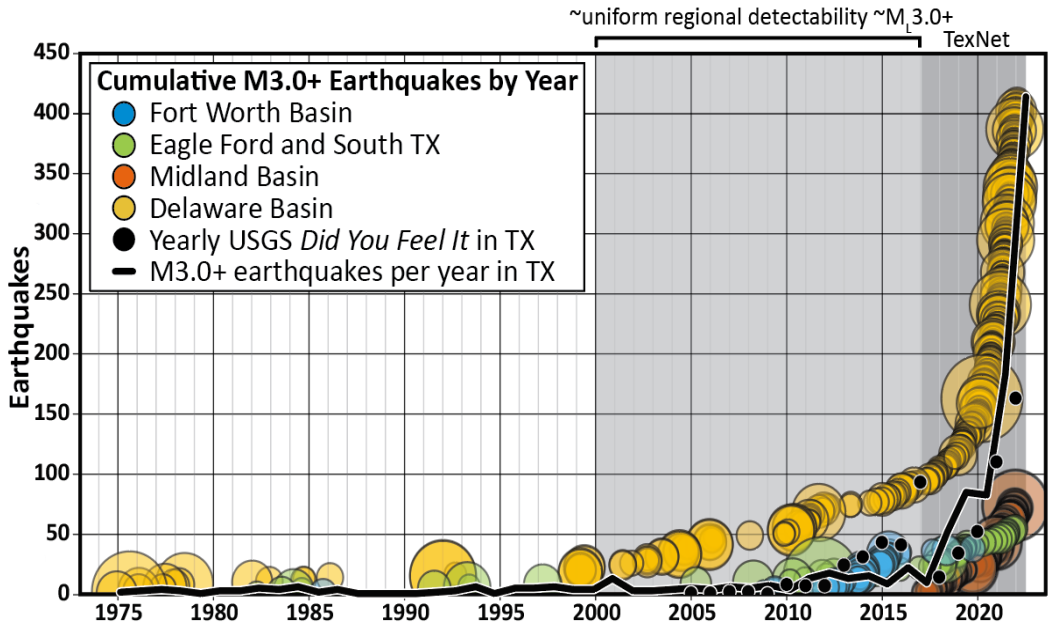
Peter Hennings, peter.hennings@beg.utexas.edu

RISC
Regional Induced Seismicity Collaborative

Earthquake history in Texas



History of instrumental seismicity in Texas for earthquakes of magnitude 3 and greater



Hennings, P. H. and Young, M. H., (in press, 2022), The TexNet-CISR Collaboration and Steps Toward Understanding Induced Seismicity in Texas: GSA Volume on Induced Seismicity.

RISC research exists within the TexNet-CISR collaboration

TexNet and CISR are 2 parts of a whole:

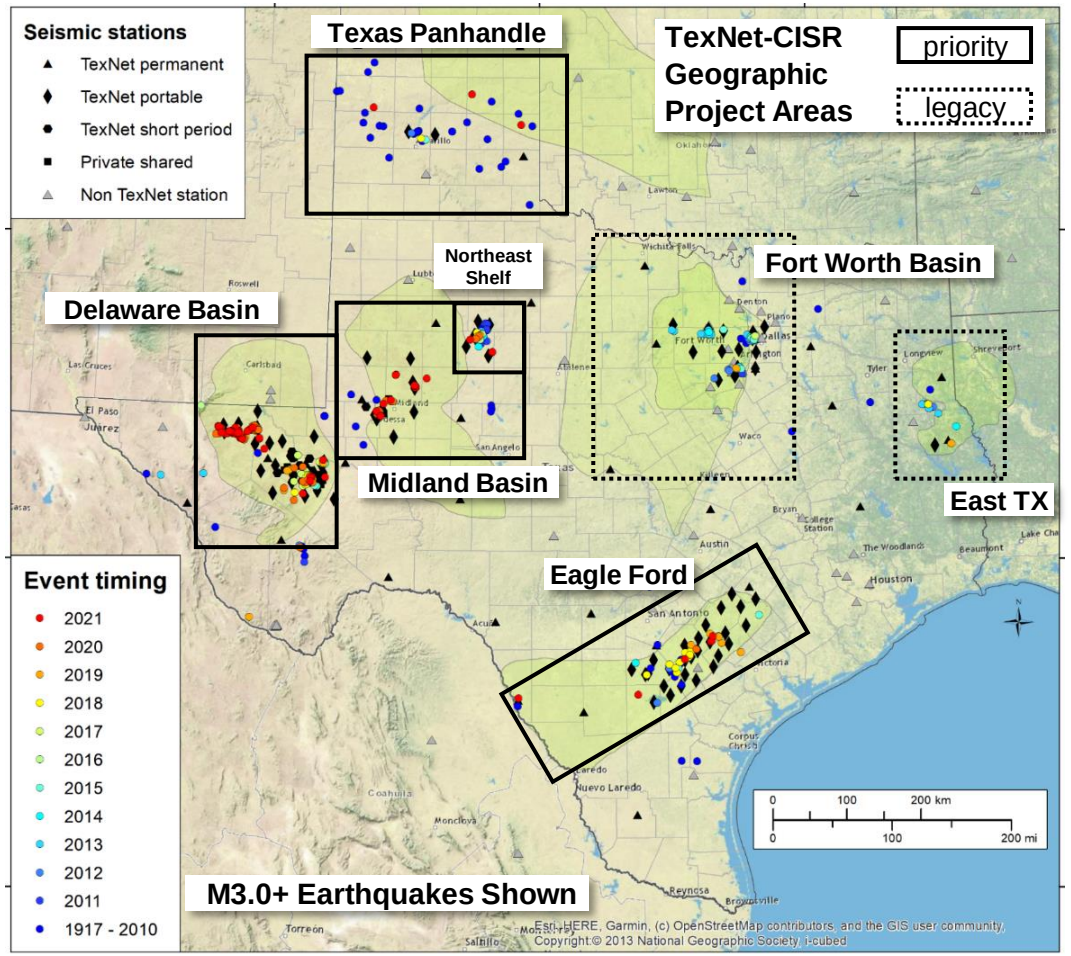
TexNet – Funded by the State of Texas, TexNet monitors, catalogs, and analyzes earthquakes using a *backbone* seismic network for State-wide coverage, and *temporary* stations for local studies.

Quality-controlled earthquake data is provided to the public.

Center for Integrated Seismicity Research – Funded by industry partnership, CISR extends TexNet data and research to more thoroughly study earthquakes to improve the understanding of the intersection of natural and anthropogenic factors so that stakeholders can mitigate induced earthquakes.

The principal research goals and activities are to:

- Understand Earthquake Activity
- Characterizing the Hazard and Understanding Causal Factors
- Understand Impacts
- Develop Applications for Mitigation

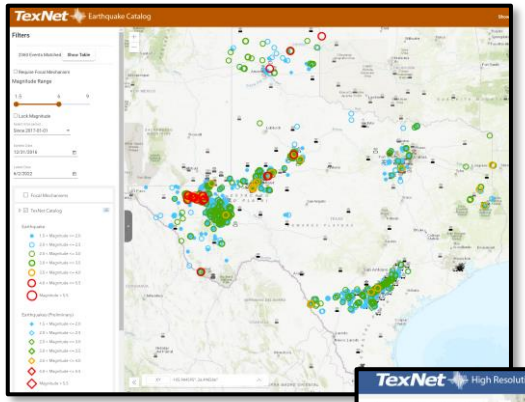


2022 CISR Sponsors:

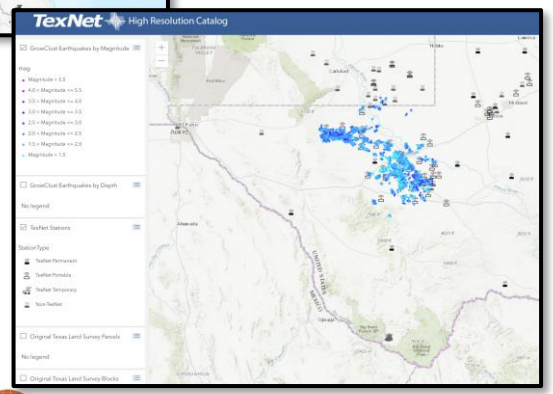
TexNet has deployed more than 160 real time stations

TexNet Seismic Stations

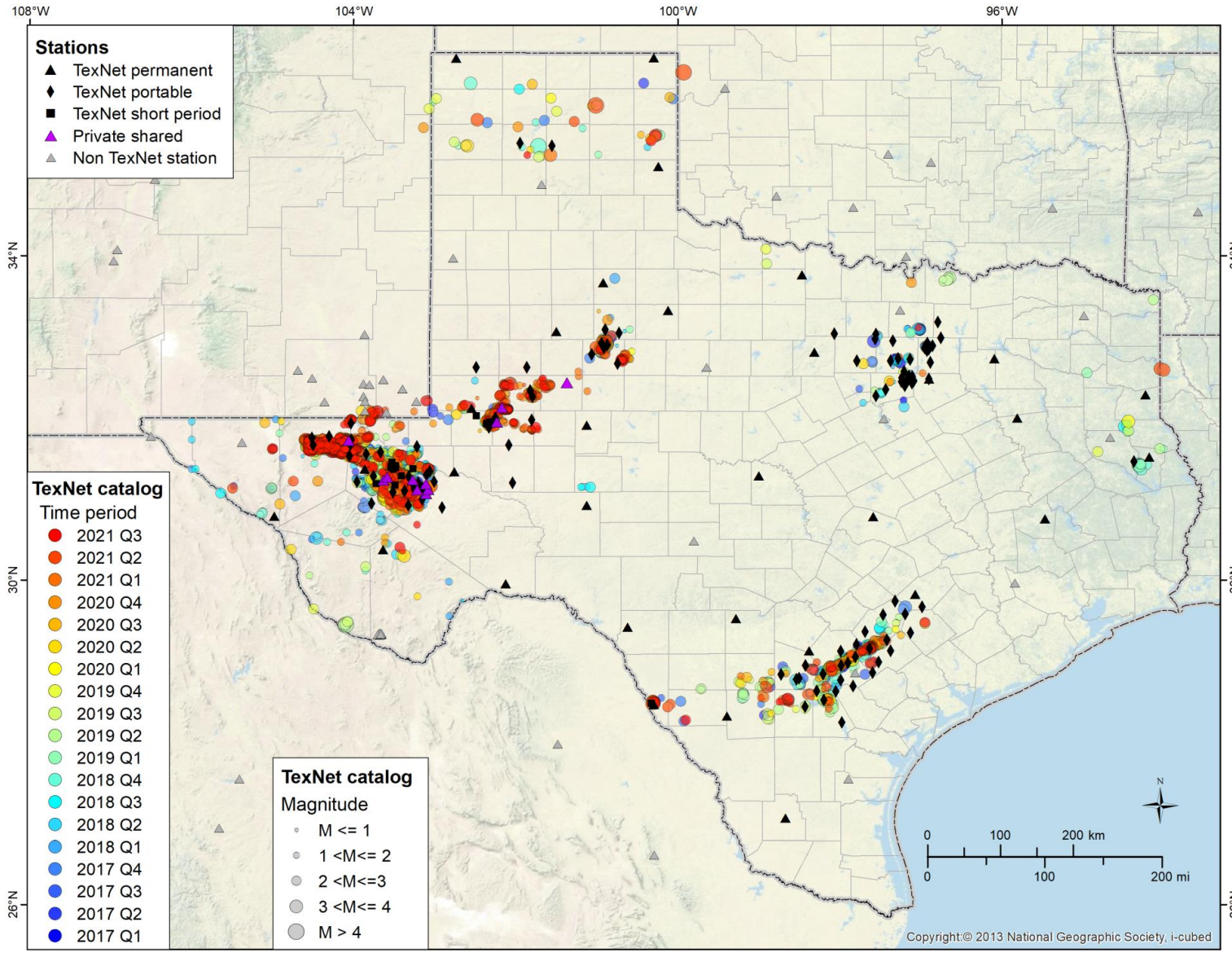
- Texas (shallow borehole) Backbone: 20
- Delaware Basin: 41
- Midland Basin: 15
- Fort Worth Basin: 31
- Eagle Ford: 31
- Cogdell Field/Snyder Area: 7
- Texas Panhandle: 5



TexNet Earthquake Catalog



TexNet High Resolution Catalog

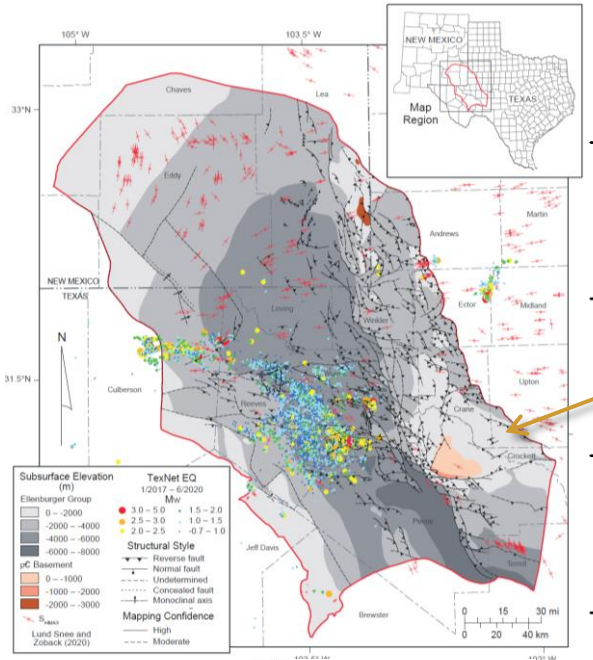


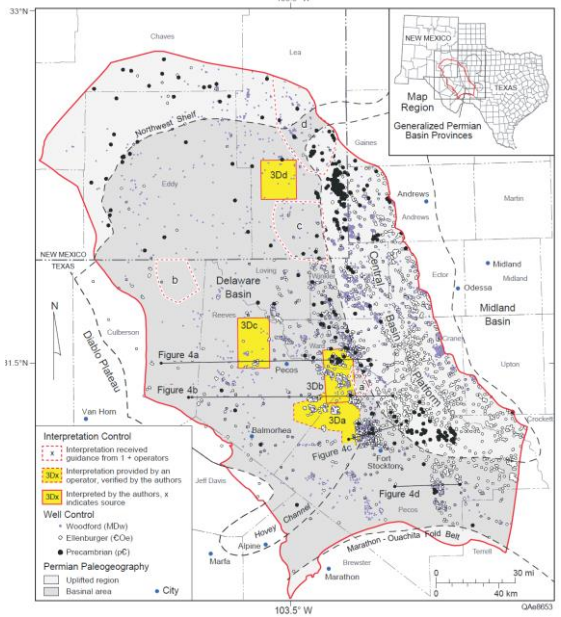
RISC Regional Induced Seismicity Collaborative

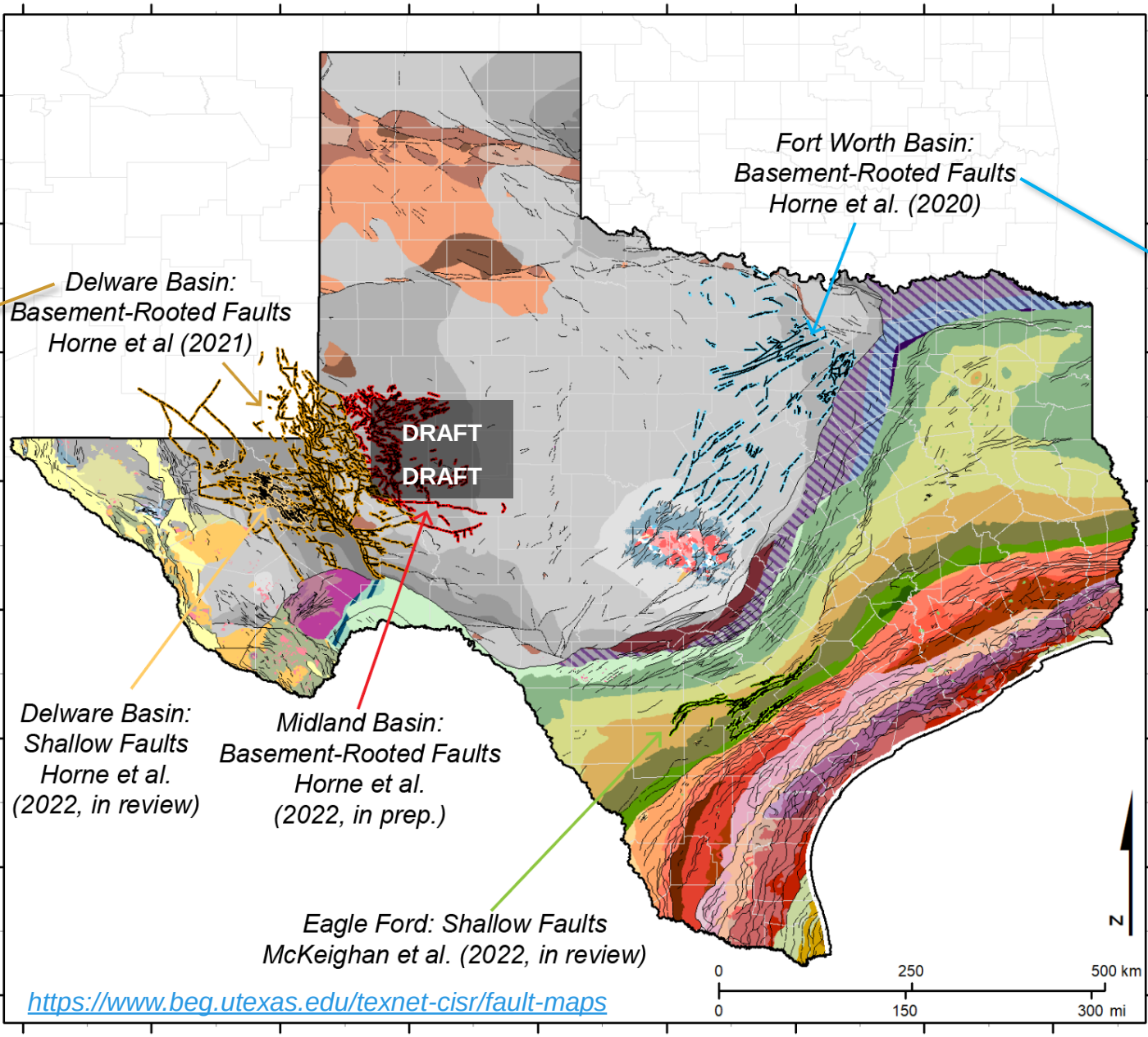
Bureau of Economic Geology · KU Kansas Geological Survey · OGS · Arkansas Geological Survey · Groundwater Protection Council

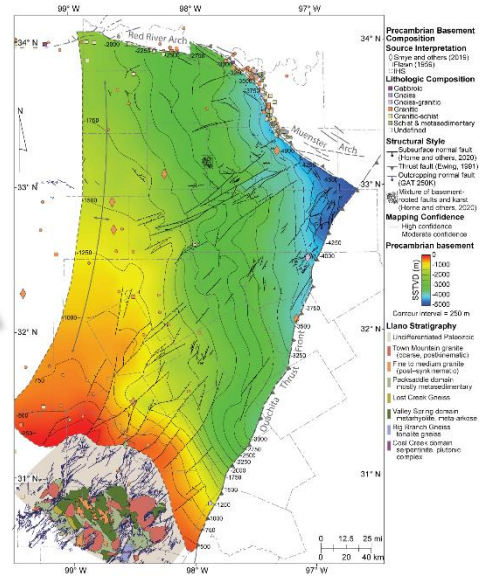
https://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog
https://hirescatalog.texnet.beg.utexas.edu/

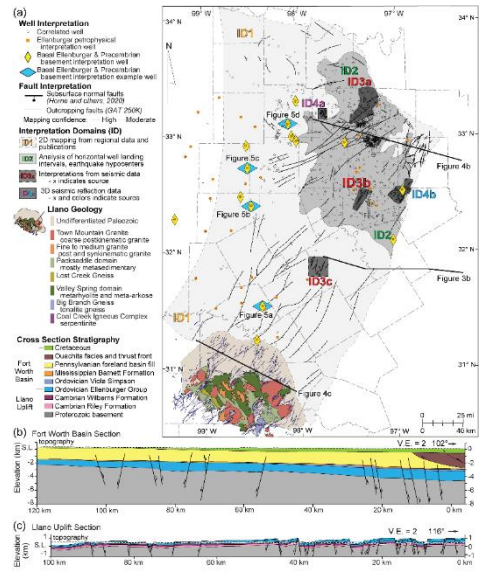
TexNet-CISR has produced basin-scale fault trace maps and 3D models











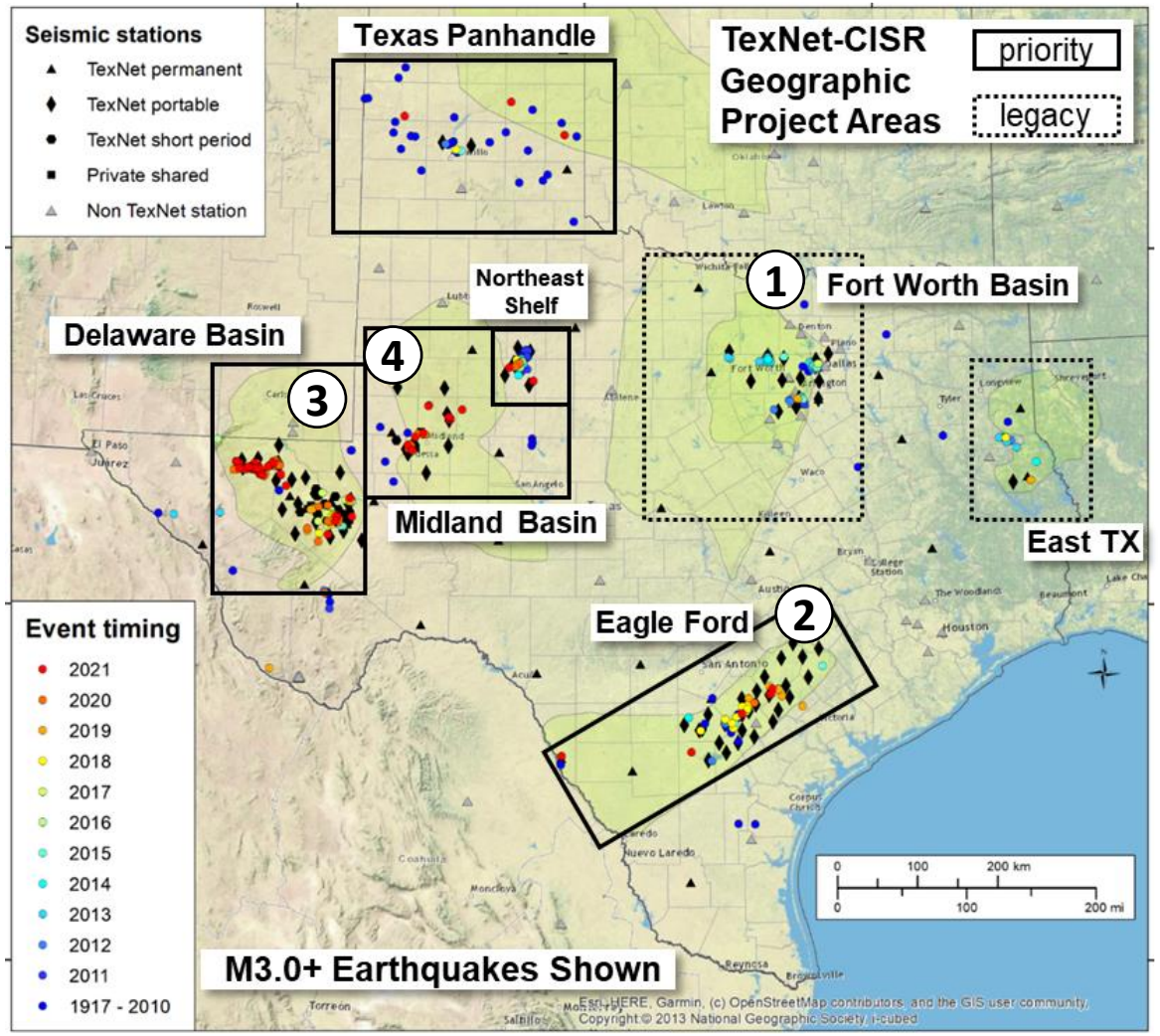
TexNet-CISR principal research efforts

1. **Understanding Injection-Induced Fault Rupture in the Fort Worth Basin *[past work, illustrative of TexNet-CISR integration]***
   Collaborating institutions: UT-BEG, SMU, UT-IG, UT-PGE, TAMU, SwRI, Stanford, Univ Miami OH

2. **Understanding Hydraulic Fracture-Induced Fault Rupture in the Eagle Ford Production Play *[finishing student work]***
   Collaborating institutions: UT-BEG, UT-IG, SwRI, Univ Miami OH

3. **Understanding Induced Seismicity Causes and Mechanisms in the Delaware Basin *[most dynamic work but in-progress]***
   Collaborating institutions: UT-BEG, UT-IG, SMU, UT-PGE, UT-AME, SwRI, Stanford, UTEP

4. **Understanding Induced Seismicity Causes and Mechanisms in the Midland Basin *[earliest phases of research]***
   Collaborating institutions: UT-BEG



Integrated analyses have illuminated the geologic setting and causation of induced seismicity in Texas

Basement High
Causes: natural and injection above basement

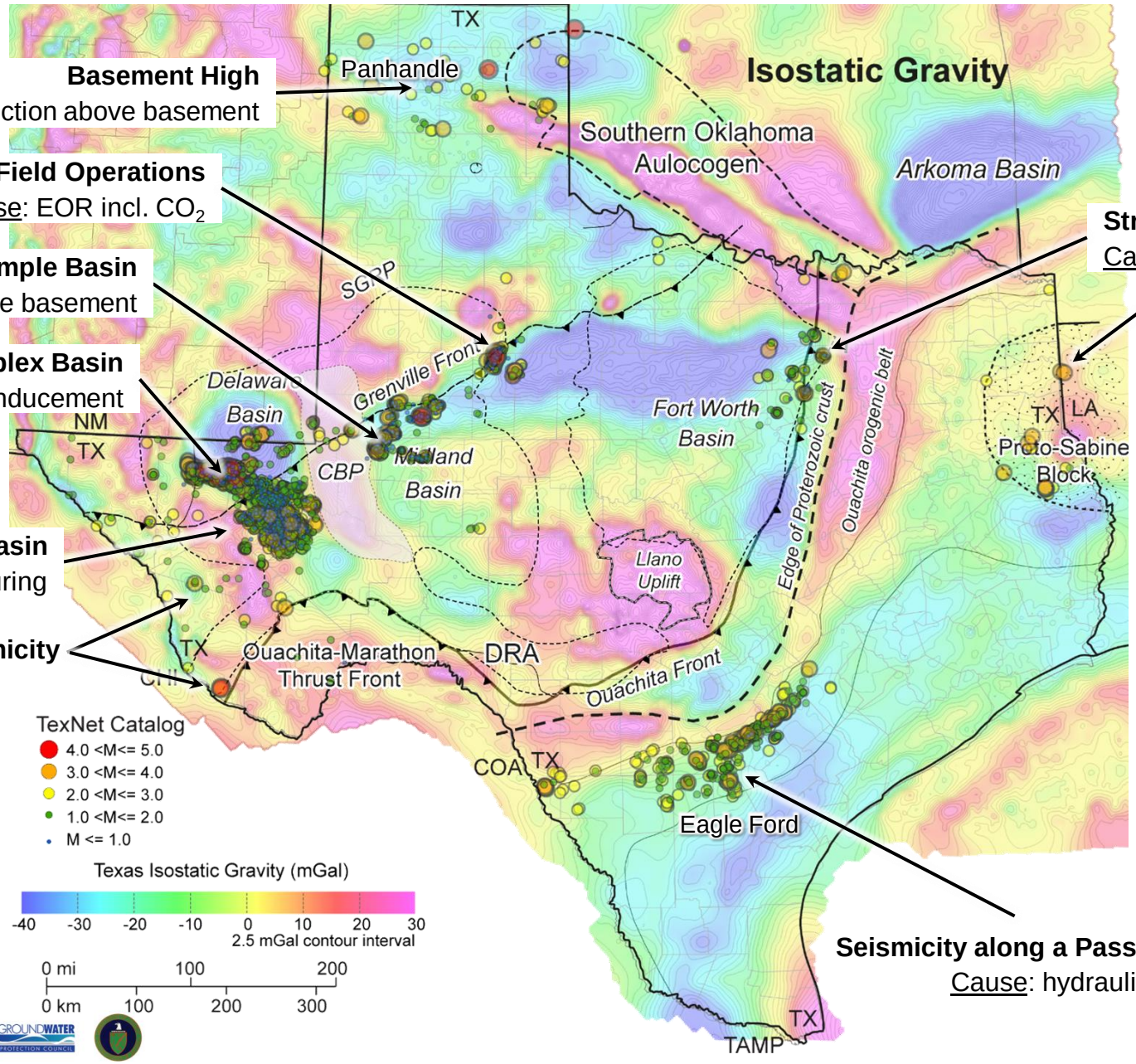
Oil Field Operations
Cause: EOR incl. CO_2

Structurally Simple Basin
Cause: injection above basement

Structurally Complex Basin
Cause: deep injection with long-distance inducement

Geomechanically-Complex Basin
Causes: shallow injection, hydraulic fracturing

Natural Seismicity



Horne et al. (in prep)

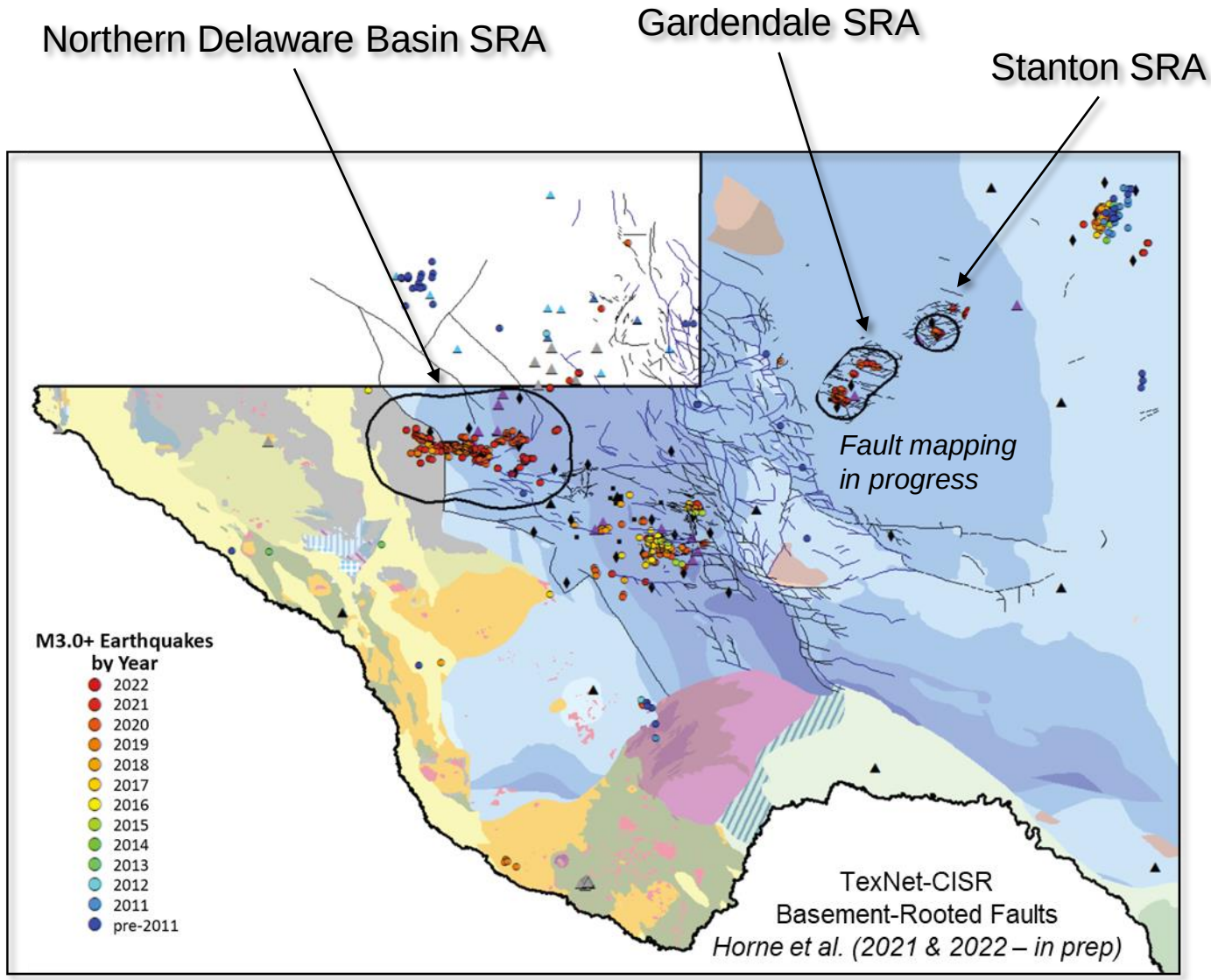
Hennings et al. (in prep)

Structurally Simple Basin
Cause: injection above basement

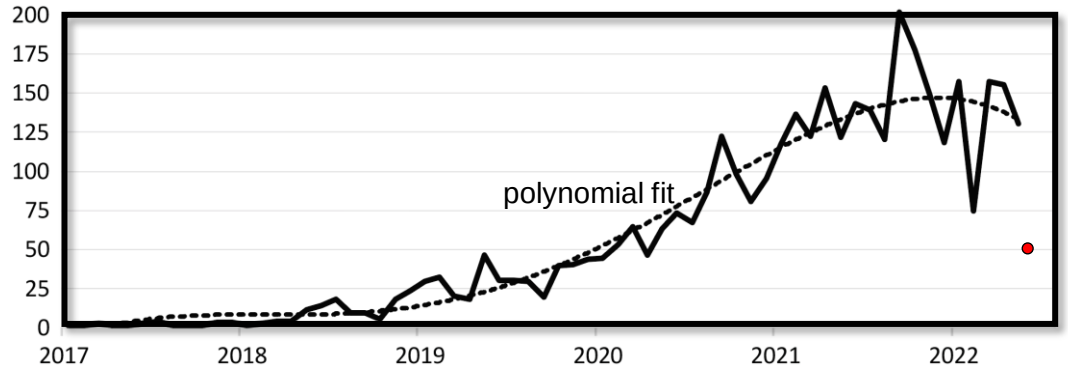
Seismicity along a Passive Margin
Cause: hydraulic fracturing

Regional Induced Seismicity Collaborative

Reason for optimism? Rate of M_L 2.0+ in the 3 RRC SRAs



Number of M_L 2.0+ per month in the 3 TX RRC SRA's



Like the IS previous cases, speaks loudly to the need to be very careful about injection above basement…

Hennings, P. H. and Young, M. H., (in press, 2022), The TexNet-CISR Collaboration and Steps Toward Understanding Induced Seismicity in Texas: GSA Volume on Induced Seismicity.

Texas Railroad Commission (TX RRC)

Paul Dubois – paul.dubois@rrc.texas.gov

RISC
Regional Induced Seismicity Collaborative

Original Seismic Permitting Guidelines

- Original Guidelines Implemented June 2019
- Evaluate 15 factors in 3 factor categories
  - 10 Seismicity and faulting factors
  - 2 Operational factors
  - 3 Reservoir factors
- Each factor receives a grade of “A”, “B”, or “C” based on a relative hazard from low to high
- Score determines maximum injection volume
- Monitoring incentive available
- Adopted ~ June 2019
- Results… ?

Updates to Seismic Permitting Guidelines

- Automation / Machine Learning
  - Python scripts to compile earthquake, injection well, and other information
  - Machine Learning Models
    - Decision Tree
    - Random Forest
    - Linear Regression
  - Data Analysis
    - Identify the factors that actually drive scoring
    - Predicts scored value 75% of the time
- Revised Guidelines Implemented January 2022
  - 9 factors
- Automated Scoring with Manual Review
  - Seismologist review for low grades

Simpler New Grading Sheet - Shallow

15 Factors

Seismicity & Faulting Factors	Seismicity & Faulting Values		
Number of Mapped Faults in AOI	0	1	> 1
Horizontal Distance to Nearest Mapped Fault	> 2.8 mi > 4.5 km	2.8 – 0.6 mi 4.5 – 1 km	< 0.6 mi < 1 km
Distance (ft) from Base of Disposal Zone to Basement or Top of Basement Fault	> 2000	2000 – 1000	< 1000
Number of Seismic Events ≥ 2.0 M in AOI	0 – 3	3 – 9	> 9
Horizontal Distance to Seismic Event ≥ 2.0M	> 4.9 mi >7.9 km	4.9 – 2.8 mi 7.9 – 4.5 km	< 2.8 mi < 4.5 km
Maximum Seismic Event Magnitude in AOI	< 2.5	2.5 – 3.0	> 3.0
Years Since Last Seismic Event in AOI	> 5	5 – 1	< 1
Seismicity & Faulting Data Confidence	High	Medium	Low
Seismicity & Faulting Factors Score	**A**	**B**	**C**
Operational Factors	**Operational Values**		
Permitted Cumulative Injection Rate (kbbl / day) within 2.8 mi (4.5 km)	< 35	35 – 70	> 70
Distance to Nearest Injection Well in Same Interval(s)	> 2.8 mi > 4.5 km	2.8 – 0.6 mi 4.5–1 km	< 0.6 mi < 1 km
Operational Factors Score	**A**	**B**	**C**
Reservoir Factors	**Reservoir Values**		
Disposal Zone Static Permeability (md)	> 50	50 – 20	< 20
Disposal Zone Cumulative Thickness (ft)	> 750	750 – 100	< 100
Disposal Zone Lithology	Clastic	Mixed	Carbonate
Reservoir Factors Score	**A**	**B**	**C**
Overall Score	**A**	**B**	**C**

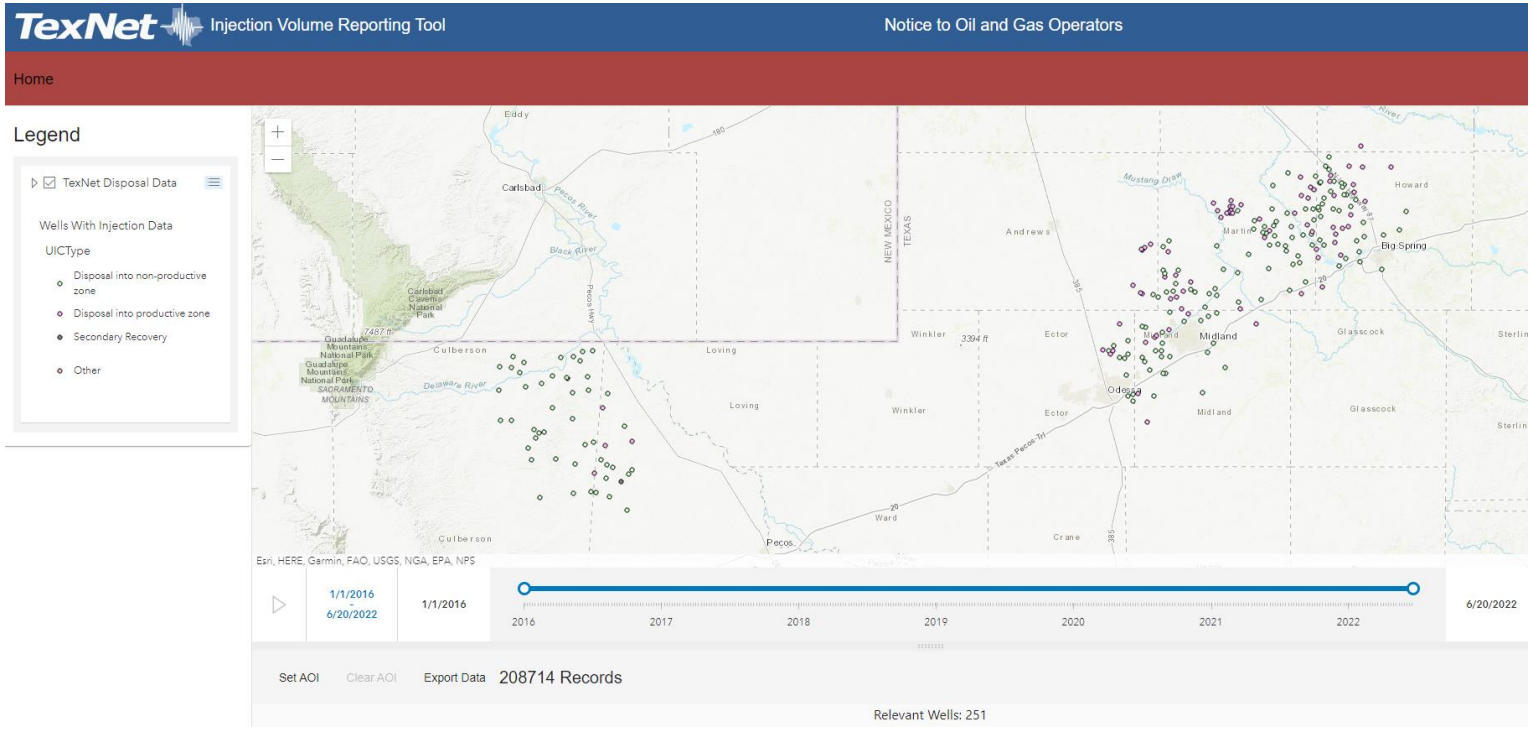
9 factors

Shallow				
Seismicity Review Factors				
Maximum Seismic Event Magnitude within 9.08 km	< 2.5	2.5 – 2.9	3.0 – 3.49	≥ 3.5
Number of Seismic Events ≥ 3.0 M within 9.08 km	0		1 – 2	> 2
Number of Seismic Events ≥ 2.0 M within 9.08 km	1 – 3	4 – 9	10 – 19	≥ 20
Horizontal Distance to Nearest Seismic Event ≥ 2.0M (km)	> 4.5	4.5 – 1	< 1	
Years Since Last Seismic Events ≥ 2.0 M within 9.08 km	> 5	5 – 1	< 1	
Number of Mapped Faults within 9.08 km	0	1	> 1	
Horizontal Distance to Nearest Mapped Fault (km)	> 9.08	9.08 – 4.5	4.5 – 1	< 1
Seismicity & Faulting Data Confidence	High	Medium	Low	
Permitted Shallow Cumulative Injection Rate (kbbl / day) within 4.54 km	< 35	35 – 70	70 – 140	> 140
Overall Score	**A**	**B**	**C**	**C-**

Permit Conditions	A	B	C	C-
Non-monitoring MDIV (kbbl)	30	20	10	≤ 10 or Denial
Seismic Monitoring MDIV (kbbl)	40	30	20	N/A
Formation Frac Pressure Data	if MDIV ≥ 25,000	if MDIV ≥ 25,000	No	No
BHP	Initial	Initial	Initial	Initial

Seismic Investigation Region (SIR)

- Define an area
- Request operators voluntarily provide daily injection pressure and volume data on a monthly basis
- Became a significant challenge
- TexNet developed a reporting tool https://injection.texnet.beg.utexas.edu/
  - Makes injection data readily available to industry, academia, and regulators



RISC Regional Induced Seismicity Collaborative

Seismic Response Areas (SRA)

- 3 Seismic Response Areas
  - Gardendale (Midland Basin, Midland – Odessa area)
  - Northern Culberson-Reeves (Delaware Basin)
  - Stanton (Midland Basin, northeast of Midland)
- Gardendale SRA
  - Voluntary reductions of all disposal (shallow and deep)
  - Met with operators and industry groups
    - High-quality information in some areas of the SRA
    - Not much information in other areas
  - Suspended 7 deep permits in 2 focus areas
  - Suspended 26 remaining deep permits in the whole SRA
- Northern Culberson-Reeves and Stanton SRAs

Operator-Led Response Plans (OLRP)

- Northern Culberson-Reeves and Stanton SRAs
  - Staff sets long-term goal for seismicity in the SRA.
  - Staff will take specific actions in 90 days
  - Encourage the formation of an operator group to develop an OLRP that meets the stated goal
  - Staff agrees to the OLRP
  - Quarterly meetings / status updates with adjustments as necessary

- OLRP Development and Implementation
  - Operator cooperation
  - Disparate operator impacts
  - Time to re-allocate water infrastructure and operations

Thinking About the Future…

- Coordination / collaboration with New Mexico Oil Conservation Division
- Continued collaboration with industry and academia (TexNet/CISR)
- Managing deep and shallow issues
  - Shallow: pressure accumulation hazards: threats to groundwater and correlative rights
  - Deep: seismicity
  - Middle: a lot of oil and gas
- What data do we need to manage these issues?
  - Daily disposal volumes and pressures reported monthly
  - Permit conditions that gather initial and long-term pressure monitoring data
  - Mapping / tracking geologic factors and known hazards
  - Integrated response strategy

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