Utilizing Physics-Based Models to Manage the Risk of Injection-Induced Seismicity Associated with Unconventional Oil and Gas Production

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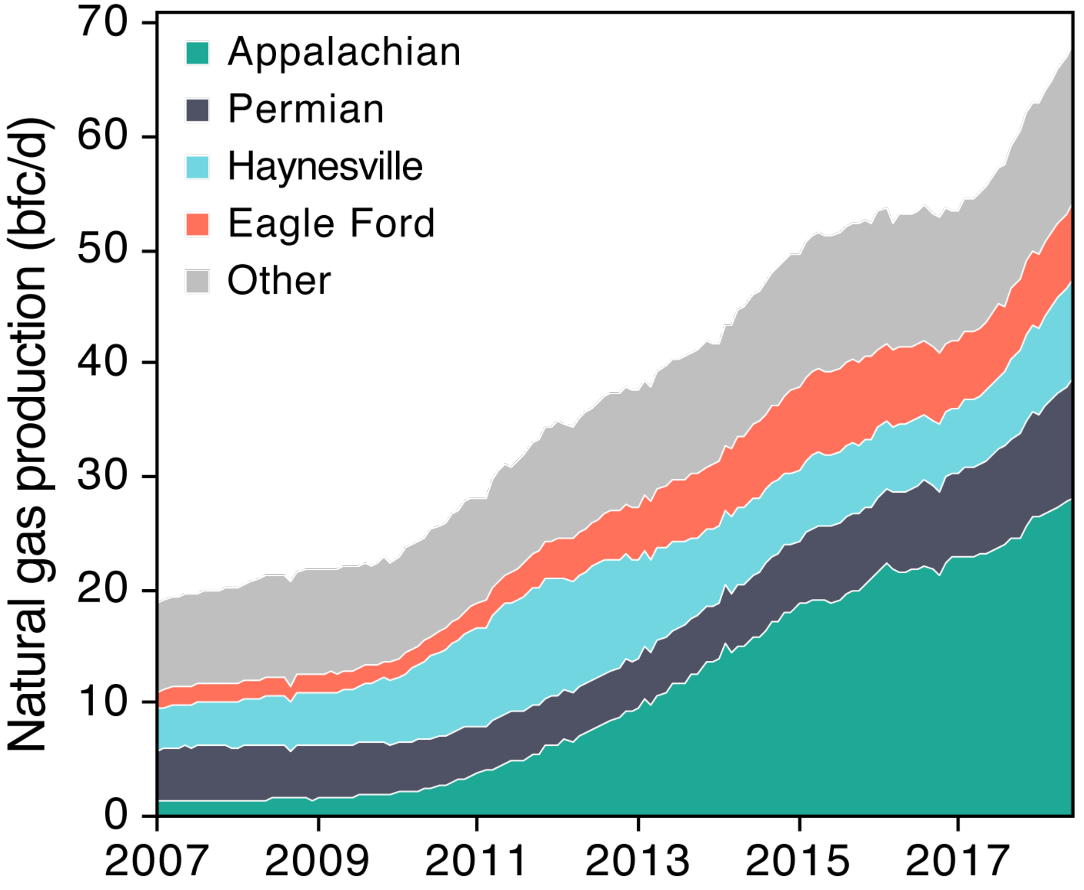
University of Toronto
January 30, 2020

The Unconventional Revolution – U.S. Production



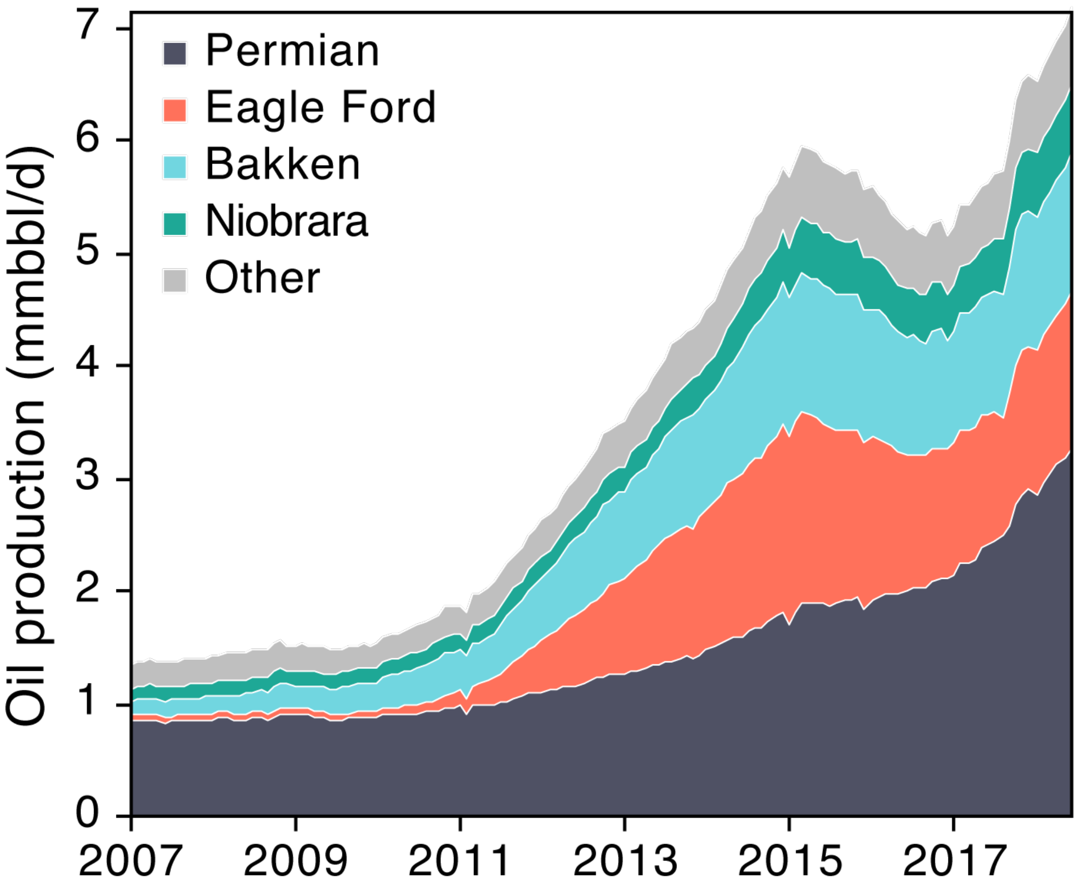
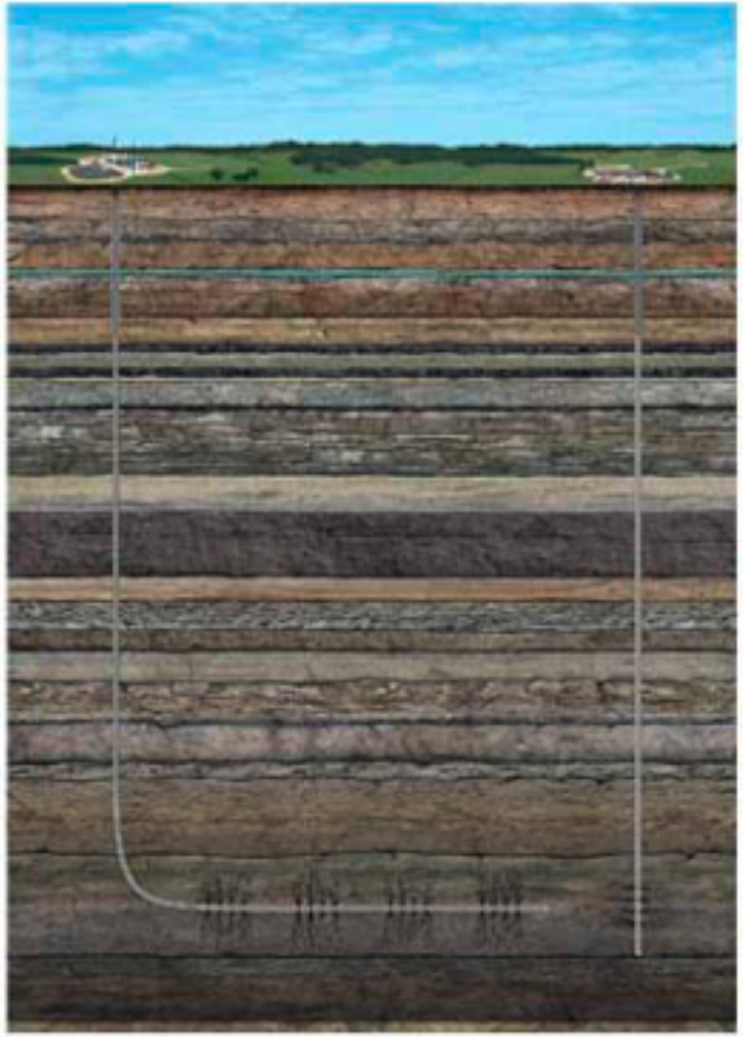
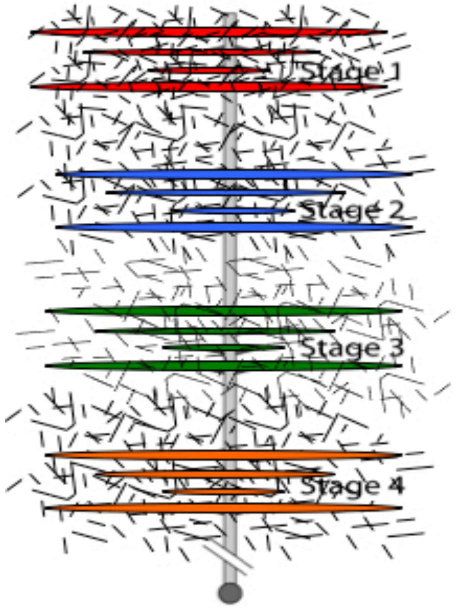
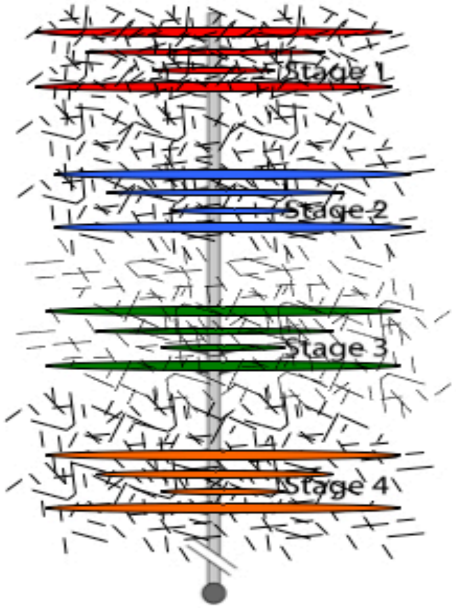
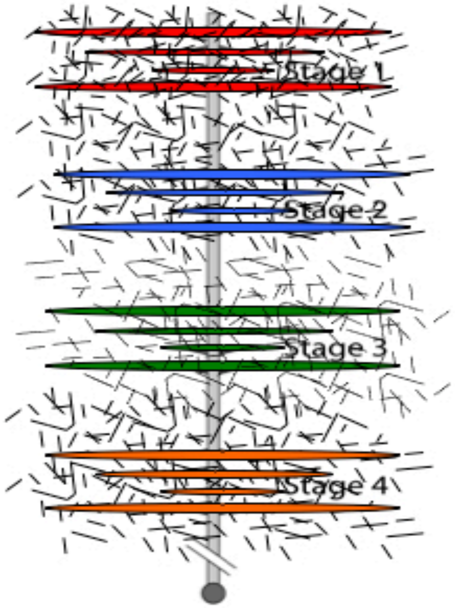


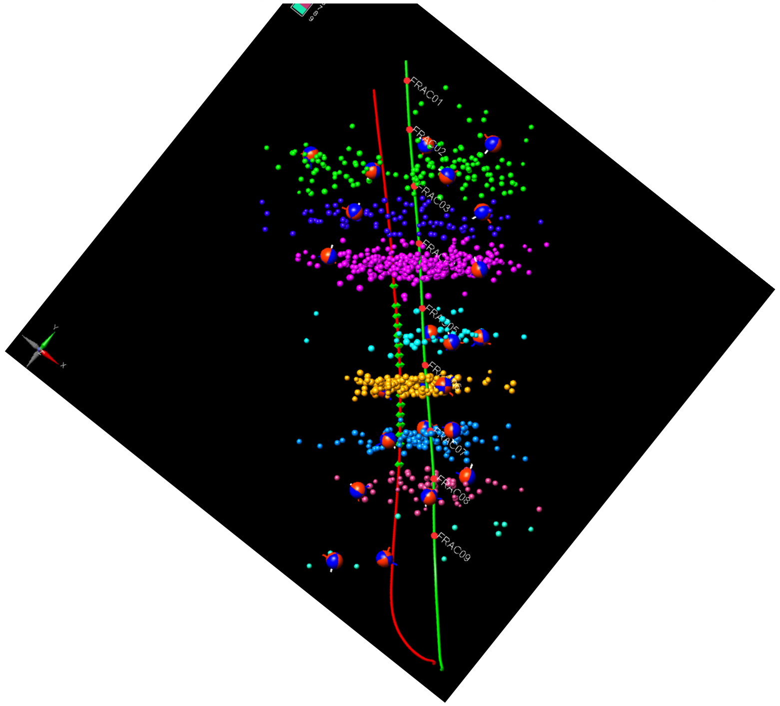
Fig. 1.2

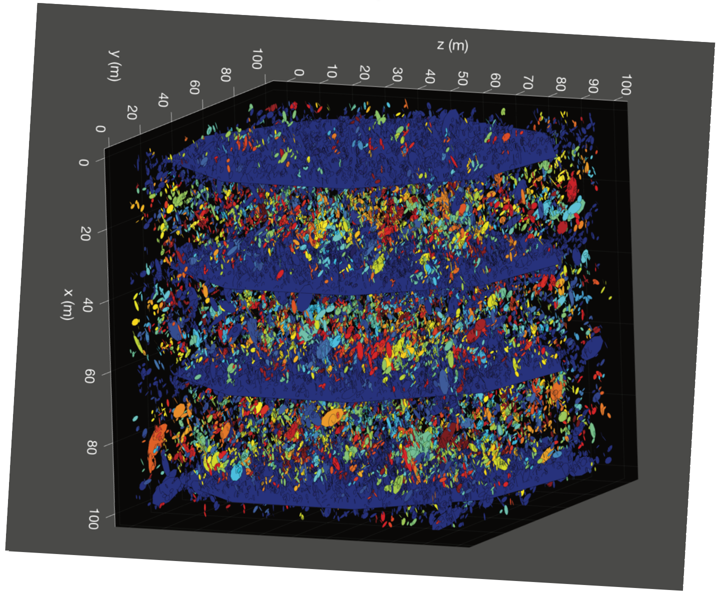



Stage 1
Stage 2
Stage 3
Stage 4


Stage 1
Stage 2
Stage 3
Stage 4


Stage 1
Stage 2
Stage 3
Stage 4




z (m)
y (m)
x (m)

Organic Rich Source Rocks Are Found Everywhere Hydrocarbons Have Ever Been Produced

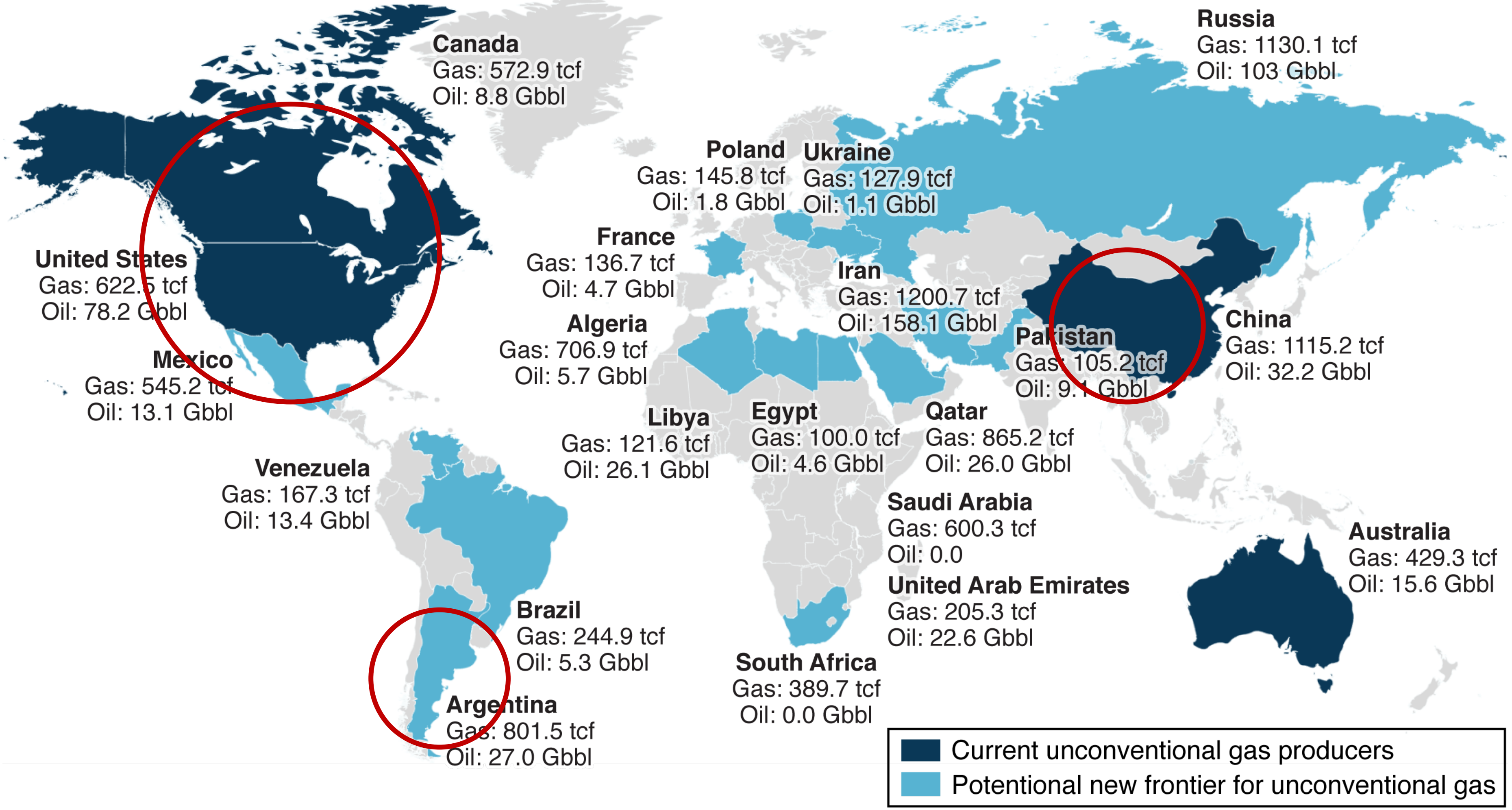
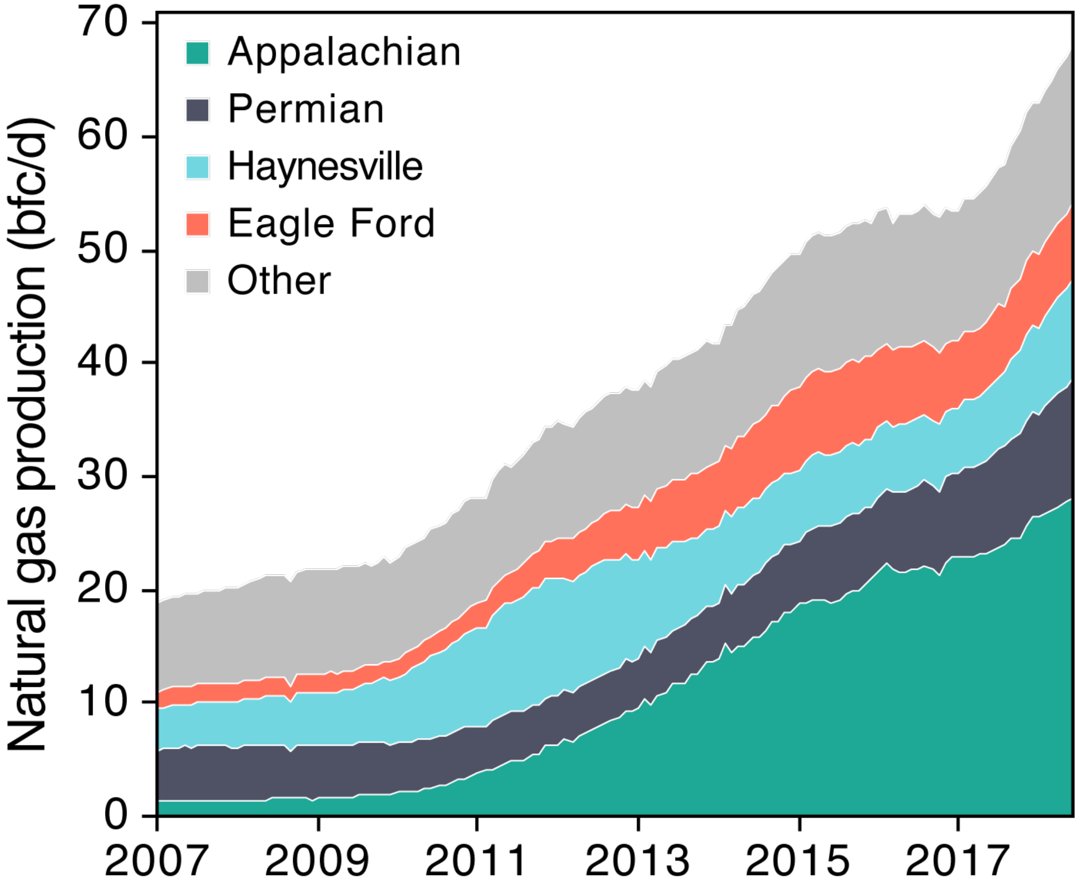
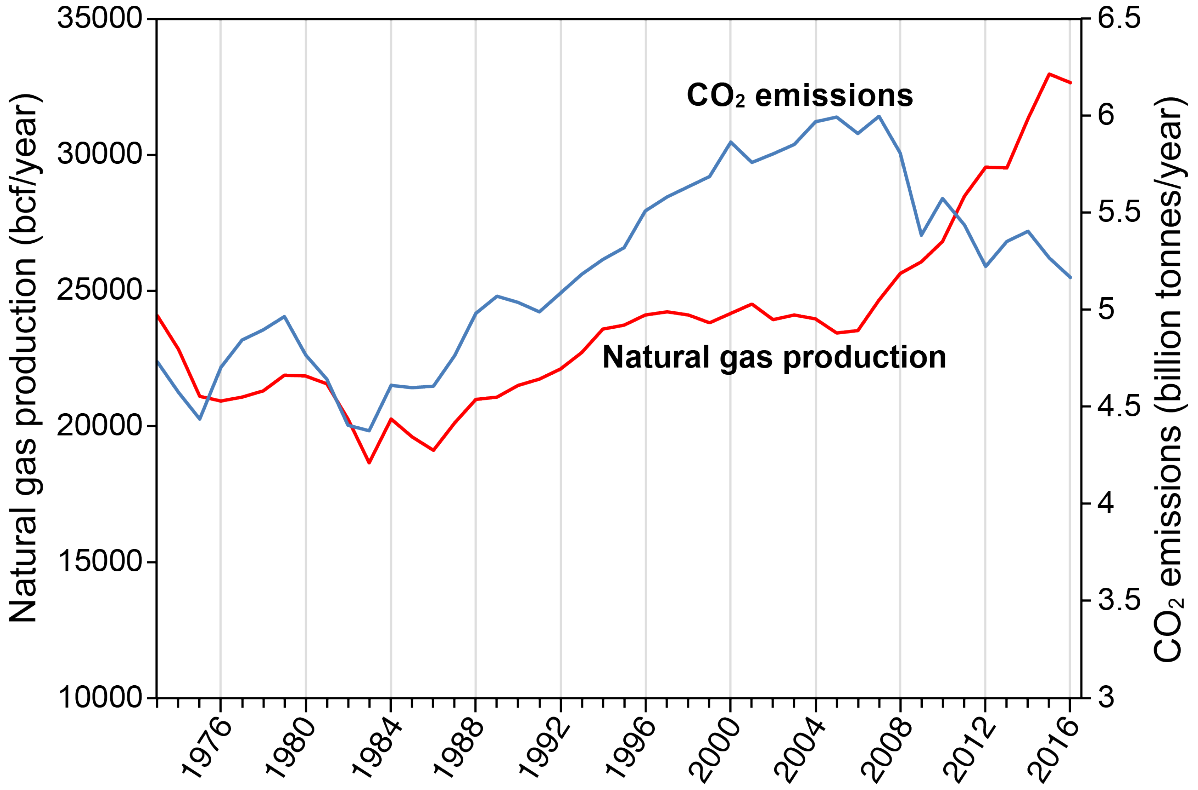


Fig. 1.4

The Unconventional Revolution – U.S. Production





The development of shale gas resources in an environmentally responsible manner presents a critical opportunity to move toward decarbonizing the global energy system.

Shale Gas Development

Opportunities and Challenges

Mark D. Zoback

Douglas J. Arent

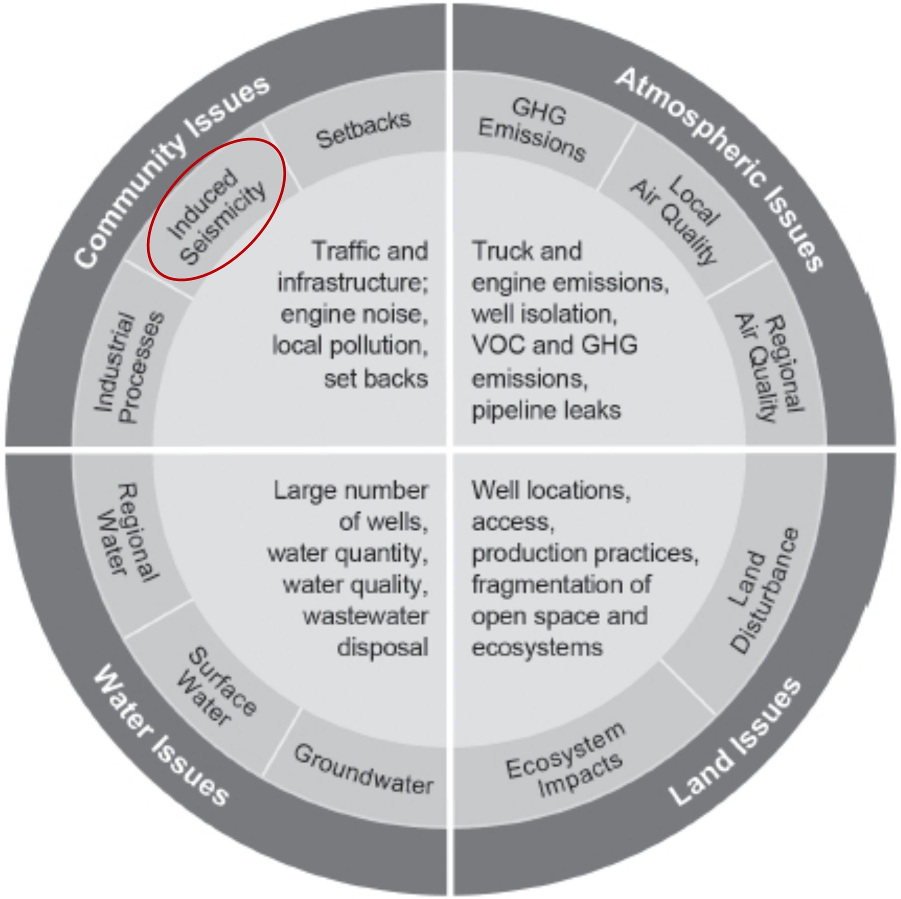
Mark D. Zoback and
Douglas J. Arent

The use of horizontal drilling and multistage hydraulic fracturing technologies has enabled the production of immense quantities of natural gas, to date principally in North America but increasingly in other countries around the world. The global availability of this resource creates both opportunities and challenges that need to be addressed in a timely and effective manner.

There seems little question that rapid shale gas development, coupled with fuel switching from coal to natural gas for power generation, can have beneficial effects on air pollution, greenhouse gas emissions, and energy security in many countries. In this context, shale gas resources represent a critically important transition fuel on the path to a decarbonized energy future. For these benefits to be realized, however, it is imperative that shale gas resources be developed with effective environmental safeguards to reduce their impact on land use, water resources, air quality, and nearby communities.

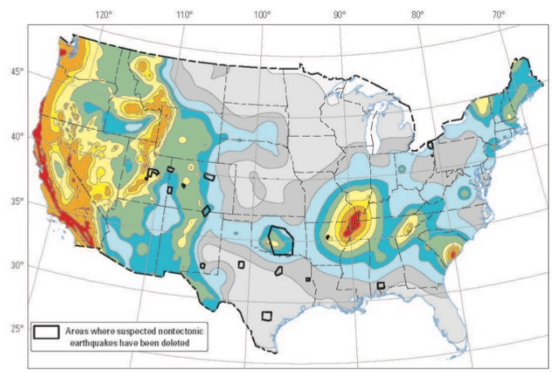
Background

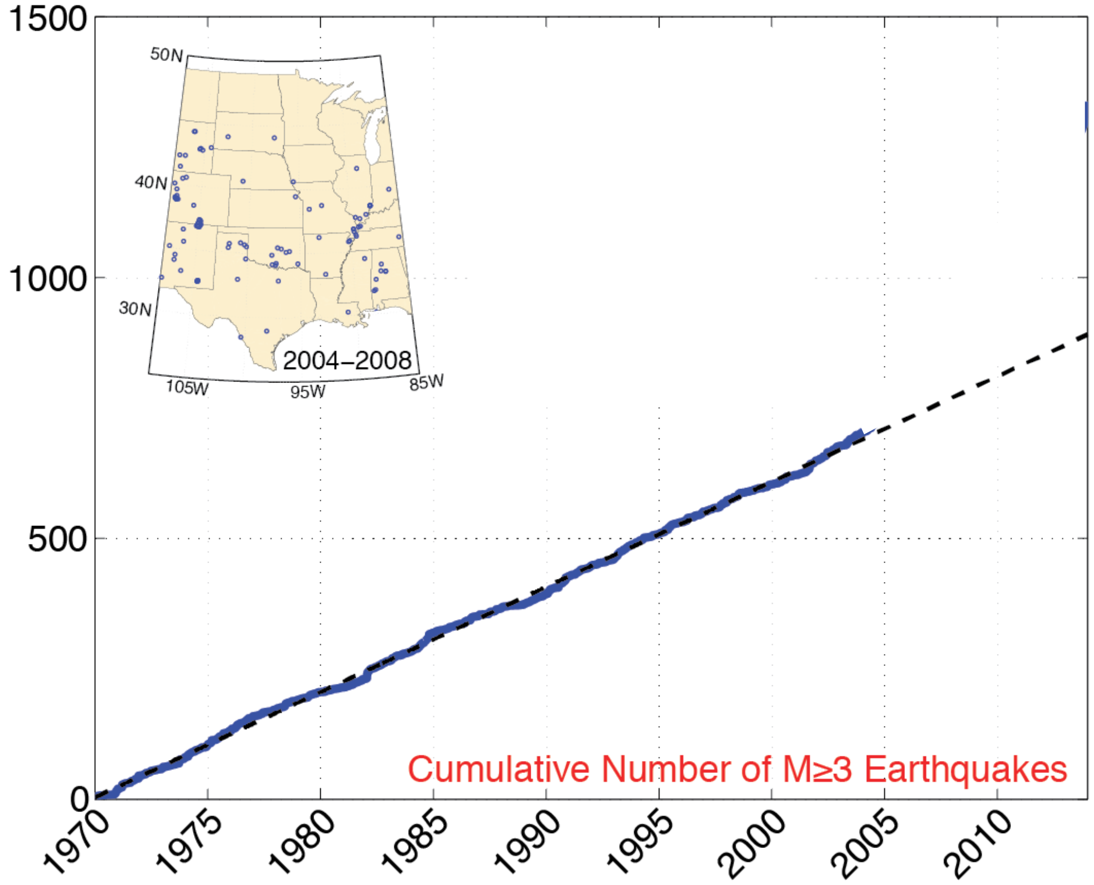
Geologists have long known that large amounts of organic matter and natural gas are trapped (usually by clay and other fine-grained minerals) in many



Like the Environmental Impacts Associated With Other Industrial Processes, These Impacts Need to Identified and Minimized Through Regulation and Enforcement

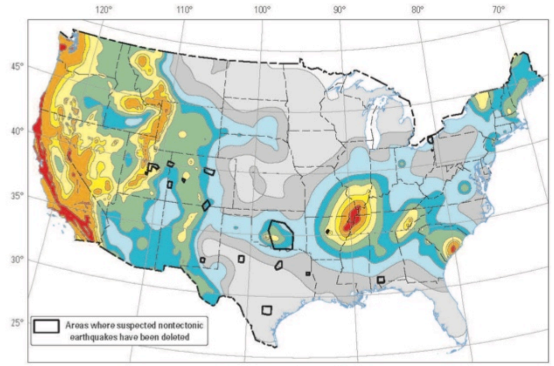
Earthquakes in the Mid-Continent

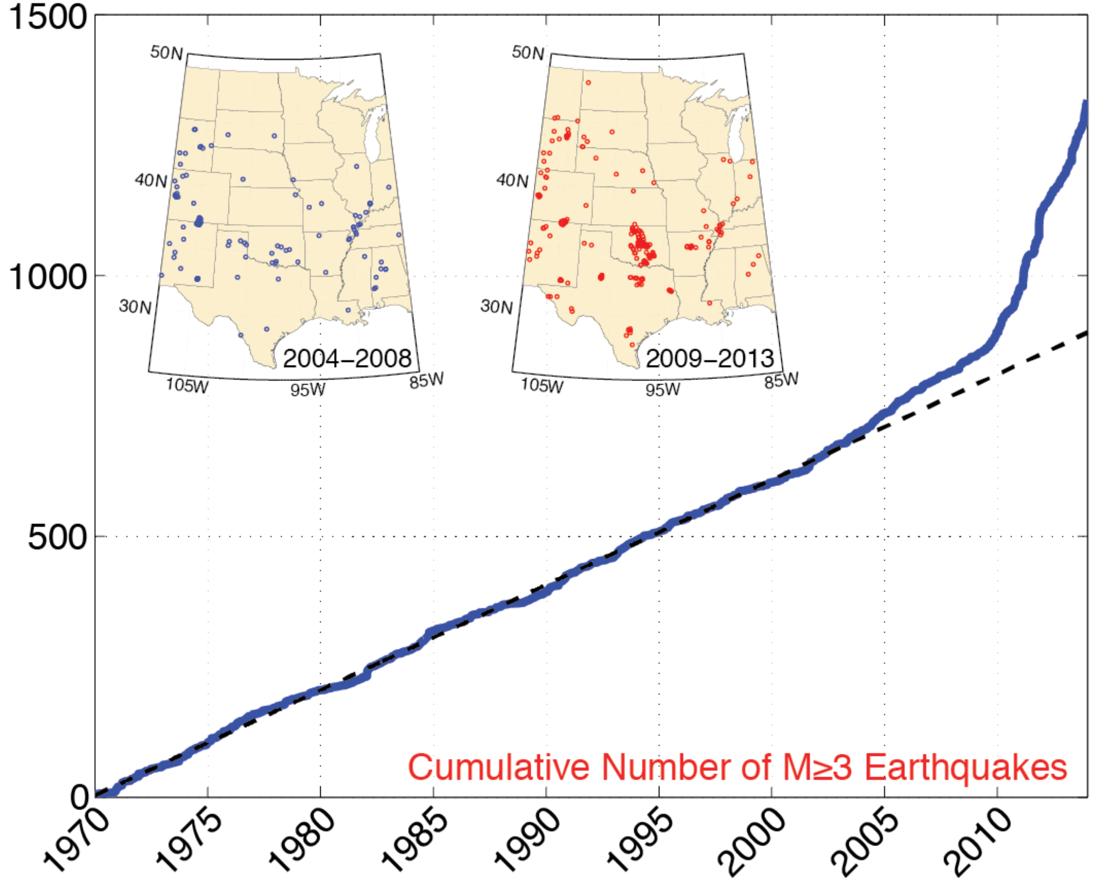




Ellsworth (2013)

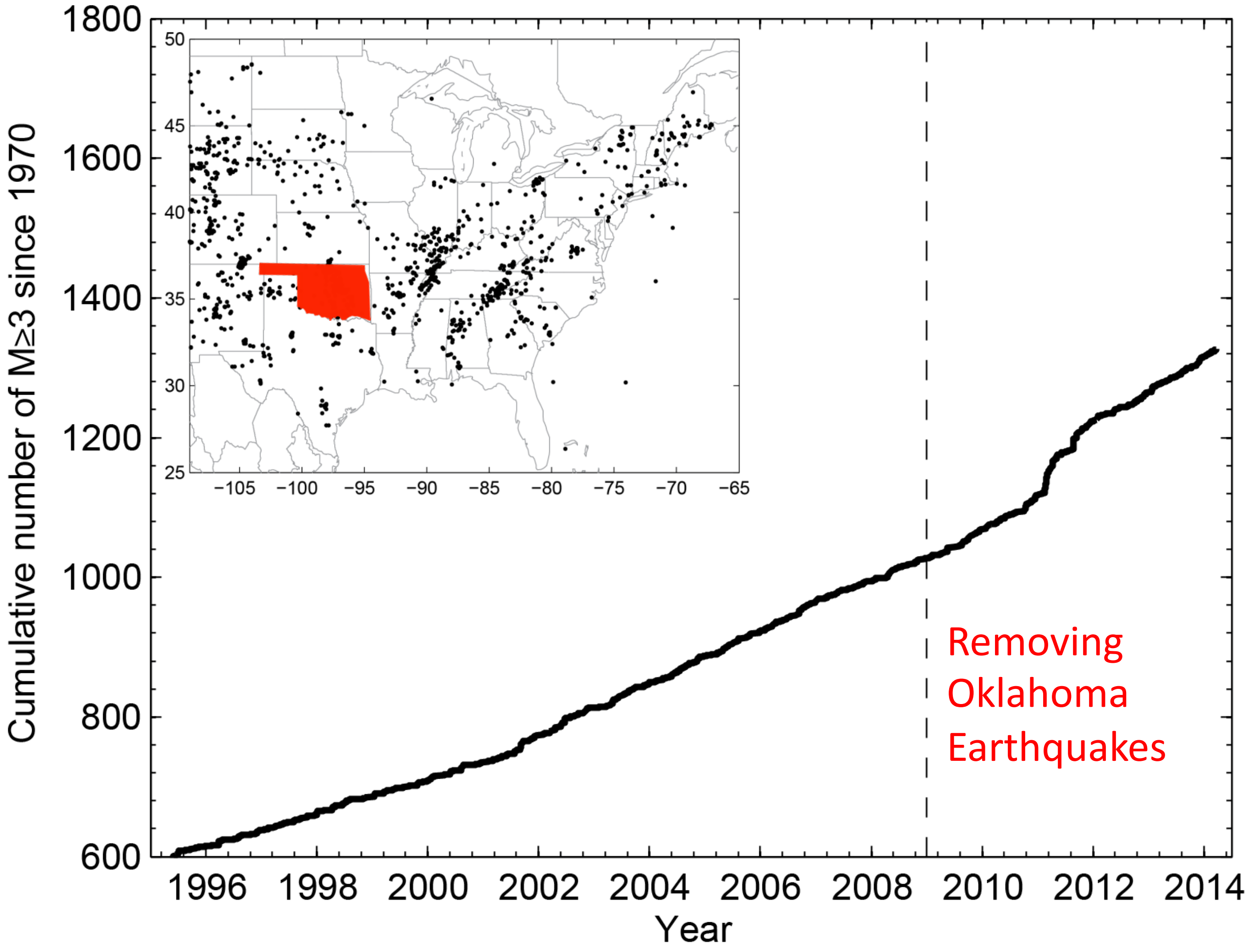
Earthquakes in the Mid-Continent





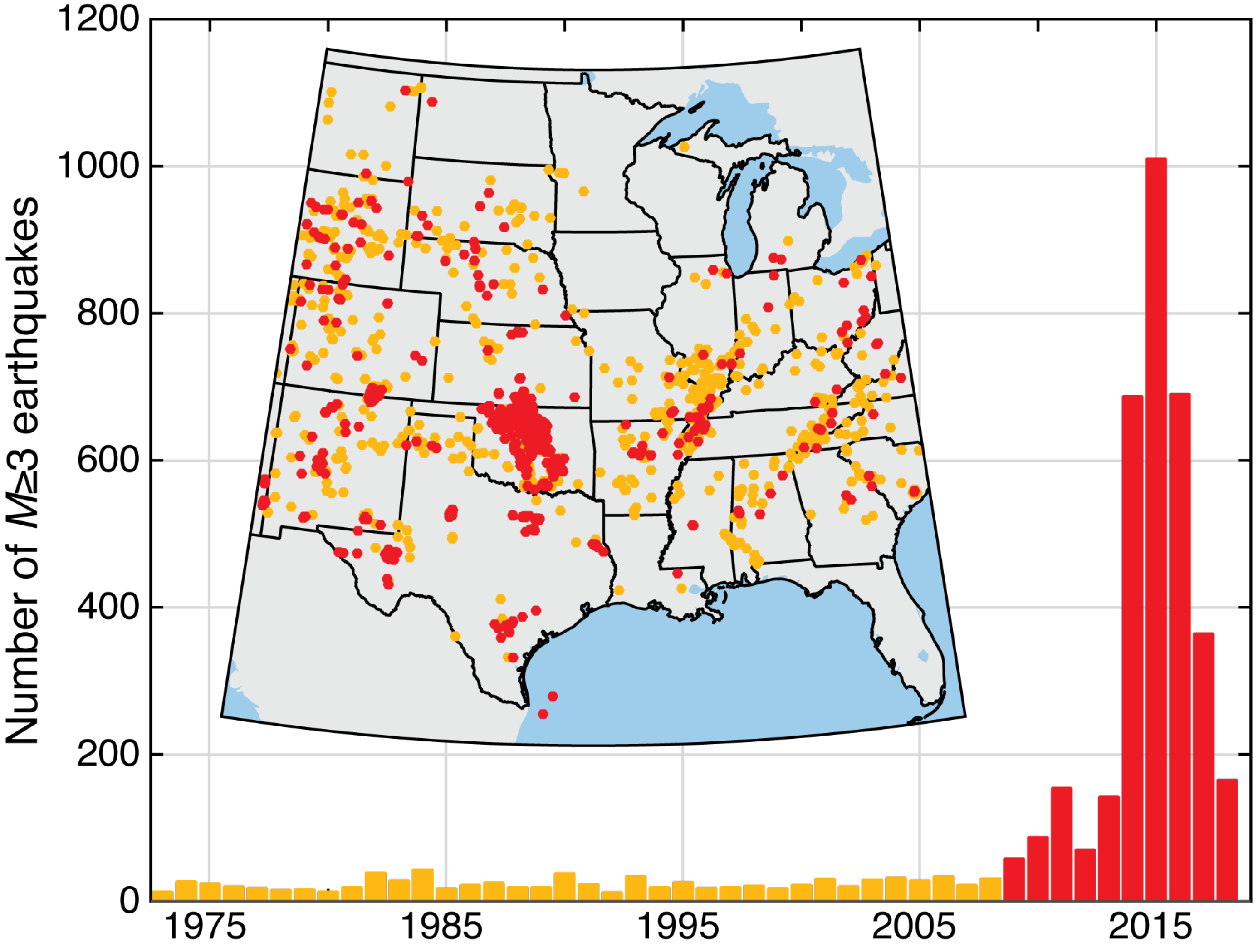
Ellsworth (2013)

About 70% of the Earthquakes Were in OK

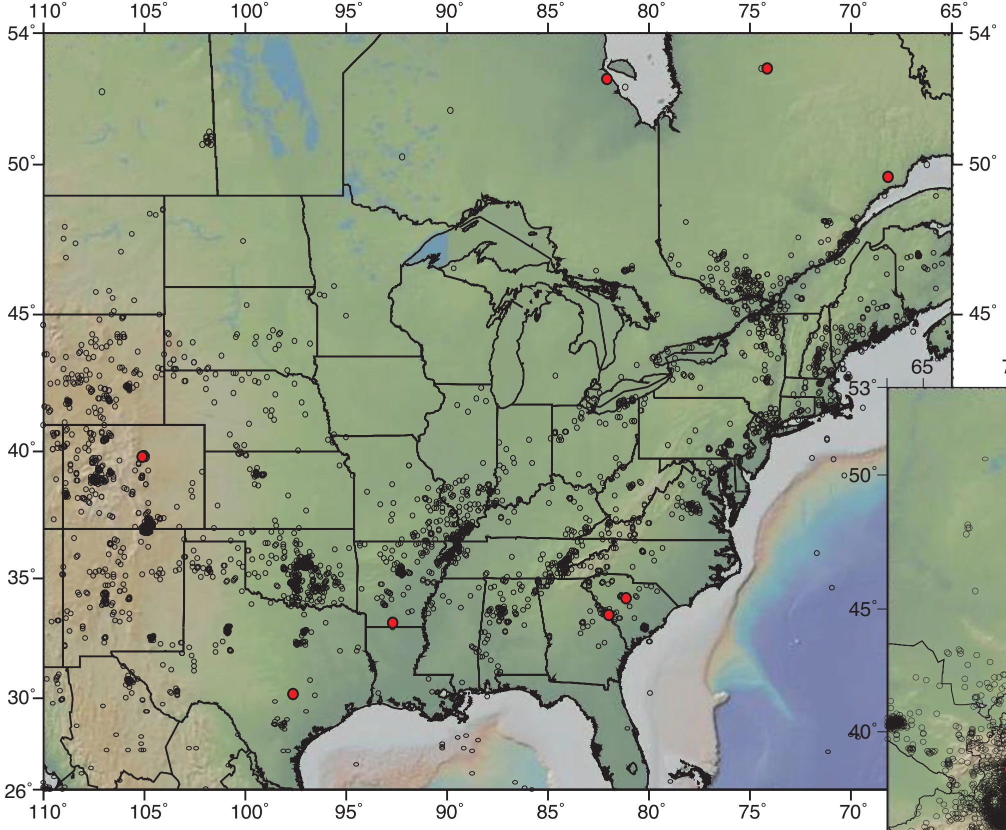


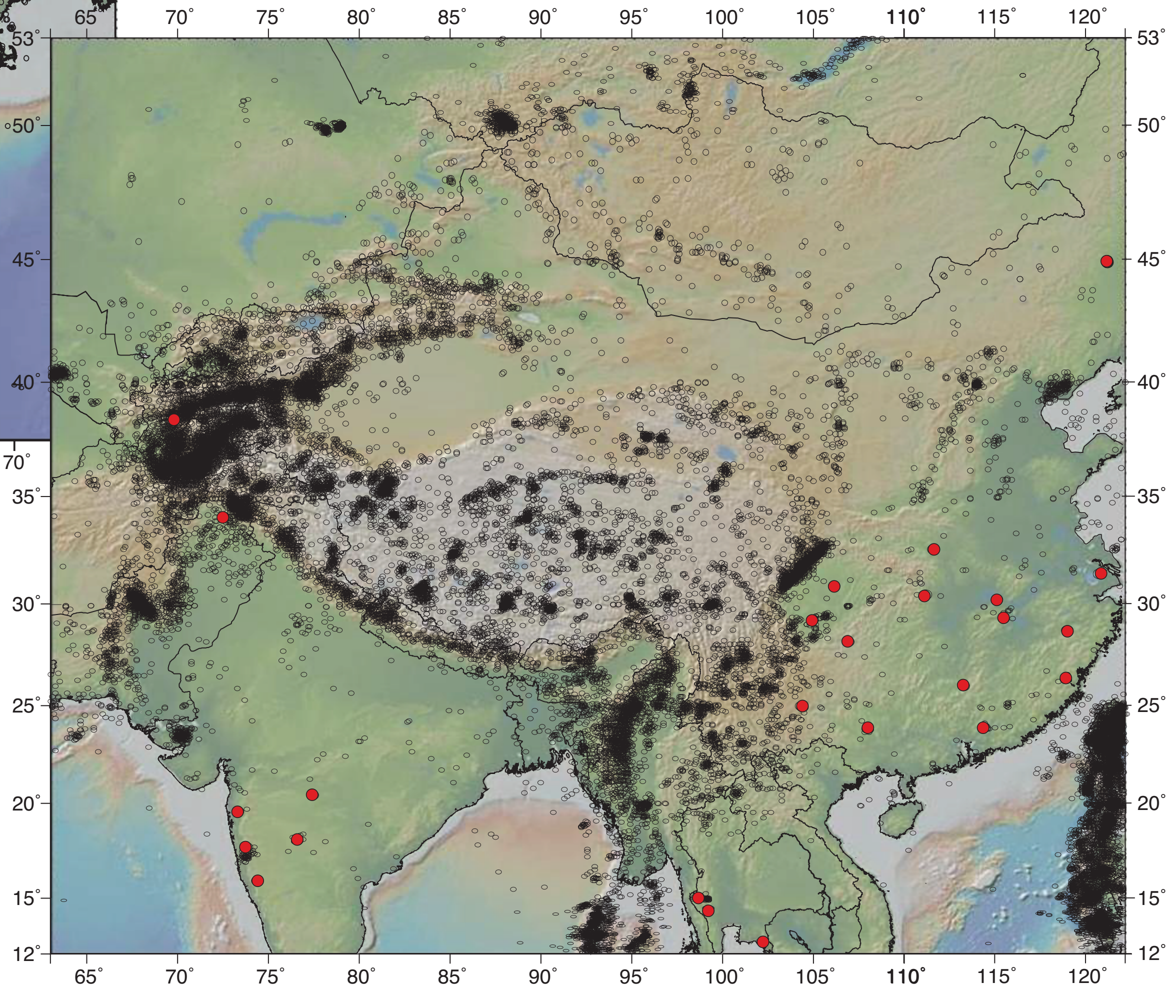
Llenos et al. (2014)

Seismicity Rates are Down – Because we Made the Effort to Understand Why, then Recommended Appropriate Actions to Regulators



The Critically-Stressed Crust

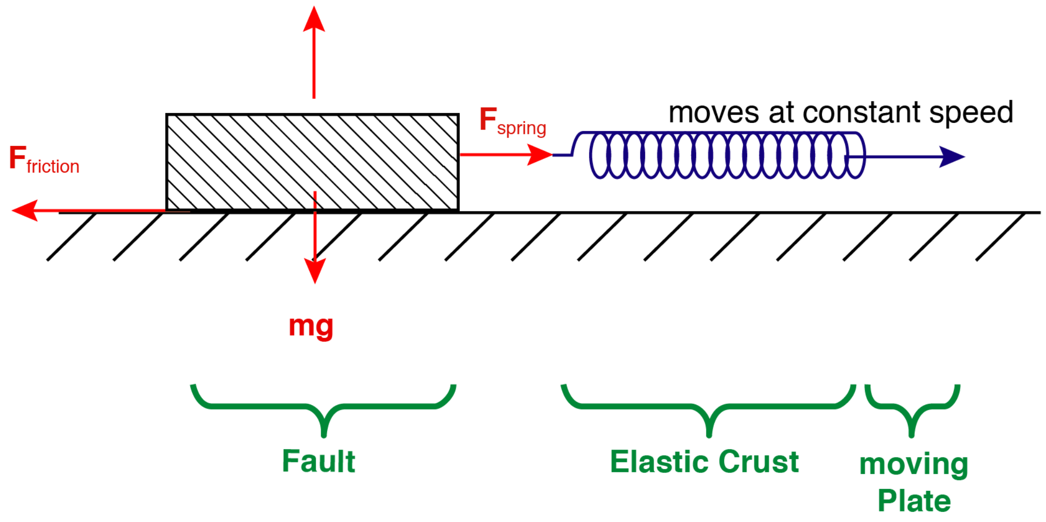


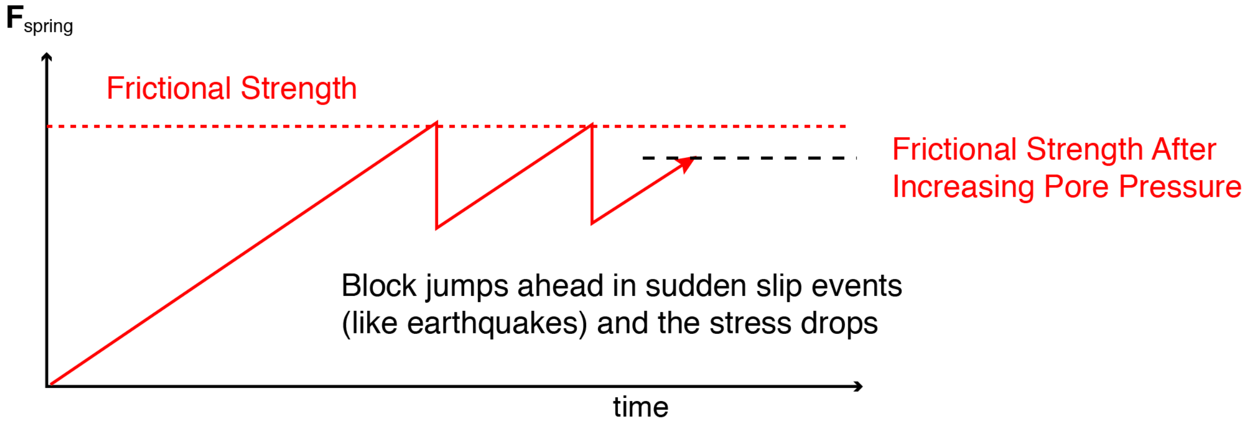


- Earthquakes Occur Nearly Everywhere in Intraplate Areas

- Small Perturbations Associated with Reservoir Induced Seismicity <RIS> Capable of Triggering Seismicity, Even in “Stable Areas”

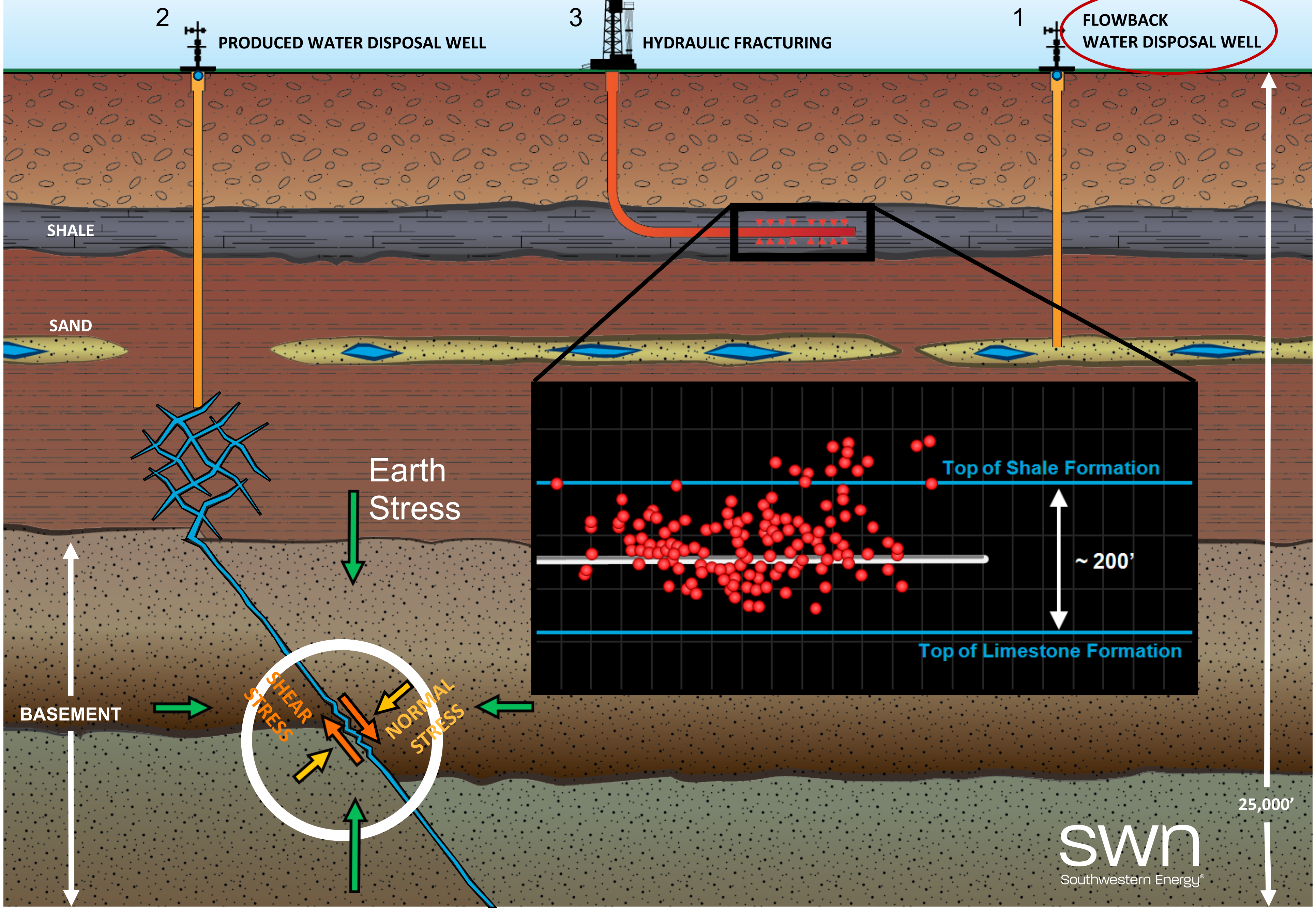
A Simple Representation of Triggered Seismicity



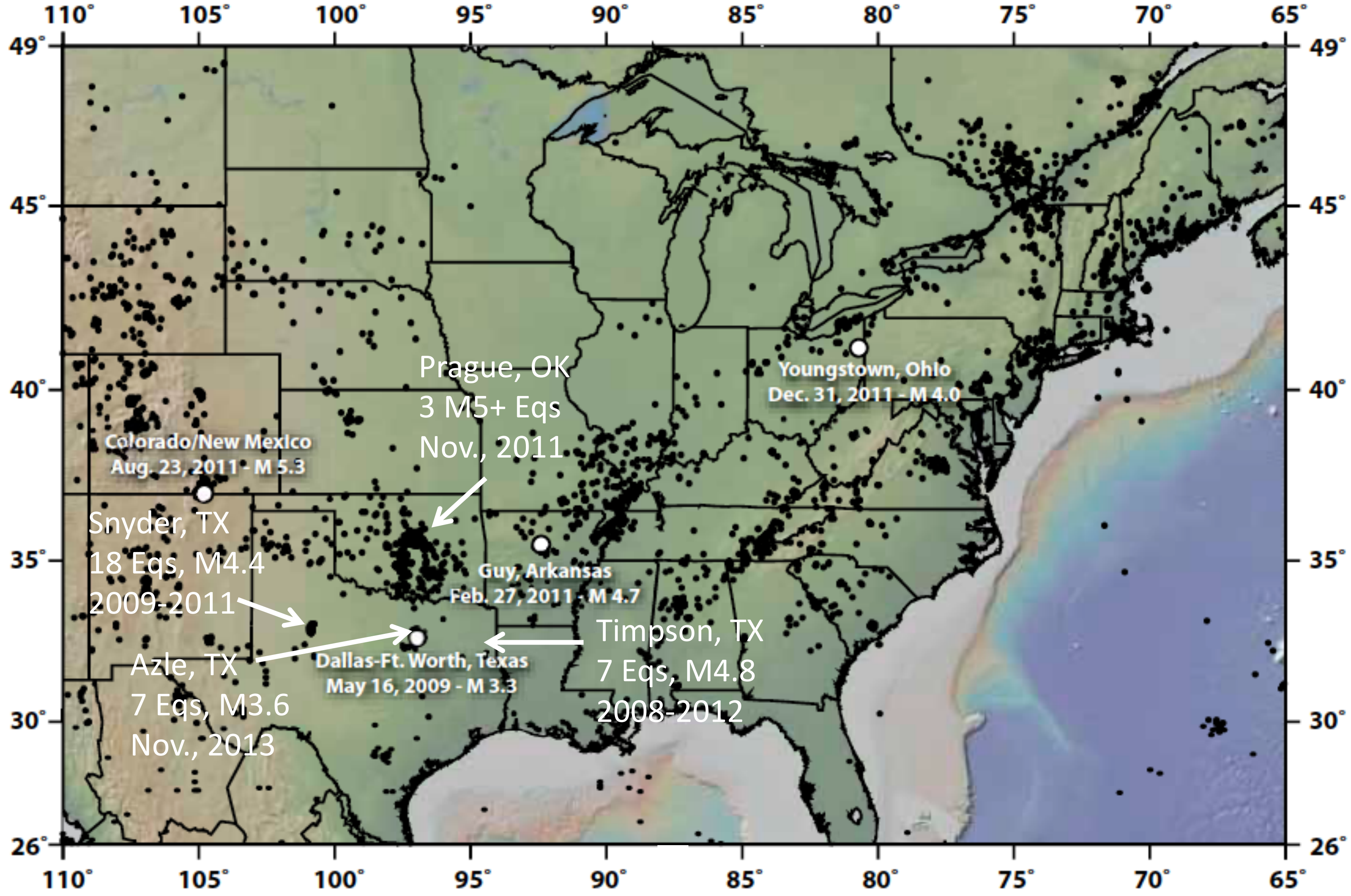


$$CFF \equiv \tau - \mu\sigma_n$$

$$\sigma_n = S_n - P_p$$

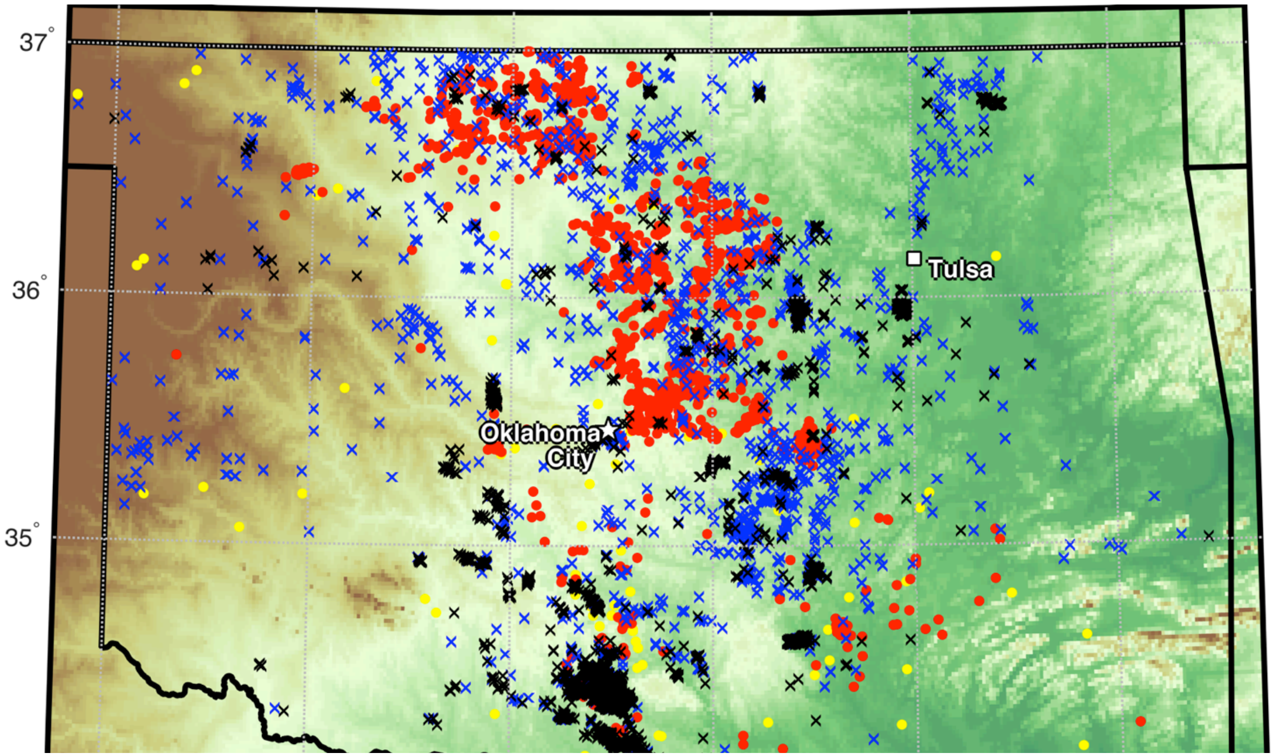


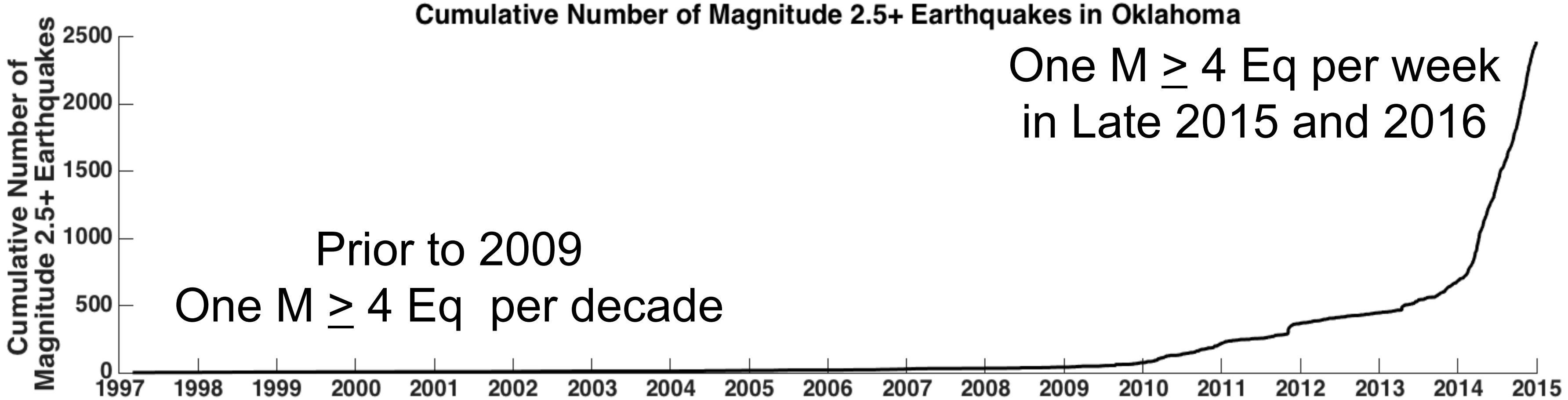
2
PRODUCED WATER DISPOSAL WELL
3
HYDRAULIC FRACTURING
1
FLOWBACK
WATER DISPOSAL WELL
SHALE
SAND
Earth
Stress
Top of Shale Formation
~ 200'
Top of Limestone Formation
BASEMENT
SHEAR
STRESS
NORMAL
STRESS
25,000'
swn
Southwestern Energy®



M.D. Zoback, Managing the seismic risk of wastewater disposal, *EARTH*, April, 2012, 38-43 (2012).

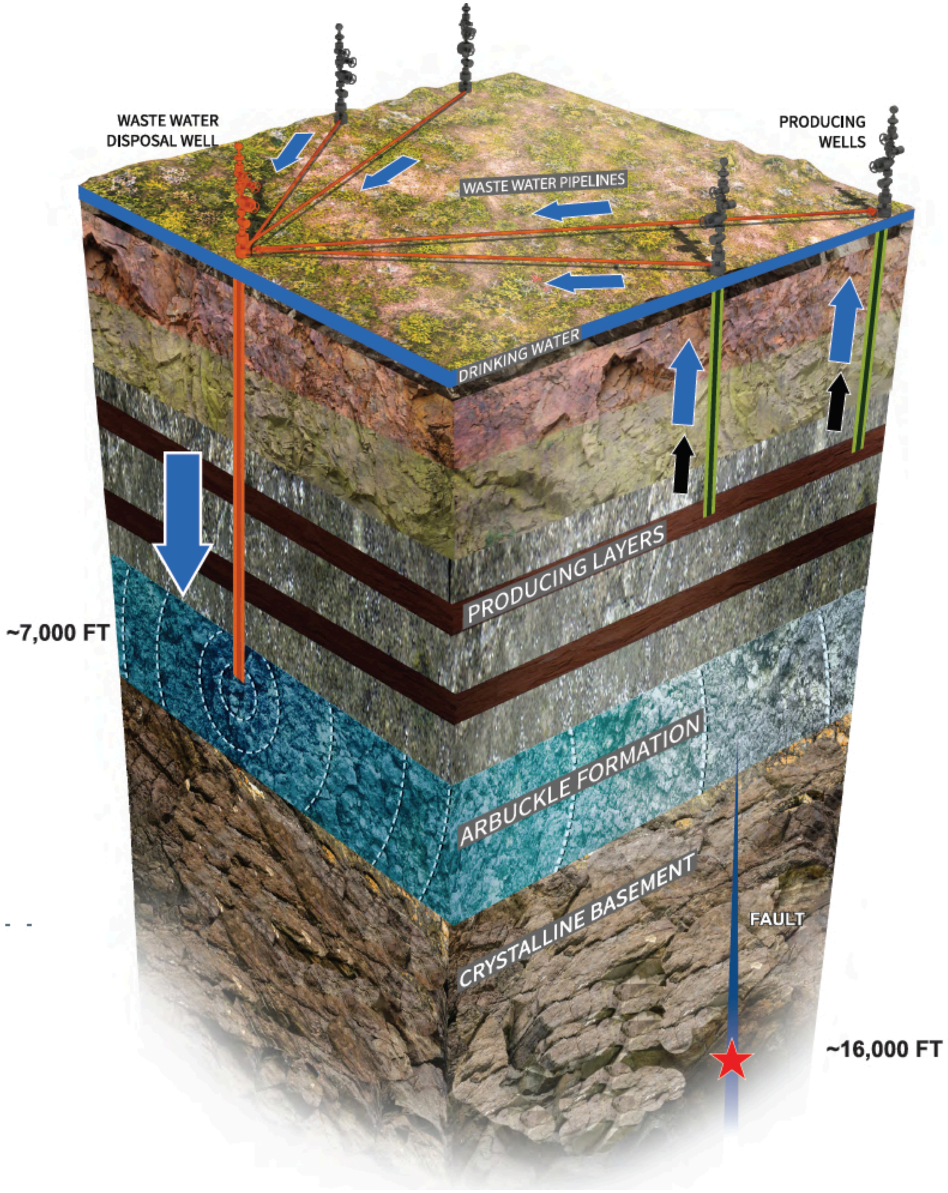
Recent Earthquakes and Disposal Wells



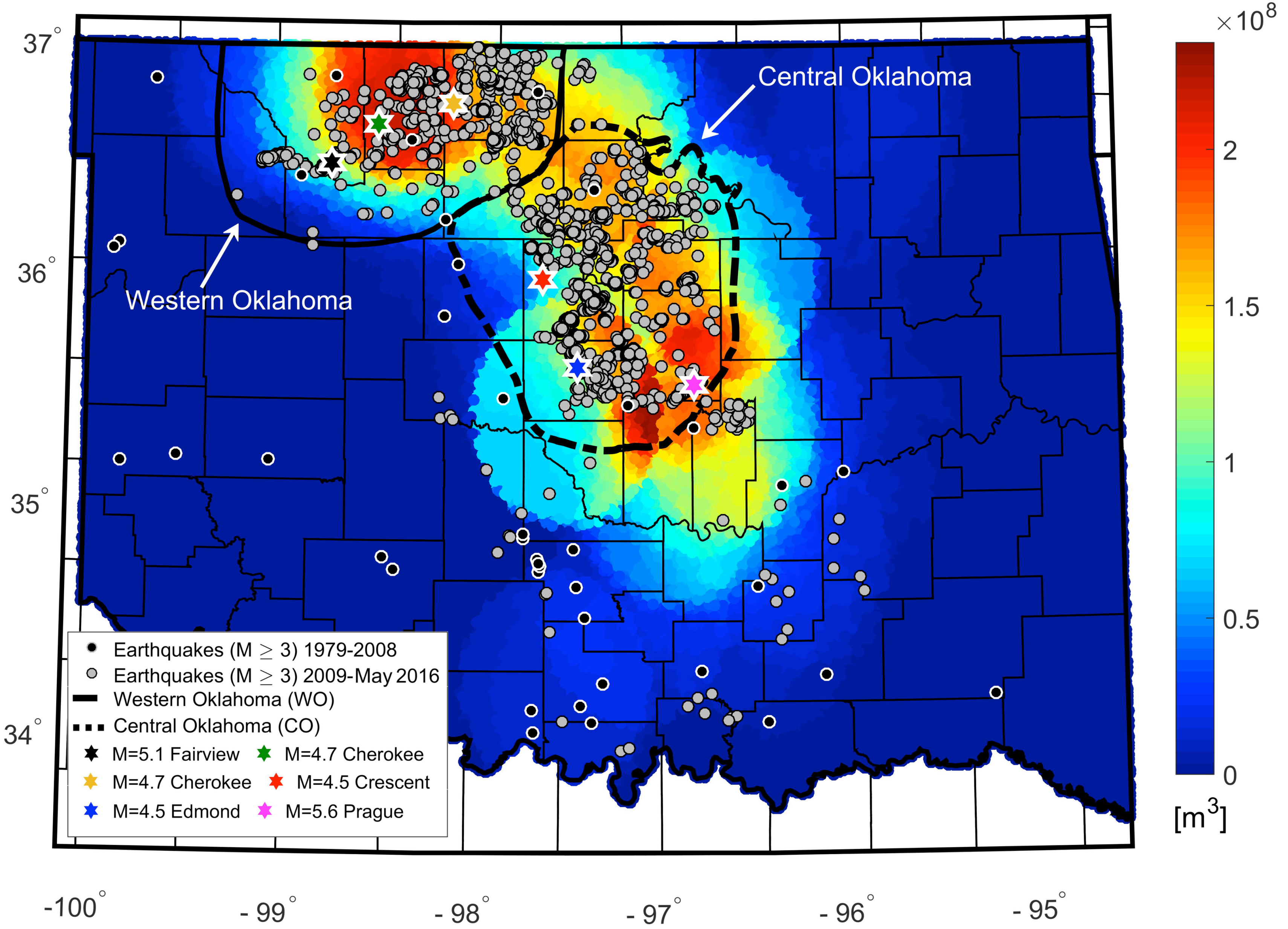


Saltwater Disposal is Triggering Earthquakes

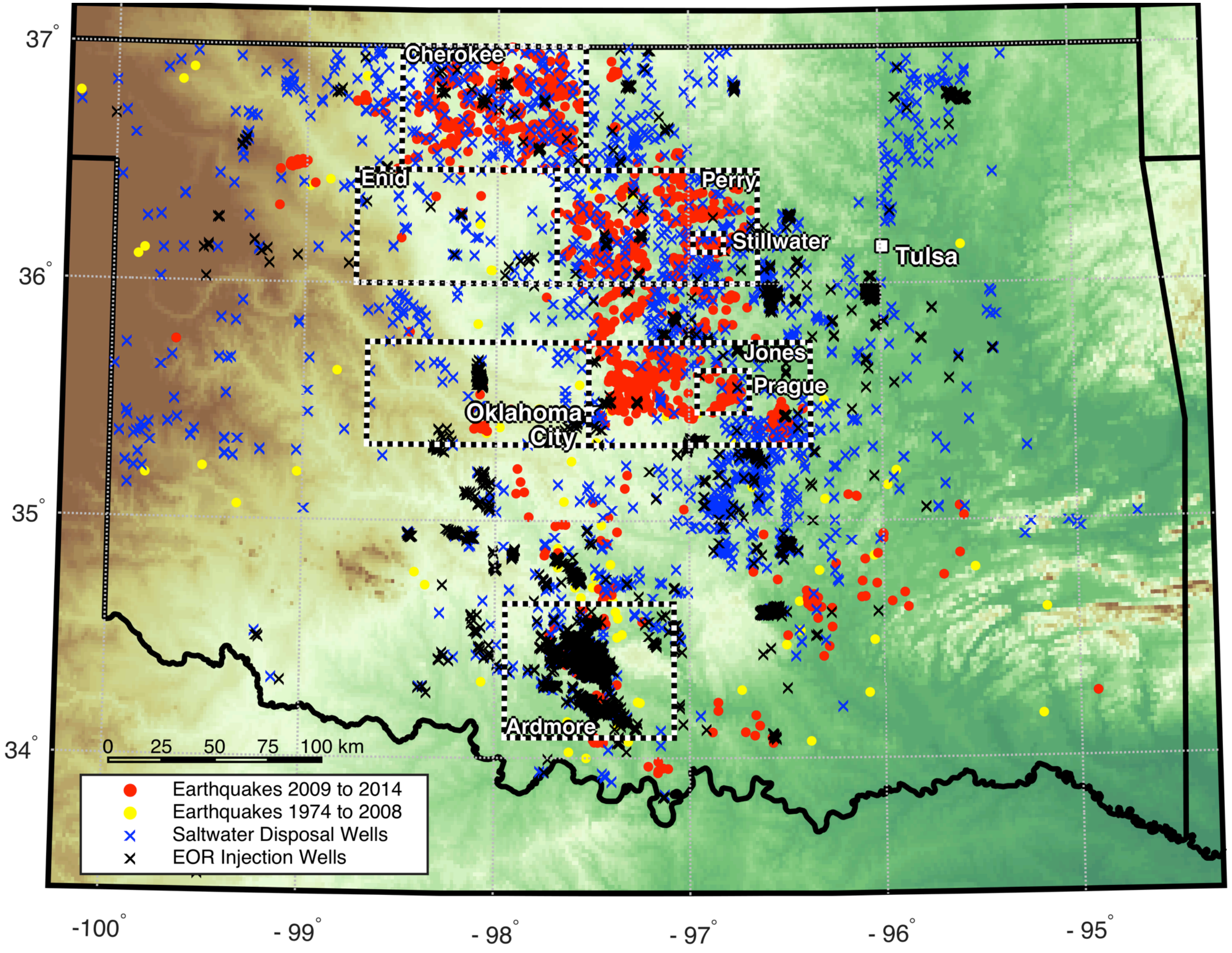
- Shallow, very high water cut producing formations – the Miss. Lime is most well known.
- Massive quantities of produced saltwater injected into into the basal Arbuckle group. Thick, porous, permeable and underpressured!
- About 700 million barrels injected in 2014 alone.
- Earthquakes occur on pre-existing faults in basement due to increases in pore pressure.
- Potentially active faults are likely to be permeable, and extend from the crystalline basement up to the Arbuckle.



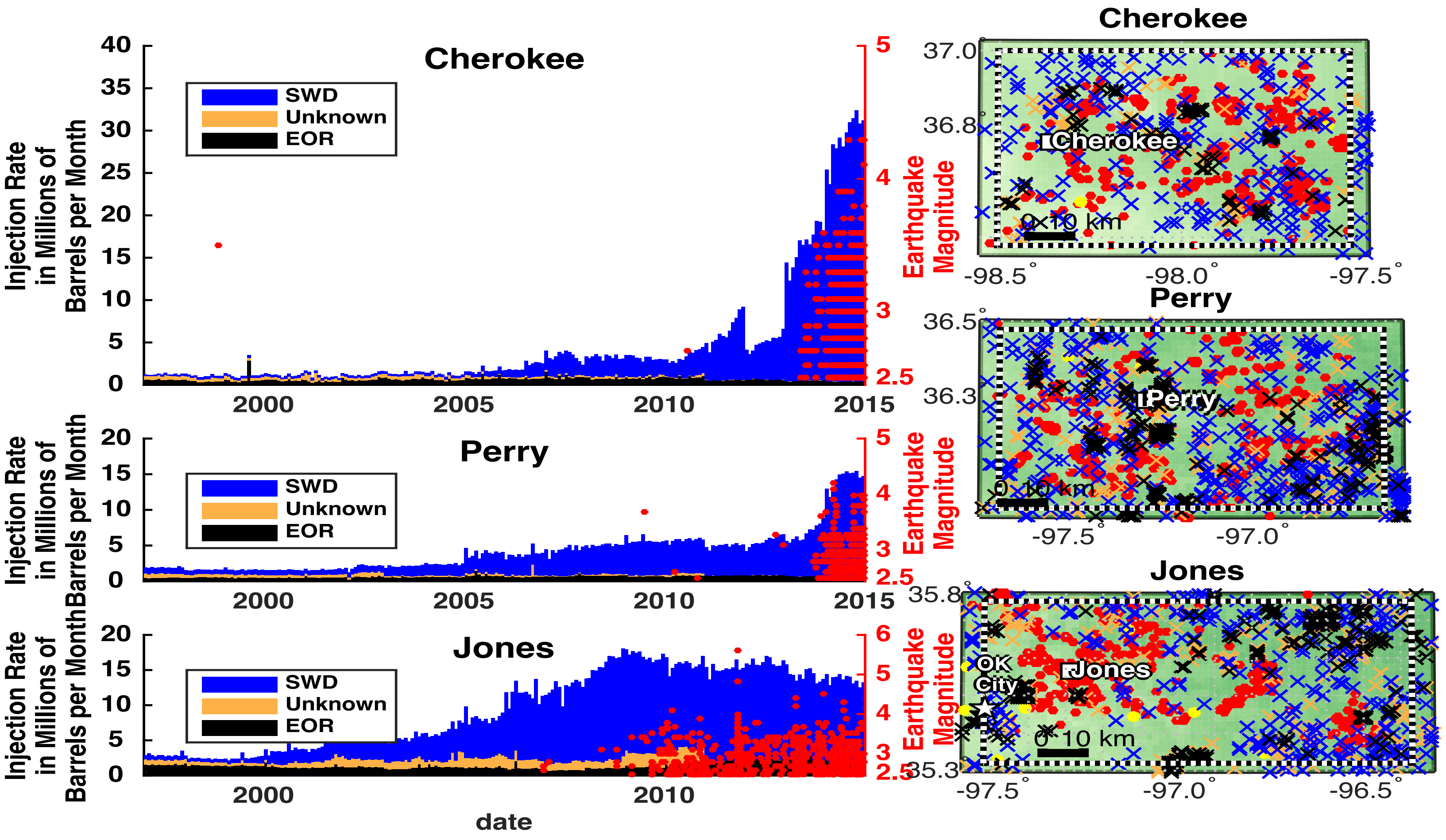
Strong Correlation Between Seismicity and SWD



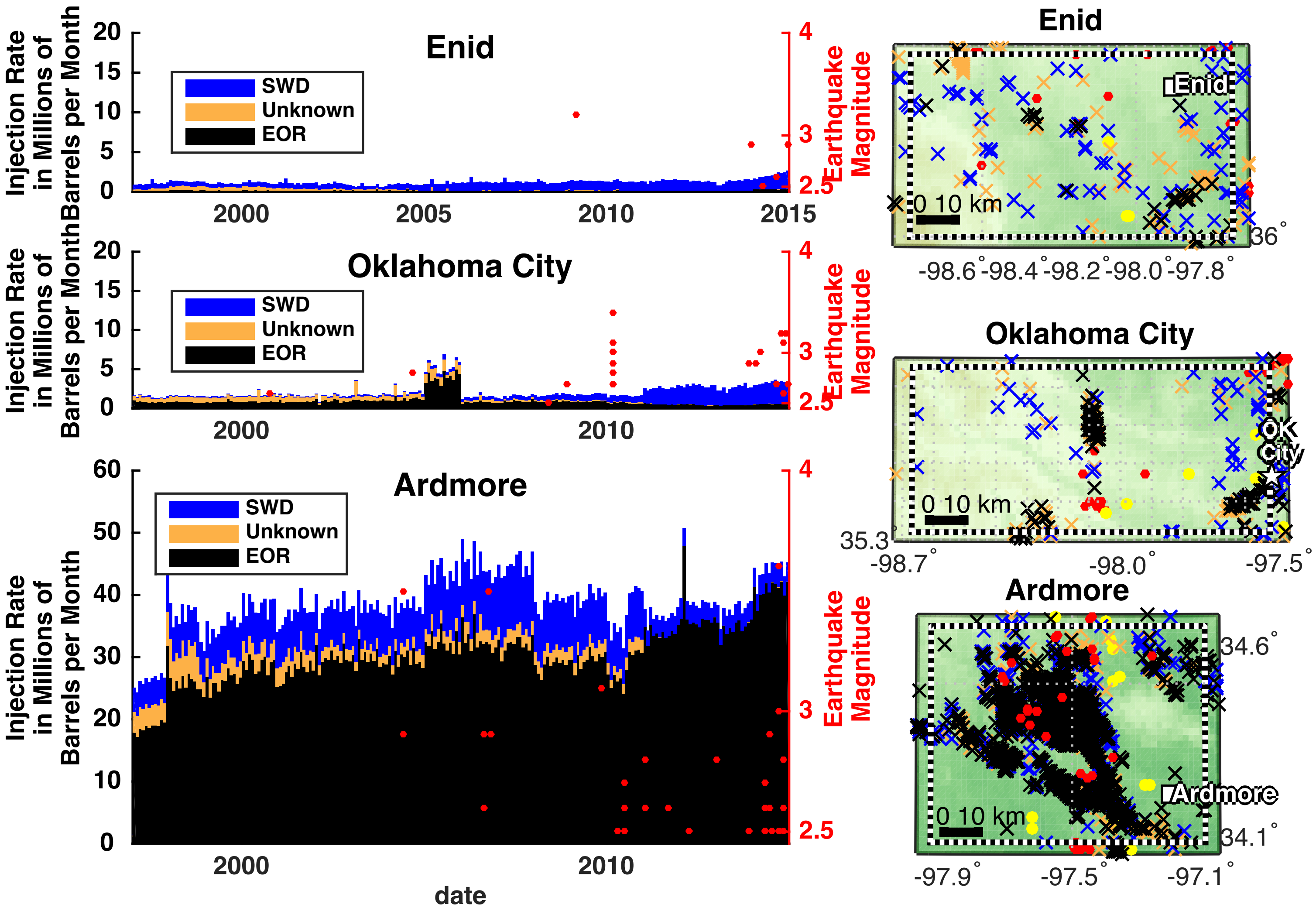
Six Study Areas – Each 5000 km²



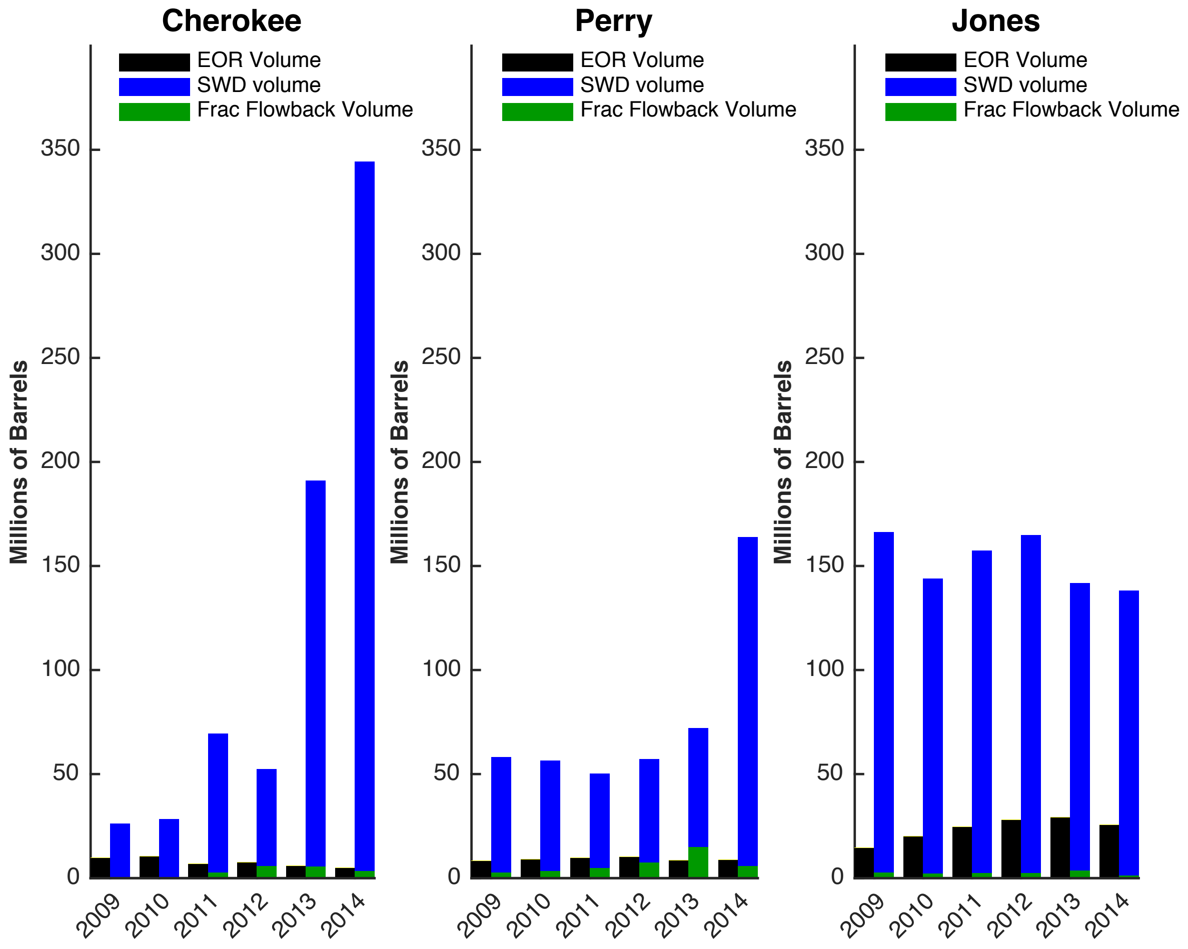
Seismicity in Active Areas in Oklahoma



Seismically Quiet Areas in Oklahoma

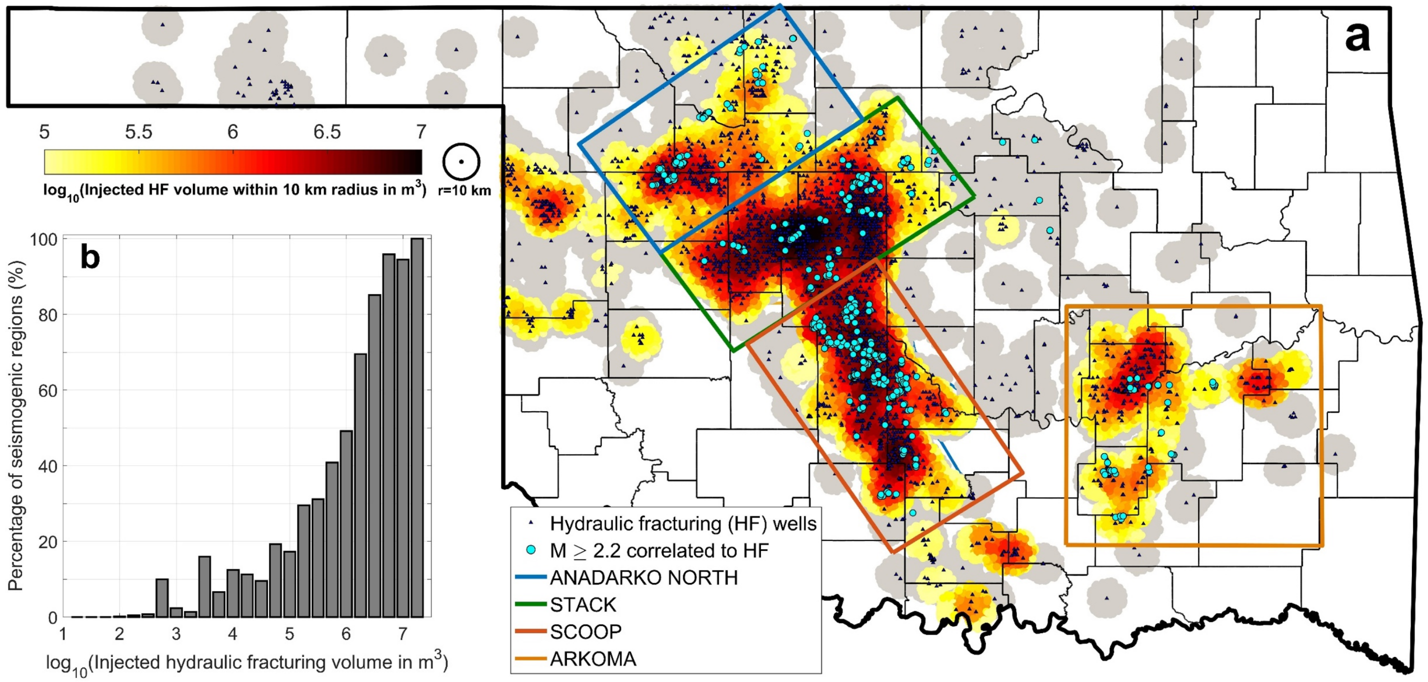


Where Does the Injected Water Come From?

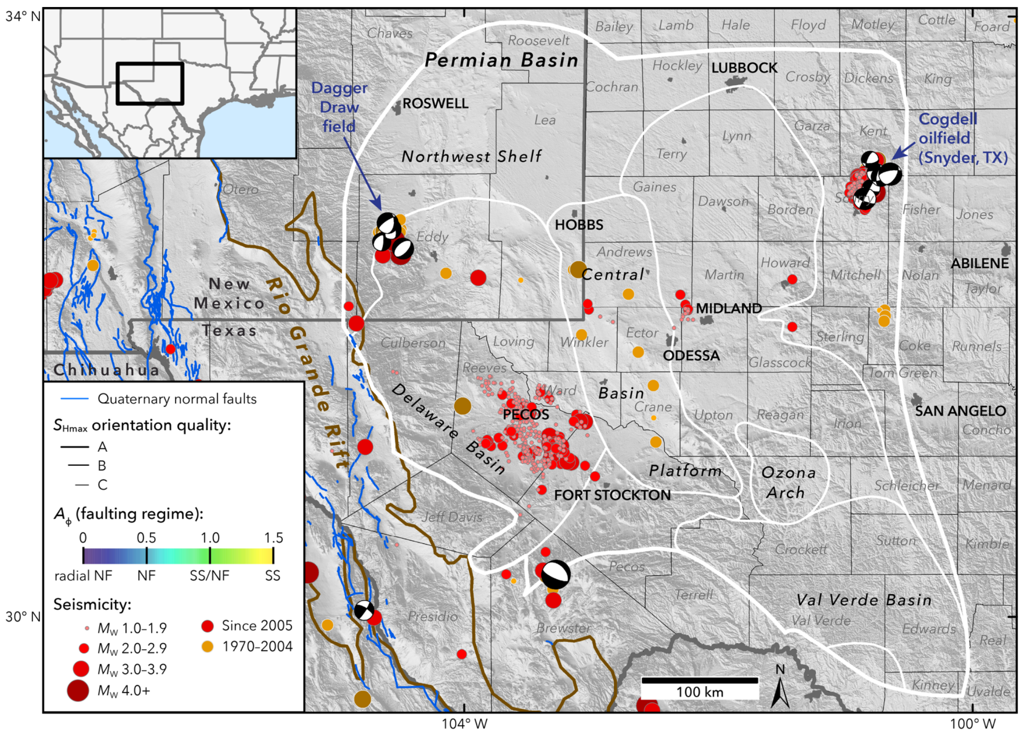


Updated Walsh and Zoback, Science Advances, 2015

Earthquakes Induced by Hydraulic Fracturing

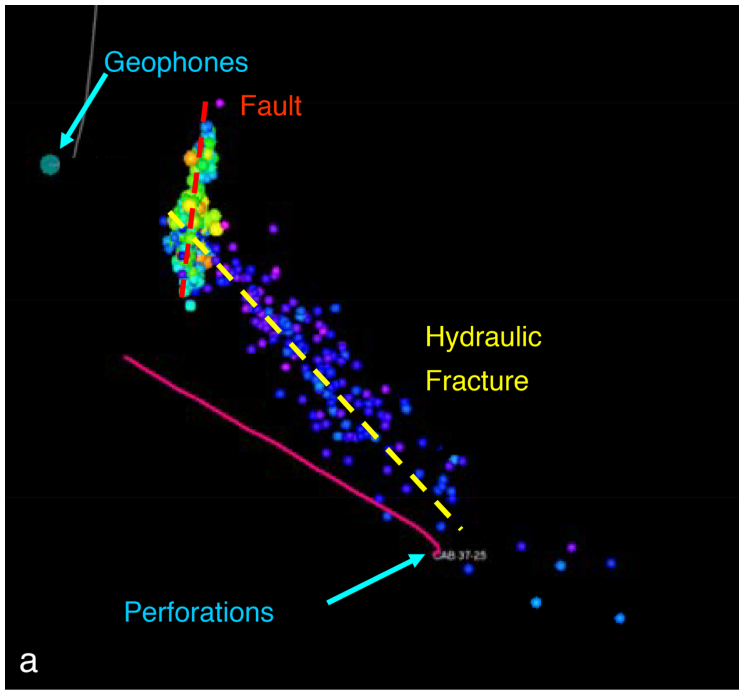


Langenbruch and Zoback (in preparation)

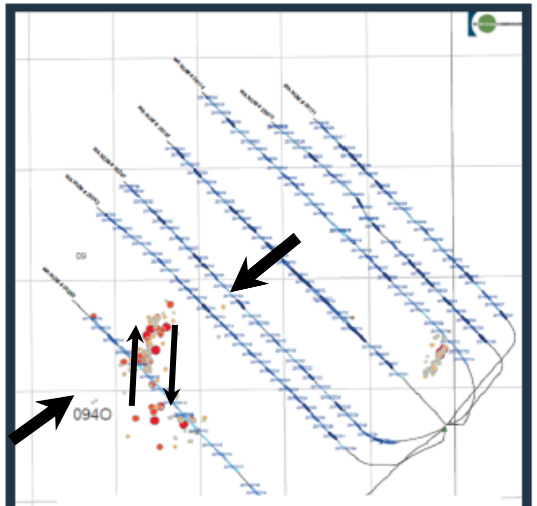


Modified from
Lund Snee and Zoback (2018)

Earthquakes Induced by Hydraulic Fracturing

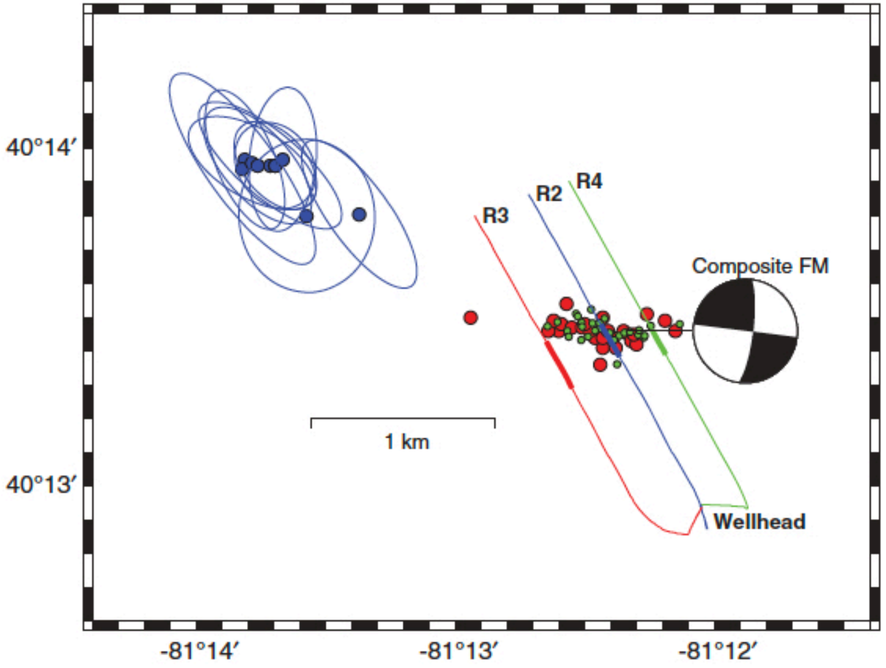


Maxwell et al. (2008)

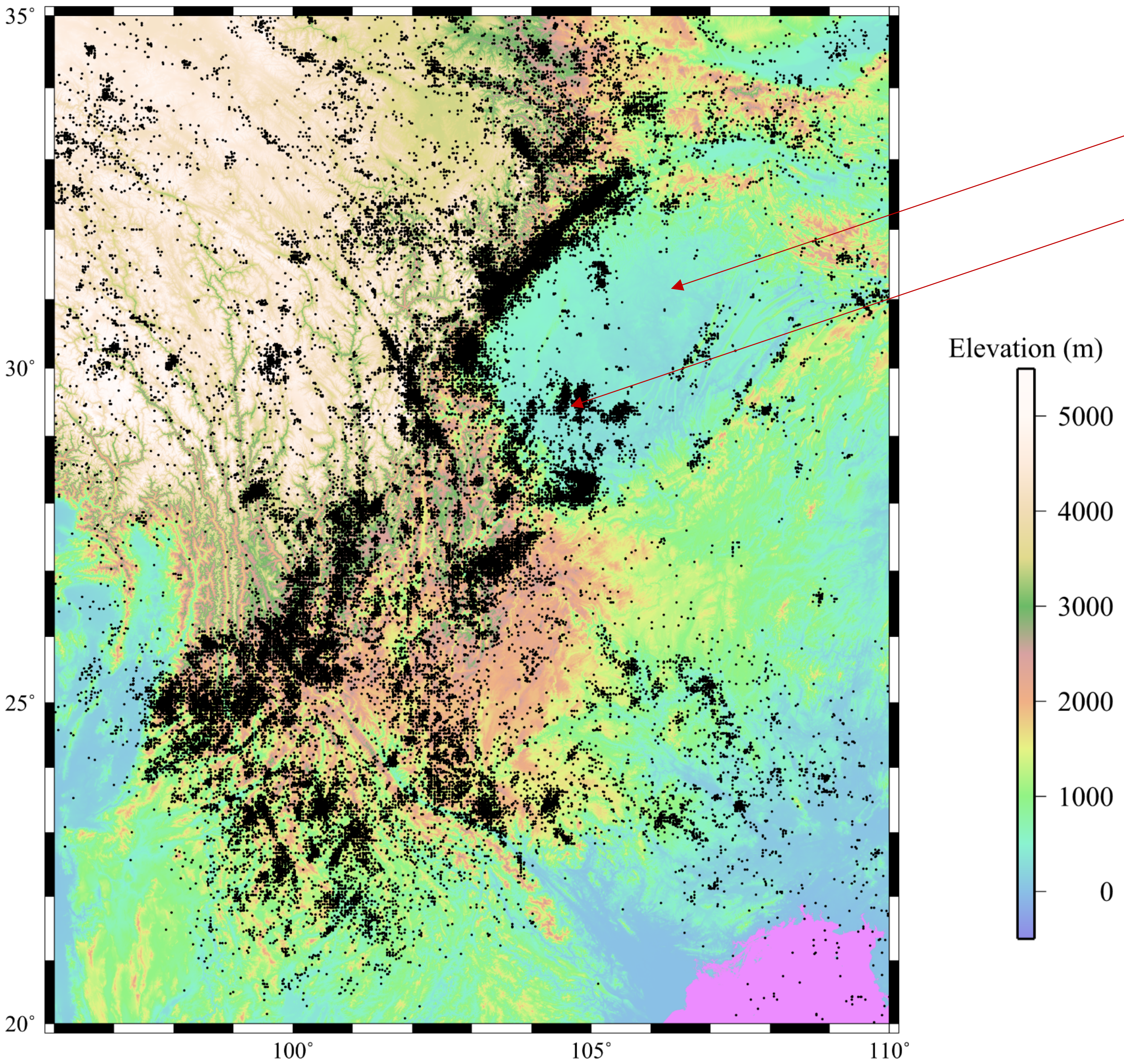


Horn River, British Columbia

BCOGC (2012)



Friberg et al. (2014)



Sichuan Basin

Rong County. It is estimated that the shale gas reserves in Rong County are 5.18 trillion cubic meters, or about one-sixth of the total estimated shale gas reserves in China. The Sichuan plan aimed to produce 2.5 billion cubic meters per year in the province and set a target for Zigong City, which administers Rong County, to produce 500 million cubic meters per year by 2018*.

*17 TCF (56% of US Consumption)

199,292 earthquakes (M>0)

From 2013 January to 2018 May

February 2019 Induced Earthquakes

Table 1. Event parameters used in this study								
Epicentral parameters					mb(Lg)		Ms	
Date (yyyy/mm/dd)	Time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	mb (Lg)	standard deviation	Ms (Rayleigh)	standard deviation
2019/02/25a	05:15:59.860	29.498	104.632	5.0	4.95	0.27	3.40	0.24
2019/02/25b	00:40:27.400	29.471	104.561	5.0	4.43	0.25	2.58	0.32
2019/02/23	21:38:10.270	29.552	104.594	5.0	4.75	0.21	3.03	0.27

Reported Magnitudes 4.43 – 4.95

A woman in Gaoshan, China, walking through the entrance to her farmhouse, which was damaged during three recent earthquakes in surrounding Rong County. Gilles Sabrie for The New York Times

The New York Times
March 2019

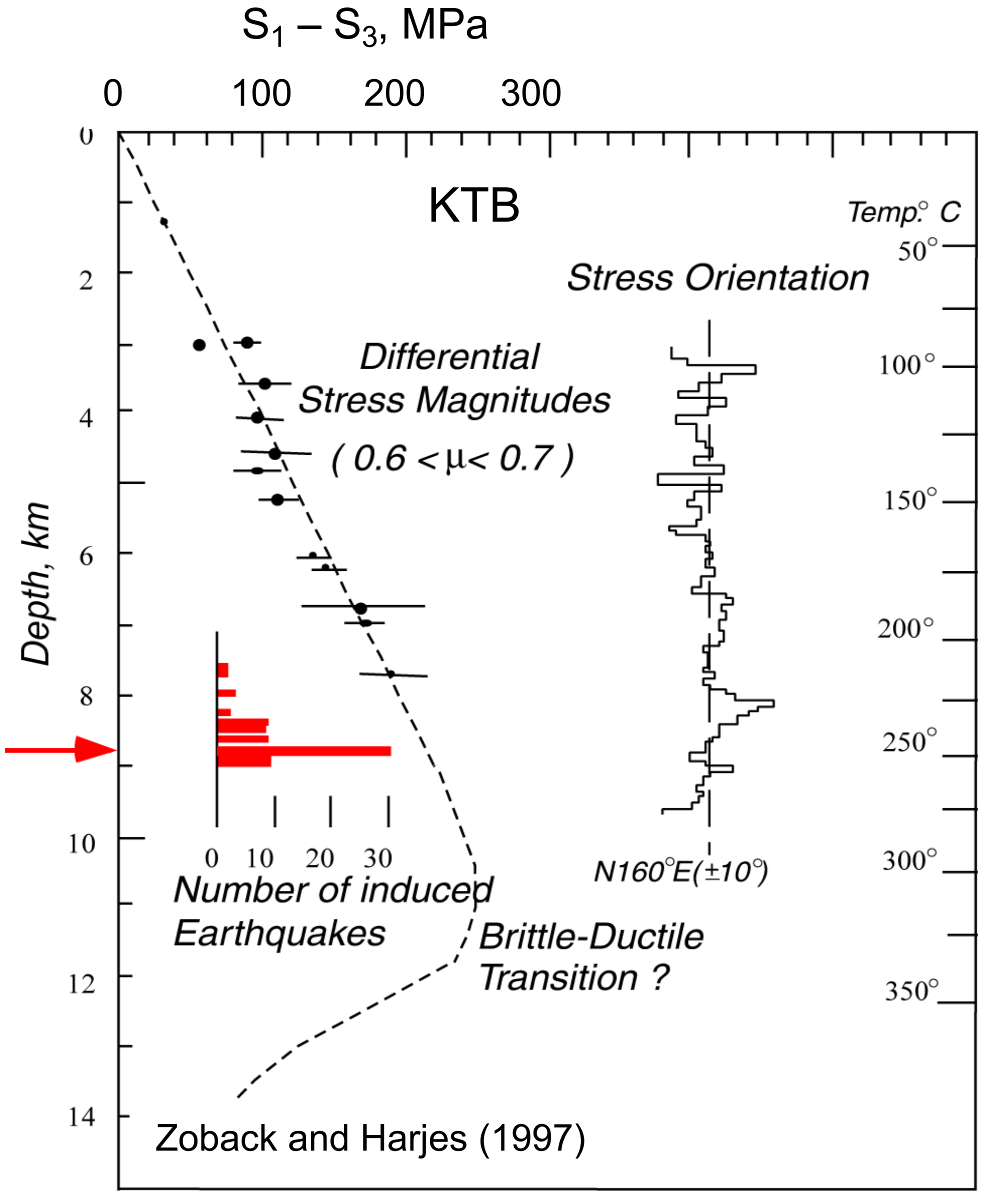
10,000 Protesting on February 24, 2019

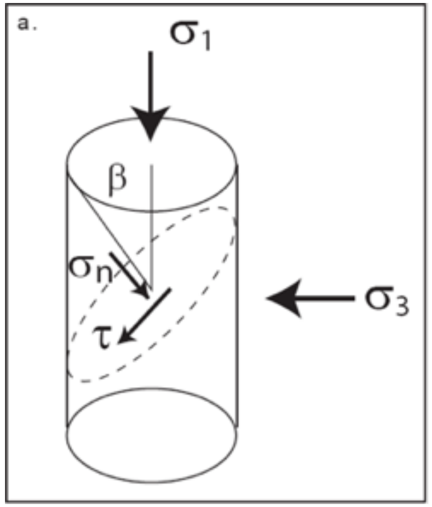
Two Questions

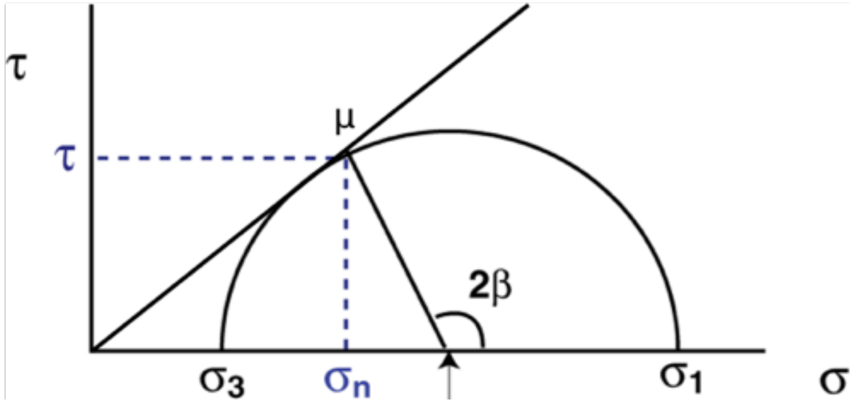
- Can we identify potentially active faults prior to hydraulic fracturing?

- Can we use physics-based models to guide oil and gas development regulations?

Coulomb Faulting Theory Works!







Friction determines both the magnitude of stress and the orientation of active faults with respect to the stress field.

$$\frac{\sigma_1}{\sigma_3} = \frac{S_1 - P_p}{S_3 - P_p} = \left(\sqrt{\mu^2 + 1} + \mu\right)^2$$

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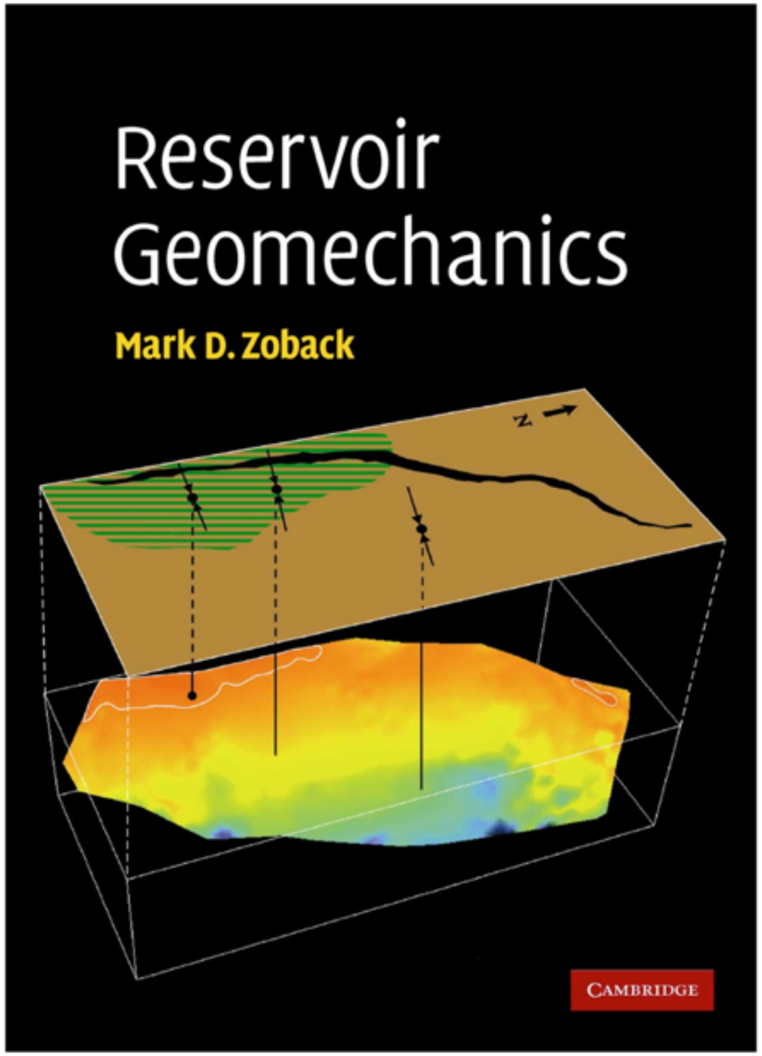

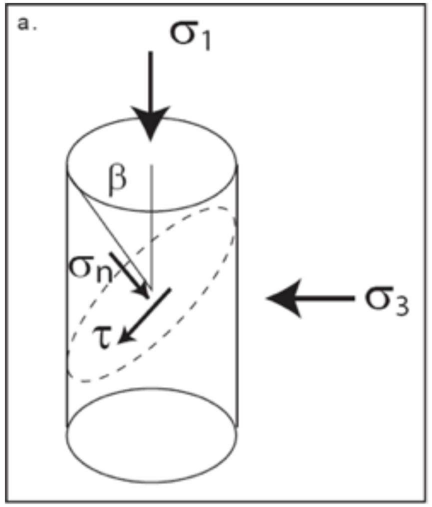

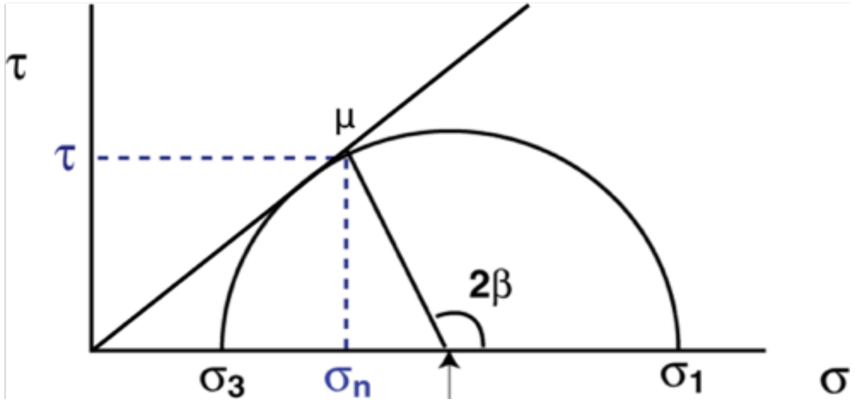

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Can We Avoid Injection into Potentially Active Faults?

THE GEOLOGICAL SOCIETY OF AMERICA®

Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA

F. Rall Walsh, III, and Mark D. Zoback
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

GEOLOGY Data Repository item 2016334 | doi:10.1130/G38275.1

Can We Avoid Injection into Potentially Active Faults?

Yes, if we Know the Key Parameters – State of Stress, Fault Orientations and Pore Pressure Perturbation

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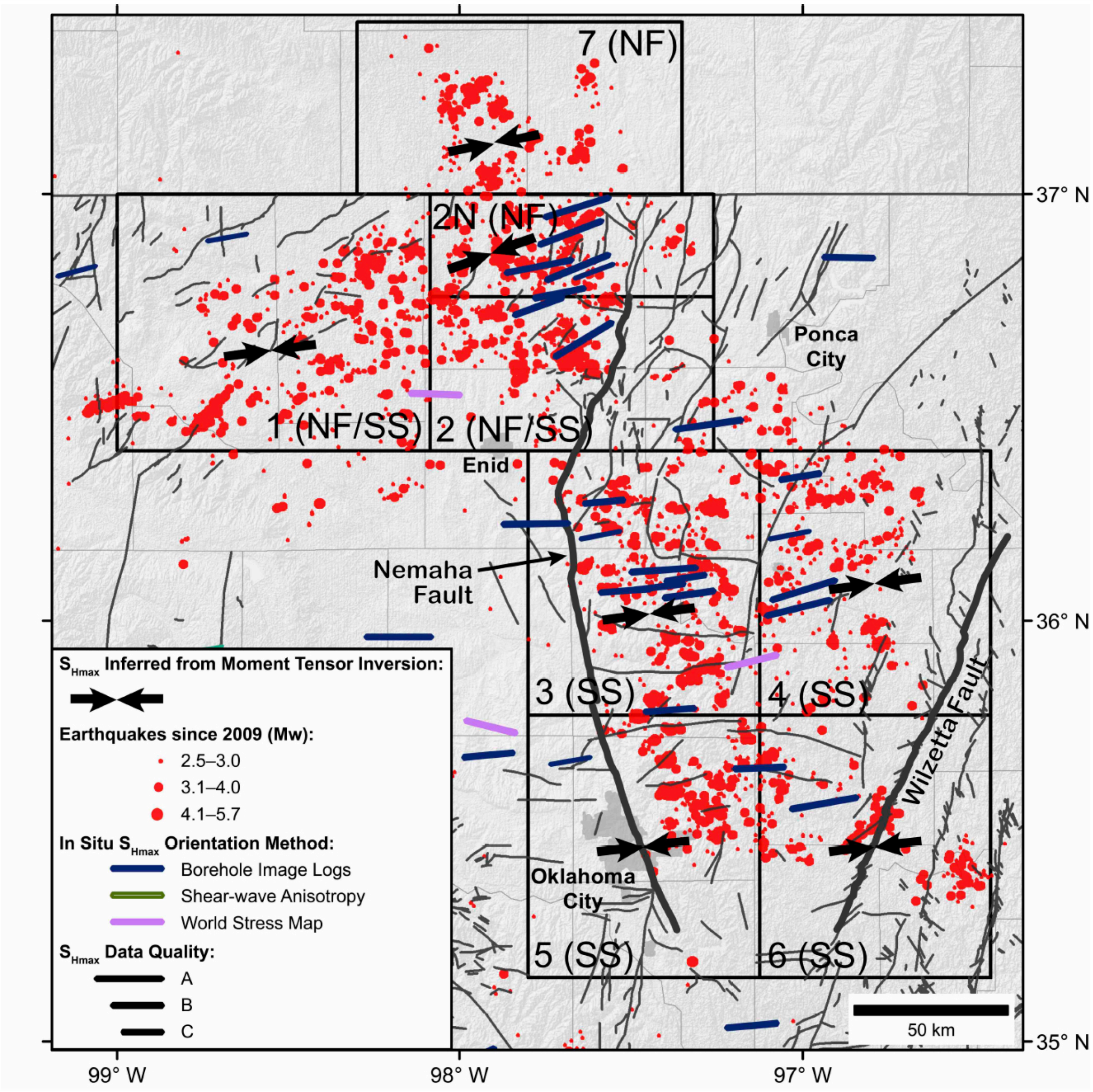
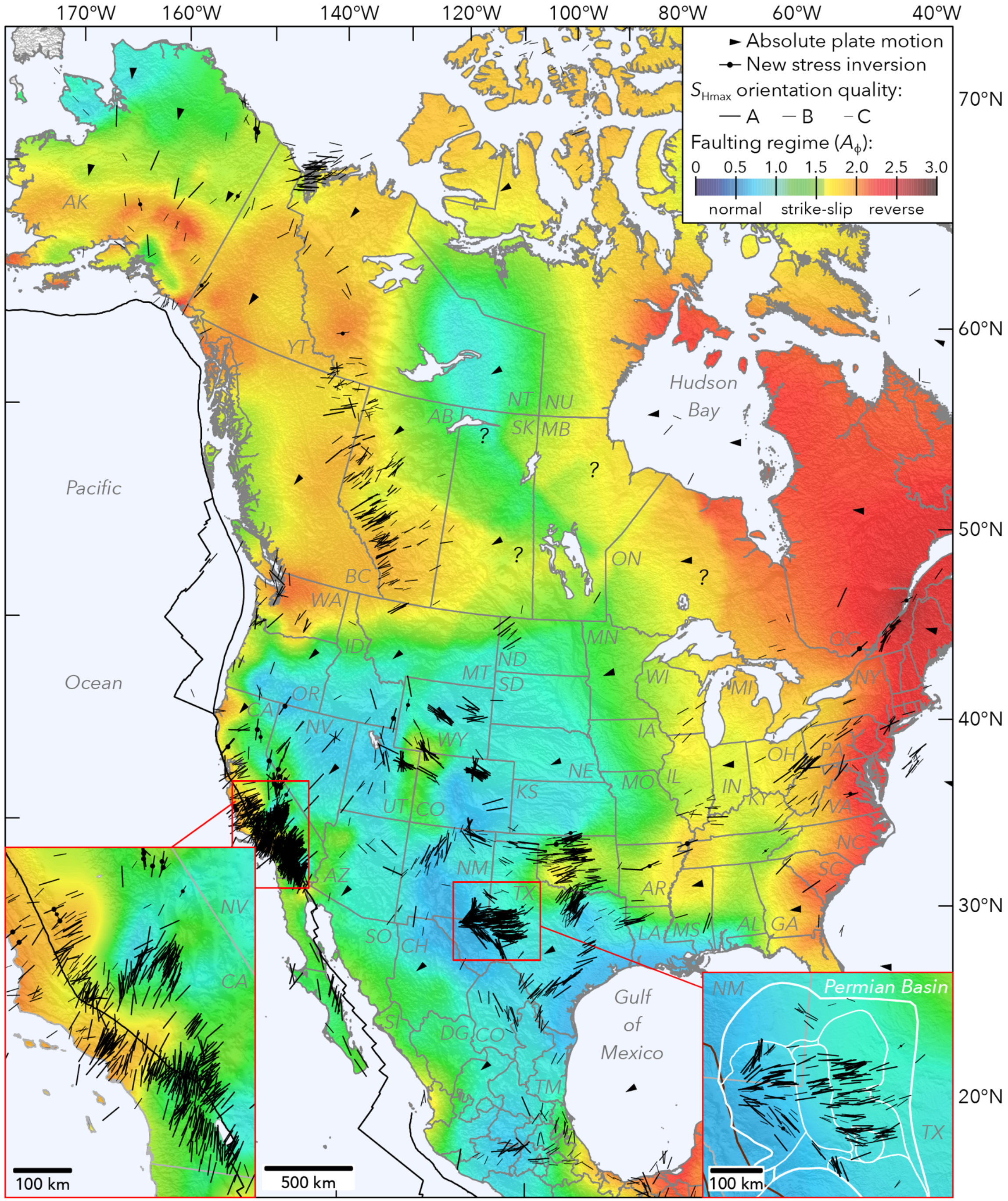
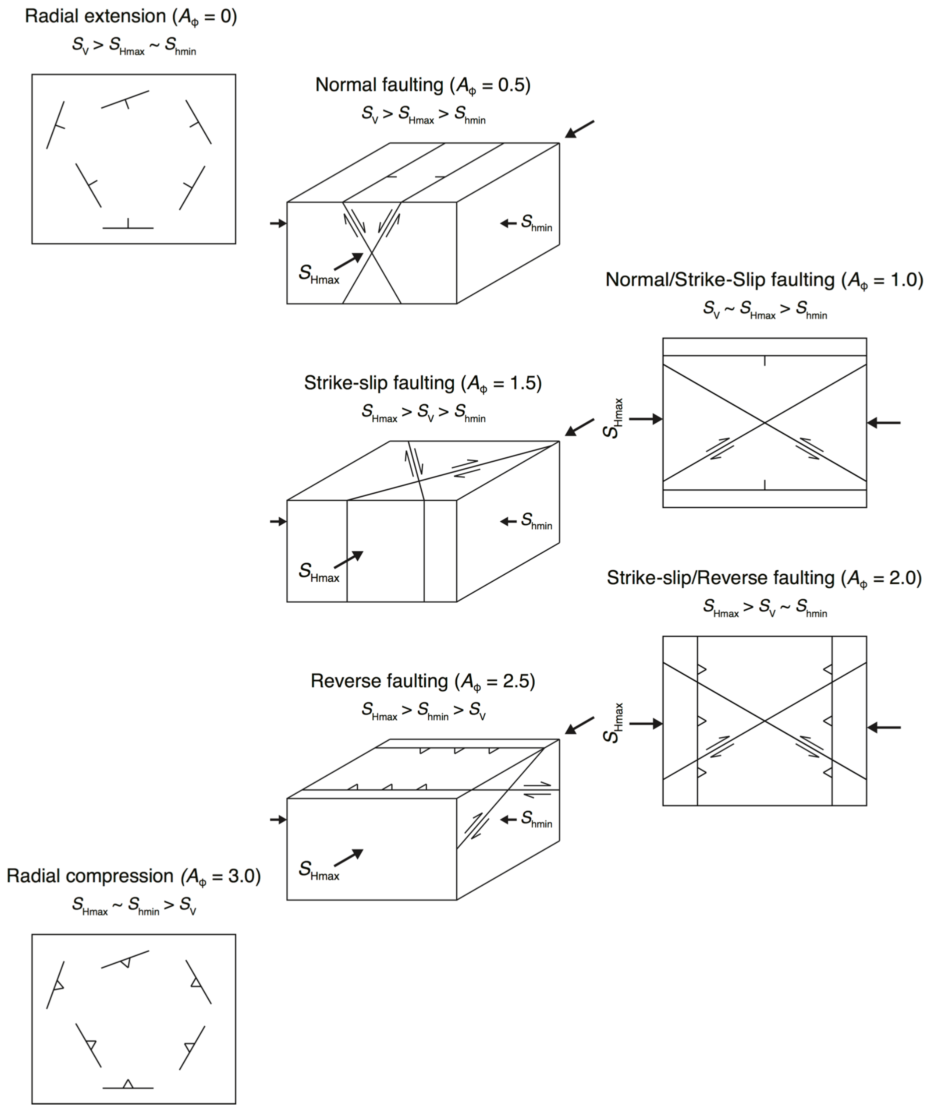


- Detailed Mapping of Stress Orientation and Relative Magnitudes
  - Wellbore Observations
  - Earthquake FM Inversions
  - Slowly Varying Relative Stress Magnitudes
- Utilize Information About Pre-Existing Faults (Darold and Holland, 2015)
- Combine Data to Identify Potentially Active Faults

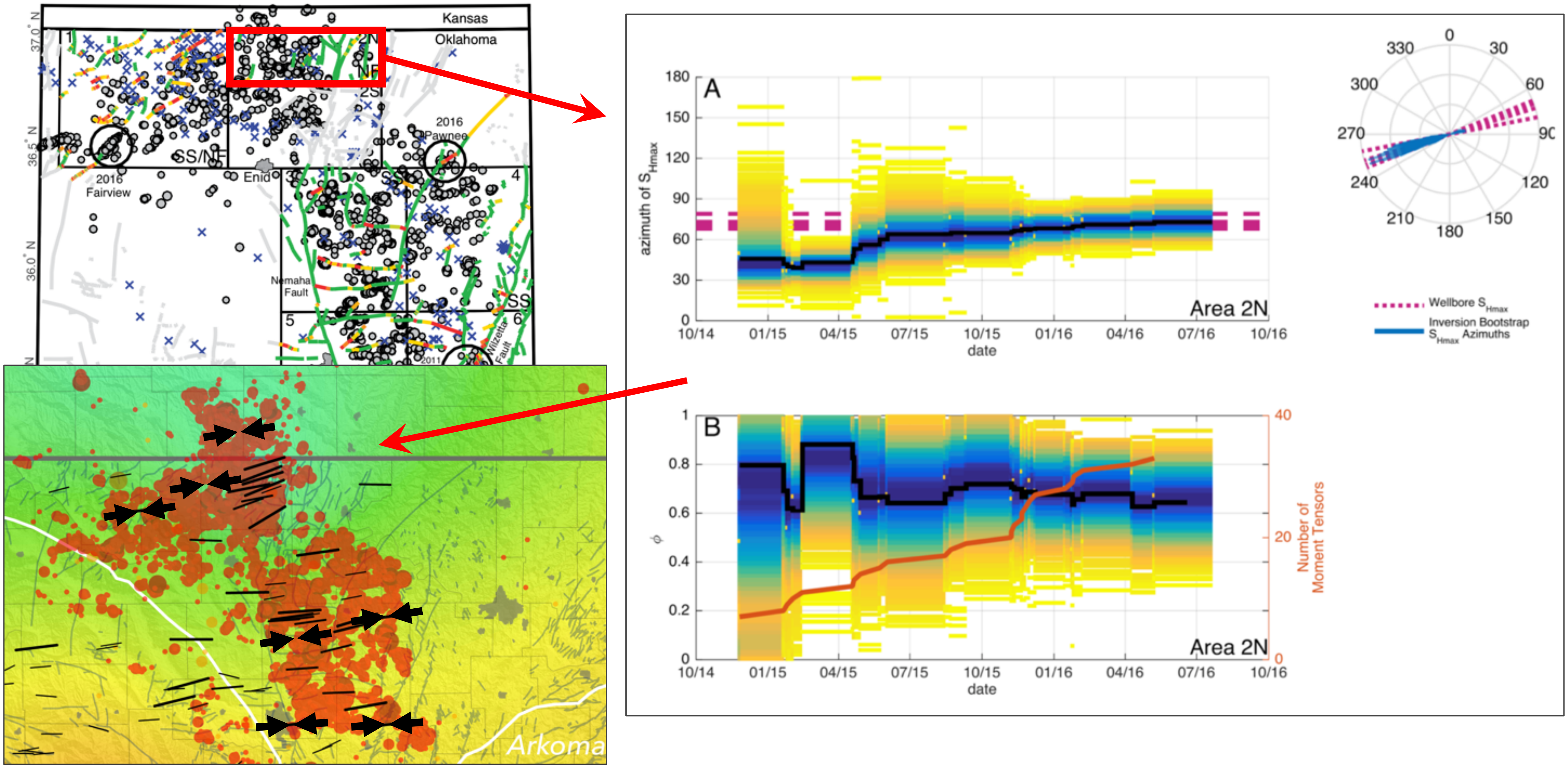
Alt and Zoback (*BSSA*, 2017)

Anderson Faulting Theory on Steroids





Earthquake Stress Measurements Agree with Wellbore Data



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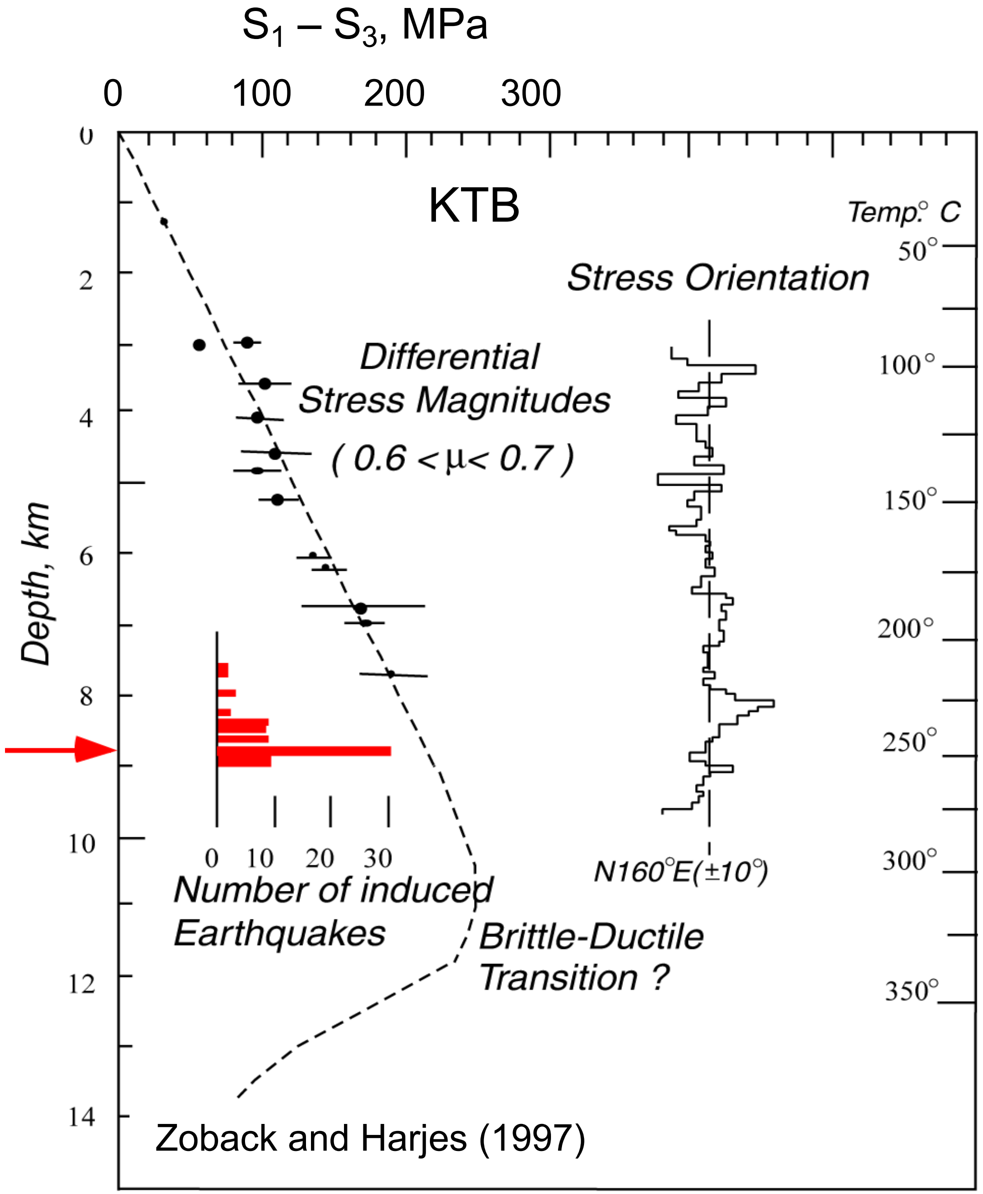

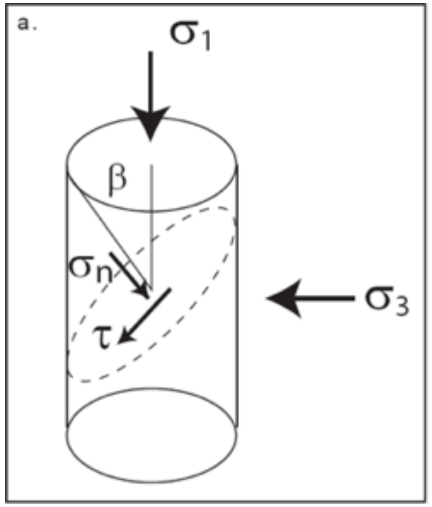

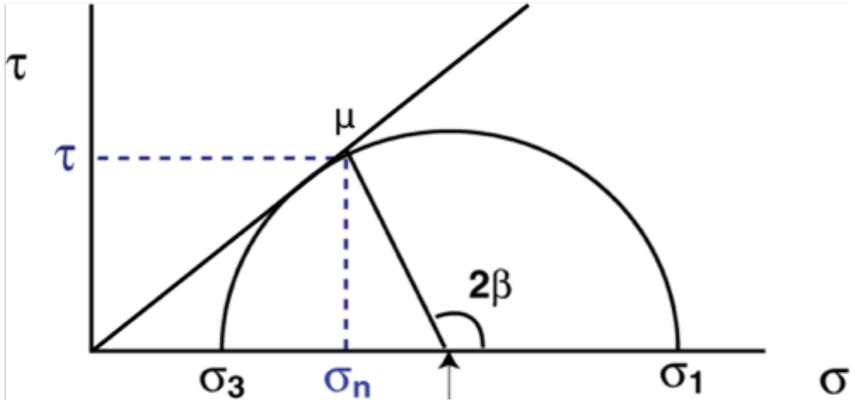

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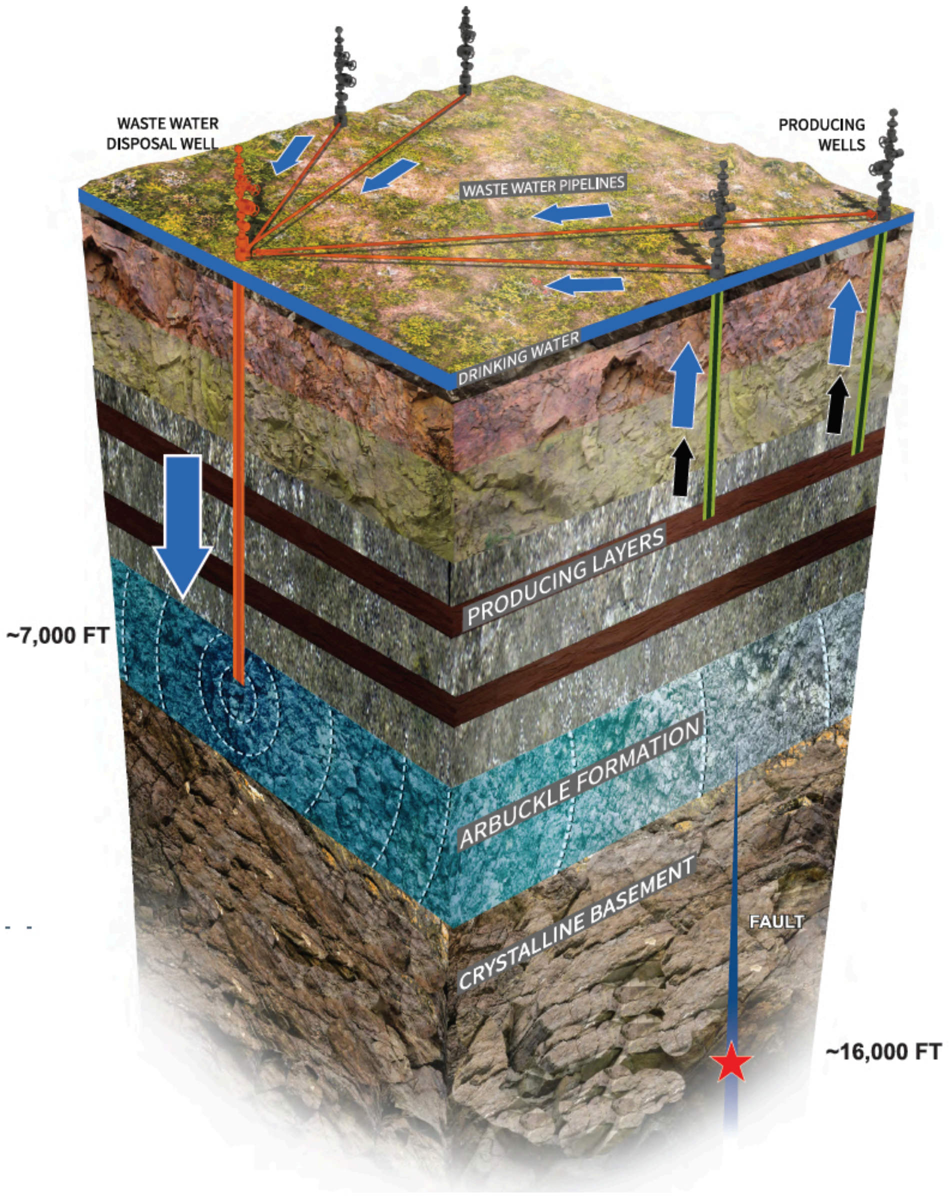

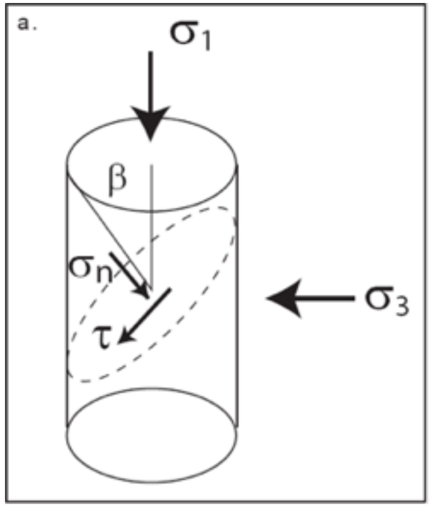

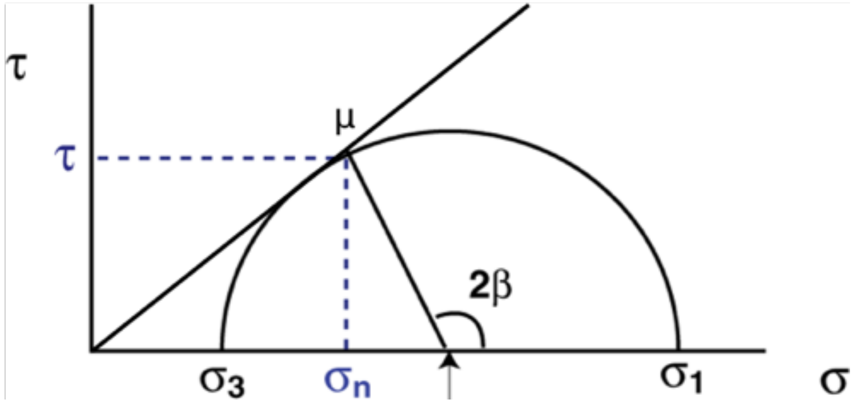

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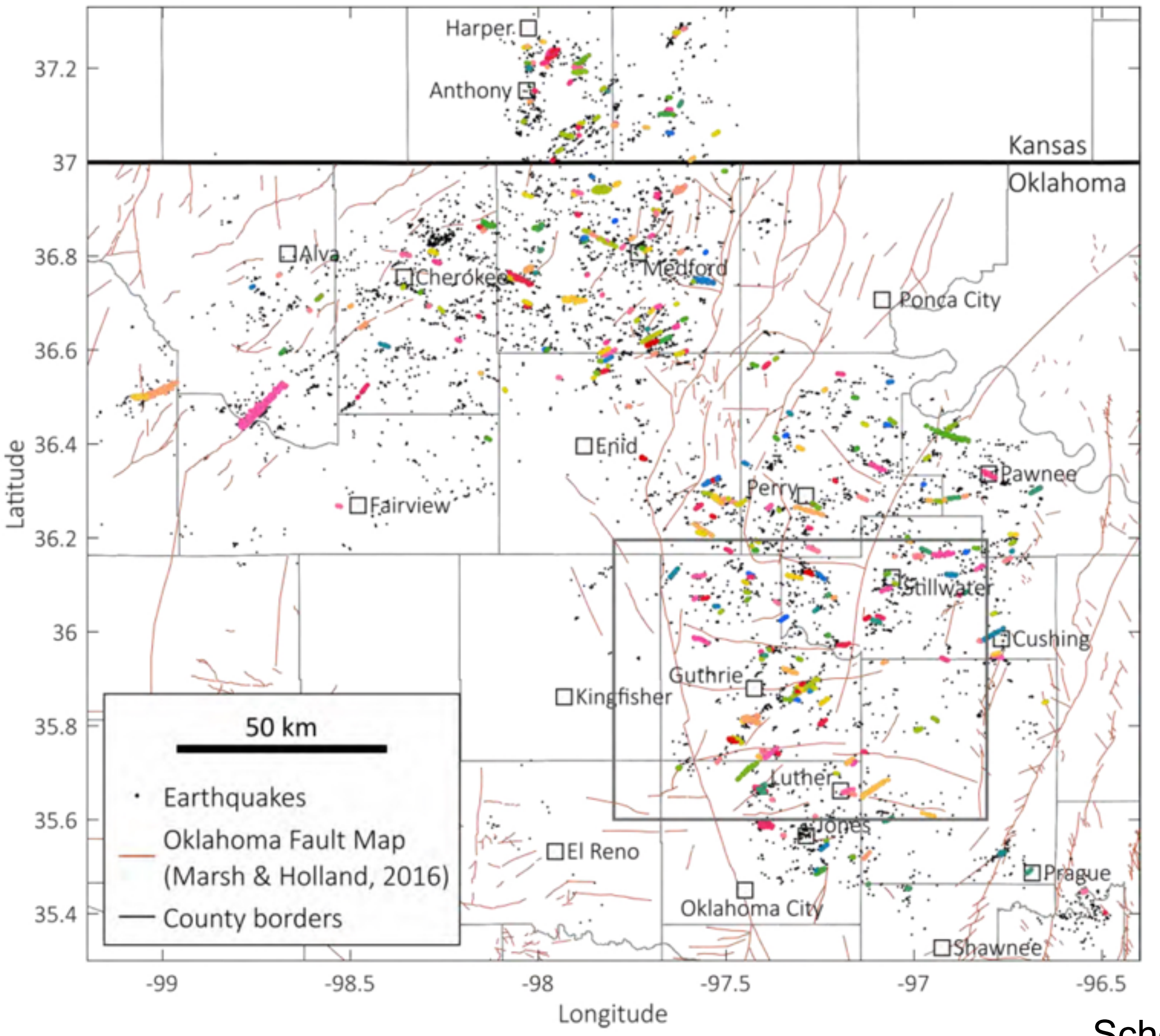
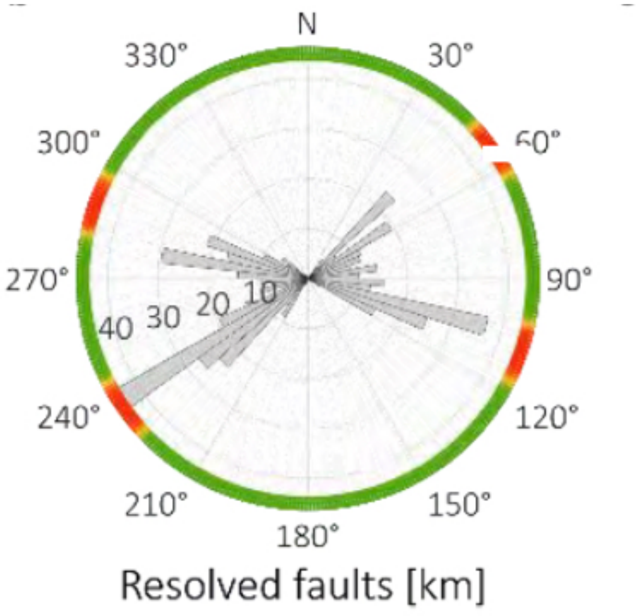
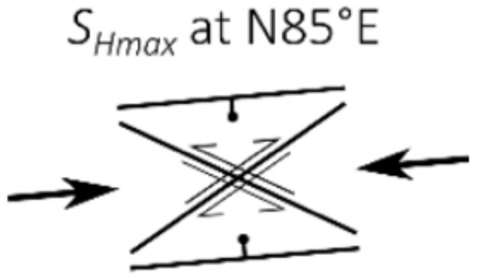
Coulomb Faulting Theory Works!







Schoenball and Ellsworth (2017)

Can We Avoid Injection into Potentially Active Faults?

Yes, But We Need to Incorporate the Uncertainties of Key Parameters – State of Stress, Fault Orientations and Pore Pressure Perturbation

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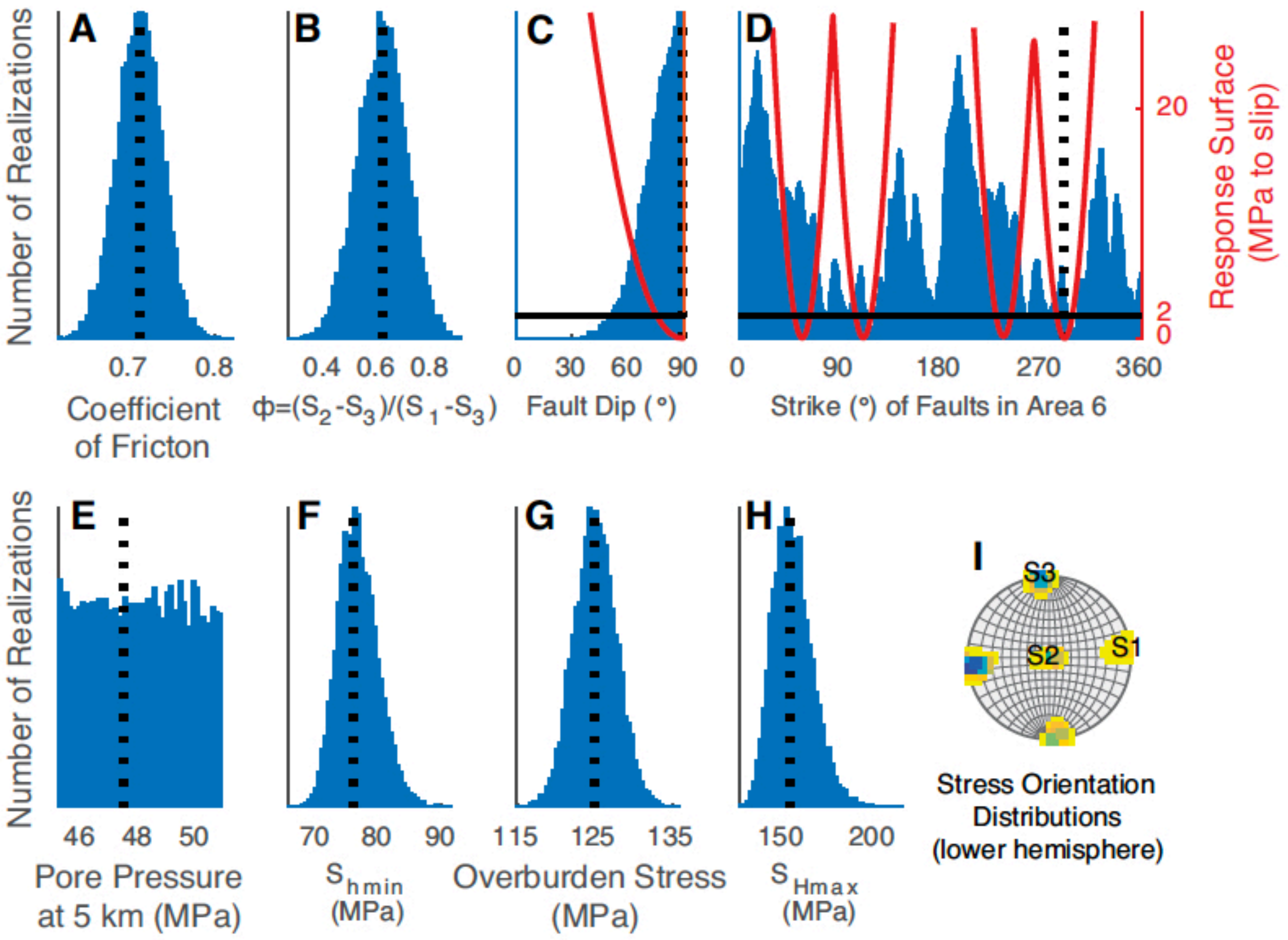
Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA

F. Rall Walsh, III, and Mark D. Zoback
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

GEOLOGY Data Repository item 2016334 | doi:10.1130/G38275.1

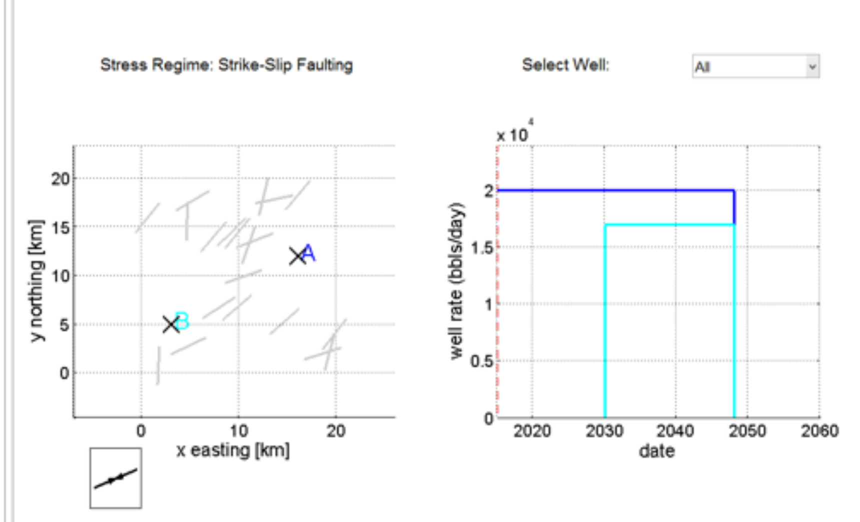
Estimating Uncertainty in Key Parameters (More Complicated than it Seems)



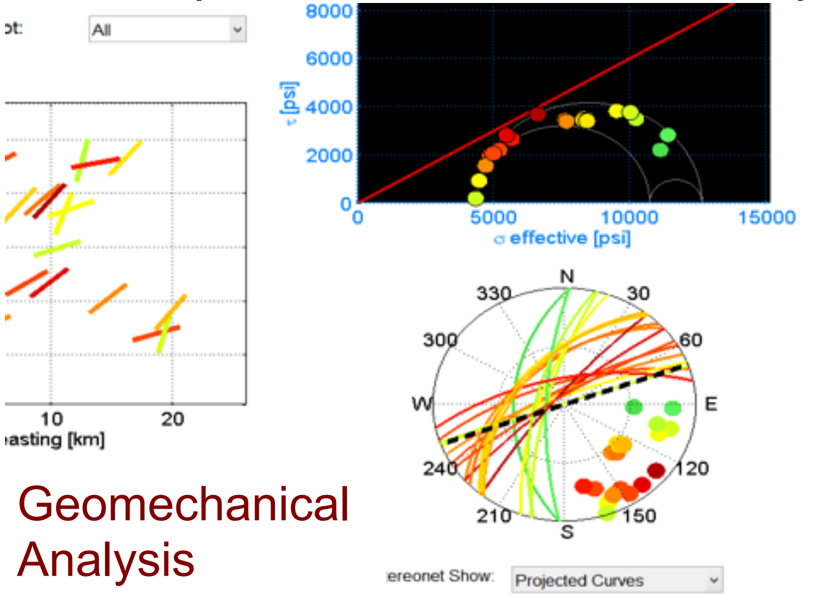
Walsh and Zoback (2016)

Free, Online Software Now Available use QRA to Assess Fault Slip Potential (*URL SCITS.stanford.edu*)

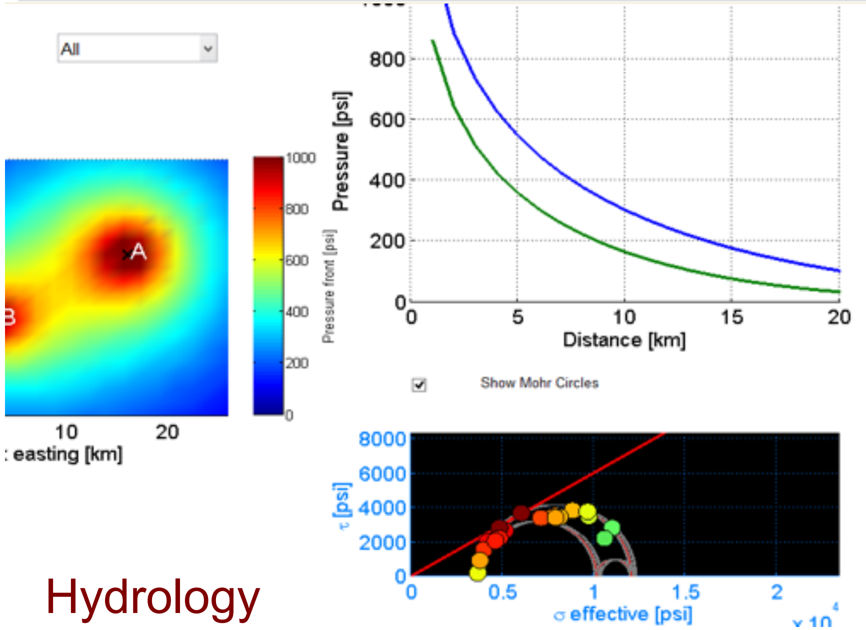
F S P
Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity



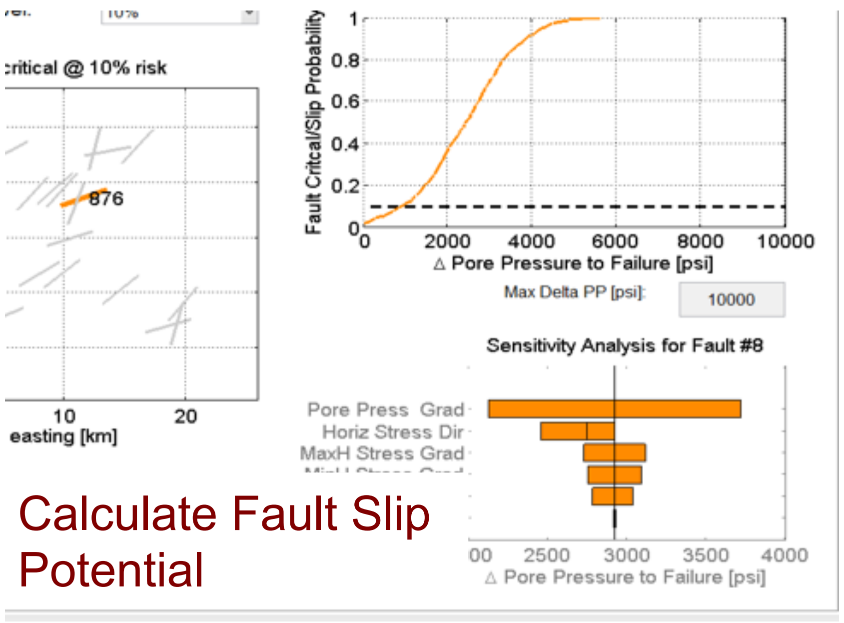
Injection Wells and Faults



Geomechanical Analysis

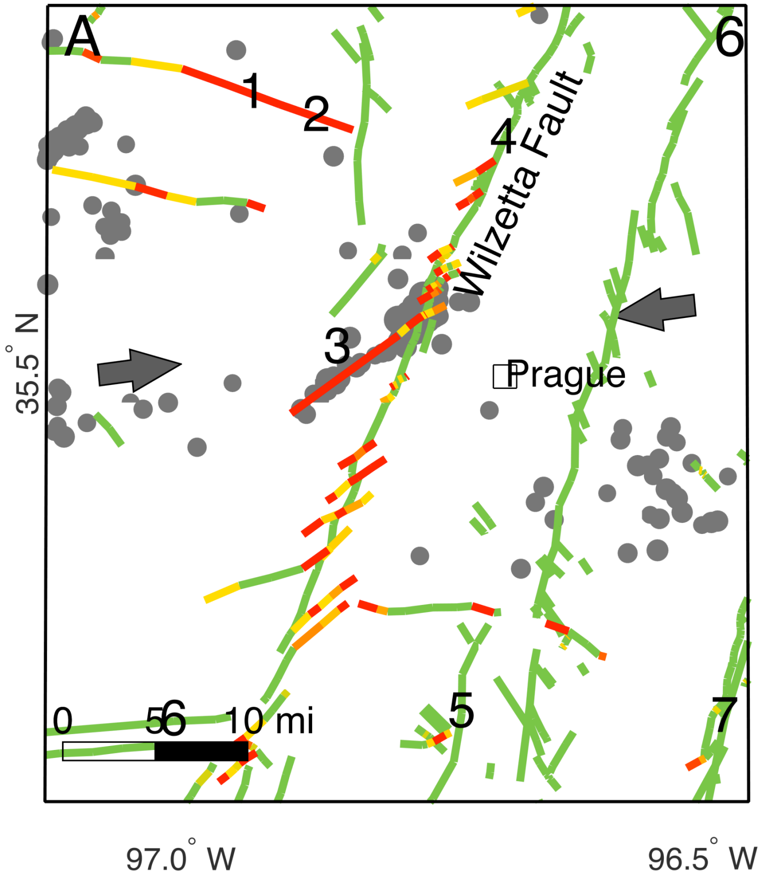


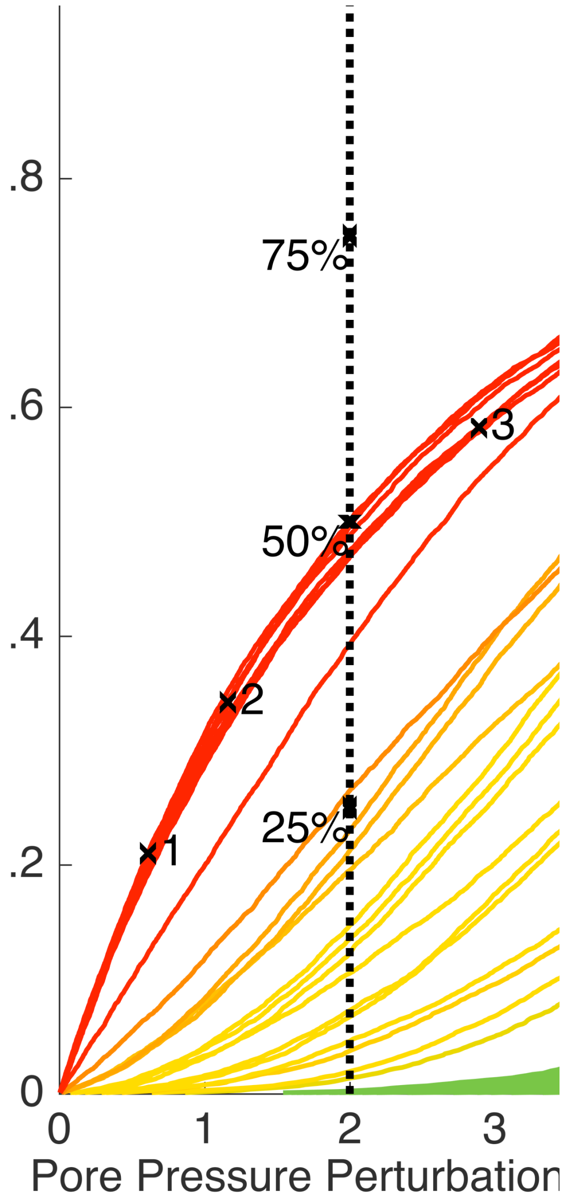
Hydrology



Calculate Fault Slip Potential

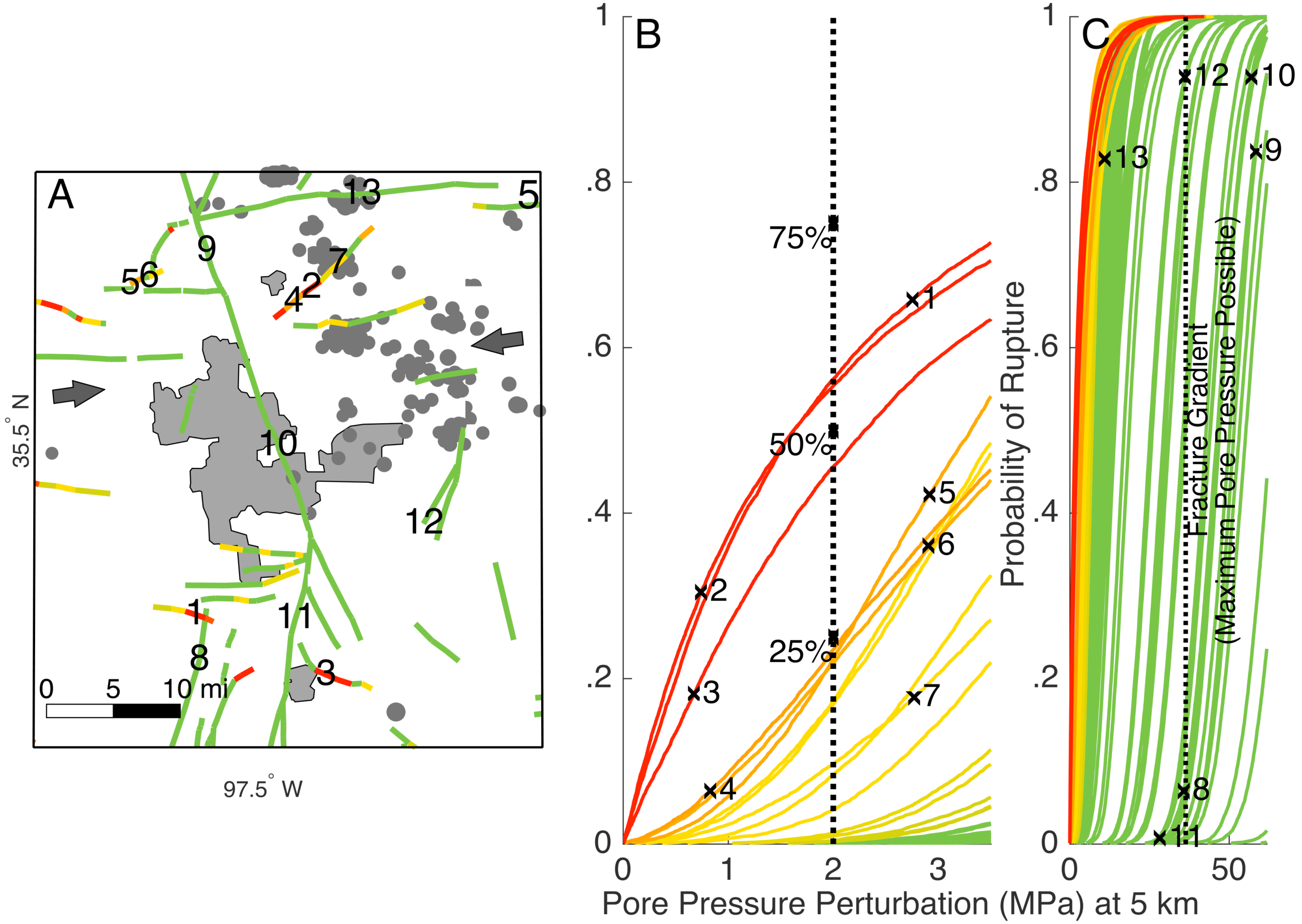
Fault Slip Probability (2 MPa Max Pressure Change)





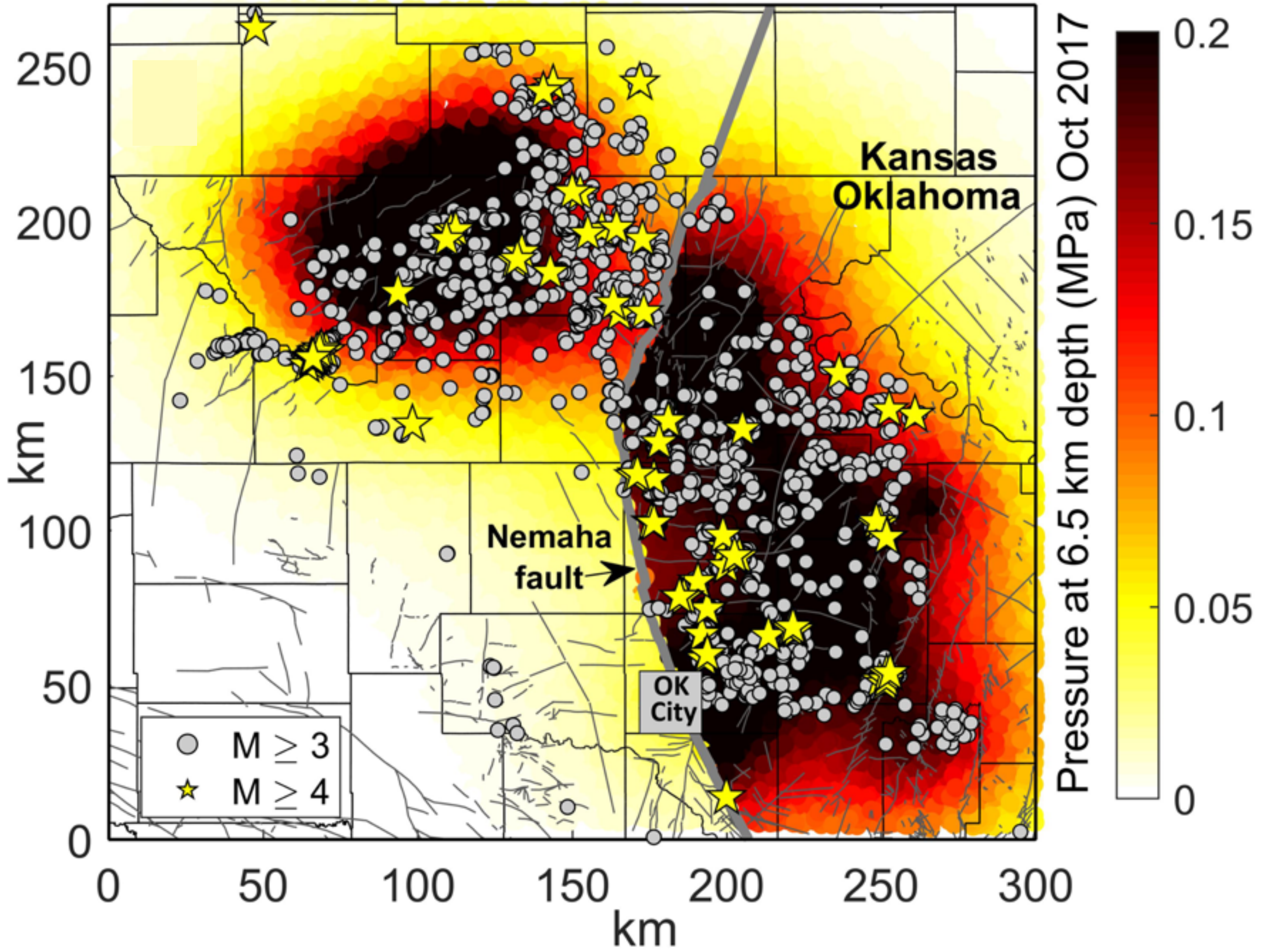
Walsh and Zoback (2016)

Identification of Faults That are Not Likely to be Problematic is Important Too!

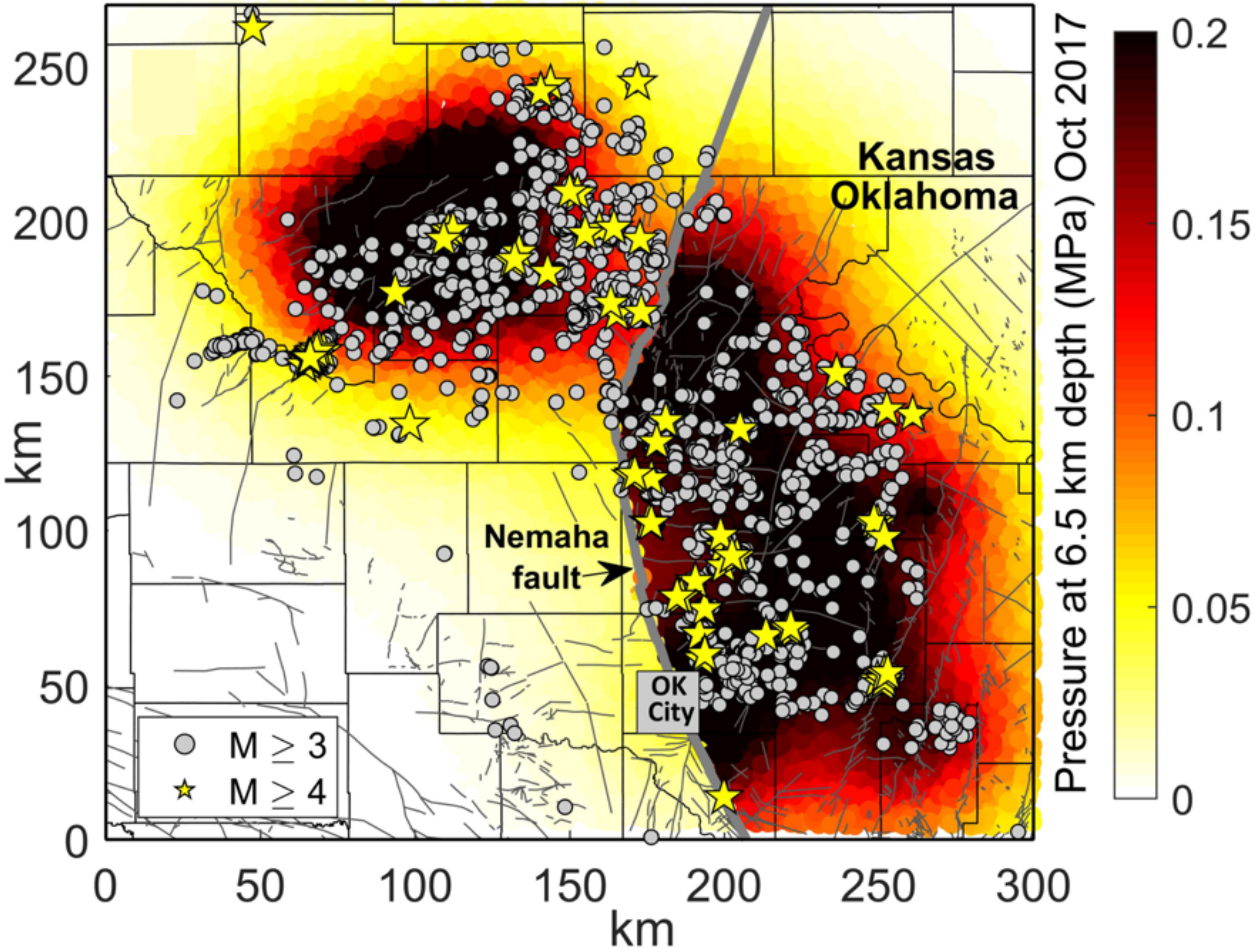


Walsh and Zoback (2016)

Does FSP Work? In Retrospect, Every Significant Eq in OK Can be Explained by Coulomb Faulting Theory



Does FSP Work? In Retrospect, Every Significant Eq in OK Can be Explained by Coulomb Faulting Theory But We Only Knew of the Presence of These Faults After the Eqs. Occurred

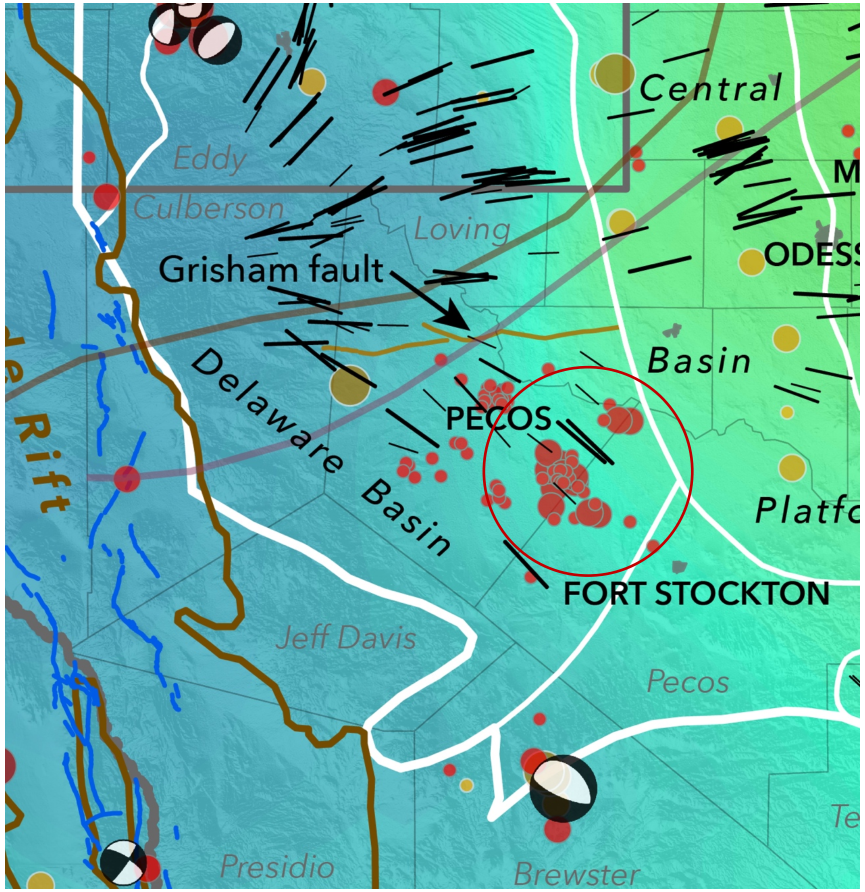


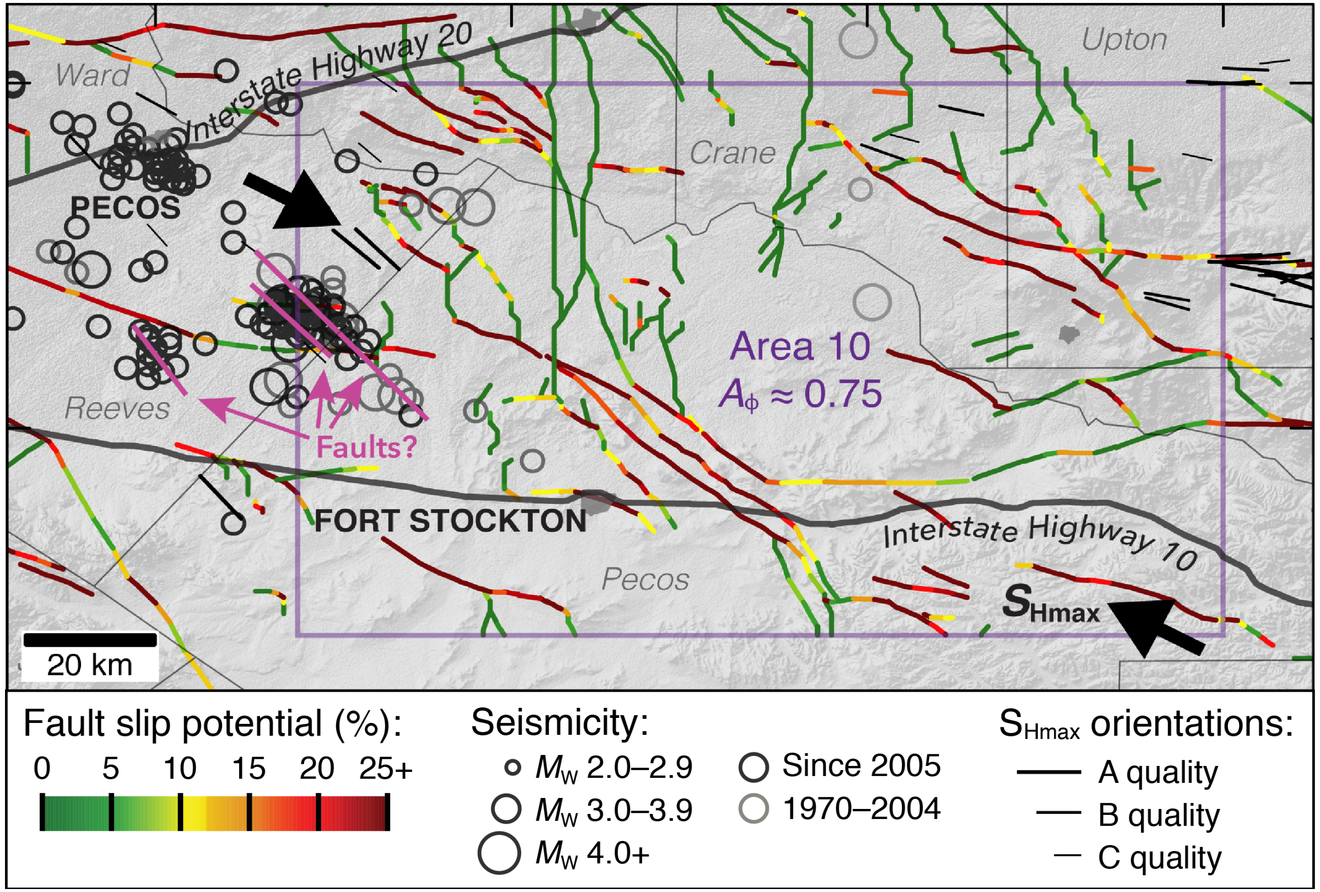
Two Questions

- Can we identify potentially active faults prior to hydraulic fracturing?
- Can we use physics-based models to guide oil and gas development regulations?

Triggered Normal Faulting on Faults Striking Parallel to S_{HMAX} Principally Below the Wolfcamp

FSP
Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity

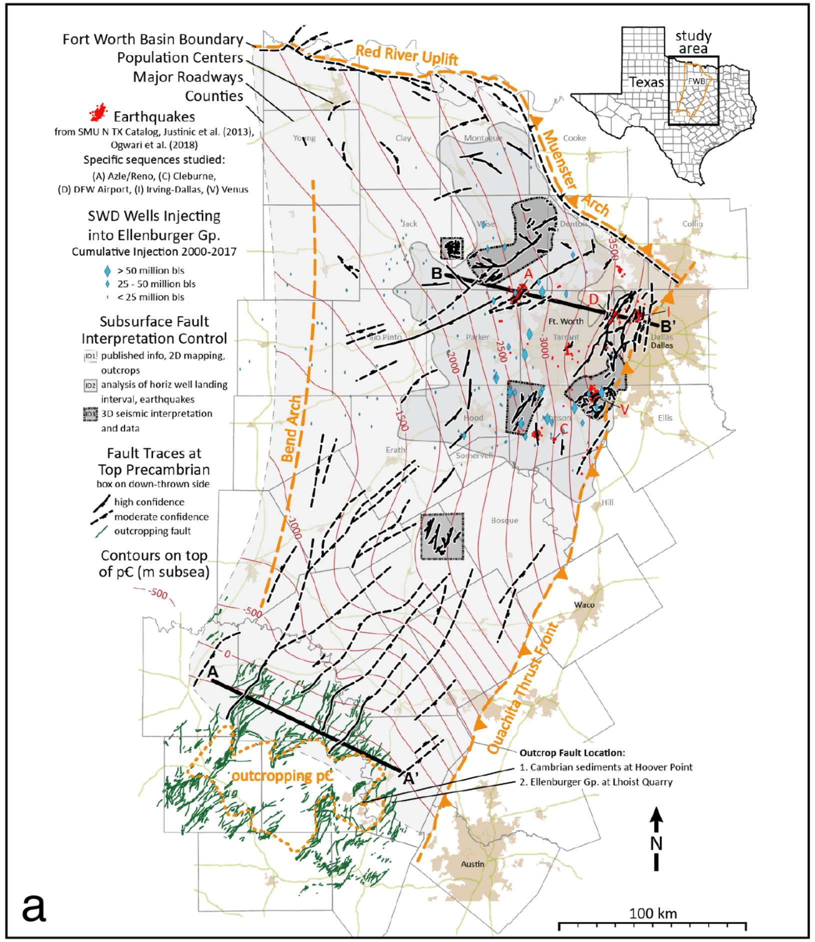




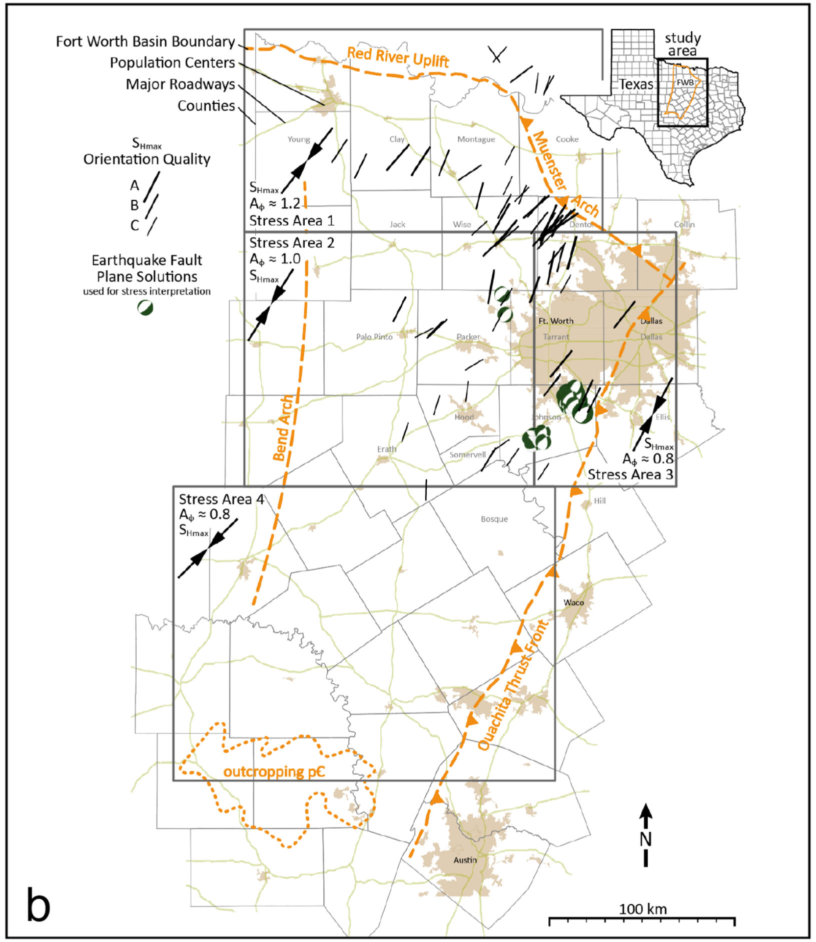
Modified from Lund Snee and Zoback (2018)

Application to the Fort Worth Basin

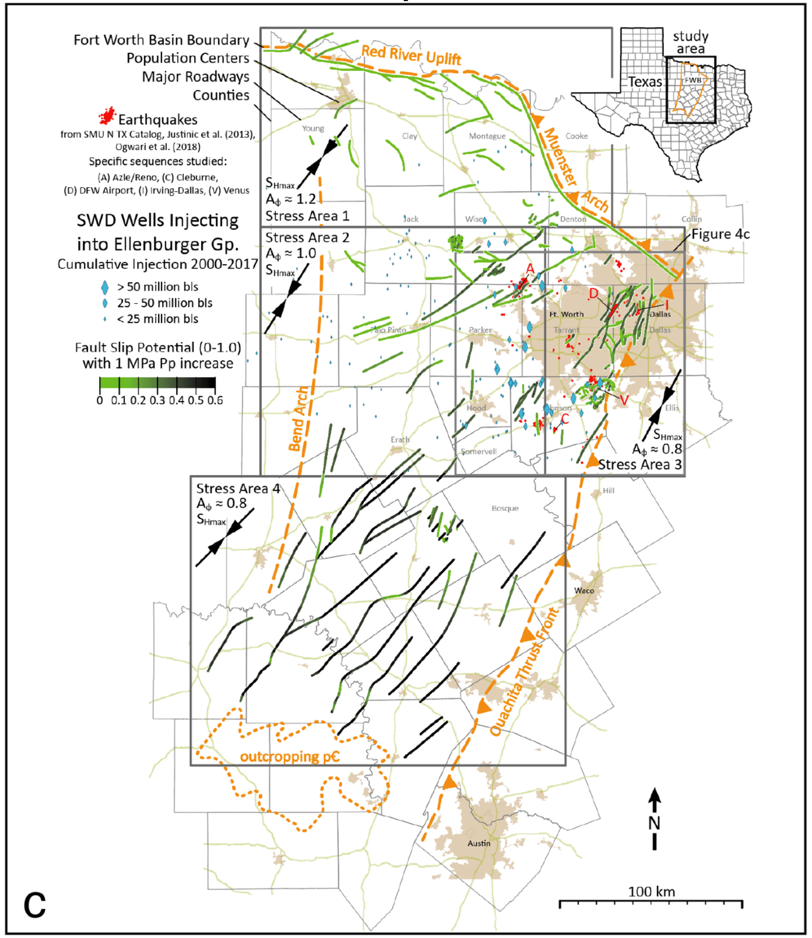
Faults



Stress



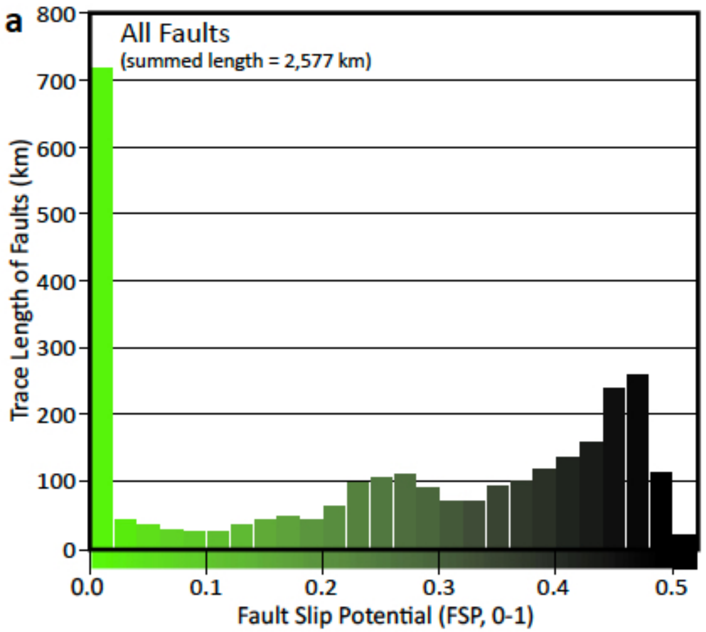
Fault Slip Potential

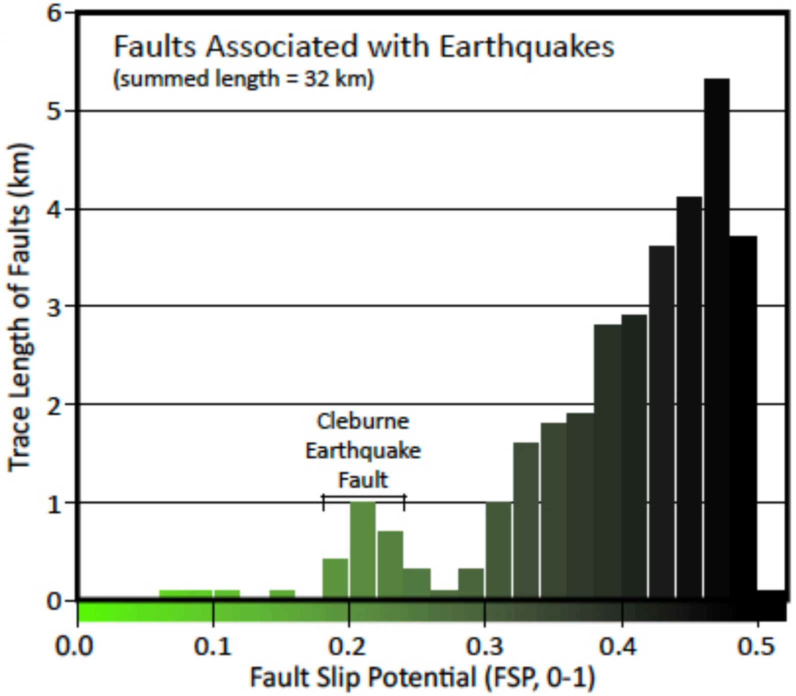


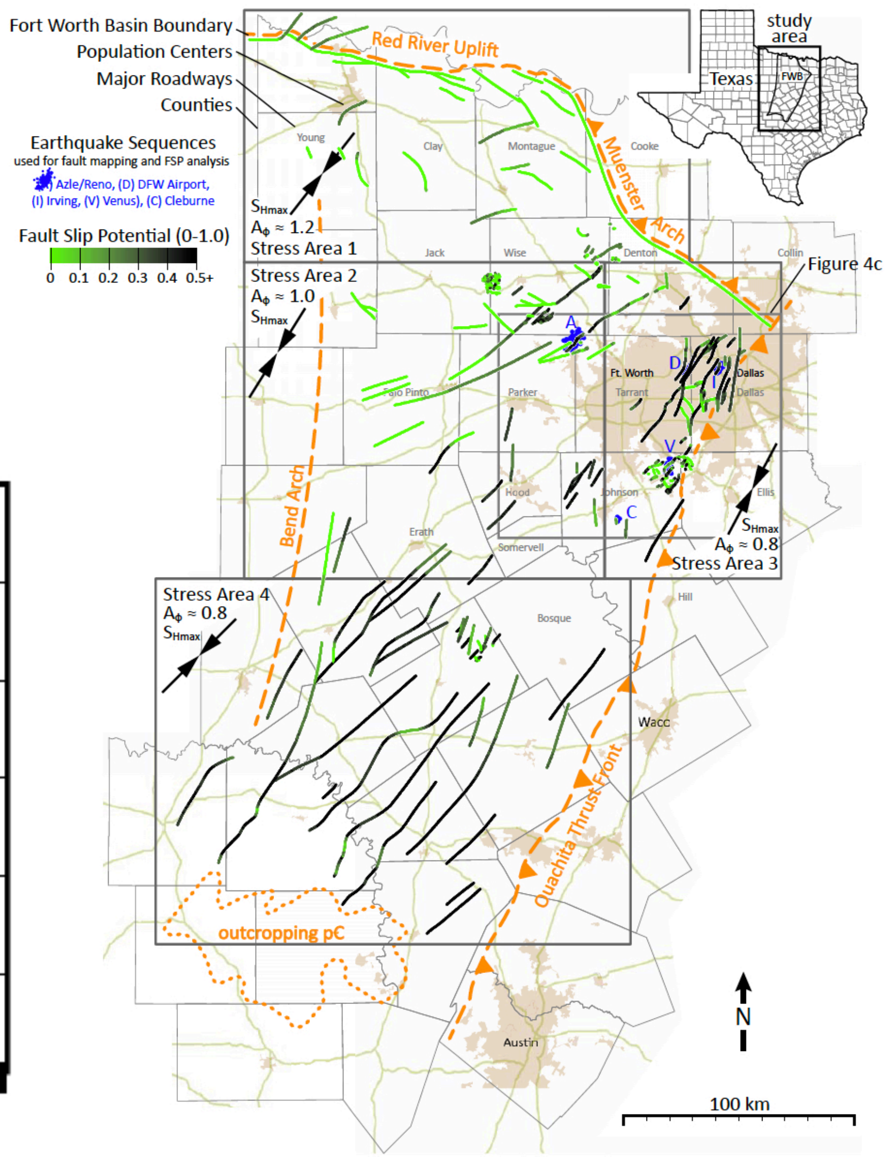
Hennings et al. (2019)

FSP
Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity

Calibration







Application

Hennings et al. (2019)

In Early 2016 Regulators in Oklahoma Mandated a 40% Reduction of Waste-water Injection Volumes.

SCIENCE ADVANCES | RESEARCH ARTICLE

SEISMOLOGY

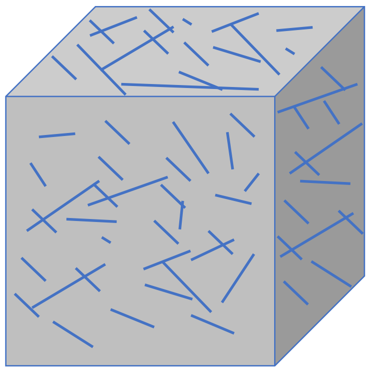
How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?

Cornelius Langenbruch* and Mark D. Zoback

In response to the marked number of injection-induced earthquakes in north-central Oklahoma, regulators recently called for a 40% reduction in the volume of saltwater being injected in the seismically active areas. We present a calibrated statistical model that predicts that widely felt $M \geq 3$ earthquakes in the affected areas, as well as the probability of potentially damaging larger events, should significantly decrease by the end of 2016 and approach historic levels within a few years. Aftershock sequences associated with relatively large magnitude earthquakes that occurred in the Fairview, Cherokee, and Pawnee areas in north-central Oklahoma in late 2015 and 2016 will delay the rate of seismicity decrease in those areas.

Pore Pressure Diffusion and Induced Seismicity

random set of pre-existing fractures

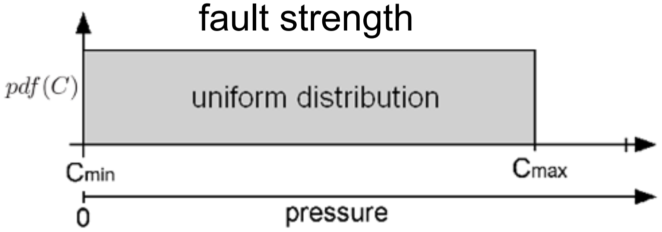


$$\zeta = \text{volume concentration of fractures}$$

general non-linear diffusion equation

$$\frac{\partial r^{d-1} p}{\partial t} = \frac{\partial}{\partial r} D(p) r^{d-1} \frac{\partial}{\partial r} p$$

fault strength



triggering criterion

$$p(\vec{r}, t) \geq C(\vec{r})$$

Physical concept:

Seismic events are directly triggered by the pore pressure perturbation created by injection.

This process can be described by diffusion of pore pressure in a fluid saturated, connected pore and fracture space of rocks!

The rate of events is proportional to the rate of injection

see e.g. [Rothert and Shapiro, (2007), Shapiro and Dinske, (2009), Shapiro et al. (2010), Langenbruch and Shapiro, (2010)]

The Seismogenic Index

[Shapiro, Dinske, Langenbruch and Wenzel, (2010), TLE]

Pore pressure diffusion:
Event number is proportional to fluid volume

$$N(t) = \frac{\zeta}{C_{max} S} V_I(t)$$

Fractal scaling of fault sizes:
Gutenberg-Richter type probability law

$$log_{10}\left[W_{ev \geq M}\right] = a_p - bM$$

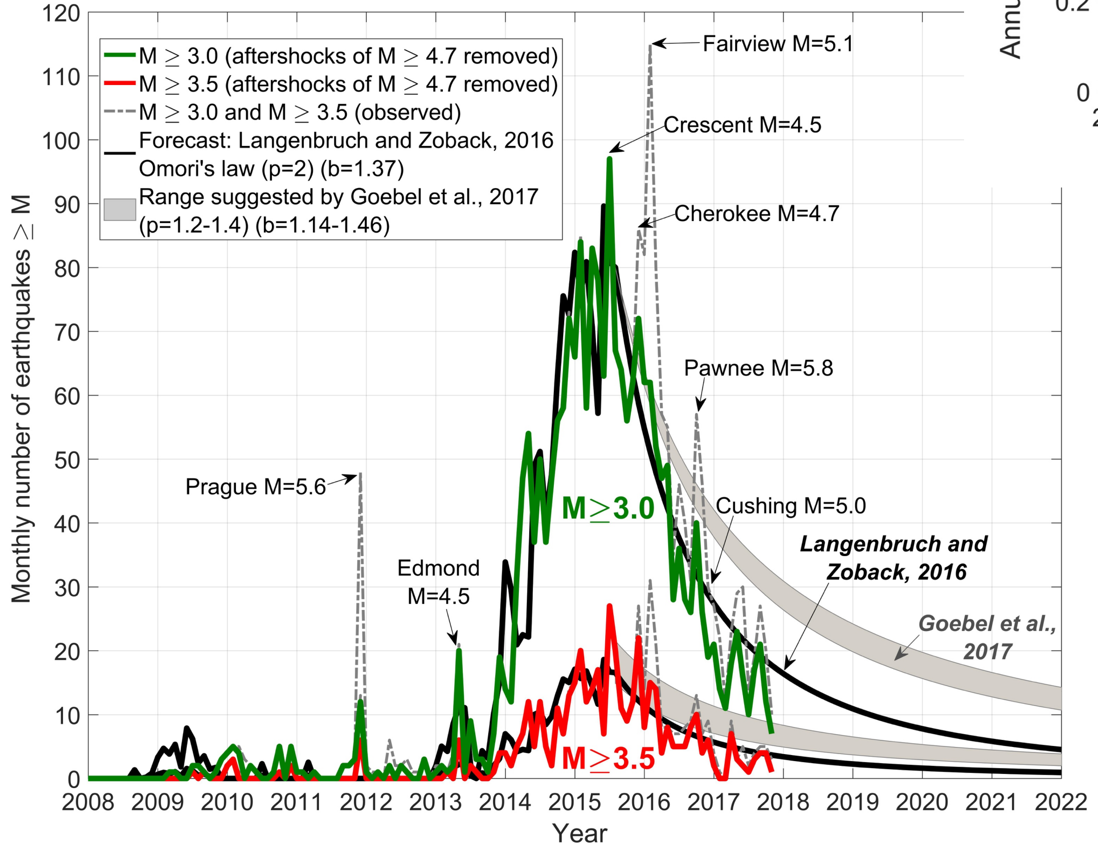
Gutenberg-Richter law for fluid injection-induced seismicity

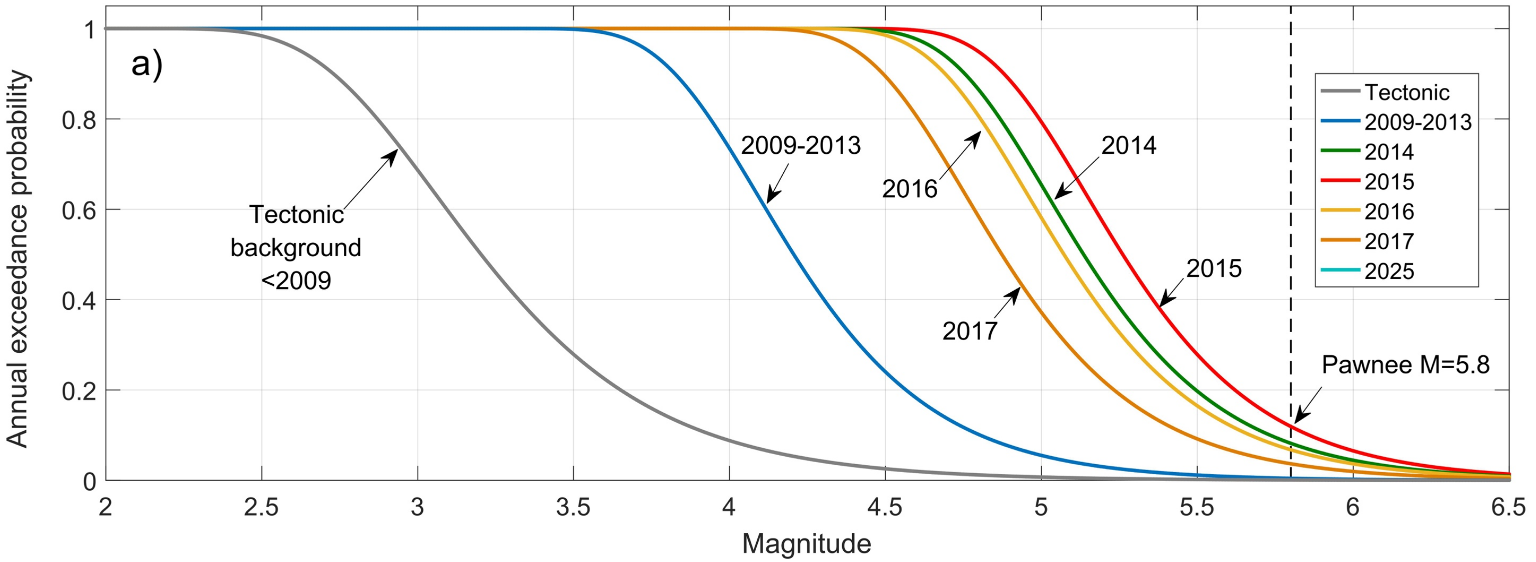
$$log_{10}\left[N_{\geq M}(t)\right] = \underbrace{log_{10}\left[V_I(t)\right] + \Sigma}_{\text{a-value of the classical GR relation}} - bM$$

$$\Sigma = log_{10}\left[\frac{\zeta}{C_{max} S}\right] + a_p = log_{10}\left[N_{\geq M}(t)\right] - log_{10}\left[V_I(t)\right] + bM$$

The Seismogenic Index combines unknown site-specific seismo-tectonic constants at an injection location.
However, it can be computed from observations.

Occurrence Probability of Potentially-Damaging Earthquakes





nature COMMUNICATIONS

ARTICLE

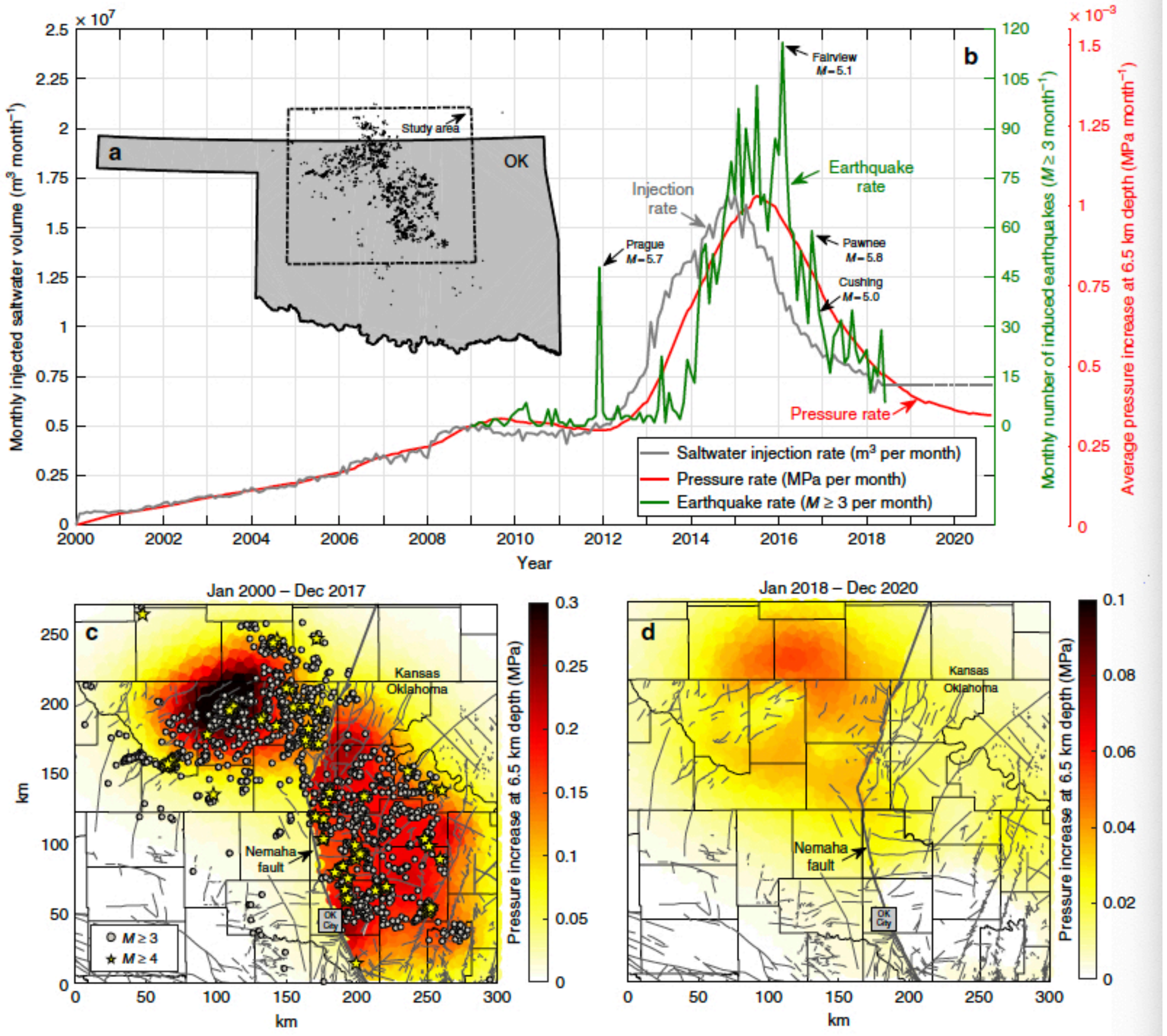
DOI: 10.1038/s41467-018-06167-4 OPEN

Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas

Cornelius Langenbruch[1], Matthew Weingarten[1,2] & Mark D. Zoback[1]

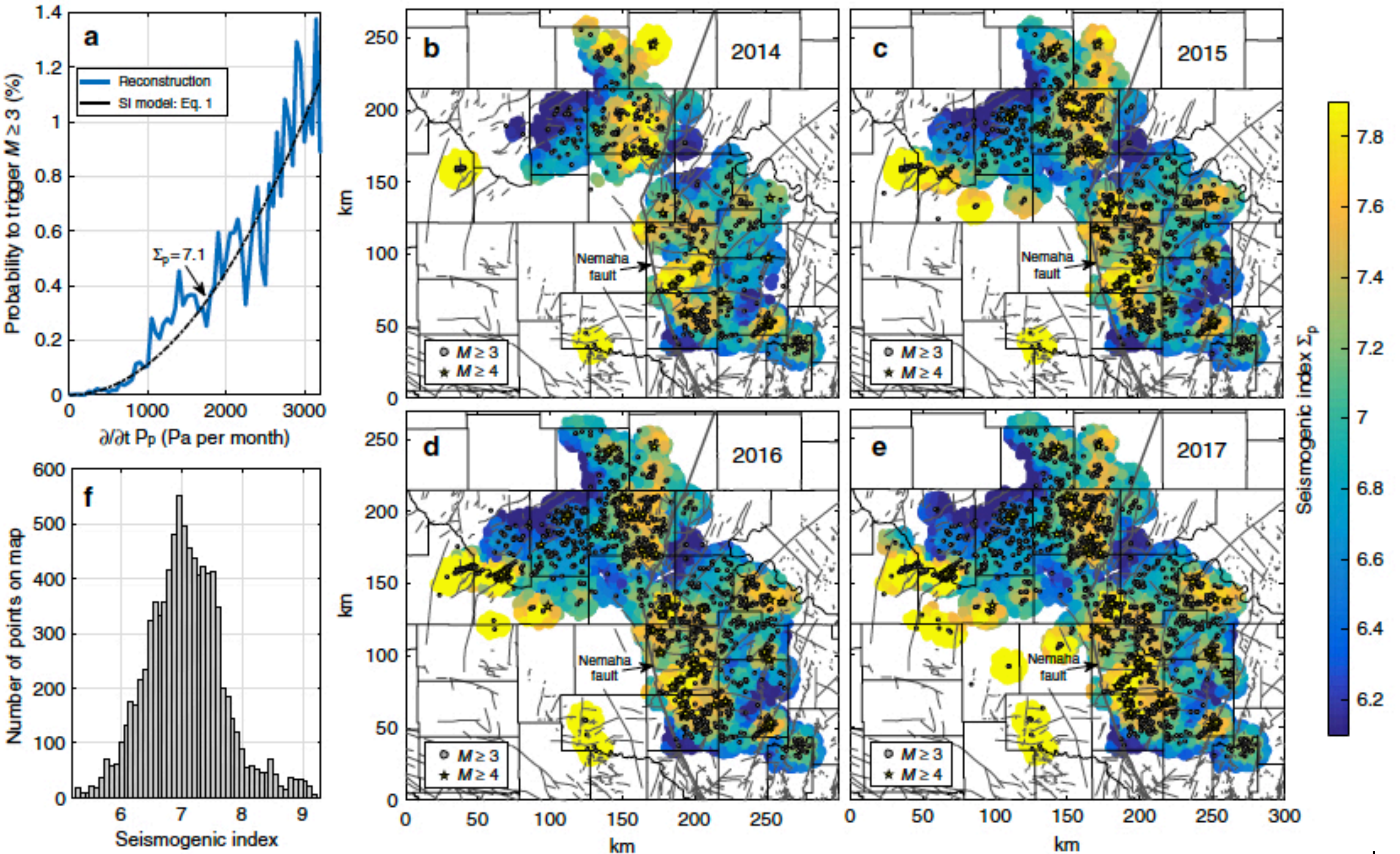
Reinjection of saltwater, co-produced with oil, triggered thousands of widely felt and several damaging earthquakes in Oklahoma and Kansas. The future seismic hazard remains uncertain. Here, we present a new methodology to forecast the probability of damaging induced earthquakes in space and time. In our hybrid physical–statistical model, seismicity is driven by the rate of injection-induced pressure increases at any given location and spatial variations in the number and stress state of preexisting basement faults affected by the pressure increase. If current injection practices continue, earthquake hazards are expected to decrease slowly. Approximately 190, 130 and 100 widely felt $M \geq 3$ earthquakes are anticipated in 2018, 2019 and 2020, respectively, with corresponding probabilities of potentially damaging $M \geq 5$ earthquakes of 32, 24 and 19%. We identify areas where produced-water injection is more likely to cause seismicity. Our methodology can be used to evaluate future injection scenarios intended to mitigate seismic hazards.

Utilization of a Regional Hydrologic Model



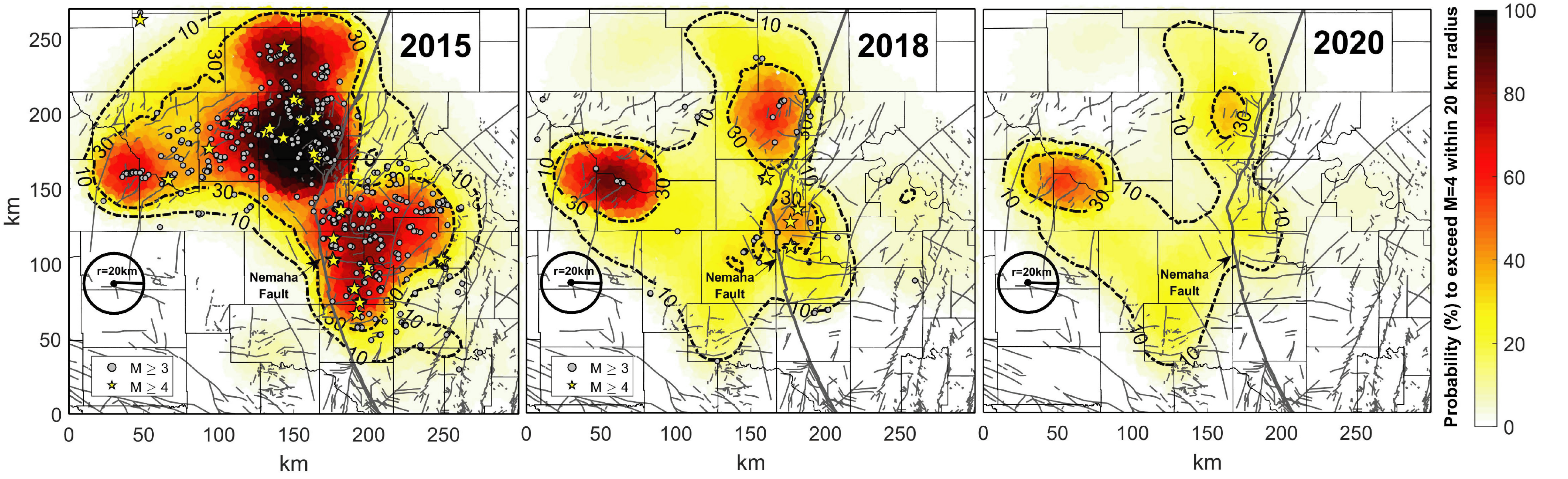
Langenbruch et al. (2018)

Local Computation of Seismogenic Index



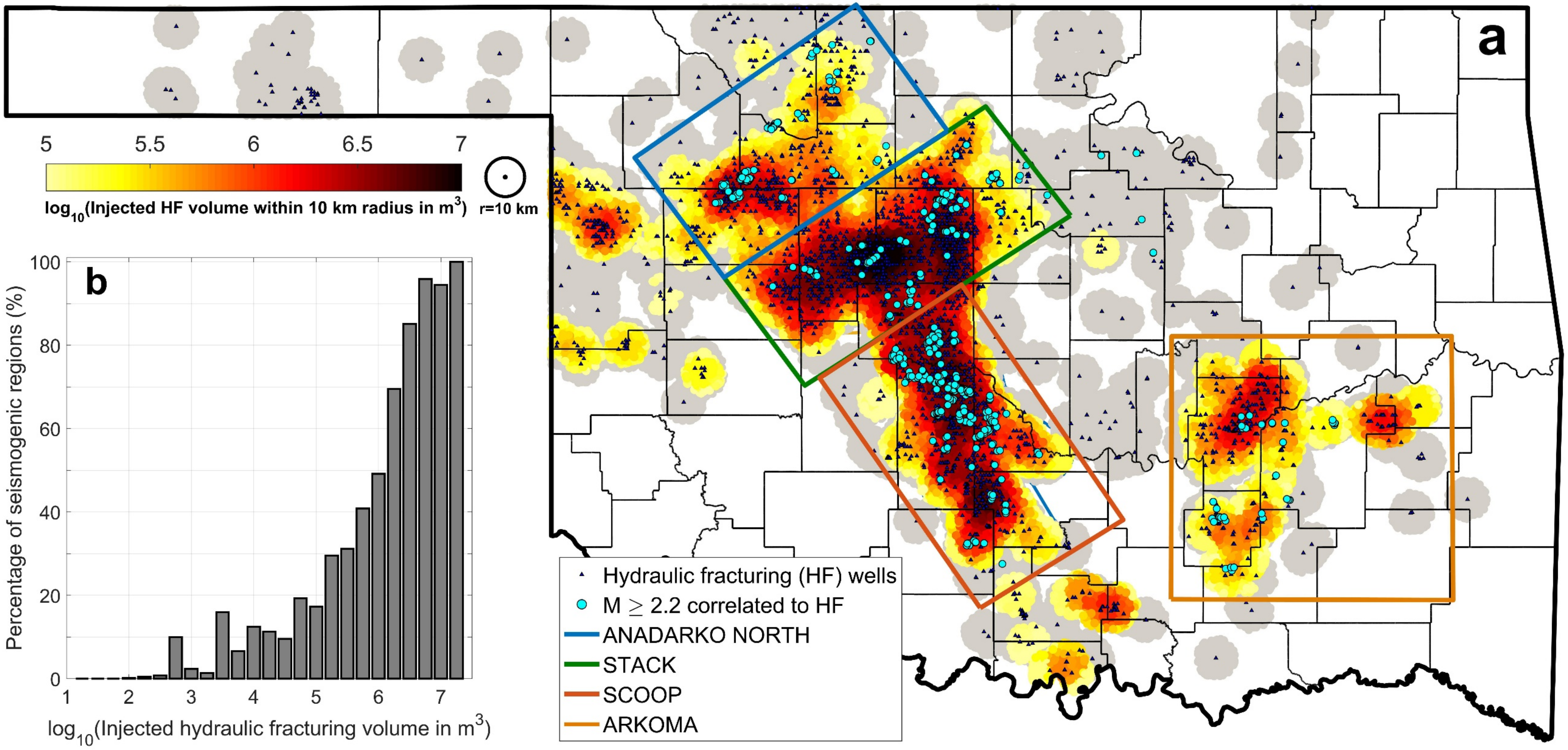
Langenbruch et al. (2018)

Local Probability of Exceeding M 4



Langenbruch et al. (2018)

Application of the SI Model to Hydraulic Fracturing Earthquakes



Langenbruch and Zoback (in prep)

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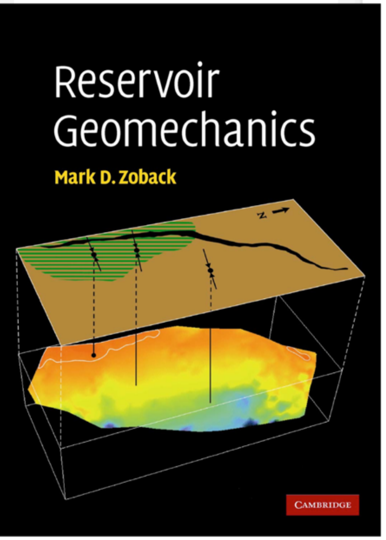

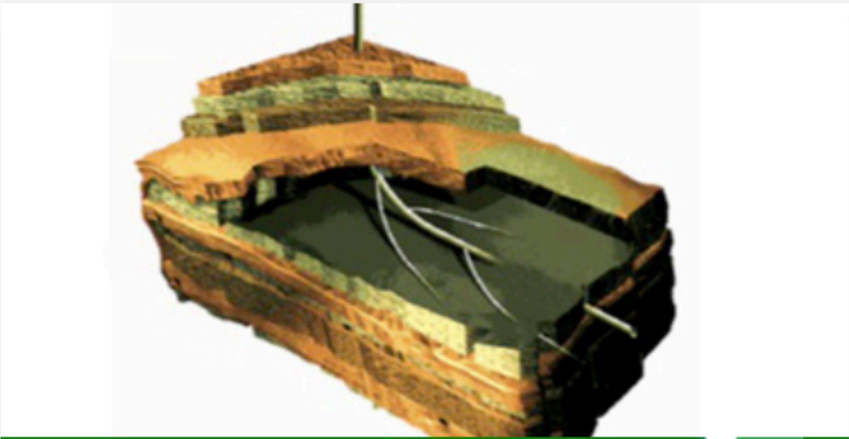

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Reservoir Geomechanics

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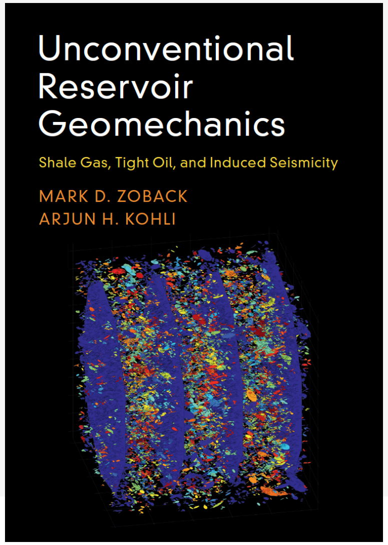
Unconventional Reservoir Geomechanics



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Thank you