Earthquake Triggering and Large-scale Geologic Storage of Carbon Dioxide

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2021 CO_2 Conference
December 6-9

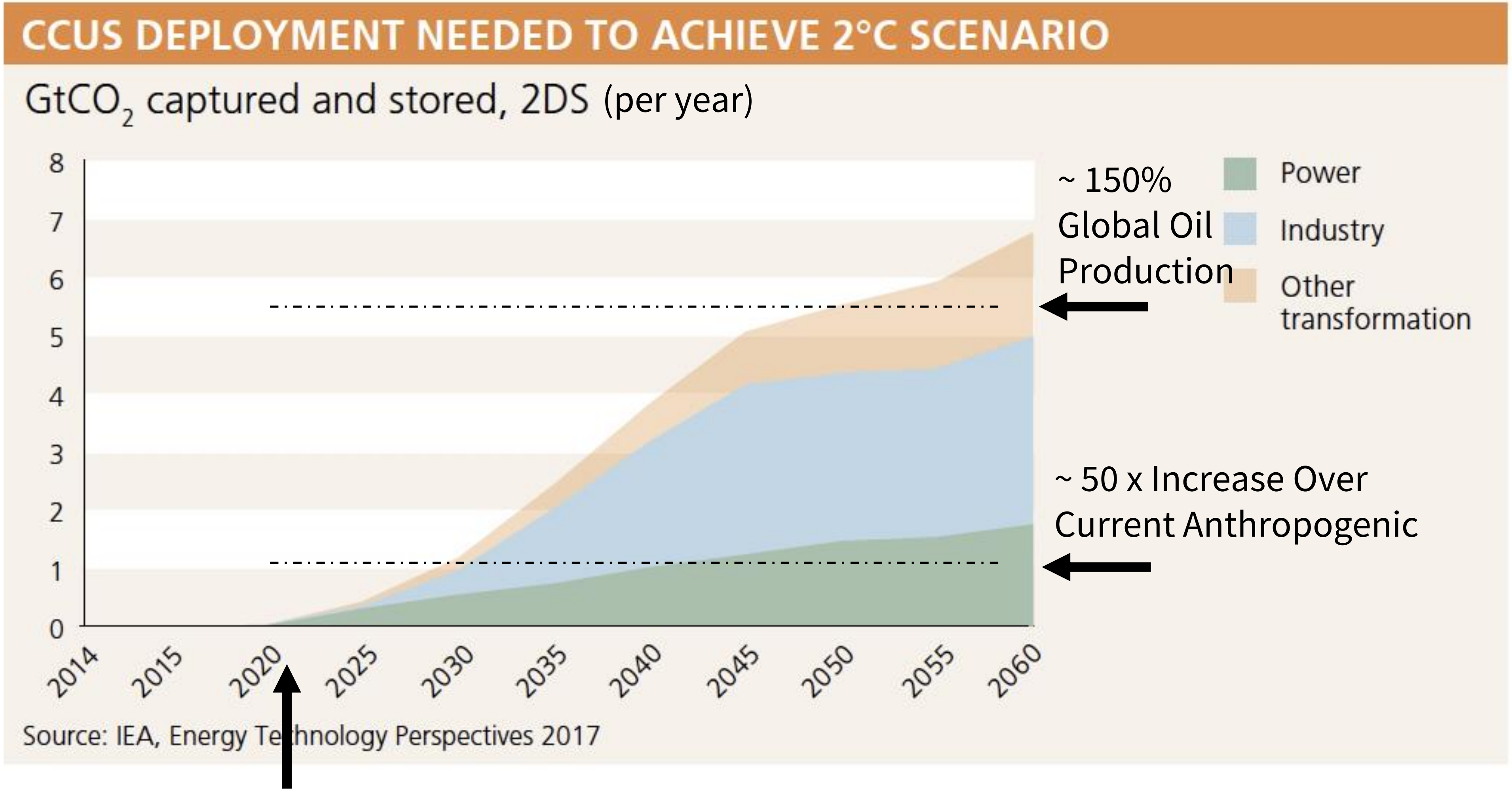
Topics – Massive Scale CCS *from a Geomechanical Perspective*

- The Need for Massive Scale for Carbon Storage
- Saline Aquifers and Induced Seismicity
  - Basal Aquifers and the Critically-Stressed Crust
    - Lessons from Induced Seismicity in Oklahoma
  - Lessons from Induced Seismicity in the Delaware Basin
- Depleted Oil and Gas Reservoirs and Induced Seismicity
  - How Poroelastic Stress Changes Limit Induced Seismicity
  - How Past Production has Depleted CCS Reservoirs (Not today)
- Progress to Date

Massive Scale CCS?

- Achieving the International Energy Agency's (IEA) Sustainable Development Scenario will require 6 Gt $scCO_2$ per year to be stored by 2050. Volumetrically equivalent to 150% of current global oil production.
- The CCS industry is expected to reach 1 Gt $scCO_2$ per year by 2030.
- Today's carbon sequestration industry must grow by 50 times. ~20 Mt per year of anthropogenic CO_2 is currently being injected in 46 projects to reach 2030 targets.
- It is estimated that about $1 trillion of investment will be needed to support this growth, necessitating investment from capital providers across the entire development pipeline (capture -> transport -> storage).
- "***Reaching net zero will be virtually impossible with CCUS***" – IEA, September 2020

Expectations for CCS are Enormous



Current CCS - ~40 Mt CO_2/year (50% is anthropogenic)

Production Tax Credits

45Q and 45X

AZIMUTH CAPITAL MANAGEMENT

Carbon Capture and Sequestration ("45Q")

- The 45Q credit would be extended to projects beginning construction before January 1, 2032. Currently, the 45Q credit only applies to projects beginning construction by December 31, 2025.
- Most facilities would be eligible for the 45Q credit if they capture at least 12,500 tons of qualified CO during the taxable year. Electric generating facilities would only be eligible for the 45Q credit if they capture at least 18,750 t of qualified CO during the taxable year and at least 75% (by mass) of the CO that would be released.
- $85/t for qualified CO disposed of by the taxpayer in secure geological storage and $60/metric ton for qualified CO used by the taxpayer as a tertiary injectant and disposed of in a qualified enhanced oil or natural gas recovery project.

Hydrogen Production Tax Credit ("45X")

- A ten-year production tax credit under new section 45X would be available to producers for clean hydrogen produced after December 31, 2021, by a taxpayer at a qualified facility beginning construction by December 31, 2028.
- If prevailing wage and apprenticeship requirements are met, the credit rate is $3.00/kg, adjusted for inflation. If not, then the credit rate if $0.60/kg. The applicable percentage is sliding scale that rises from 8% ($0.25) to 100% ($3.00) as CI falls.
- CI is measured in kg CO_2 per kg H_2 produced. If our CI rises >3.99 kg CO_2 per kg H_2 we're better off with 45Q. The exact $ / kg credit is influenced by a producer's choices.
- A taxpayer **cannot** benefit from both the clean hydrogen PTC and the 45Q Credit.

Illustrative Example: Production Process Emissions Only

	Hi CO_2 /kg	Lo CO_2/kg	%	$/kg applicable from 45X	Minimum % Avoided vs. 9kg (SMR Baseline)	Captured vs. Avoided	$/kg from 45Q	Technology
A	6.00	4.00	8%	$0.25	33%	1.03	$0.26	
B	3.99	2.50	20%	$0.60	56%	1.06	$0.45	SMR shift tail gas
C	2.49	1.50	33%	$1.00	72%	1.09	$0.60	
D	1.49	0.45	50%	$1.50	83%	1.11	$0.71	
E	0.44	0.00	100%	$3.00	95%	1.13	$0.82	ATR or SMR flue gas

Certain

Both 45Q and 45X are direct pay credits. In almost all cases, consider process emissions only, the benefit from 45X is more favorable than from 45Q.

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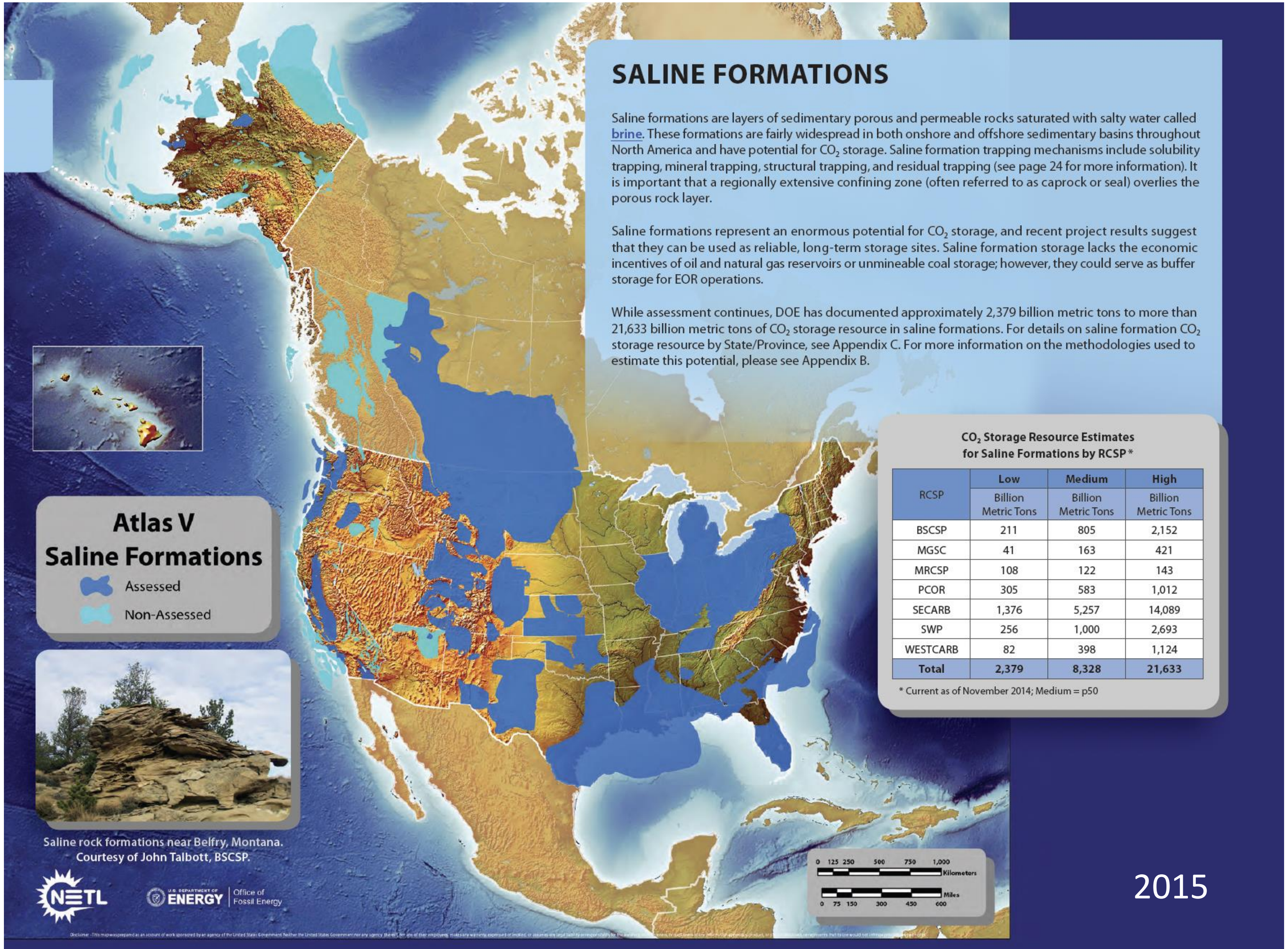
Volumetric Assessments of Saline Aquifer Storage (Theoretically Available Pore Space)



SALINE FORMATIONS

Saline formations are layers of sedimentary porous and permeable rocks saturated with salty water called brine. These formations are fairly widespread in both onshore and offshore sedimentary basins throughout North America and have potential for CO_2 storage. Saline formation trapping mechanisms include solubility trapping, mineral trapping, structural trapping, and residual trapping (see page 24 for more information). It is important that a regionally extensive confining zone (often referred to as caprock or seal) overlies the porous rock layer.

Saline formations represent an enormous potential for CO_2 storage, and recent project results suggest that they can be used as reliable, long-term storage sites. Saline formation storage lacks the economic incentives of oil and natural gas reservoirs or unmineable coal storage; however, they could serve as buffer storage for EOR operations.

While assessment continues, DOE has documented approximately 2,379 billion metric tons to more than 21,633 billion metric tons of CO_2 storage resource in saline formations. For details on saline formation CO_2 storage resource by State/Province, see Appendix C. For more information on the methodologies used to estimate this potential, please see Appendix B.

CO_2 Storage Resource Estimates for Saline Formations by RCSP*

RCSP	Low	Medium	High
	Billion Metric Tons	Billion Metric Tons	Billion Metric Tons
BSCSP	211	805	2,152
MGSC	41	163	421
MRCSP	108	122	143
PCOR	305	583	1,012
SECARB	1,376	5,257	14,089
SWP	256	1,000	2,693
WESTCARB	82	398	1,124
Total	**2,379**	**8,328**	**21,633**

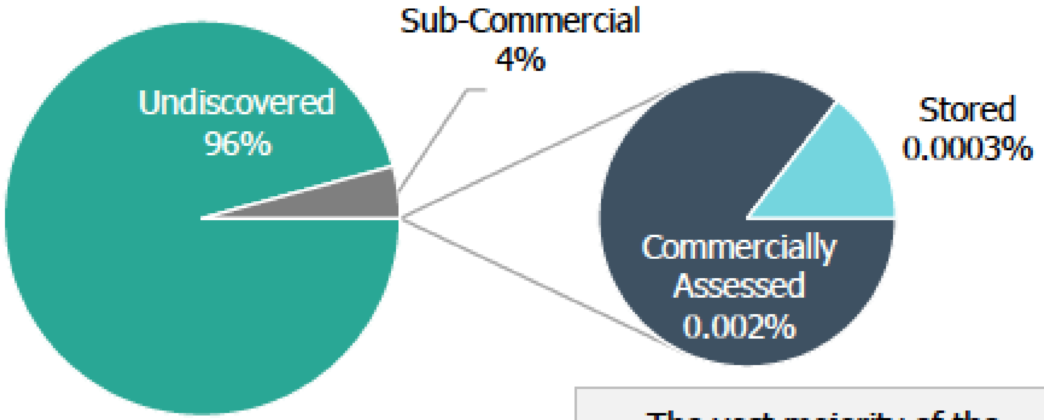
* Current as of November 2014; Medium = p50

2015

Mid-range est.
8328 GT tonnes

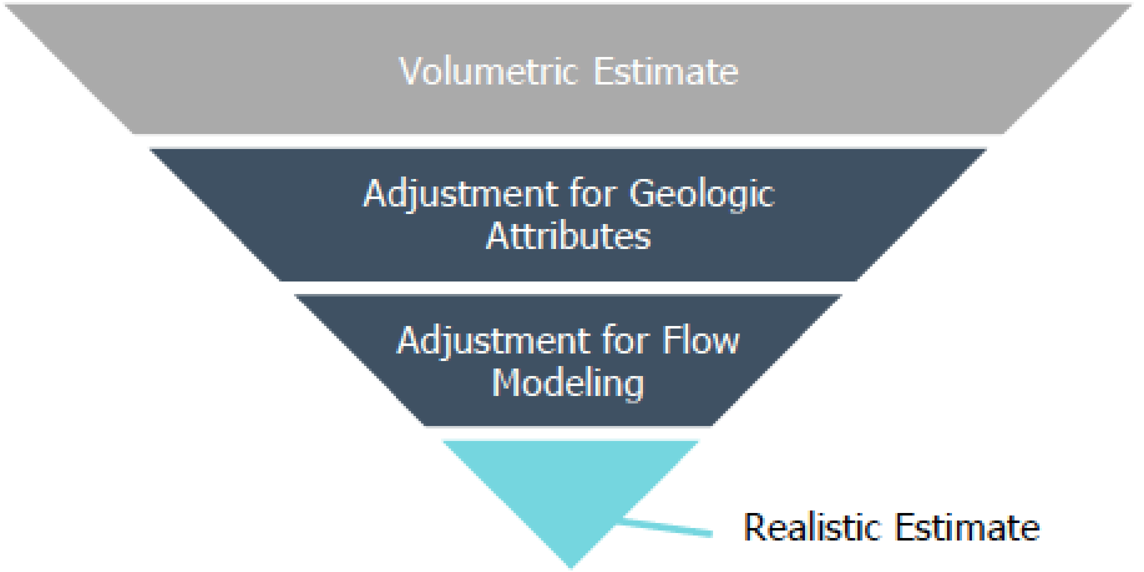
Realistically Assessing Capacity

Global Storage Resource Classification
Using SPE Storage Resources Management System (SRMS)



The vast majority of the global sequestration resource is not well characterized.

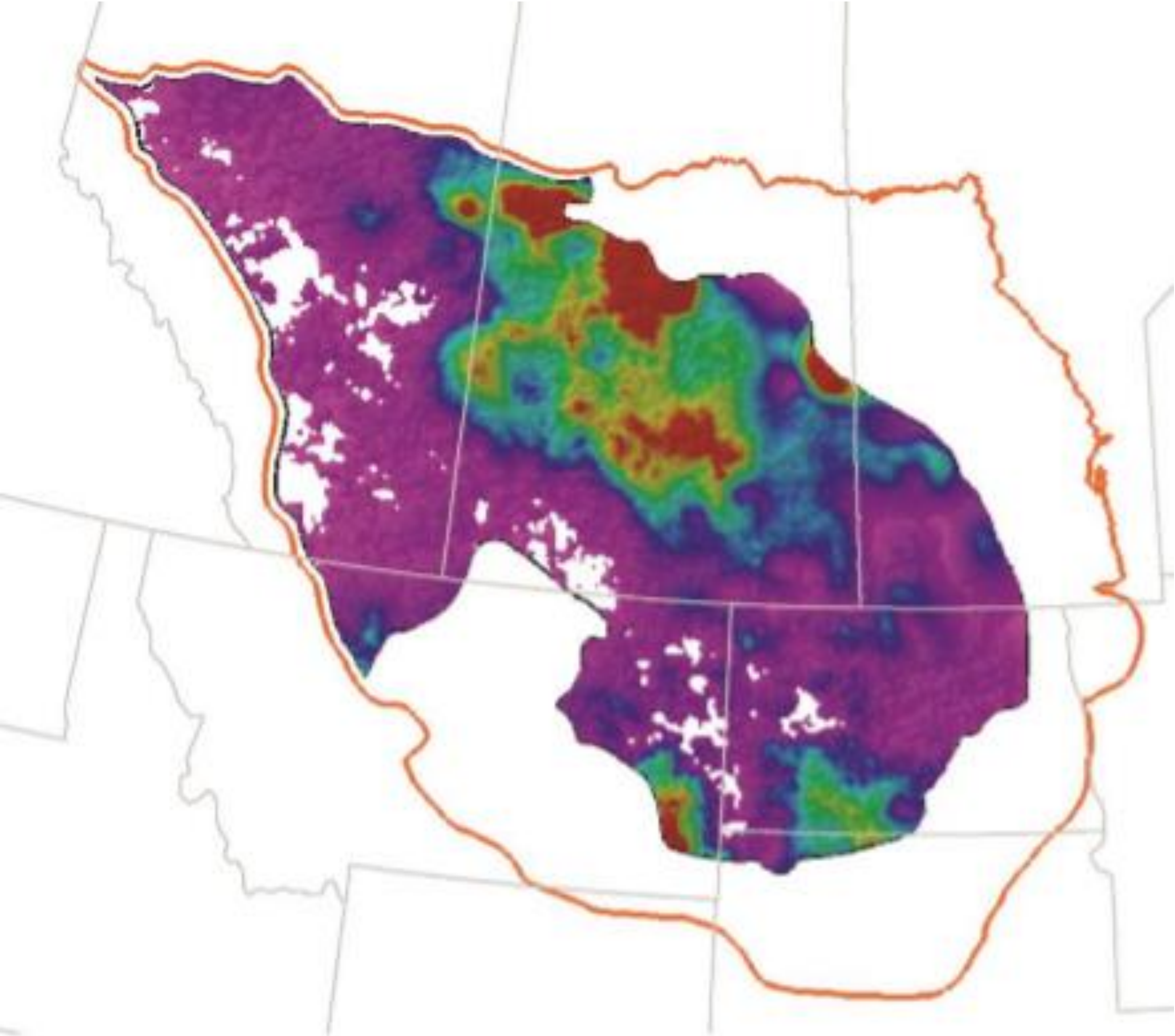
Illustrative Sequestration Resource Volume
Volumetric Estimate vs. Realistic Estimate



Basal Saline Aquifers

Basal Cambrian Sandstone,
Great Plains of the U.S. and Canada

- The aquifer with largest estimated resources in the area
- Volumetric approach: 223 – 721 Gt resources
- Storage formation for Quest and Aquistore projects



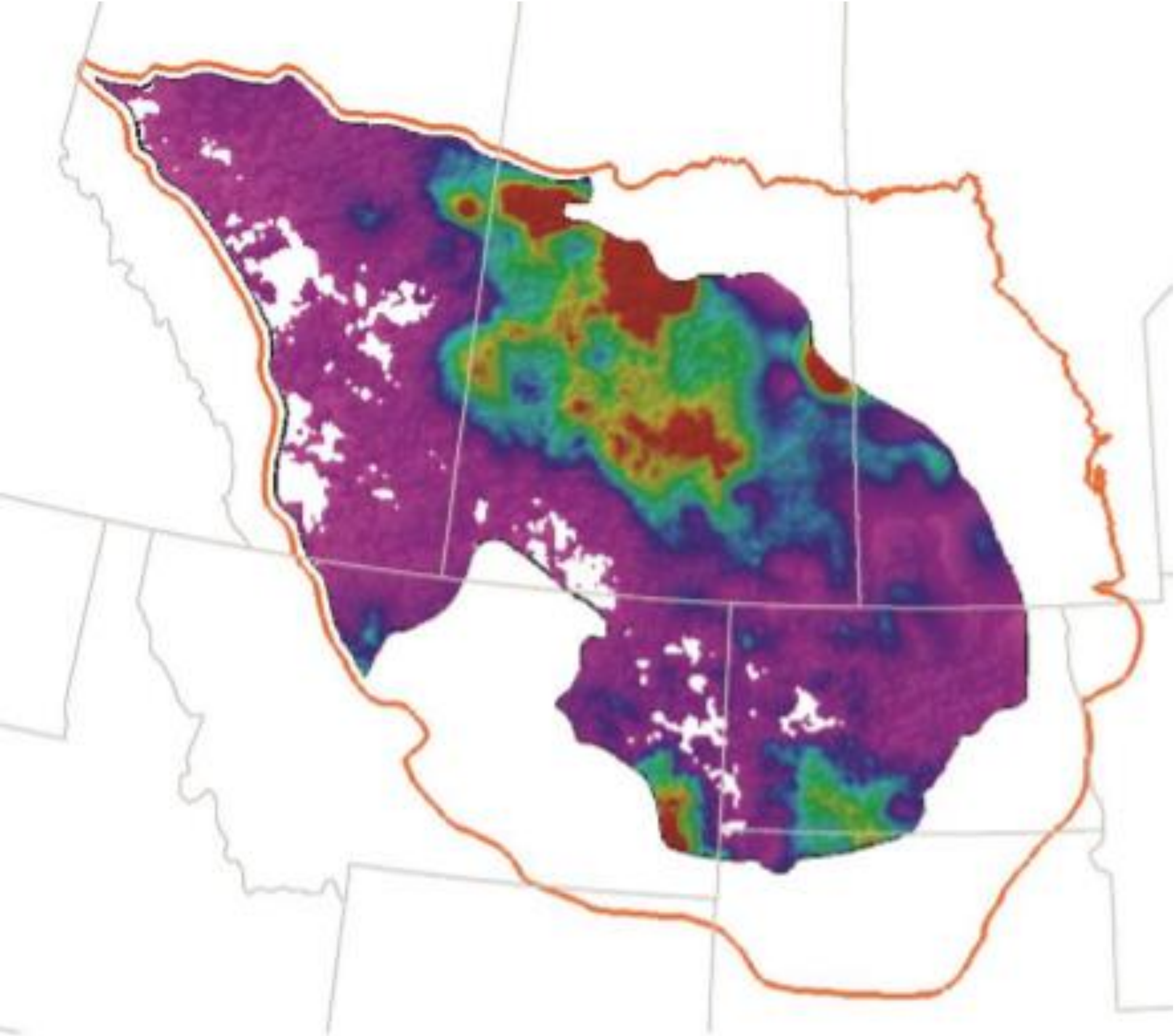
Teletsky et al. (2019) argue that from a flow modeling perspective, volumetric estimates are ~10 x too high

Basal Saline Aquifers

OGCI assessment of the Great Plains Basal Cambrian Sandstone storage resource

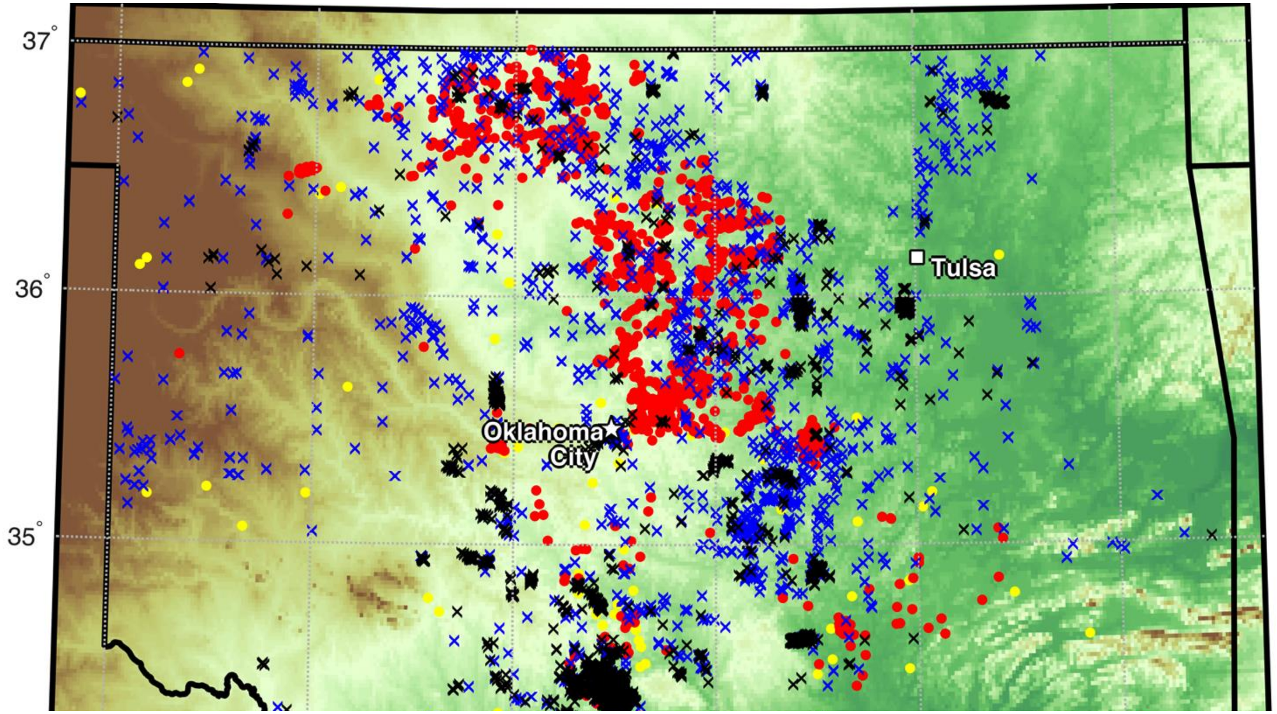
- Flow modeling: ~3 Gt of capacity based on injection from 16 major sources in the area at ~100 MTPA

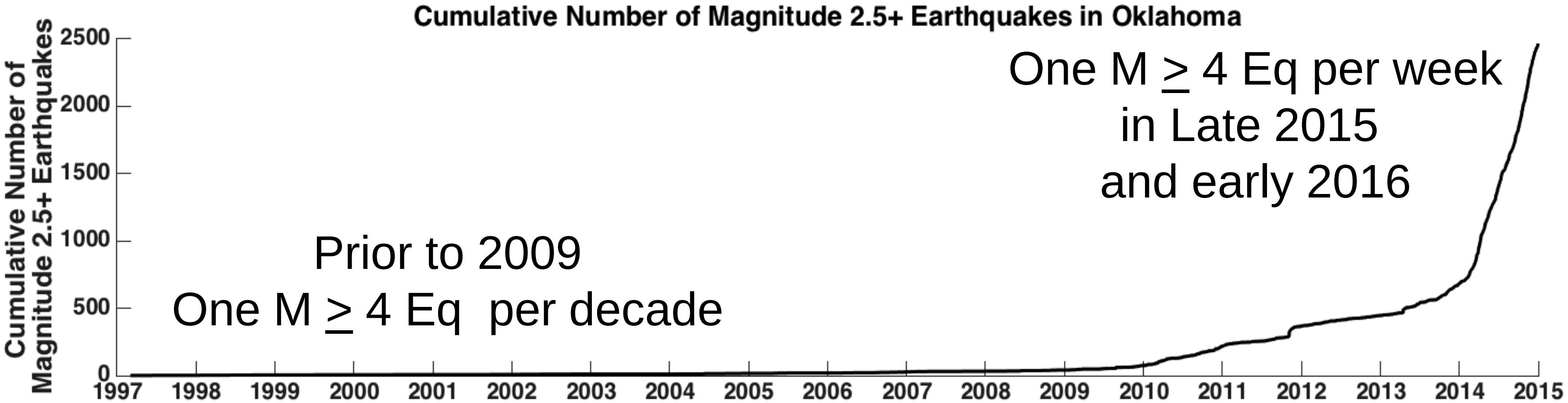
➢ Large gap between volumetric and capacity assessments



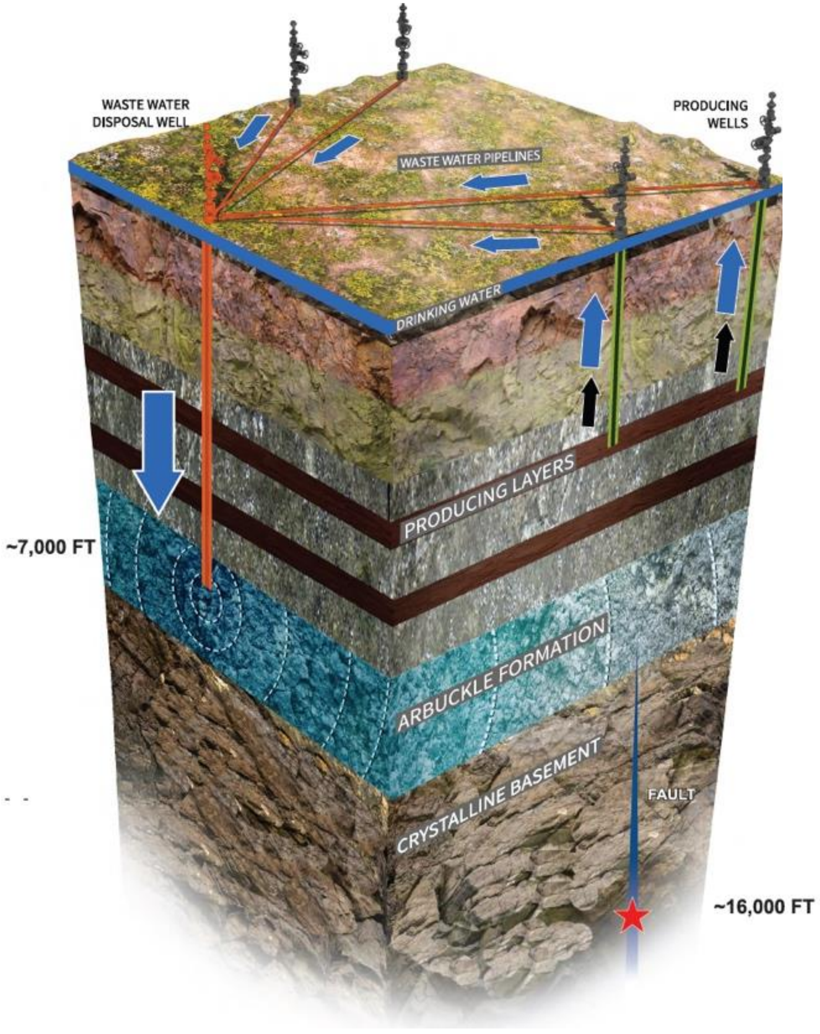
* EERC report 2015-EERC-02-14

Is Injection into Basal Formations Viable?
Triggered Earthquakes in Oklahoma



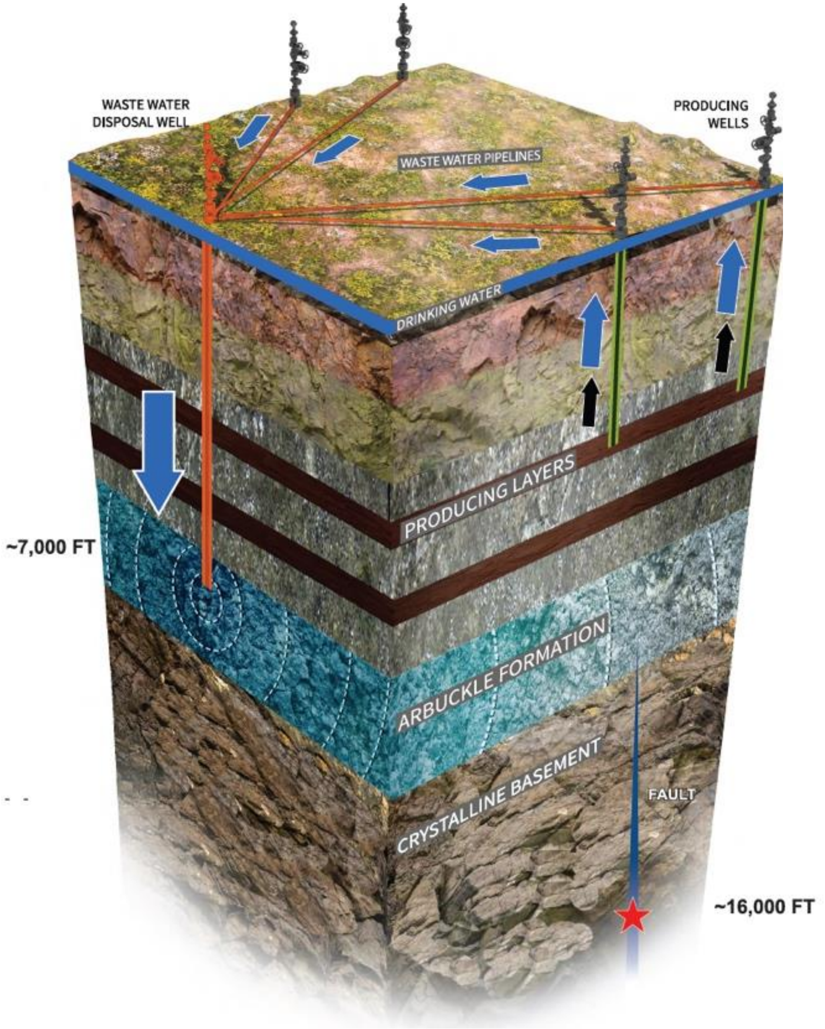


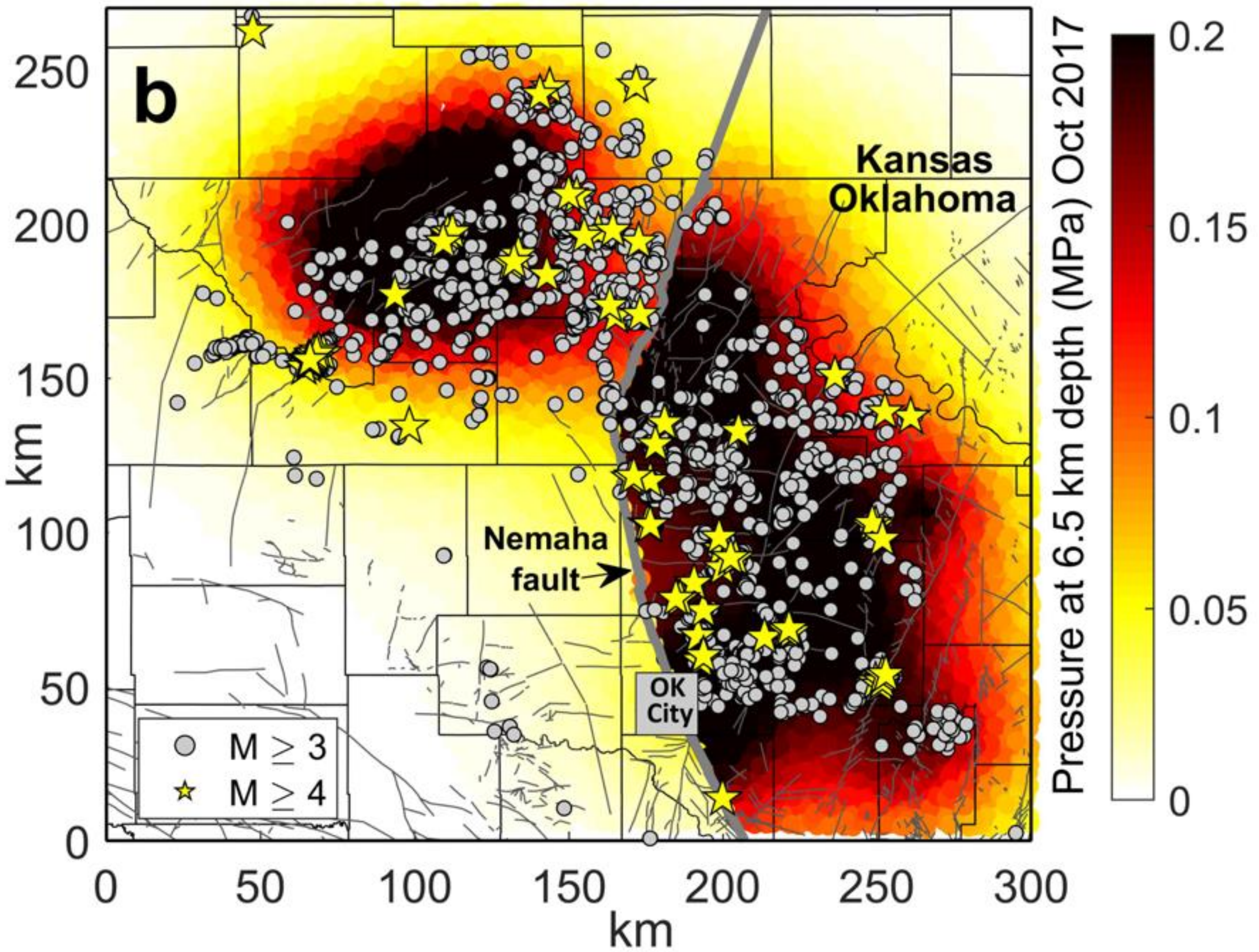
Produced Water Disposal is Triggering Earthquakes



- Massive quantities of produced saltwater (from formations like the Mississippi Lime) was being injected into the basal Arbuckle group.
- About 3 billion barrels were injected in north-central Oklahoma (AOI) over a few years.
- Earthquakes occurring on pre-existing critically-stressed faults in basement due to small increases in pore pressure in the Arbuckle Group
- Potentially active faults are likely to be permeable and extend from the crystalline basement up into the Arbuckle.

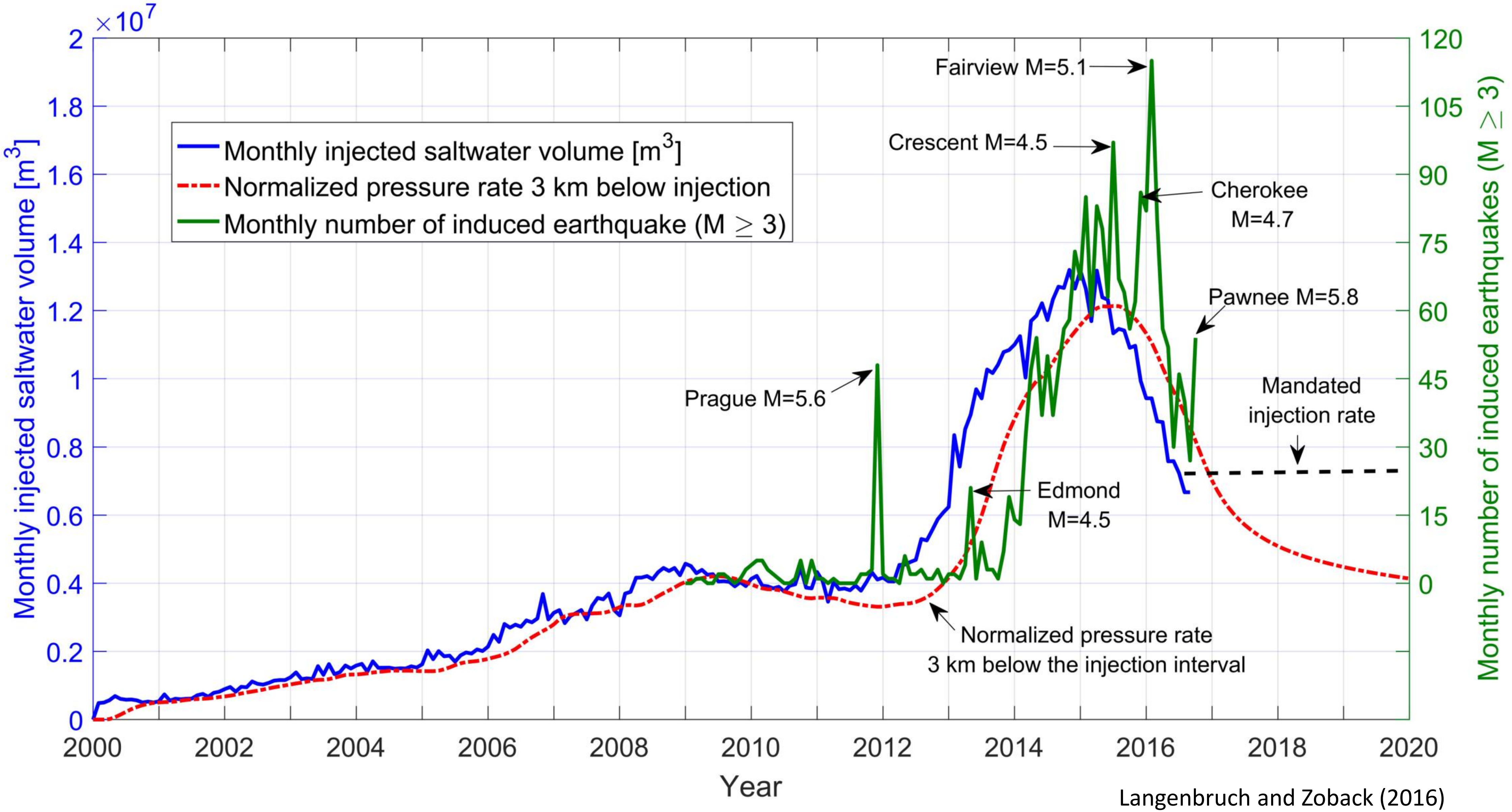
Produced Water Disposal is Triggering Earthquakes





Langenbruch, Weingarten and Zoback (2018)

Using the Seismogenic Index Model to Predict How the Rate of Produced Water Disposal Controls the Rate of Earthquake Triggering



Langenbruch and Zoback (2016)

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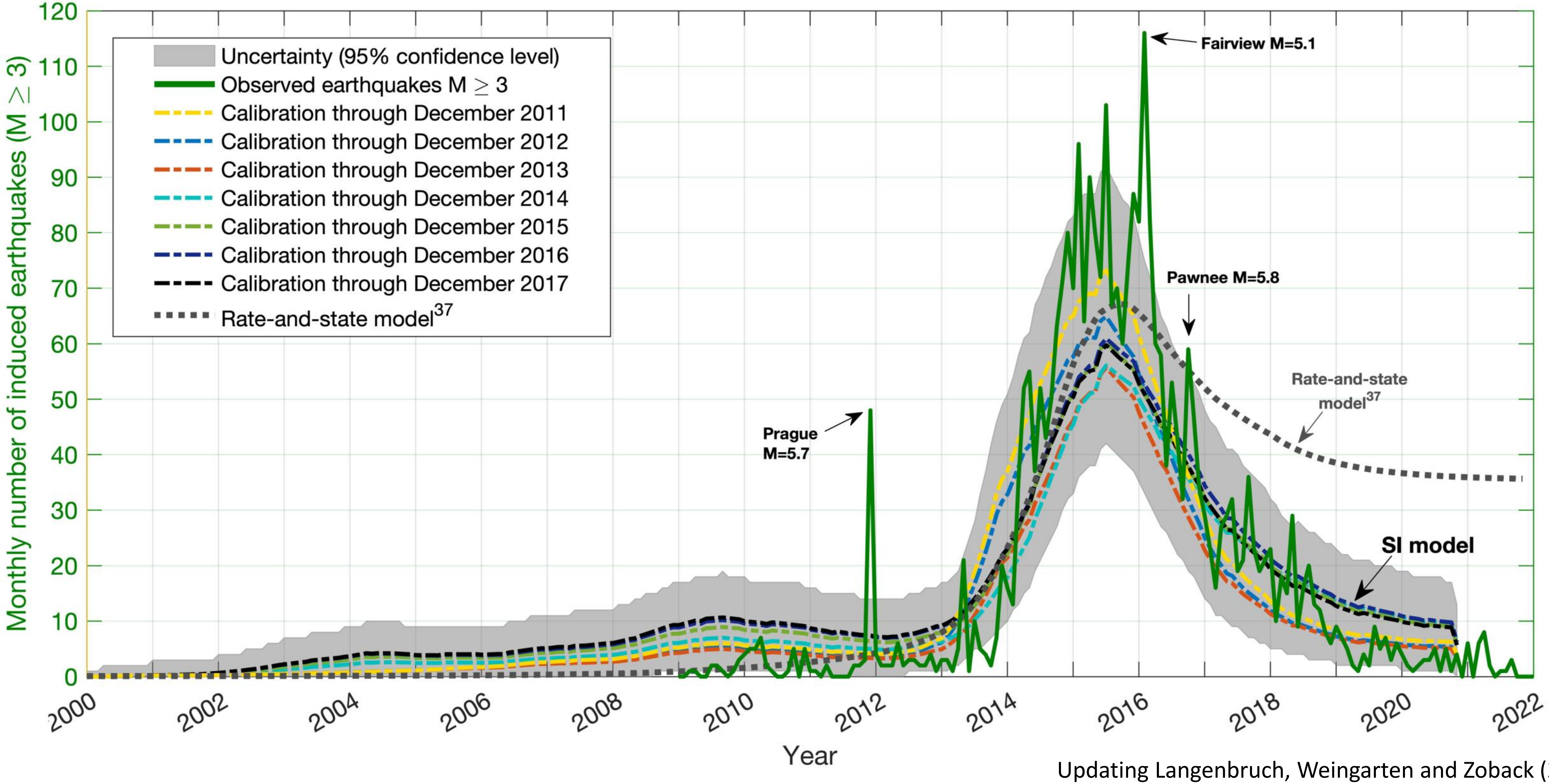
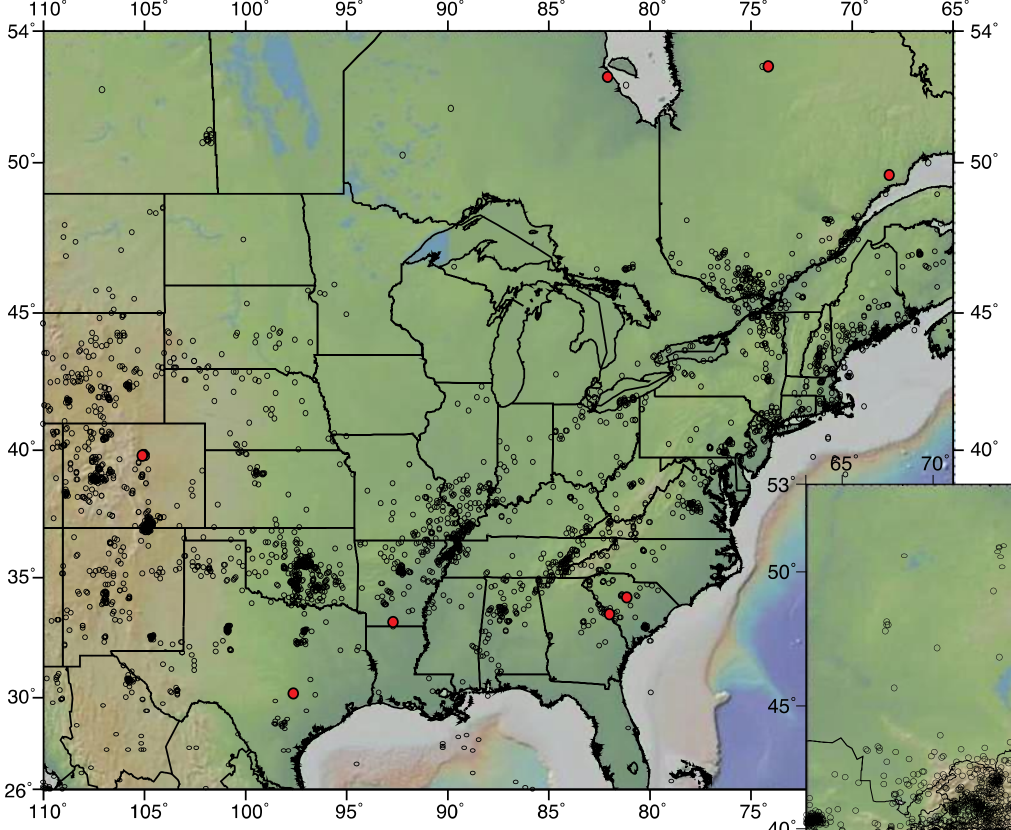
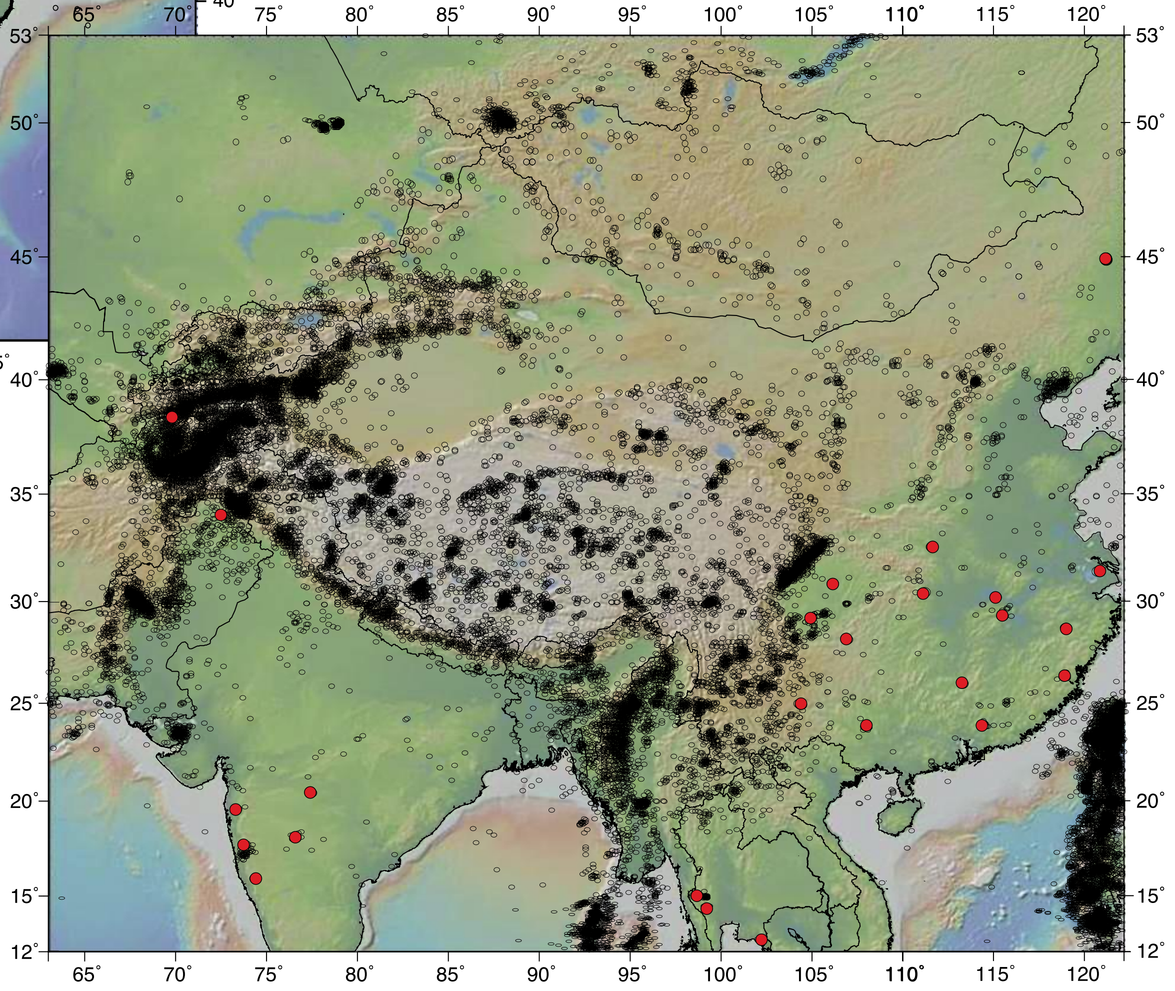


Updating Langenbruch, Weingarten and Zoback (2018)

The *Critically-Stressed* Crust

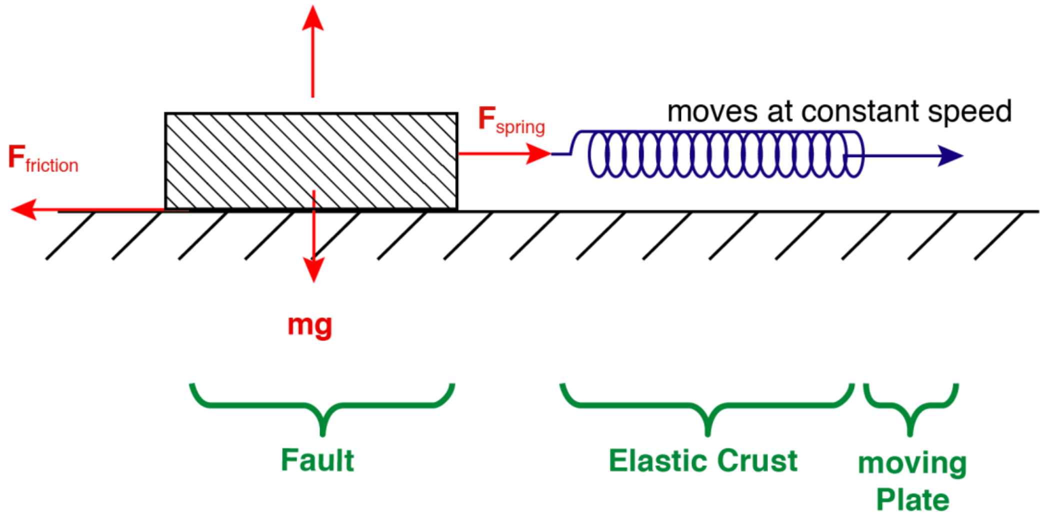


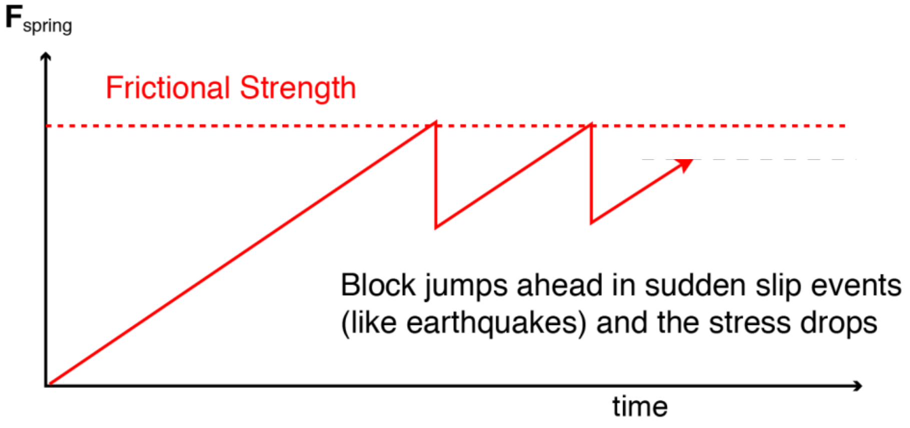


- Earthquakes Occur in Basement Rocks Nearly Everywhere in Intraplate Areas

- The Occurrence of Reservoir-Induced Seismicity Indicates that Very Small Pore Pressure Perturbations are Capable of Triggering Seismicity, Even in "Stable Areas"

A Simple Representation of Crustal Seismicity

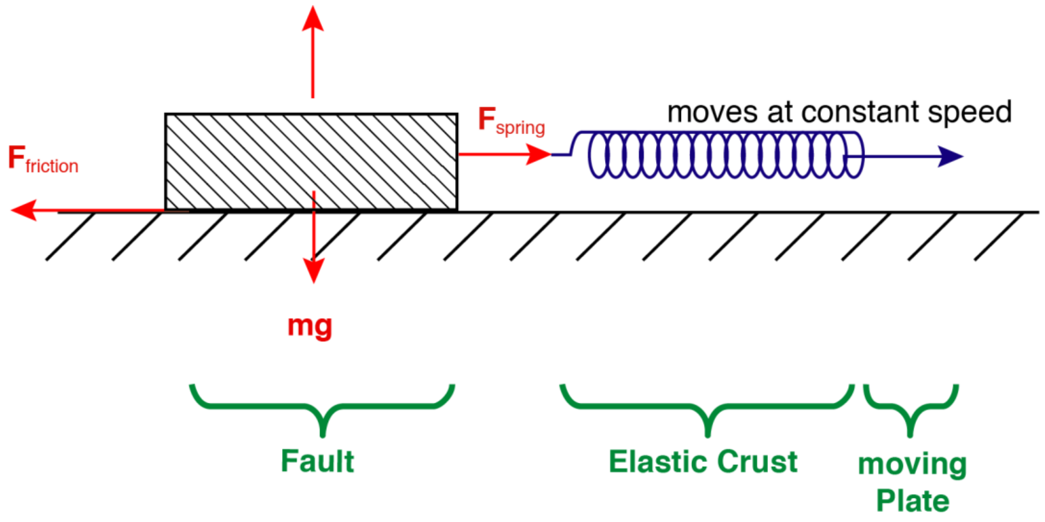


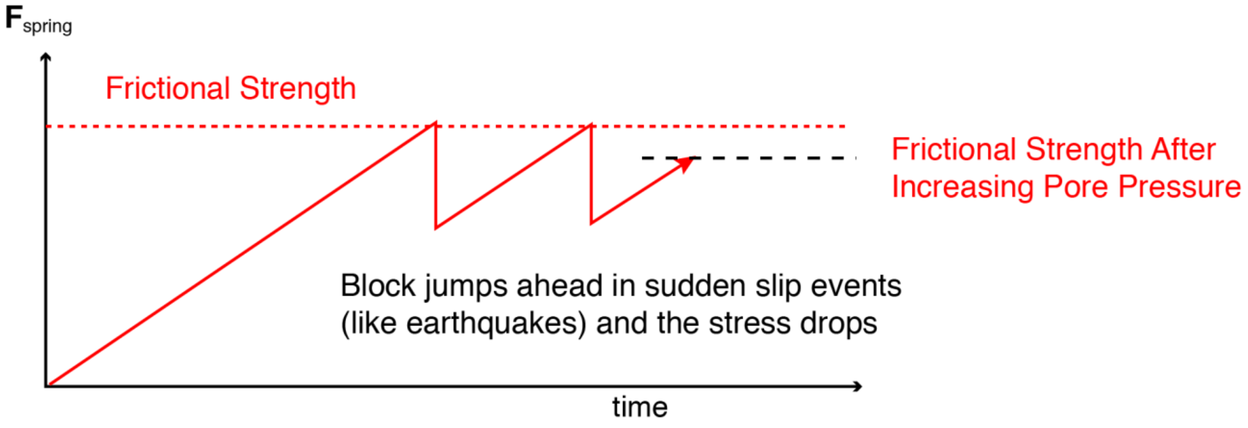


On a Fault

Slip Occurs when $\tau = \mu\sigma_n$

A Simple Representation of Crustal Seismicity and Earthquake Triggering



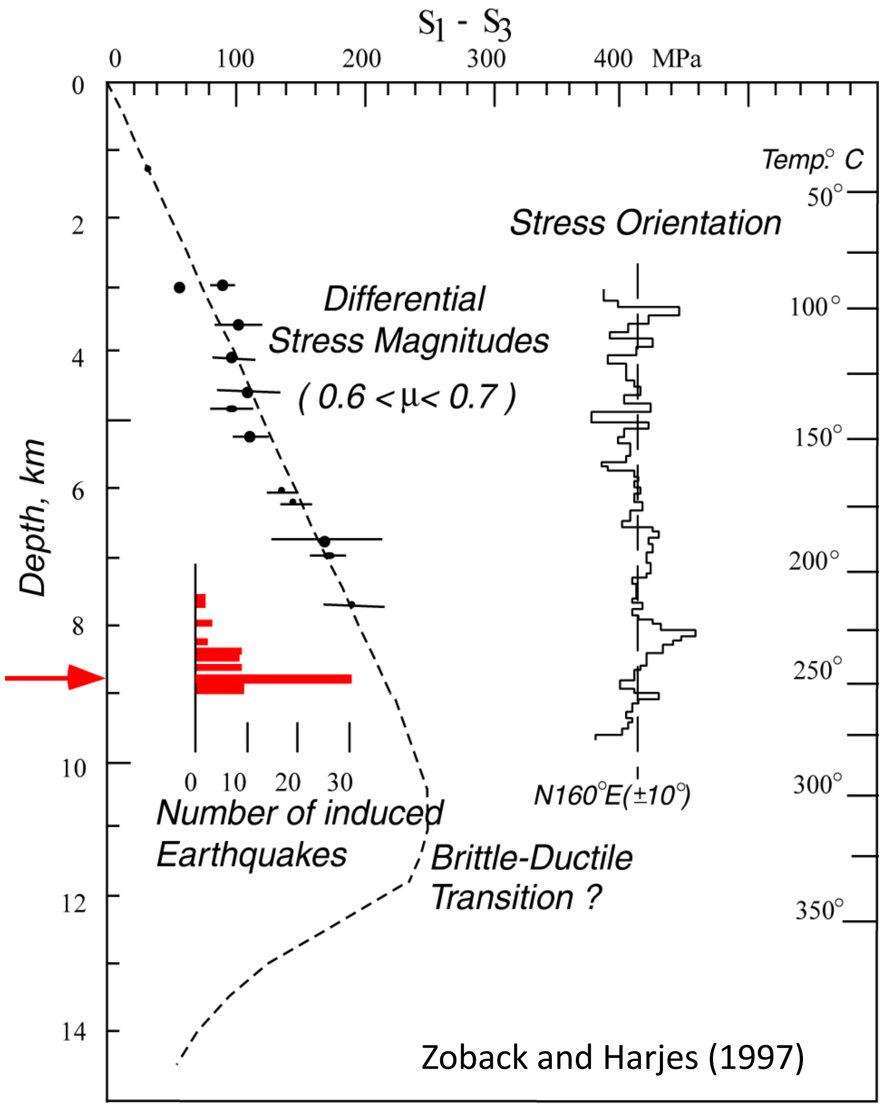


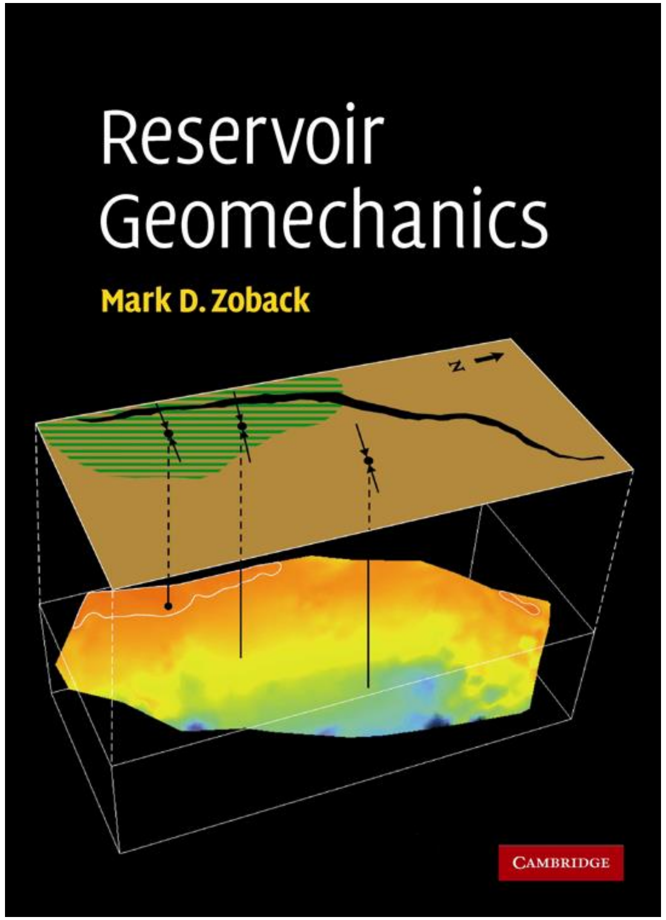
On a Fault

Slip Occurs when $\tau = \mu\sigma_n$

$\sigma_n = S_n - P_p$

Stress Measurements Confirm Critically-Stressed Crust (and the Applicability of Coulomb Faulting Theory)





These principles are applicable to brittle sedimentary formations

PNAS

Earthquake triggering and large-scale geologic storage of carbon dioxide

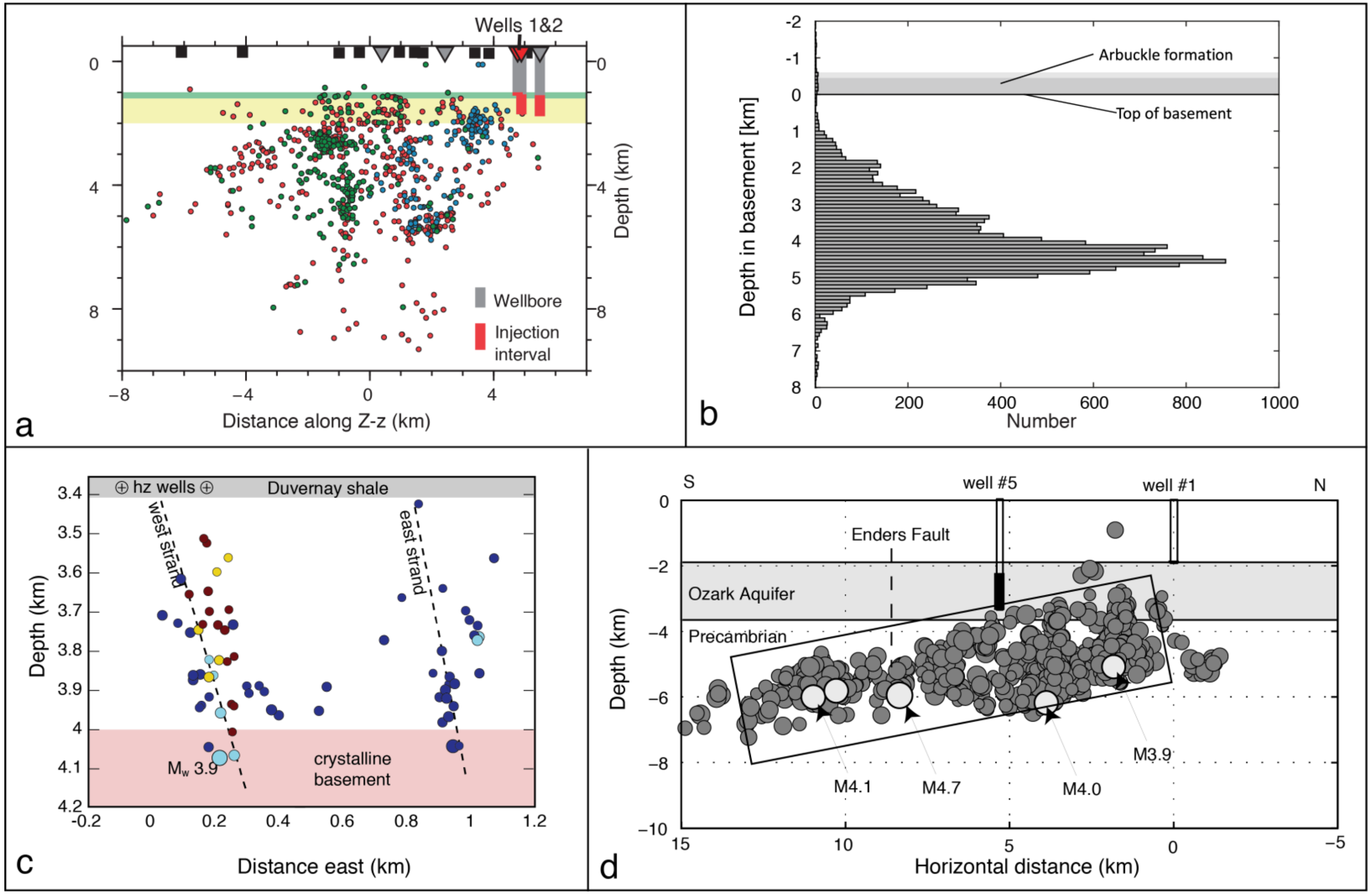
Mark D. Zoback[a,1] and Steven M. Gorelick[b]
Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

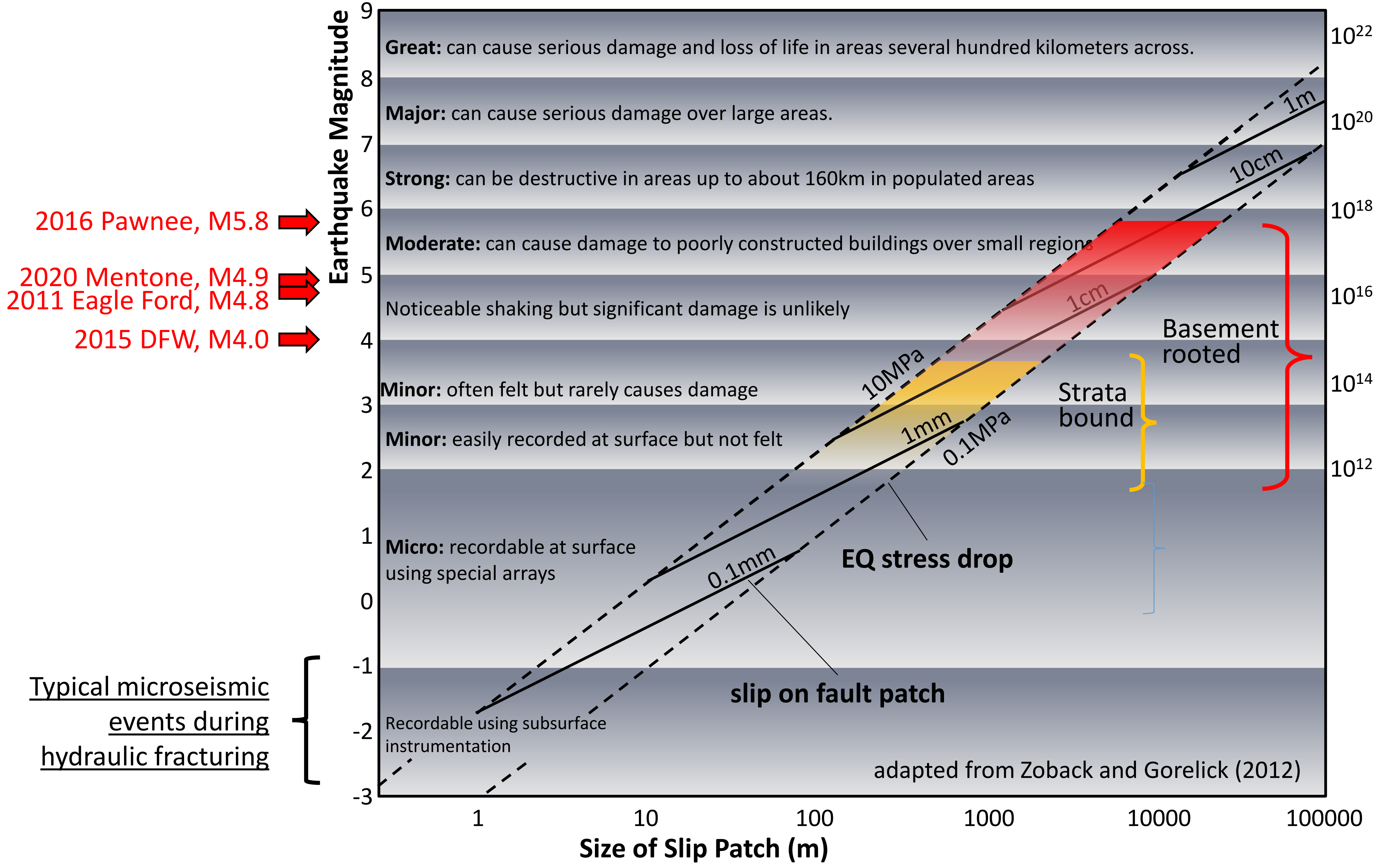
PERSPECTIVE

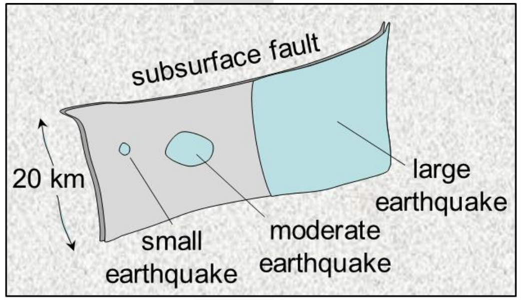
Earthquake Magnitude Depends on Whether Injection Increases Potentially Activate Basement Faults

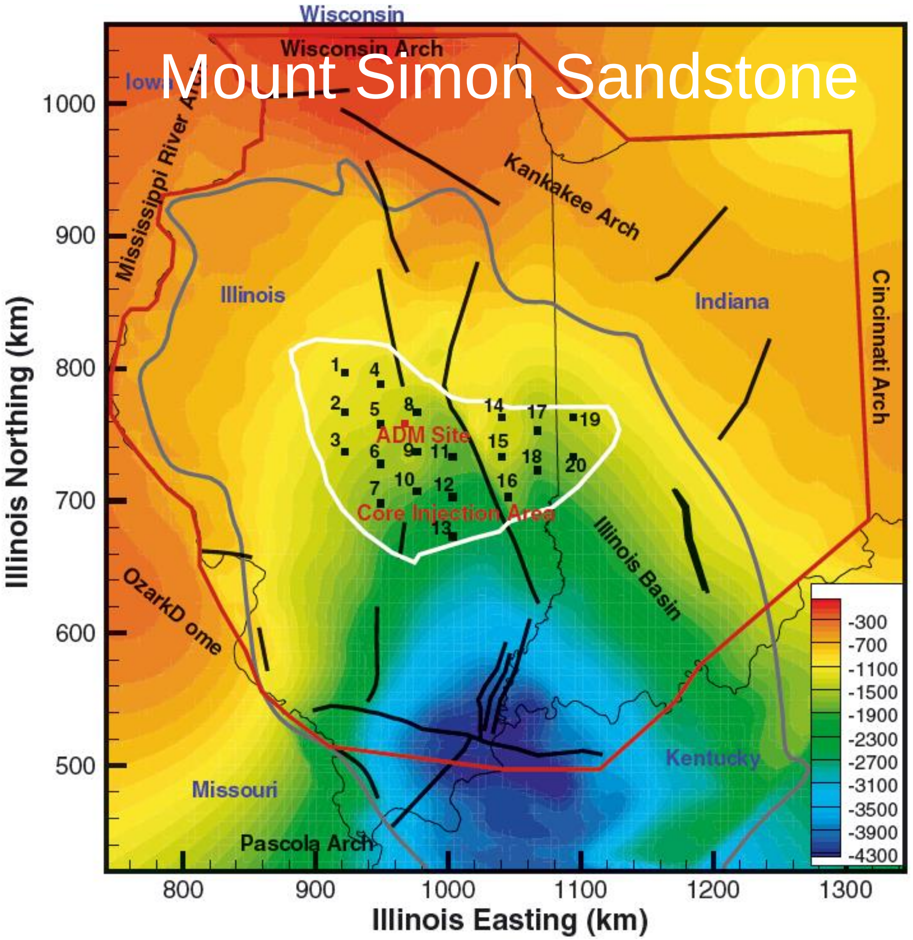


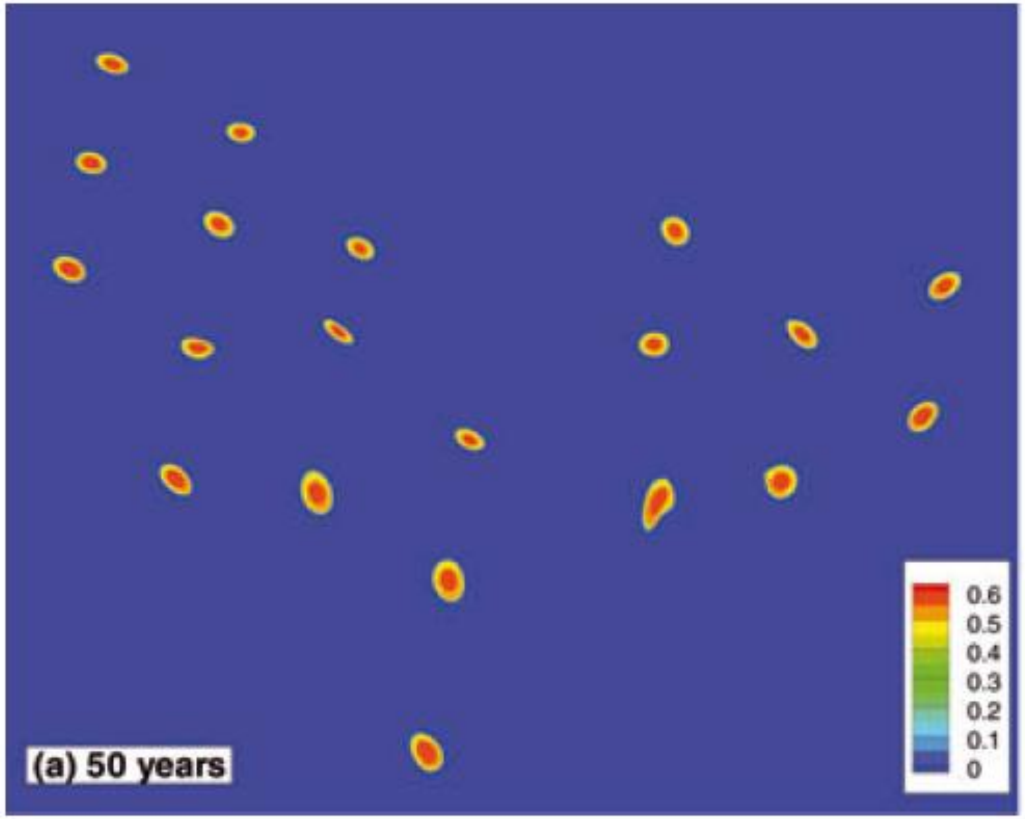
Faulting on Basement Faults is Occurring in Response to Injection in Overlaying Sedimentary Formations

Shallow (Strata-bound) vs Basement-Rooted Faults









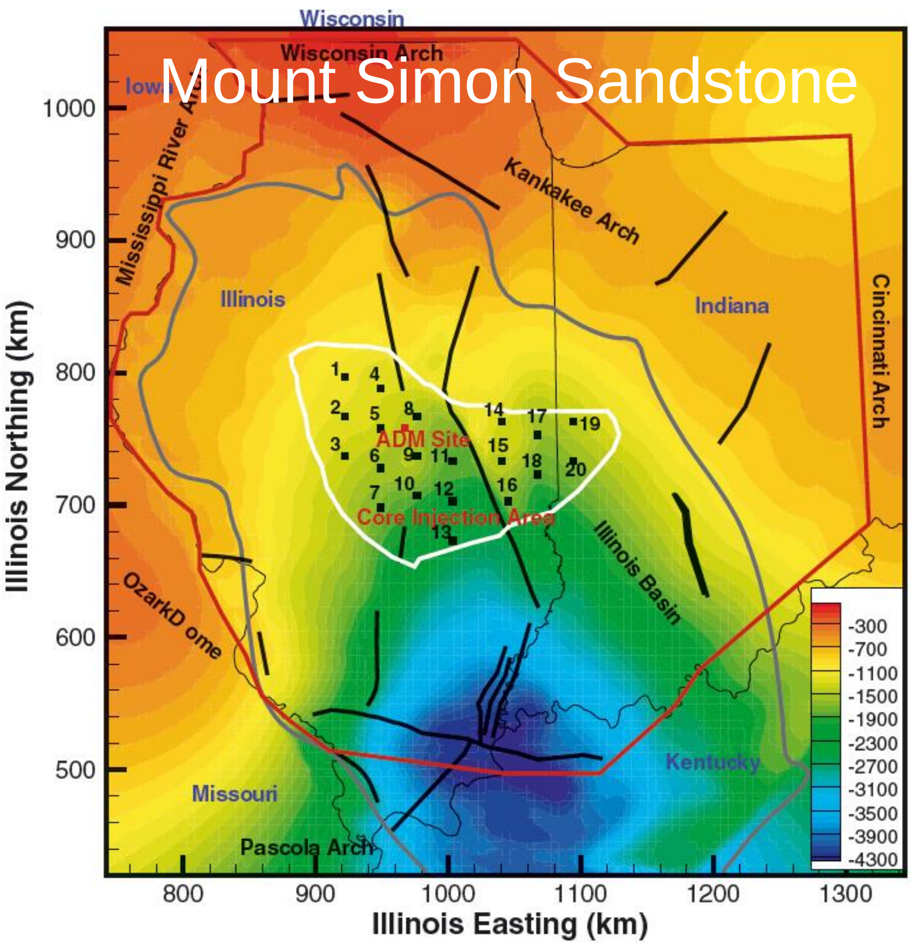
CO_2 Footprint

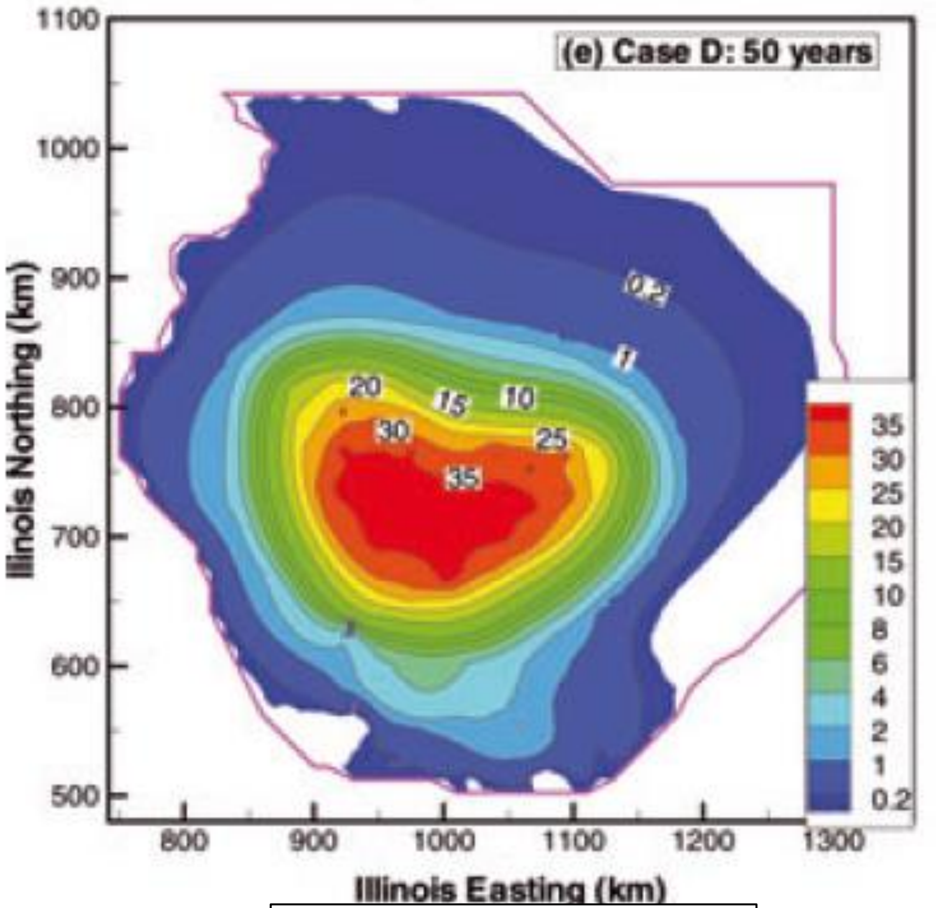
100 MT/year
20 Wells

groundwater

Modeling Basin- and Plume-Scale Processes of CO_2 Storage for Full-Scale Deployment

by Quanlin Zhou[1], Jens T. Birkholzer[1], Edward Mehnert[2], Yu-Feng Lin[3], and Keni Zhang[1] (2010)





Pressure Change

100 MT/year
20 Wells

groundwater

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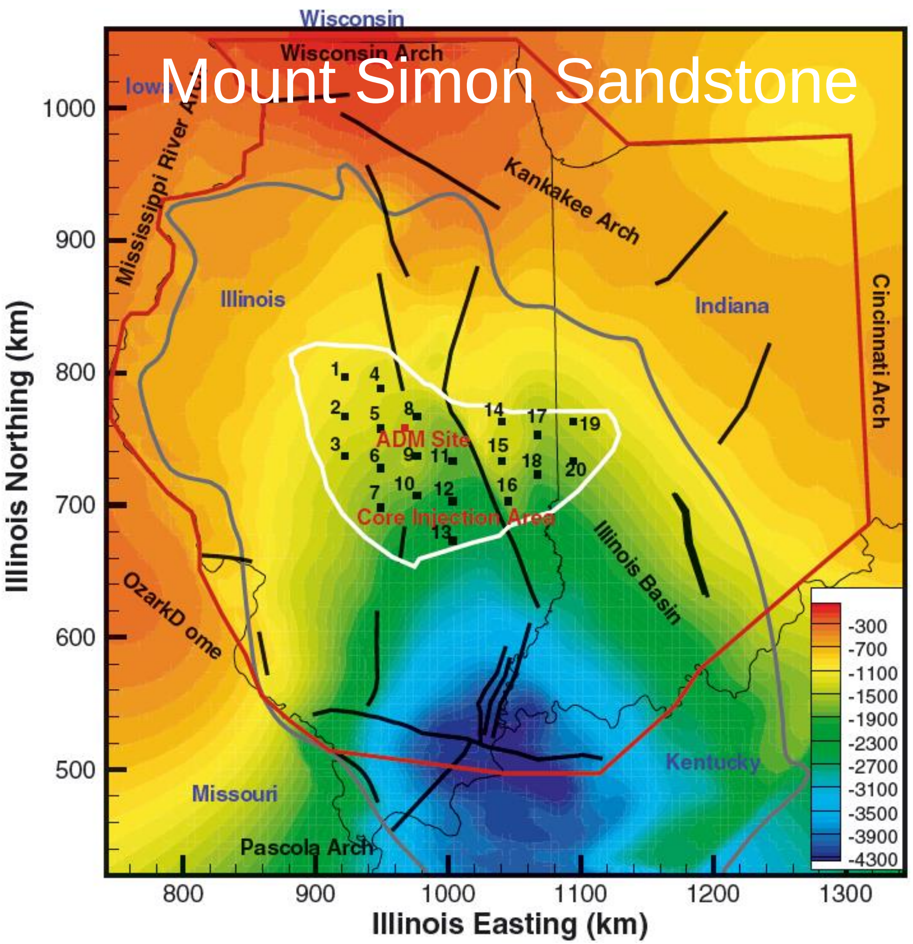

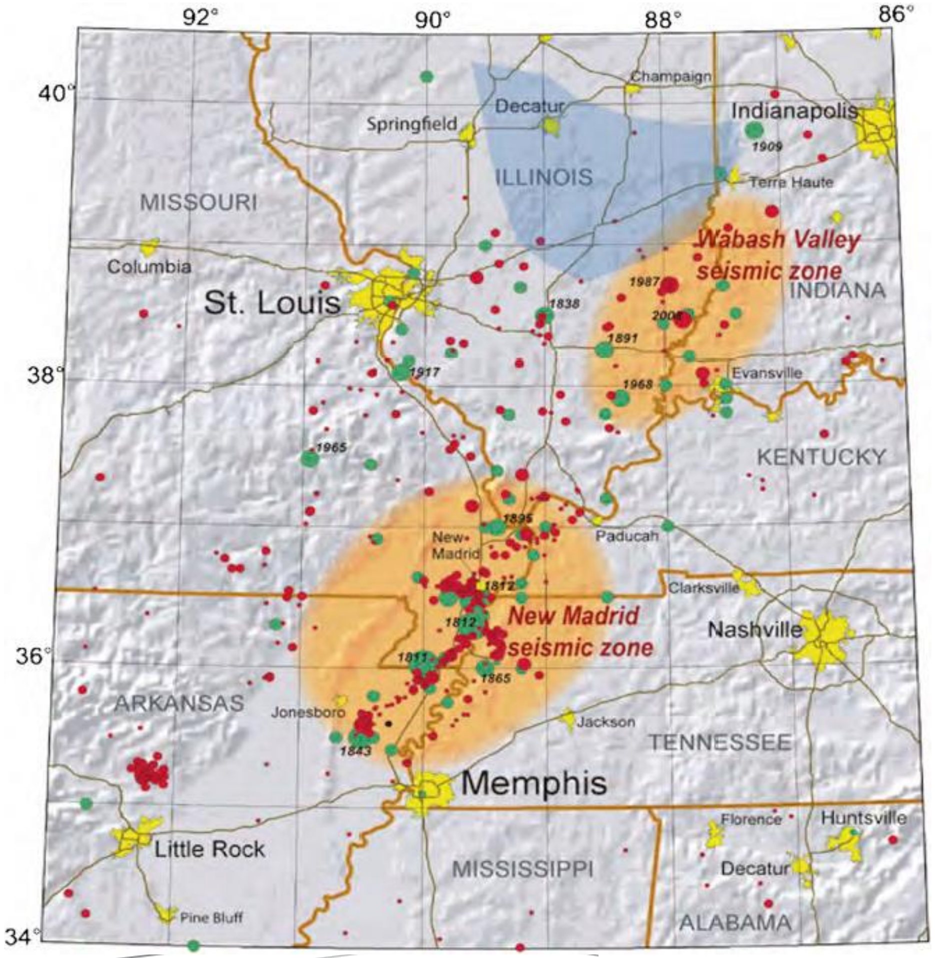

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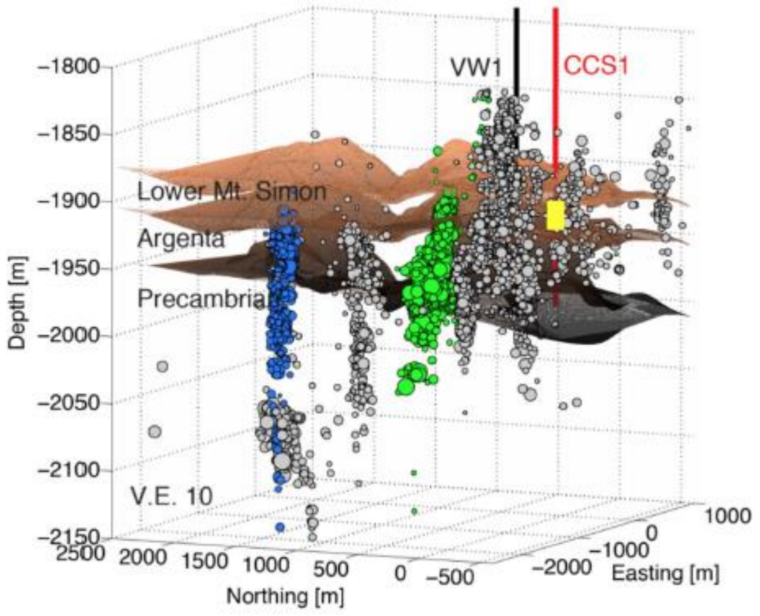
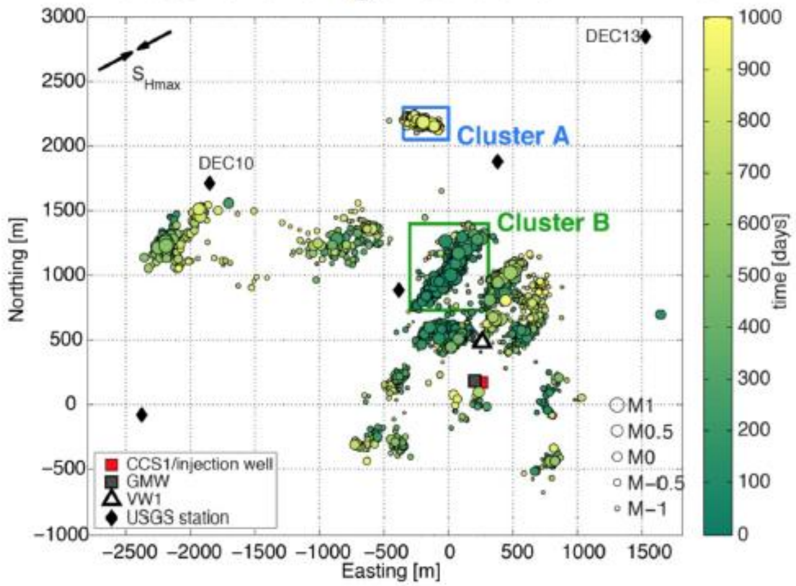
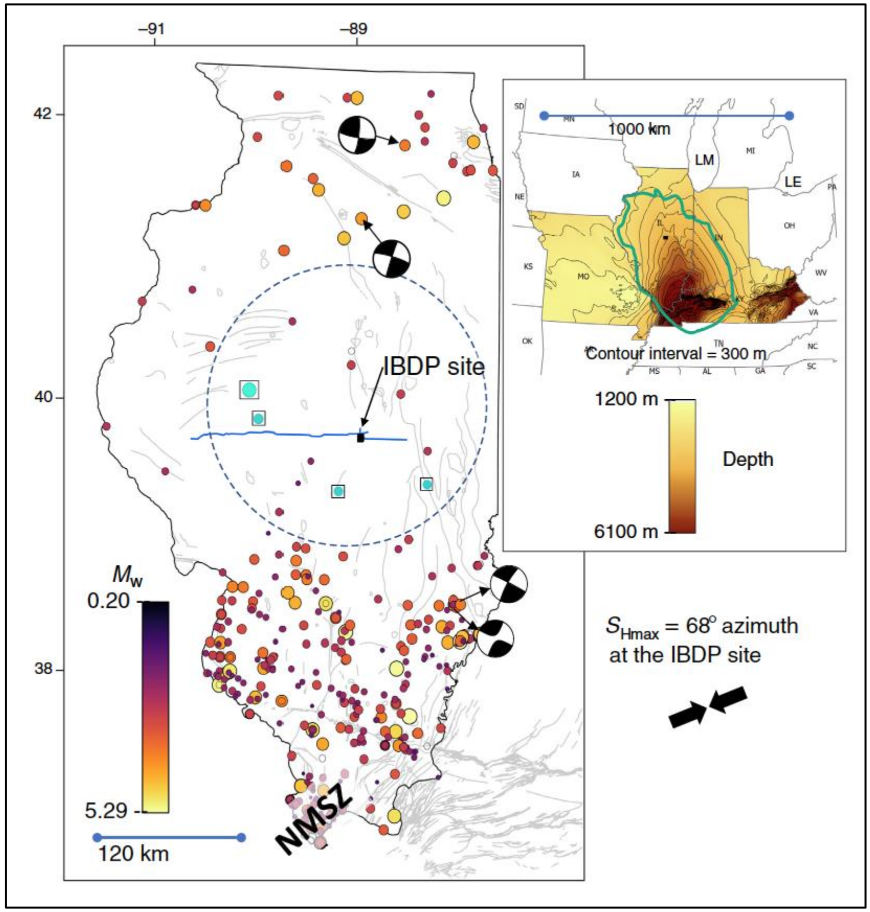
CO_2 Injection Into the Mt. Simon Sandstone At Decatur, Illinois



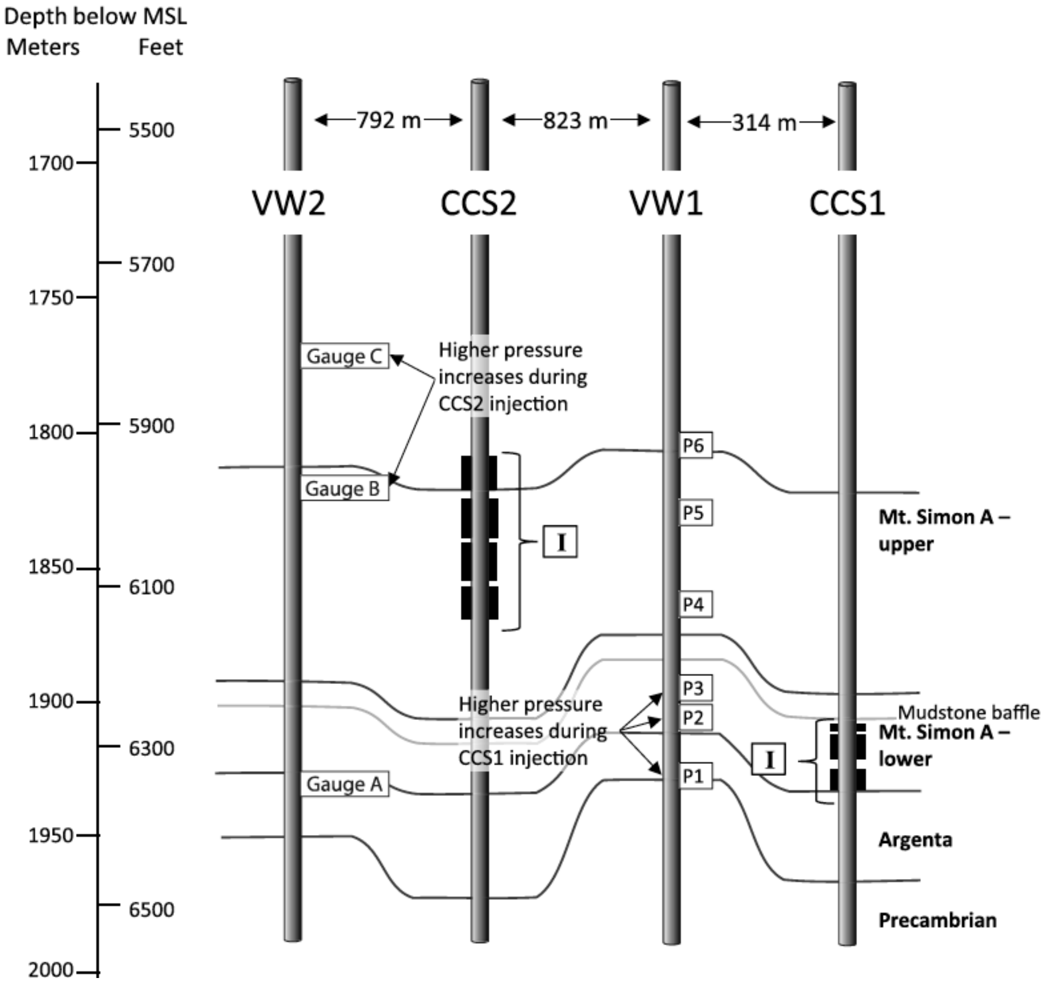
- Injection of 1 million tons of CO_2 over a 3-year period into the Mt. Simon (8 million barrels, 1.3 million m^3)
- Small earthquakes define faults in Precambrian basement
- Pressure change less than 1 MPa



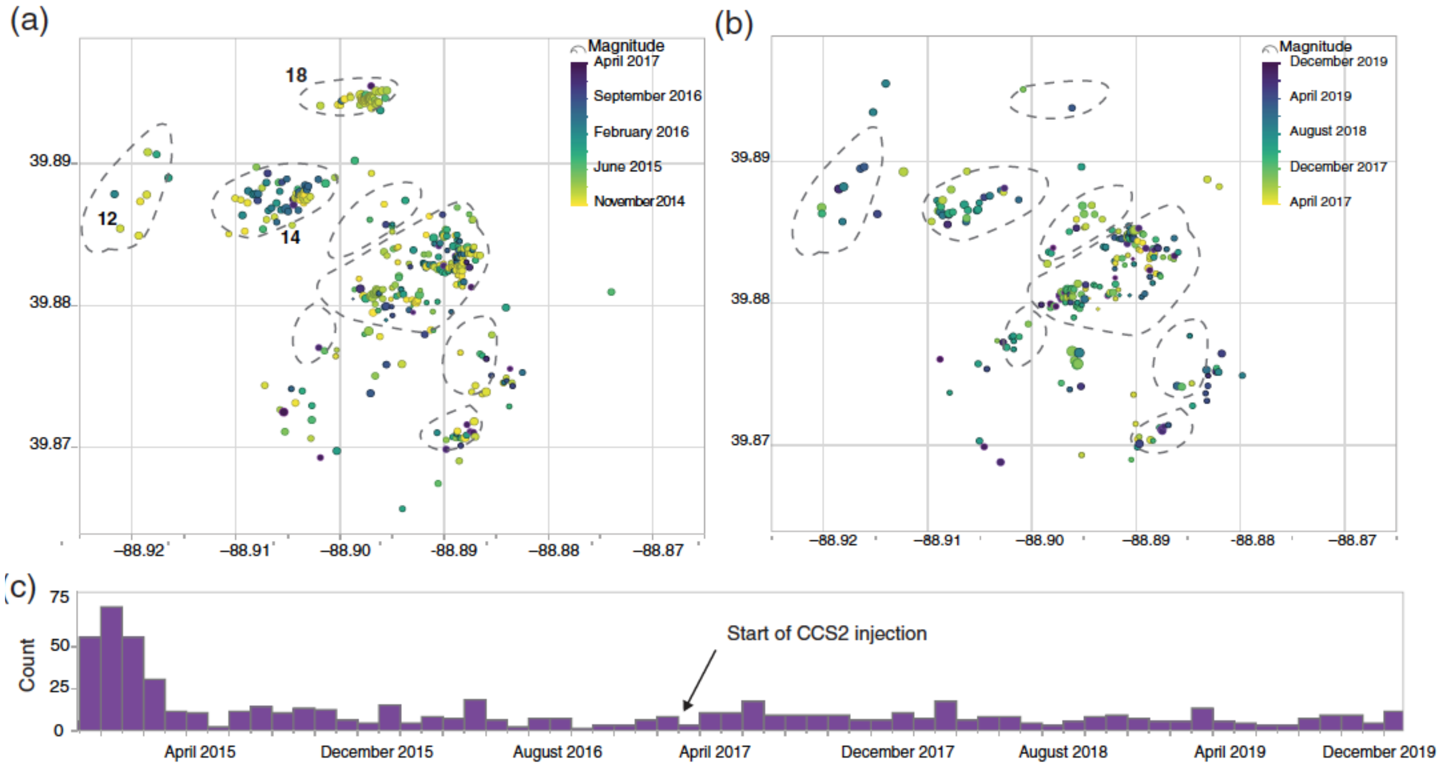


Goertz-Allman et al. (2017, JGR)

New Injection Zone is Still in the Mt. Simon (Above a Mudstone *Baffle*) Seismicity is Continuing (at a Lower Rate) on the Same Basement Faults



Williams-Stroud et al. (BSSA, 2020)

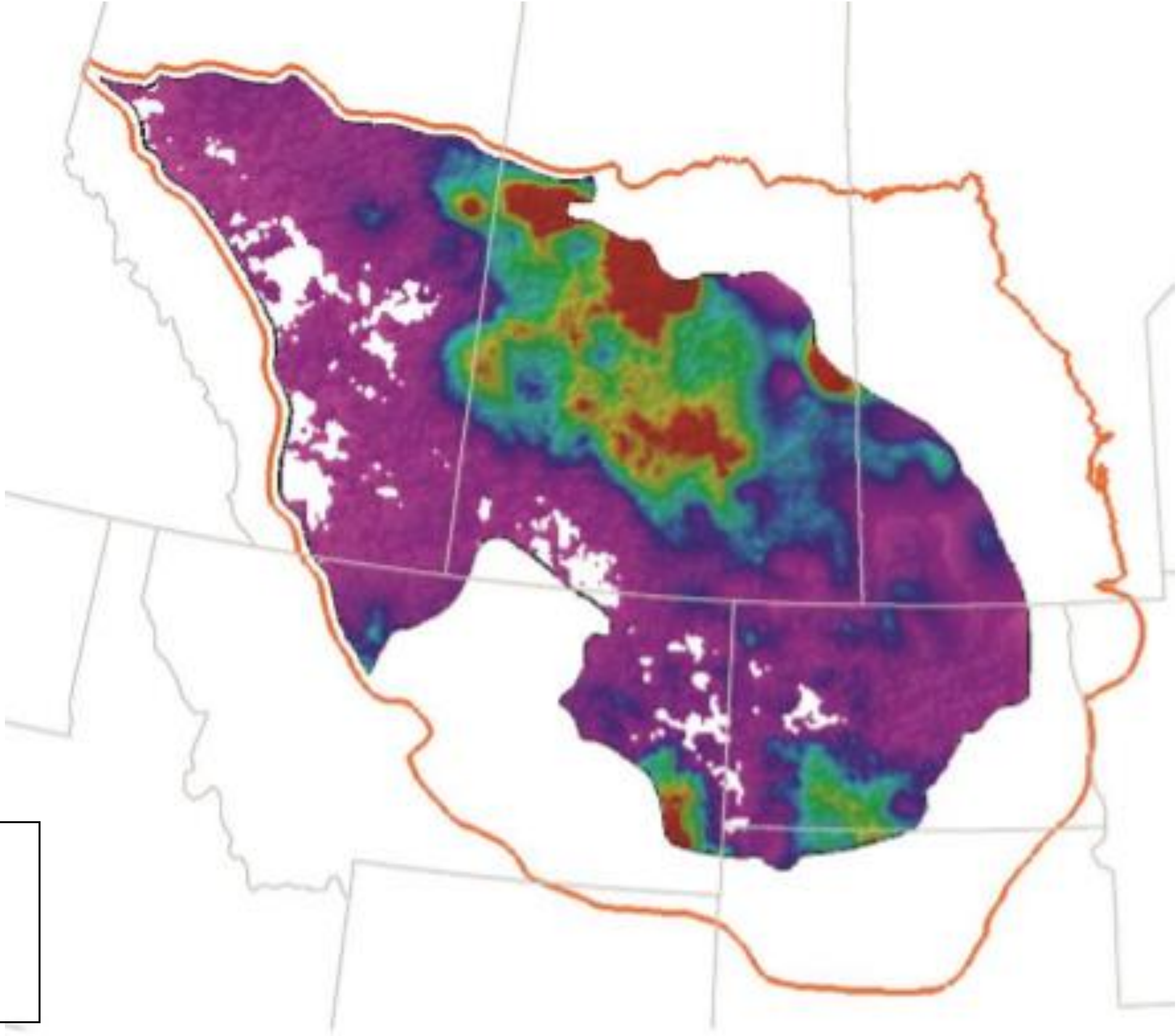


Injection Rate in CCS2 Well is 1.7 times that in CCS1 (~560,000 tonnes/year)

Basal Saline Aquifers

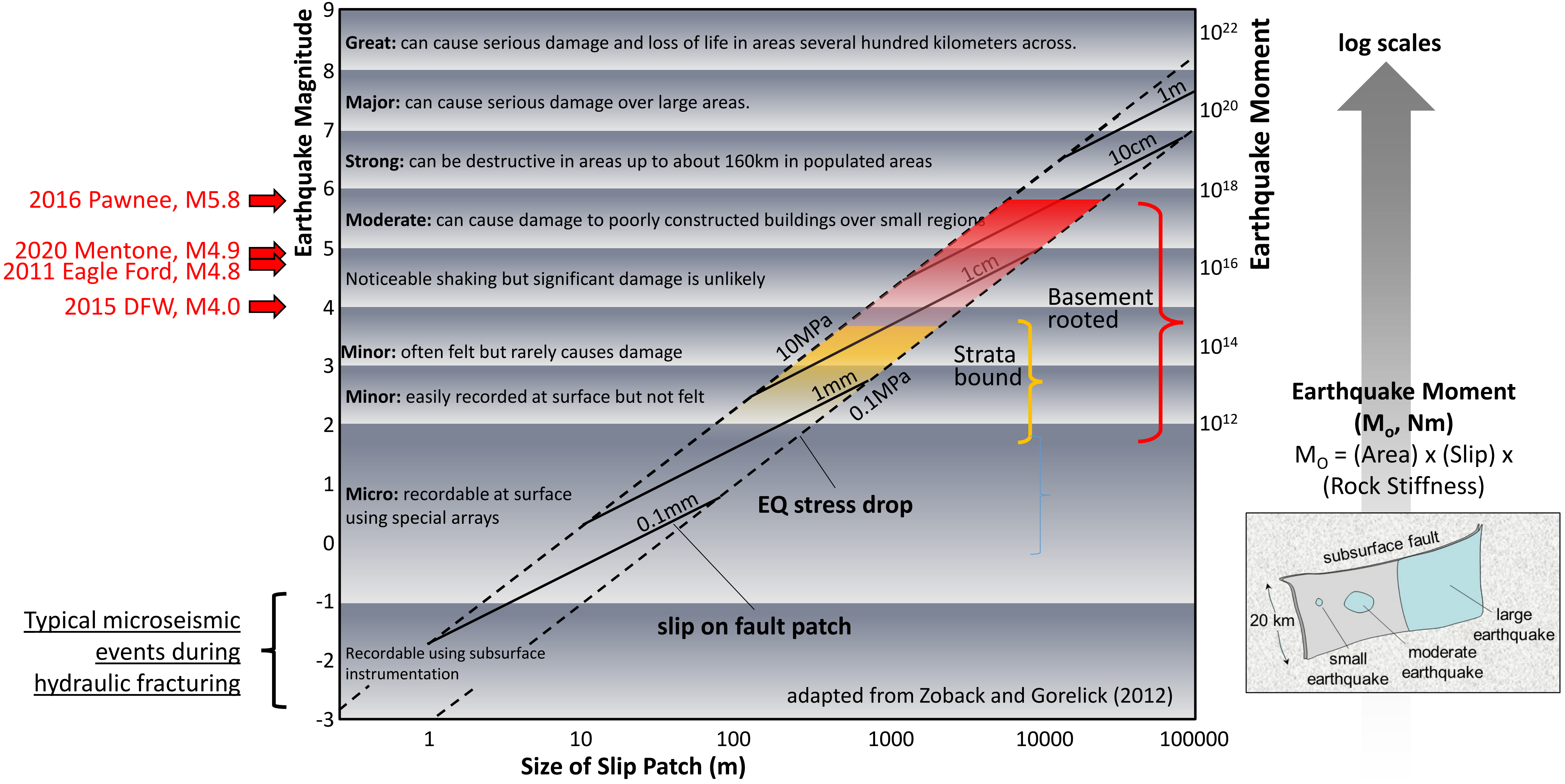
Example

- Basal Cambrian Sandstone, Great Plains
- The aquifer with largest estimated resources in the area
- Storage formation for Quest and Aquistore projects

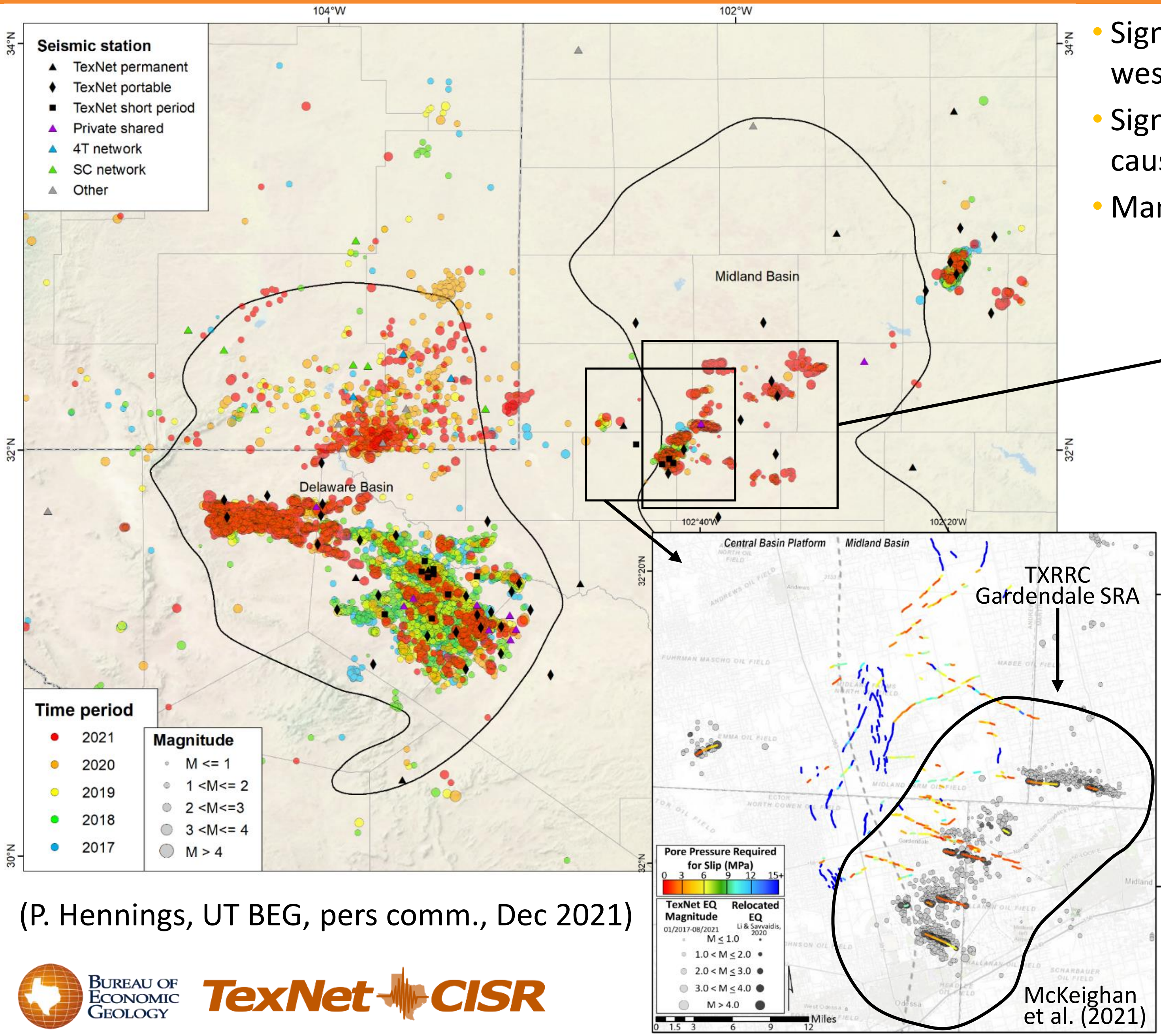


Is it Feasible to Consider Large-Scale CO_2 Storage in Basal Saline Aquifers?

What About Recent Seismicity in the Midland Area?

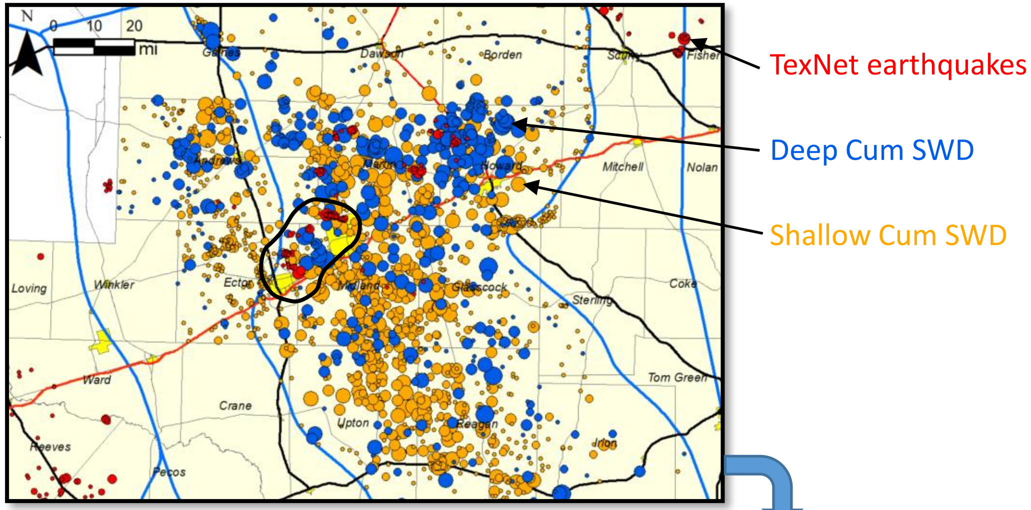


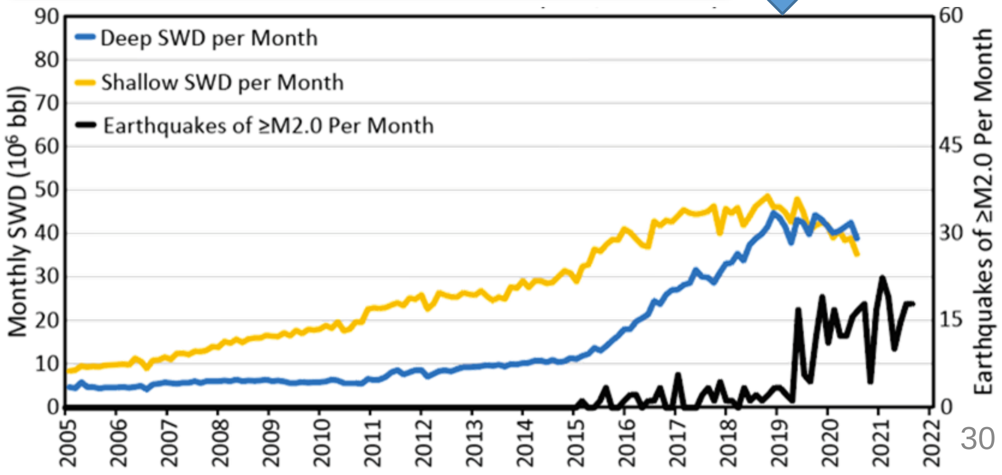
Seismicity in West Texas and the TexNet-CISR Collaboration



(P. Hennings, UT BEG, pers comm., Dec 2021)

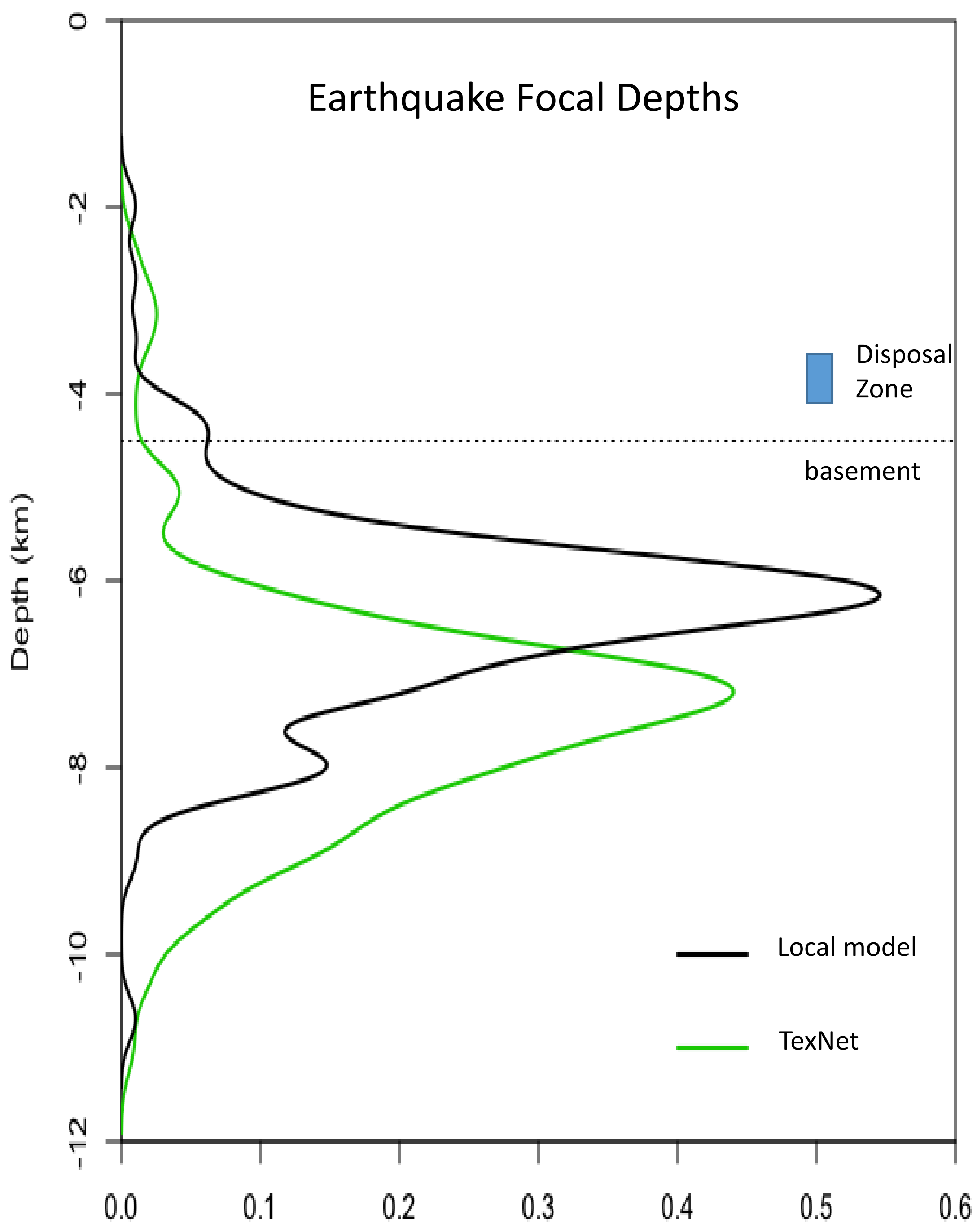
- Significant increase in seismicity in last two years including in the western Midland Basin
- Significant recent increases in operations currently assumed to be causal factors (SWD, especially into deep strata above basement)
- Many critically-stressed faults in the region

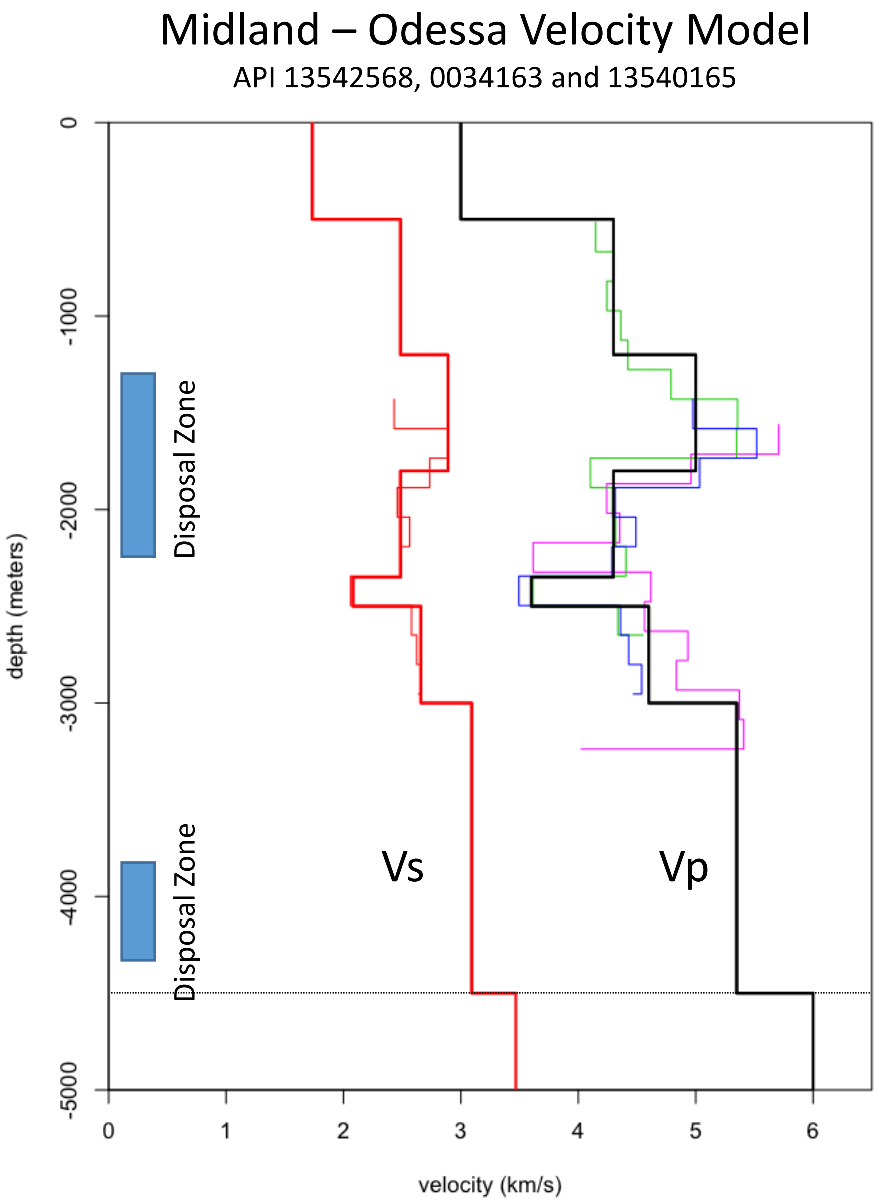




Bureau of Economic Geology

TexNet CISR





Stanford | Stanford Center for Induced and Triggered Seismicity

School of Earth, Energy & Environmental Sciences

Can We Avoid Injection into Potentially Active Faults?

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

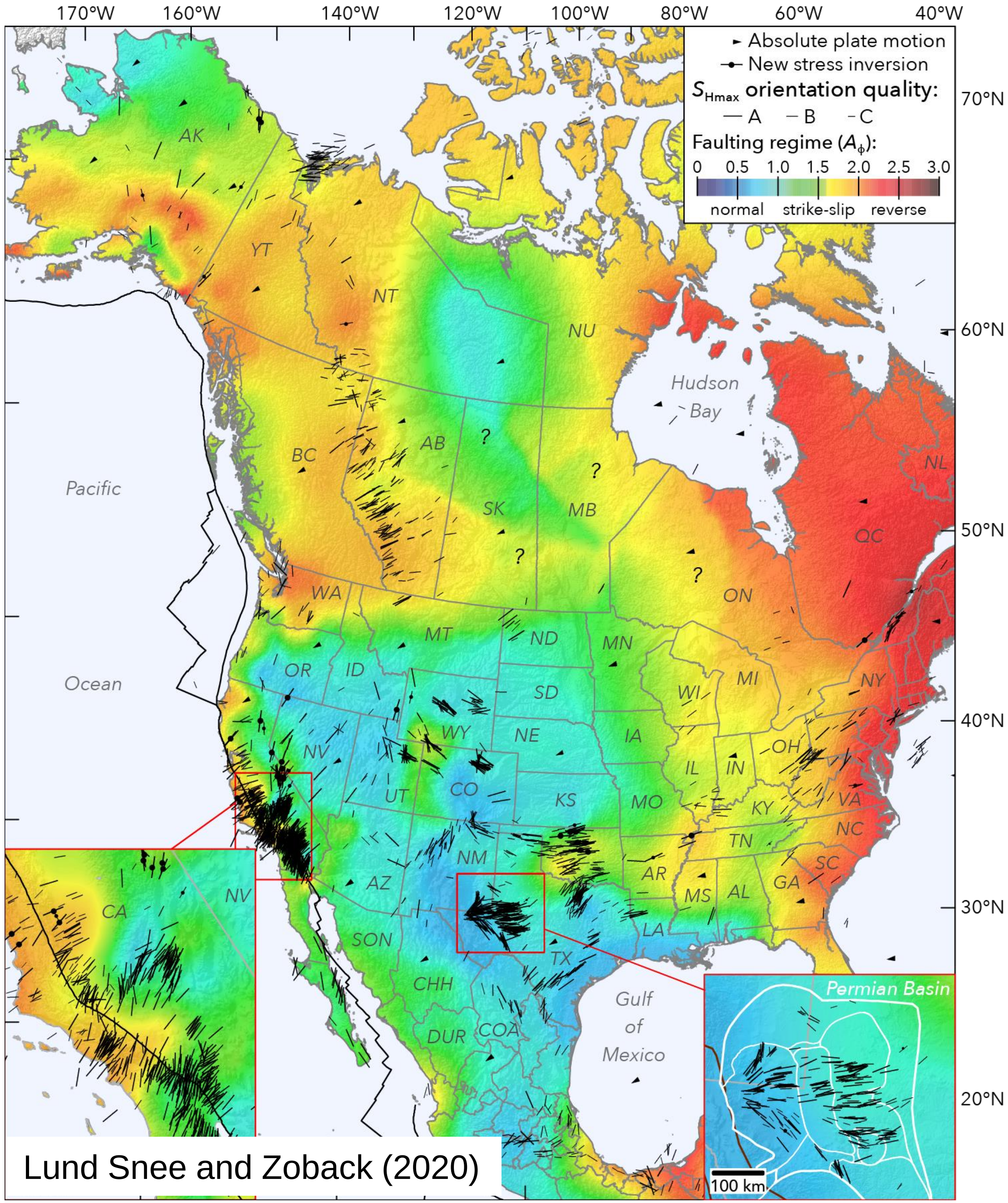
THE GEOLOGICAL SOCIETY OF AMERICA®

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

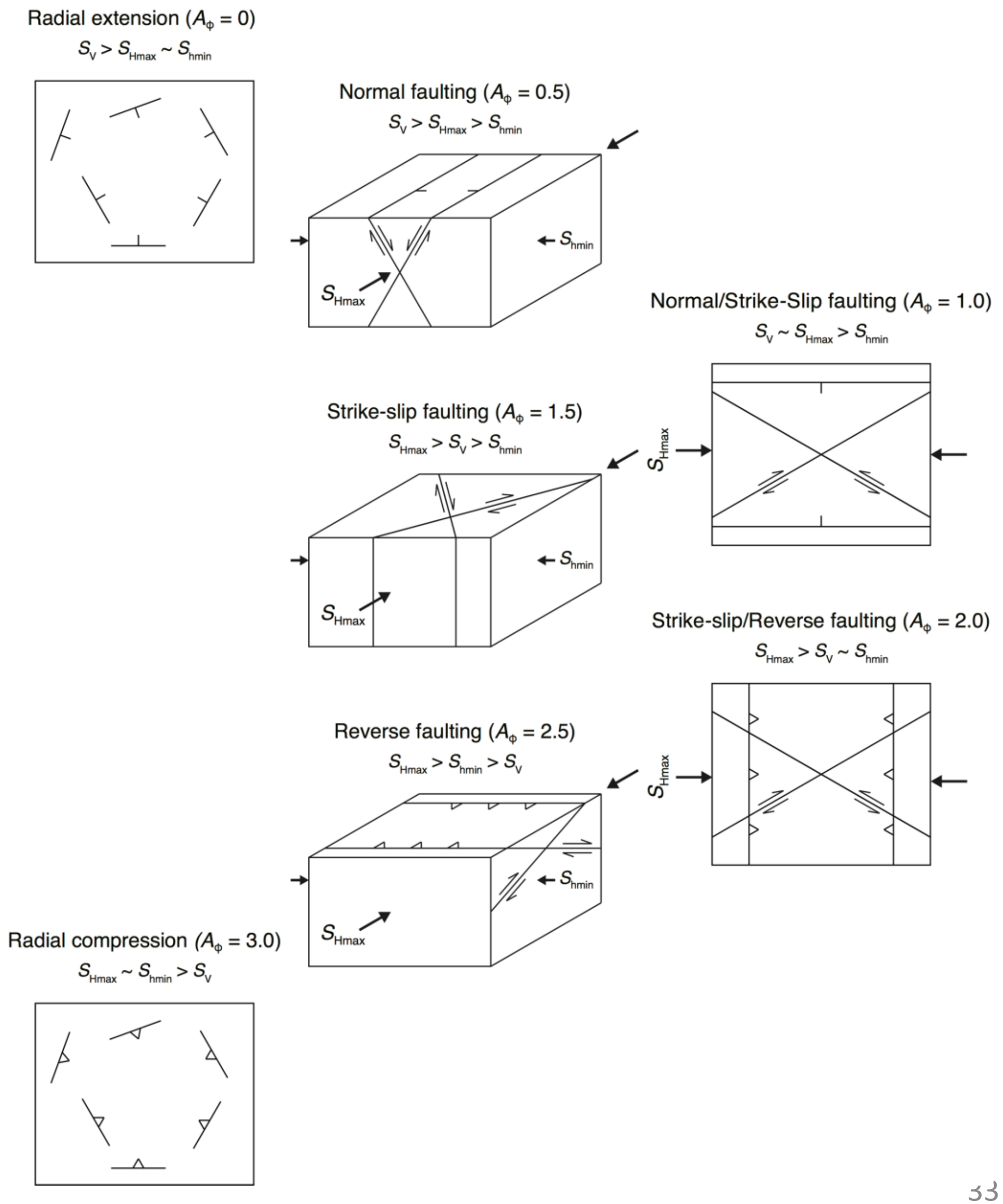
F. Rall Walsh, III, and Mark D. Zoback
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

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

Anderson Faulting Theory Revisited



Lund Snee and Zoback (2020)



Permian Basin

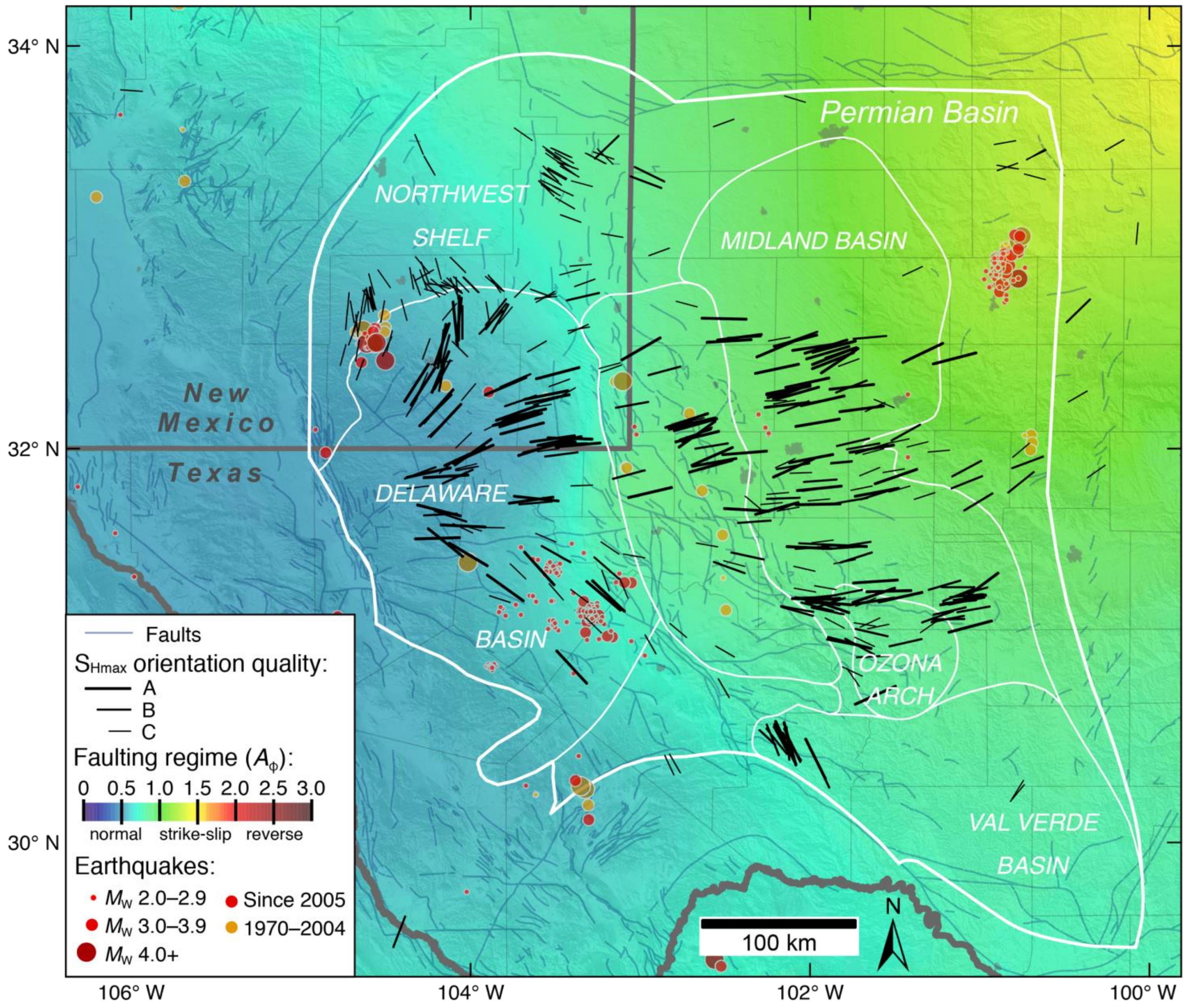


Fig. 7.3

Lund Snee and Zoback (2017)

Can We Avoid Injection into Potentially Active Faults?

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

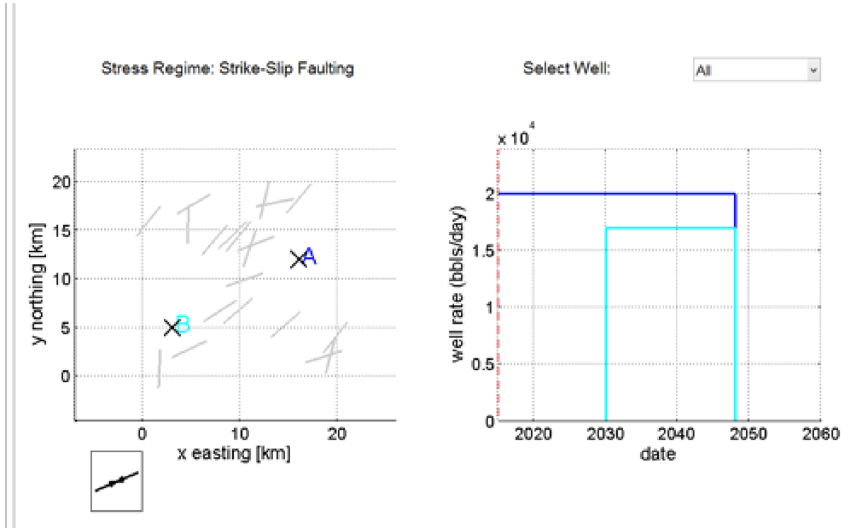
Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA

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

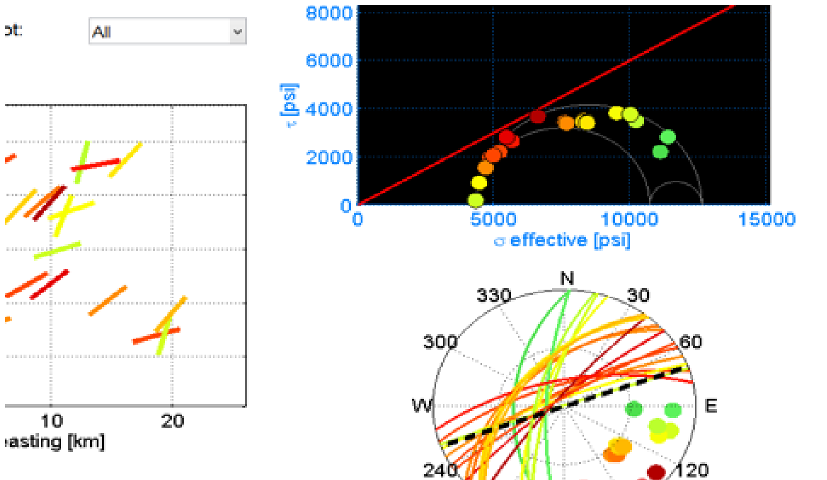
GEOLOGY Data Repository item 2016334 | doi:10.1130/G38275.1

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

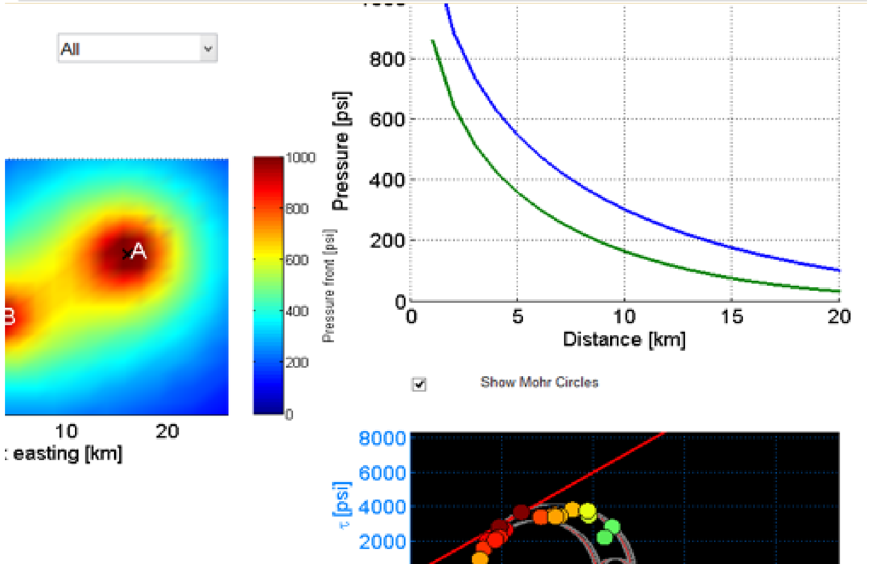
FSP
Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity



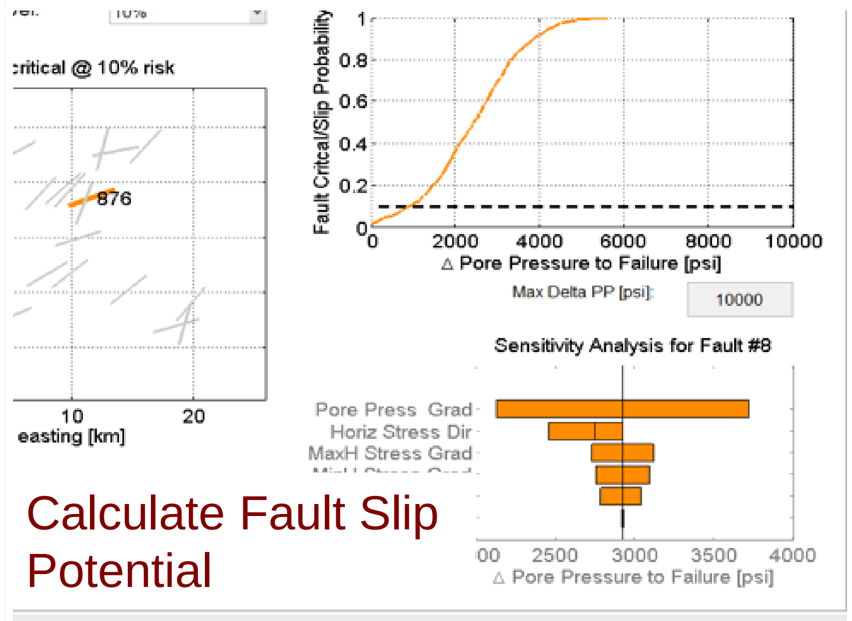
Injection Wells and Faults



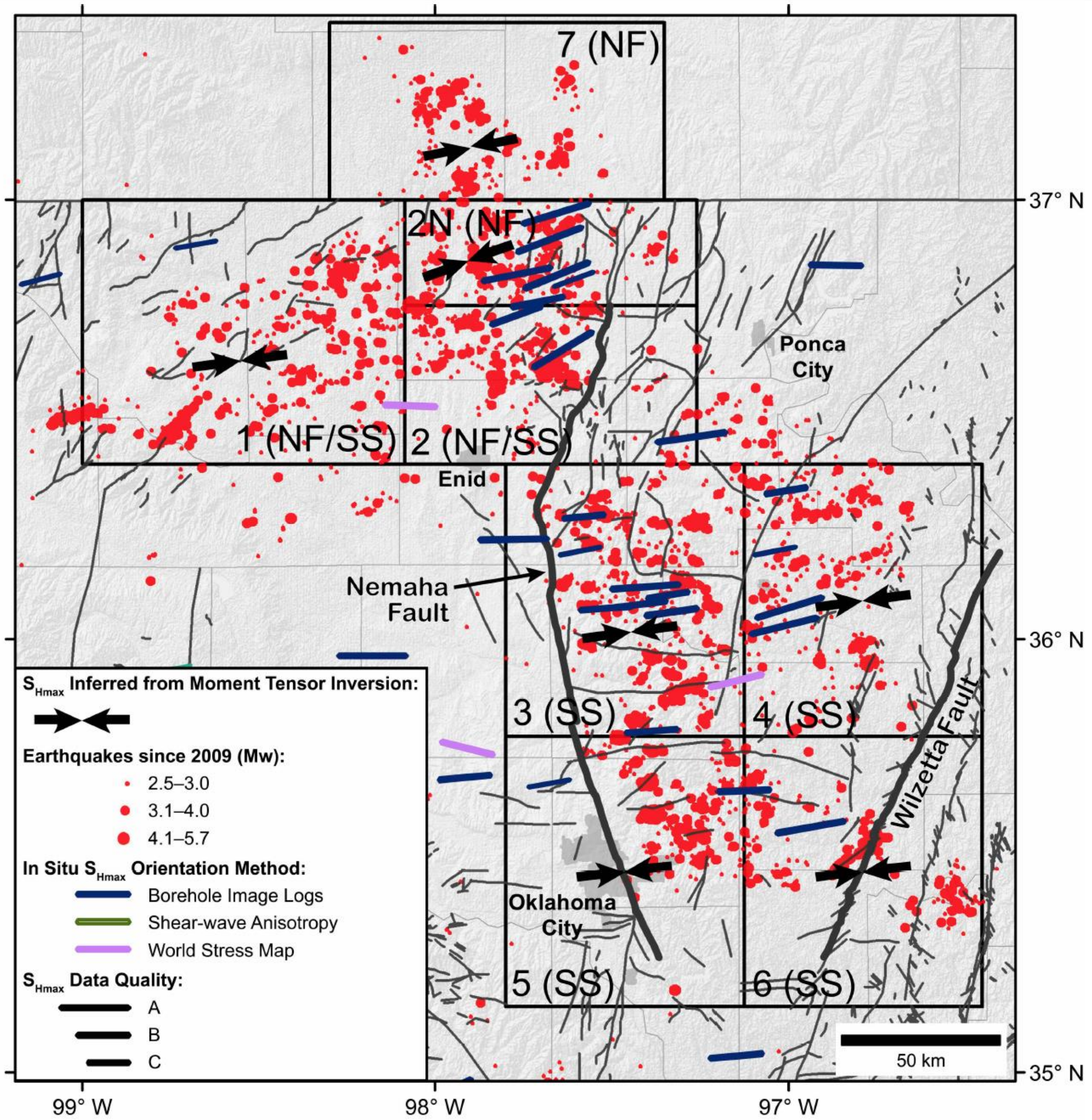
Geomechanical Analysis



Hydrology



Calculate Fault Slip Potential

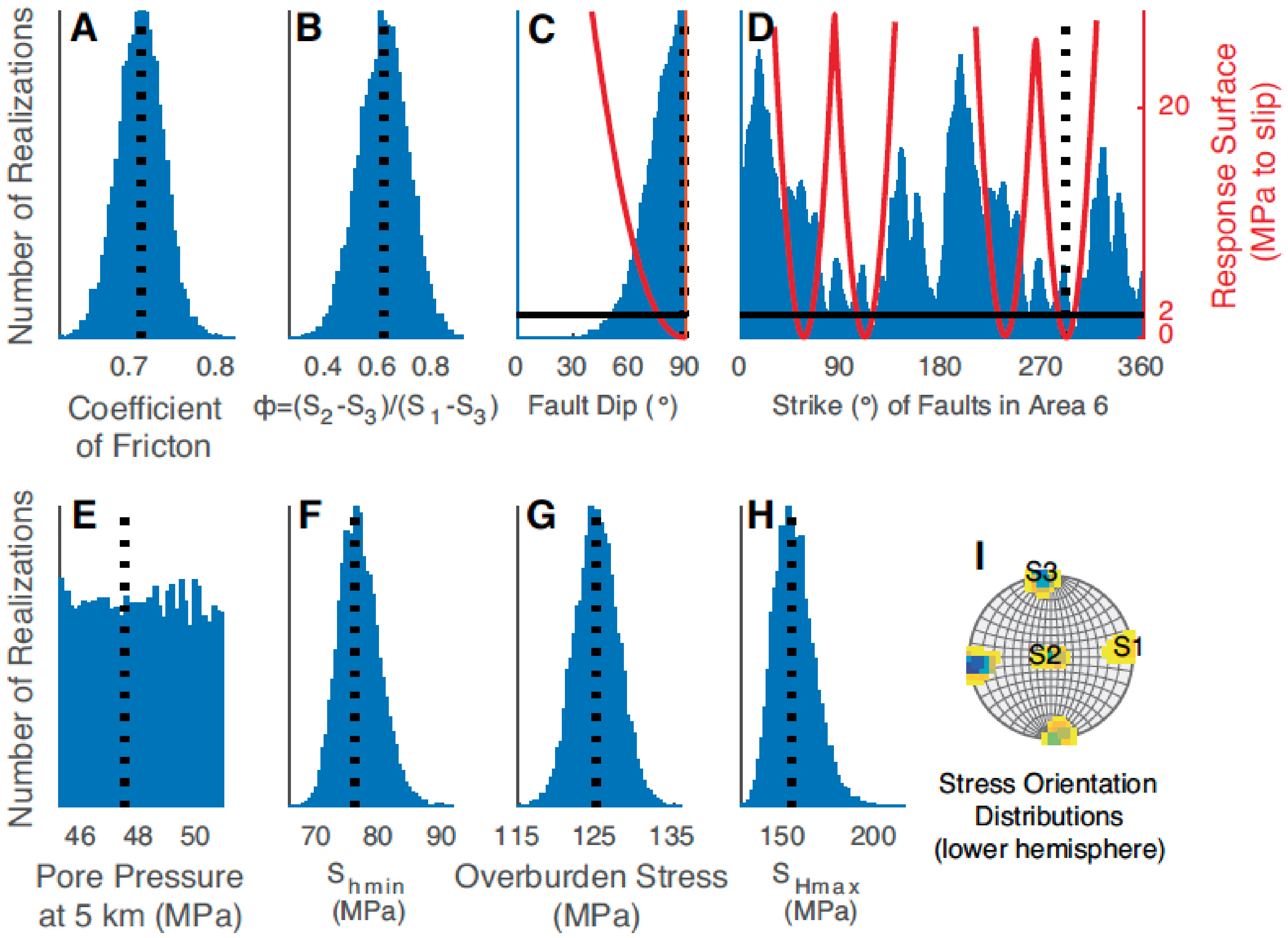


Alt and Zoback (BSSA, 2017)

- 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 Knowing the Maximum Change in Pore Pressure

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

FSP
Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity



Fault Slip Probability (2 MPa Max Pressure Change)

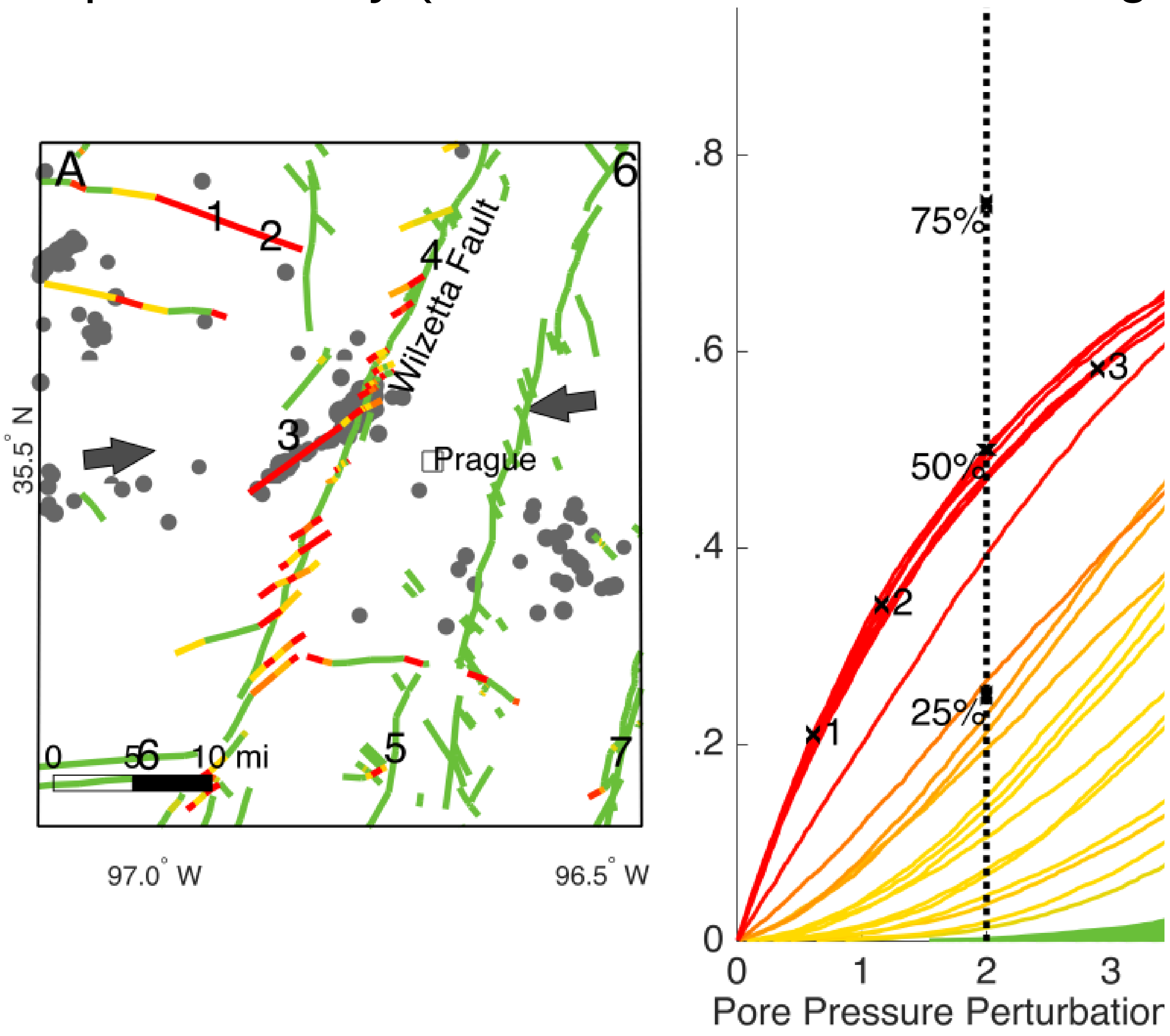
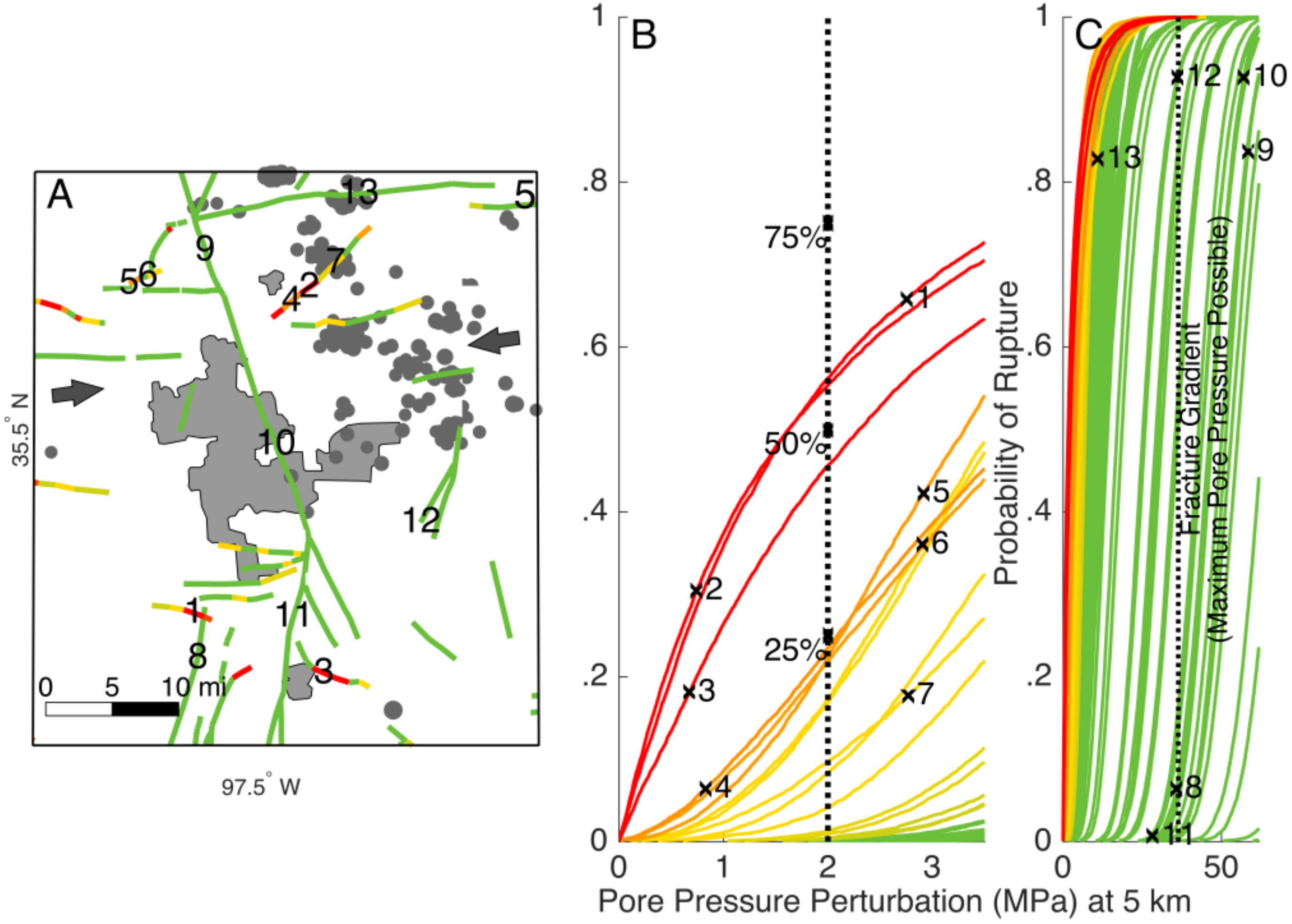


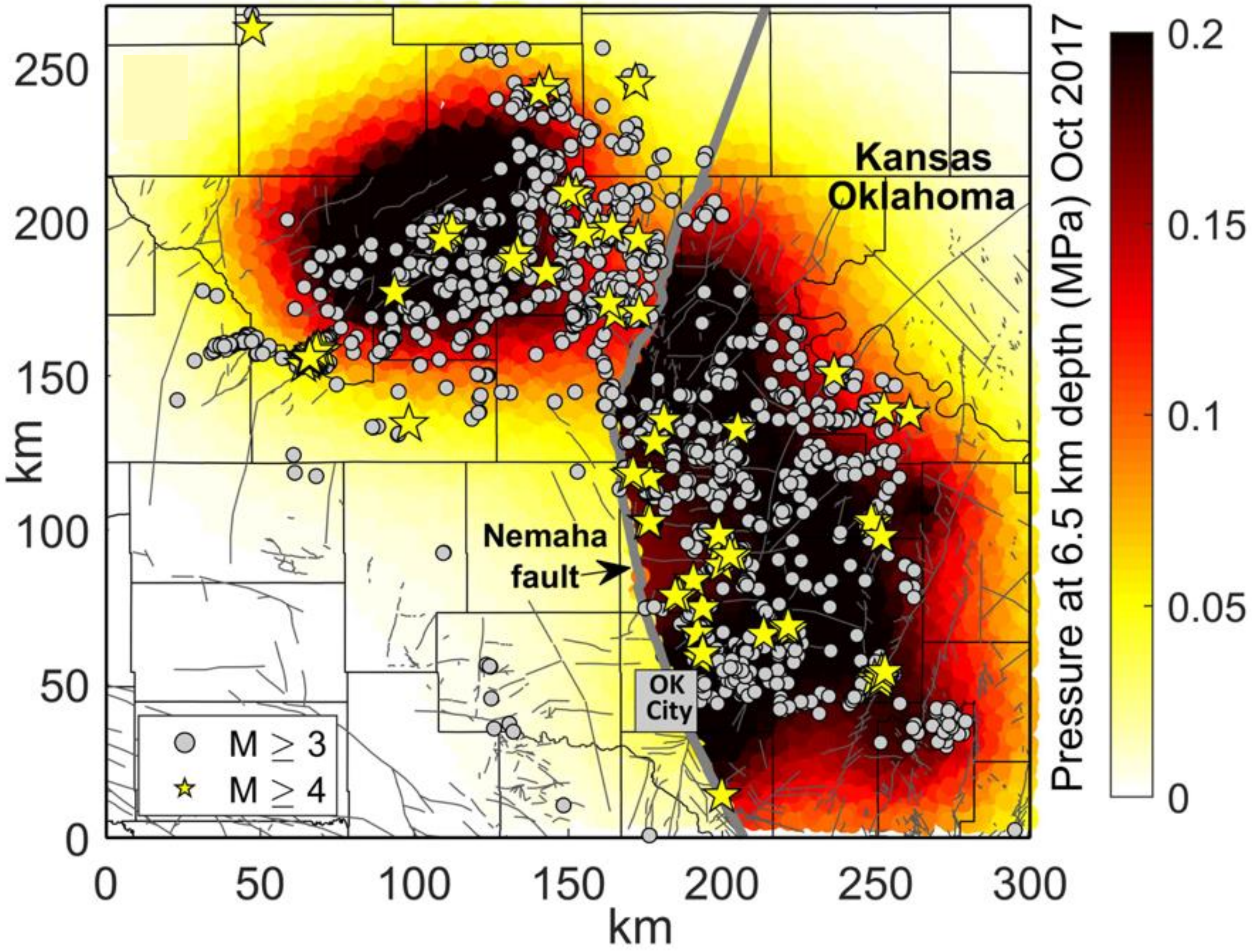
Fig. 14.4

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



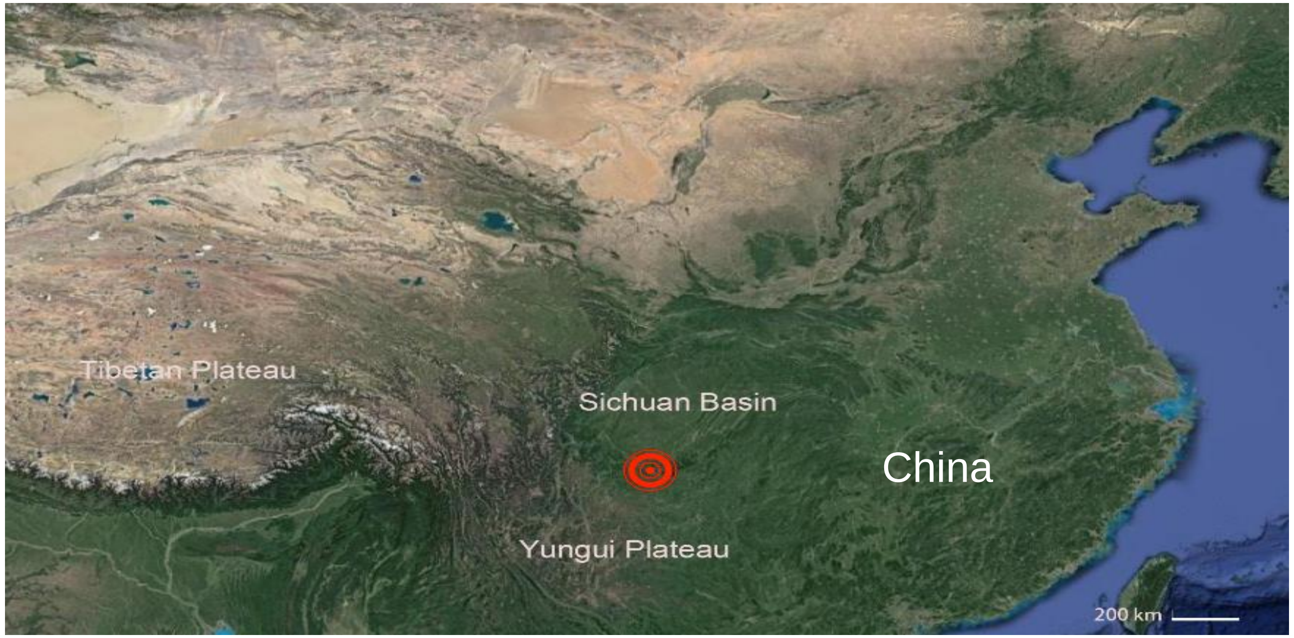
Walsh and Zoback (2016)

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



Langenbruch and Zoback, 2016

Well Shearing and Seismicity Due to Triggered Aseismic Fault Slip



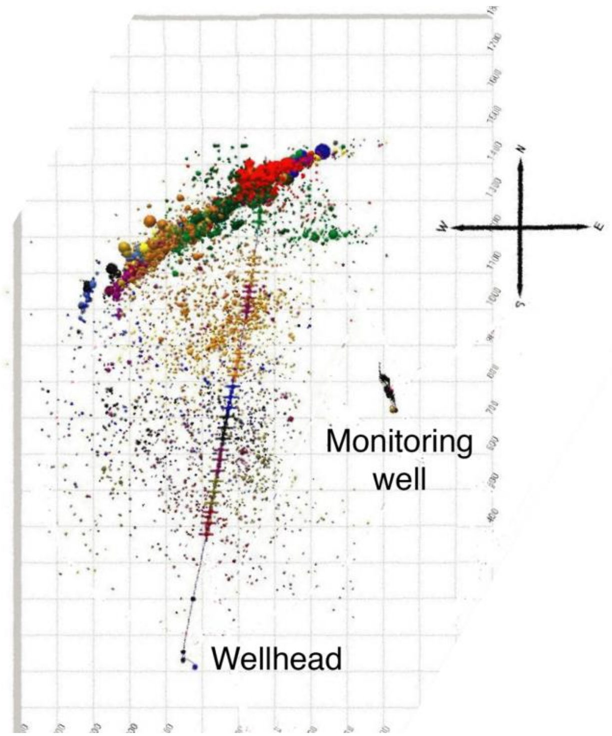


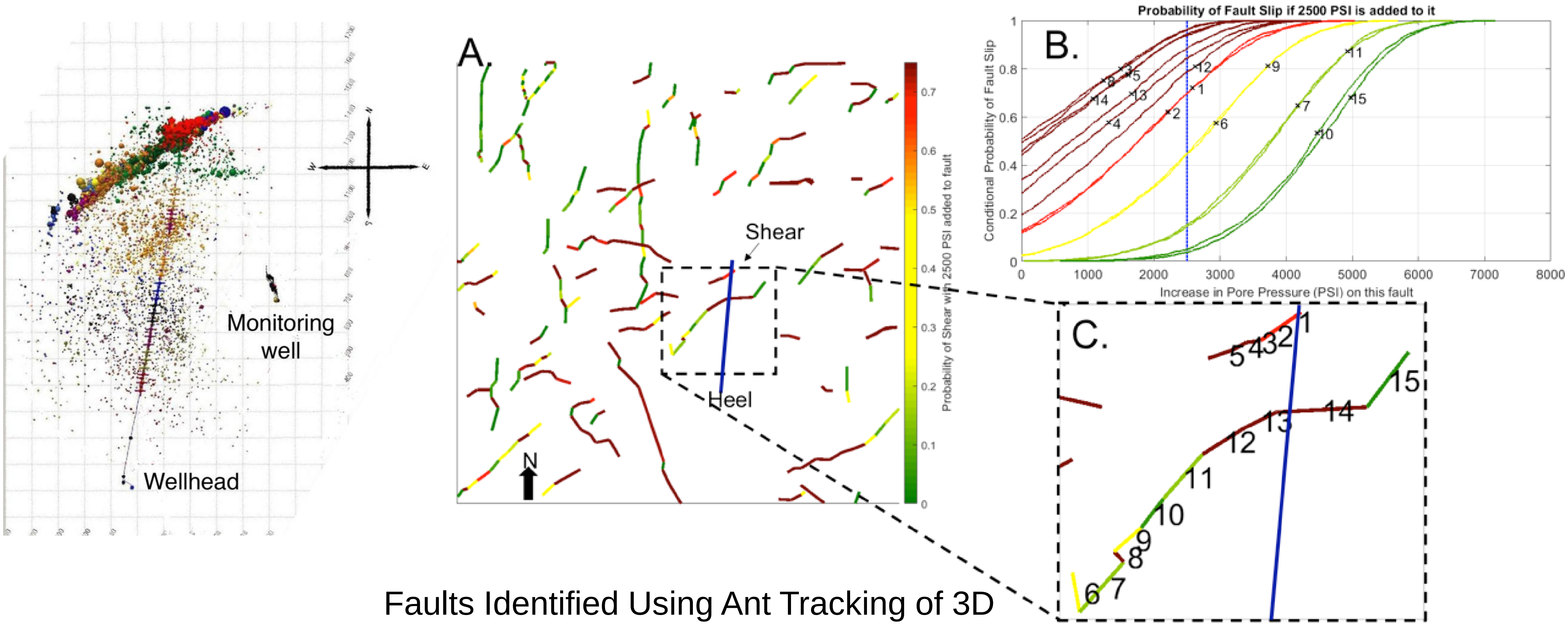
Fig. 13.21

Longmaxi play in Sichuan Basin:

- The most commercially successful shale play in China.
- Adjacent to two plateaus, complex tectonics.

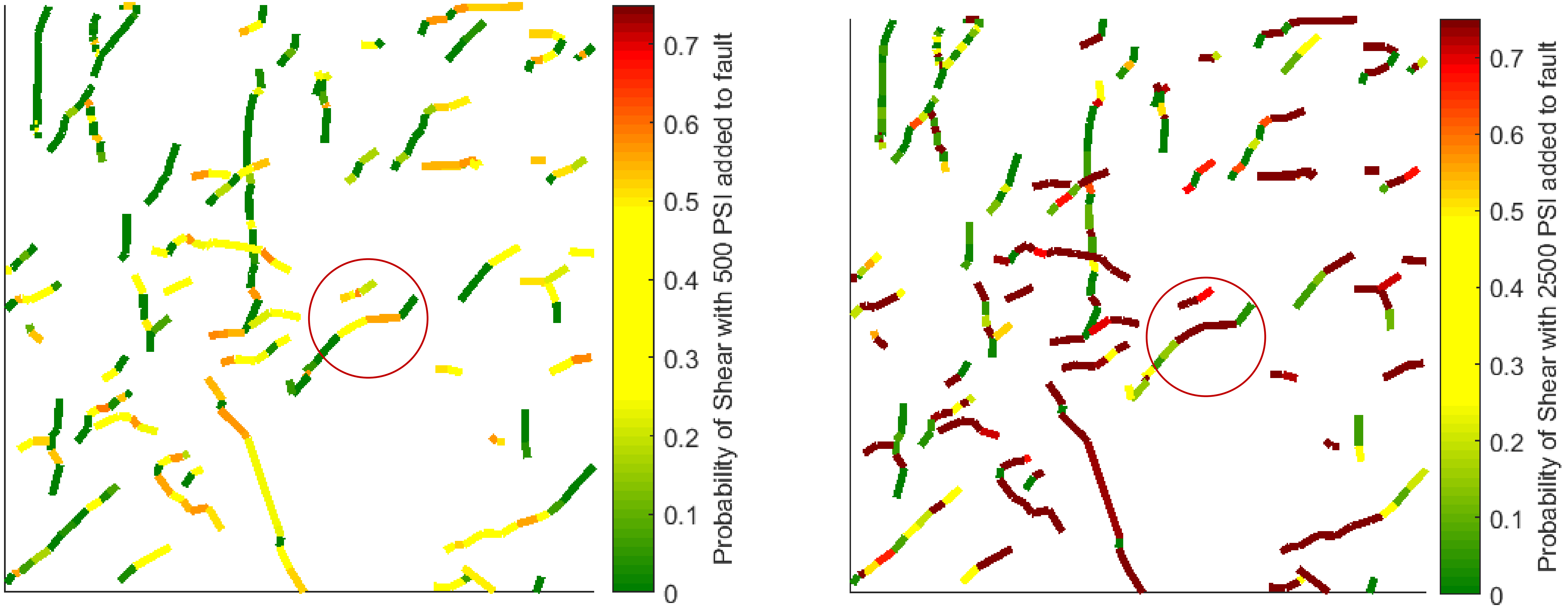
- Strike: N57° E
- Dip: 70 degrees
- Several magnitude 2+ events
- The casing deformation point is about 100m away from the fault.

Probability of Induced Fault Slip as a Function of the Increase in Pore Pressure During Hydraulic Fracturing



Faults Identified Using Ant Tracking of 3D Seismic Reflection Data

During Hydraulic Fracturing, Many Faults Could Potentially Slip In the Sichuan Basin



ΔP_P 500 psi

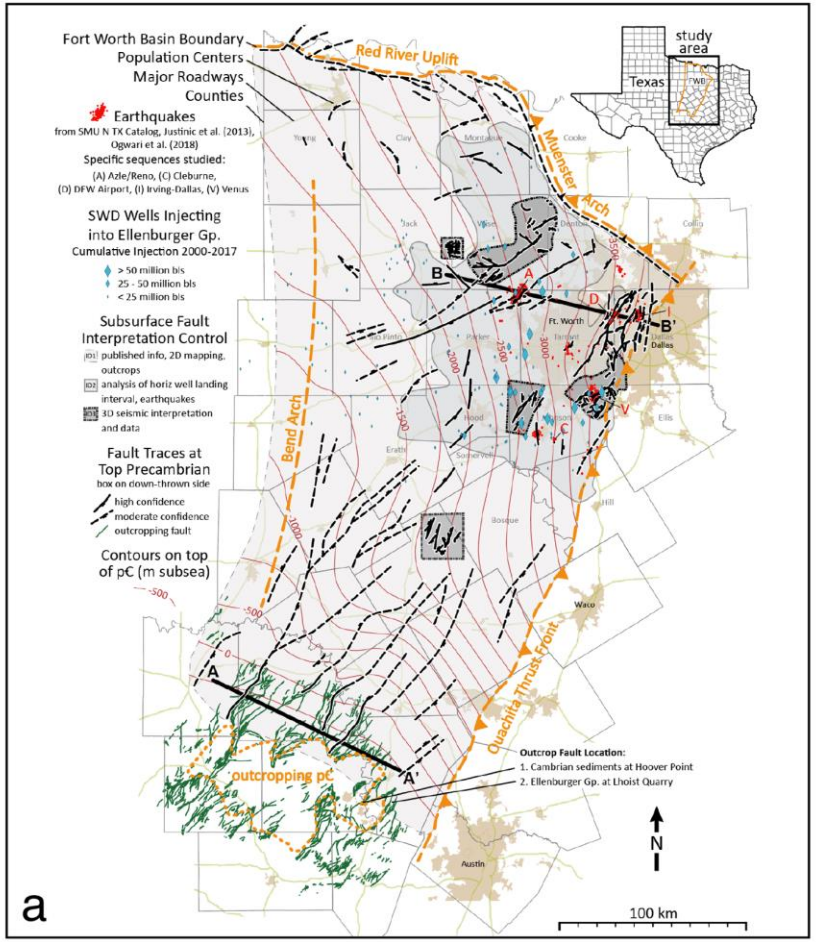
ΔP_P 2500 psi

FSP Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity

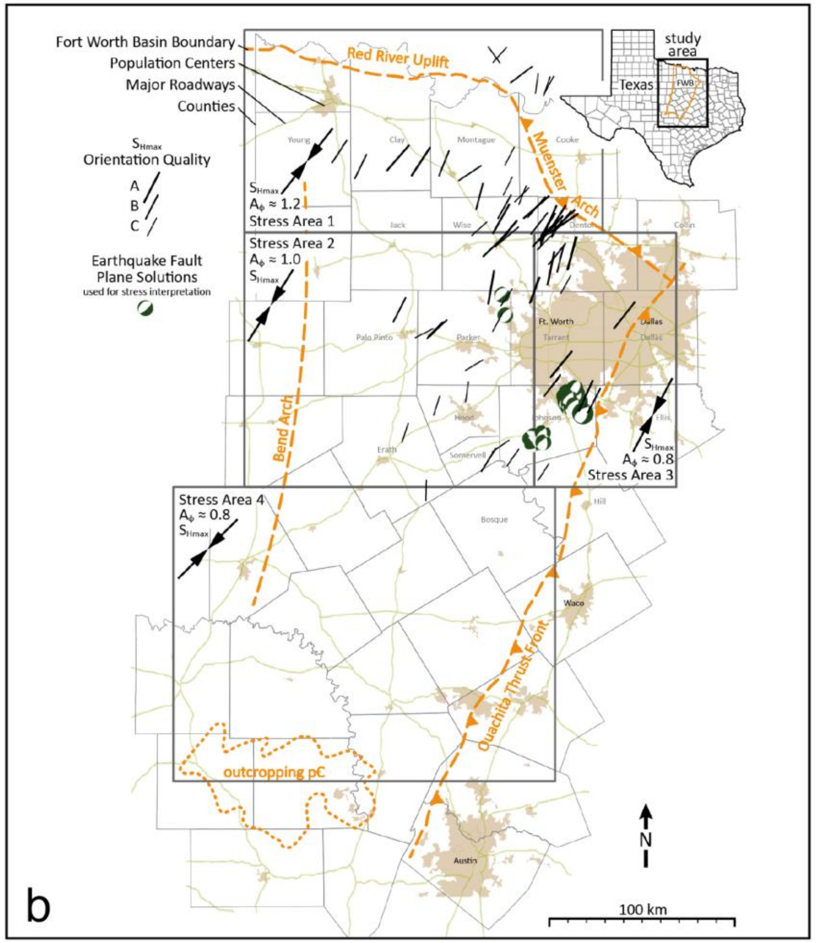
Application to the Fort Worth Basin

Fault Slip Potential
Stanford Center for Induced & Triggered Seismicity

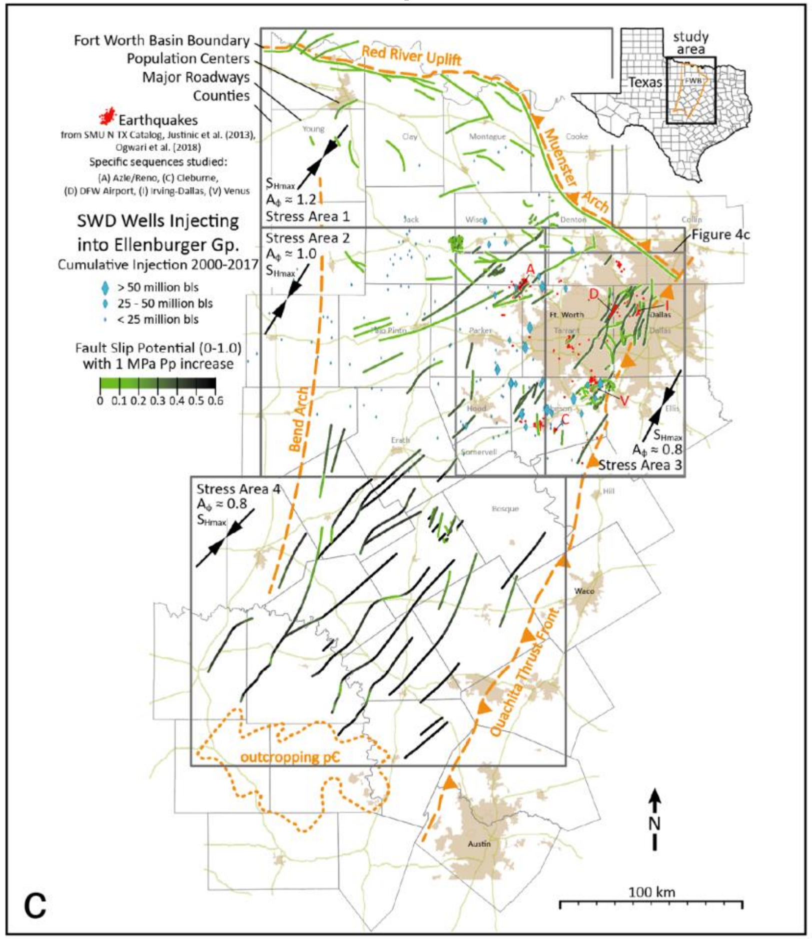
Faults



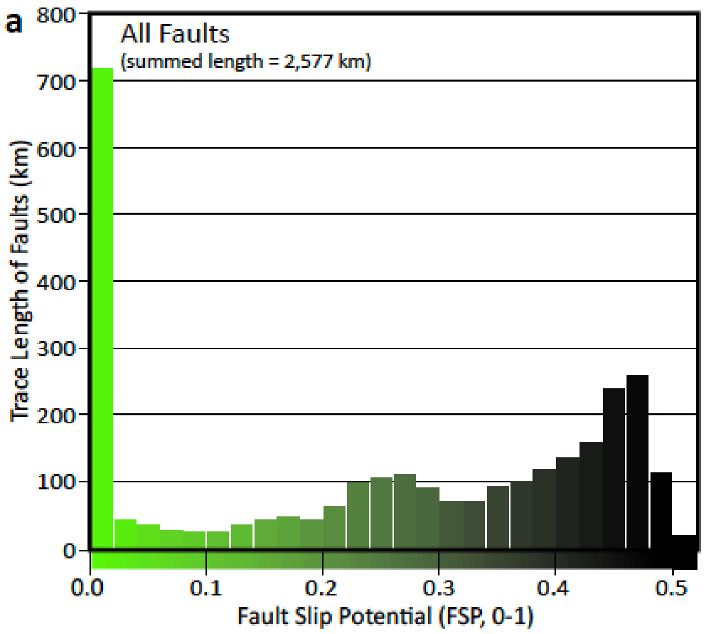
Stress



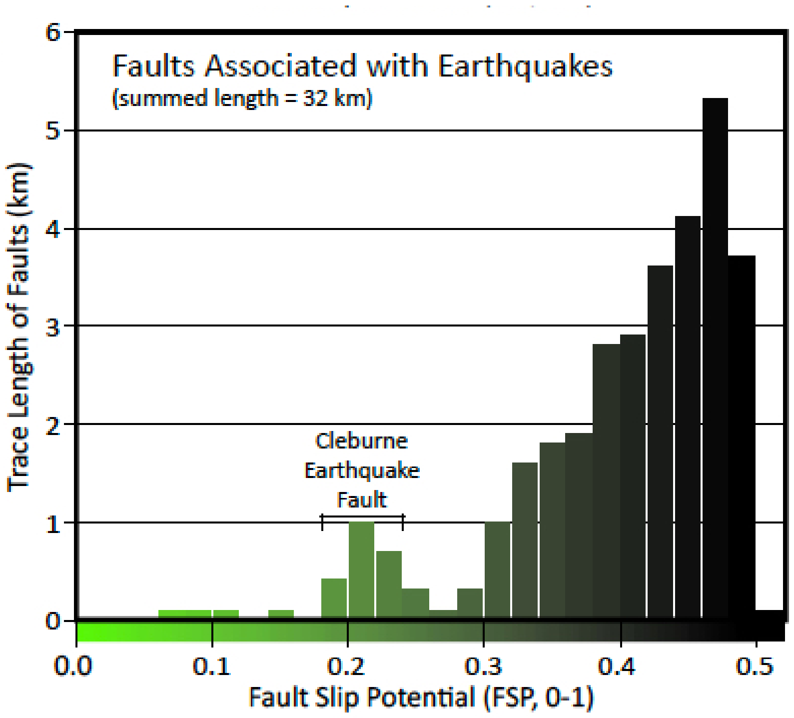
Fault Slip Potential

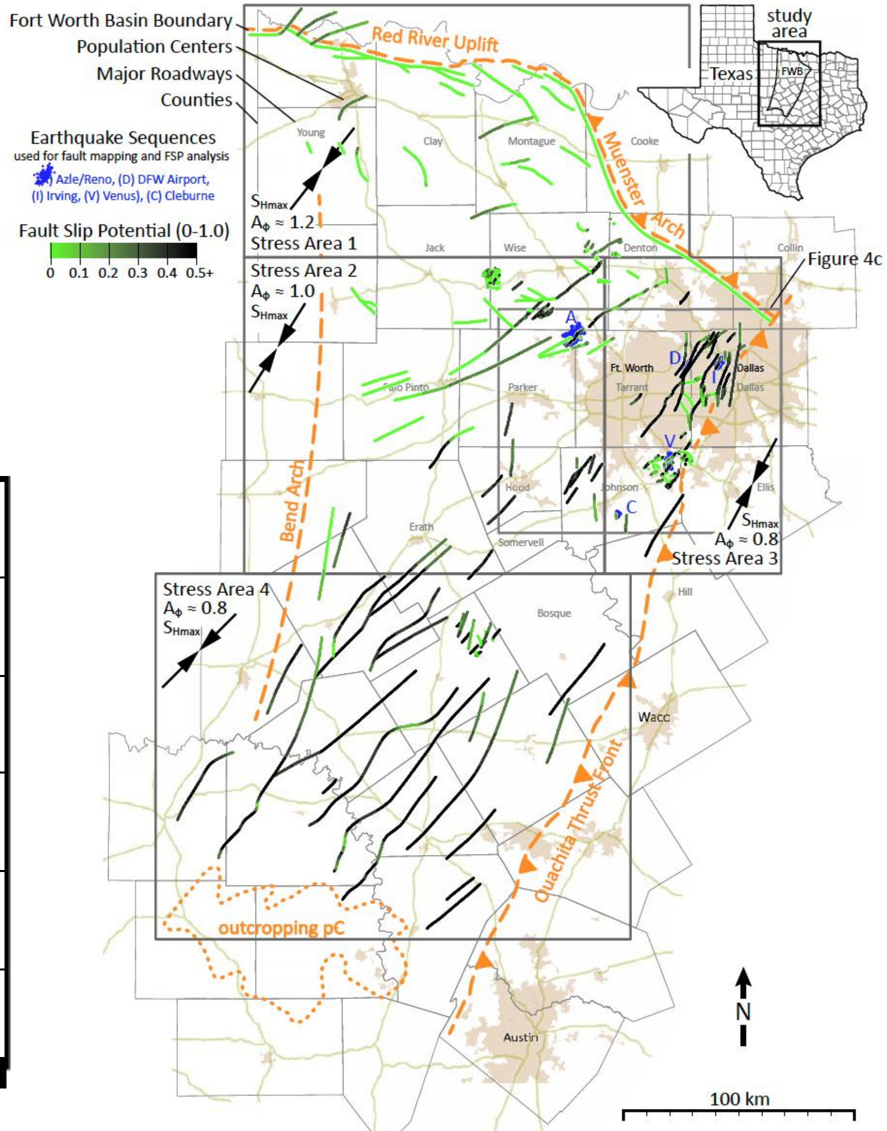


Hennings et al. (2019)



Calibration





Application

Hennings et al. (2019)

Topics – Massive Scale CCS *from a Geomechanical Perspective*

- The Need for Massive Scale for Carbon Storage
- Saline Aquifers and Induced Seismicity
  - Basal Aquifers and the Critically-Stressed Crust
    - Lessons from Induced Seismicity in Oklahoma
  - Lessons from Induced Seismicity in the Delaware Basin
- Depleted Oil and Gas Reservoirs and Induced Seismicity
  - How Poroelastic Stress Changes Limit Induced Seismicity
  - How Past Production has Depleted CCS Reservoirs (Not today)
- Progress to Date

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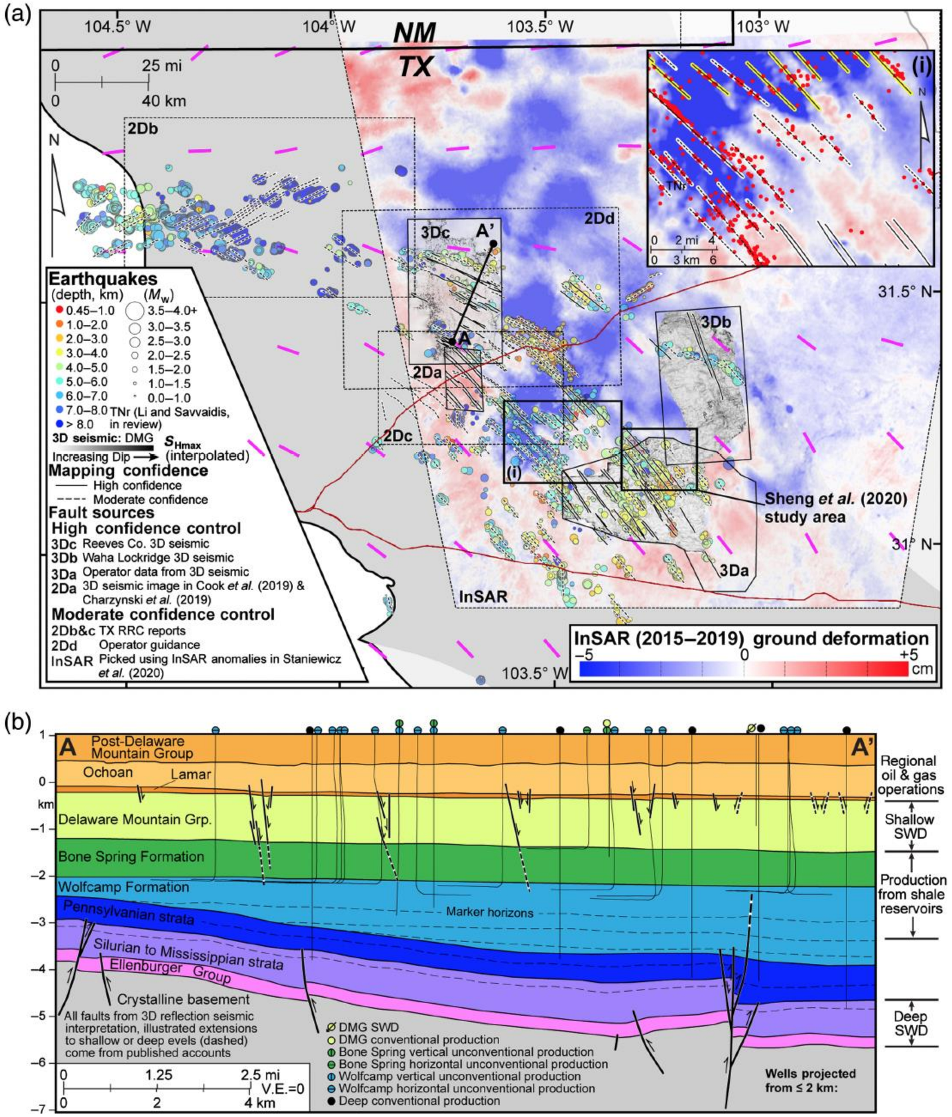
Manuscript accepted 18 April 2021

Prior oil and gas production can limit the occurrence of injection-induced seismicity: A case study in the Delaware Basin of western Texas and southeastern New Mexico, USA

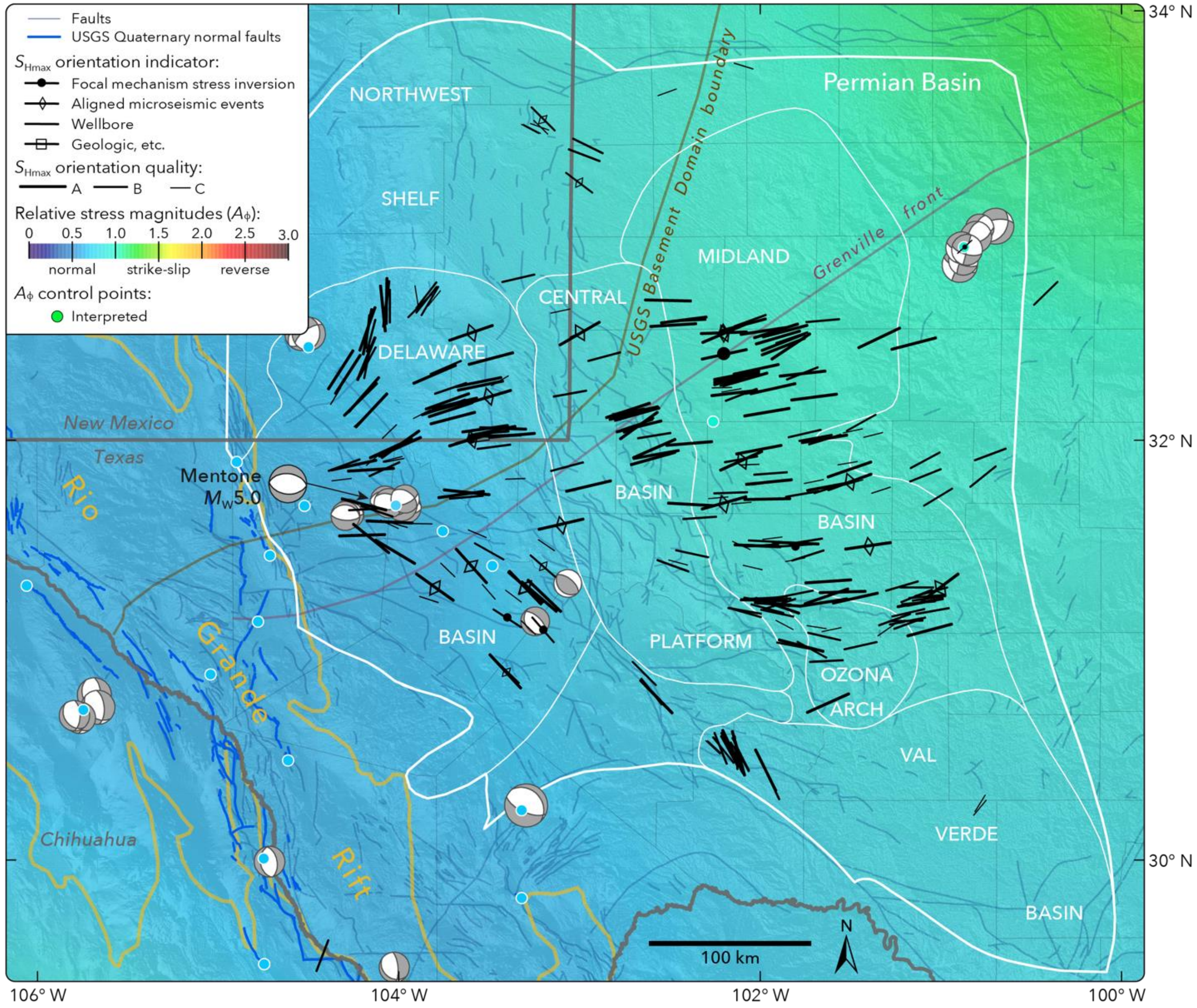
Noam Z. Dvory and Mark D. Zoback
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

In the Seismically Active Area the Delaware Mountain Group and Bone Spring are Saline Aquifers



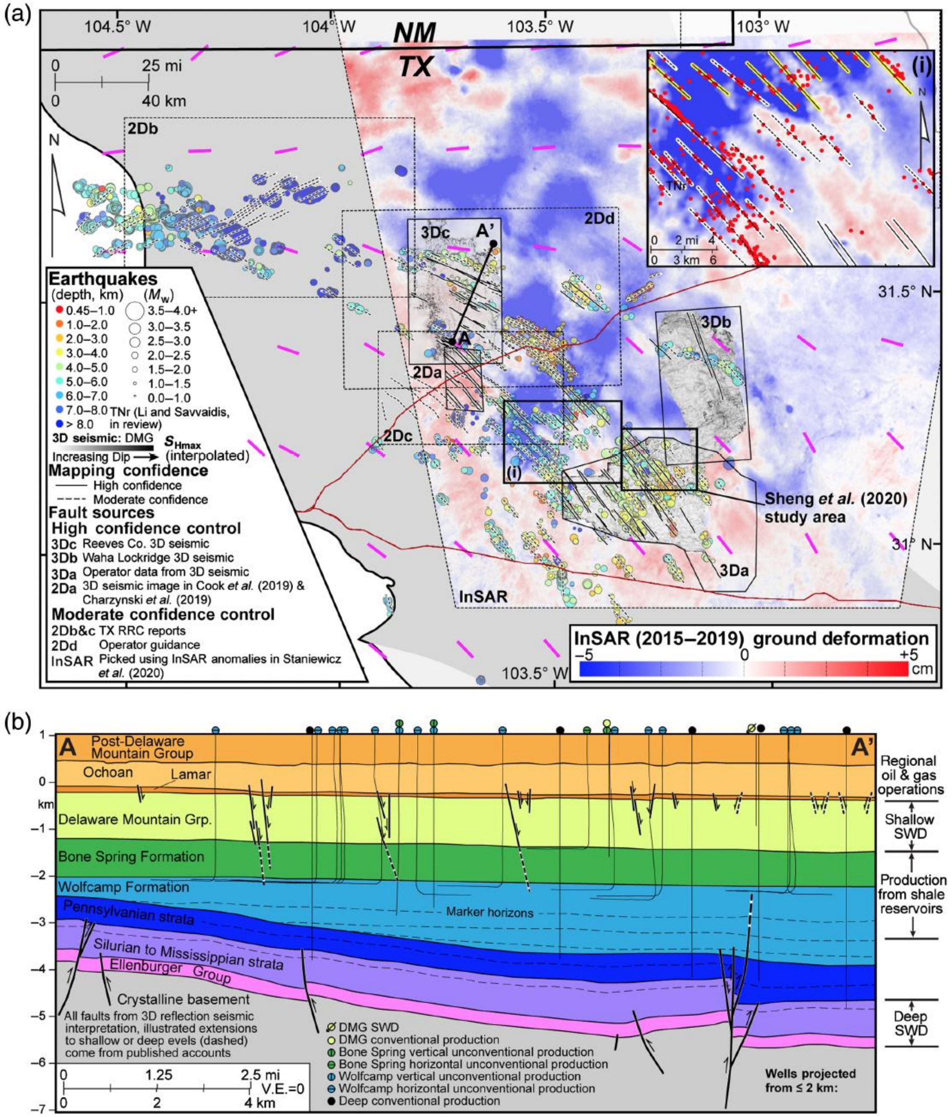
Fault mapping from Hennings et al. (2021)

State of Stress in the Permian Basin



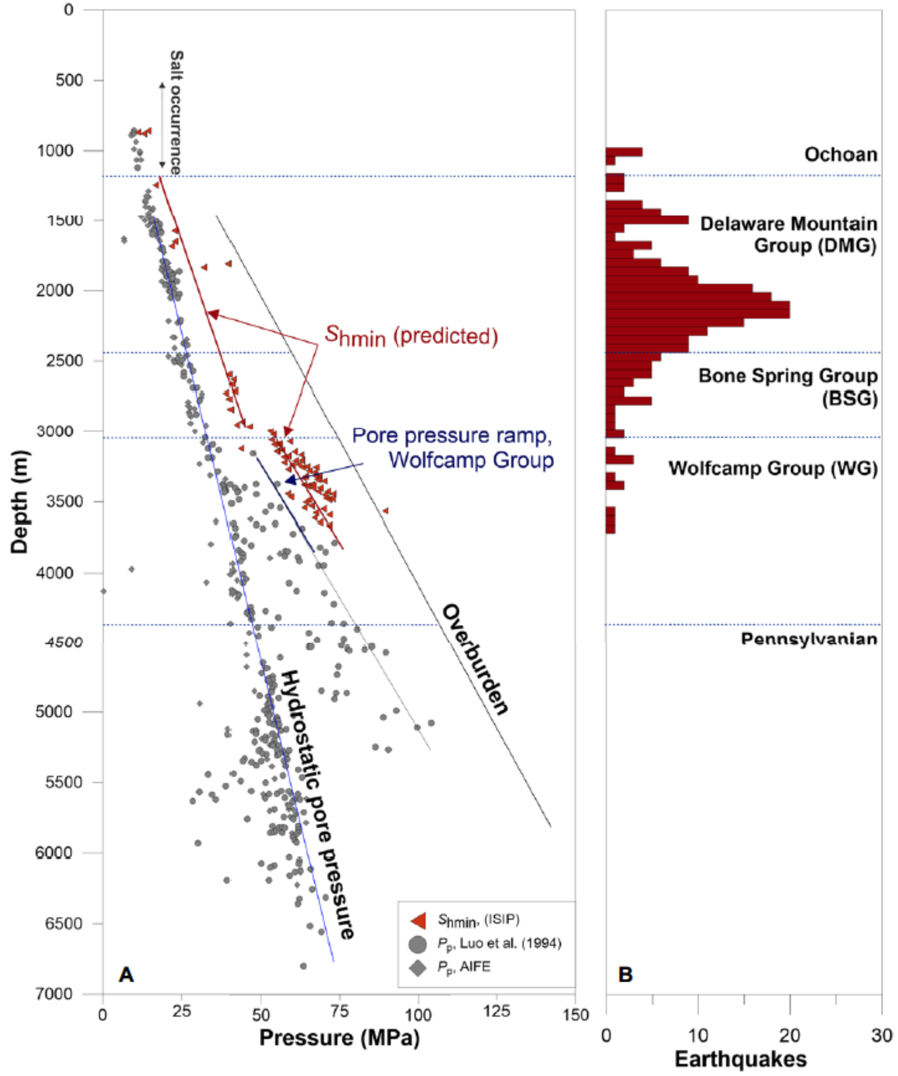
Stress data from Lund Snee and Zoback (2021)

In the Seismically Active Area the Delaware Mountain Group and Bone Spring are Saline Aquifers



Fault mapping from Hennings et al. (2021)

Pore Pressure is Hydrostatic and Normal Faults are in a State of Frictional Equilibrium



Dvory and Zoback (2021)

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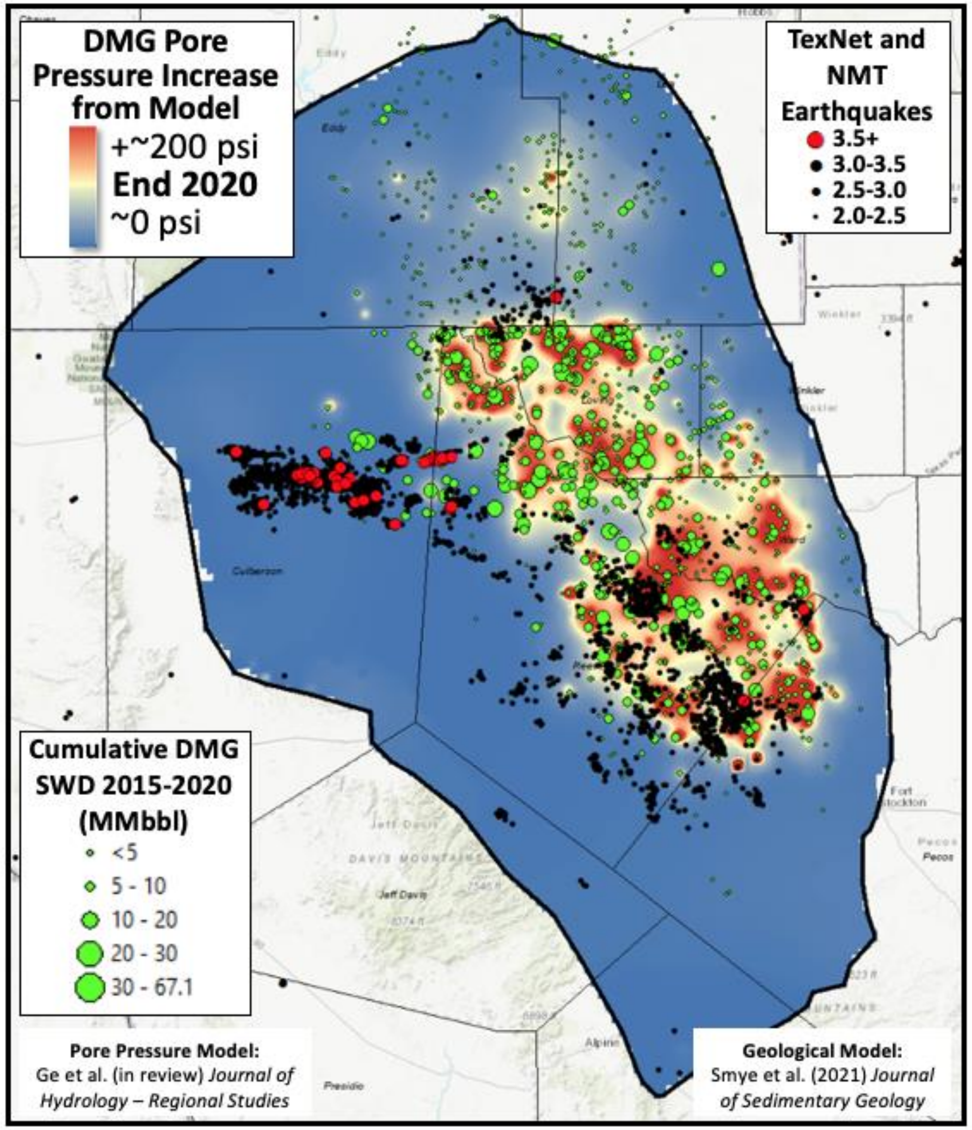
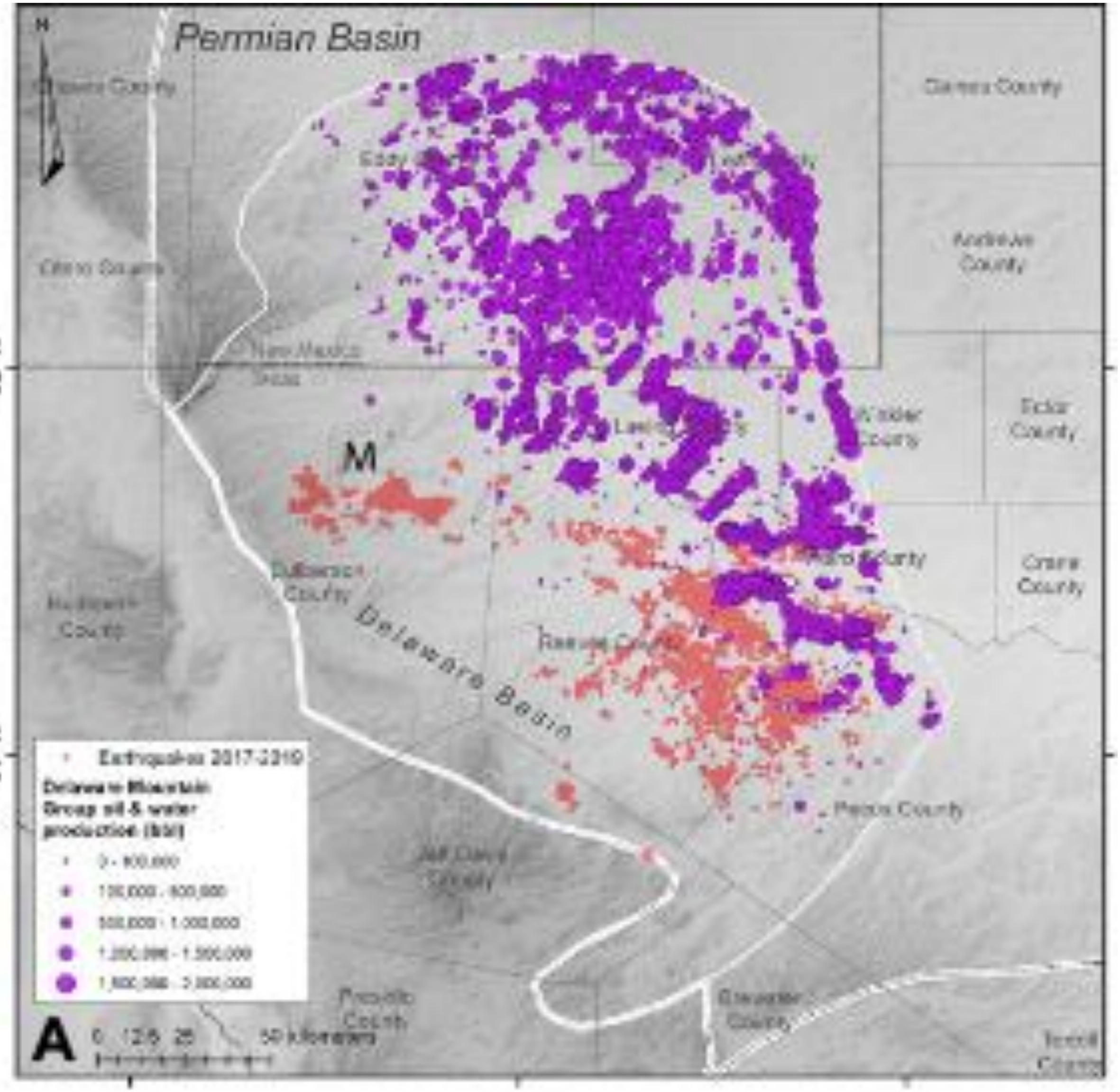
Shallow Seismicity in DMG Induced by Very Small Pressure Changes

No Shallow Seismicity Where There Has Been Previous DMG Production

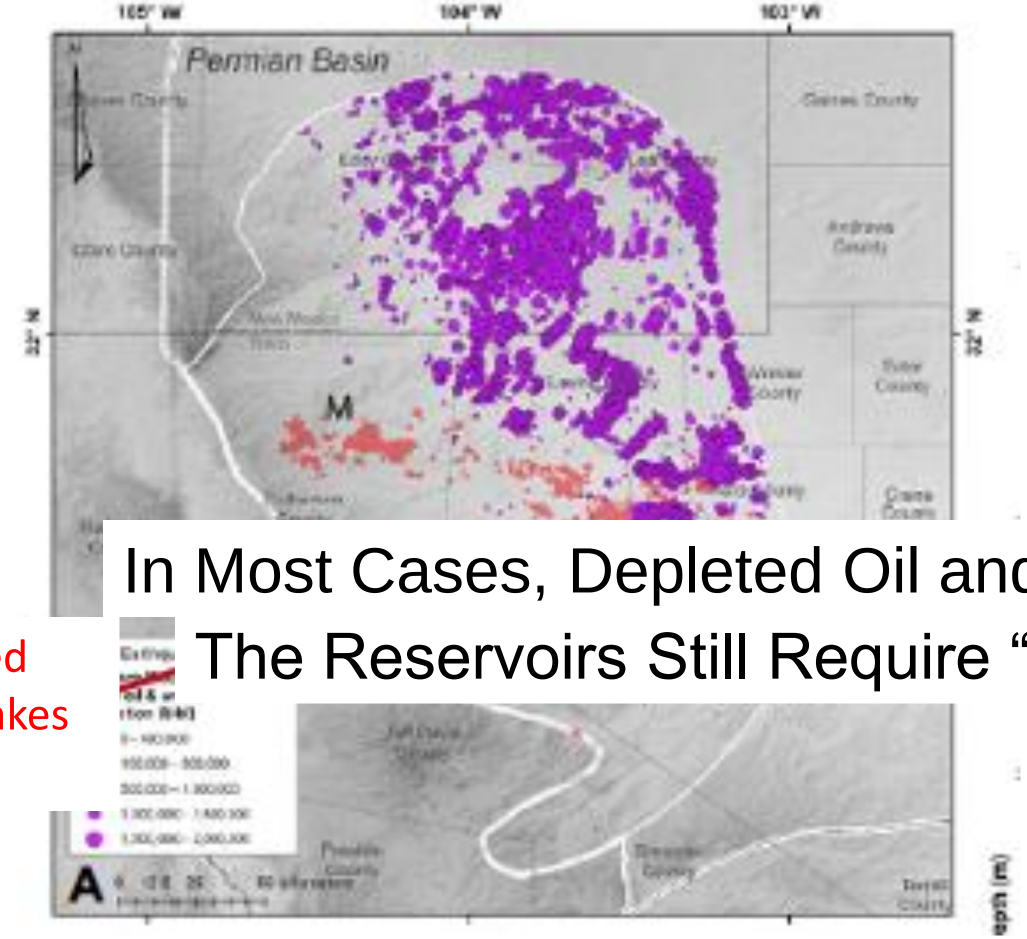




P. Hennings, pers. comm.

Dvory and Zoback (2021)

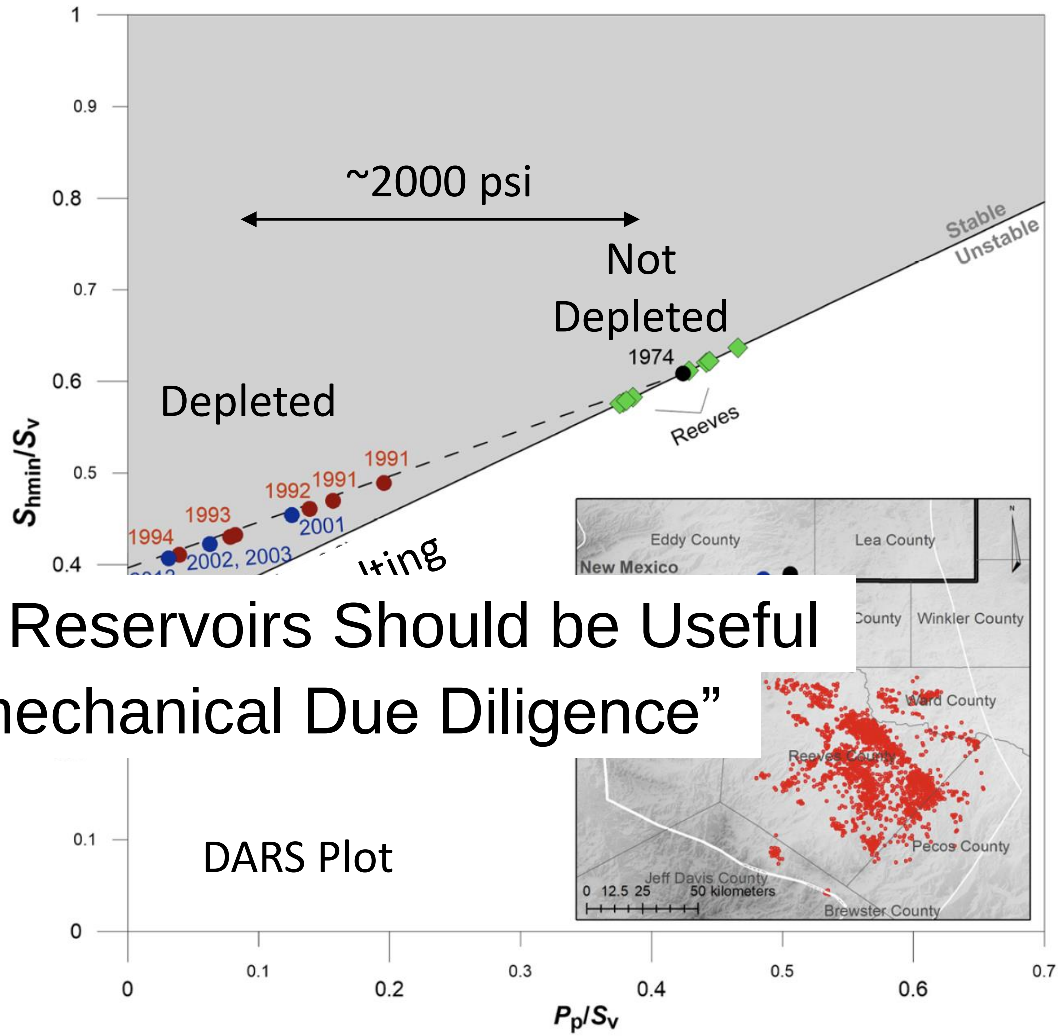
No Earthquakes are Not Being Triggered Where There Has Been Past Production



Induced Earthquakes

Delaware Mountain Group Production

Poroelastic Stress Path Associated with Depletion Makes Normal Faults More Stable



In Most Cases, Depleted Oil and Gas Reservoirs Should be Useful

The Reservoirs Still Require “Geomechanical Due Diligence”

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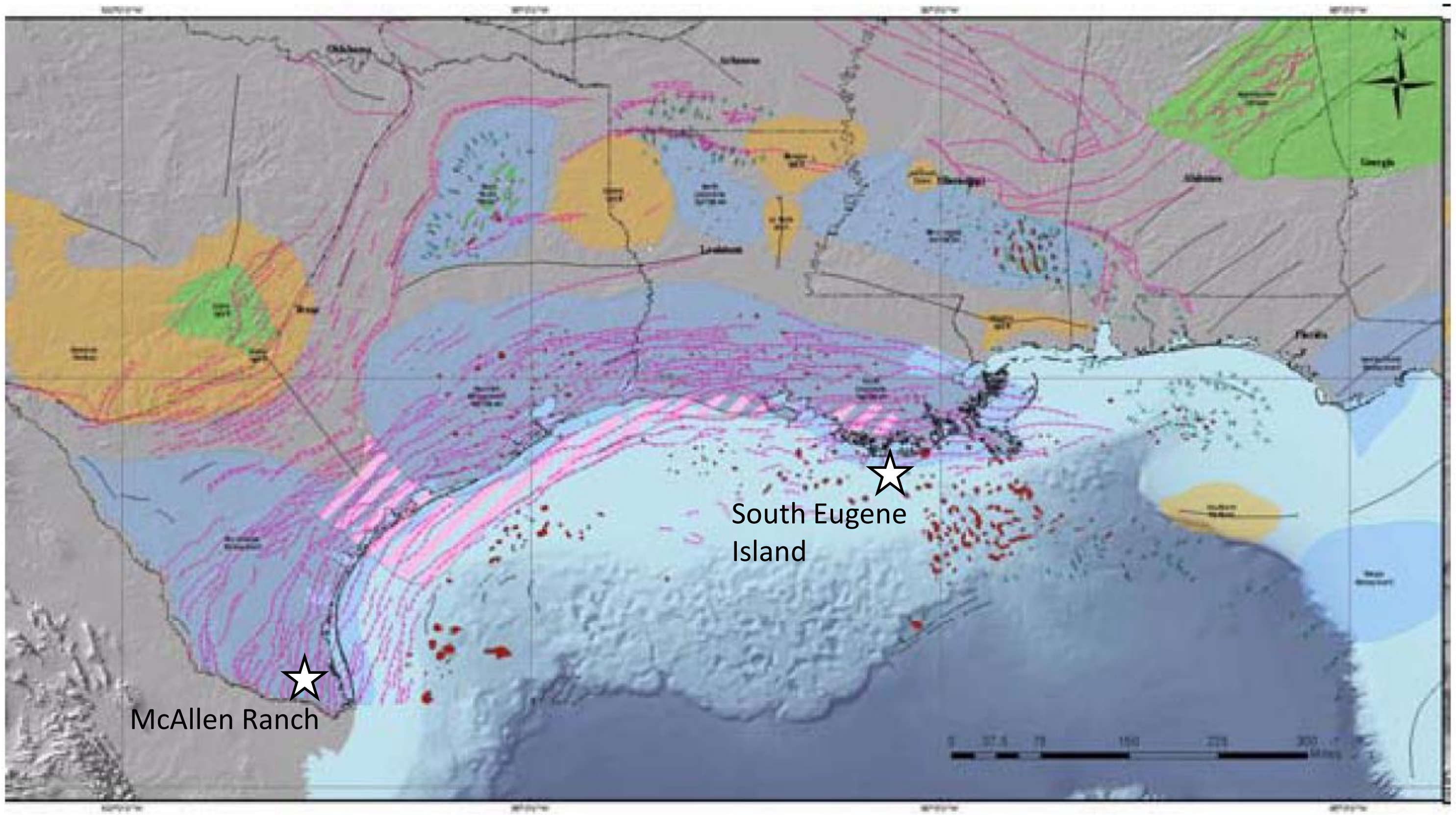
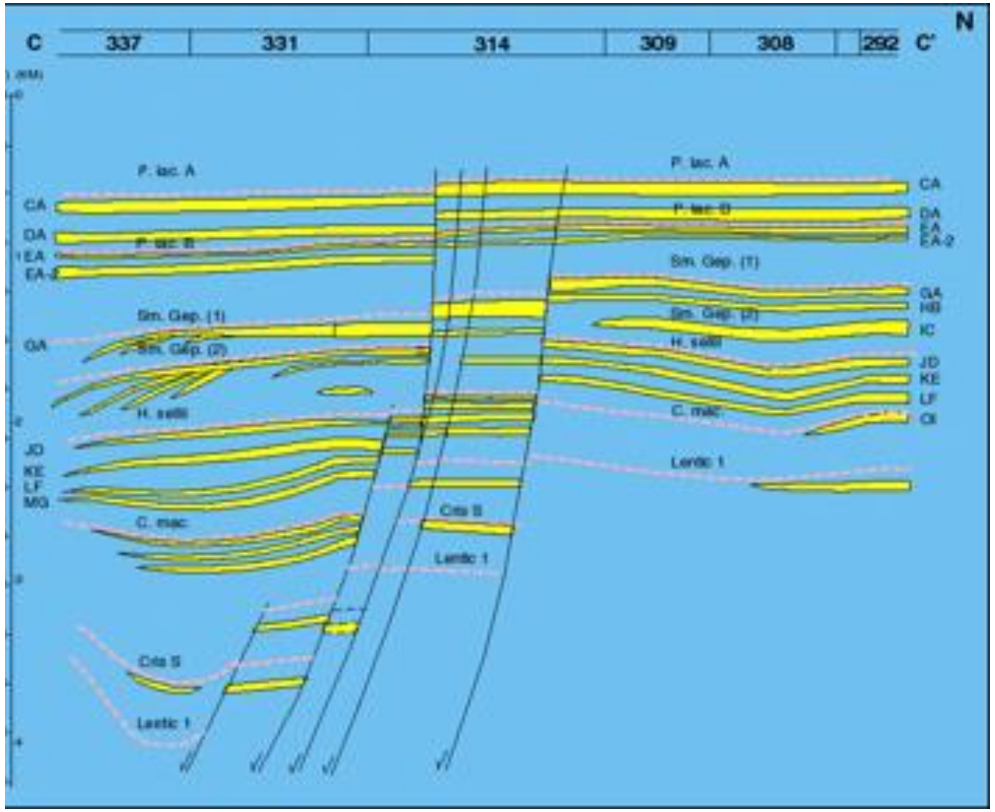
Weak Sands of the Gulf of Mexico

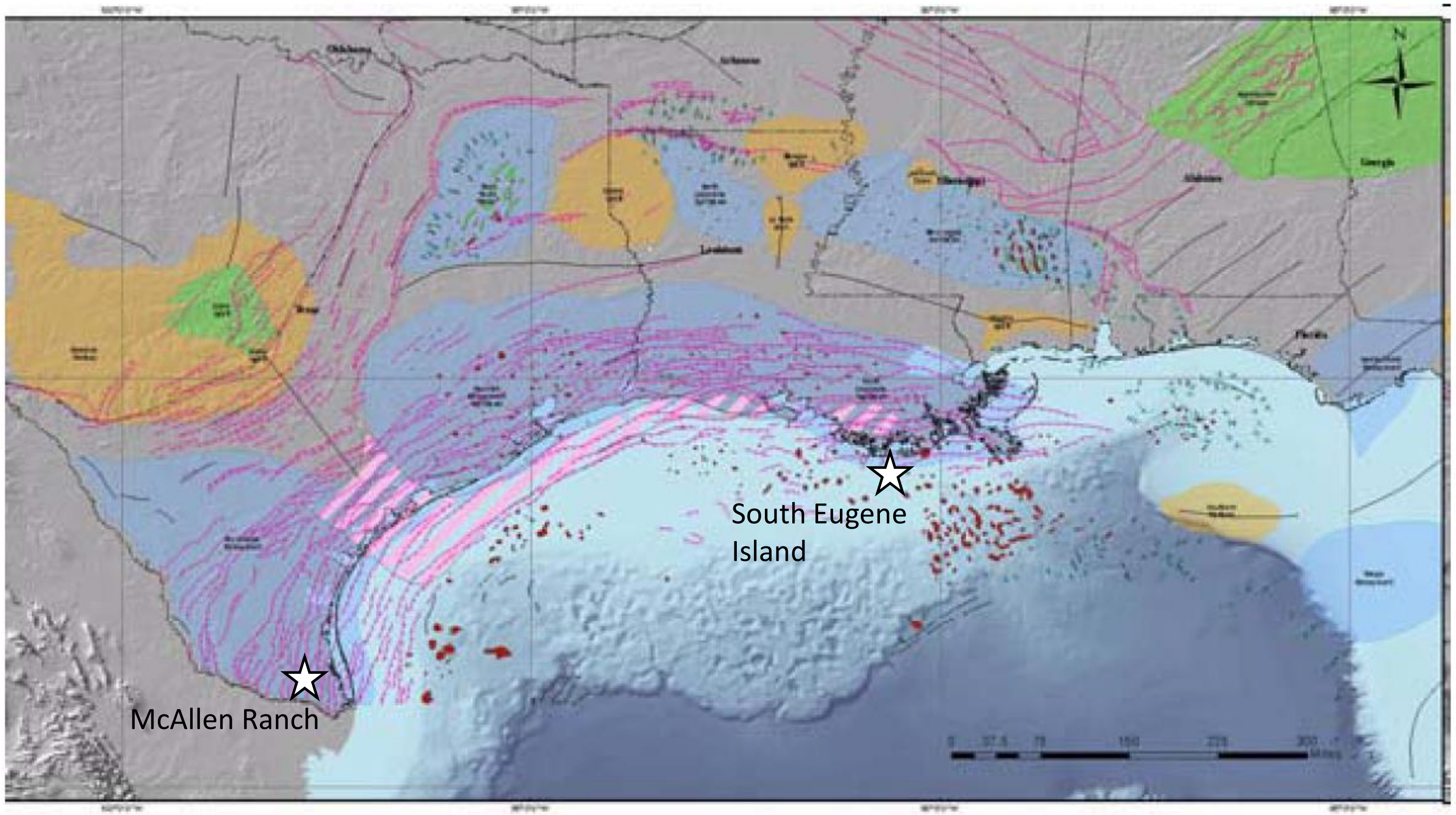


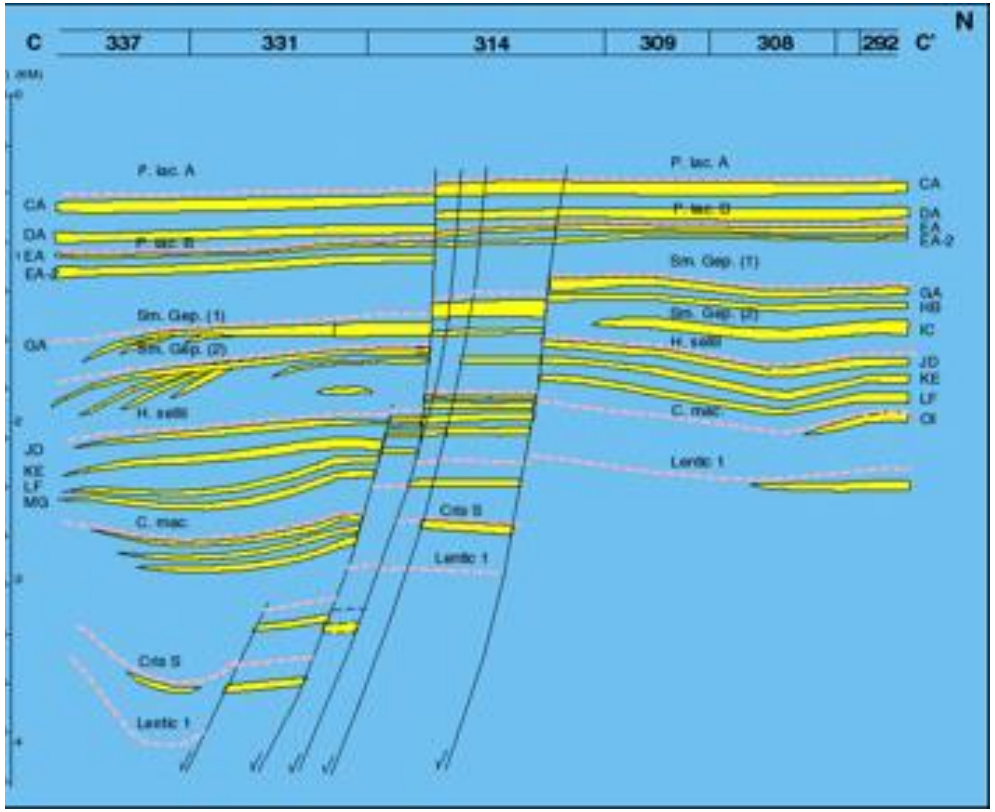


The Good News:

- Weakly-Cemented Sands are Not Likely to Produce Earthquakes
- Both Depleted Reservoirs and Saline Aquifers are Relatively Well Characterized

Weak Sands of the Gulf of Mexico





Requires Further Study:

- How Has Production Has Affected Depleted Oil and Gas Reservoirs?

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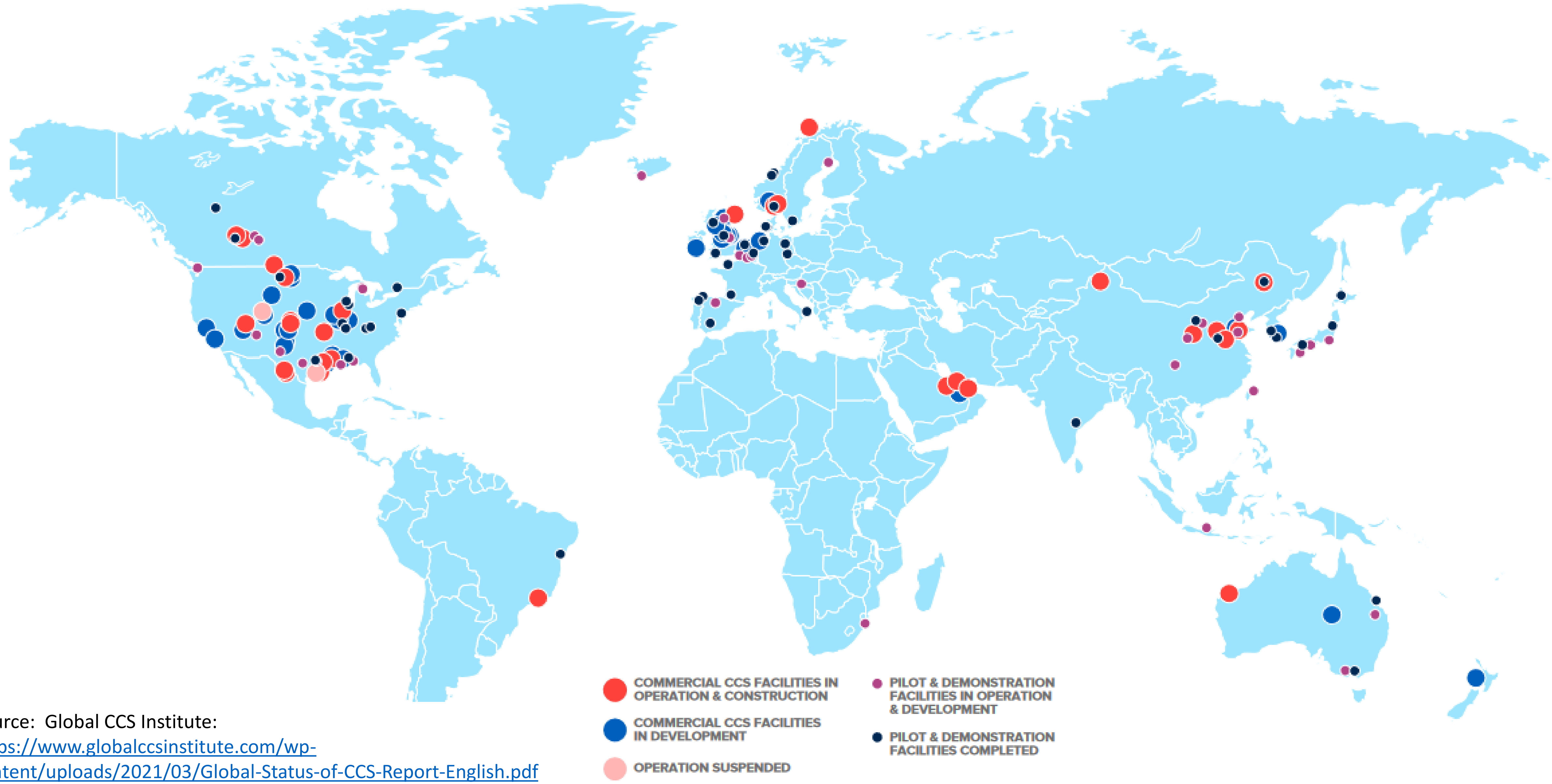
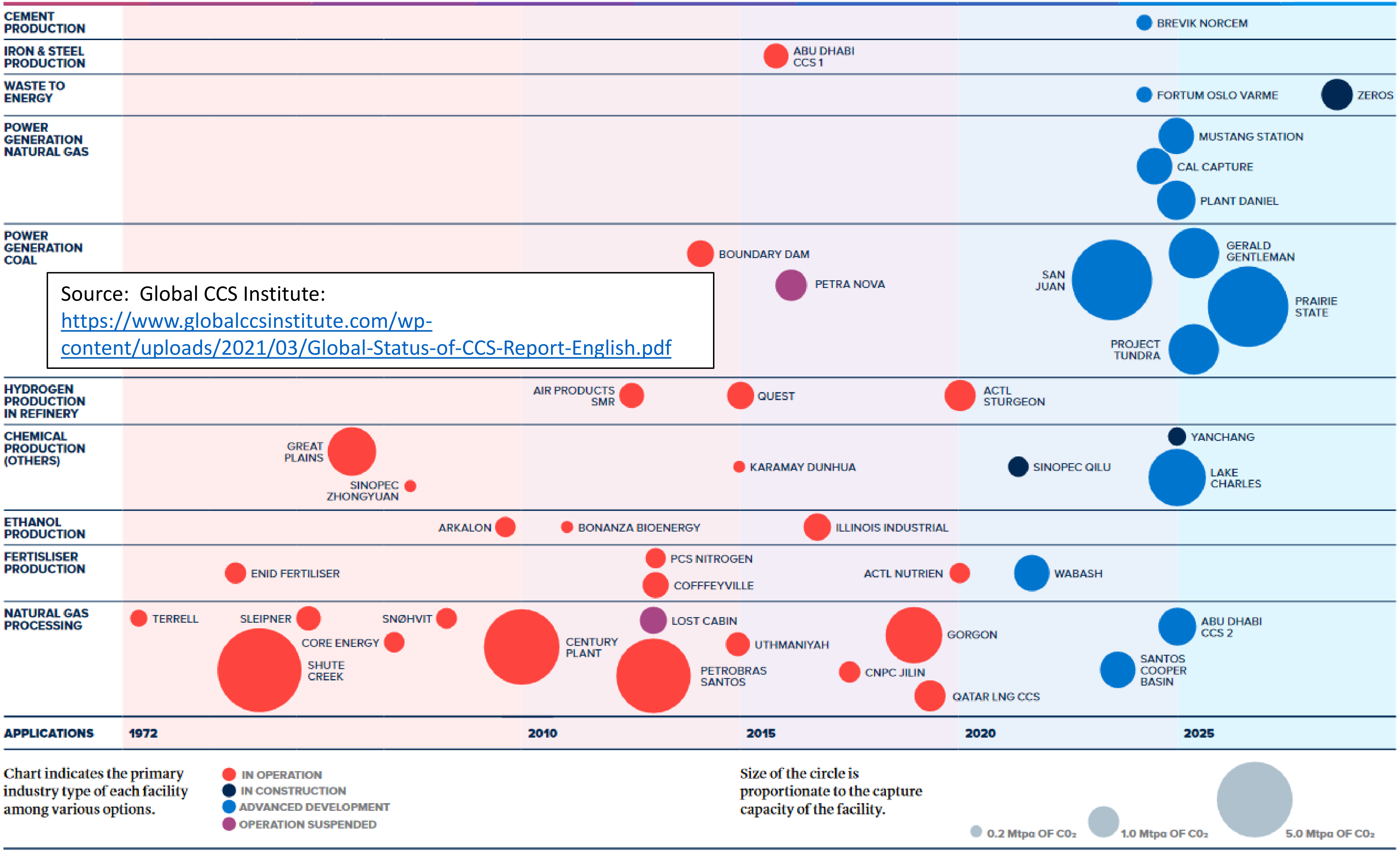
Global CCS Projects 2020



Source: Global CCS Institute: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf

Global CCS Projects 2020

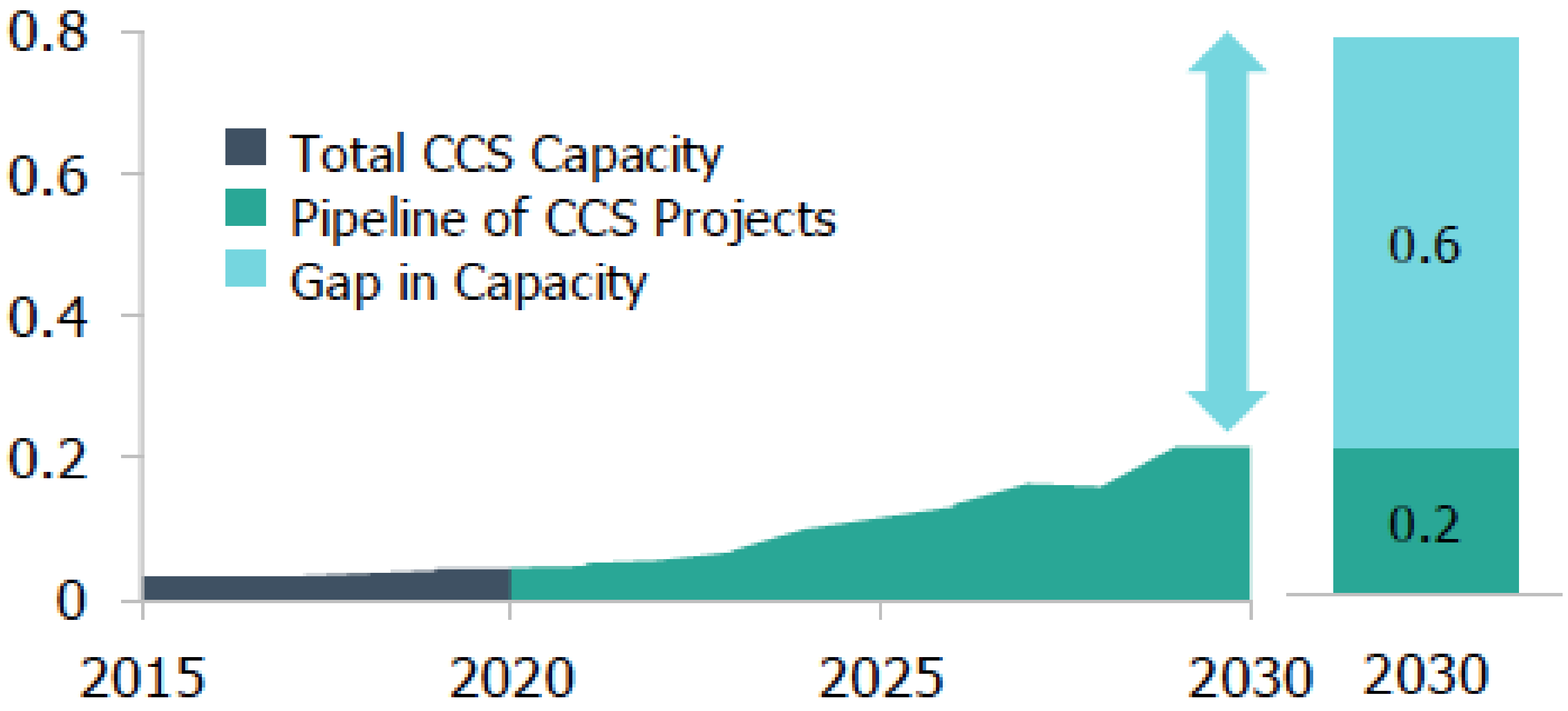


Source: Global CCS Institute: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf

If all these new planned projects go forward, the total injection capacity would increase by 175 $MtCO_2$/yr

Global Carbon Capture Capacity

GtCO₂ per year



There is a large gap (0.6 $GtCO_2$ per year) between industry targets and the capacity of CCS projects currently being planned.

<u>70-100 new projects must be commissioned annually</u> to achieve the necessary rate of growth.

Topics – Massive Scale CCS *from a Geomechanical Perspective*

Over the Next Decade, if You Remember Nothing Else

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Topics – Massive Scale CCS *from a Geomechanical Perspective*

Over the Next Decade, if You Remember Nothing Else

- The Need for Massive Scale for Carbon Storage
- Saline Aquifers and Induced Seismicity ← Don't Do This !
  - Basal Aquifers and the Critically-Stressed Crust
    - Lessons from Induced Seismicity in Oklahoma
  - Lessons from Induced Seismicity in the Delaware Basin
- Depleted Oil and Gas Reservoirs and Induced Seismicity ← Do This !
  - How Poroelastic Stress Changes Limit Induced Seismicity
  - How Past Production has Depleted CCS Reservoirs (Not today)
- Progress to Date

Thank you