

Geomechanical Challenges Associated with Massive Storage of CO₂

Mark D. Zoback

Benjamin M. Page Professor of Geophysics

Stanford University

zoback@stanford.edu



SPE Webinar
December 3, 2021



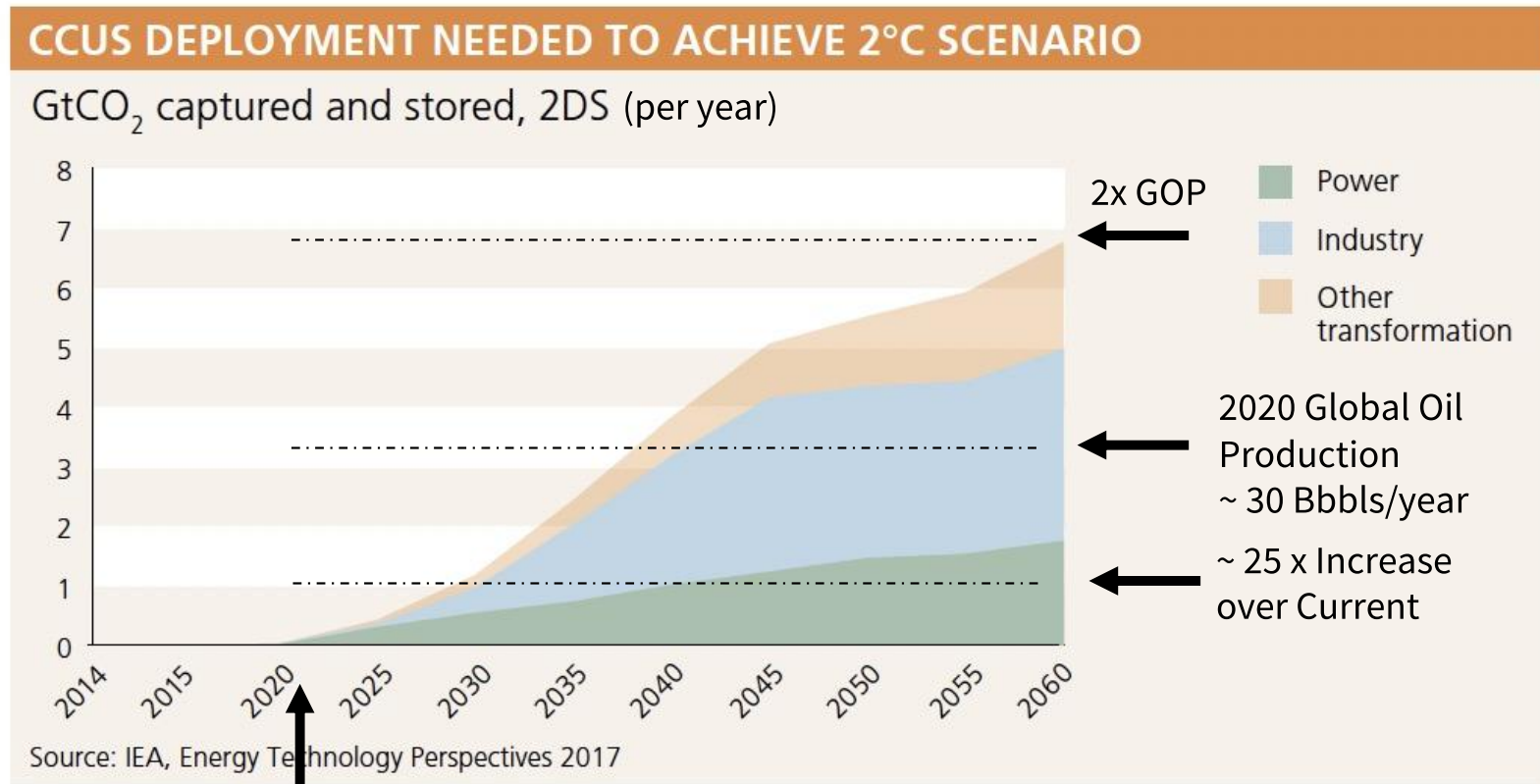
Topics – Massive Scale CCS *from a Geomechanical Perspective*

- The Need for Massive Scale for Carbon Storage
- Saline Aquifers
 - Basal Aquifers and the Critically-Stressed Crust
 - Lessons from Induced Seismicity in Oklahoma
 - Geomechanical Characterization
 - Lessons from Induced Seismicity in the Delaware Basin
- Depleted Oil and Gas Reservoirs
 - How Poroelastic Stress Changes Limit Induced Seismicity
 - How Past Production has Affected Potential CCS Reservoirs
- Progress to Date

Massive Scale CCS?

- Achieving the International Energy Agency's (IEA) Sustainable Development Scenario will require 6 Gt CO₂ 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 CO₂ per year by 2030.
- Today's carbon sequestration industry must grow by 50 times. ~20 Mt per year of anthropogenic CO₂ 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

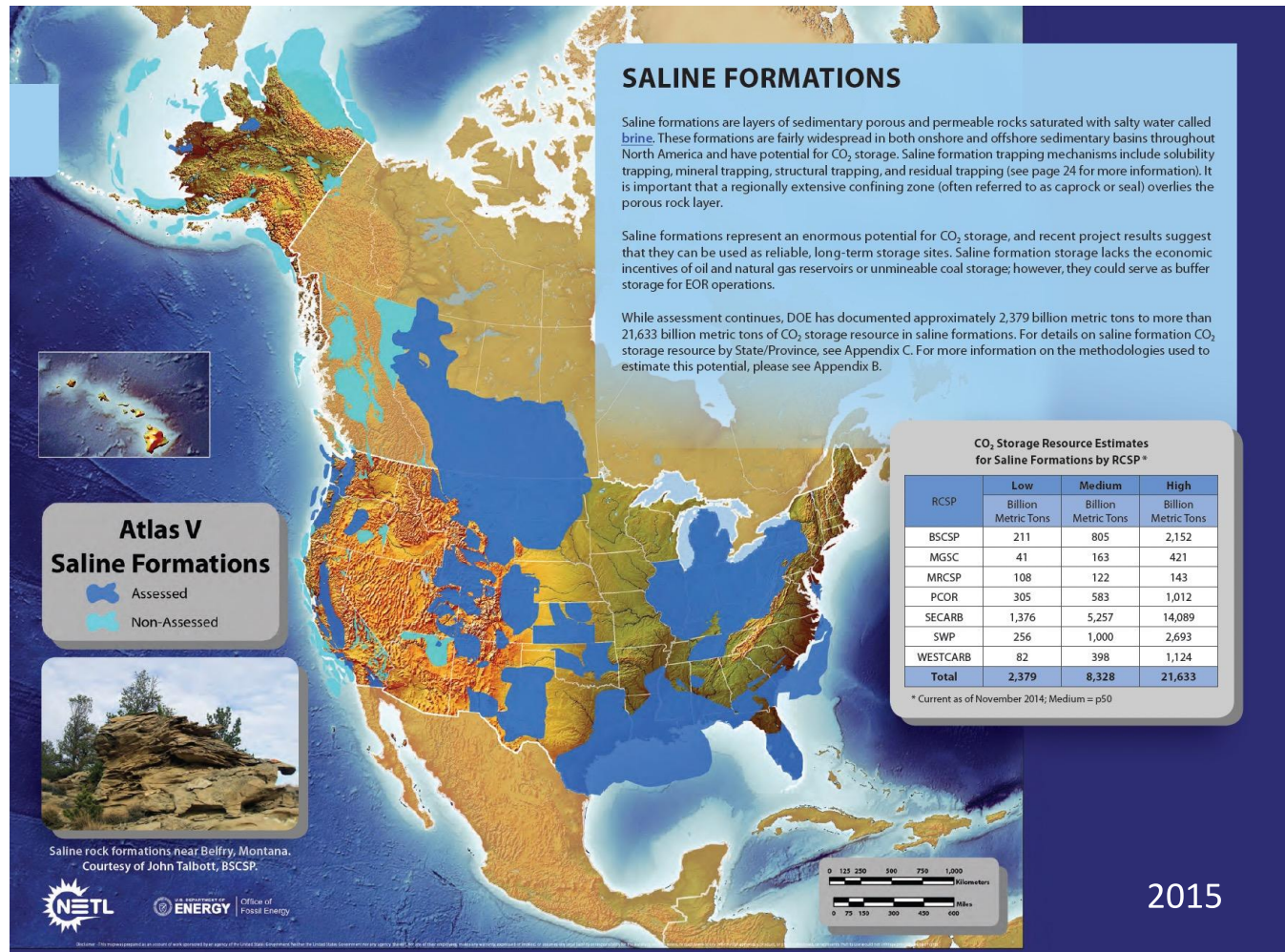


Current CCS - ~40 Mt CO₂/year (50% is anthropogenic)

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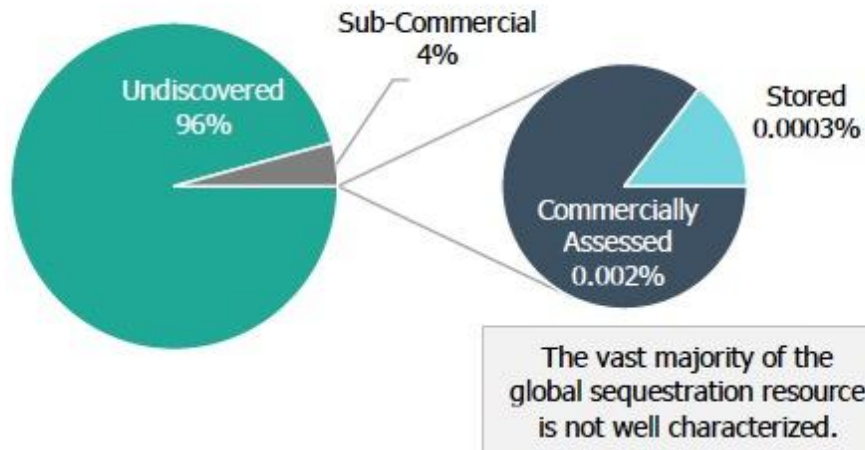
Volumetric Assessments of Saline Aquifer Storage (Theoretically Available Pore Space)



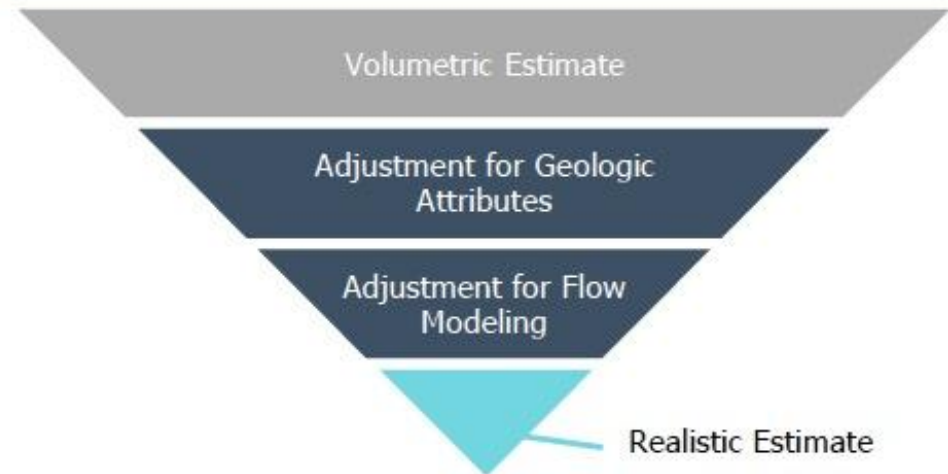
Mid-range est.
8328 GT tonnes

Realistically Assessing Capacity

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



Illustrative Sequestration Resource Volume Volumetric Estimate vs. Realistic Estimate

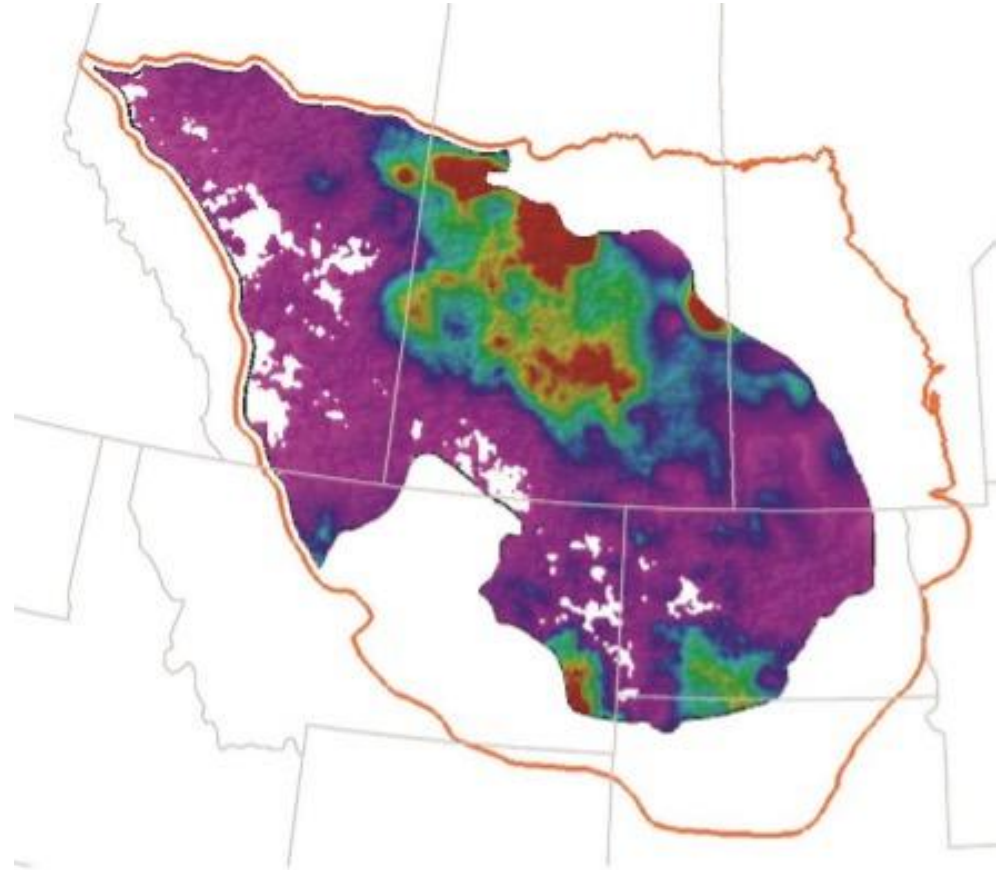


Basal Saline Aquifers

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

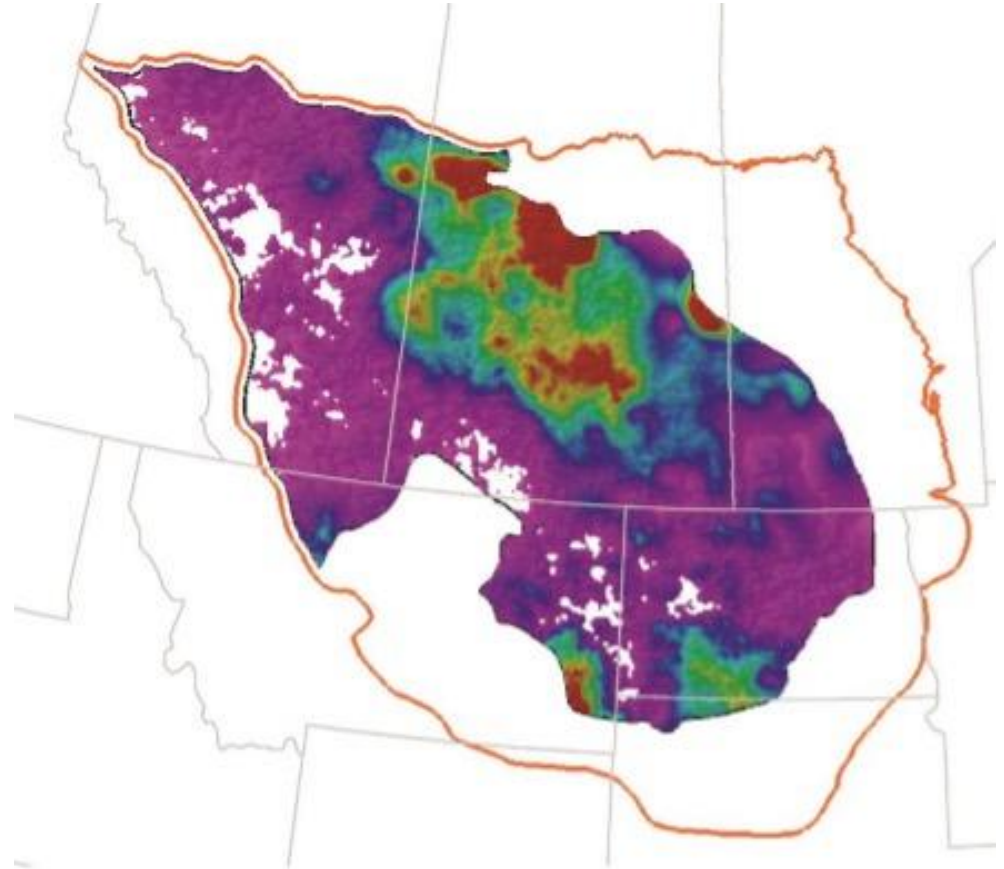


Basal Saline Aquifers

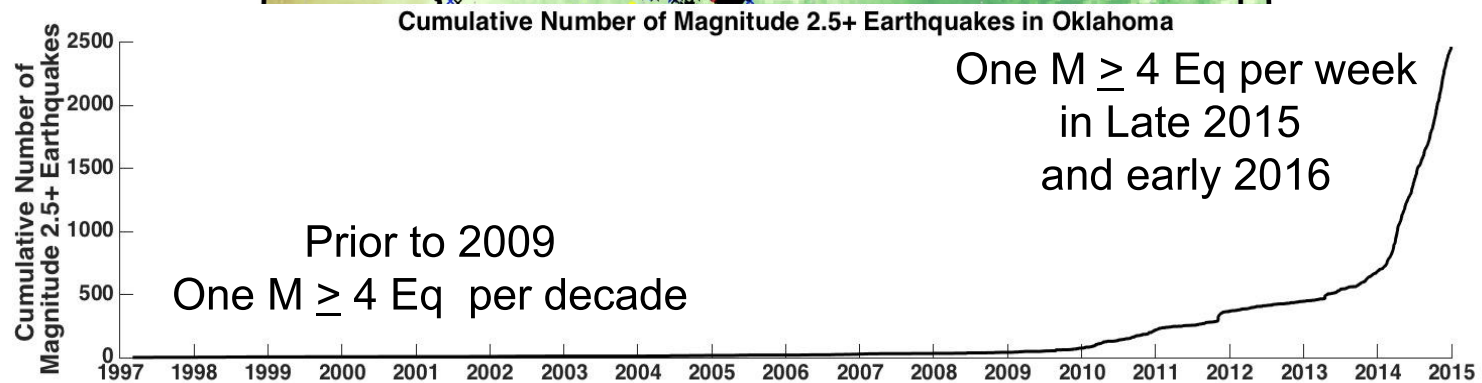
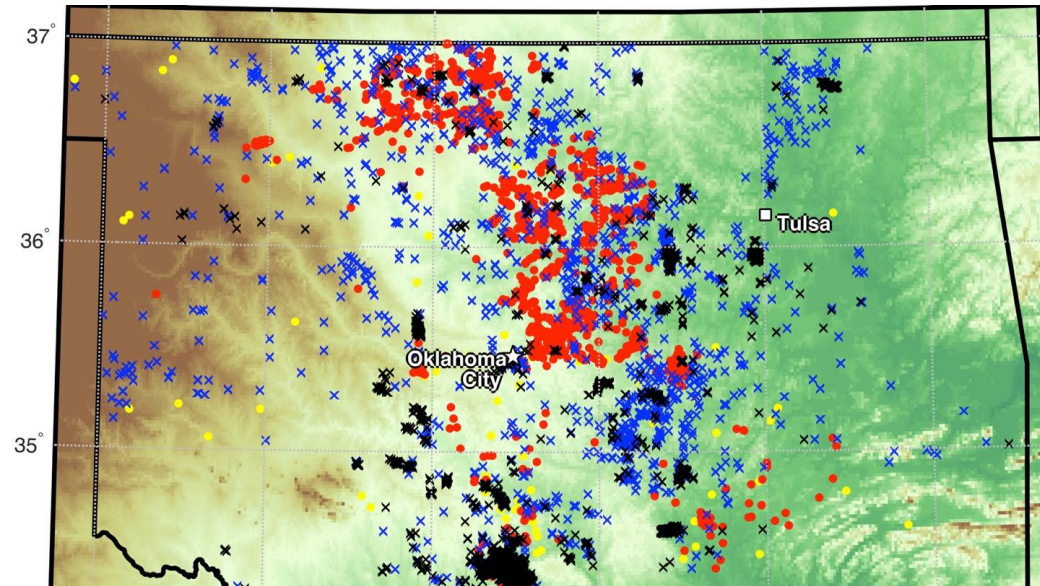
OGCI assessment of the Great Plains
Basal Cambrian Sandstone storage
resource

- 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

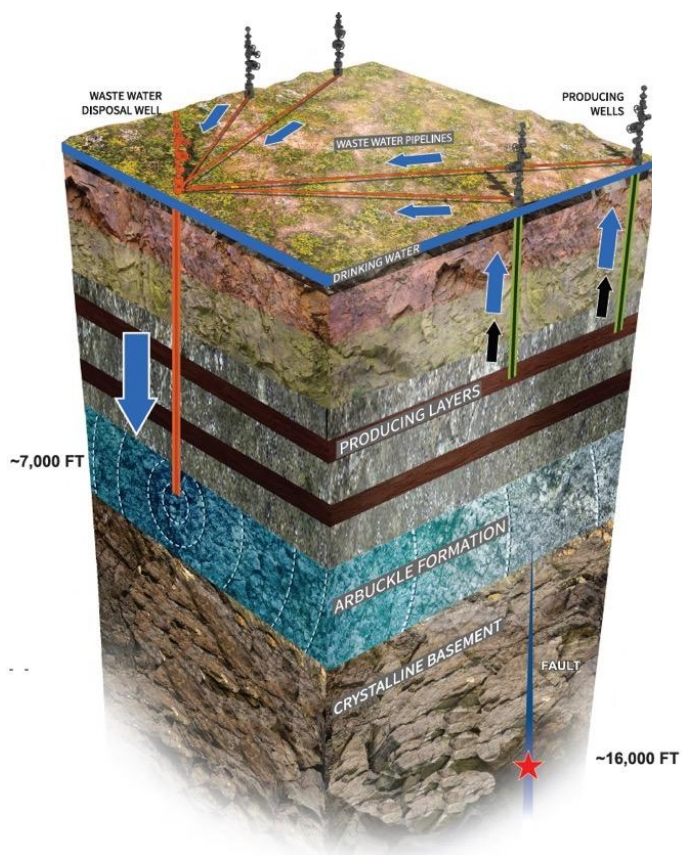
* EERC report 2015-EERC-02-14



Is Injection into Basal Formations Viable? Triggered Earthquakes in Oklahoma

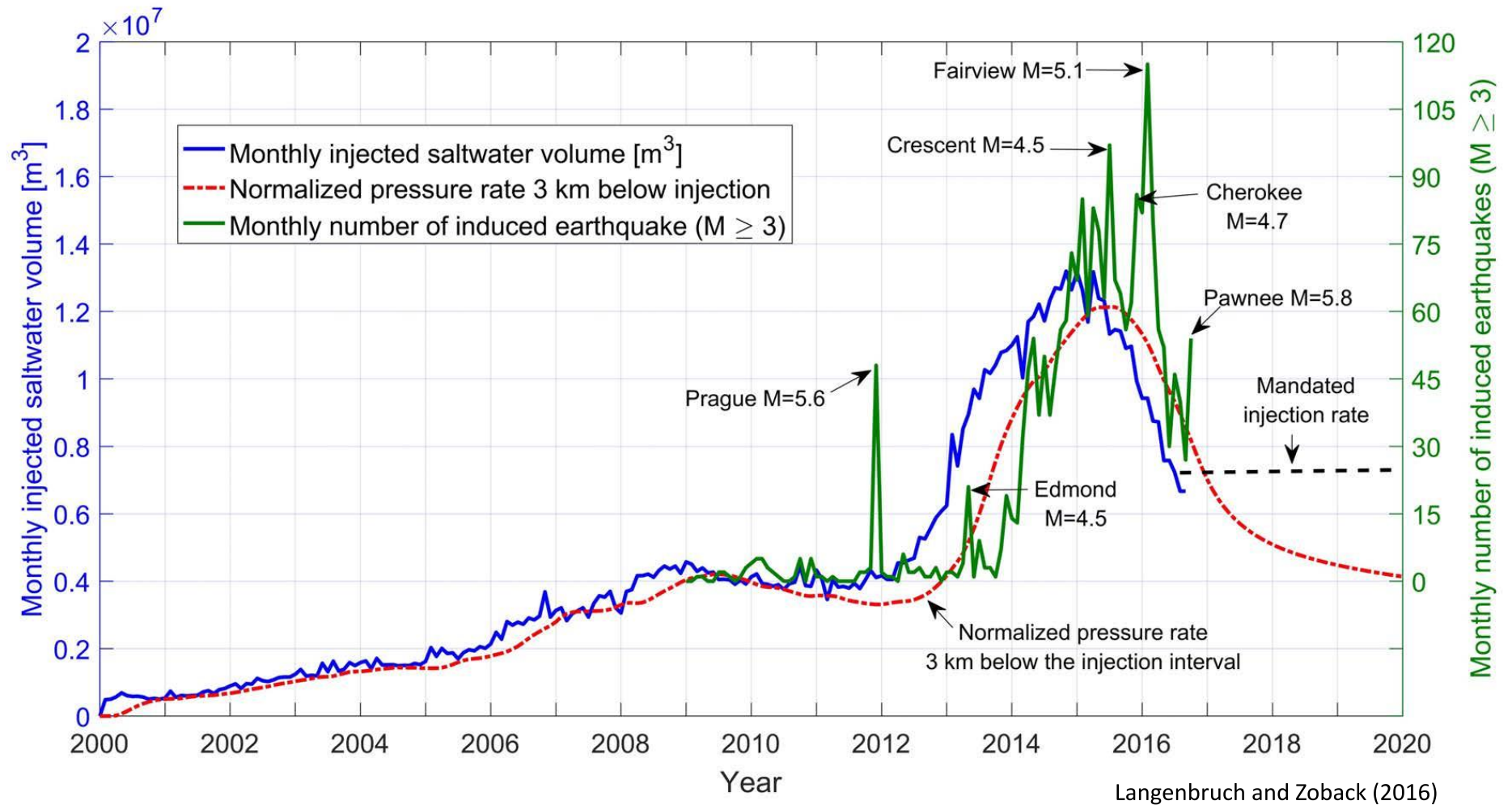


Produced Water Disposal is Triggering Earthquakes

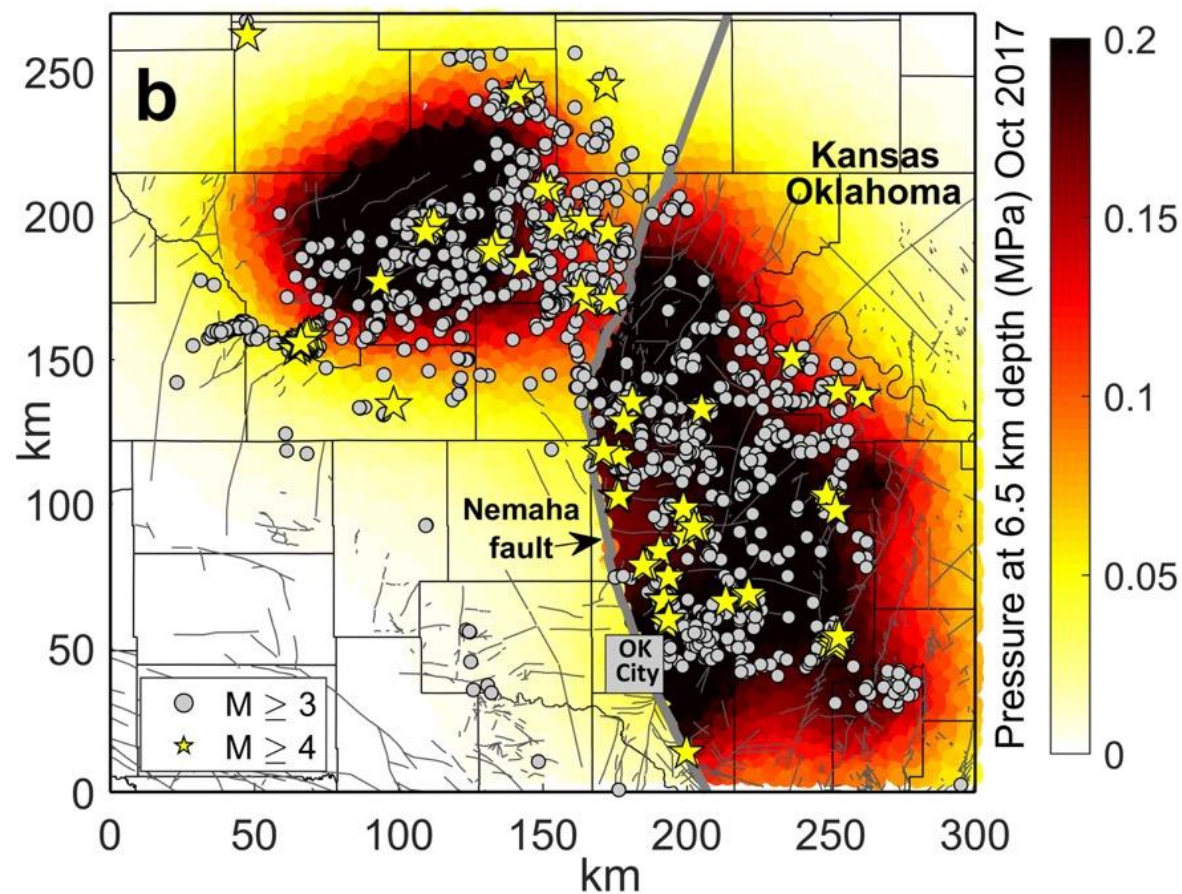
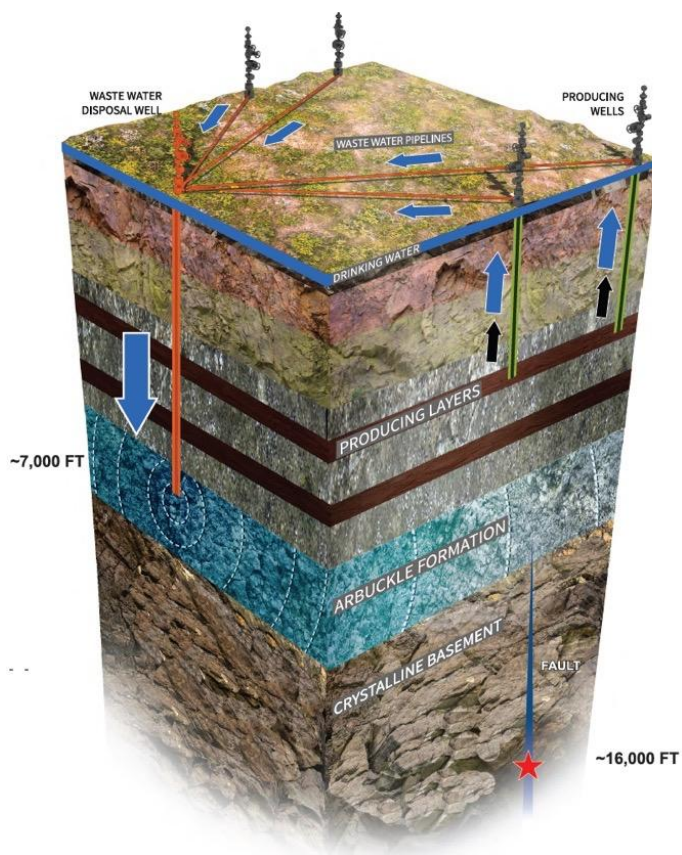


- Massive quantities of produced saltwater (from formations like the Mississippi Lime) was being injected into the basal Arbuckle group.
- About 3 billion barrels were injected in north-central Oklahoma (AOI) over a few years.
- Earthquakes occurring on pre-existing faults in basement due to small increases 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.

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

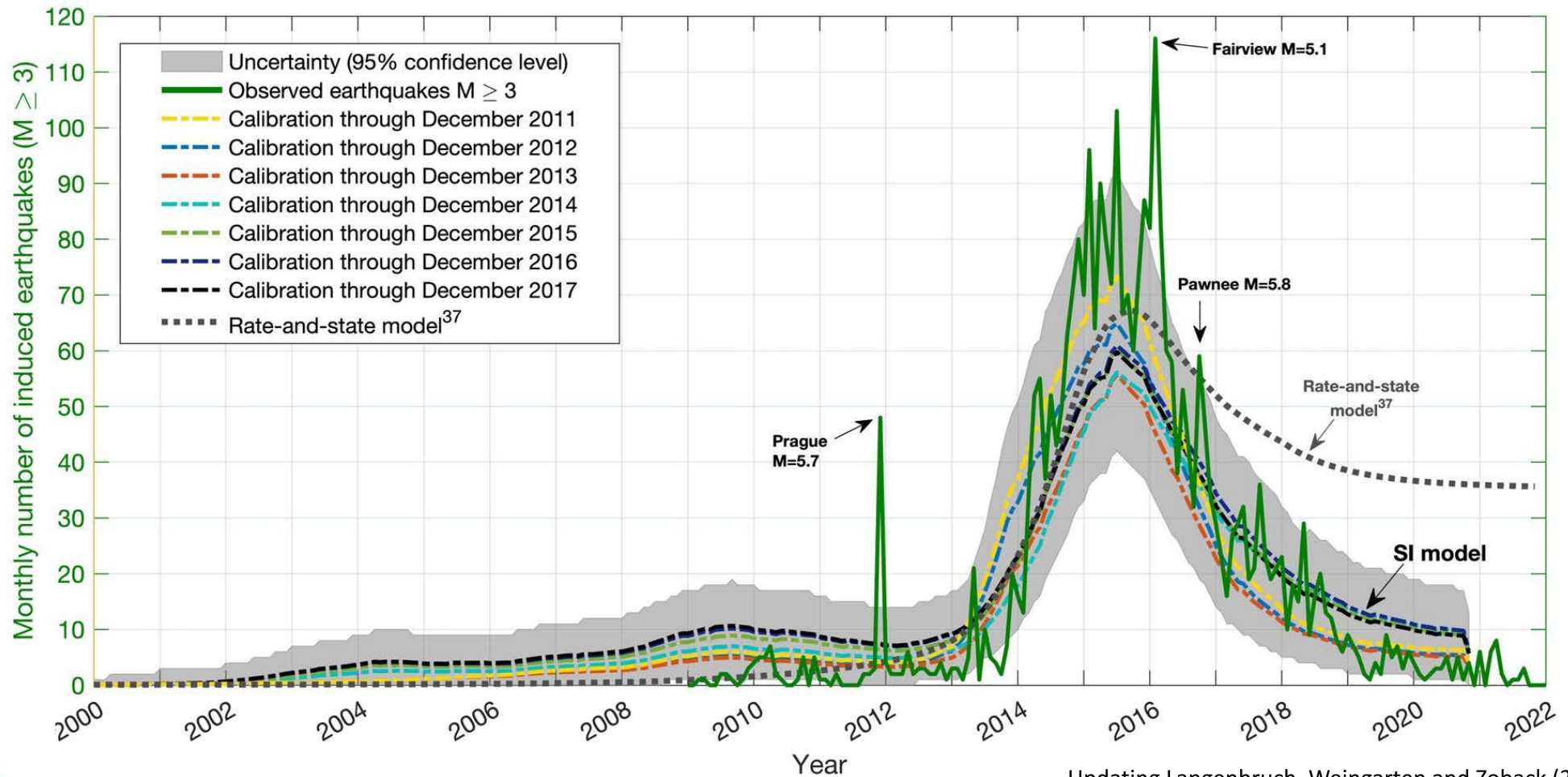


Produced Water Disposal is Triggering Earthquakes

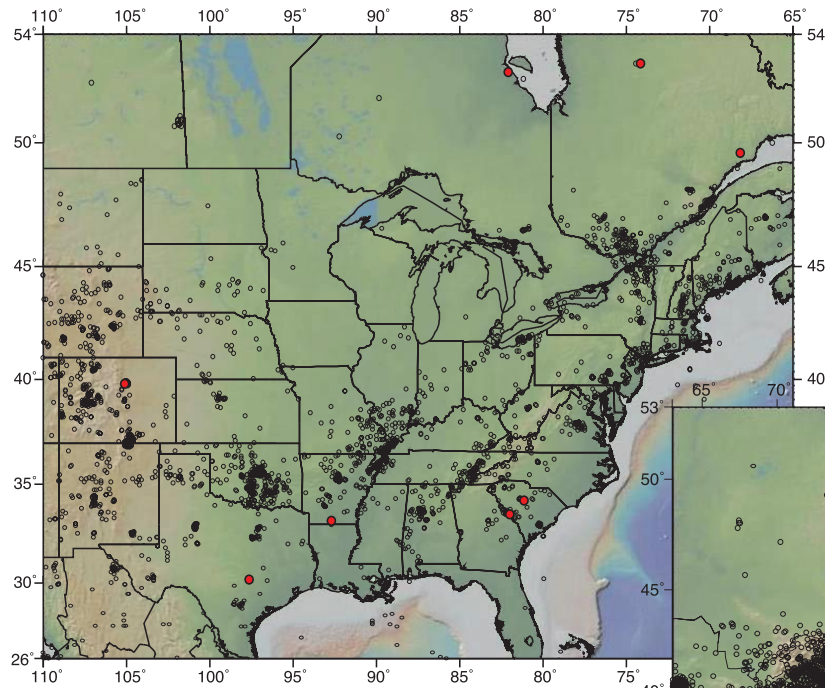


Langenbruch, Weingarten and Zoback (2018)

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

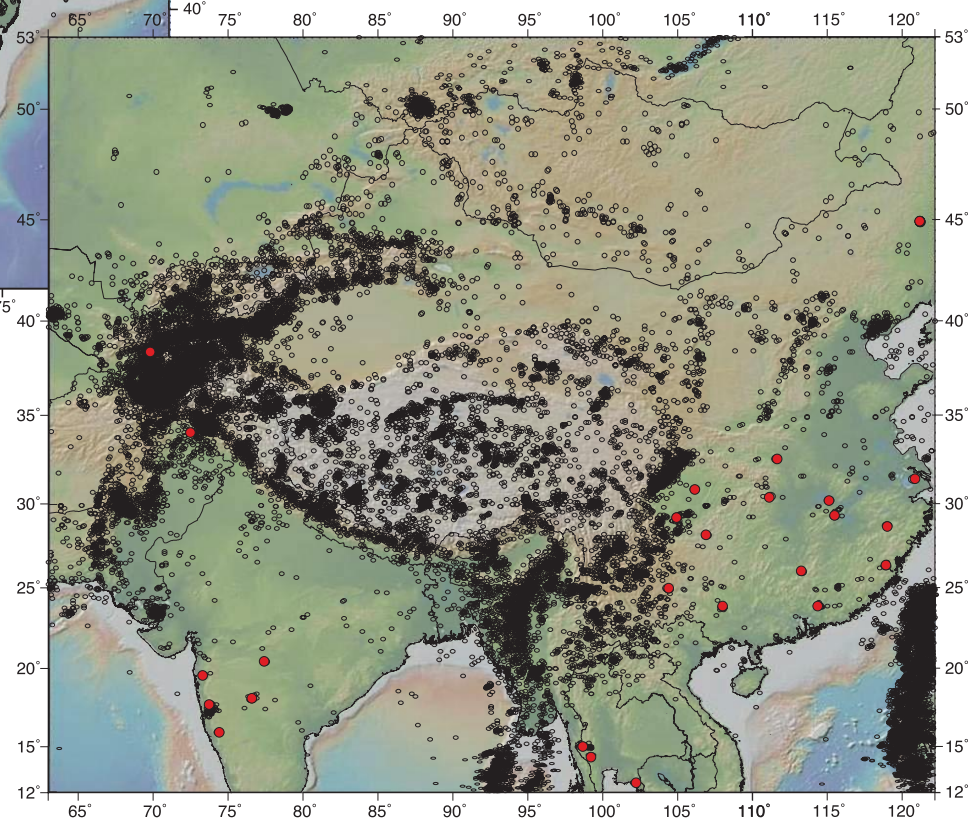


Updating Langenbruch, Weingarten and Zoback (2018)

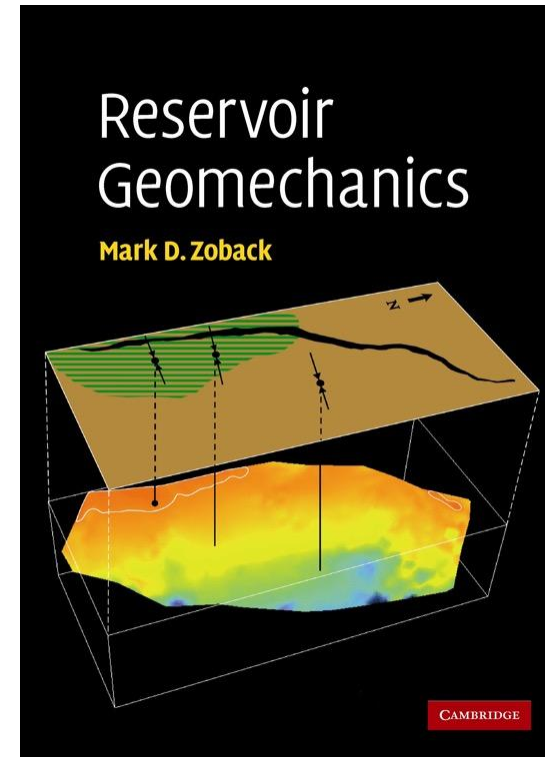
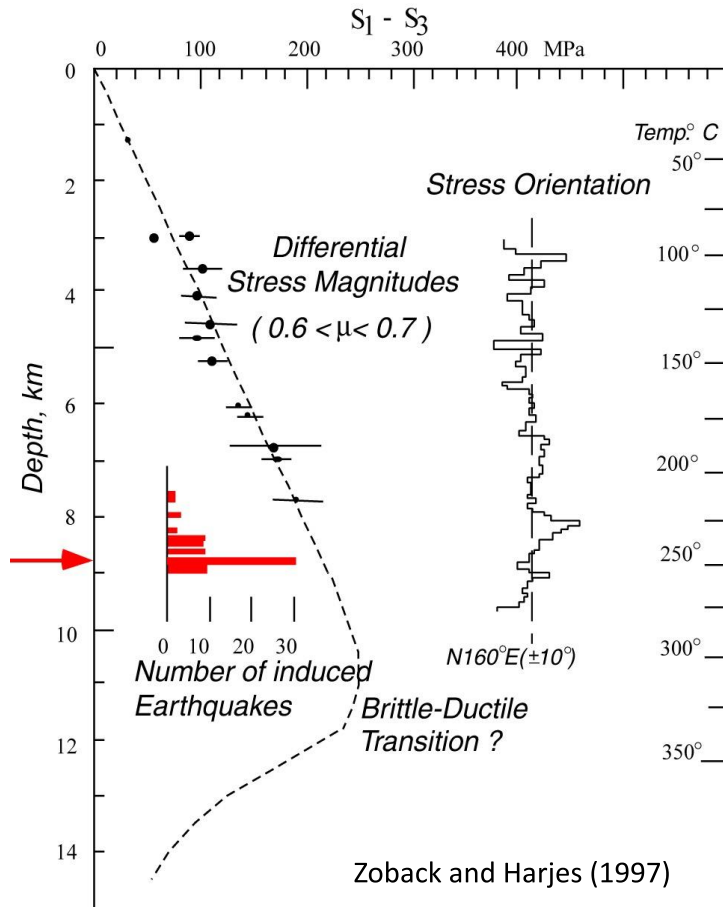


The Critically-Stressed Crust

- 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”



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



These principles are applicable to brittle sedimentary formations

Earthquake triggering and large-scale geologic storage of carbon dioxide

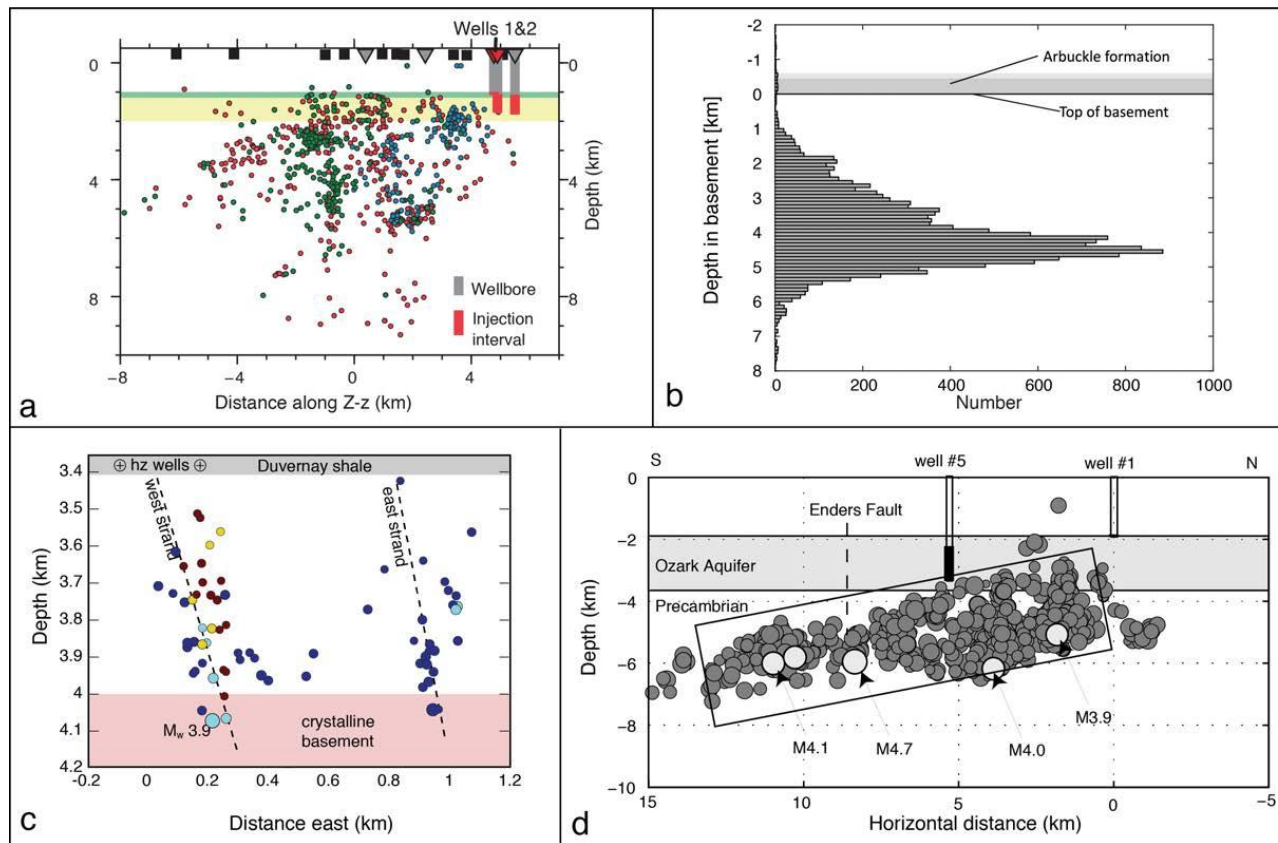
Mark D. Zoback^{a,1} and Steven M. Gorelick^b

Departments of ^aGeophysics and ^bEnvironmental 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)

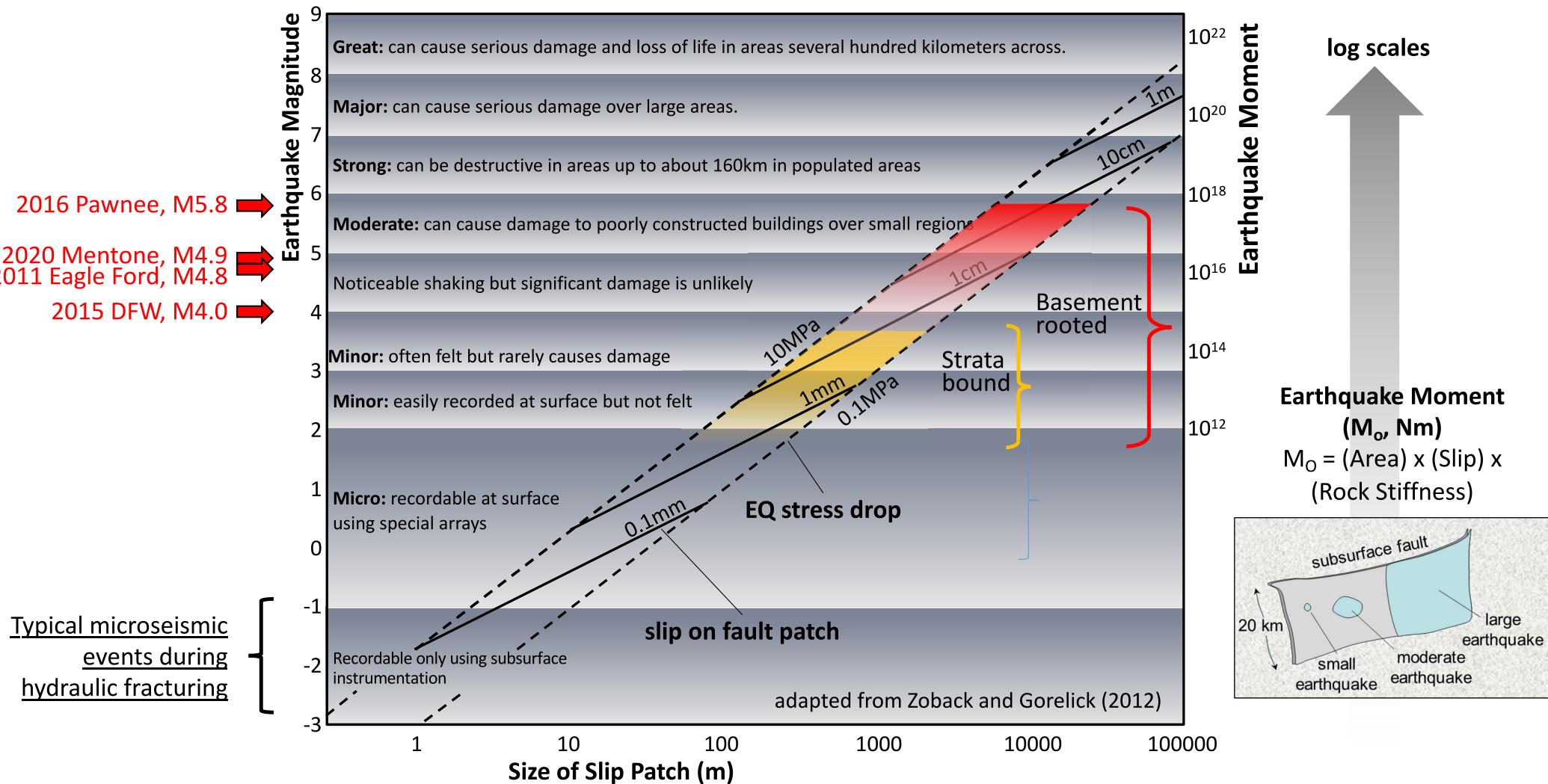
Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO₂ emissions associated with coal-based electrical power generation and other industrial sources of CO₂ [Intergovernmental Panel on Climate Change (2005) IPCC Special Report 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 CO₂ into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO₂ repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

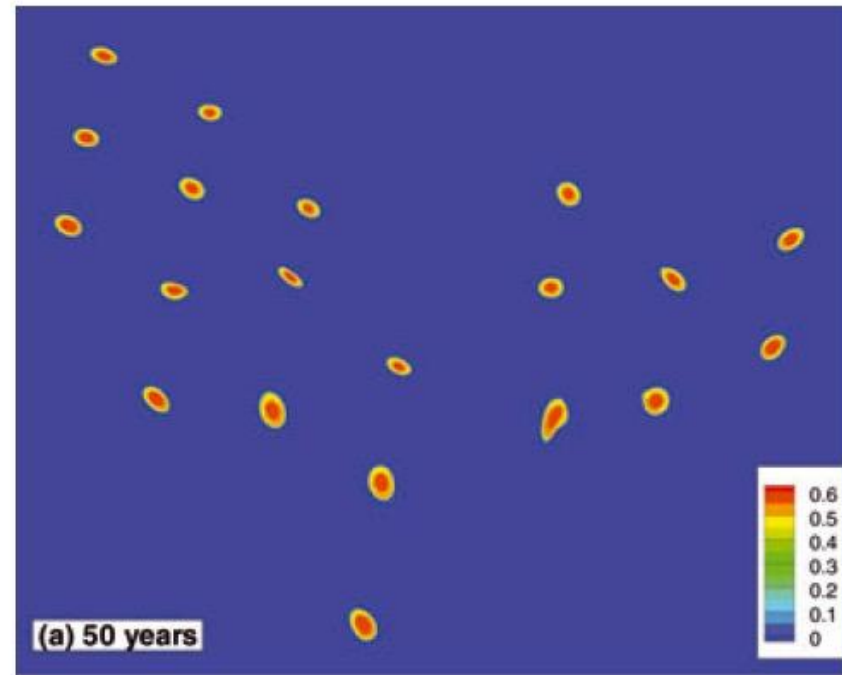
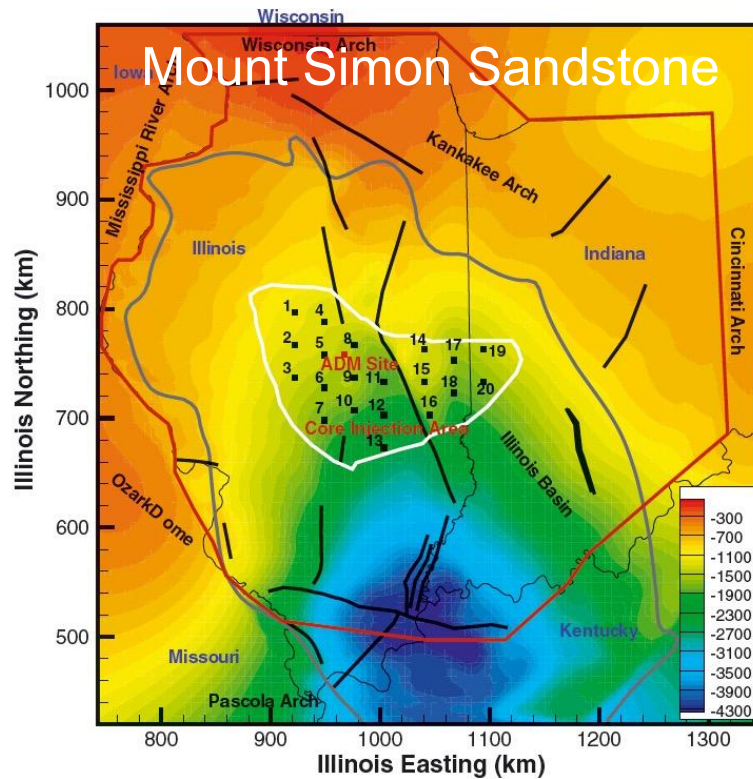
Earthquake Magnitude Depends on Whether Injection Increases Potentially Activate Basement Faults



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

Shallow (Strata-bound) vs Basement-Rooted Faults





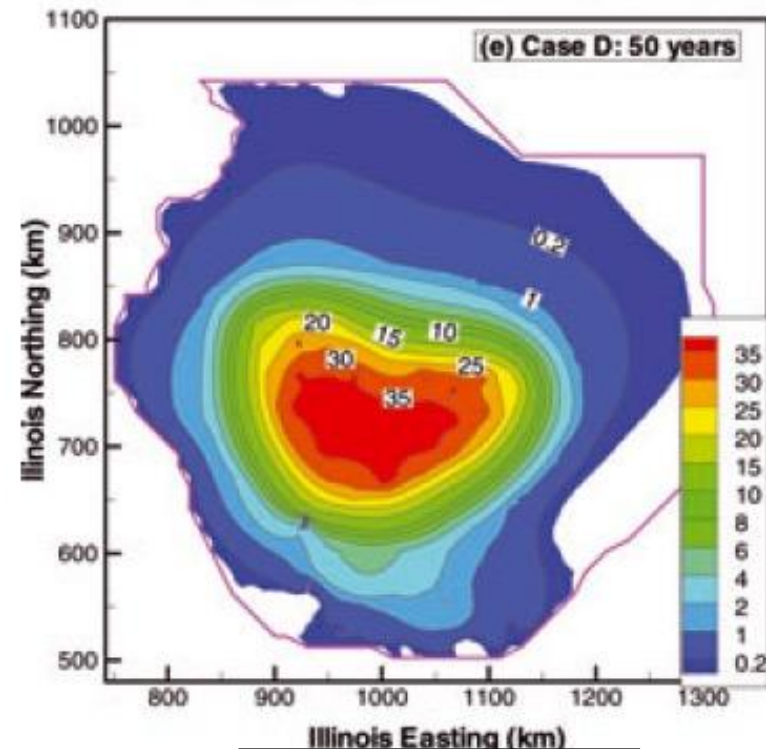
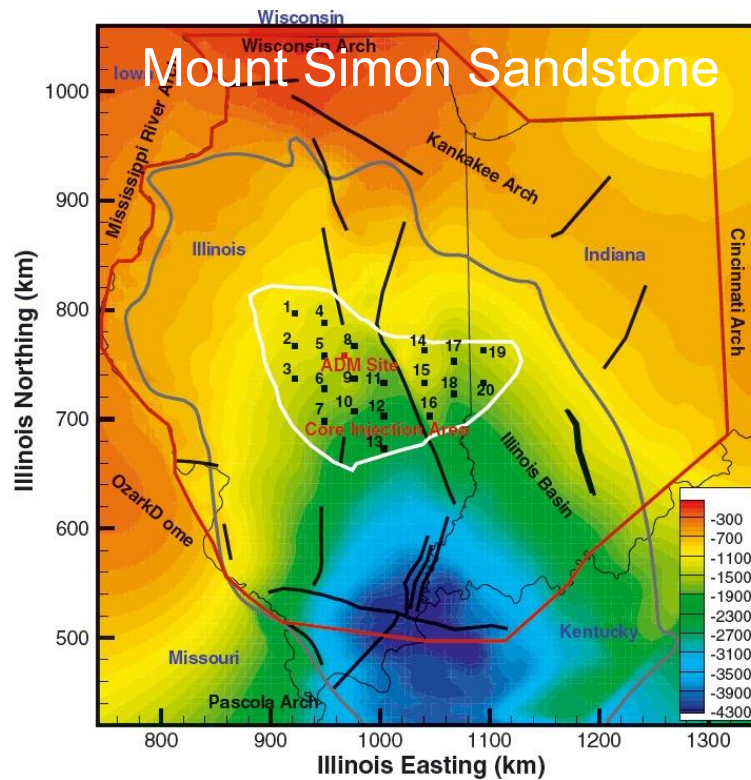
ground
water

CO₂ Footprint

100 MT/year
20 Wells

Modeling Basin- and Plume-Scale Processes of CO₂ Storage for Full-Scale Deployment

by Quanlin Zhou¹, Jens T. Birkholzer¹, Edward Mehnert², Yu-Feng Lin³, and Keni Zhang¹ (2010)



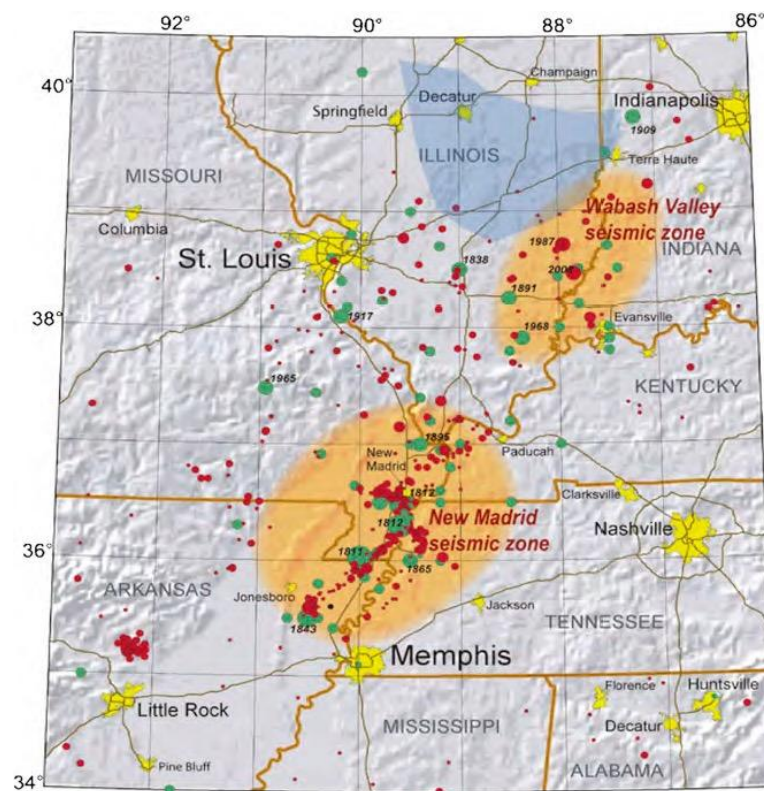
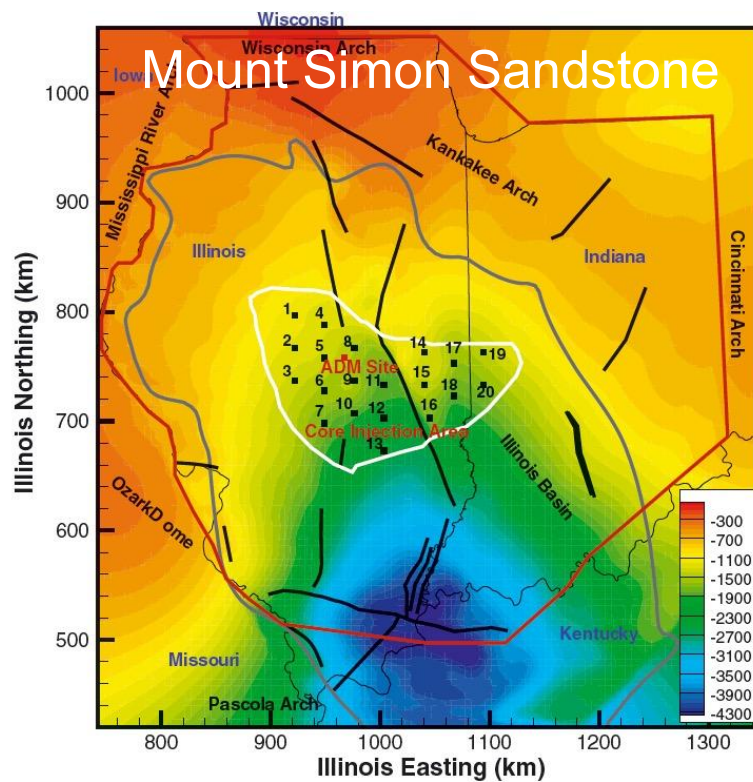
ground
water

Pressure Change

100 MT/year
20 Wells

Modeling Basin- and Plume-Scale Processes of CO₂ Storage for Full-Scale Deployment

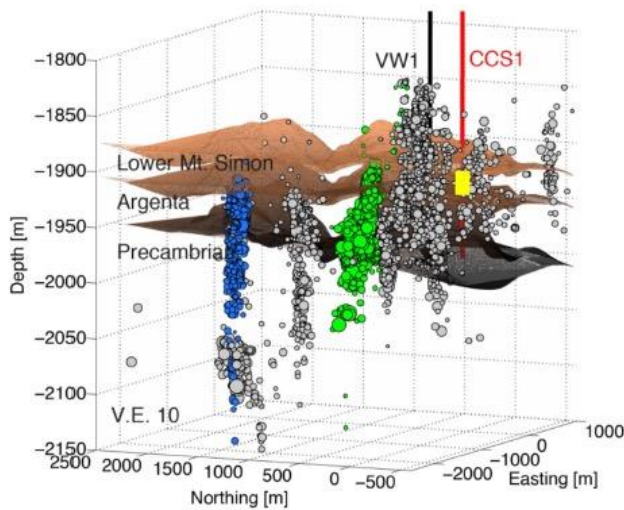
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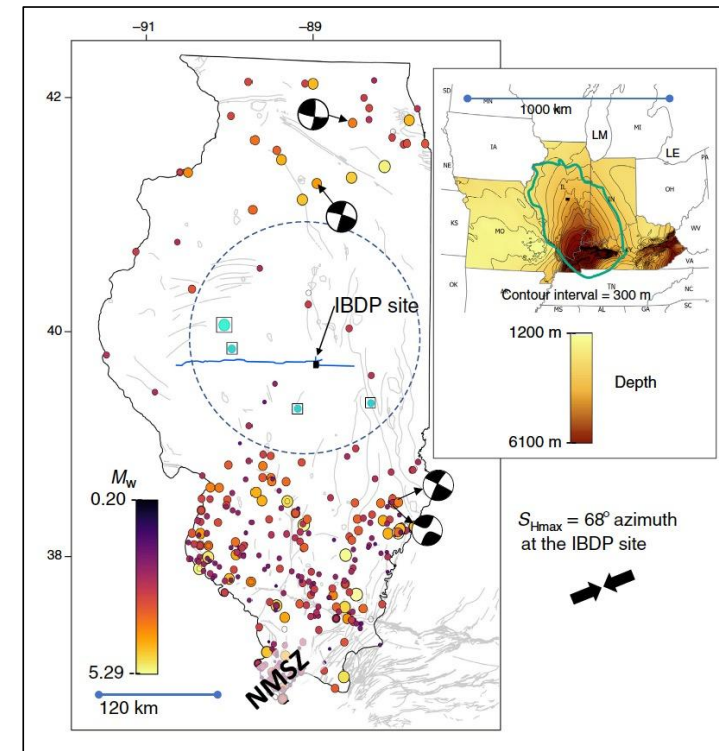
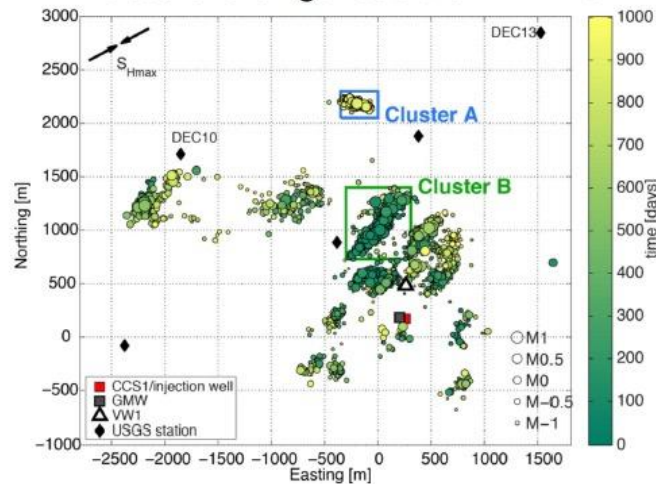
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CO₂ Injection Into the Mt. Simon Sandstone At Decatur, Illinois

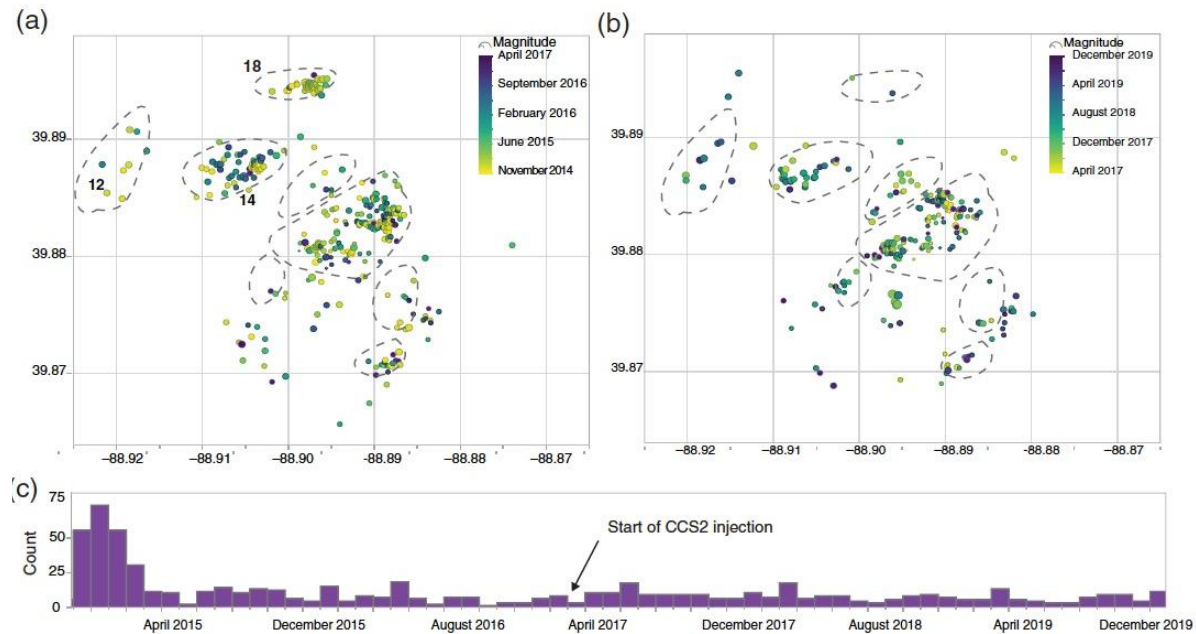
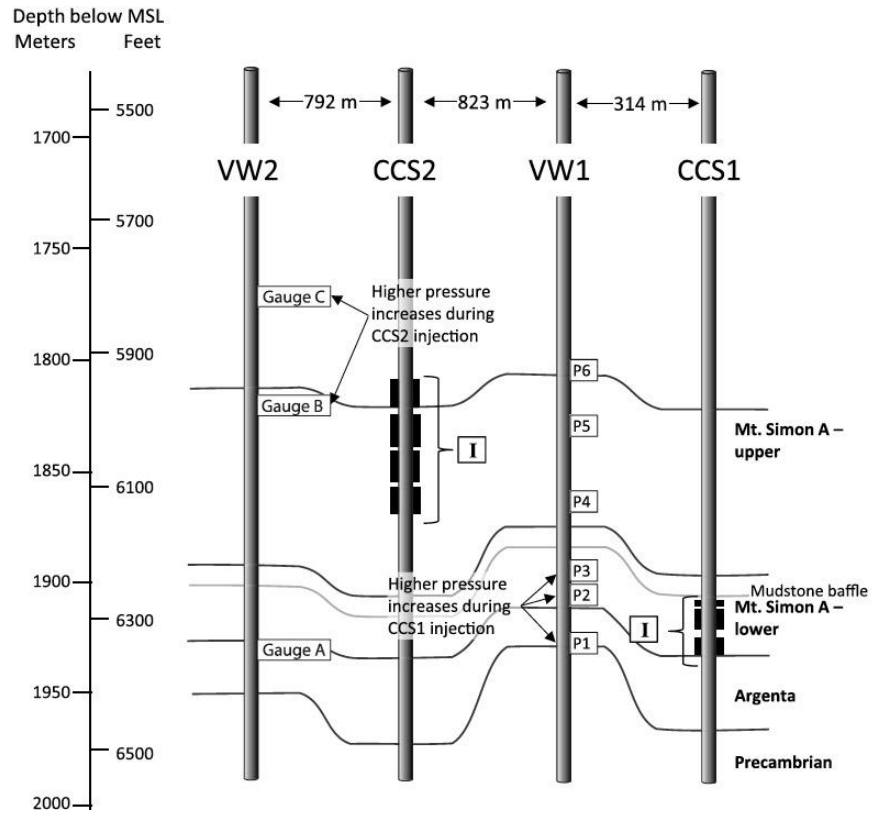


Goertz-Allman et al. (2017, JGR)

- Injection of 1 million tons of CO₂ over a 3-year period into the Mt. Simon (8 million barrels, 1.3 million m³)
- Small earthquakes define faults in Precambrian basement
- Pressure change less than 1 MPa



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

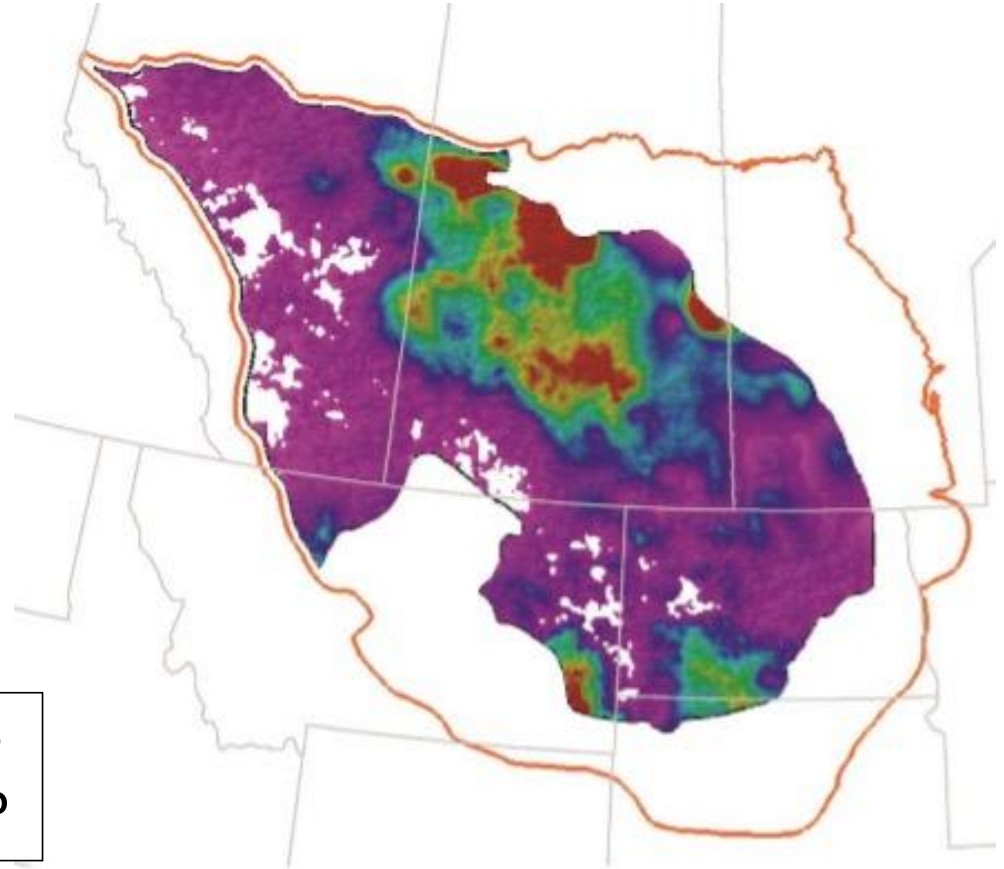


Injection Rate in CCS2 Well is 1.7
times that in CCS1 (~560,000
tonnes/year)

Basal Saline Aquifers

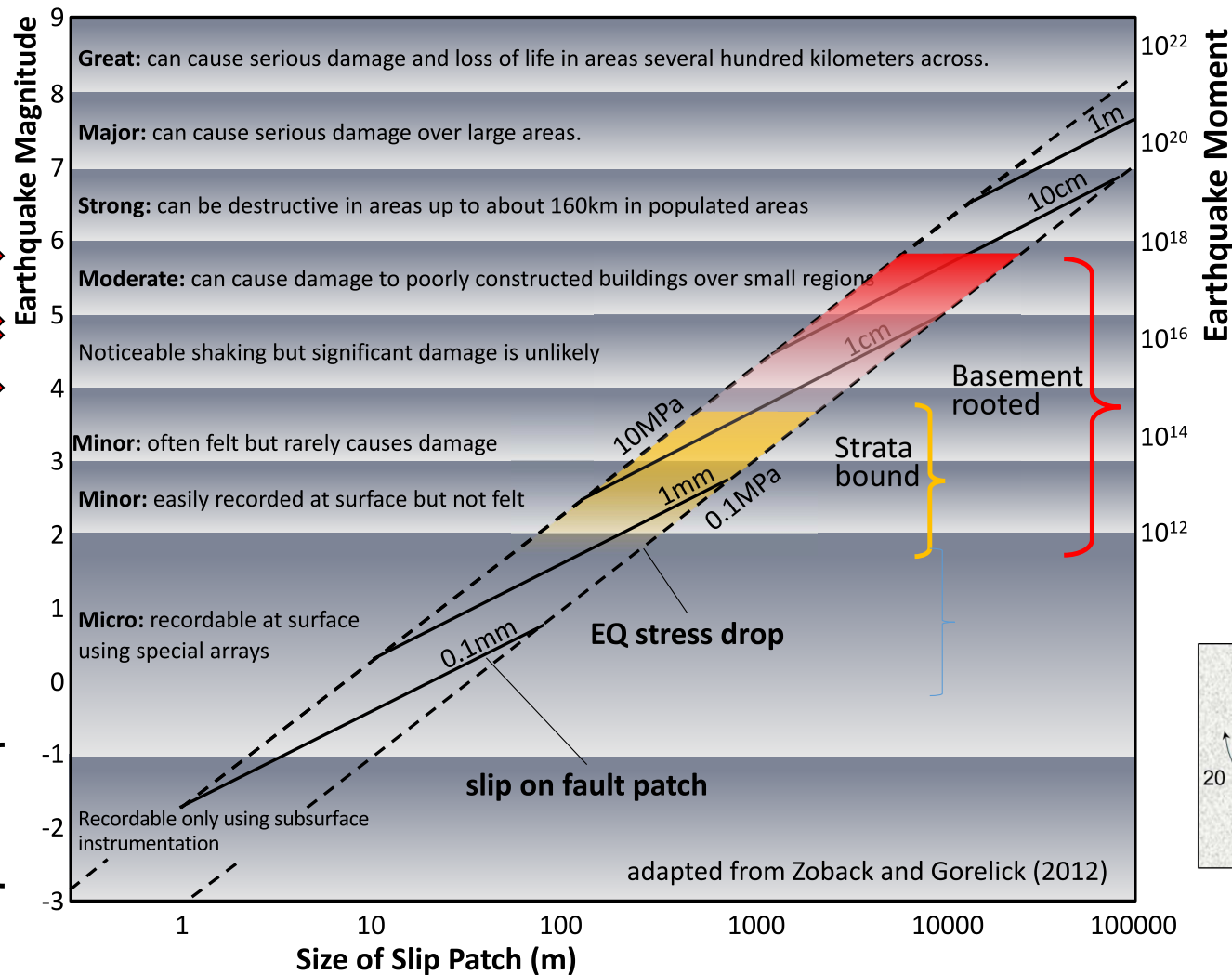
Example

- 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 CO₂ Storage in Basal Saline Aquifers?

Shallow (Strata-bound) vs Basement-Rooted Faults



2016 Pawnee, M5.8 →

2020 Mentone, M4.9 →

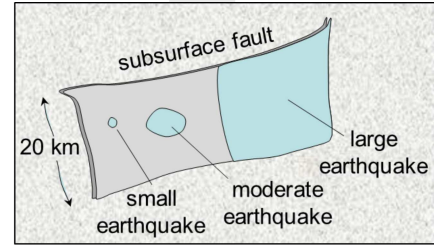
2011 Eagle Ford, M4.8 →

2015 DFW, M4.0 →

Typical microseismic events during hydraulic fracturing

Earthquake Moment (M_0 , Nm)

$$M_0 = (\text{Area}) \times (\text{Slip}) \times (\text{Rock Stiffness})$$



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Can We Avoid Injection into Potentially Active Faults?



Yes, if we Know the 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

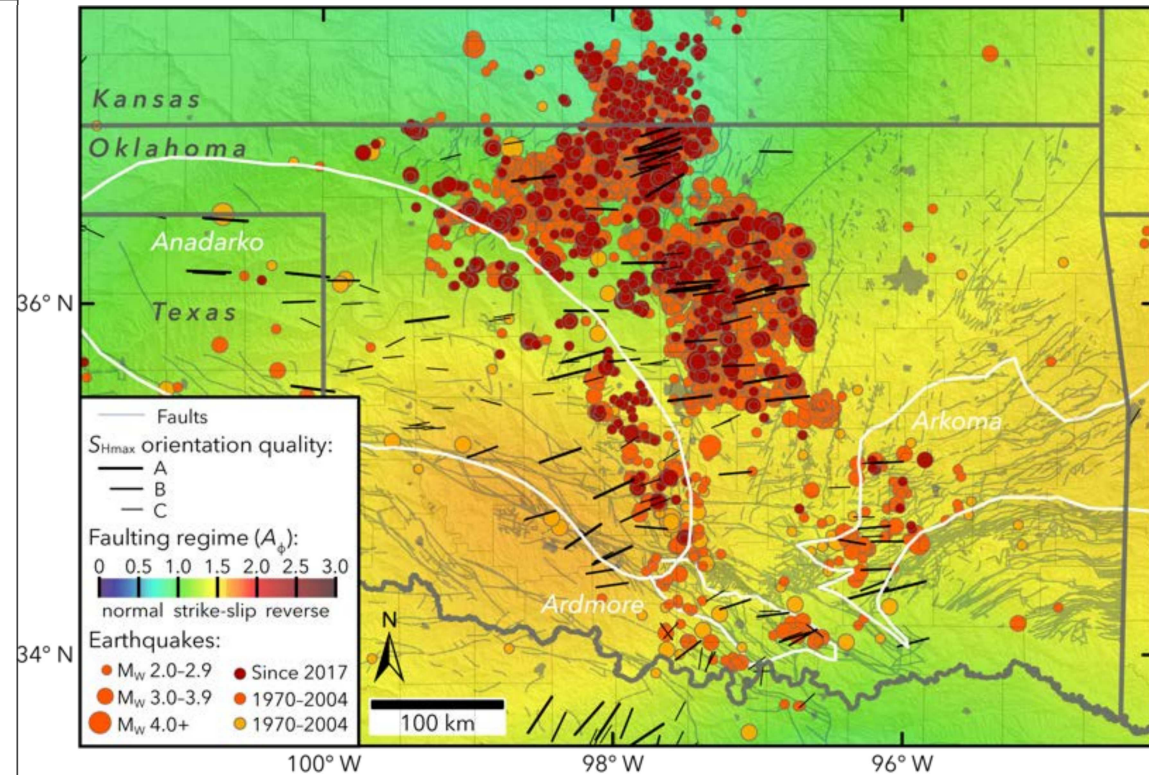
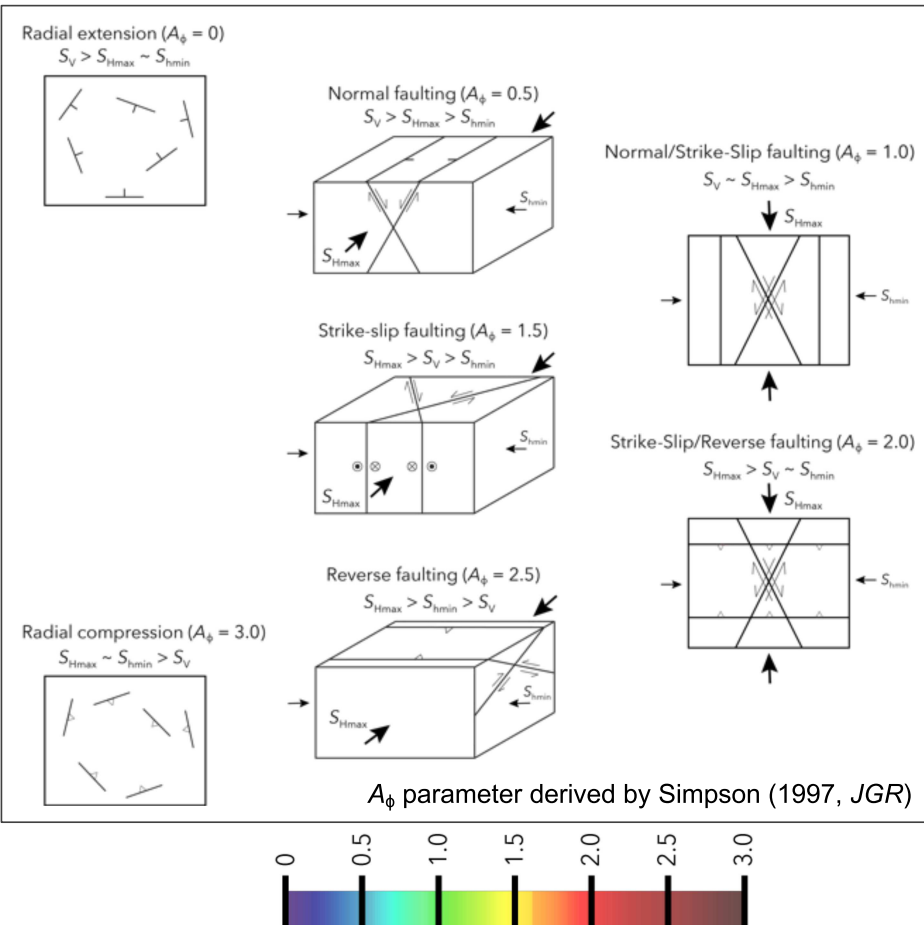
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

GEOLOGY

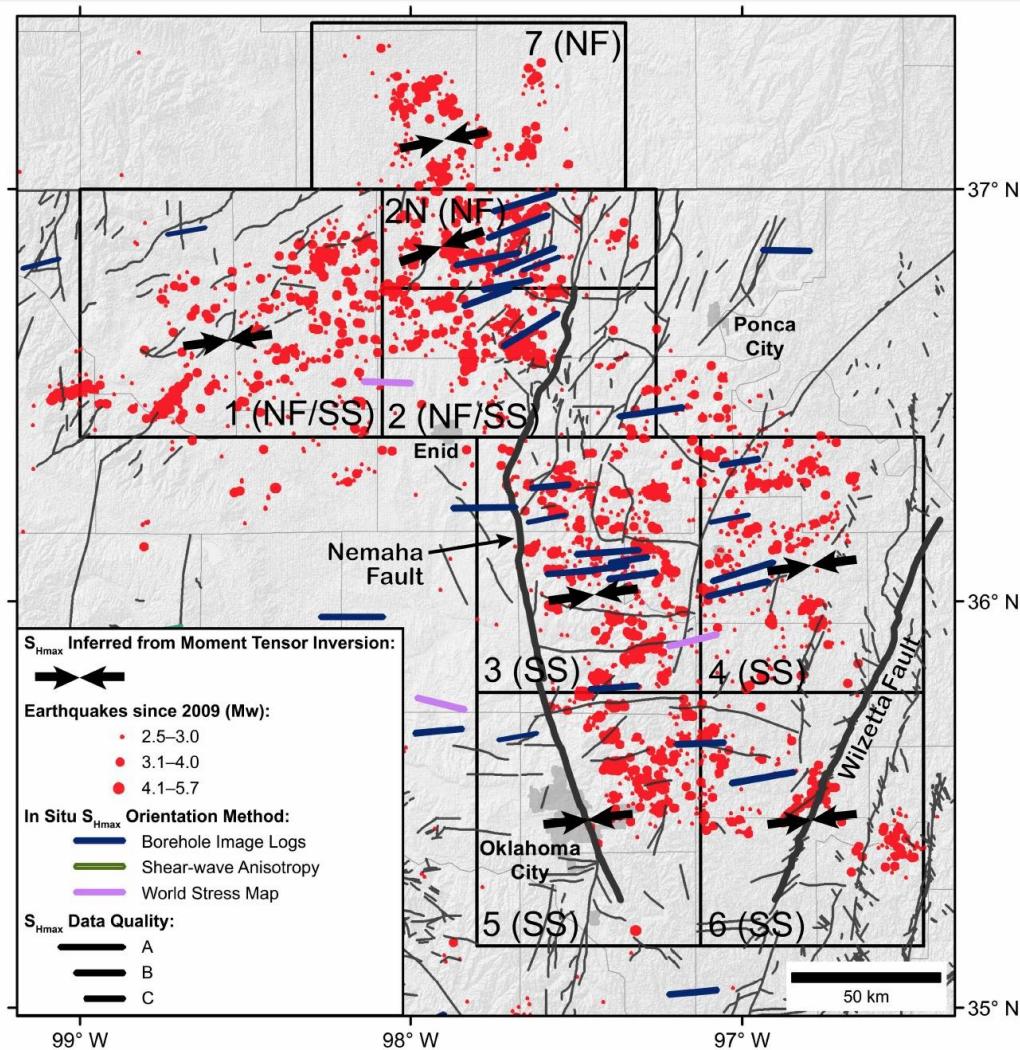
Data Repository item 2016334 | doi:10.1130/G38275.1

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Oklahoma Earthquakes Induced by Produced Water Injection



Lund Snee and Zoback (AAPG, in press)



- 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

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

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

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GEOLOGY

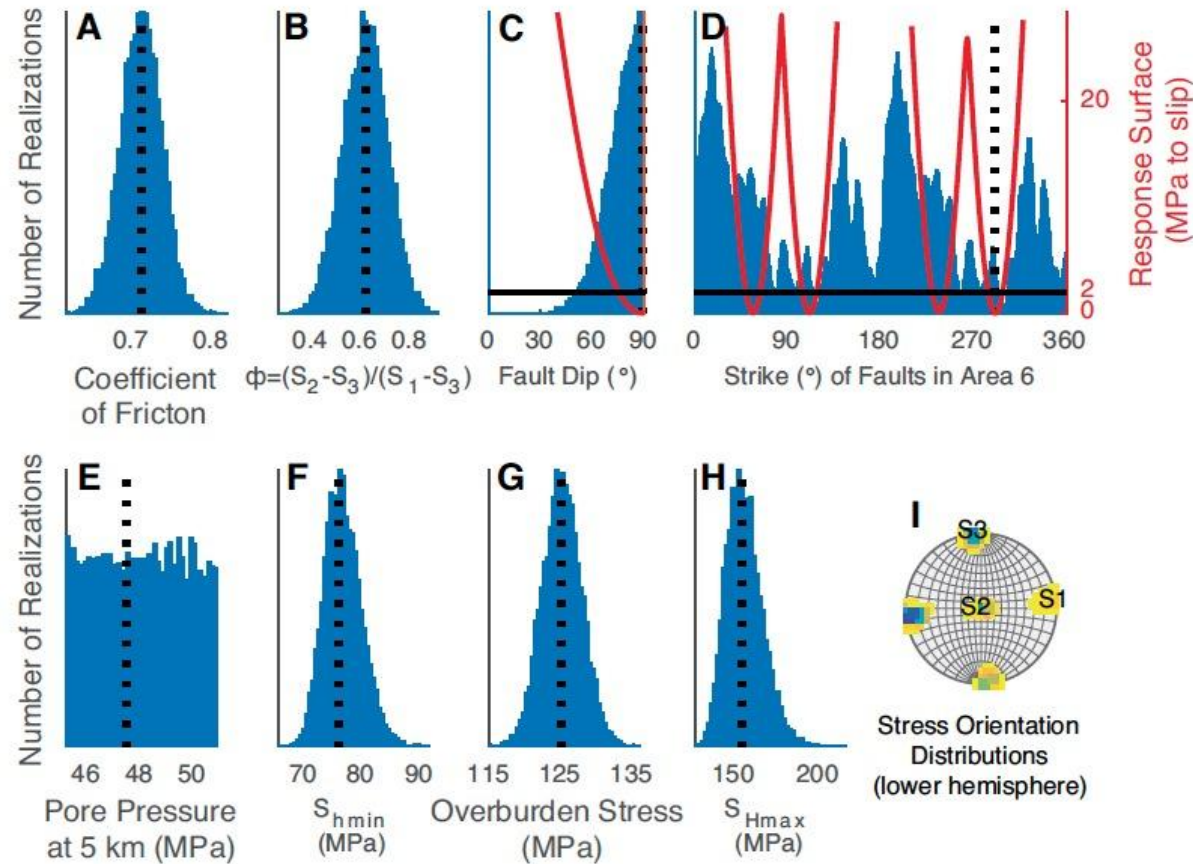
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F S P
Fault Slip Potential
 Stanford Center for Induced & Triggered Seismicity



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



Fault Slip Probability (2 MPa Max Pressure Change)

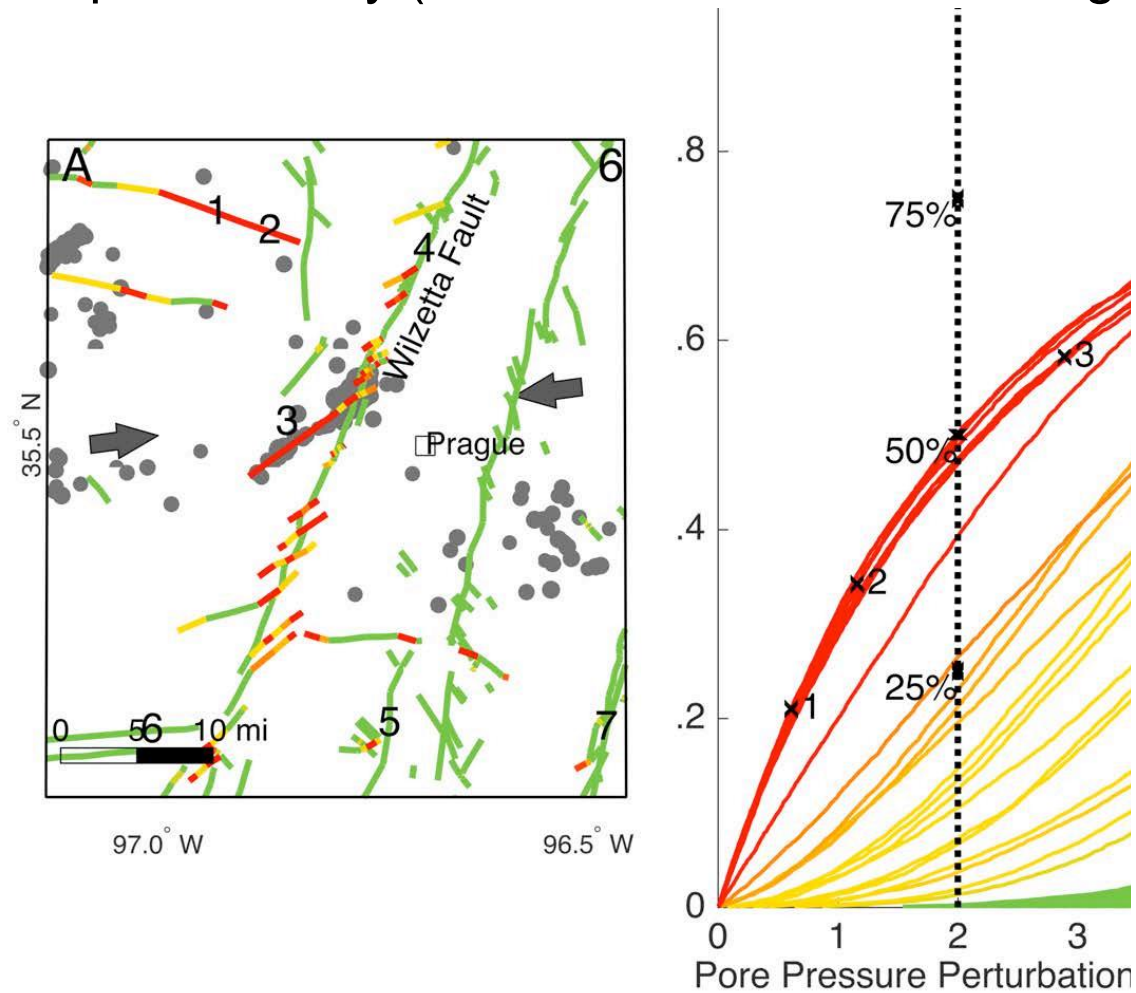
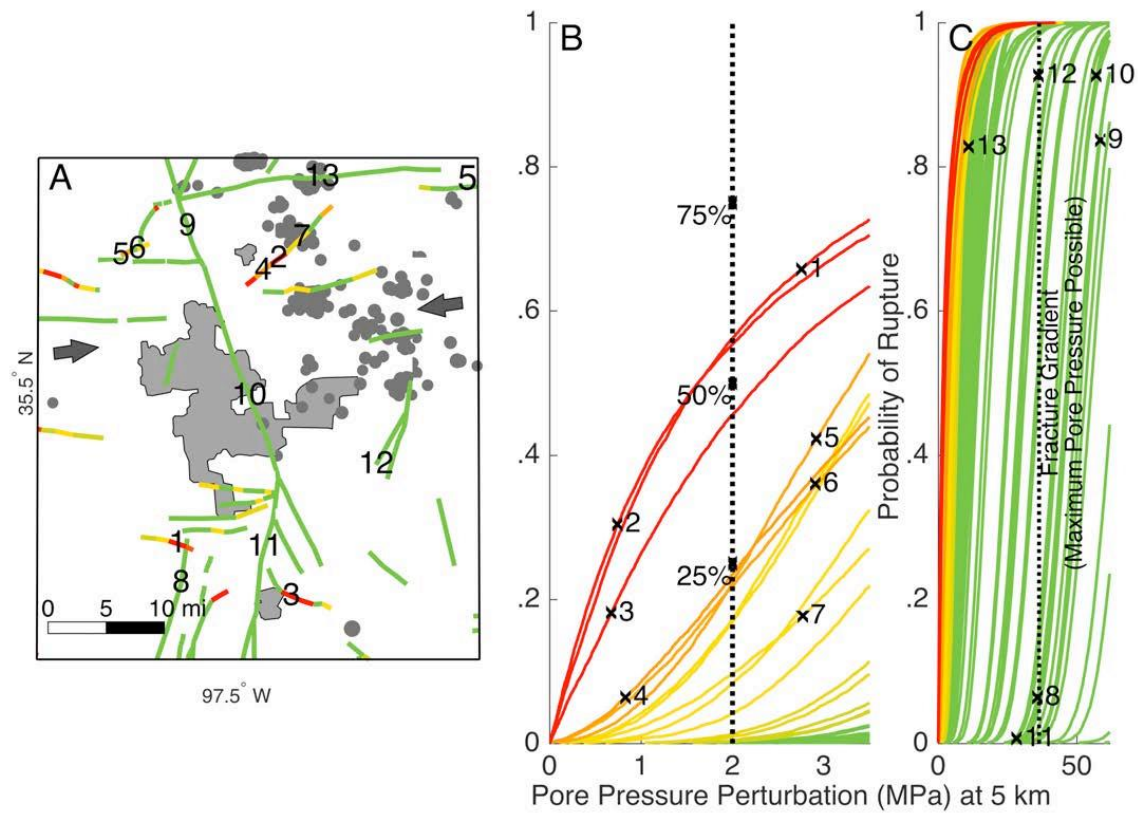


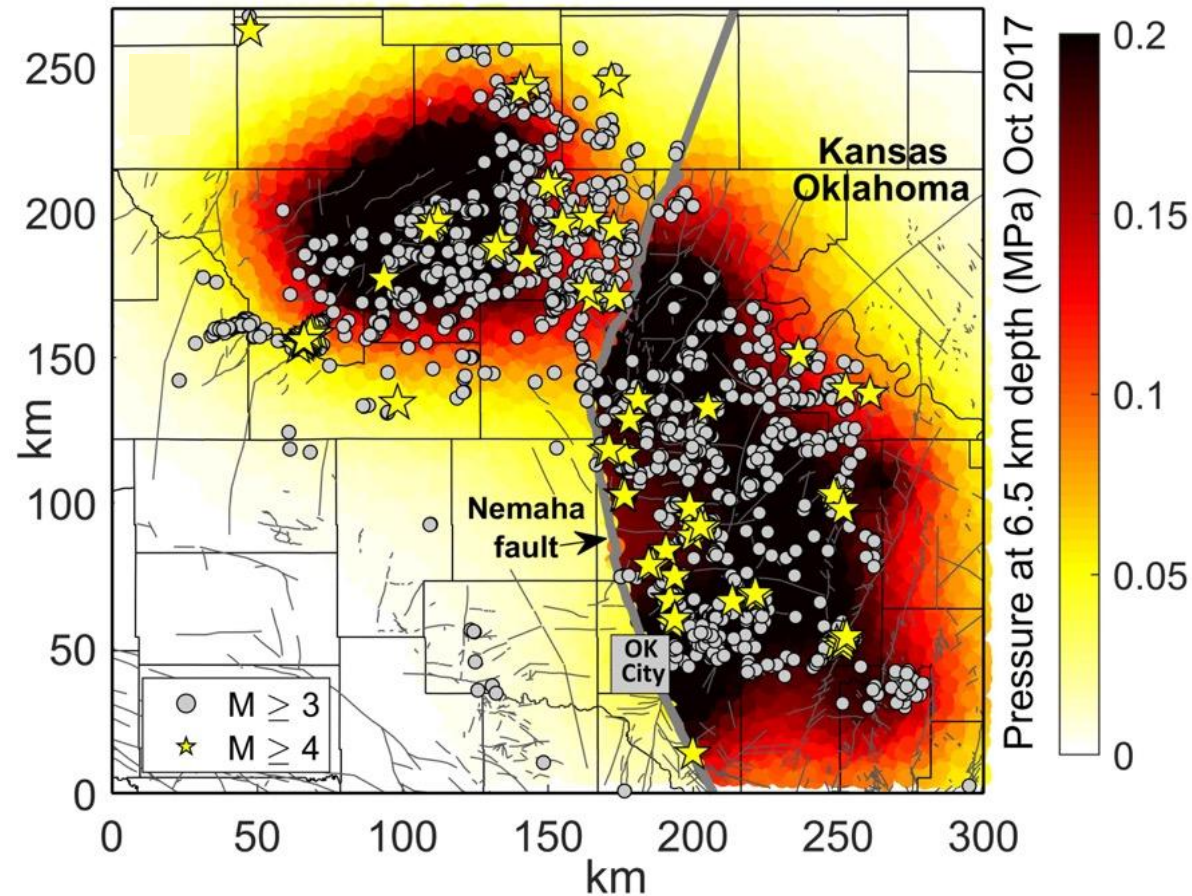
Fig. 14.4

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

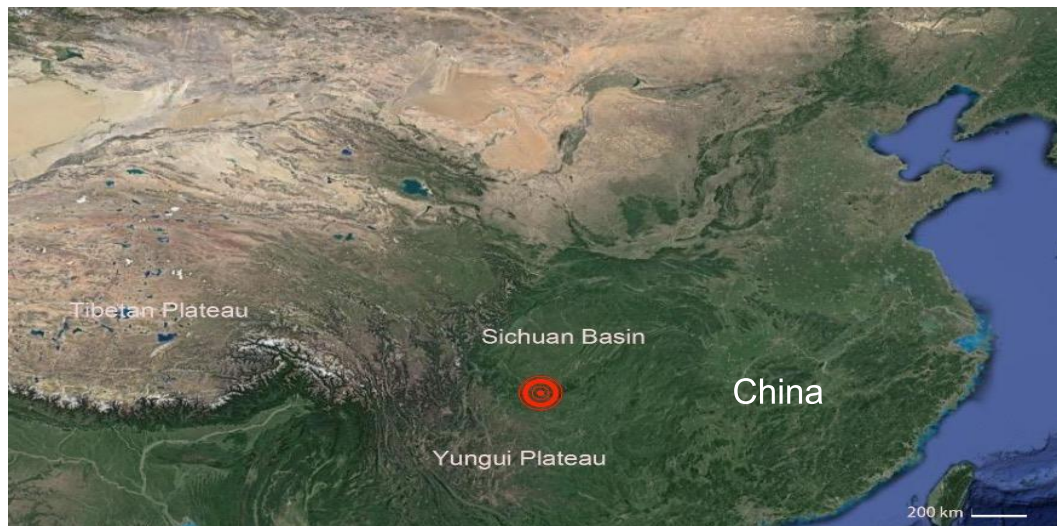


Walsh and Zoback (2016)

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



Well Shearing and Seismicity Due to Triggered Aseismic Fault Slip



Longmaxi play in Sichuan Basin:

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

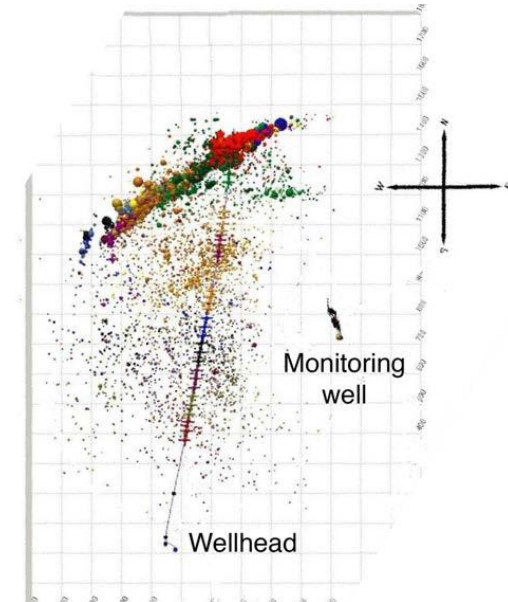
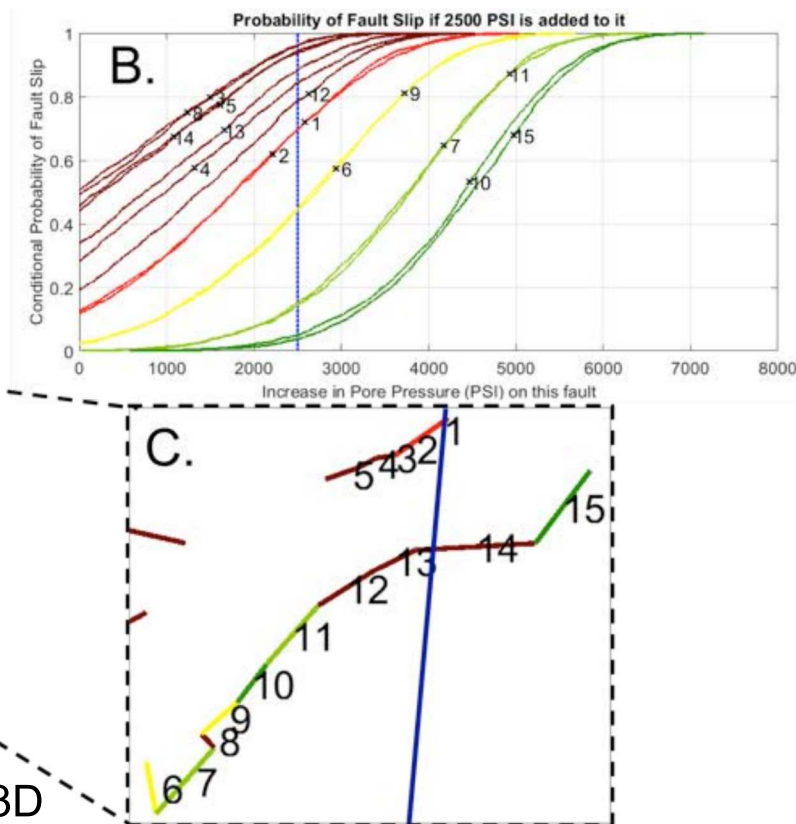
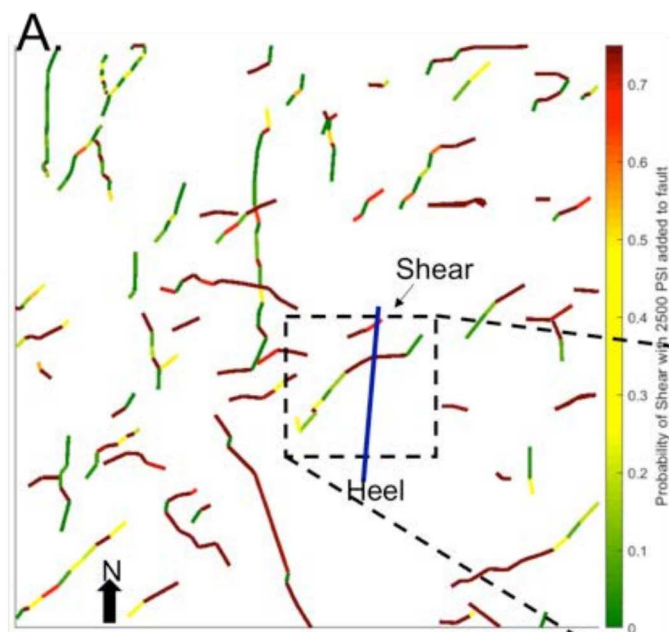
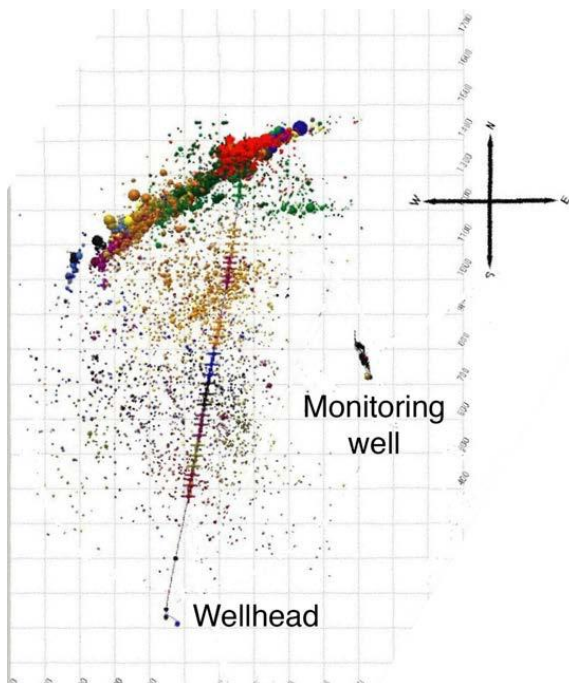


Fig. 13.21

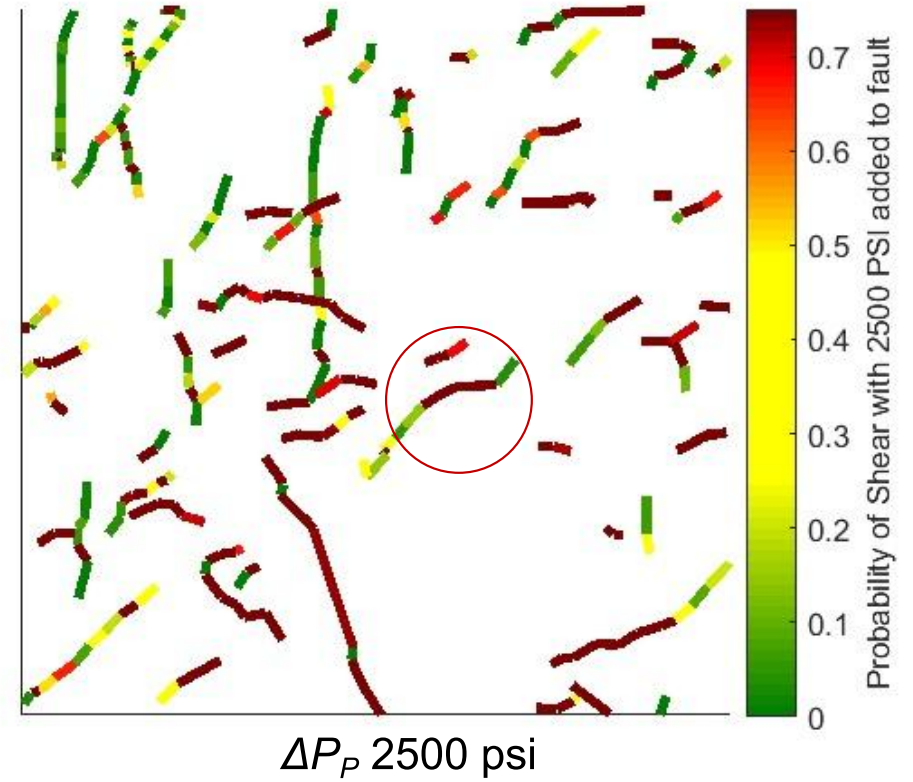
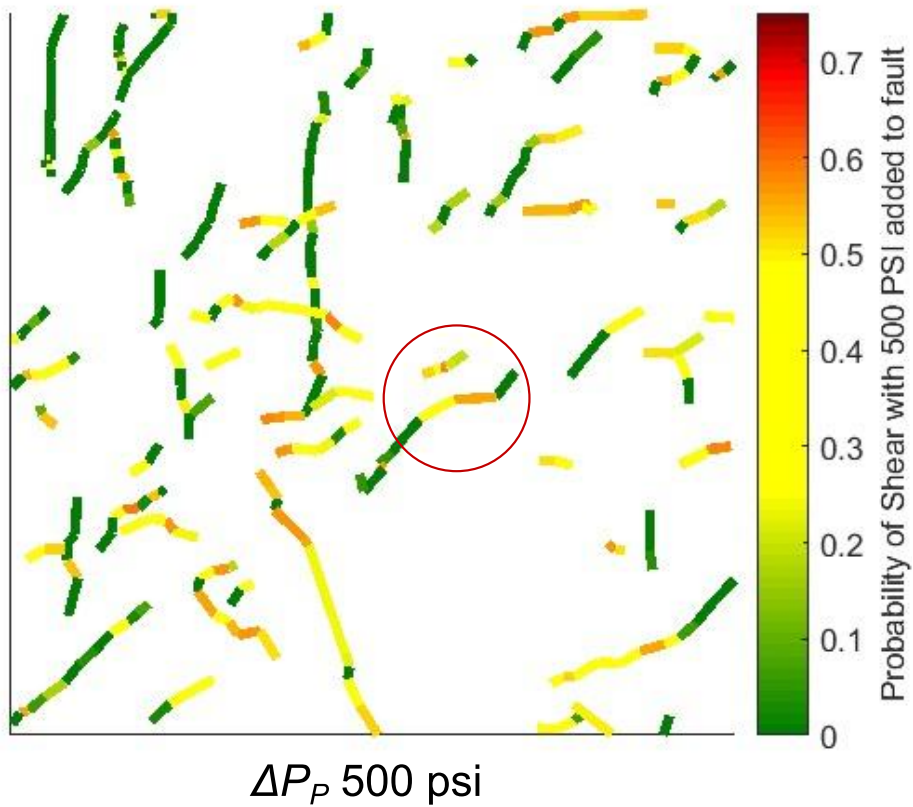
- Strike: $N57^{\circ} E$
- Dip: 70 degrees
- Several magnitude 2+ events
- The casing deformation point is about 100m away from the fault.

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



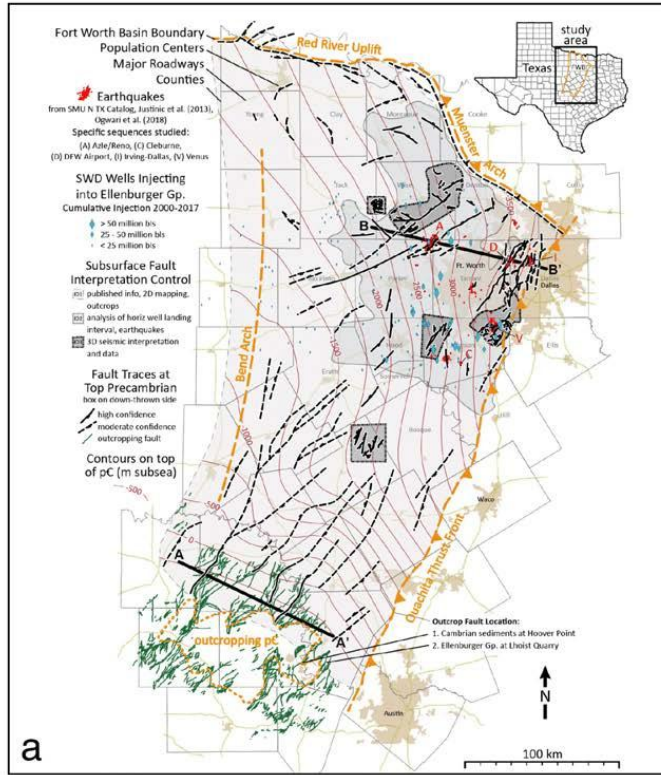
Faults Identified Using Ant Tracking of 3D Seismic Reflection Data

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

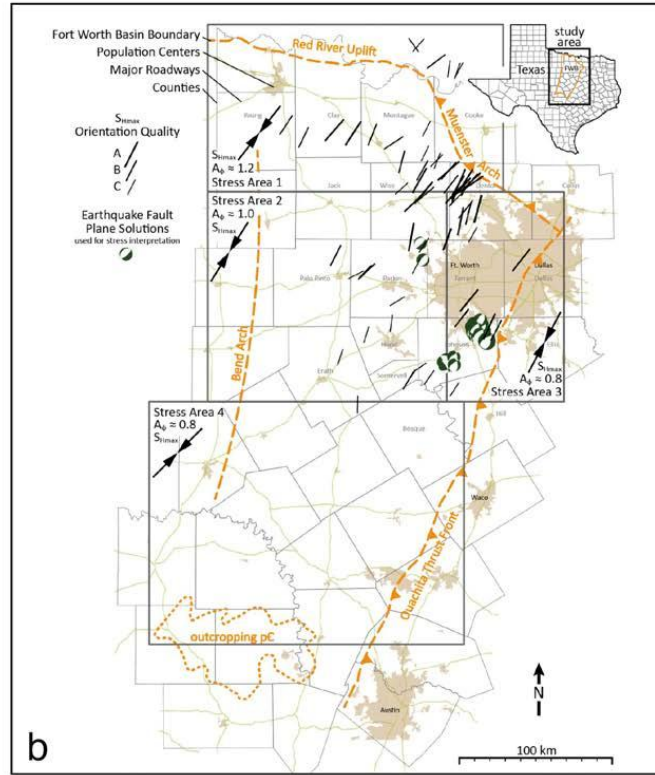


Application to the Fort Worth Basin

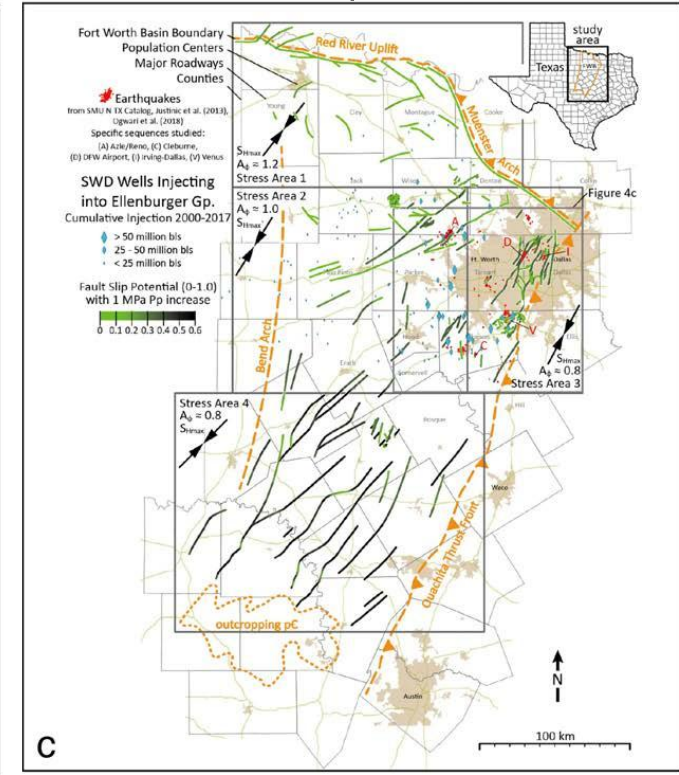
Faults



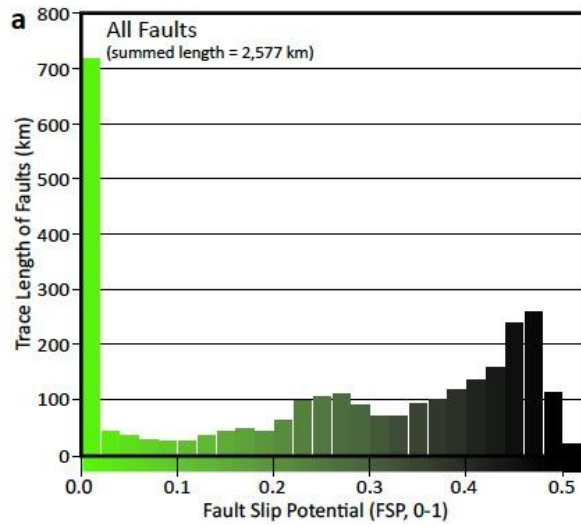
Stress



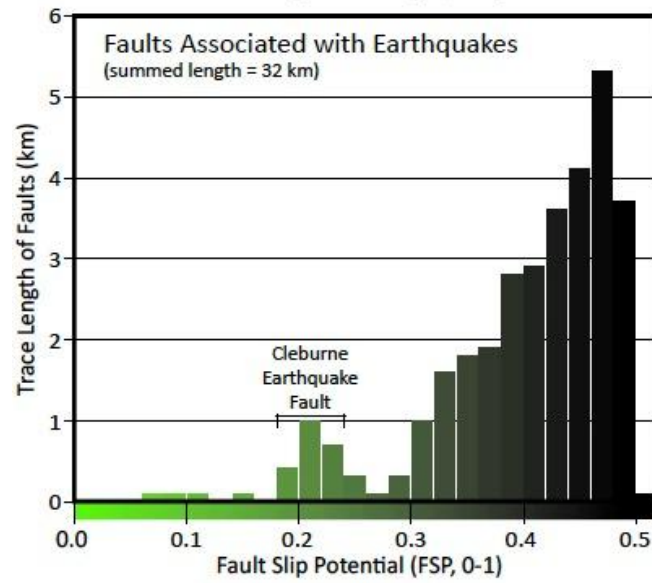
Fault Slip Potential



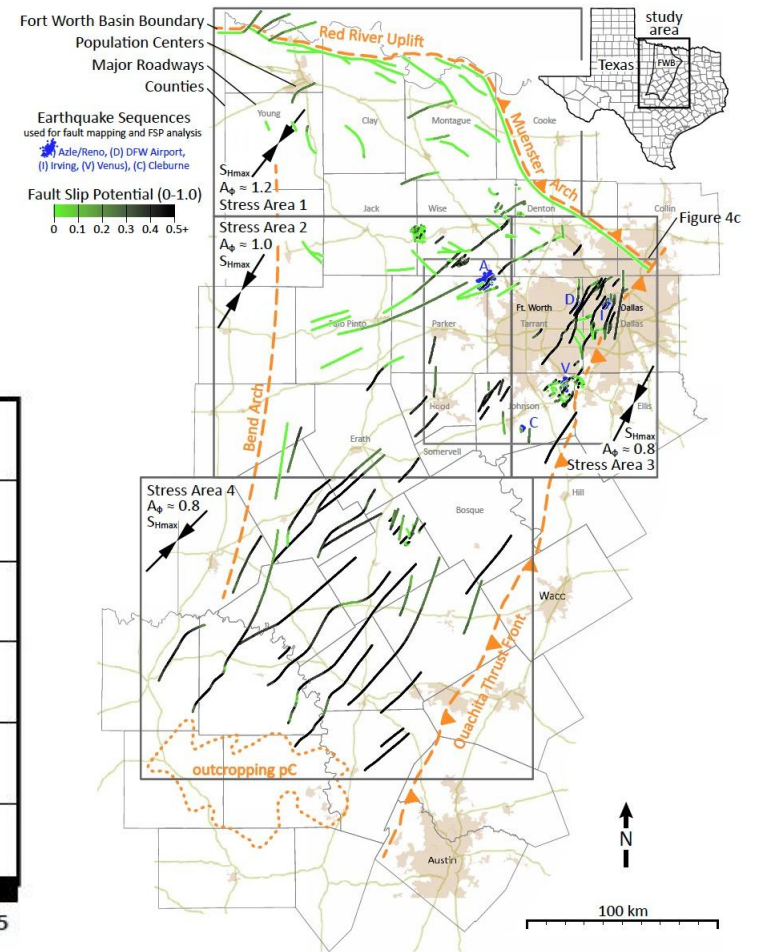
Hennings et al. (2019)



Calibration



Hennings et al. (2019)



Application



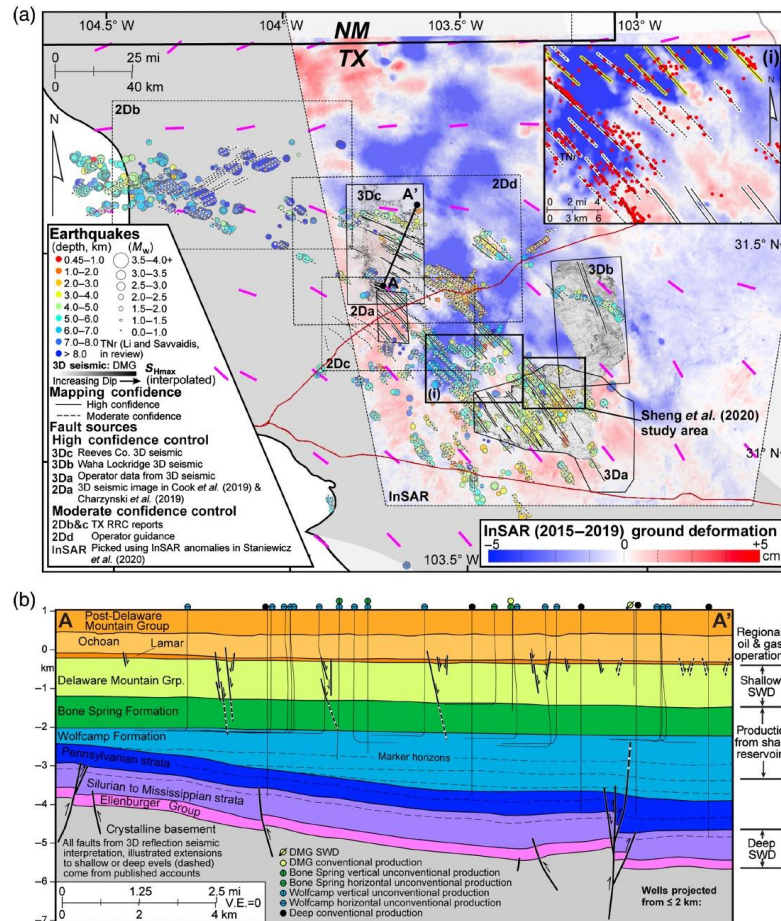
Prior oil and gas production can limit the occurrence of injection-induced seismicity: A case study in the Delaware Basin of western Texas and southeastern New Mexico, USA

Noam Z. Dvory and Mark D. Zoback

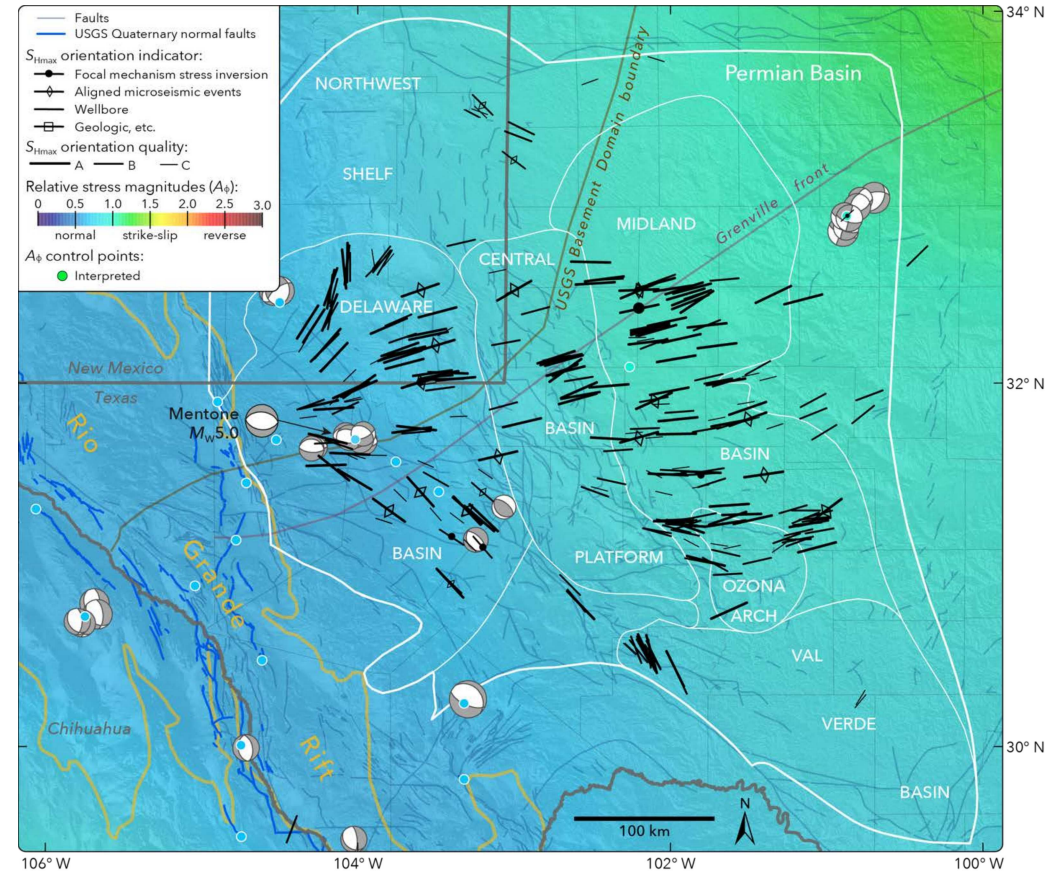
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

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

State of Stress in the Permian Basin

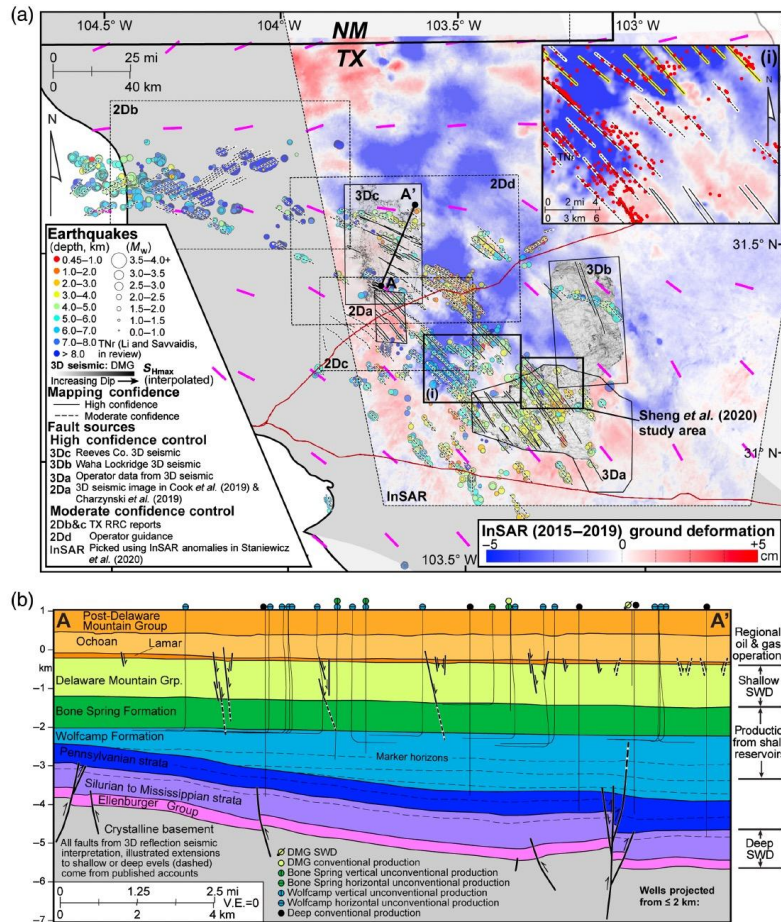


Fault mapping from Hennings et al. (2021)



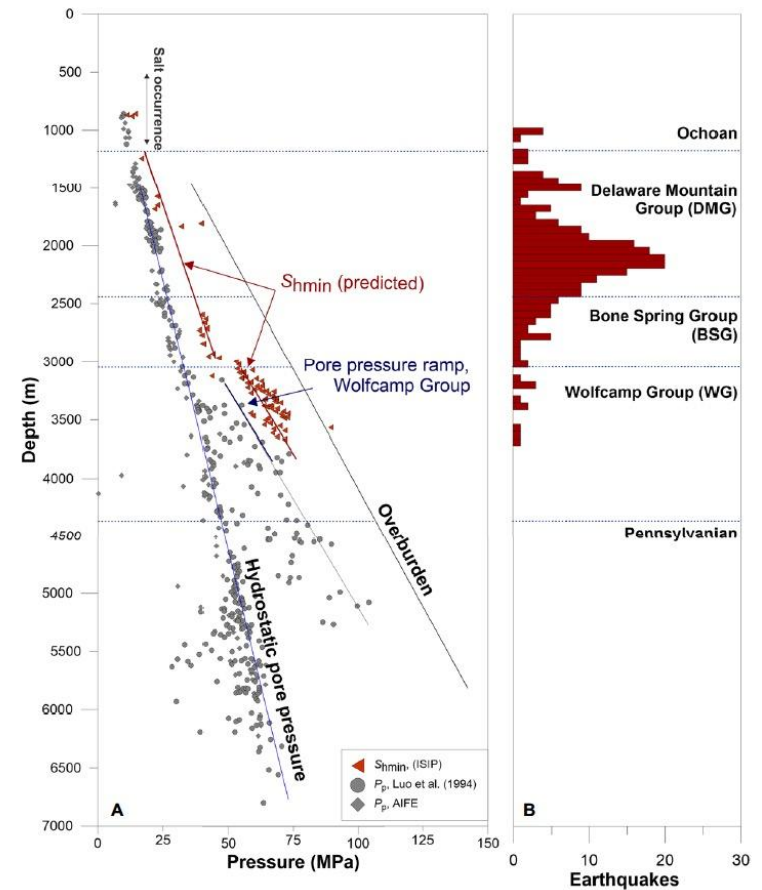
Stress data from Lund Snee and Zoback (2021)

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



Fault mapping from Hennings et al. (2021)

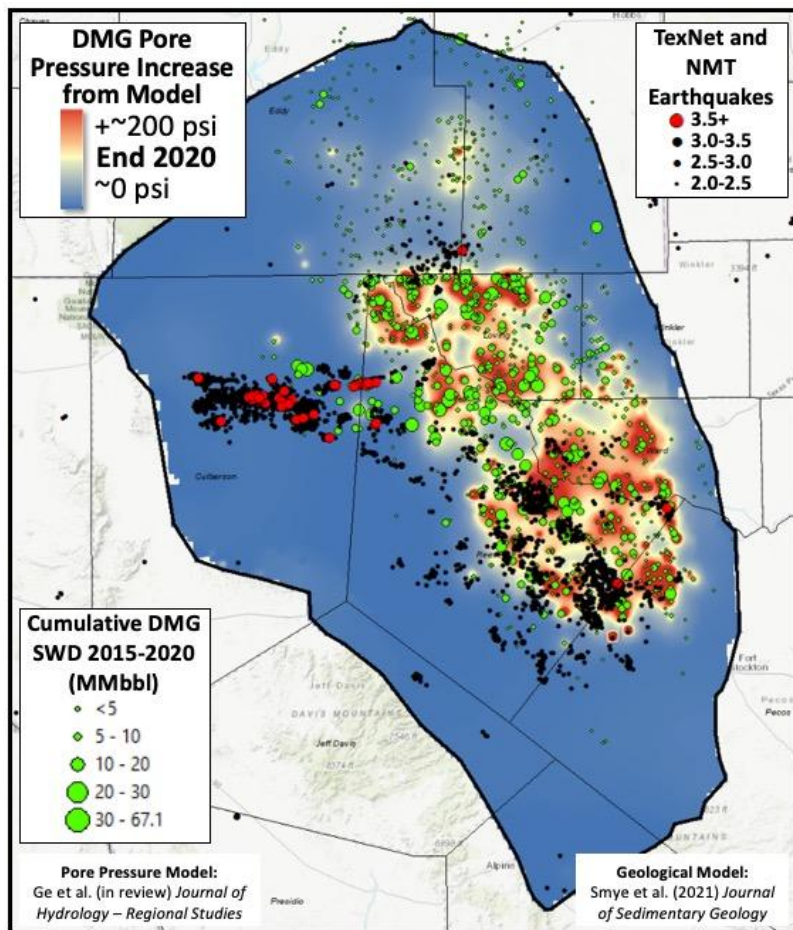
Pore Pressure is Hydrostatic and Normal Faults are in a State of Frictional Equilibrium



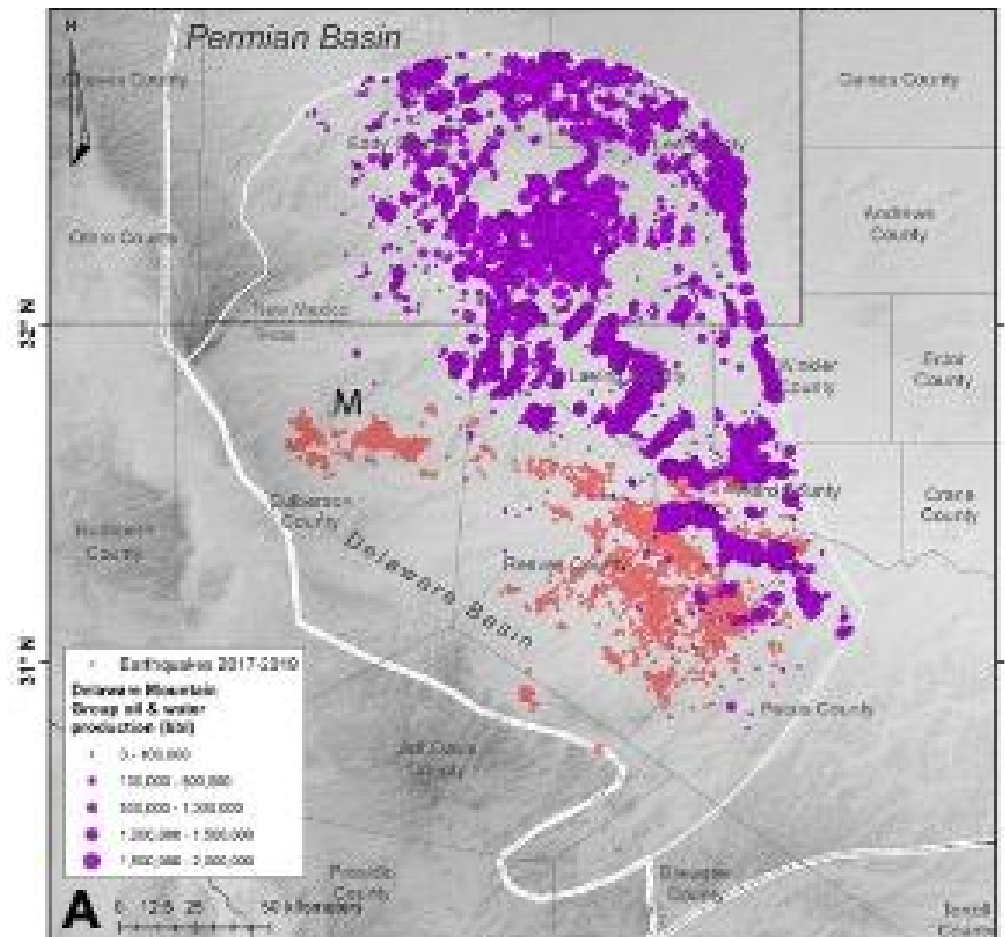
Dvory and Zoback (2021)

Shallow Seismicity in DMG Induced by Very Small Pressure Changes

No Shallow Seismicity Where There Has Been Previous DMG Production

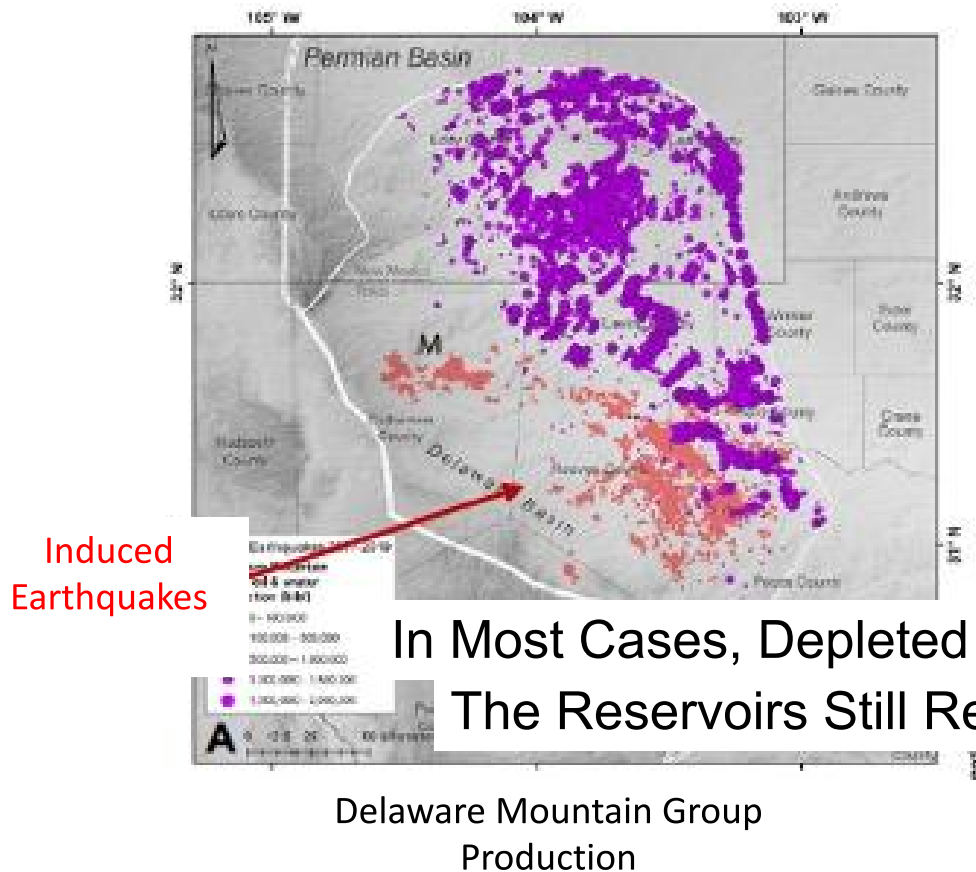


P. Hennings, pers. comm.

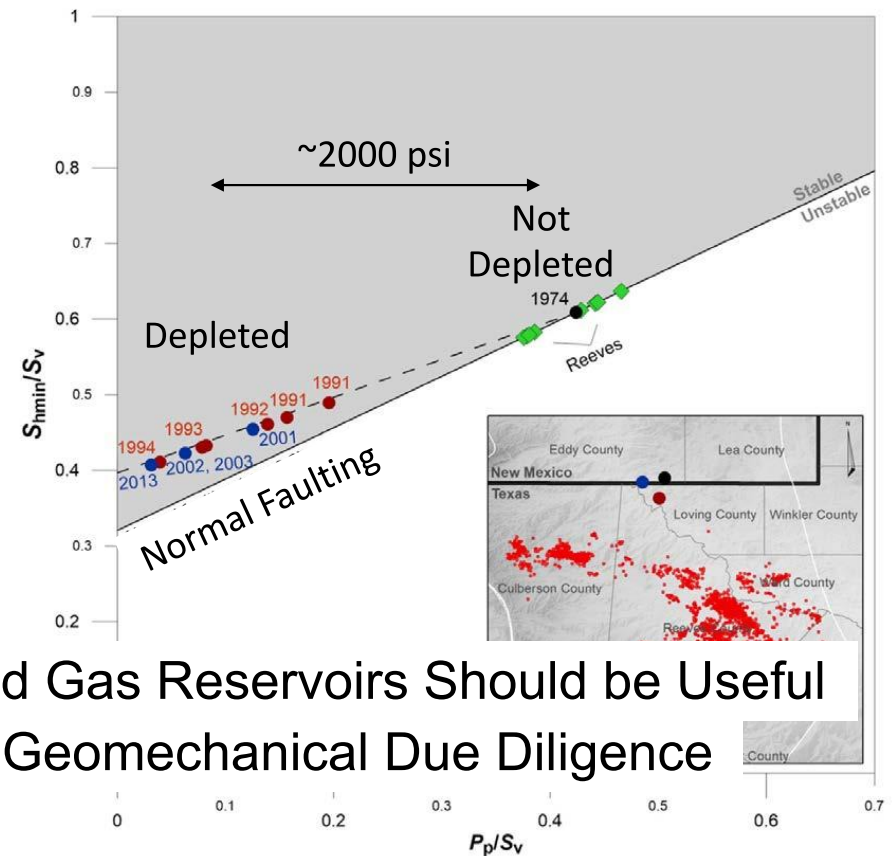


Dvory and Zoback (2021)

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



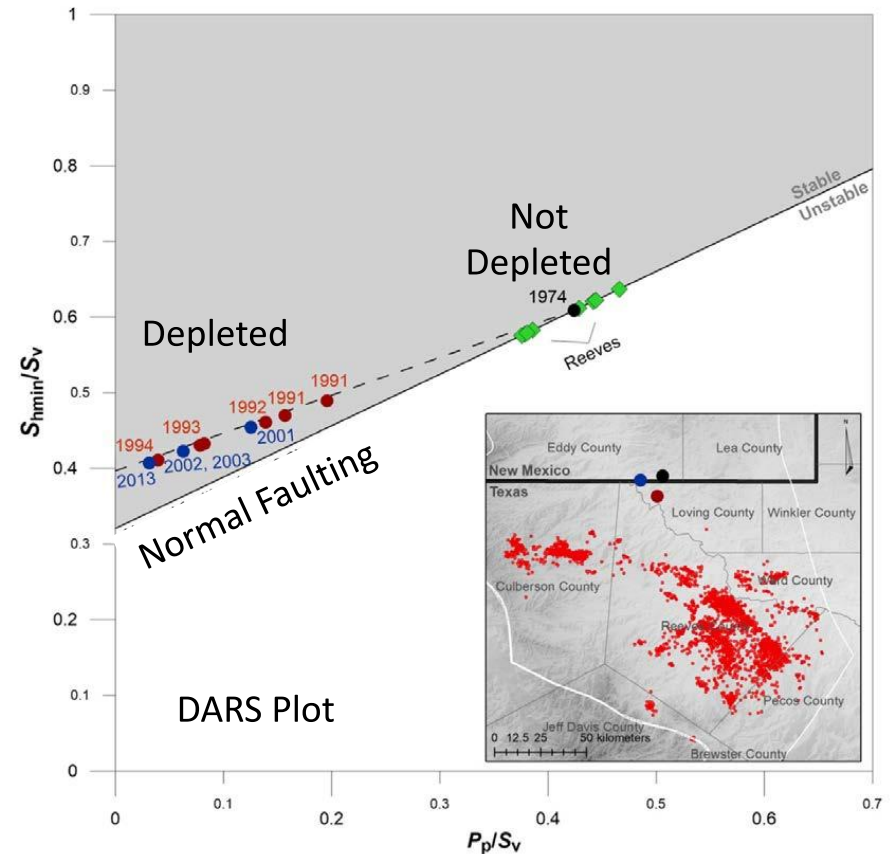
Poroelastic Stress Path Associated with
Depletion Makes Normal Faults More Stable



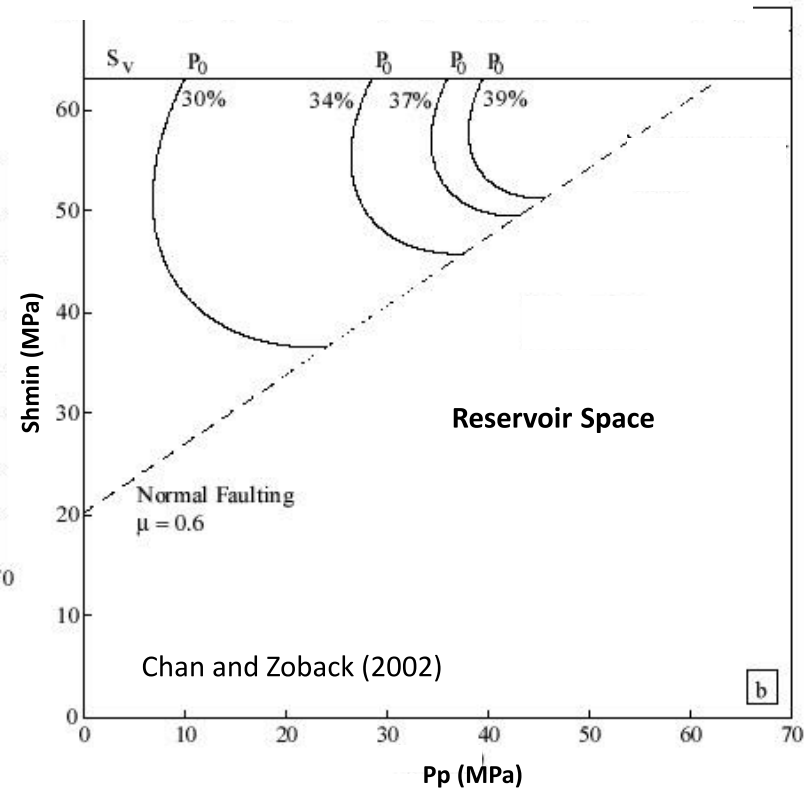
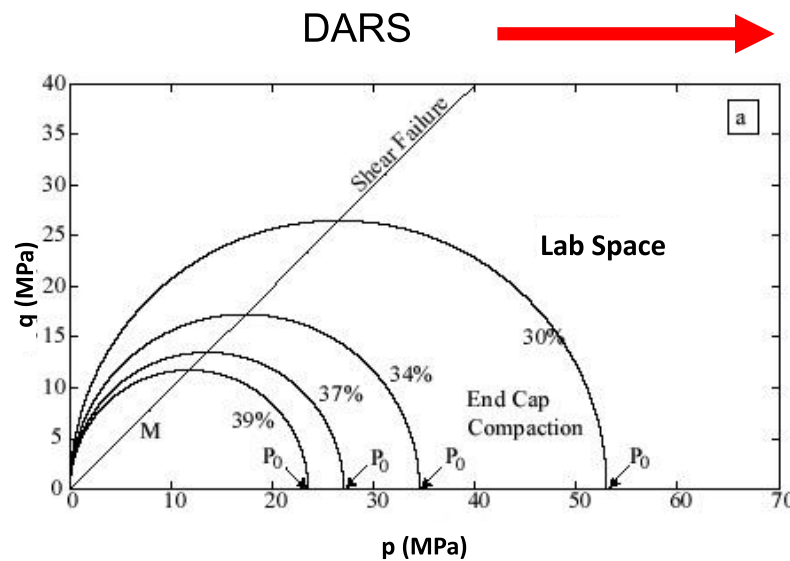
In Most Cases, Depleted Oil and Gas Reservoirs Should be Useful
The Reservoirs Still Require Geomechanical Due Diligence

Deformation Analysis in Reservoir Space (DARS)

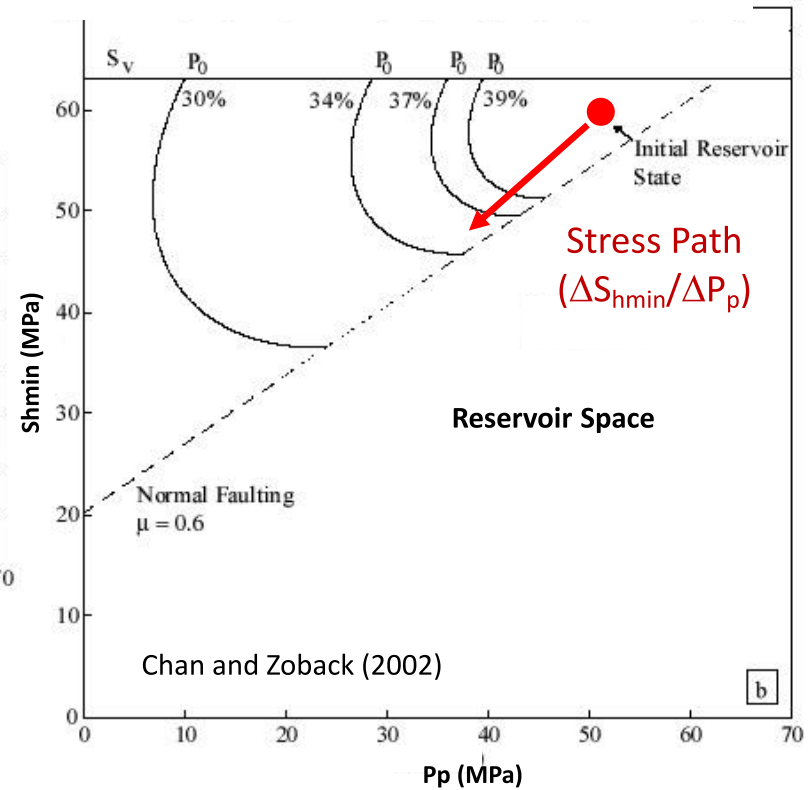
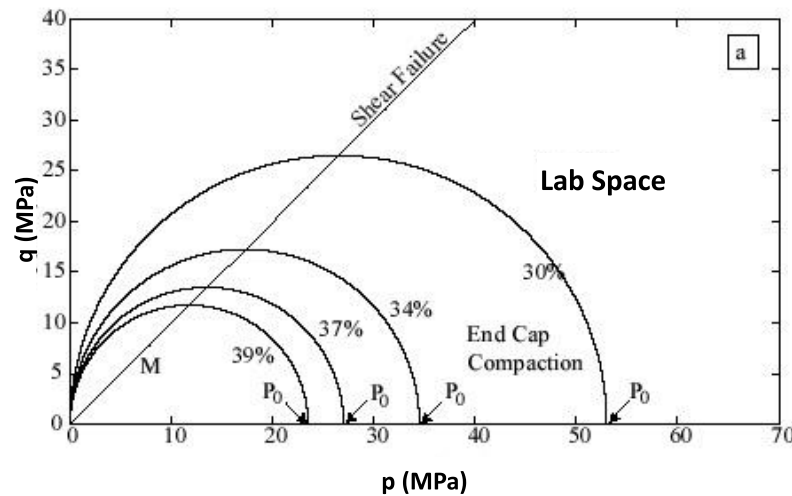
- To understand the deformation mechanisms of a producing reservoir utilizing relatively simple laboratory tests and in situ measurements
- DARS is a formalism for estimating the evolution of porosity (and permeability) and the potential for induced normal faulting in a producing reservoir



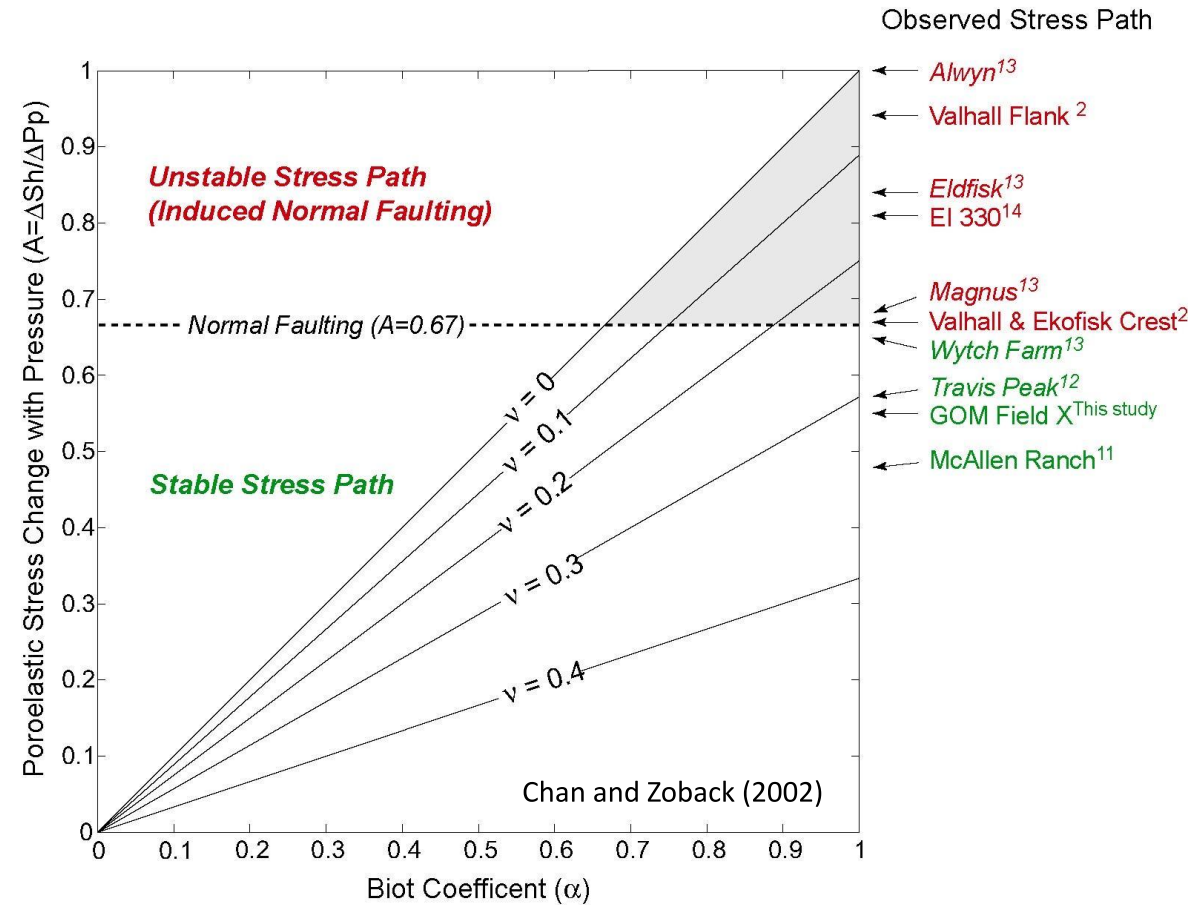
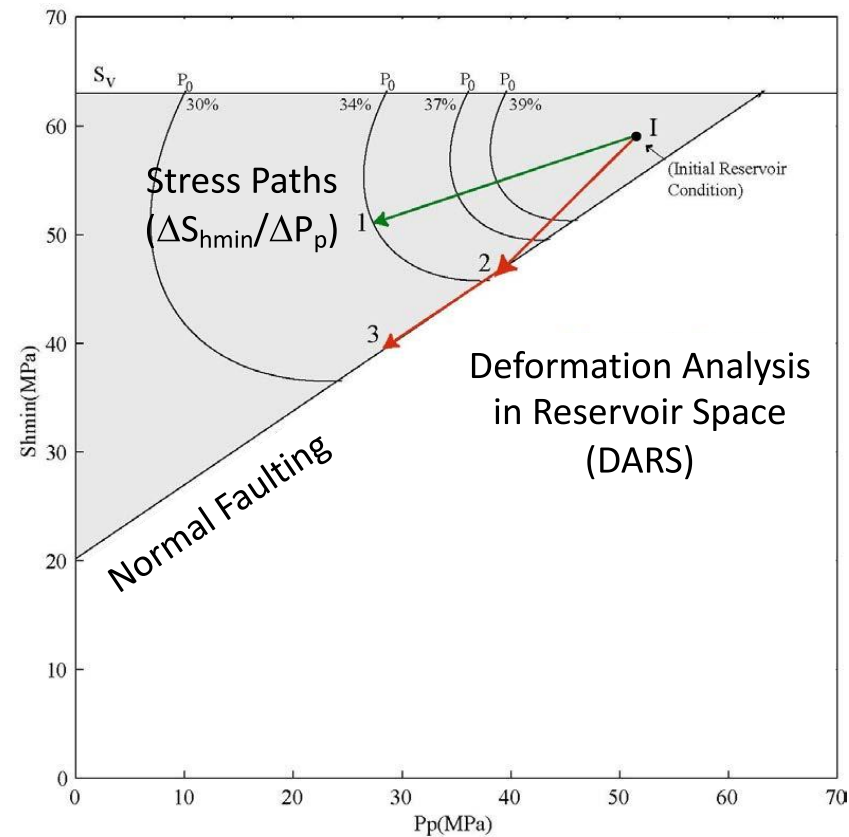
Deformation Analysis in Reservoir Space (DARS)



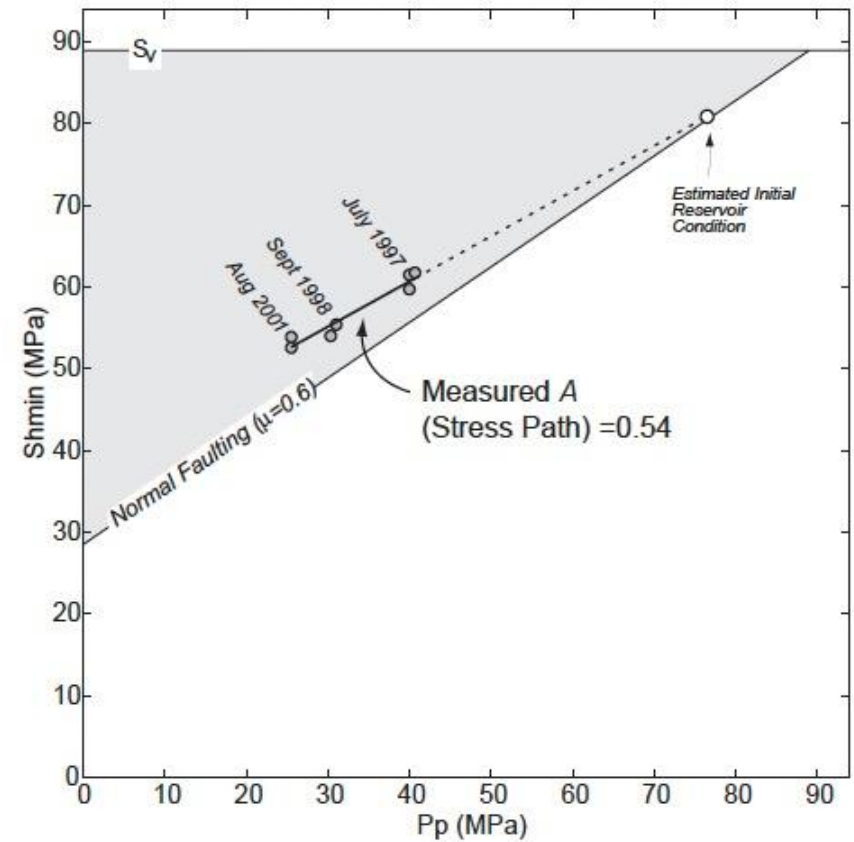
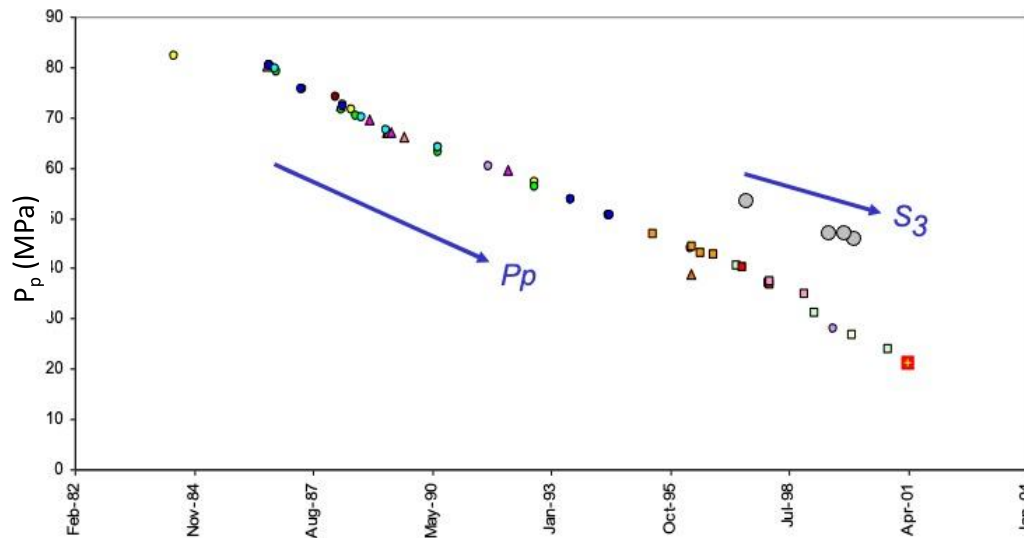
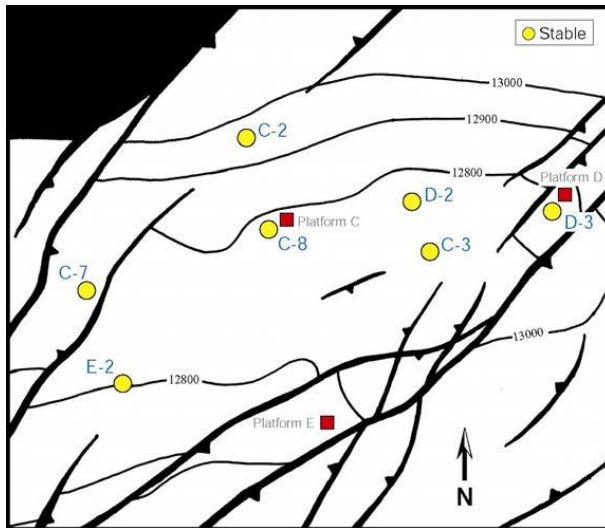
Deformation Analysis in Reservoir Space (DARS)



Deformation Analysis in Reservoir Space (DARS)

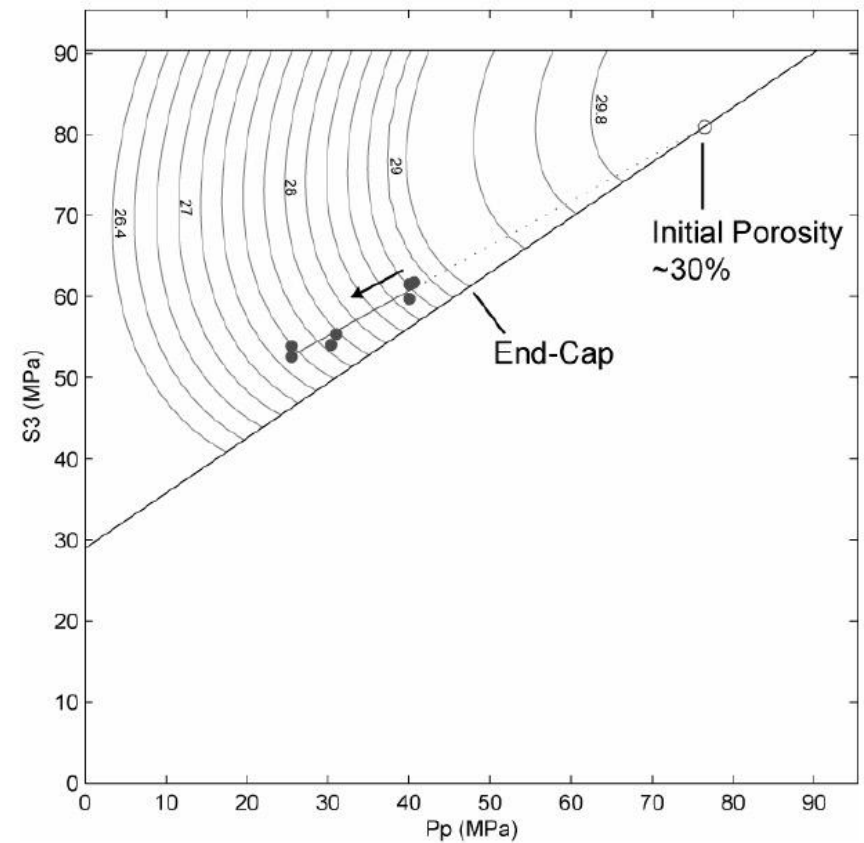
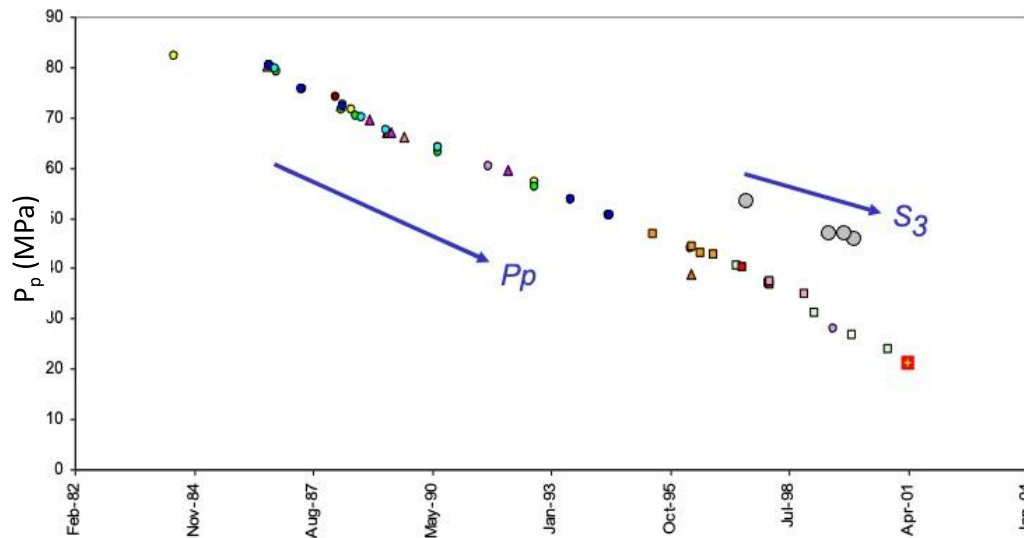
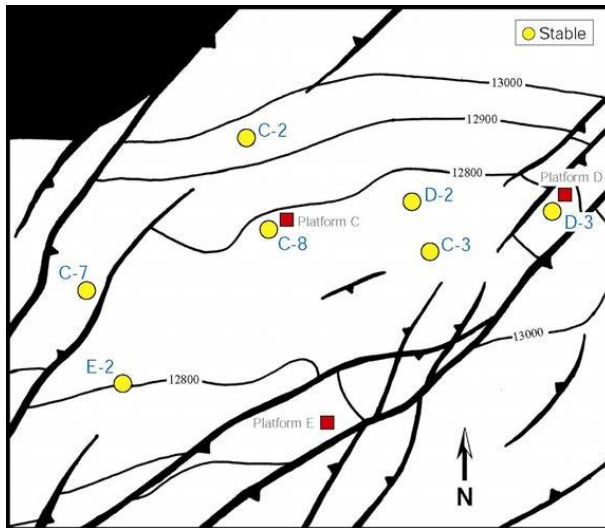


DARS Applied to a GOM Offshore Field



Zoback (2007)

DARS Applied to a GOM Offshore Field

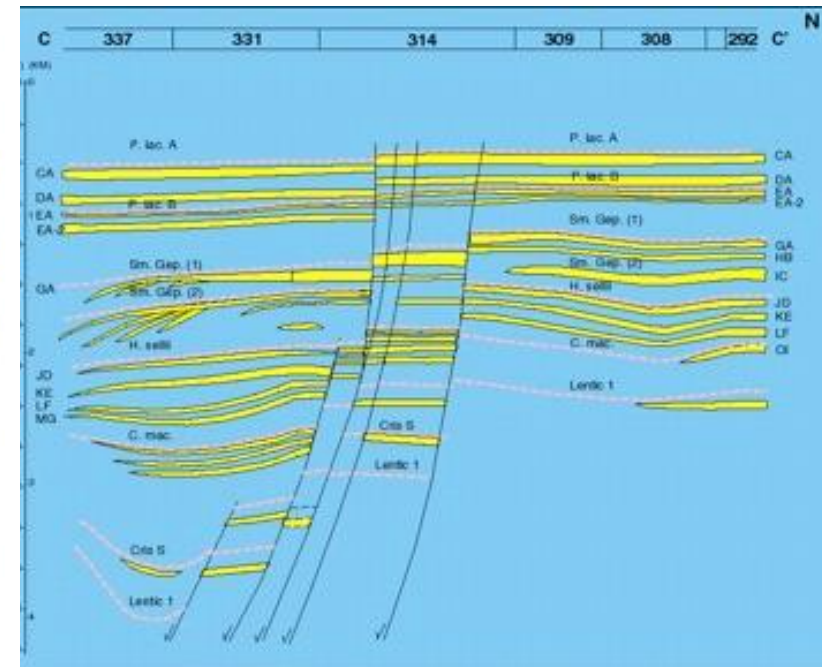
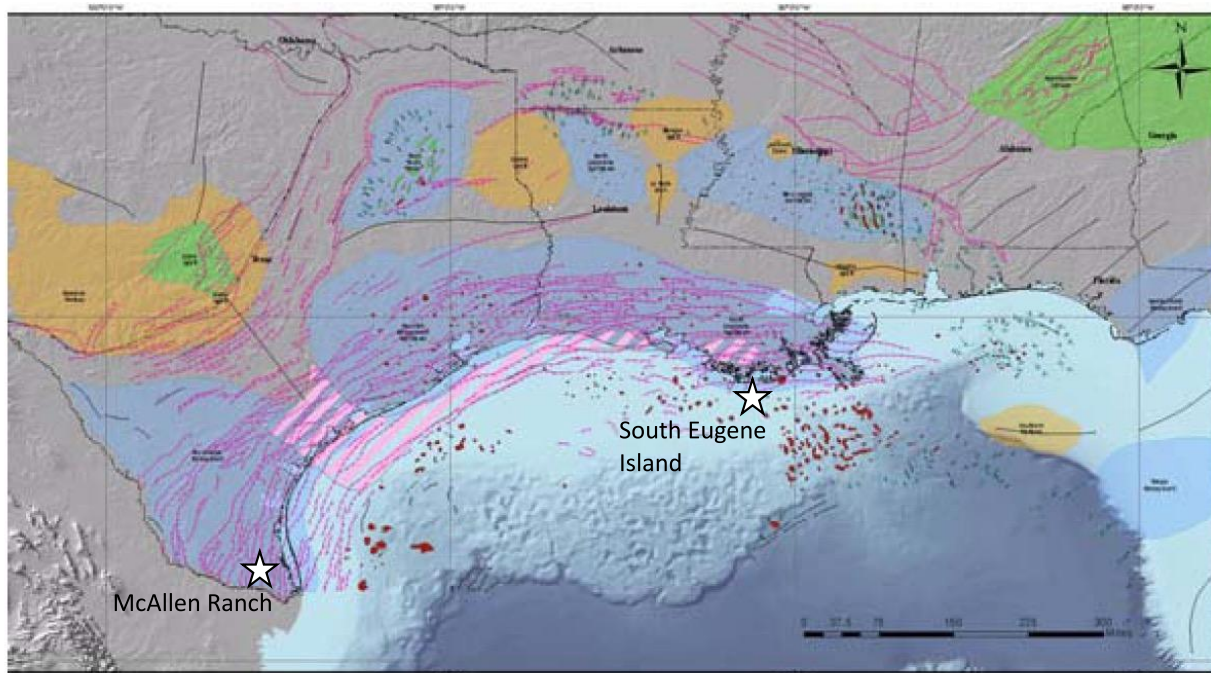


Zoback (2007)

Topics – Massive Scale CCS from a Geomechanical Perspective

- The Need for Massive Scale for Carbon Storage
- Saline Aquifers
 - Basal Aquifers and the Critically-Stressed Crust
 - Lessons from Induced Seismicity in Oklahoma
 - Geomechanical Characterization
 - Lessons from Induced Seismicity in the Delaware Basin
- Depleted Oil and Gas Reservoirs
 - How Poroelastic Stress Changes Limit Induced Seismicity
 - How Past Production has Affected Potential CCS Reservoirs
- Progress to Date

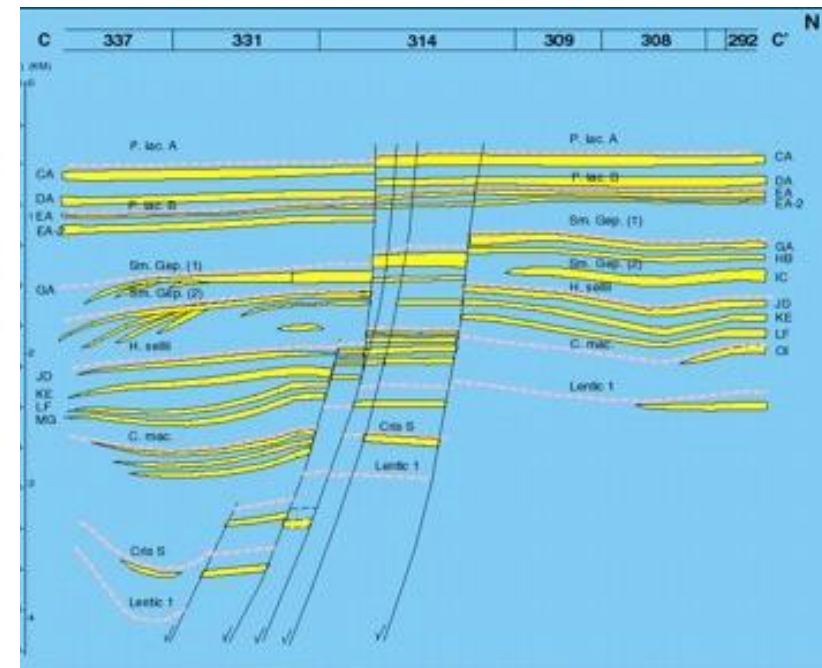
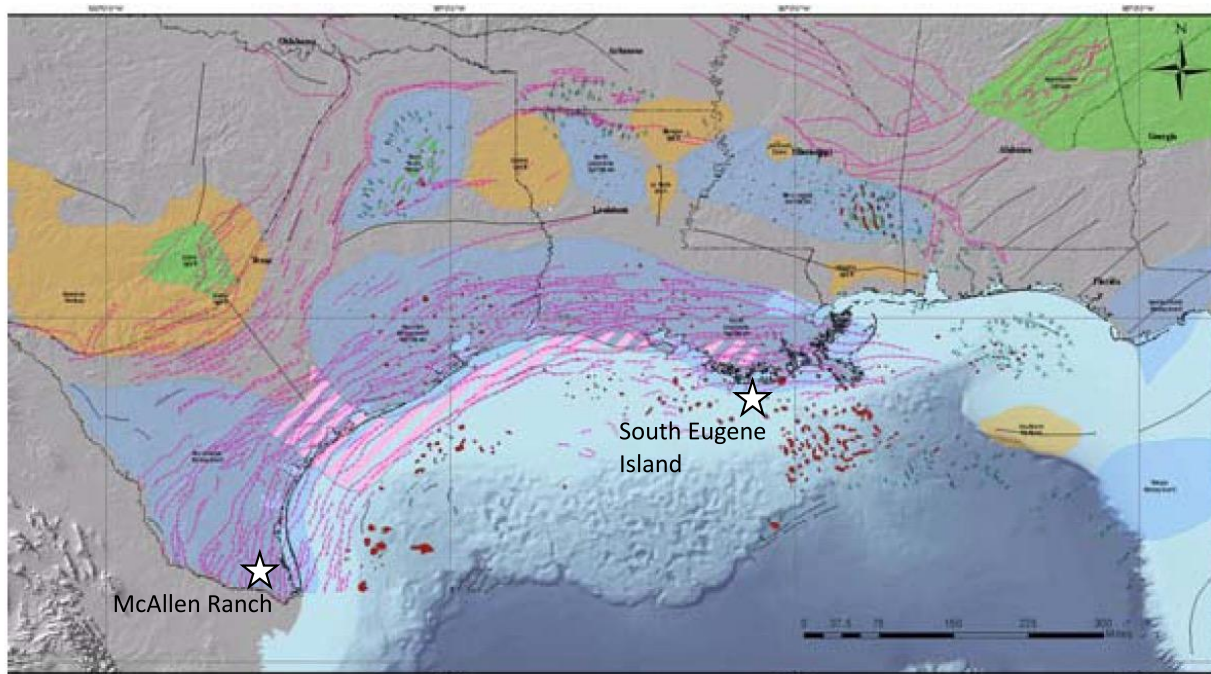
Weak Sands of the Gulf of Mexico



The Good News:

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

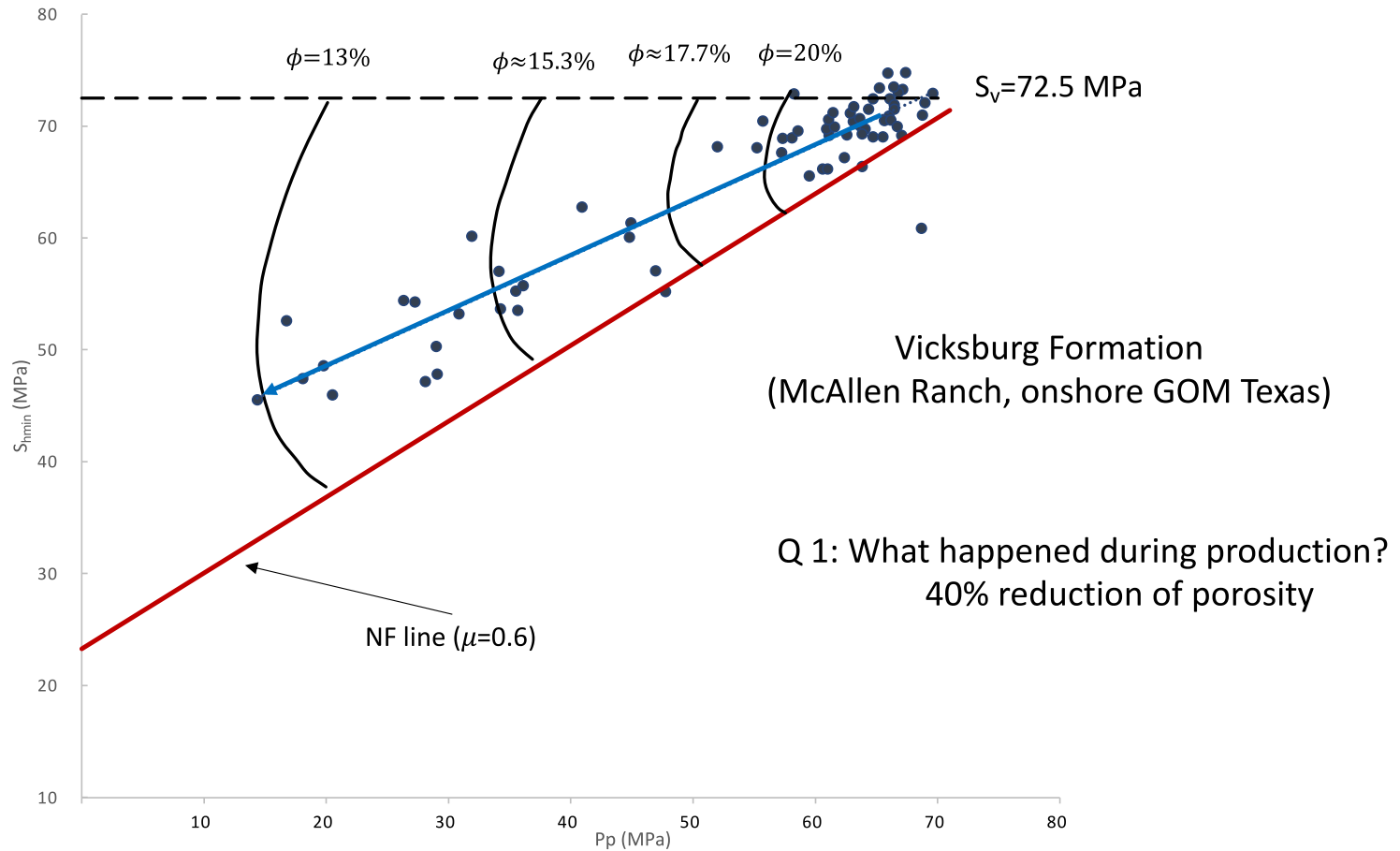
Weak Sands of the Gulf of Mexico



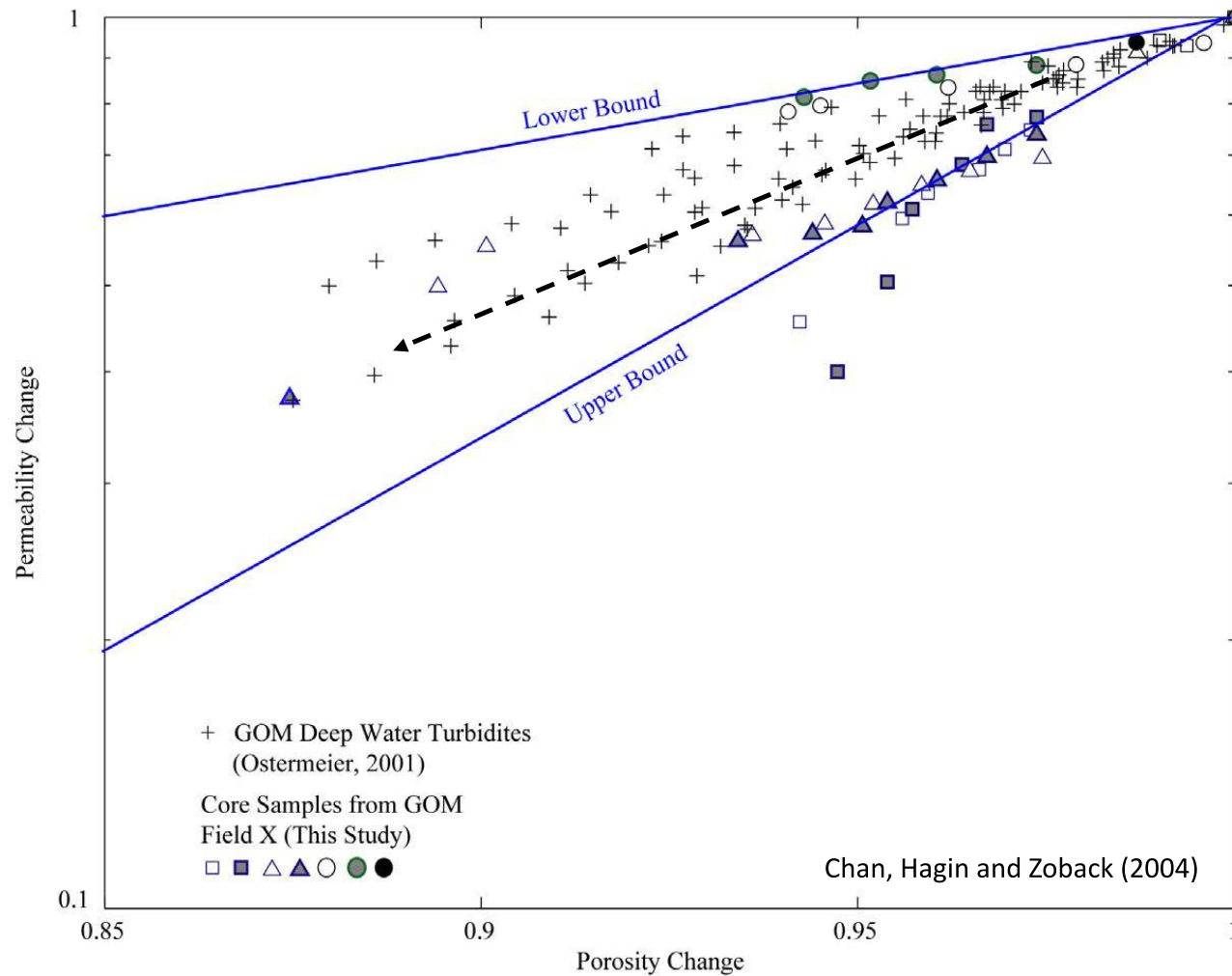
Requires Further Study:

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

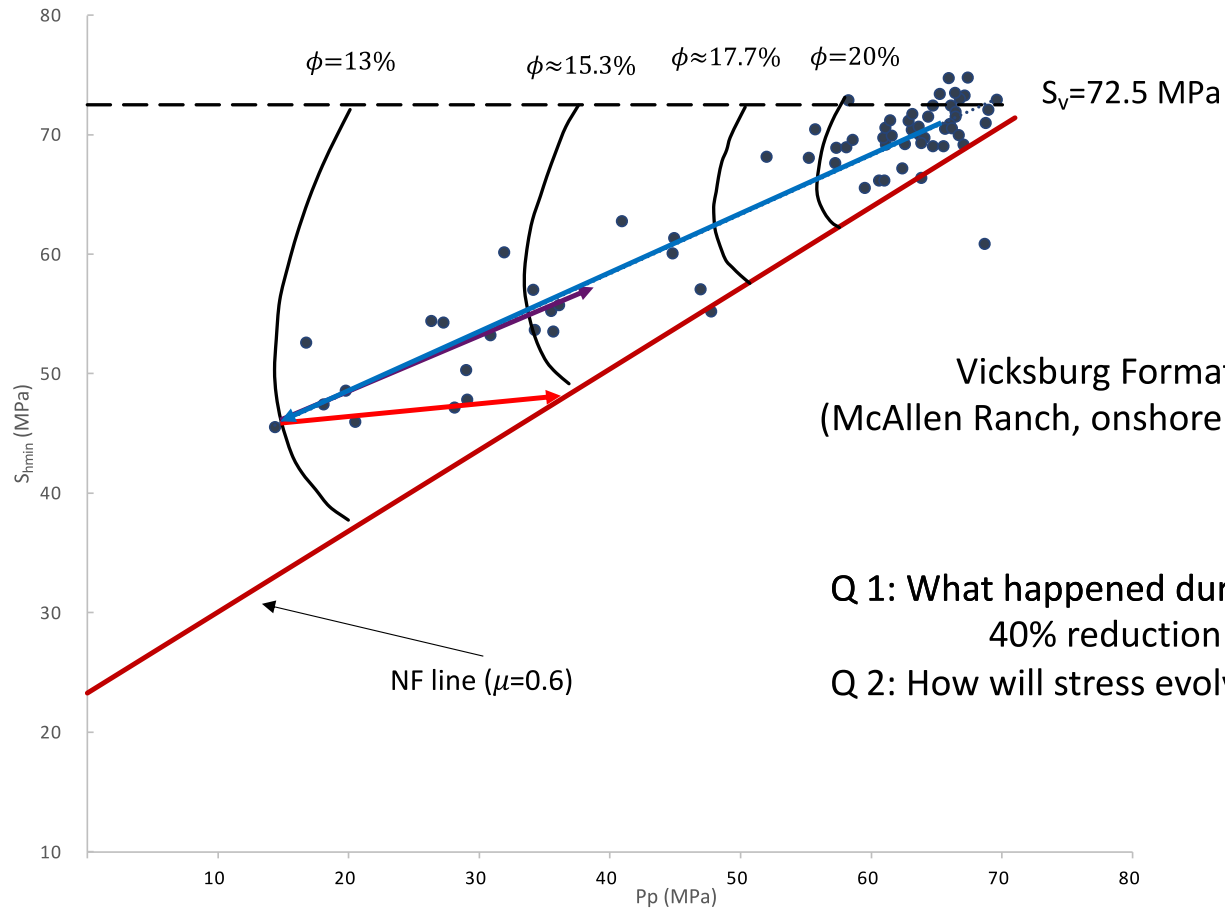
Depletion and Stress Path in Reservoir Space

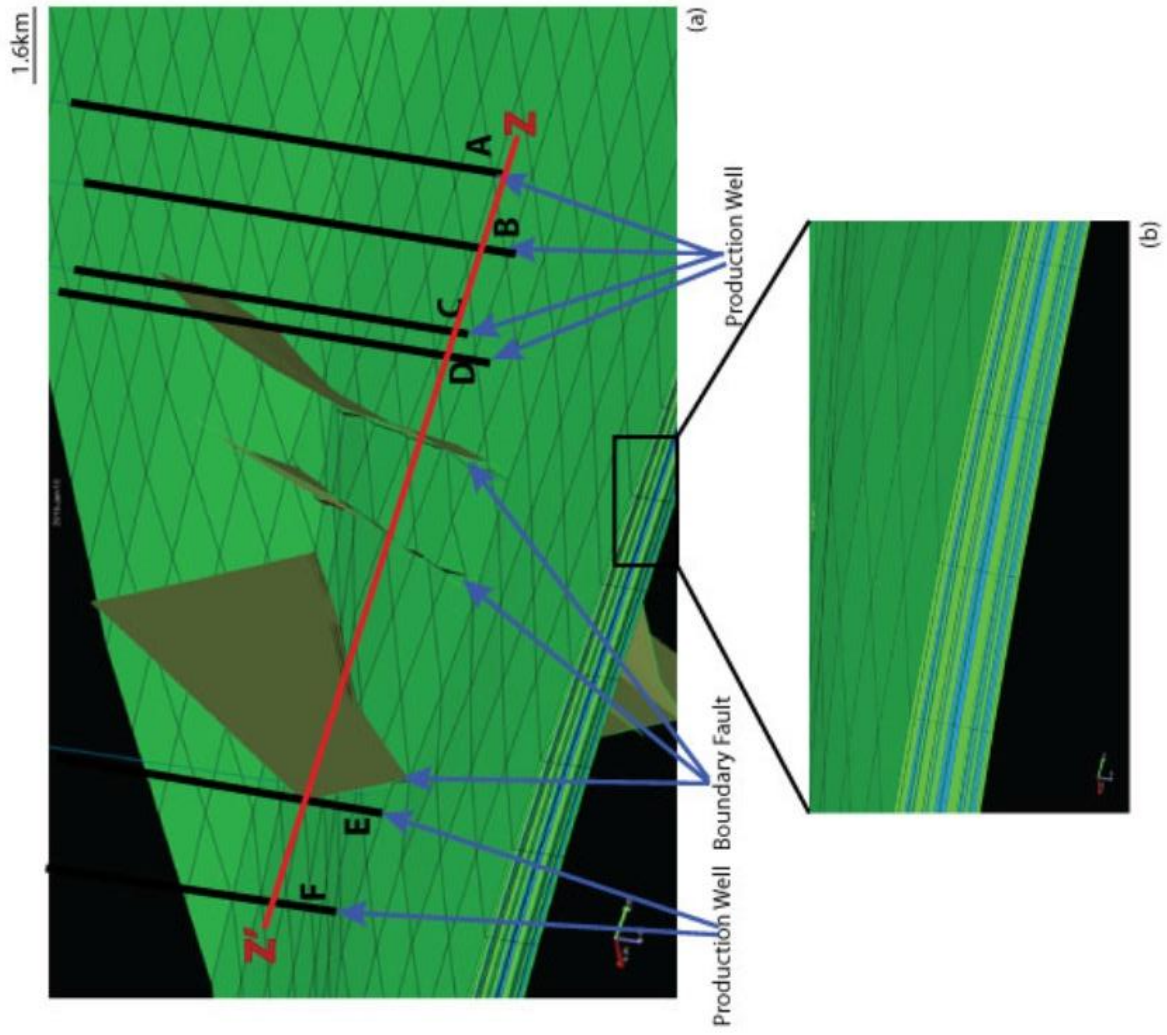


Compaction and Permeability Loss in Weak GOM Sands

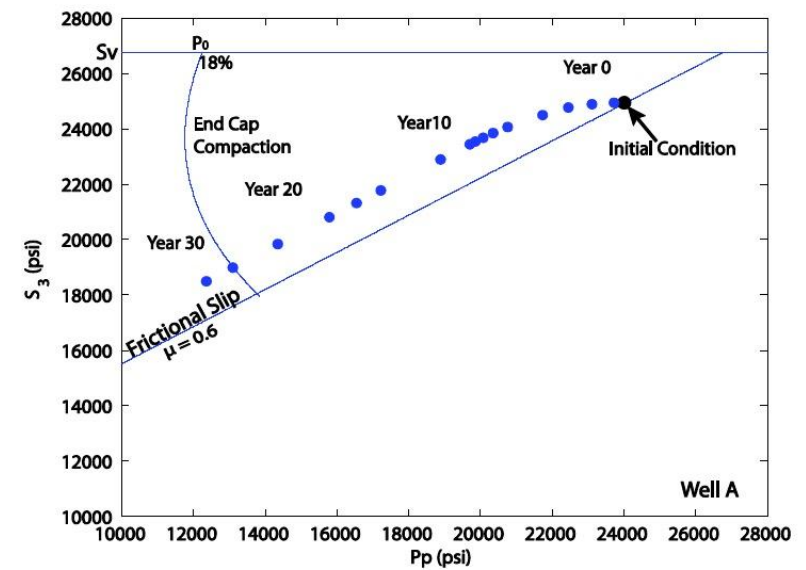
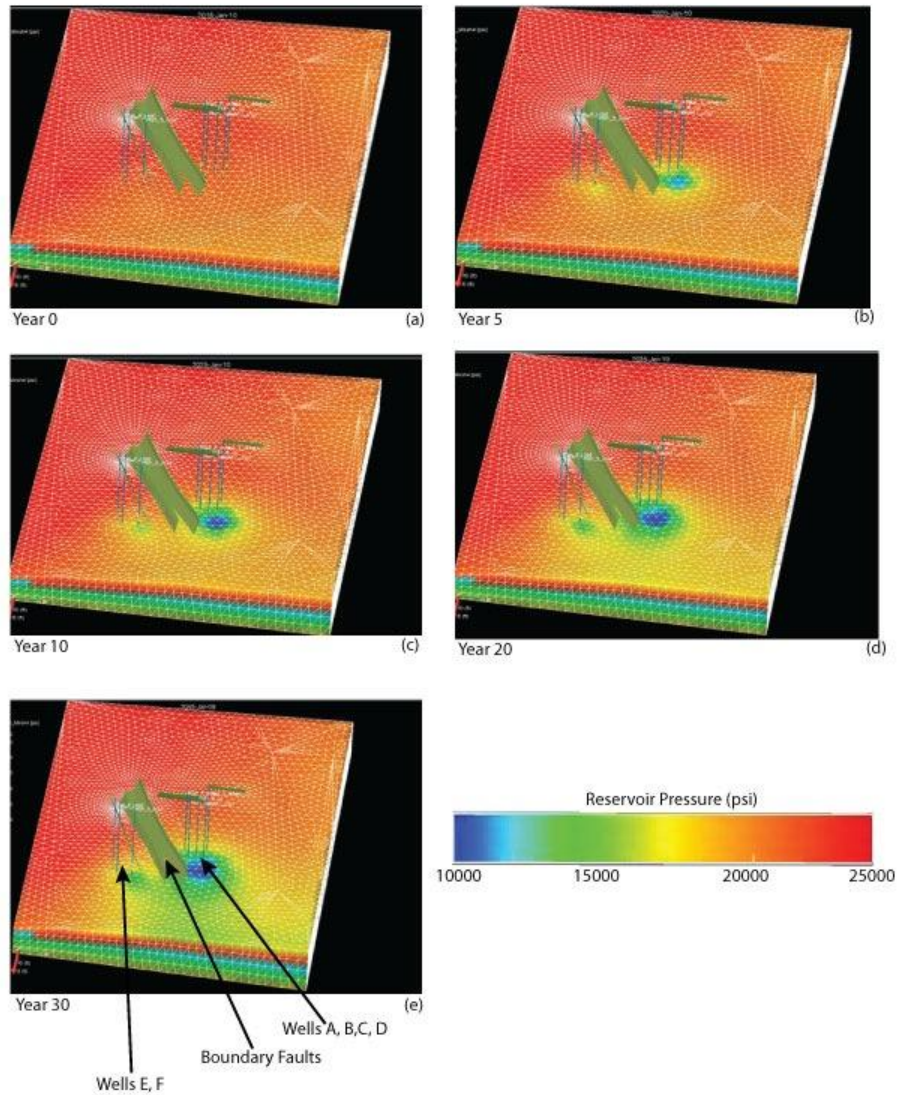


Depletion and Stress Path in Reservoir Space

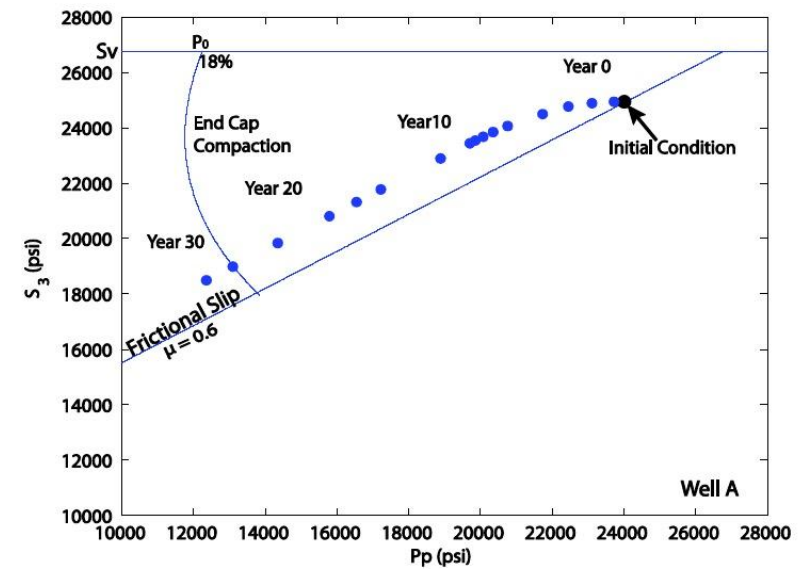
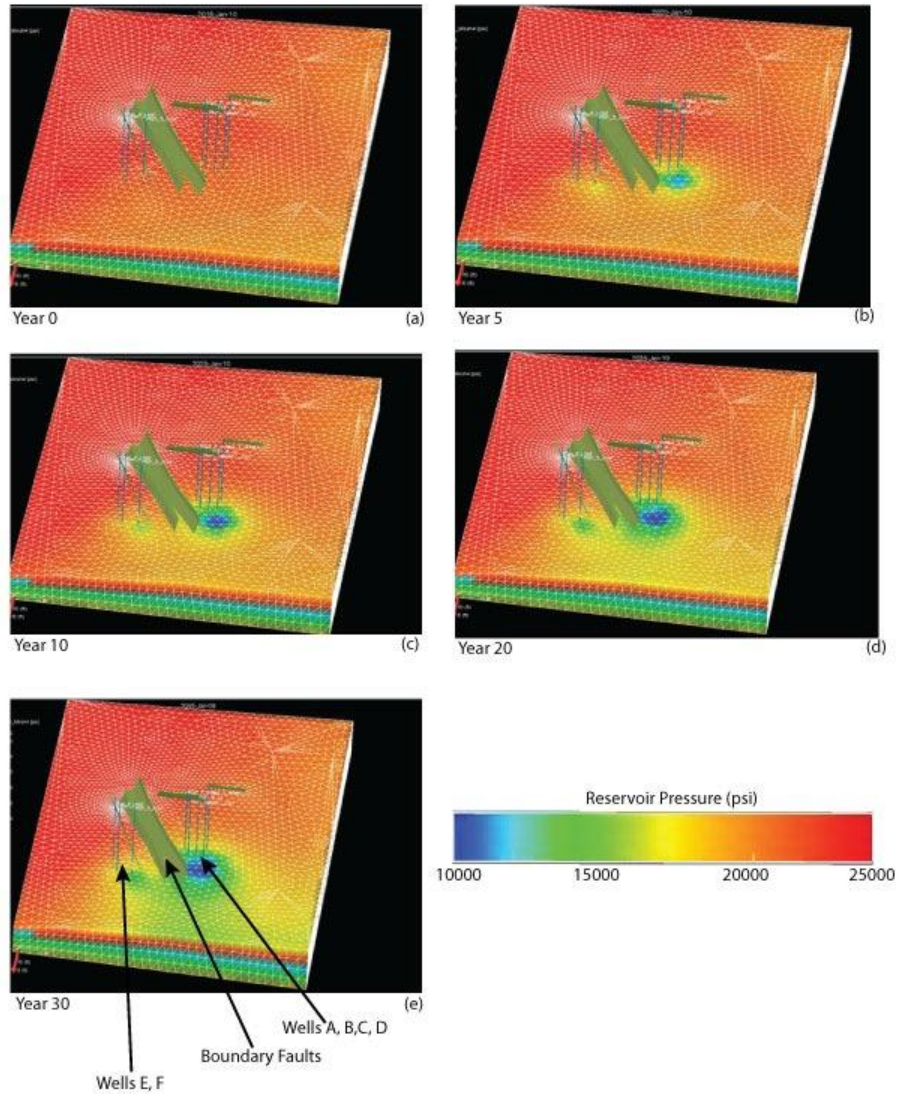




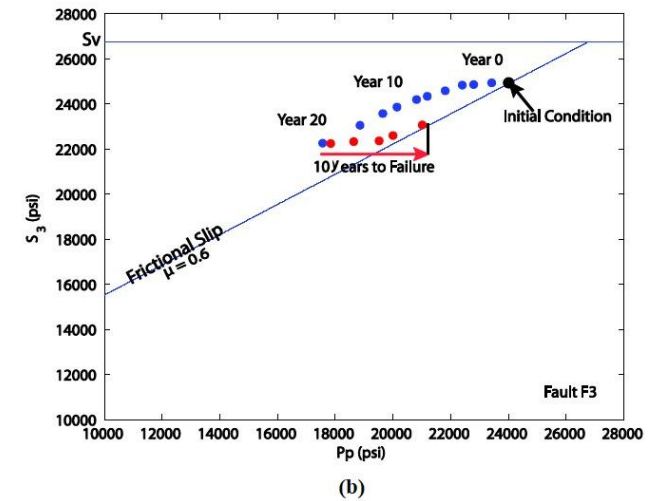
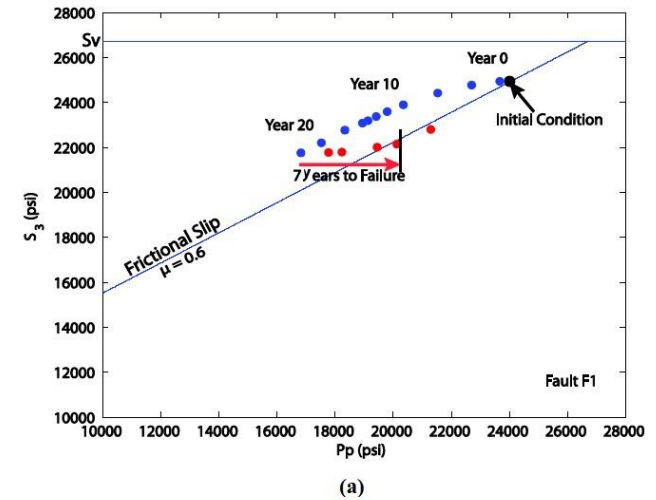
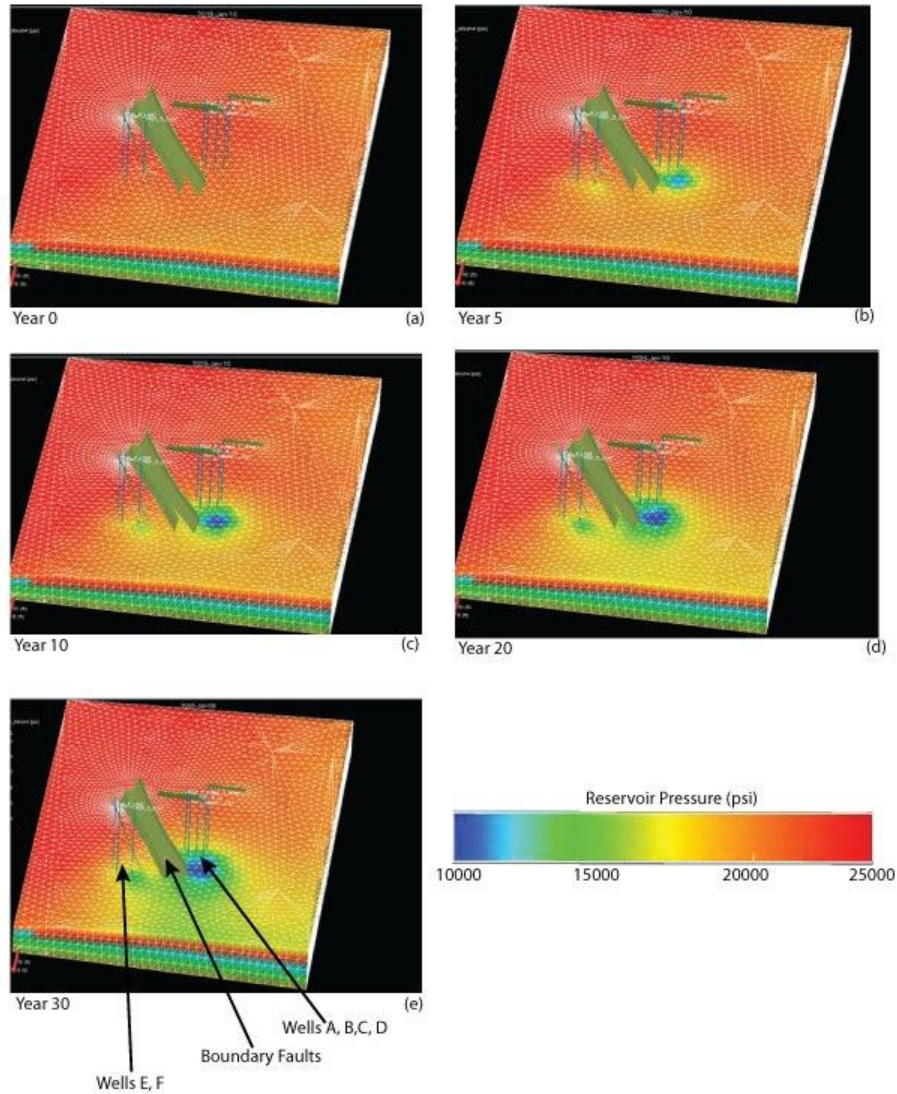
Why Curvature of Stress Path?



What Does This Mean for Injection?



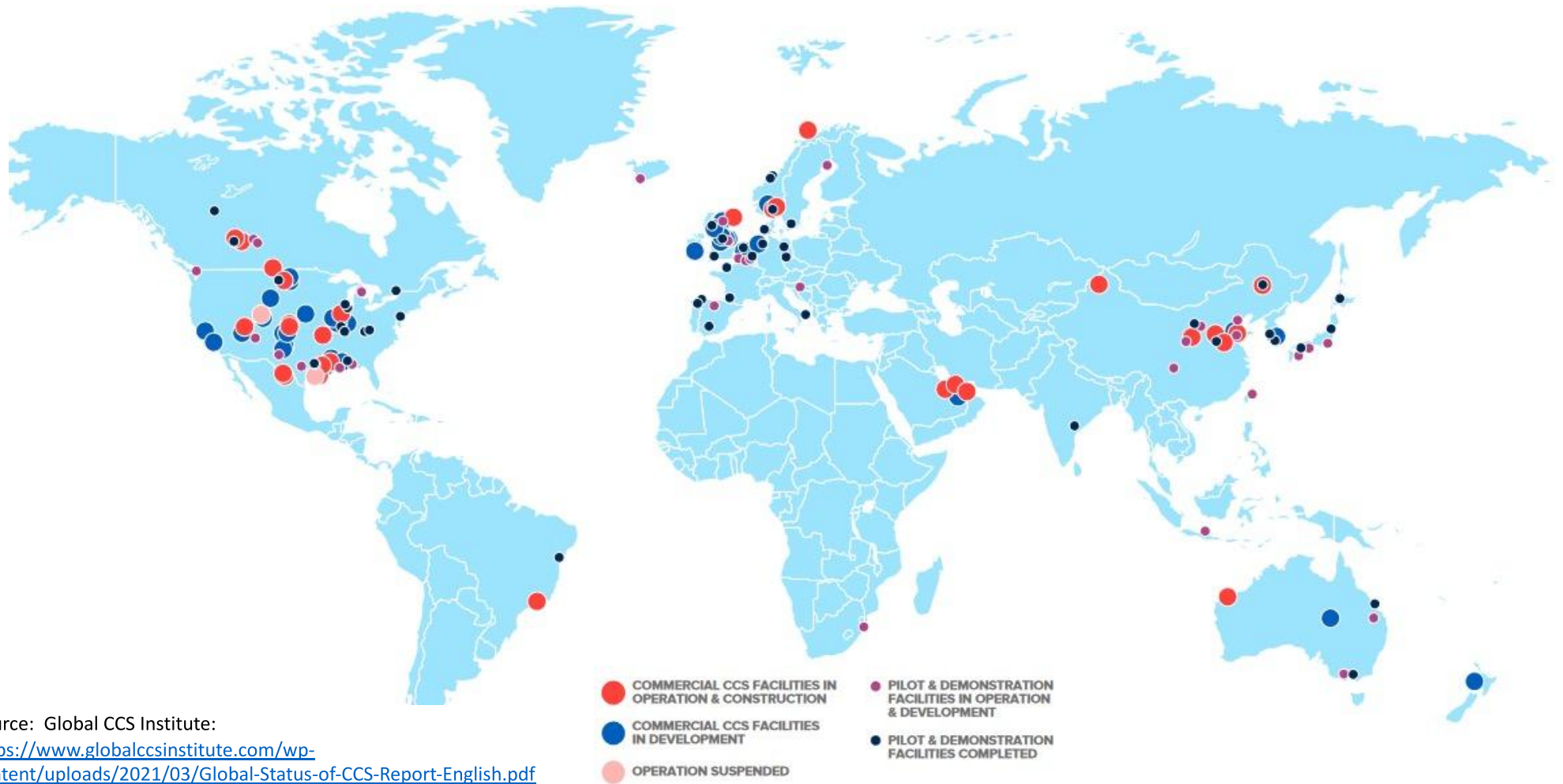
Faulting Induced Before Initial Reservoir Pressure is Reached



Topics – Massive Scale CCS from a Geomechanical Perspective

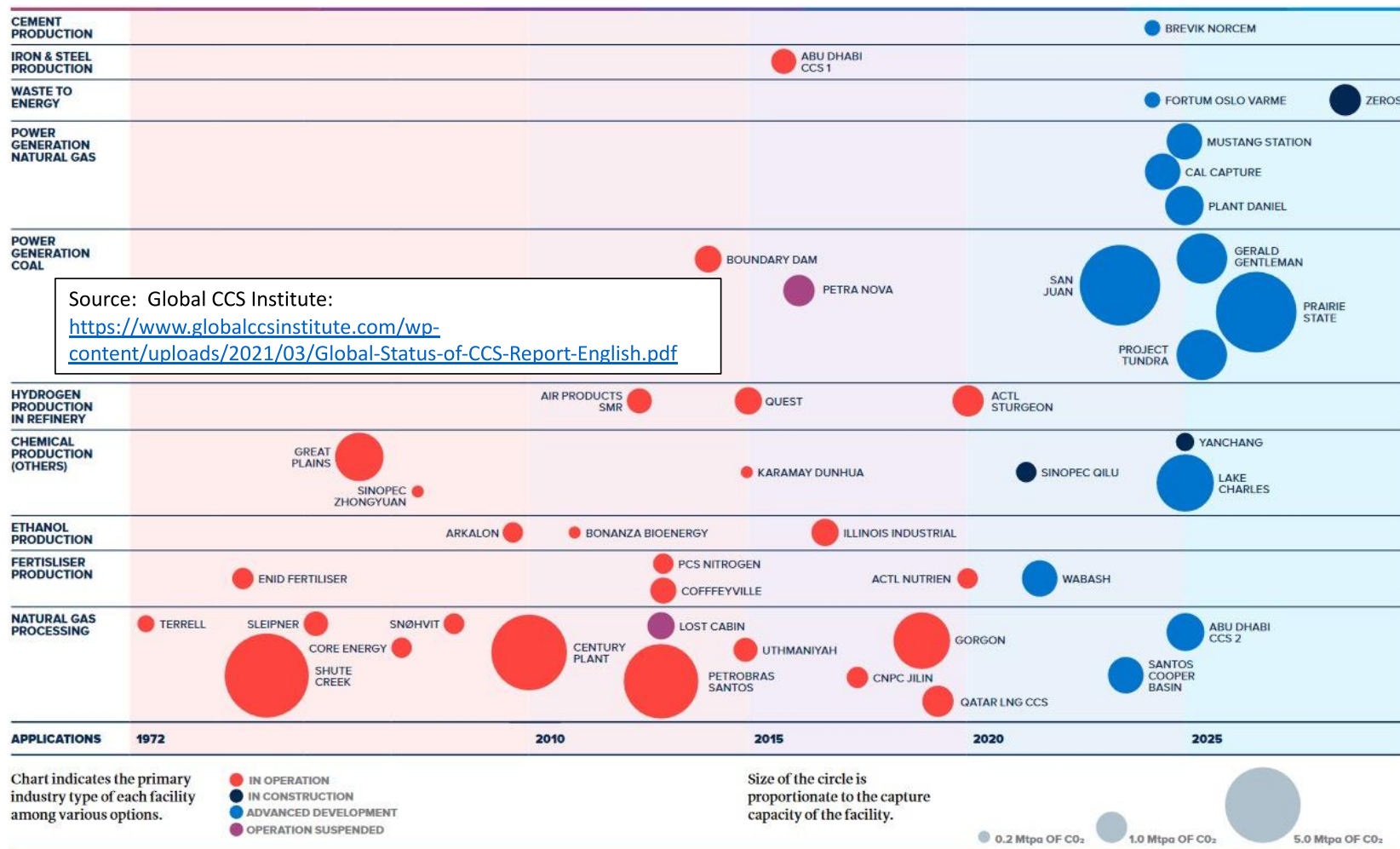
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Global CCS Projects 2020



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

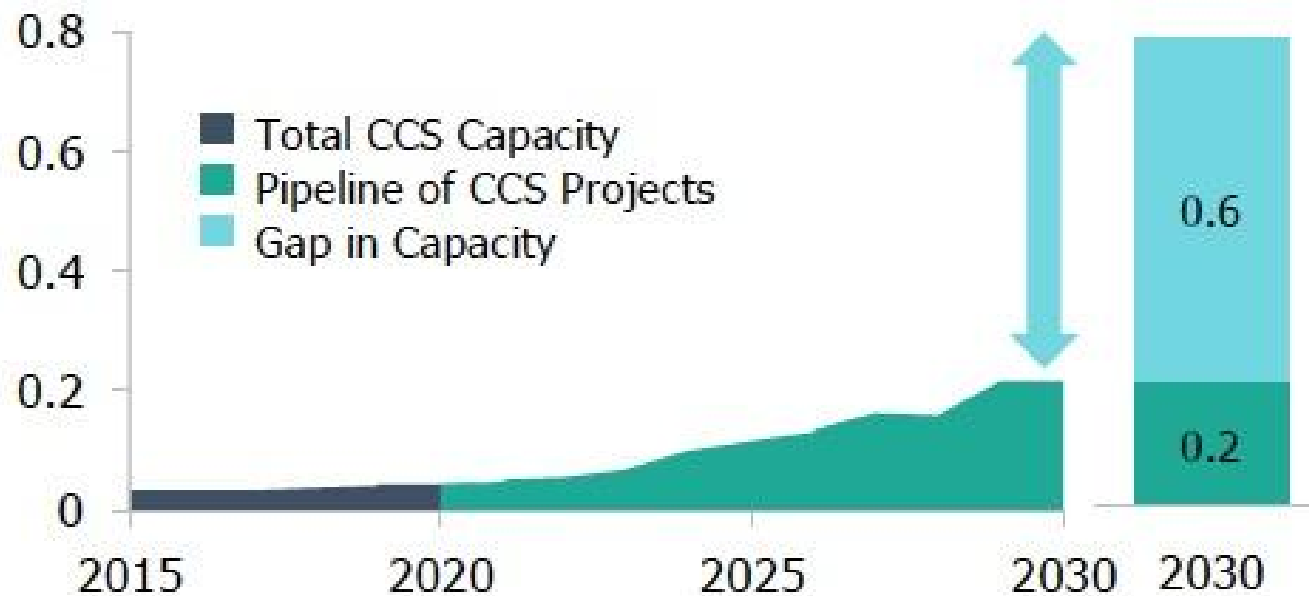
Global CCS Projects 2020



If all these new planned projects go forward, the total injection capacity would increase by 175 MtCO₂/yr

Global Carbon Capture Capacity

GtCO₂ per year



There is a large gap (0.6 GtCO₂ per year) between industry targets and the capacity of CCS projects currently being planned.

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

Thank you

