Assessing Potential Magnitudes of Injection-Induced Seismicity

Mark D. Zoback
Benjamin M. Page Professor of Geophysics
Stanford University

Co-Director, Stanford Center for Induced and Triggered Seismicity

Schatzalp Conference, Davos
March 15-17, 2017

Topics

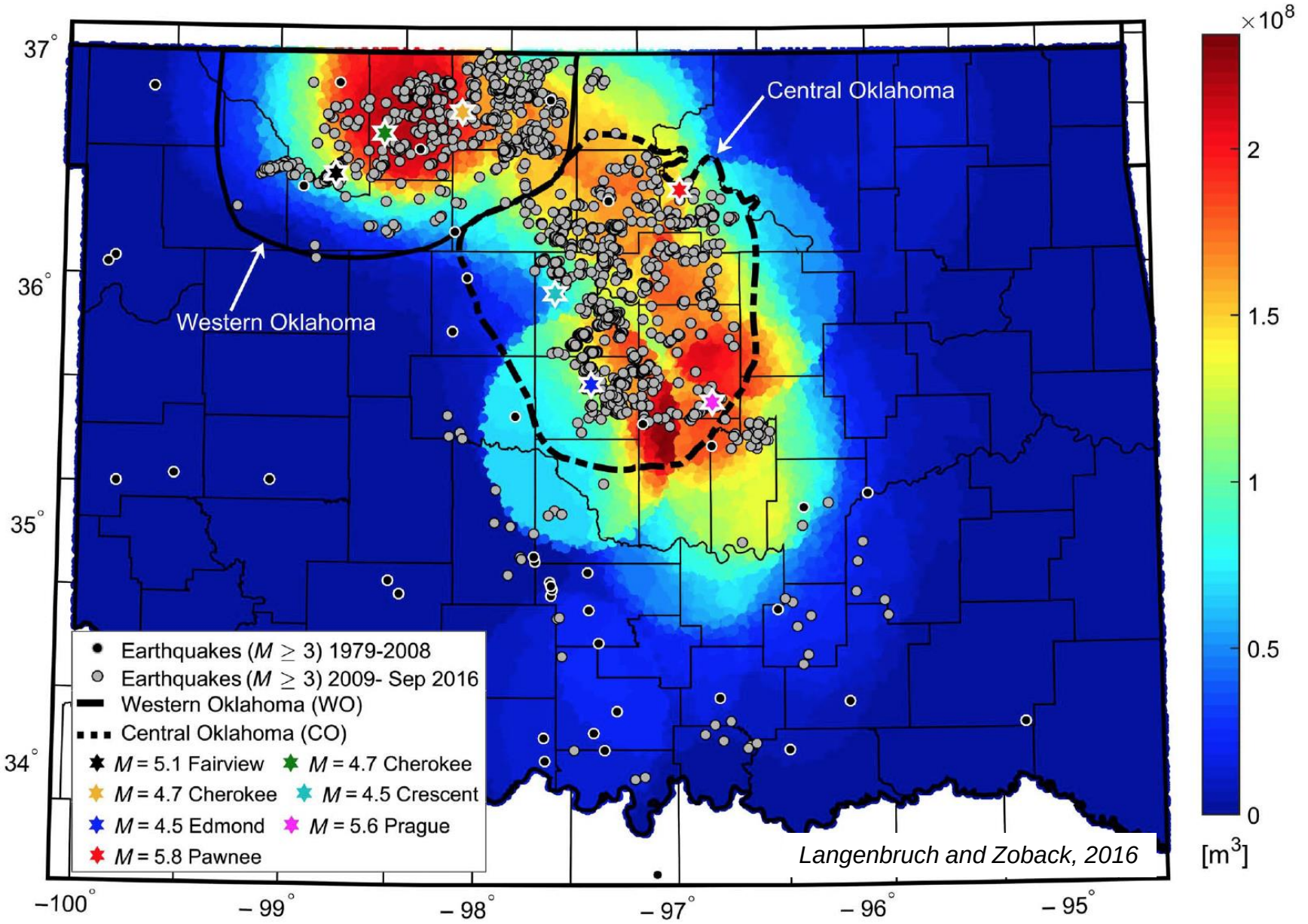
1. The Stress Field Matters - Identification (and Avoidance) of Potentially Active Faults Especially Those That May Extend into Crystalline Basement

   Rall Walsh and M. Zoback, Geology (2016)
   Fault Slip Potential (FSP) Software,
   released to the public March 6, 2017
   J-E Lund Snee and M. Zoback, GRL (2016)

2. The Rocks Matter –Viscoplasticity and the Velocity Strengthening Frictional Behavior of Some Sedimentary Rocks Can Limit the Extent of Seismic Rupture

   Hiroki Sone, Arjun Kohli, Xiaodong Ma
   Fatemeh Rassouli, Shaochuan Xu

Strong Correlation Between Seismicity and SWD ($\Delta P < 2$ MPa see Poster P2-16)



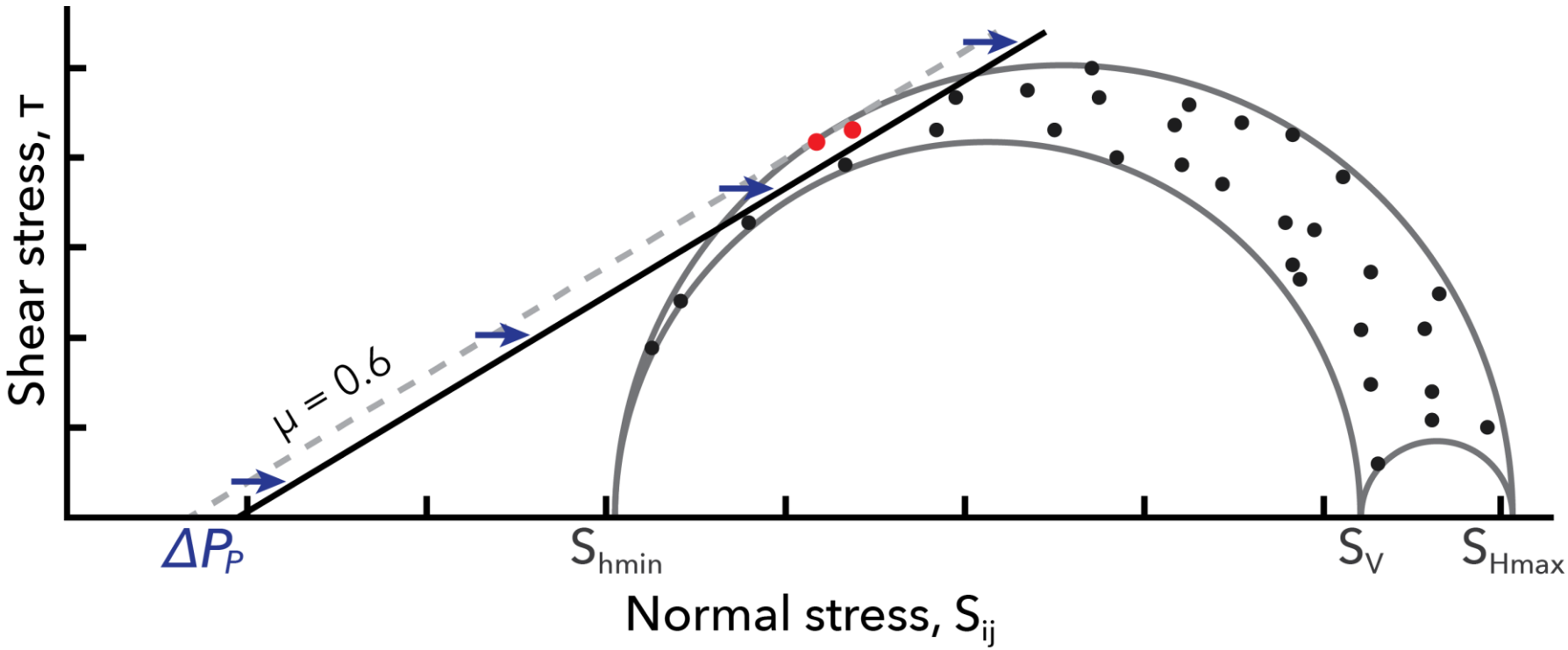
THE GEOLOGICAL SOCIETY OF AMERICA®

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

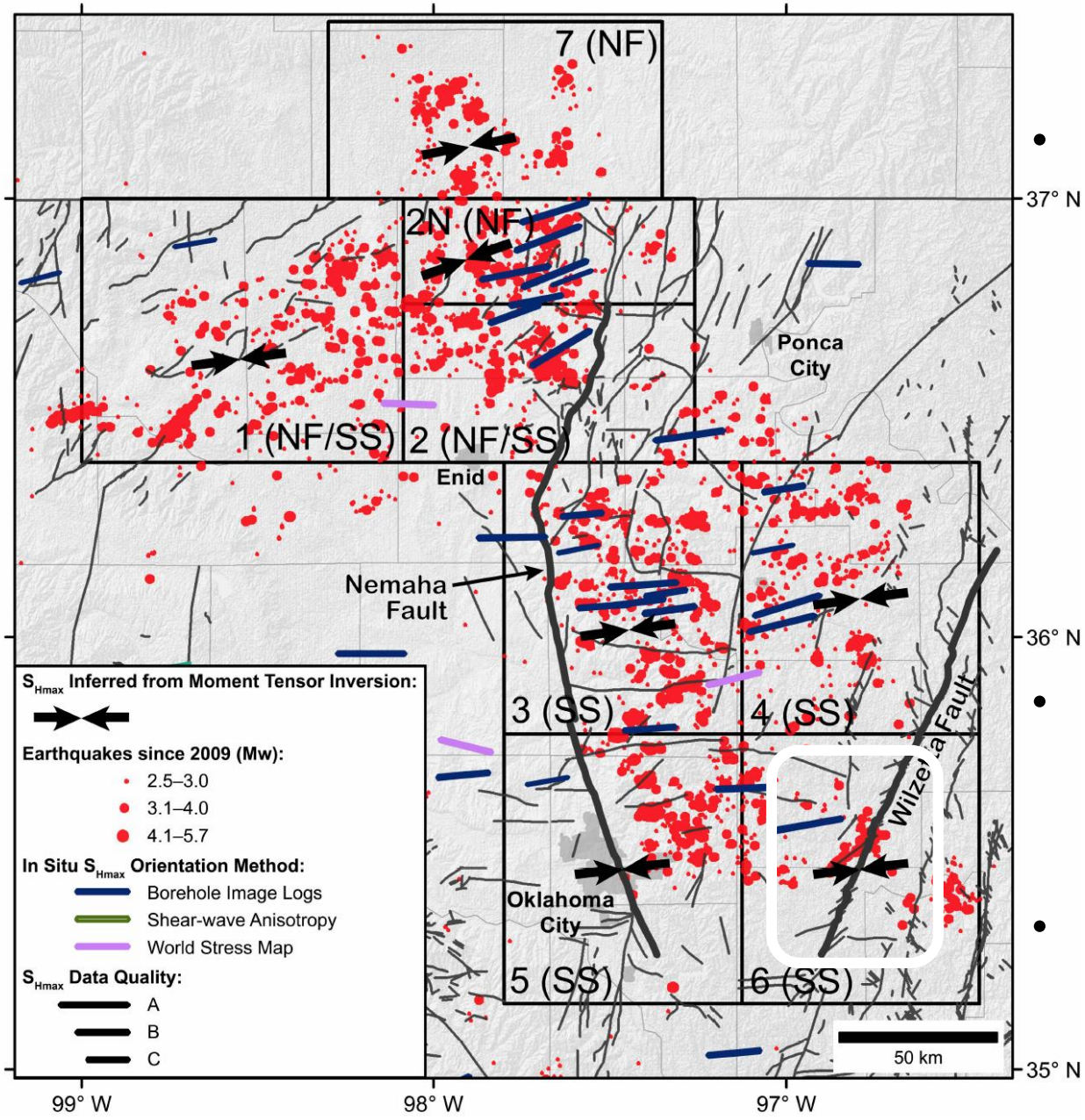
F. Rall Walsh, III, and Mark D. Zoback
Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, California 94305, USA

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

What is the Probability That a Modest* ΔP_P Might Make a Known Pre-Existing Fault Slip (Prior to Injection)?



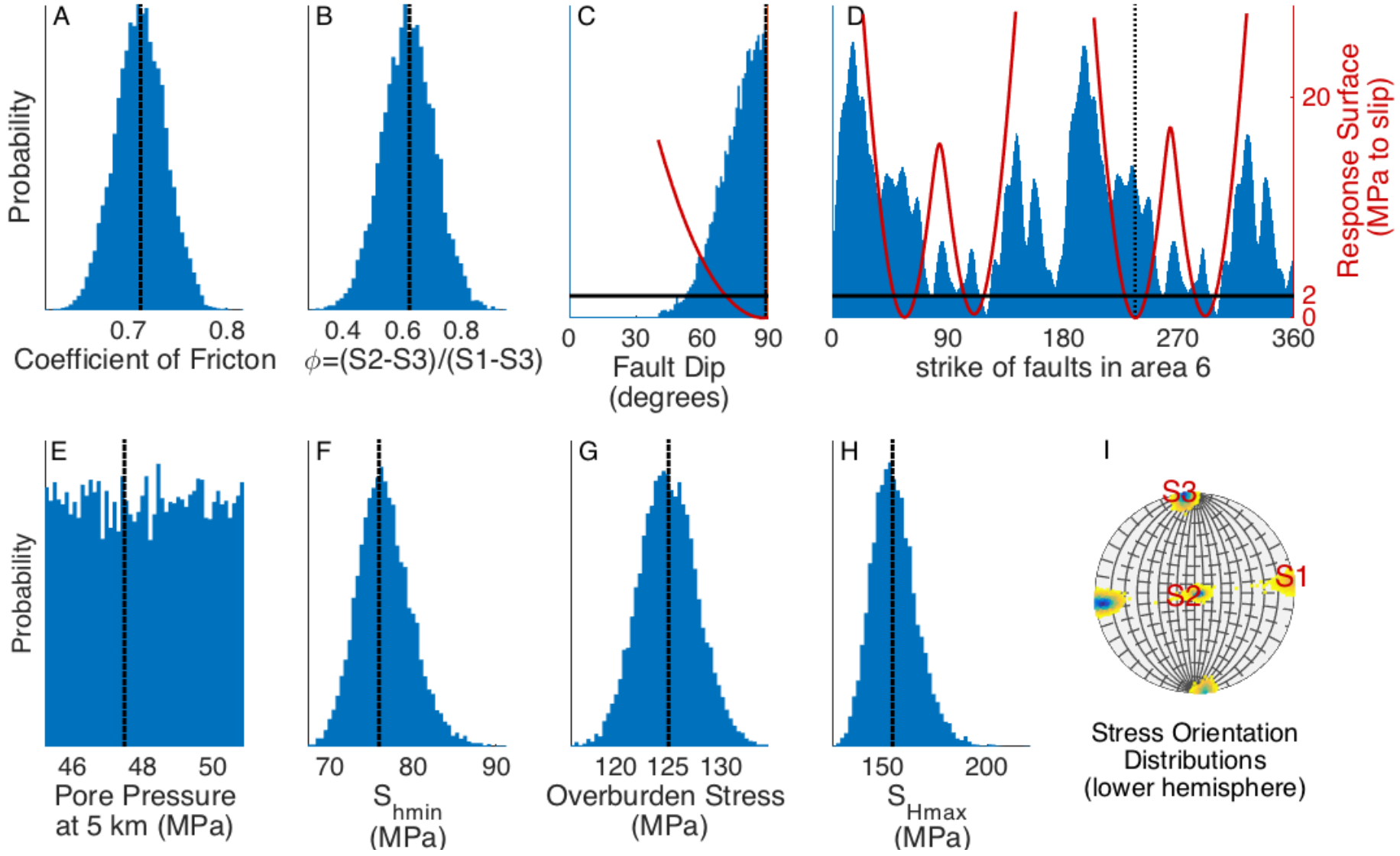
*Modest Means ΔP_P Small With Respect to Ambient Stresses



- Detailed Mapping of Stress Orientation and Relative Magnitudes
  - Wellbore Observations
  - Earthquake FM Inversions
  - Consistent S_{Hmax} Dir.
  - Slowly Varying Relative Stress Magnitudes
- Utilize Information About Pre-Existing Faults (Darold and Holland, 2015)
- Can We Determine Which Faults are Potentially Problematic?

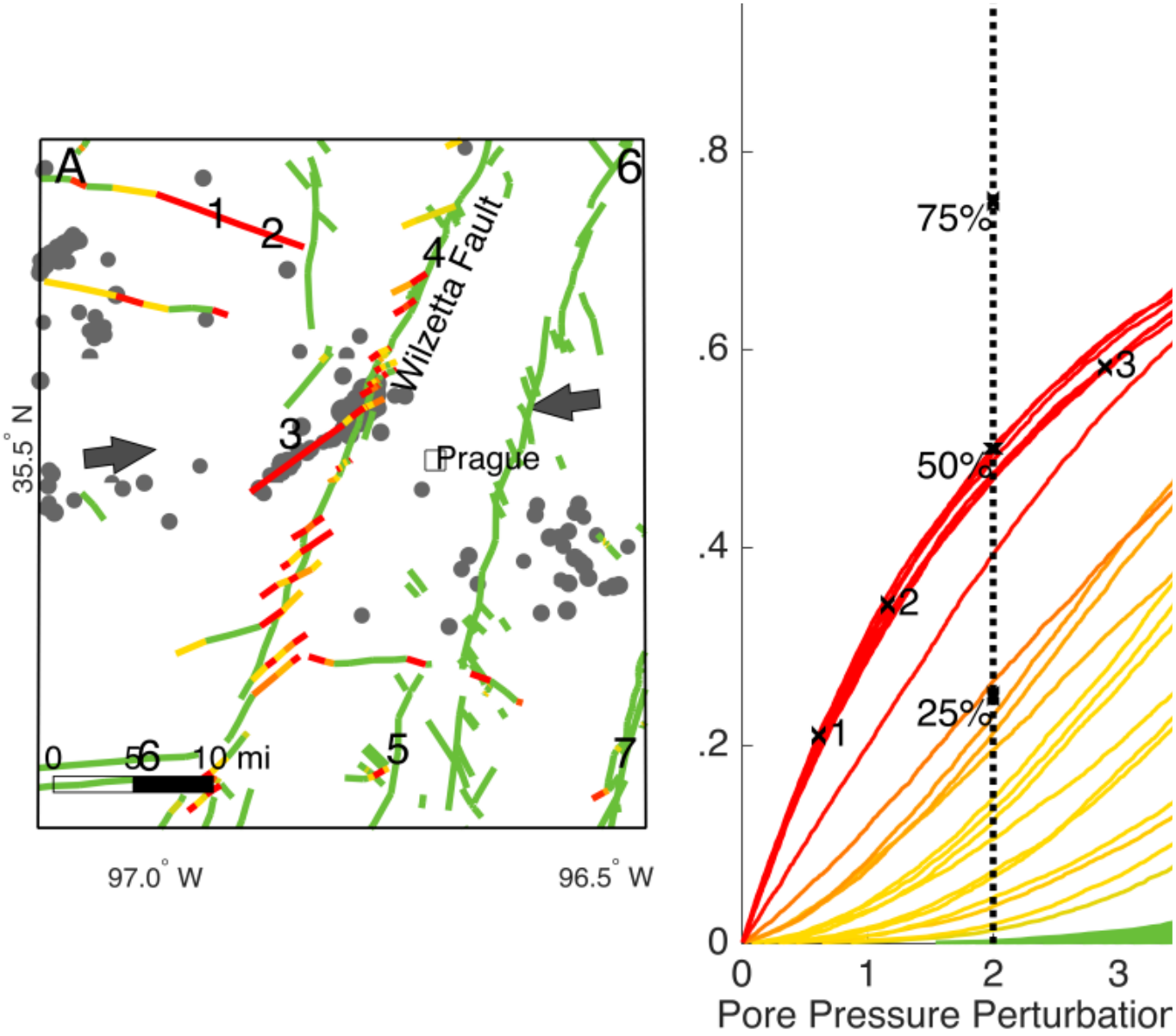
Alt and Zoback (*BSSA*, 2017)

QRA - Prague Area Parameter Distributions

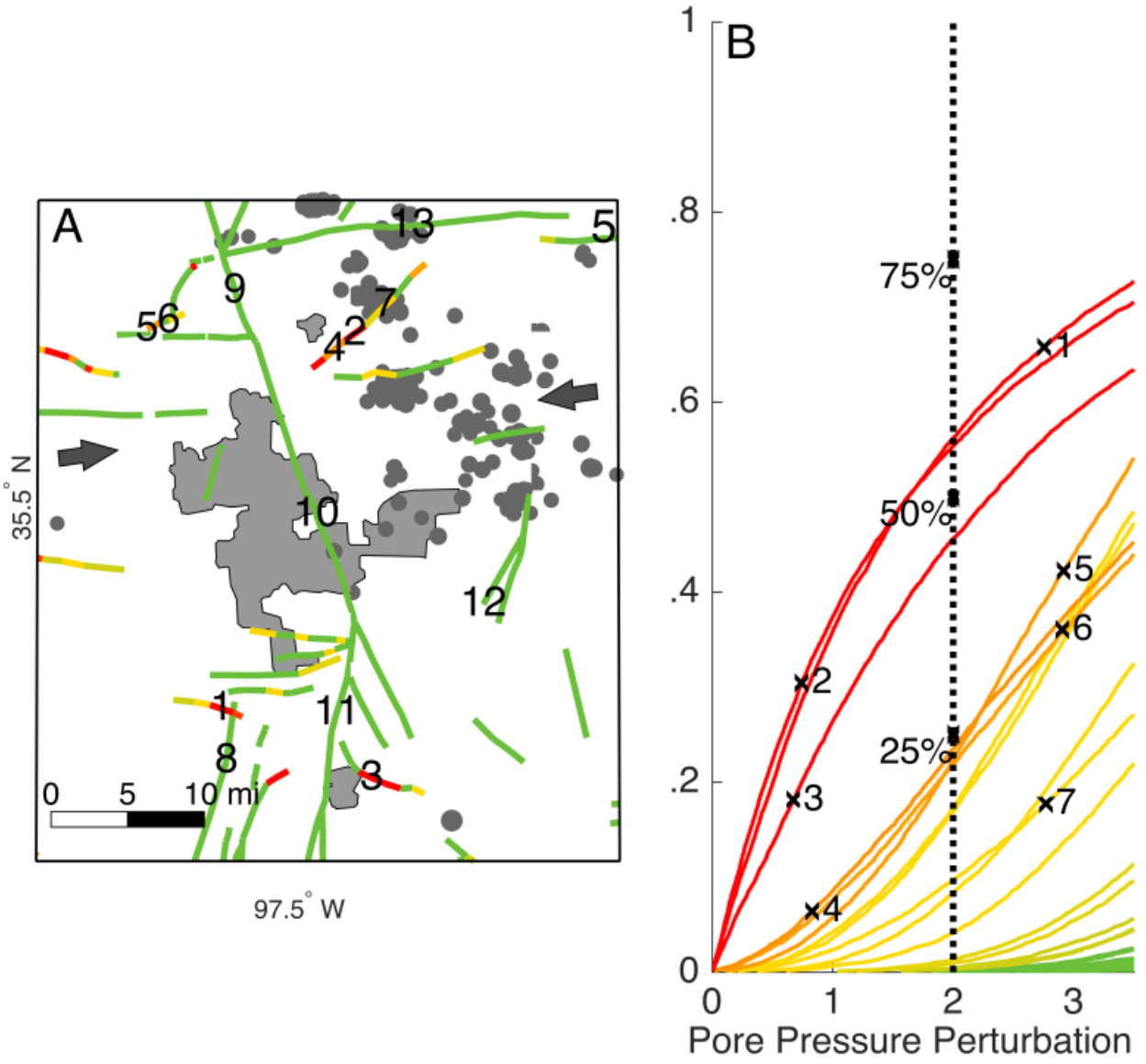


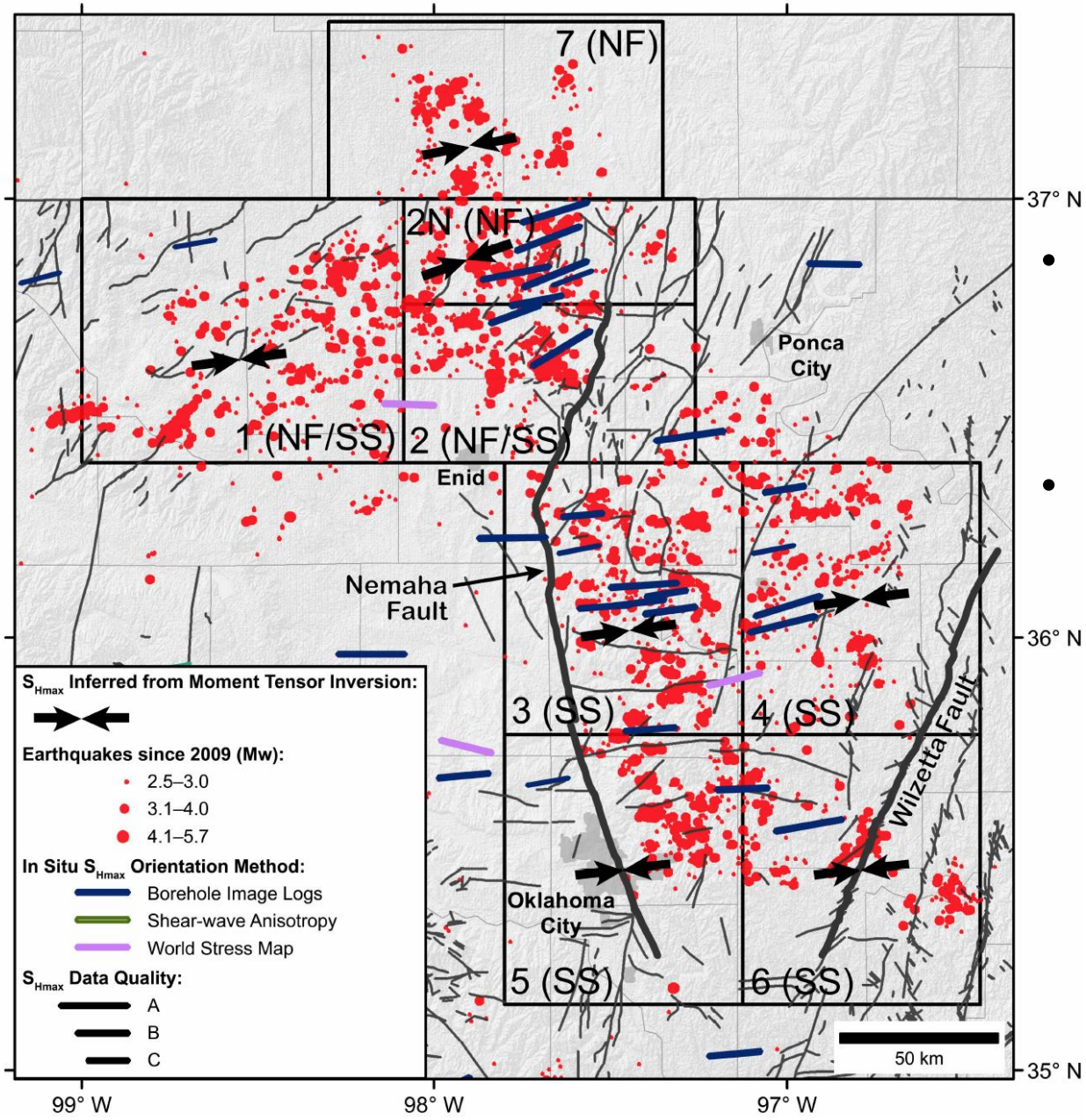
Walsh and Zoback, *Geology,* 2016

Fault Slip Probability (2 MPa Max Pressure Change)



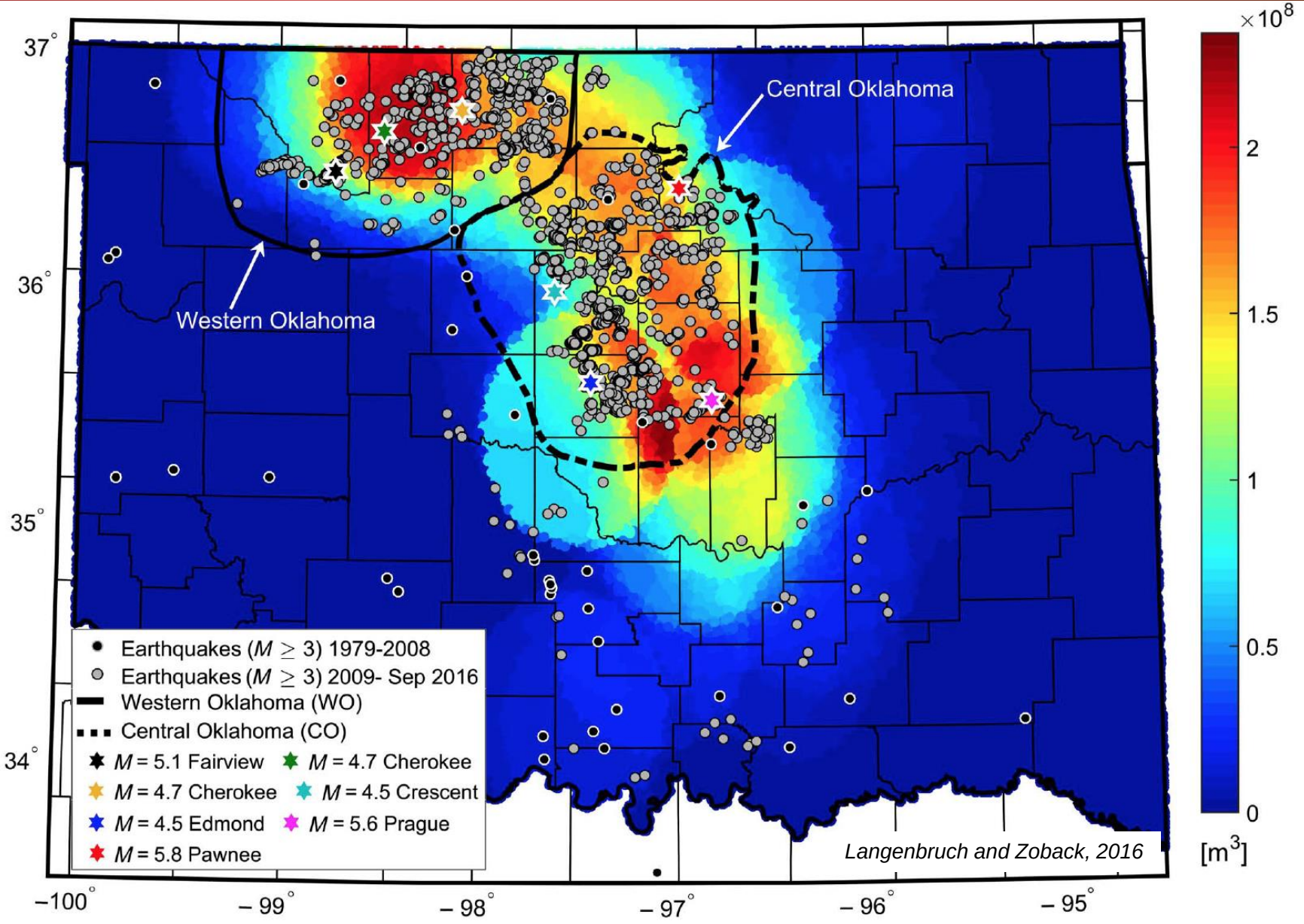
Identification of Faults That are Not Likely to be Problematic is Important Too!



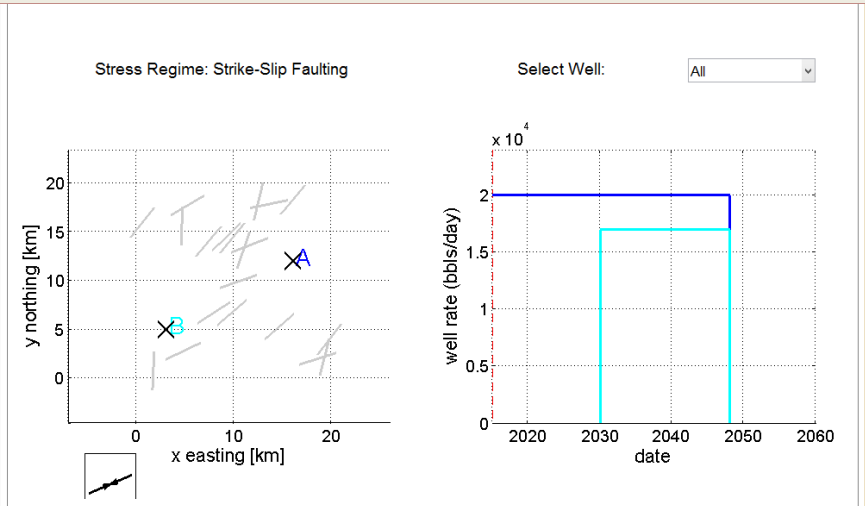


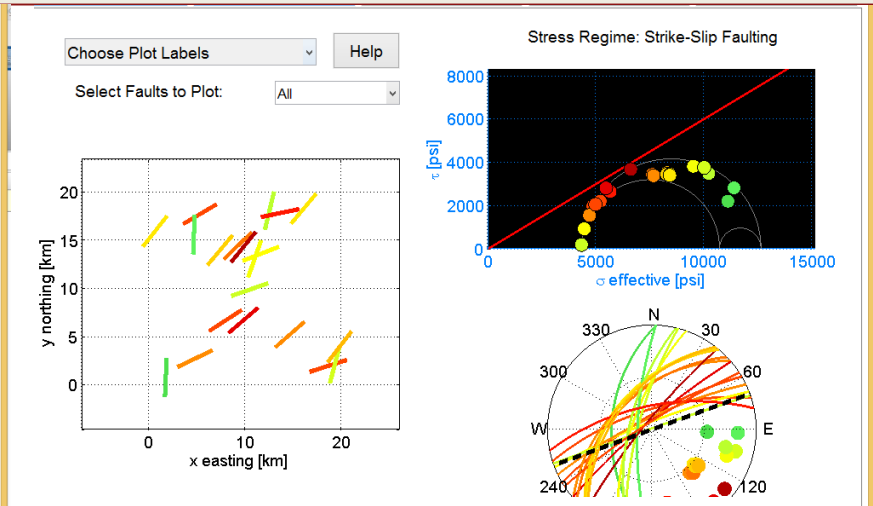
- Most Earthquakes are NOT Associated with Known Faults
- You Need to Know Your Faults!

All Relatively Large Recent Earthquakes in OK Occurred on "*Predictable*" Faults



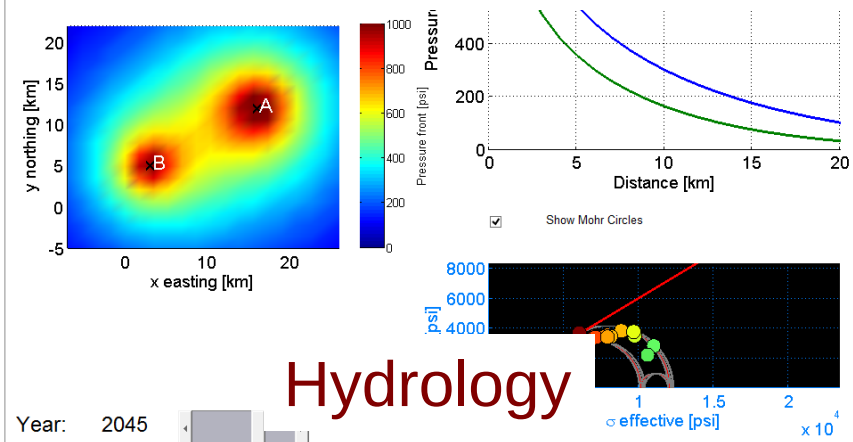
Free, Online Software Released March 6, 2017
QRA to Assess Fault Slip Potential



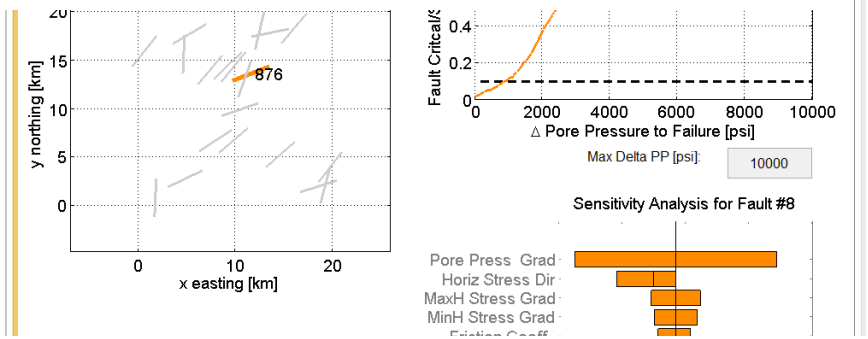


Y

Screening Tool for Identification of Potentially Problematic Faults Associated with Wastewater Injection (Usually Small ΔP)

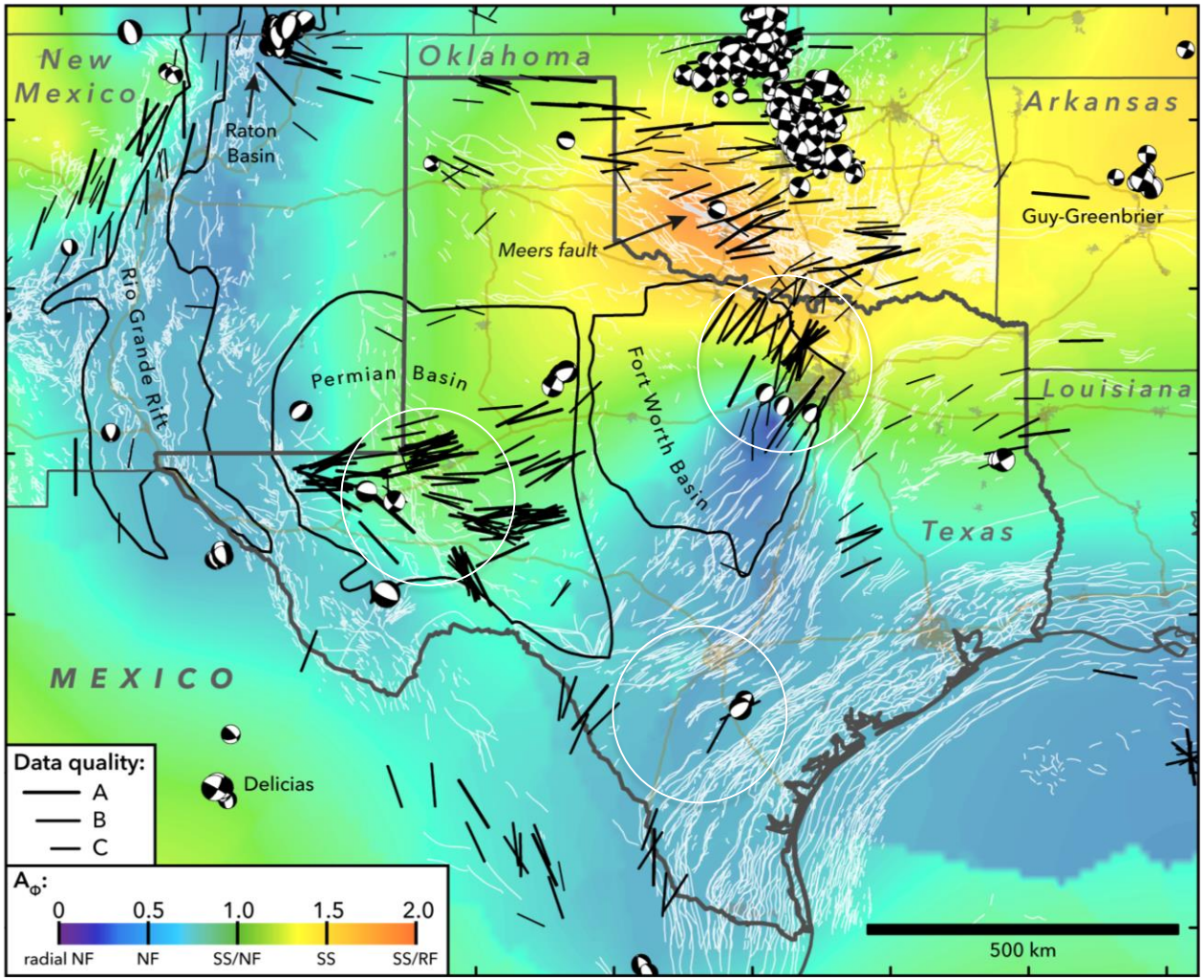


Hydrology



Calculate Fault Slip Potential

New Stress Map of Texas and Oklahoma - Poster P2-02



Lund Snee & Zoback (2016, *GRL*)

Properties of Sedimentary Rocks that Limit The Magnitude of Triggered Earthquakes

1. Viscoplastic Stress Relaxation (Relatively Isotropic Stress State)

   Clay Rich Rocks - Sone and Zoback (2013a,b; 2014)

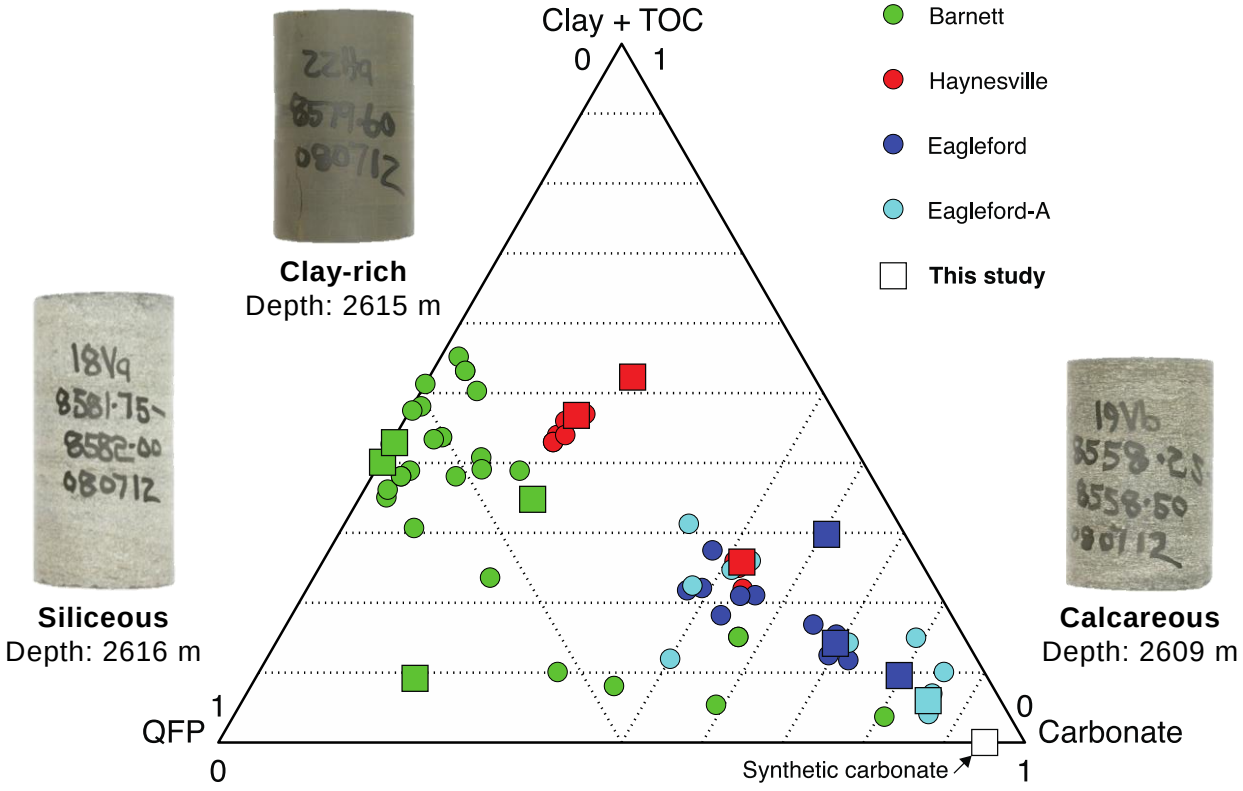
   Carbonate Rich Rocks - Rassouli and Zoback (in preparation)

2. Velocity Strengthening (Fault Slip via Stable Sliding)

   Clay Rich Rocks - Kohli and Zoback (2013)

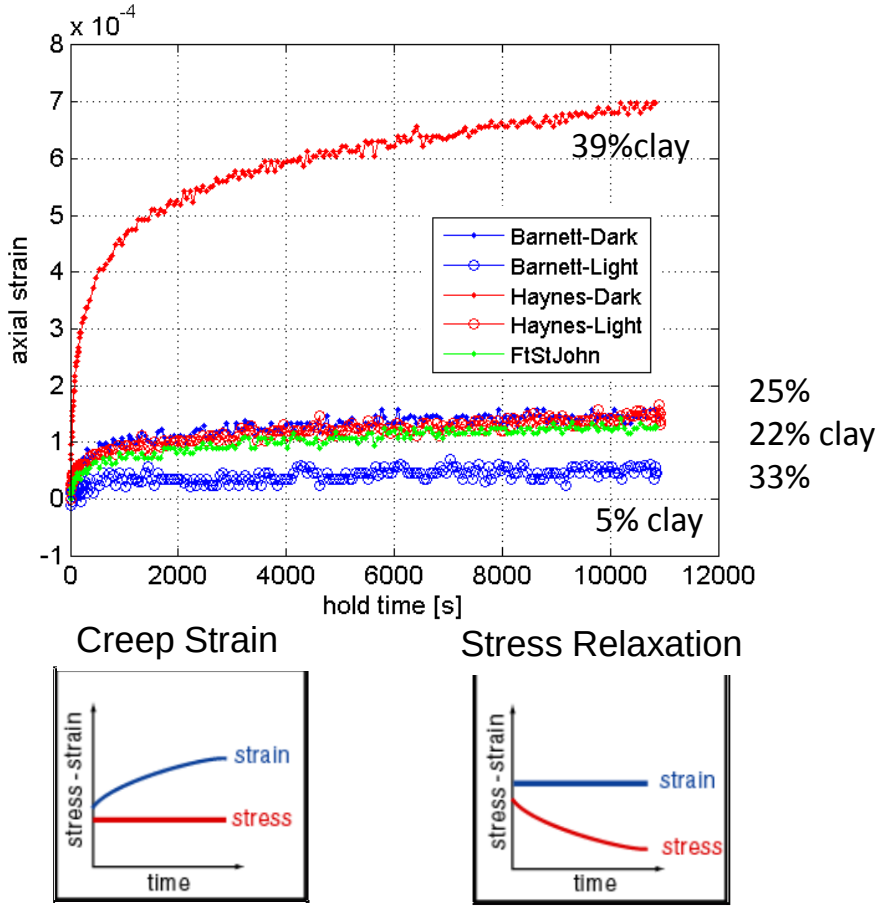
   Carbonate Rich Rocks – Kohli and Zoback (in prep)

Sample Compositions



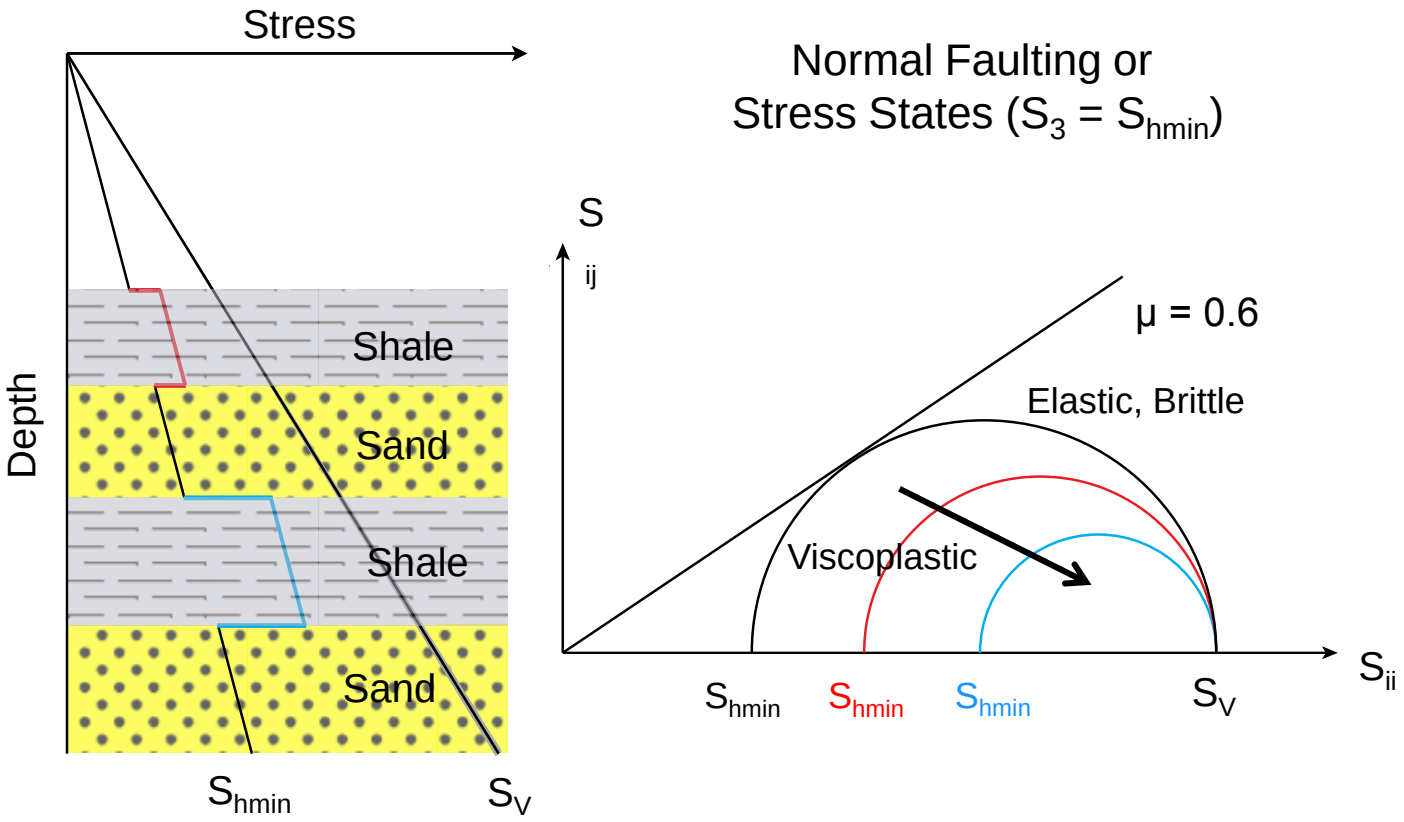
Kohli and Zoback, 2013

Variations in Clay Content Affects Creep

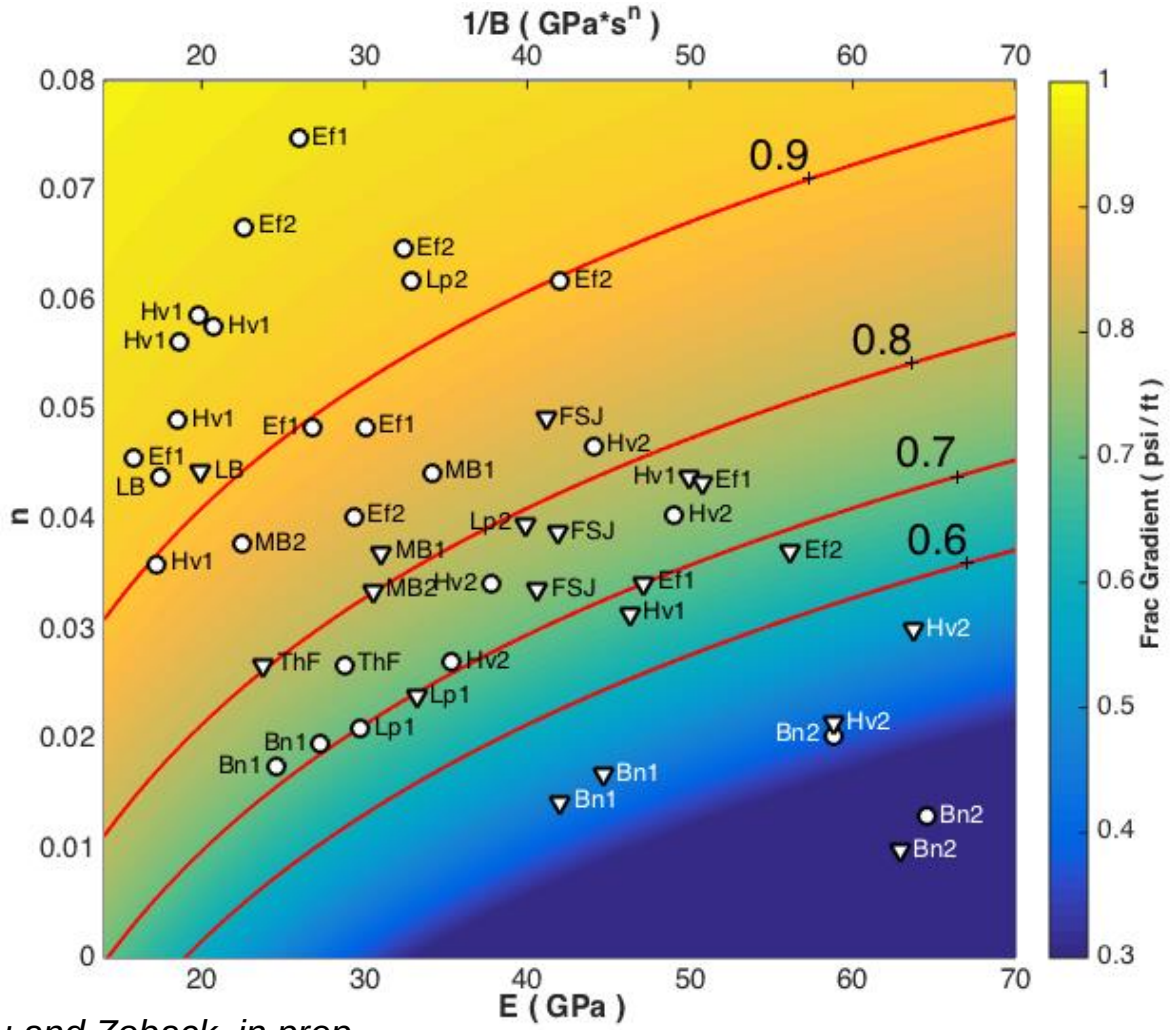


Sone and Zoback, 2013

Stress Relaxation in Viscoplastic Formations



S_{hmin}/S_V Prediction



Xu and Zoback, in prep

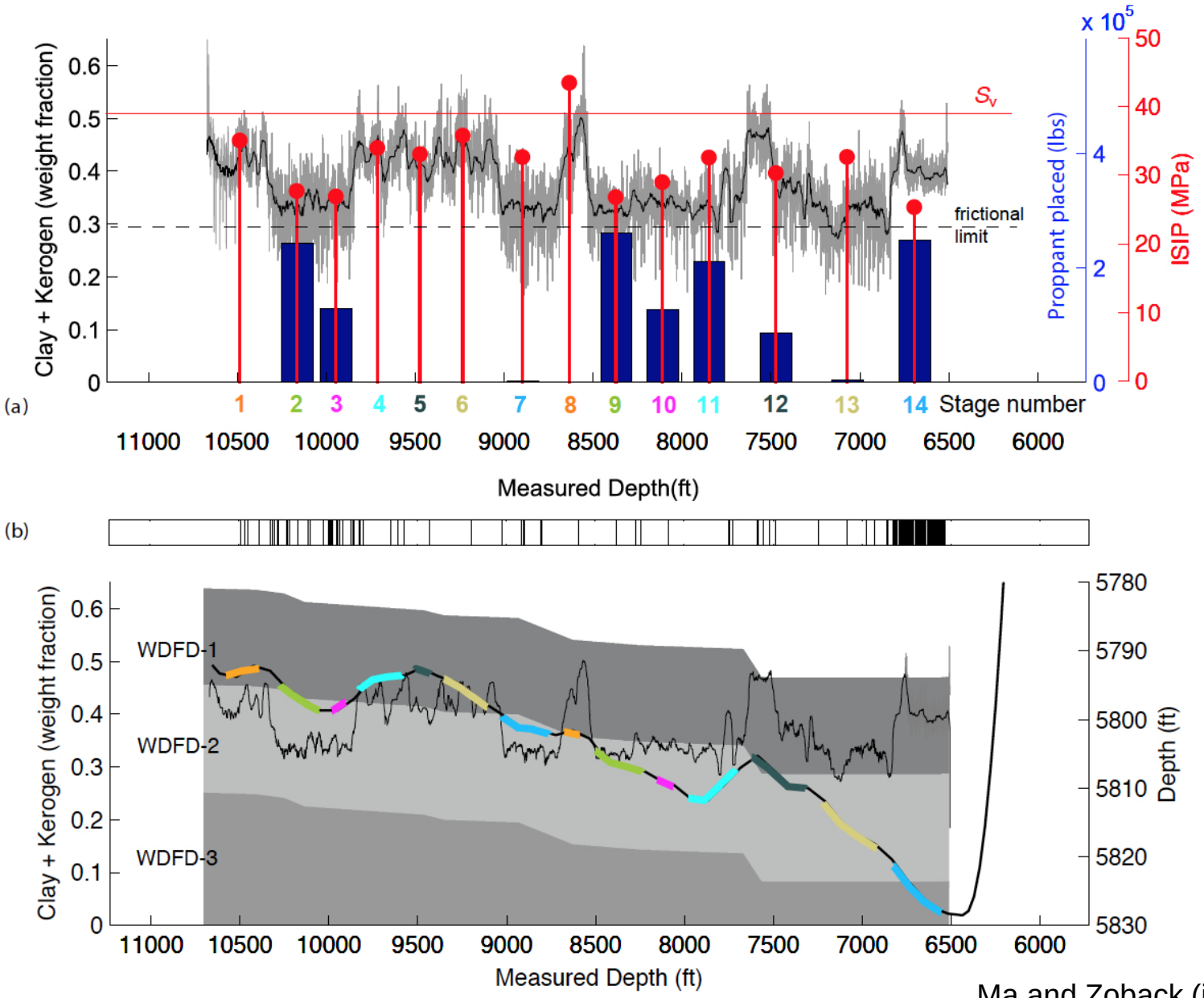
Normal Faulting
$S_v > S_{Hmax} > S_{hmin}$

Bn: Barnett
Hv: Haynesville
Ef: Eagle Ford
FSJ: Fort St. John
Lp: Lodgepole
MB: Middle Bakken
LB: Lower Bakken
ThF: Three Forks

White circles: vertical
White triangles: horizontal

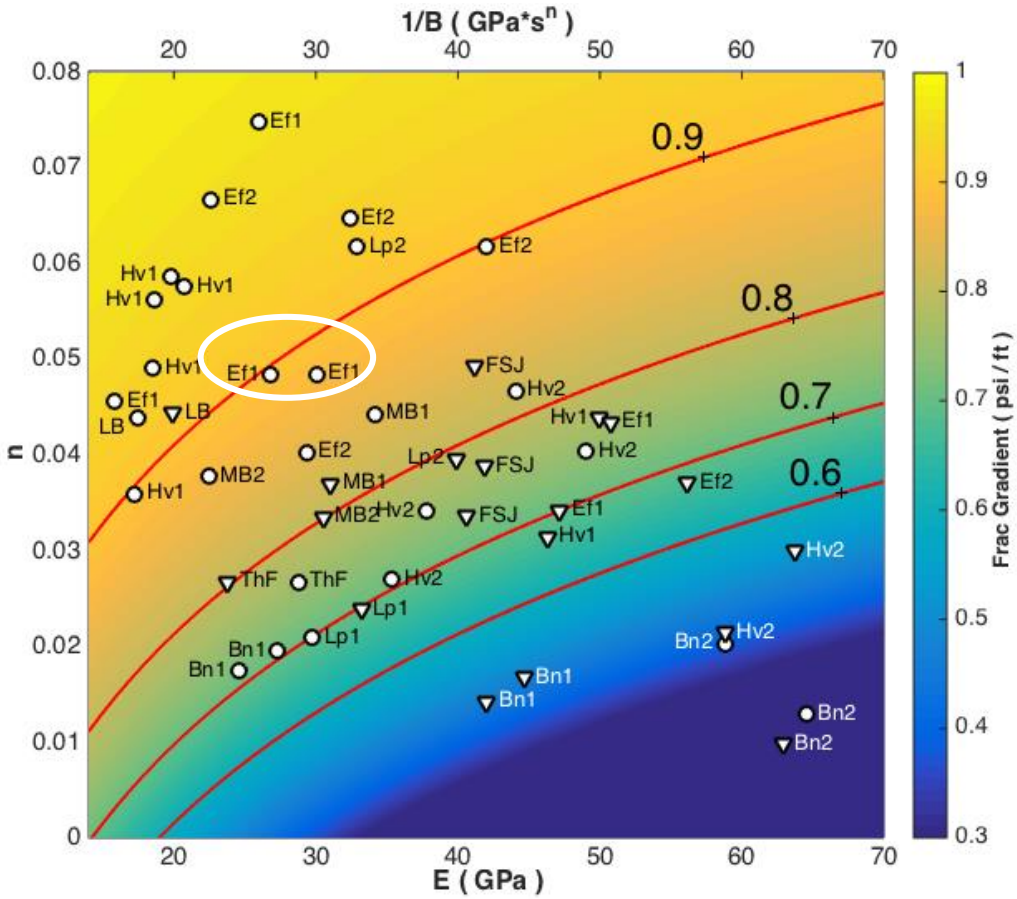
$$s(t) = e_0 \frac{1}{B(1-n)} t^{-n}$$

$$S_1 - S_3 = e_0 \frac{E}{1-n} t^{-n}$$

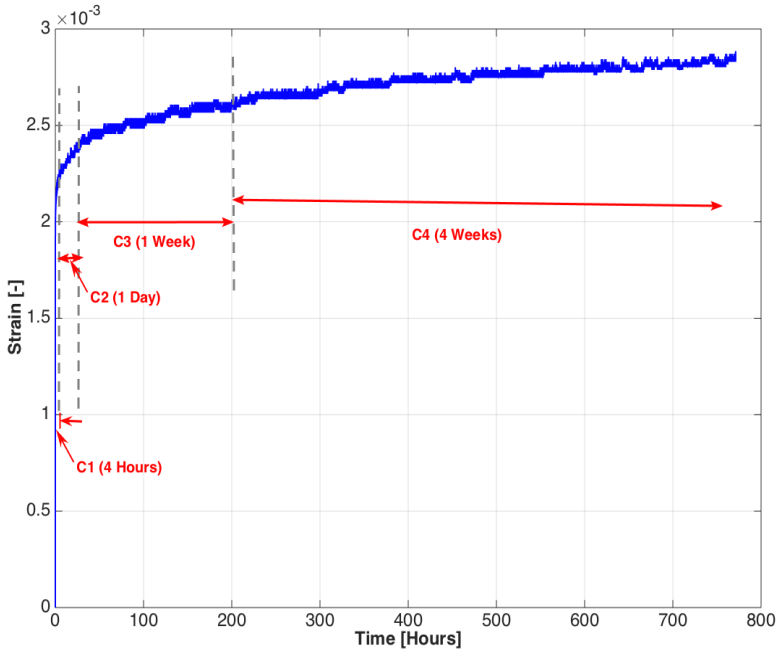


Ma and Zoback (in review)

Creep and Stress Relaxation in Carbonate Rich Rocks



Eagleford sample ~50% Carbonate



Rassouli and Zoback, in prep

Properties of Sedimentary Rocks that Limit The Magnitude of Triggered Earthquakes

1. Viscoplastic Stress Relaxation (Relatively Isotropic Stress State)

   Clay Rich Rocks - Sone and Zoback (2013a,b; 2014)

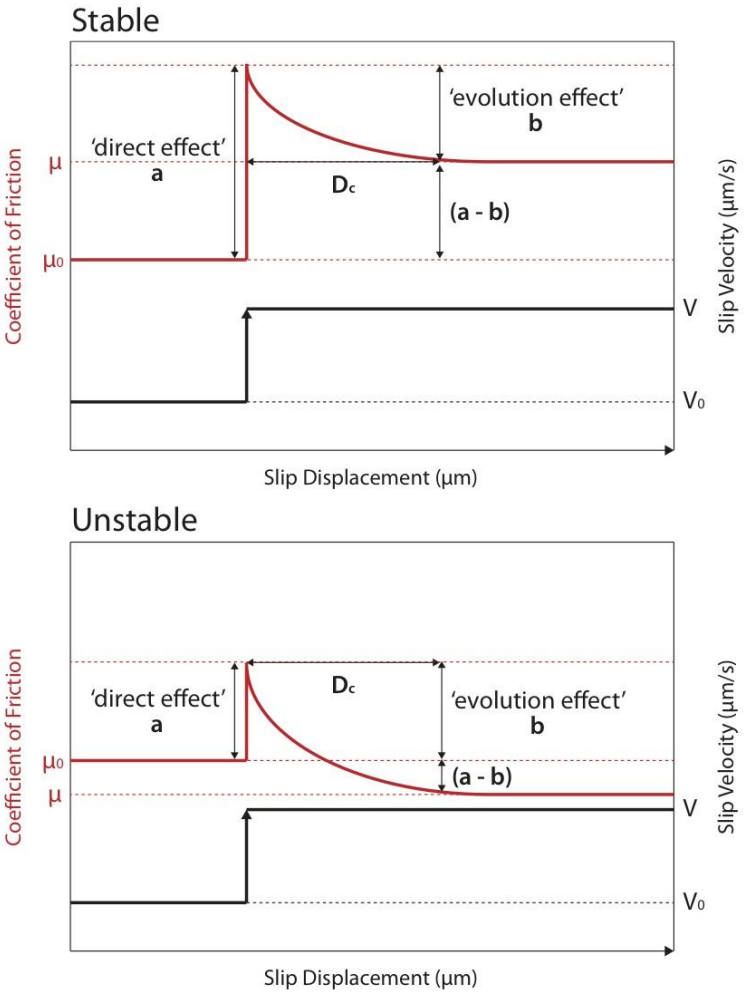
   Carbonate Rich Rocks - Rassouli and Zoback (in preparation)

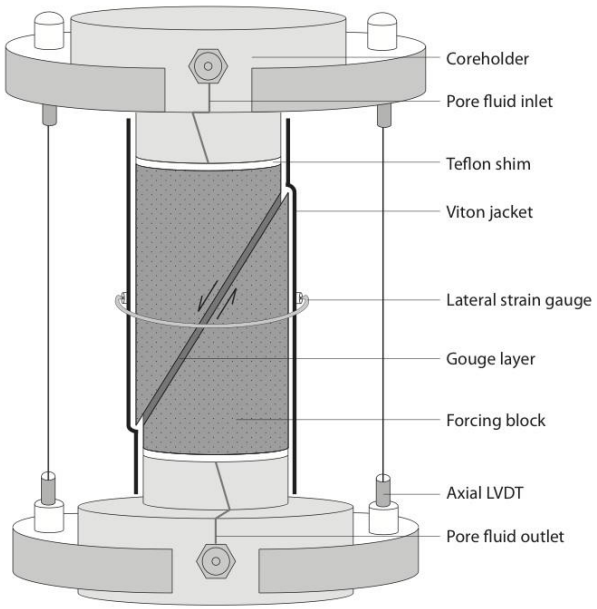
2. Velocity Strengthening (Fault Slip via Stable Sliding)

   Clay Rich Rocks - Kohli and Zoback (2013)

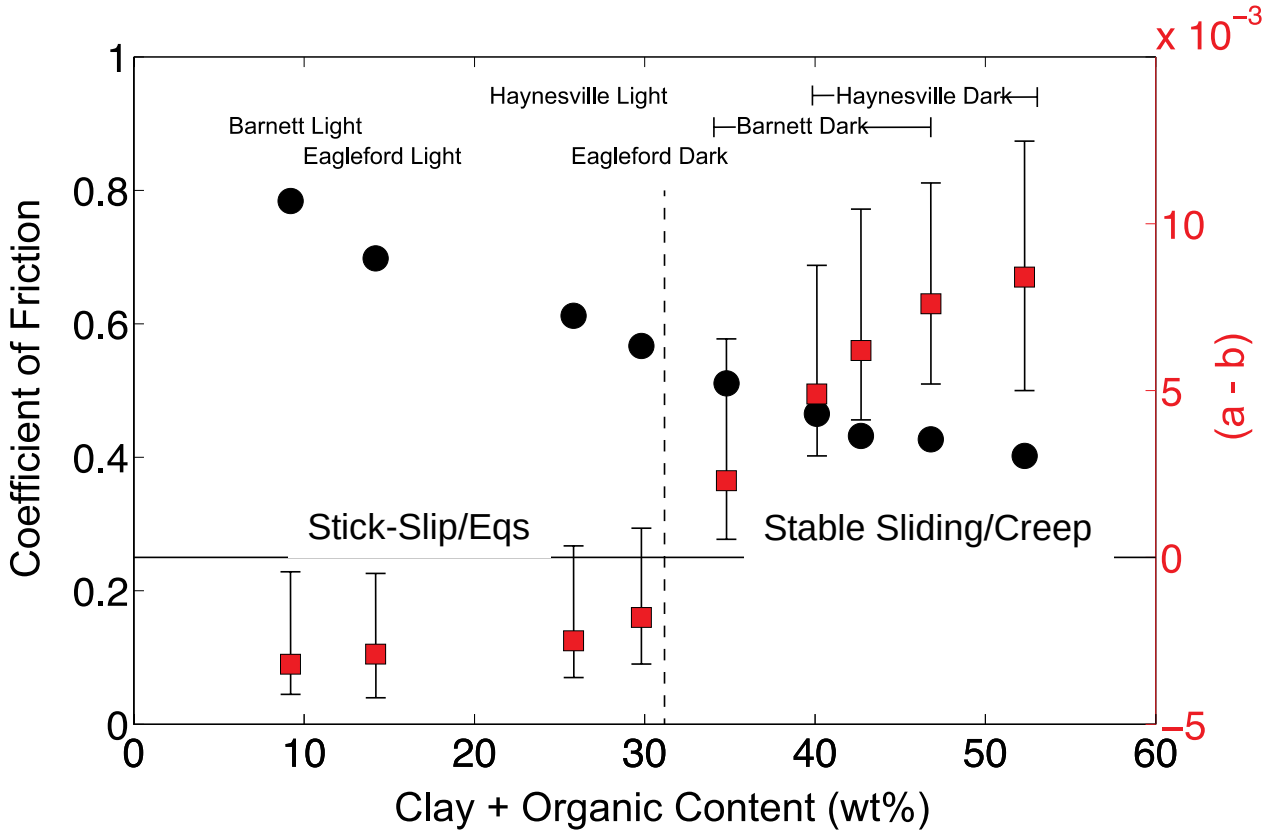
   Carbonate Rich Rocks – Kohli and Zoback (in prep)

Rate and State Friction Experiments



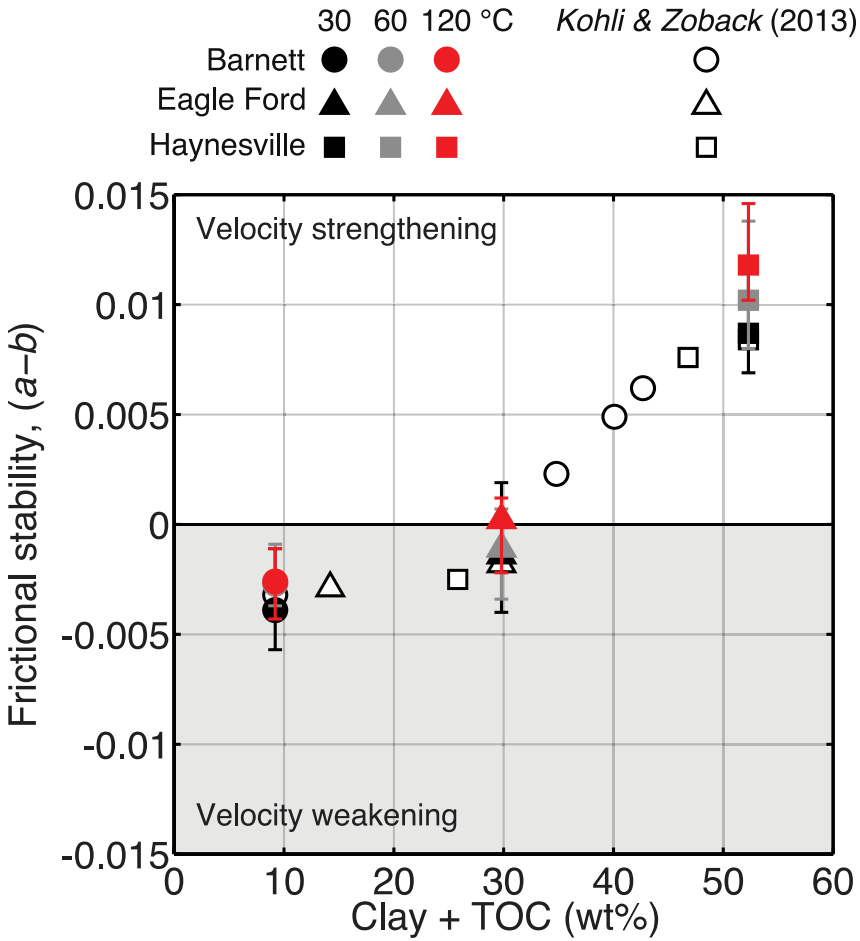


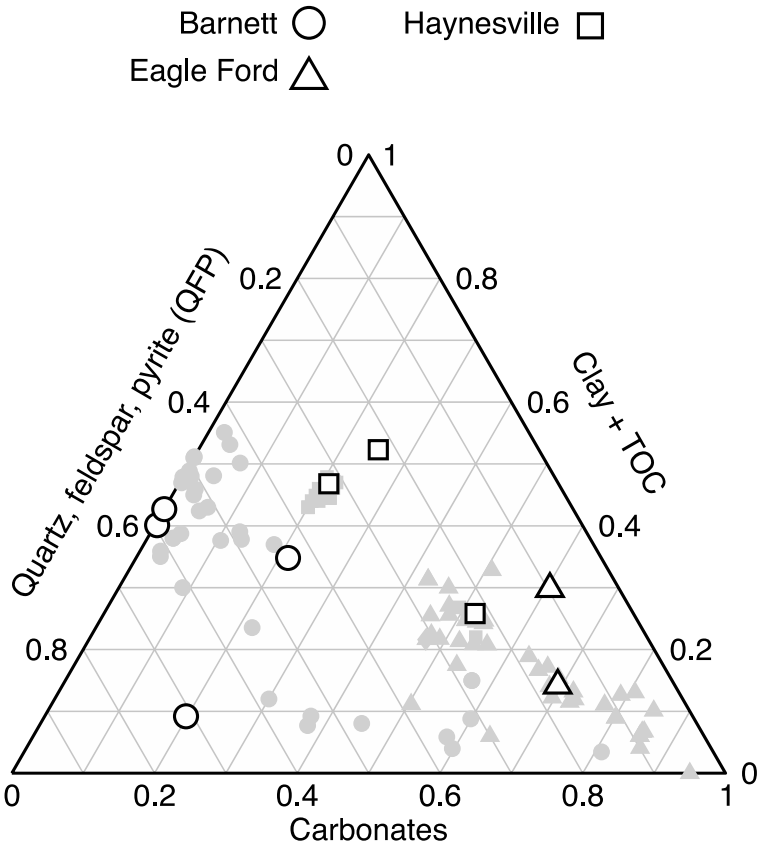
Stable Sliding on Faults With High Clay



Kohli and Zoback (2013)

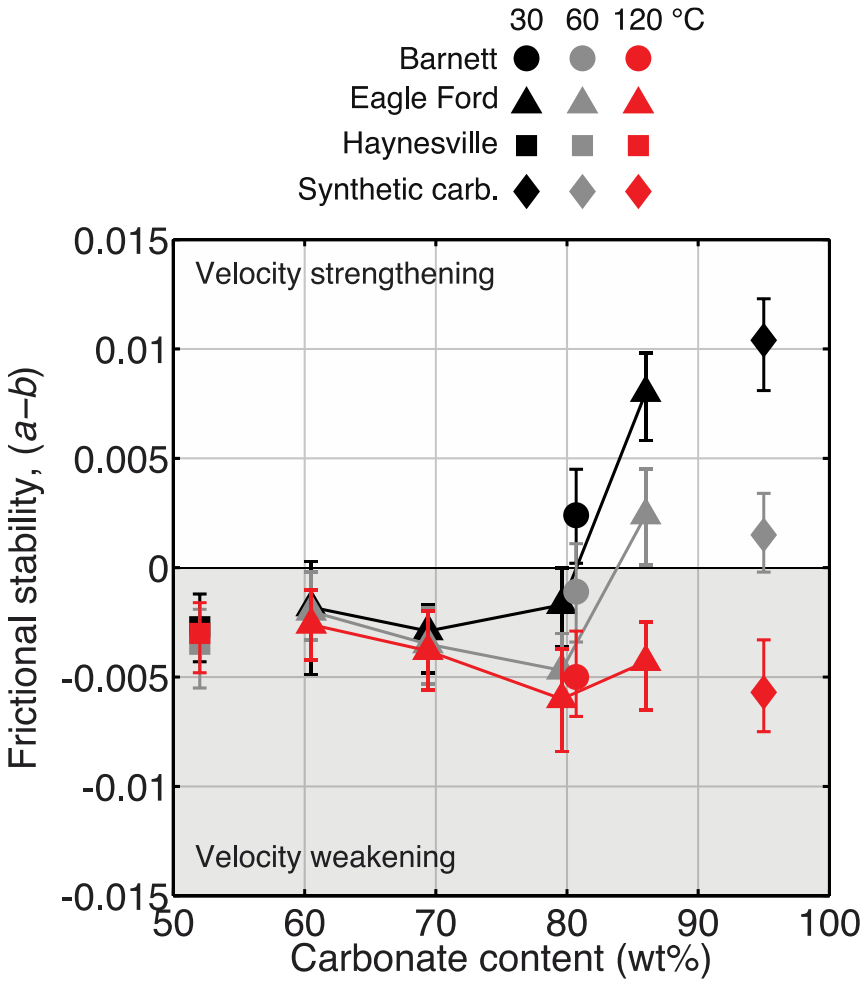
Rate and State Friction Experiments – Temperature Effects

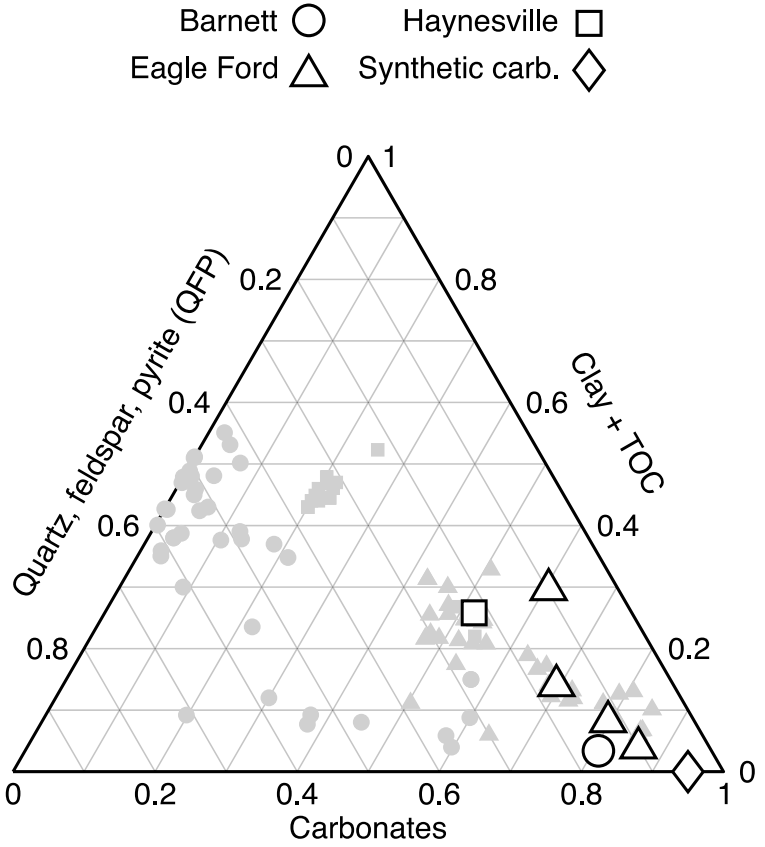




Kohli and Zoback, in prep

Rate and State Friction Experiments – Temperature Effects – Carbonates





Kohli and Zoback, in prep

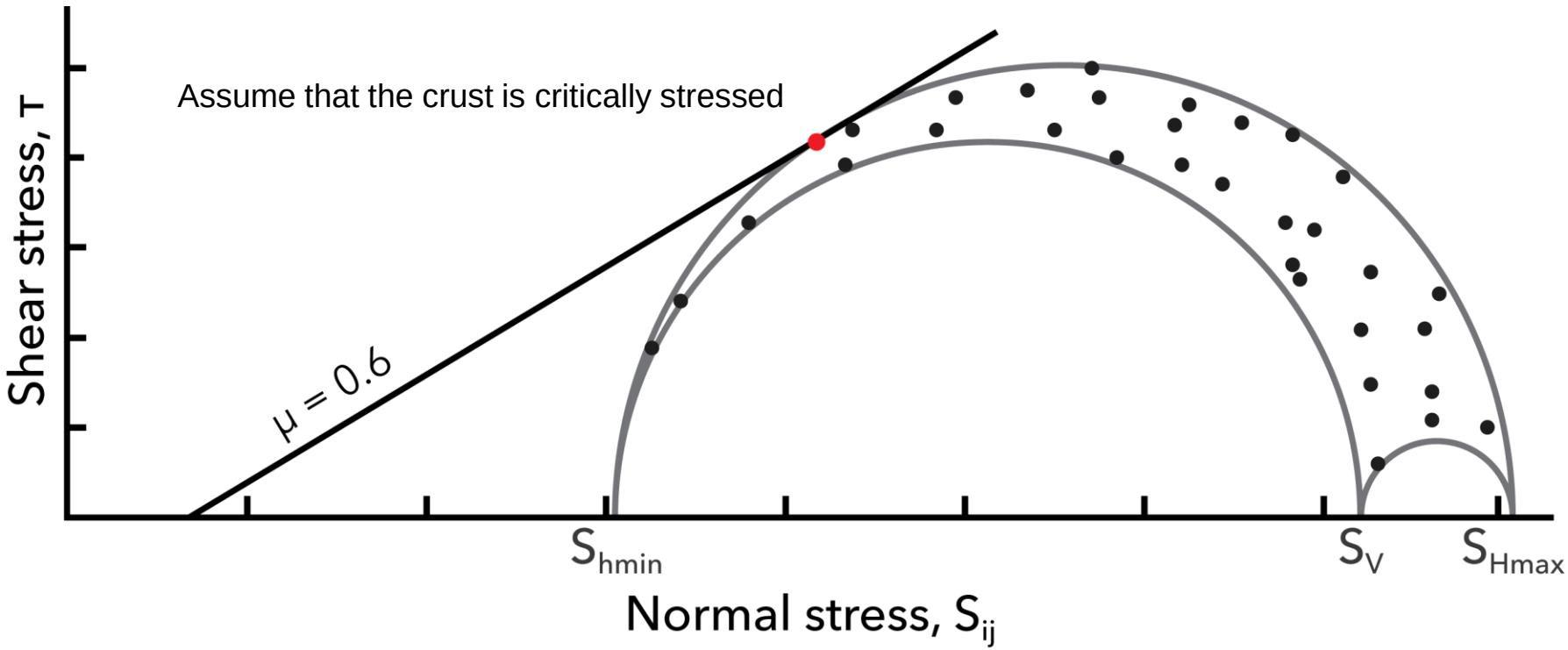
Take Away Messages

1. With Routinely Available Stress and Fault Information – It is Possible to Avoid Potentially Active Faults – Proactively!

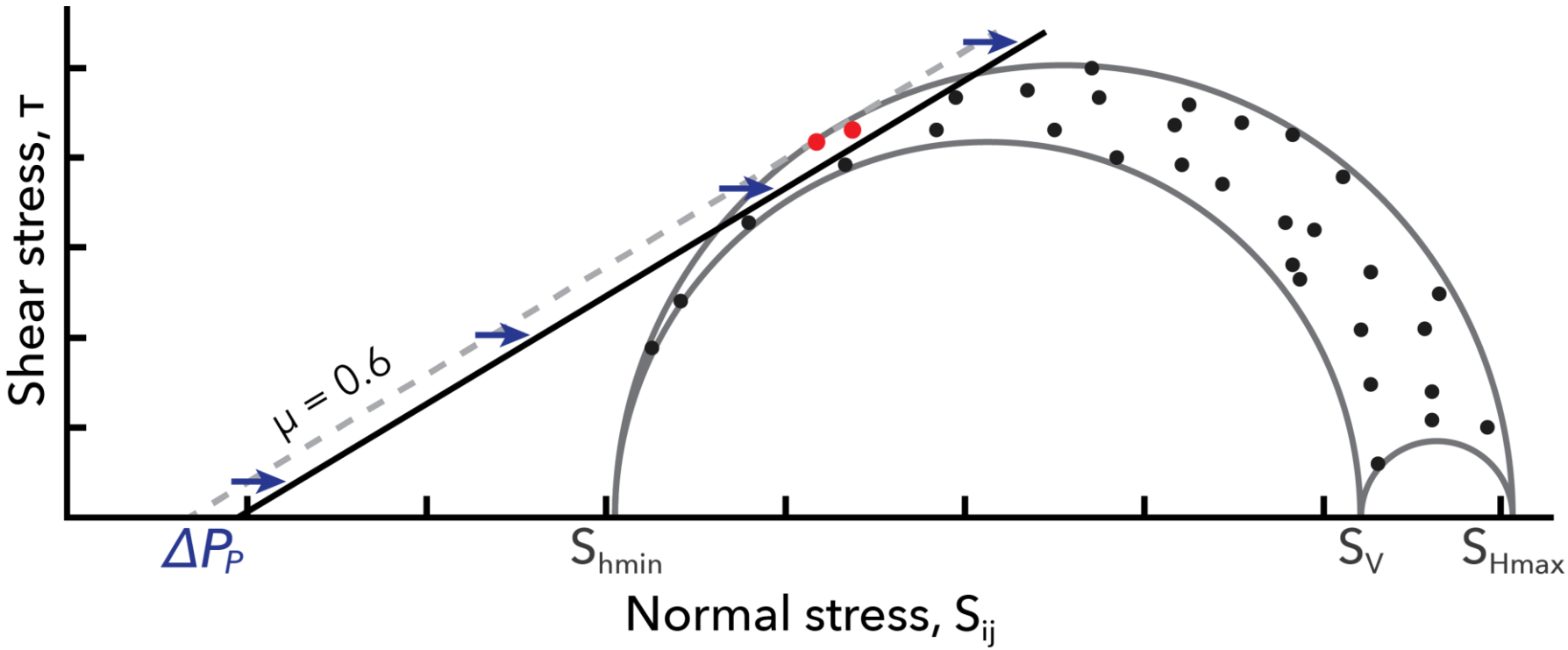
2. Layered Nature of Sedimentary Sequences Suggests That When Earthquakes Occur (Whether Natural or Triggered) There Will Often be a Limited Scale of Seismogenic Fault Slip (and Hence, Earthquake Magnitude)


Thank you

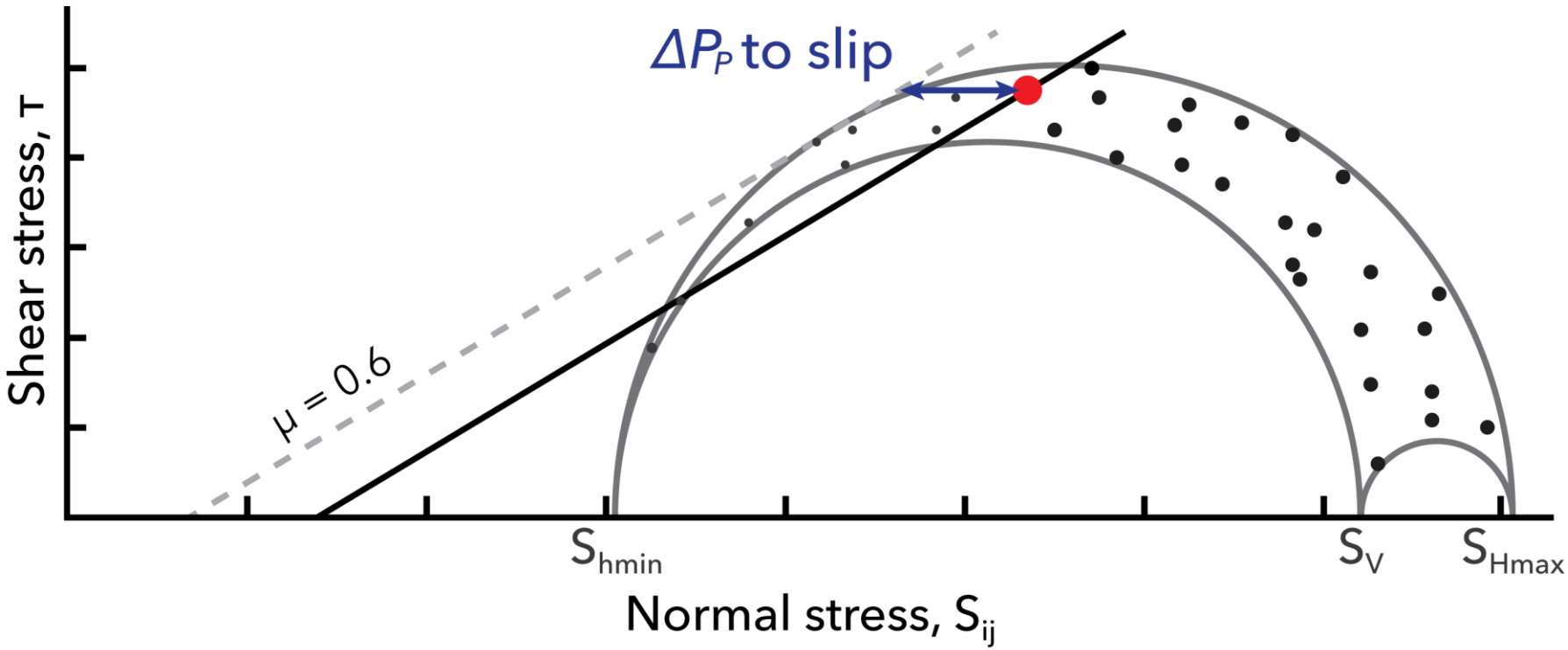
Basic Mohr-Coulomb Analysis



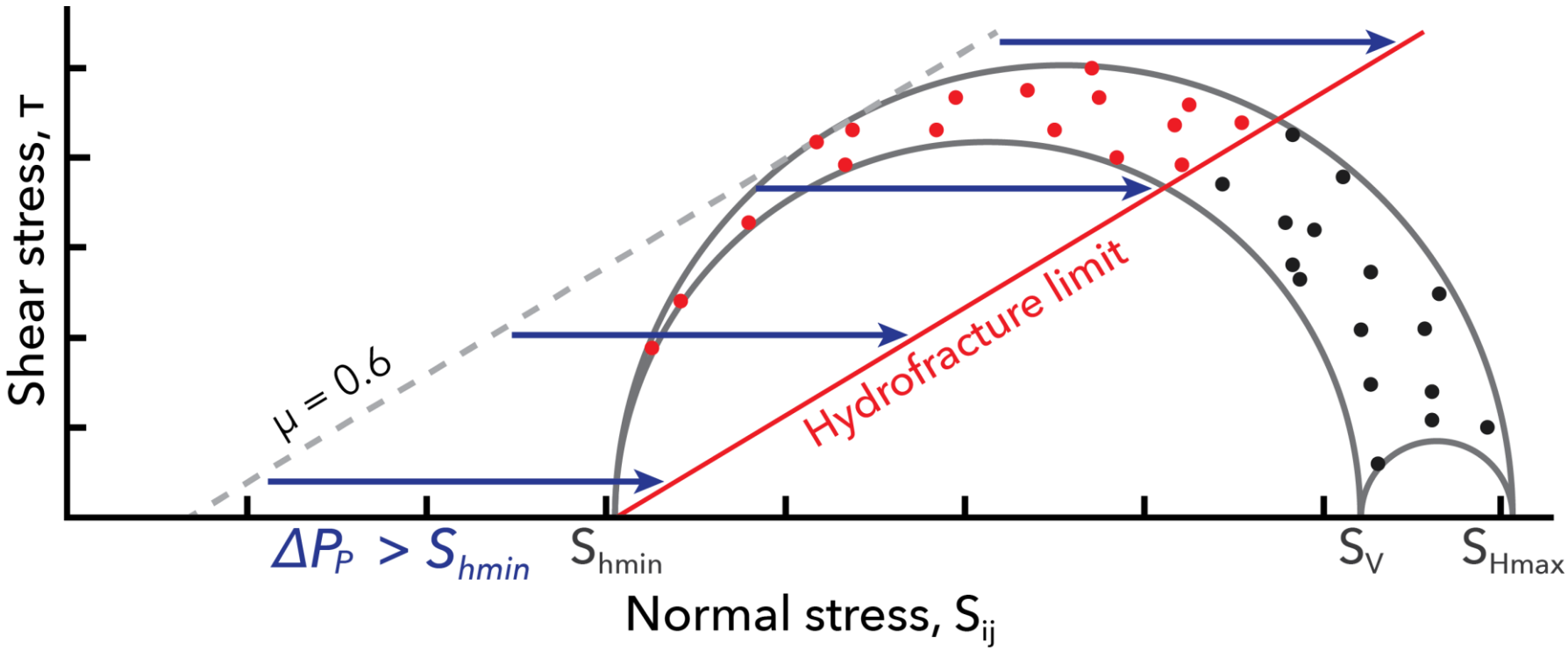
Increasing ΔP_P Can Makes Some Faults Slip



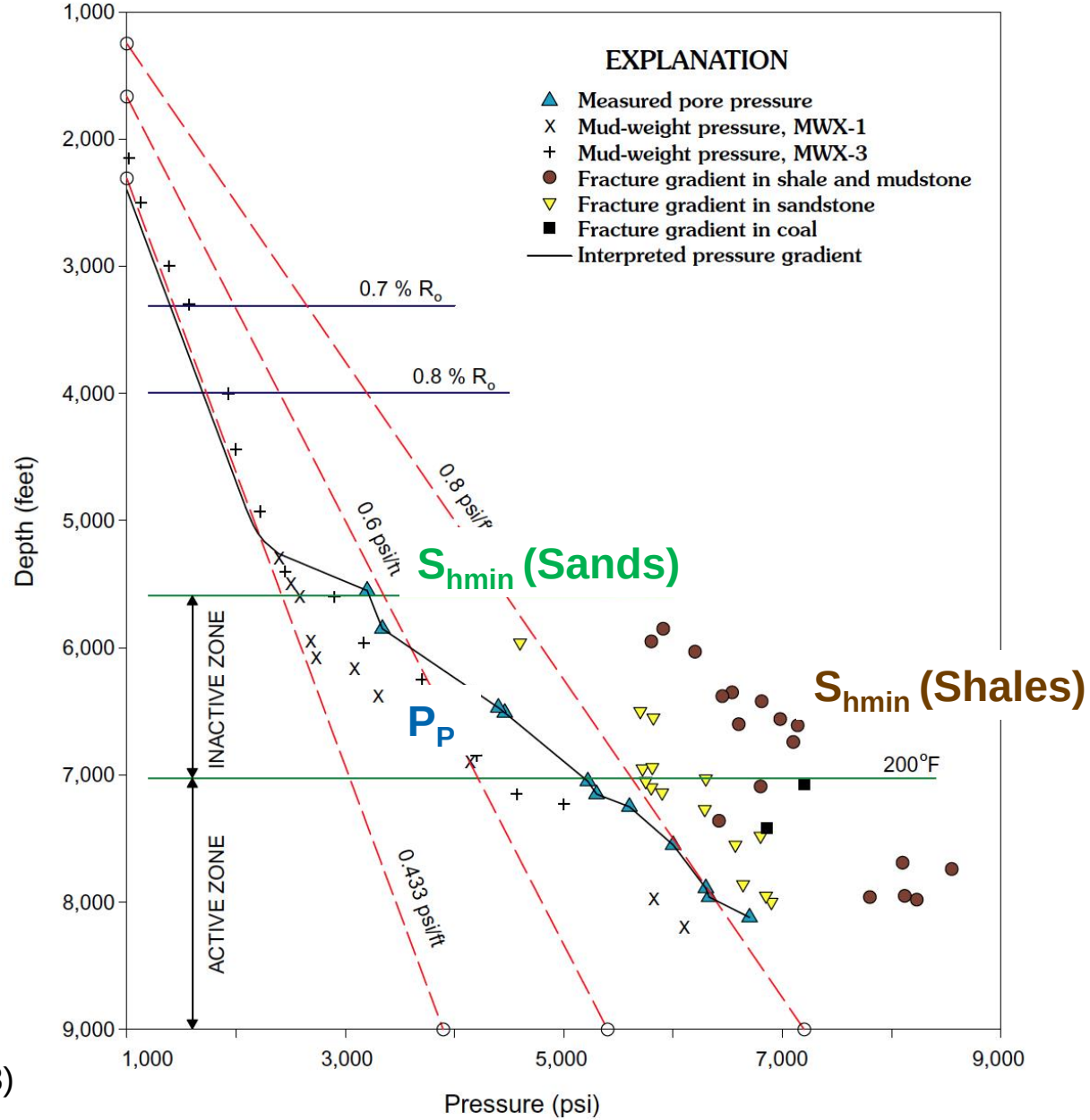
We Assess Likelihood of Slip in Terms of the ΔP_P Needed to Initiate Slip



Some Faults Can *Never* be Made to Slip

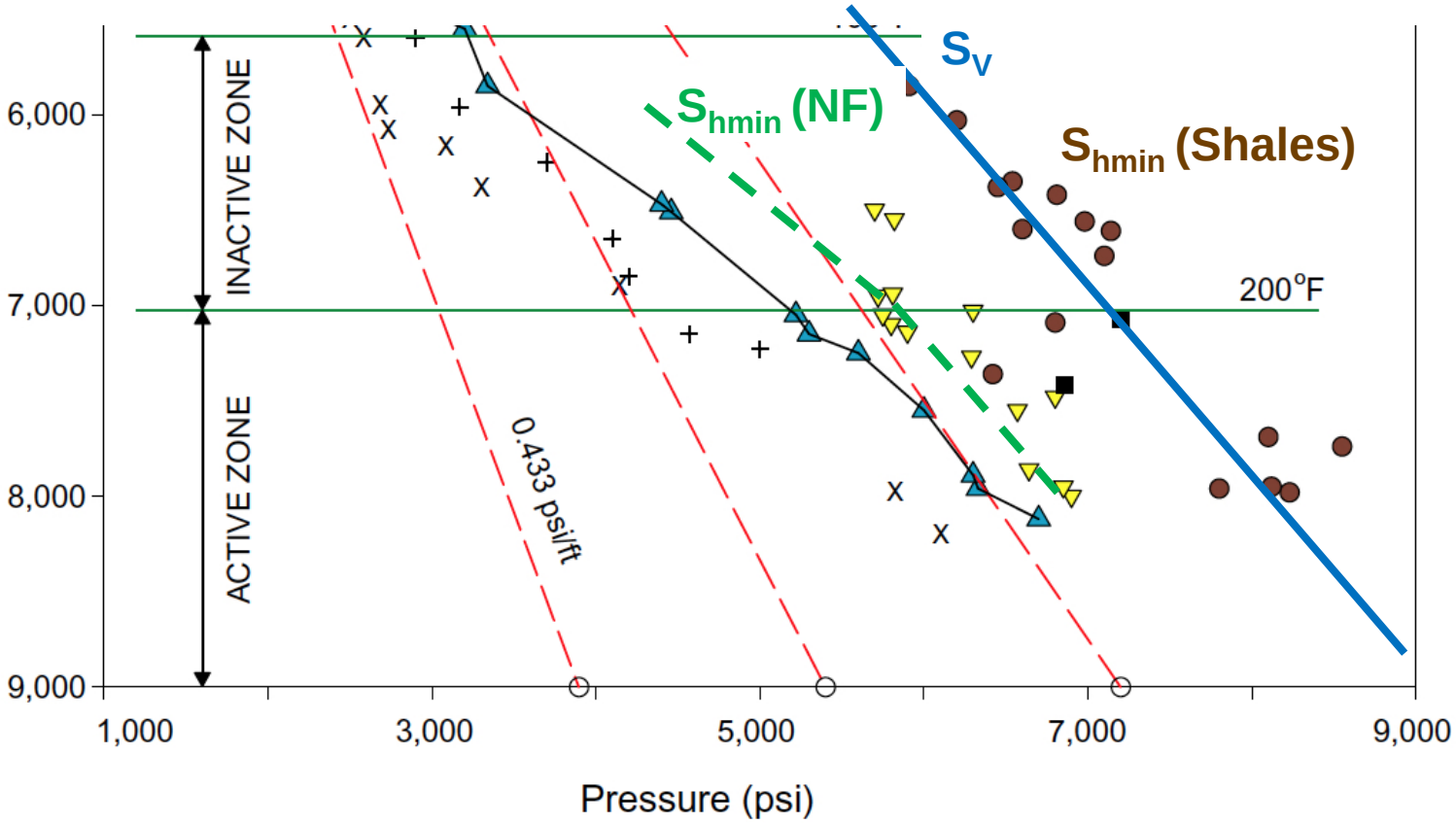


Multi-Well Experiment – Western Colorado (1981-1988)



From Nelson (2003)

Multi-Well Experiment – Western Colorado



Generalized Constitutive Law from Lab to Reservoir

$$s(t) = e_0 \frac{1}{B(1-n)} t^{-n}$$

$$S_1 - S_3 = e_0 \frac{E}{1-n} t^{-n}$$

S_1: maximum in situ principal stress
S_3: minimum in situ principal stress
E: Young's modulus
t: total geological time
ε_0: total tectonic strain } Fitting Parameter
n: dimensionless parameter that describes tendency for time-dependent deformation

Sone and Zoback, 2013