A Geomechanical Perspective Of Permeability and Fluid Flow in Crystalline Rocks in the Upper Crust

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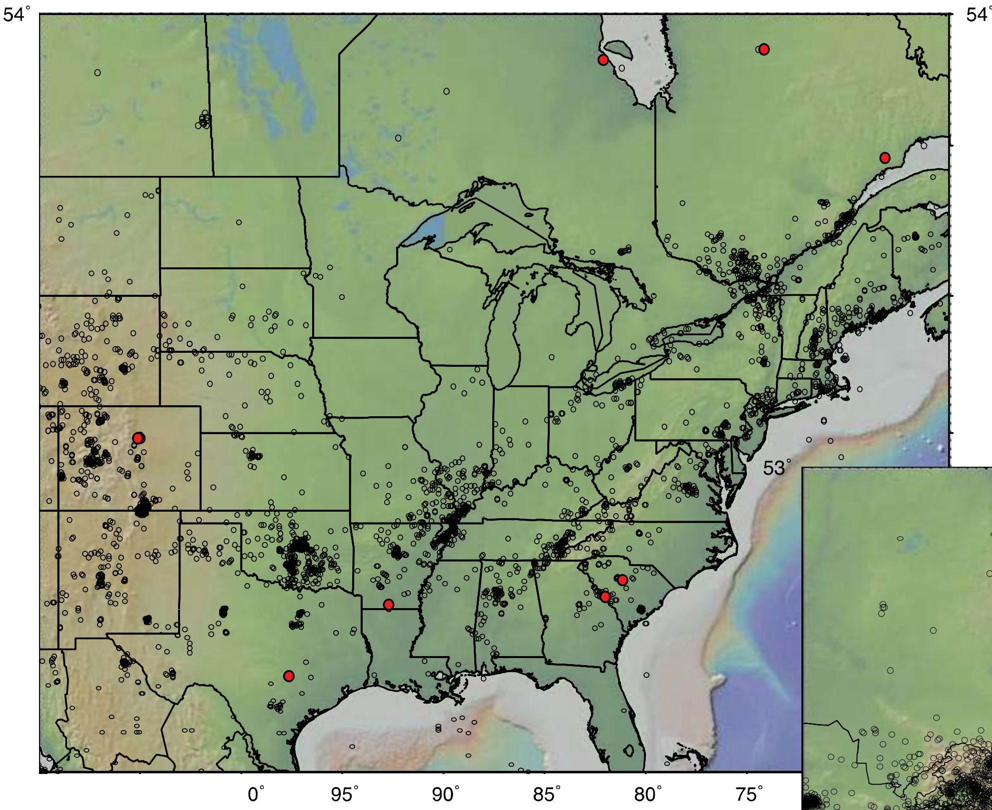
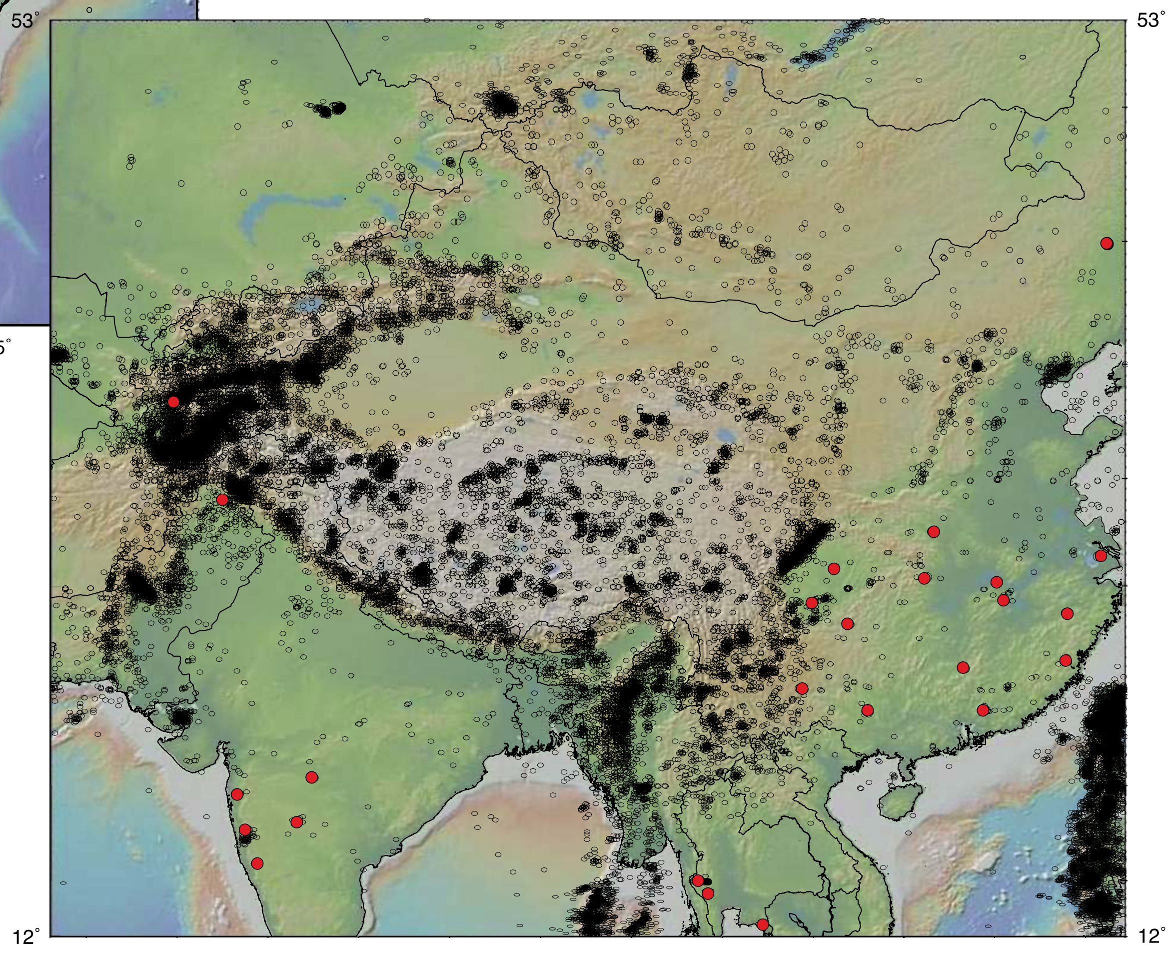
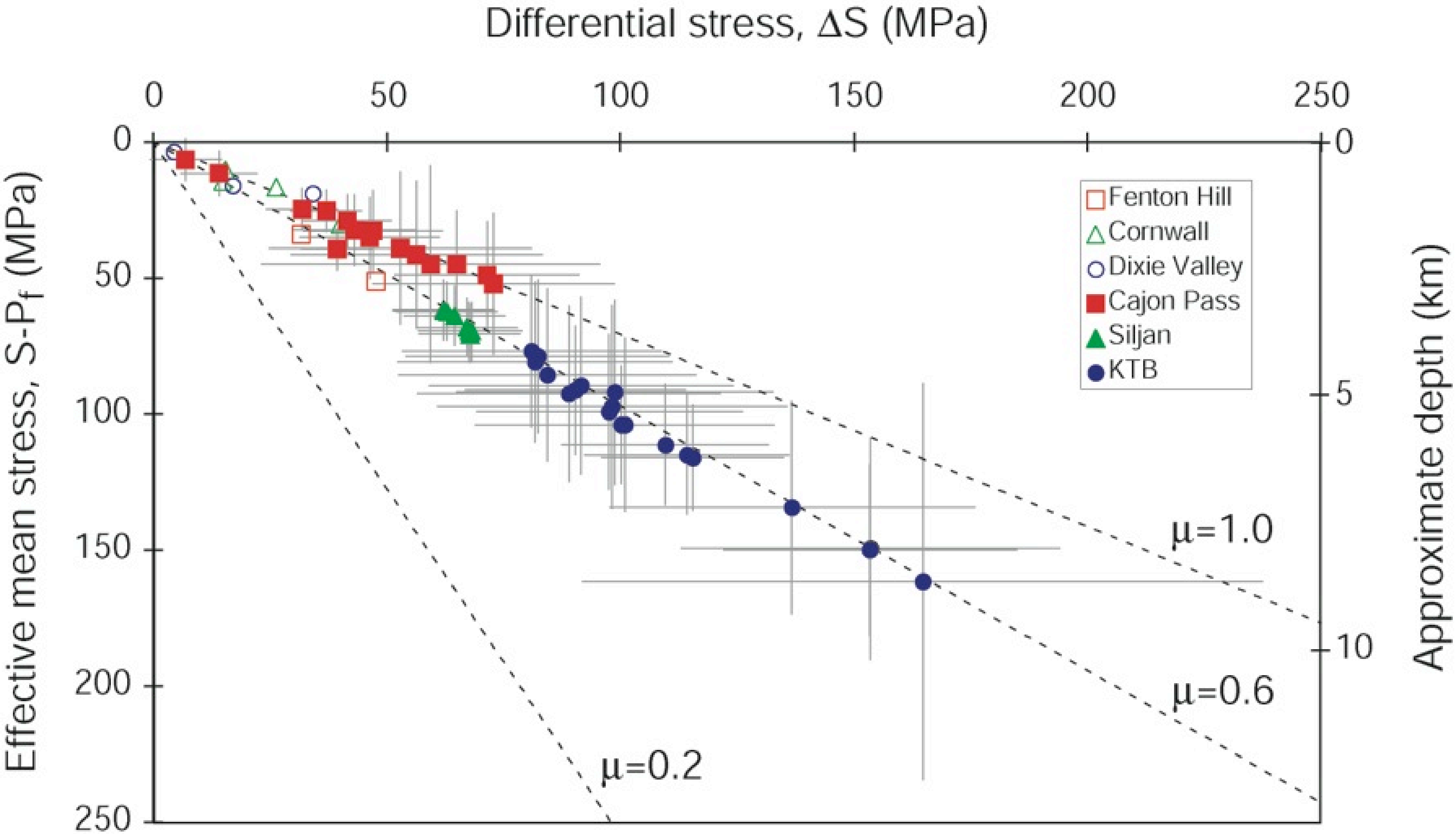
I-We Live on a Critically-Stressed Crust





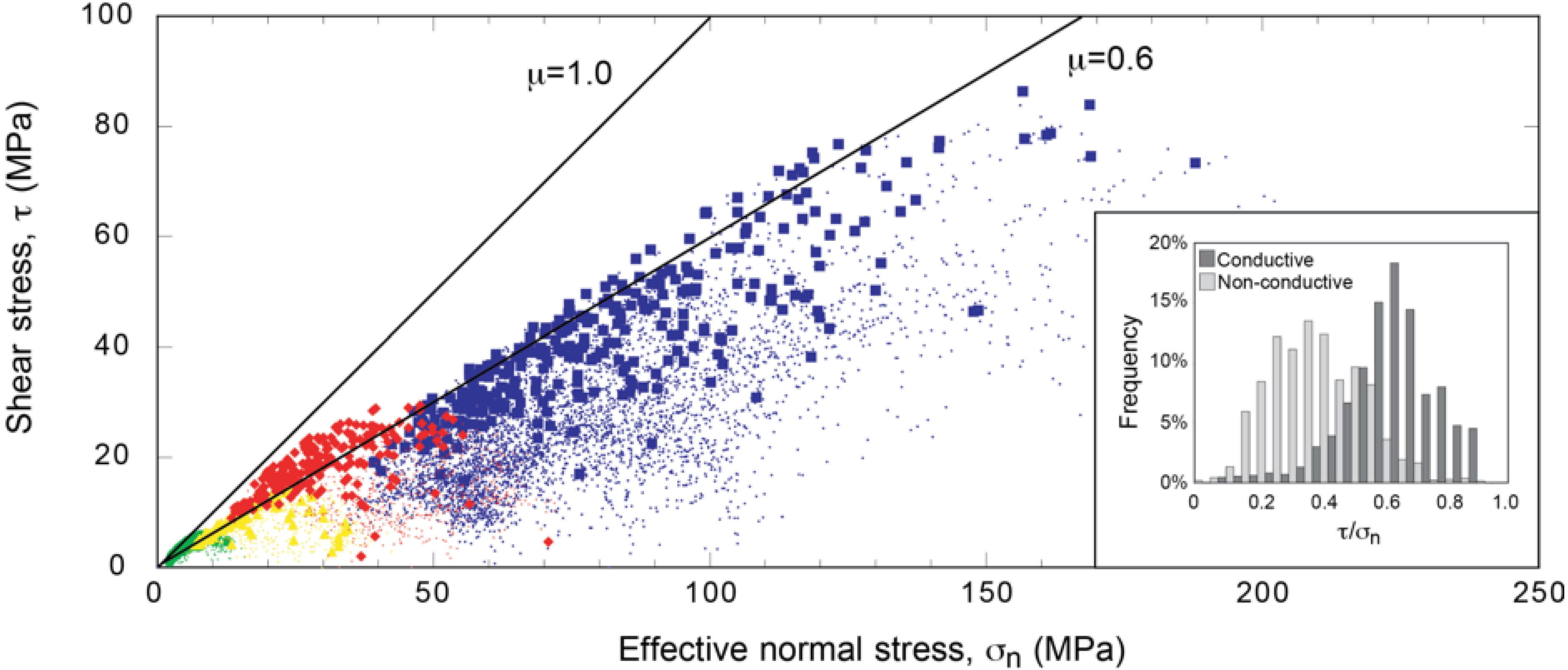
- Earthquakes Occur Nearly Everywhere in Intraplate Areas
- Stress is Near-Critical Everywhere - Earthquake Rate Reflects Intraplate Strain Rate

How Faulting Keeps The Crust Strong



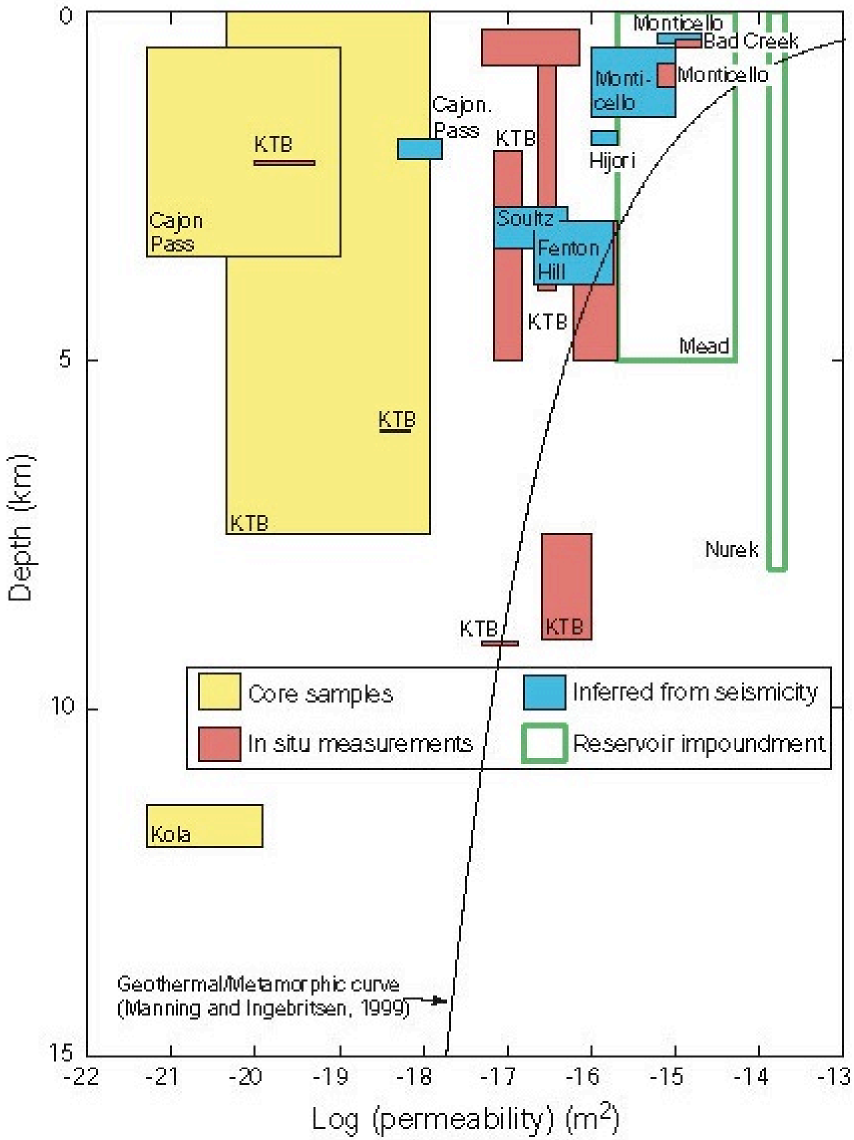
Townend and Zoback (2000)

II. Basement Faults That are *Potentially Active* in the Current Stress Field Are Also *Hydraulically Conductive*



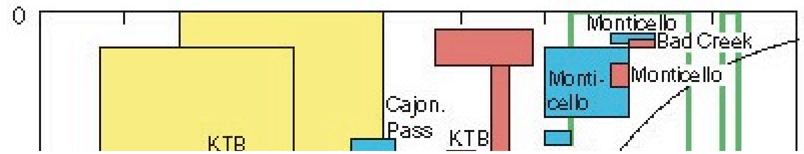
Zoback and Townend (2001)

III. Faulting Keeps The Crust Permeable



Townend and Zoback (2000)

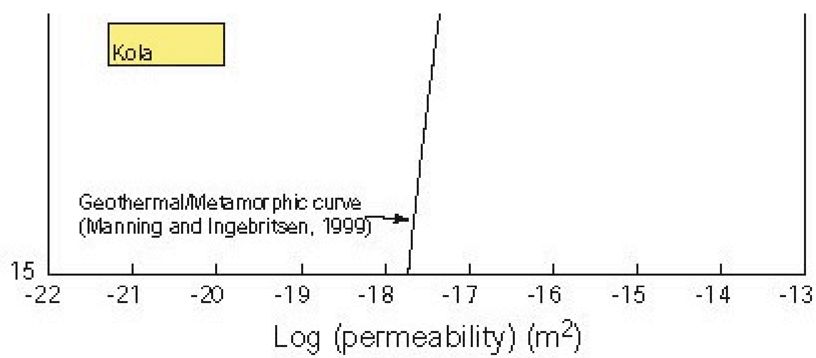
III. Faulting Keeps The Crust Permeable



High Permeability Maintains Near-Hydrostatic Pore Pressure

Well location	Regime	Depth (km)	Observation	Source	Evidence for critical stress
Cornwall HDR, England	SS	2.5	DST	Pine et al. (1983)	Stress magnitudes; induced seismicity
Fenton Hill HDR, New Mexico	N, SS	3.0	SWC	Barton et al. (1988)	Stress magnitudes
Dixie Valley, Nevada	N	2–3, 5–7	DST, SG	Hickman et al. (1997)	Stress magnitudes; prehistoric fault offsets
Cajon Pass, California	SS	3.5	DST	Coyle and Zoback (1988)	Stress magnitudes; breakout rotations
Soultz HDR, France	N, SS	5.0	DST	Baumgärtner et al. (1998)	Stress magnitudes; induced seismicity
Siljan, Sweden	SS	7.0	DST	Lund and Zoback (1999)	Stress magnitudes
KTB, Germany	SS	9.1	DST, SWC	Huenges et al. (1997) Zoback and Harjes (1997)	Stress magnitudes; induced seismicity
Kola, Russia	?R	12.2	SWC	Borevsky et al. (1987)	N.A.

Note: HDR—hot dry rock; KTB—Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (German Continental Deep Drilling Program); SS—strike-slip faulting regime; N—normal faulting regime; R—reverse faulting regime; DST—drill stem test; SWC—static water column; SG—silica geothermometry; N.A.—not available.



Townend and Zoback (2000)

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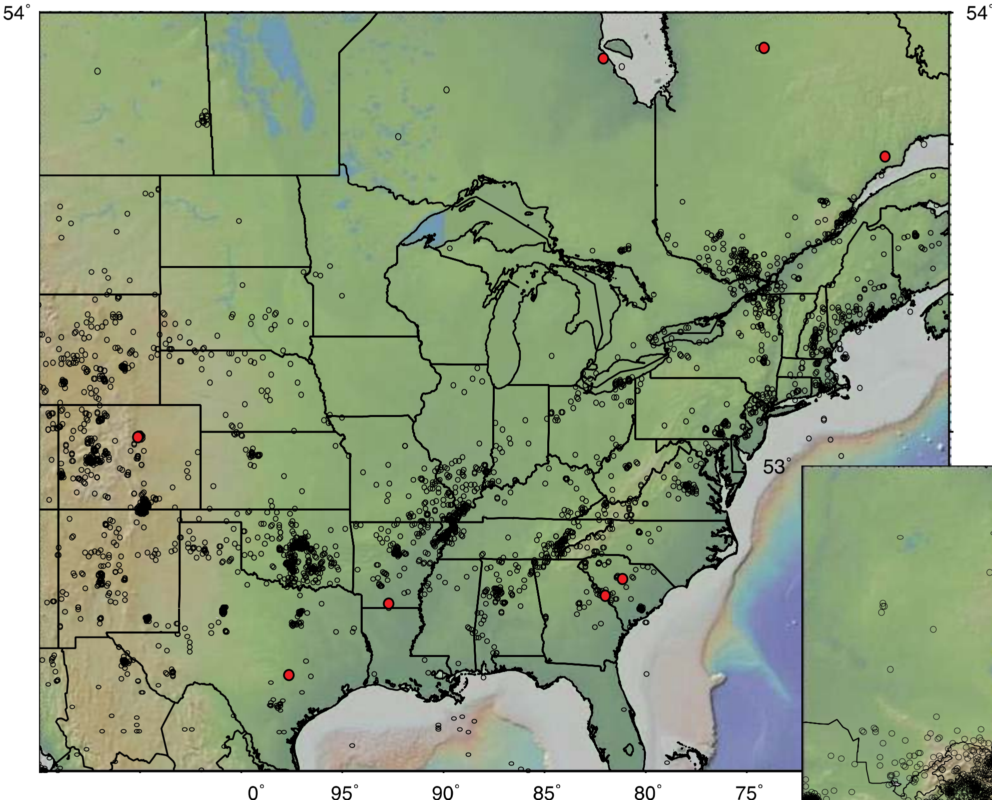
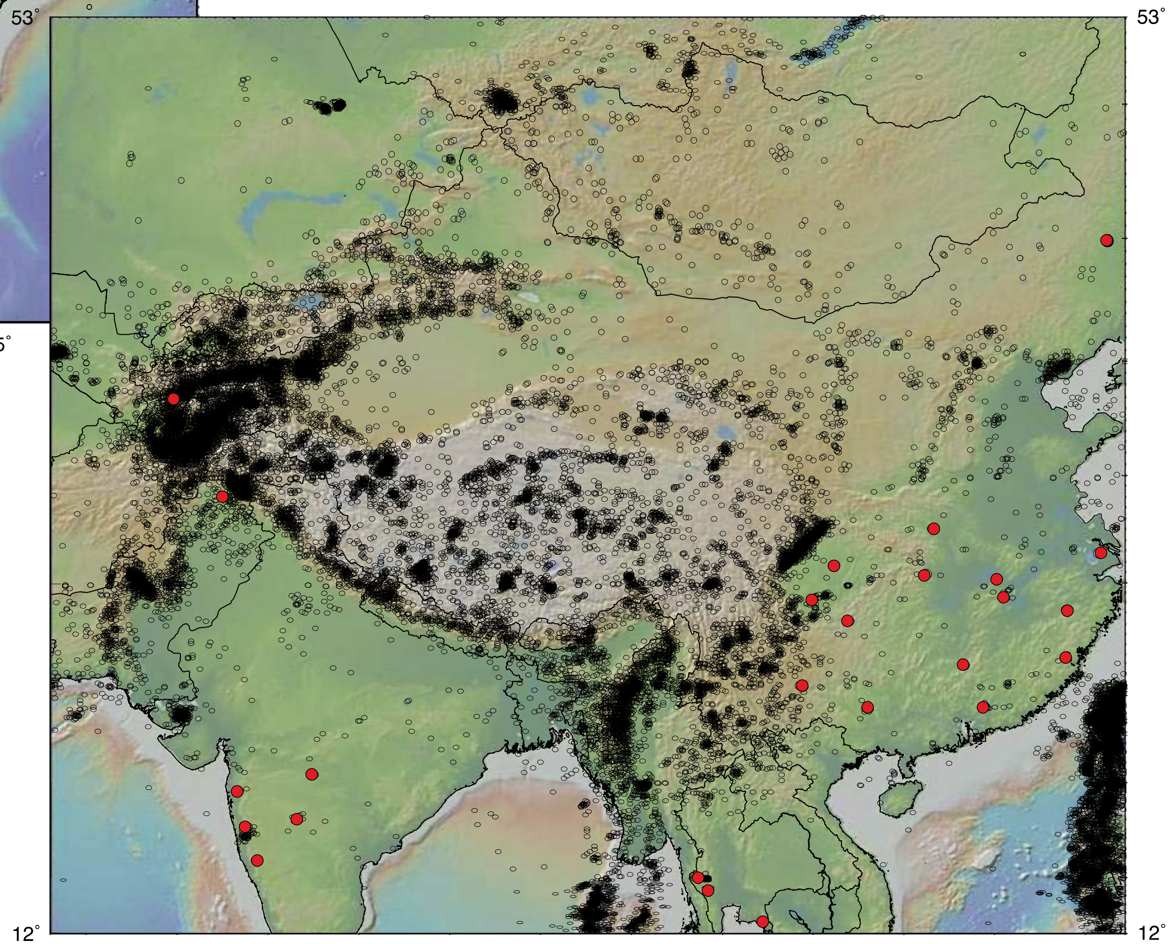
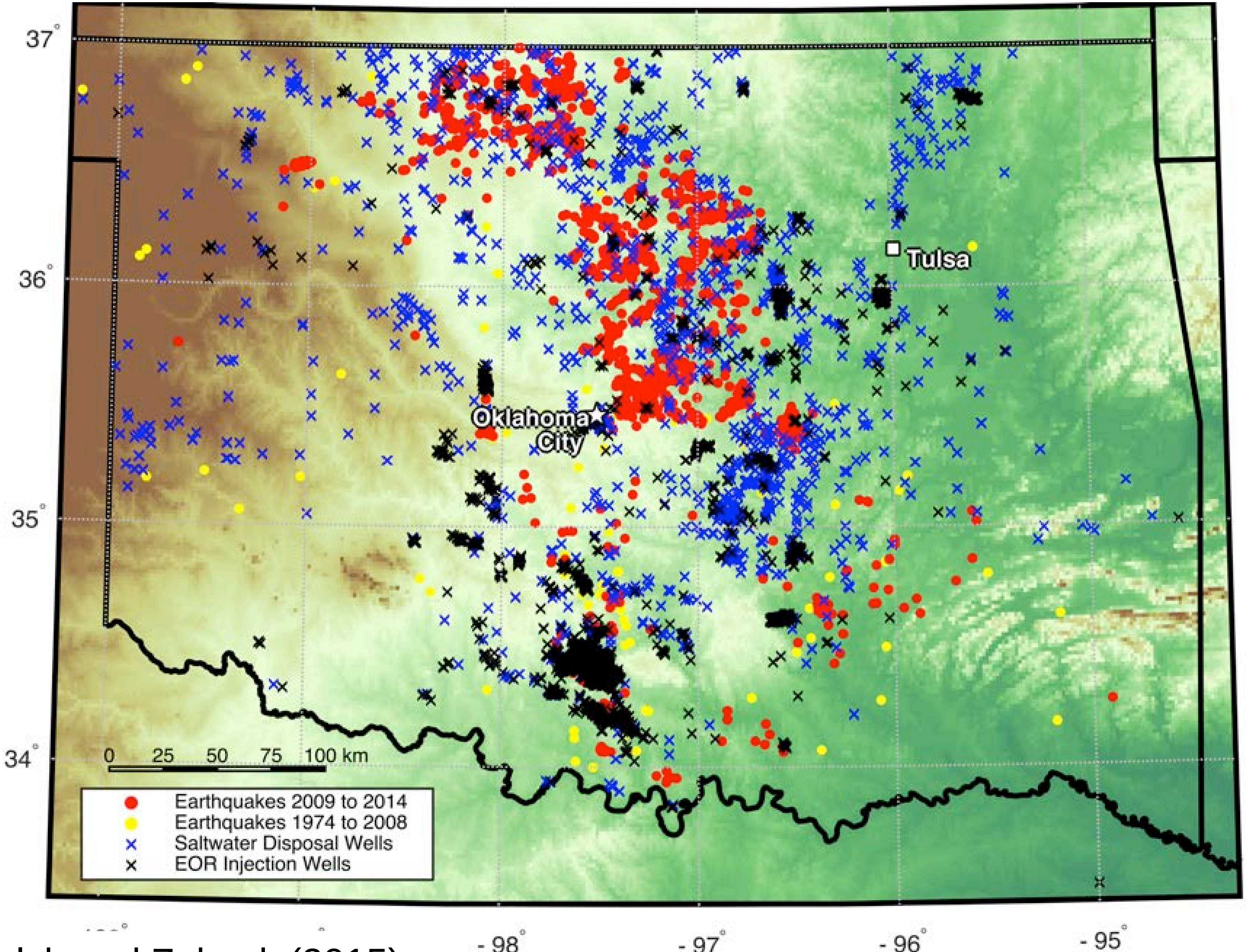




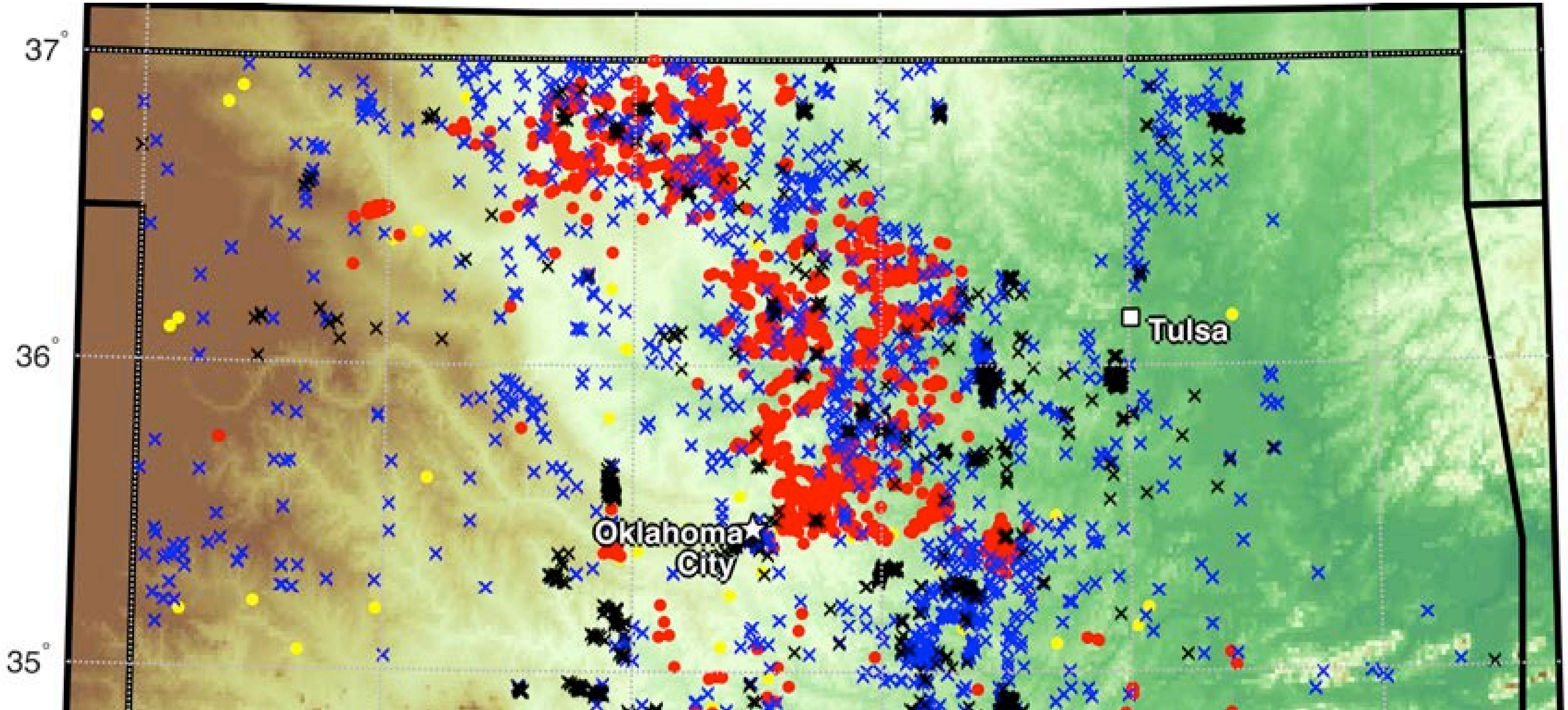
- Earthquakes Occur Nearly Everywhere in Intraplate Areas

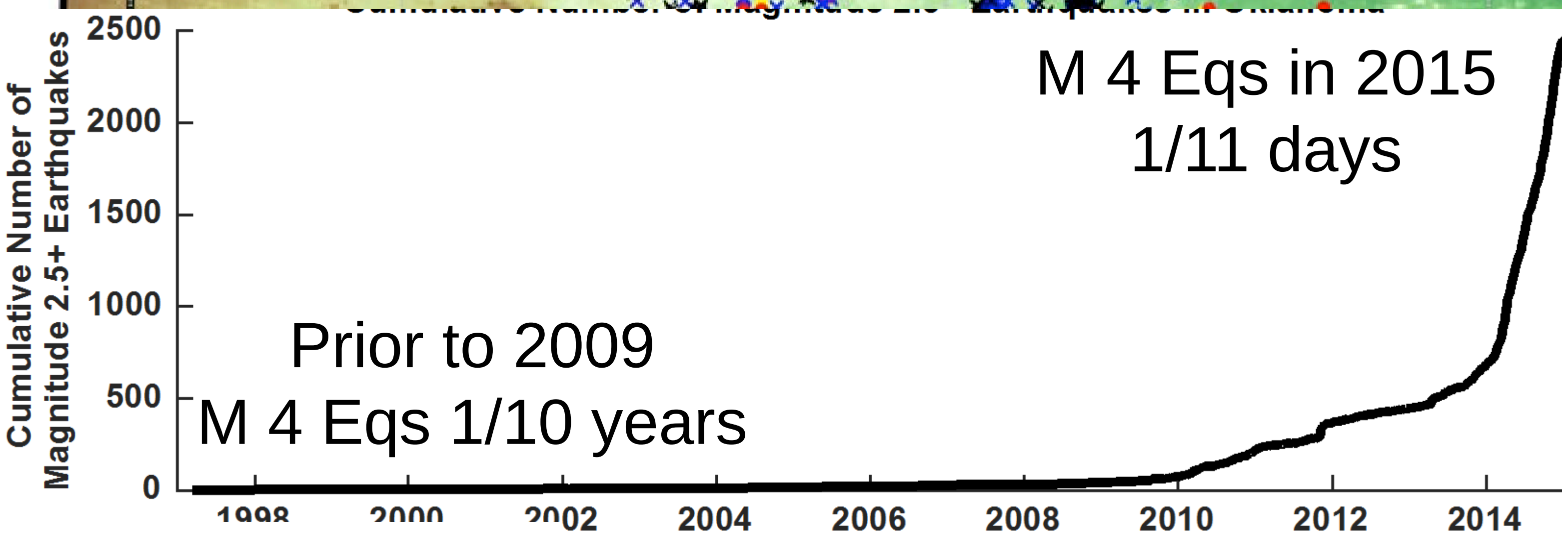
- Stress is Near-Critical Nearly Everywhere, Earthquake Rate Reflects Intraplate Strain Rate

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



Walsh and Zoback (2015)



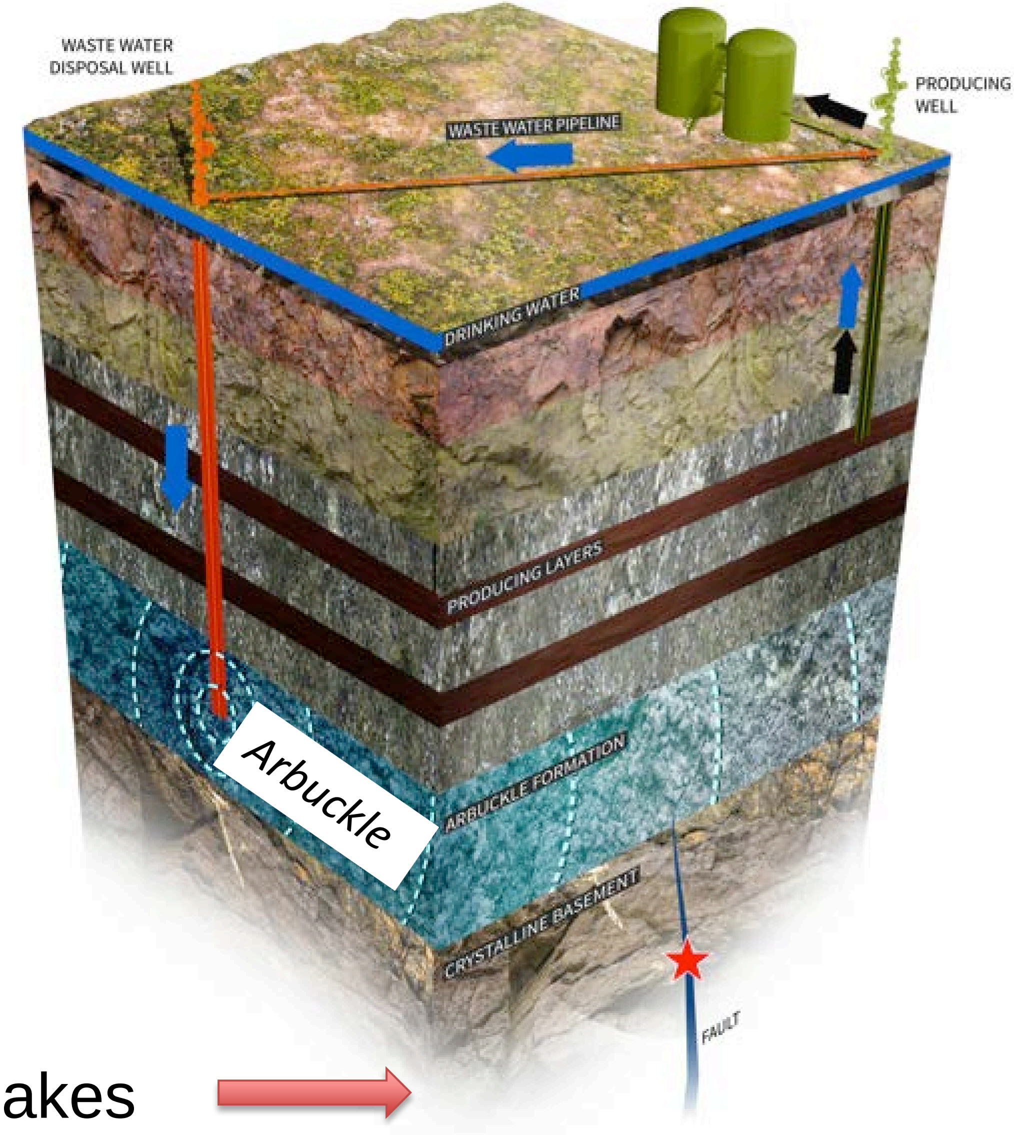


Walsh and Zoback (2015)

Massive Injection of Produced Water

Oil and Saltwater Production

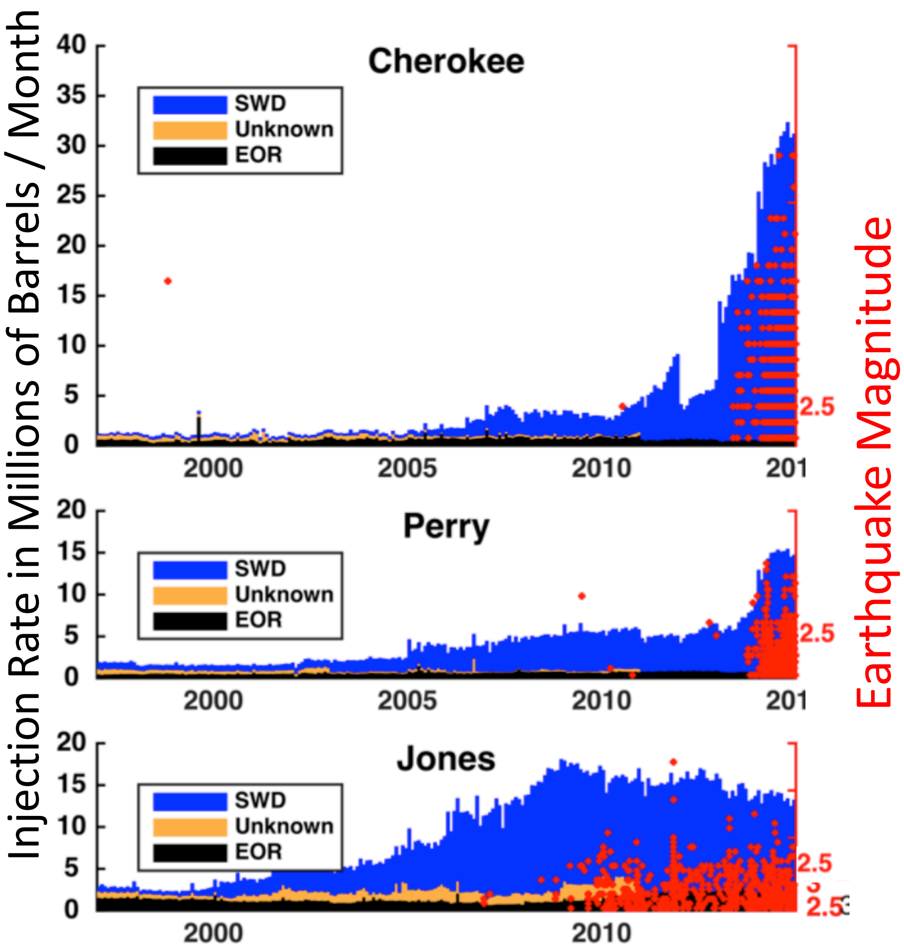
Salt Water Injection at 2 – 2.5 km
~700 Million Barrels
<1 MPa Pressure Change



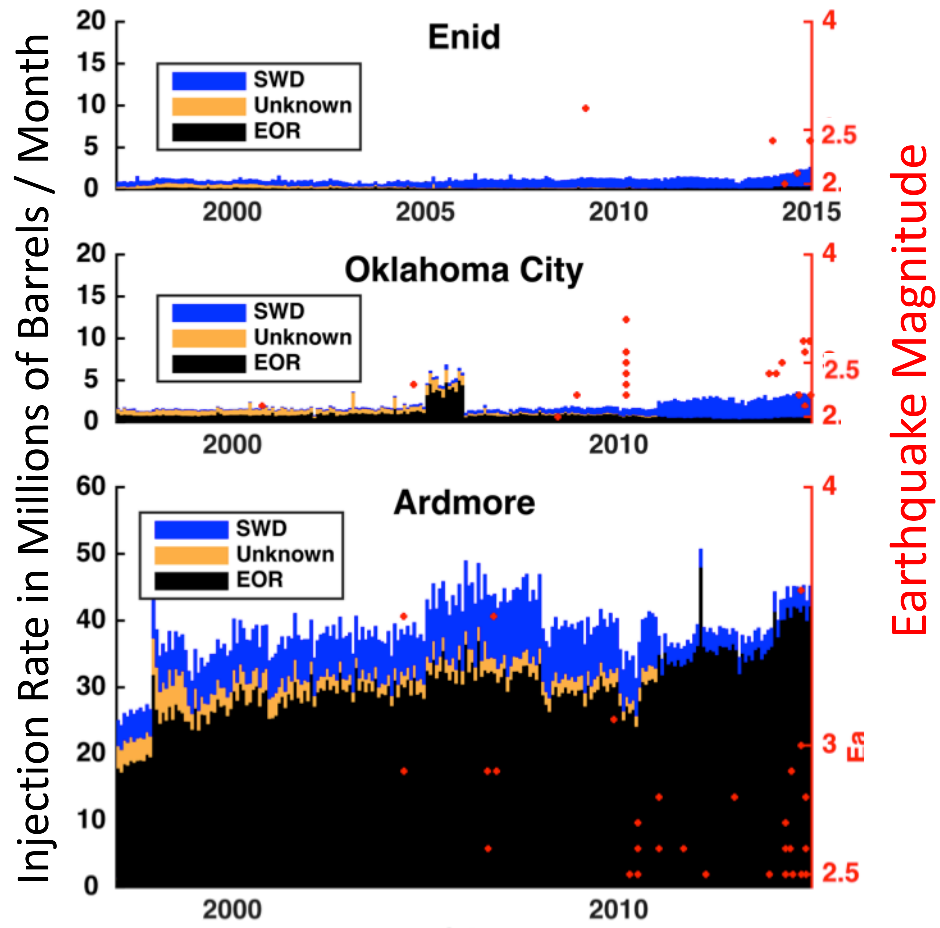
Earthquakes
5-6 km Depth

Areas With Increased Disposal Have Earthquakes

3 Areas with 71% of Oklahoma's Earthquakes

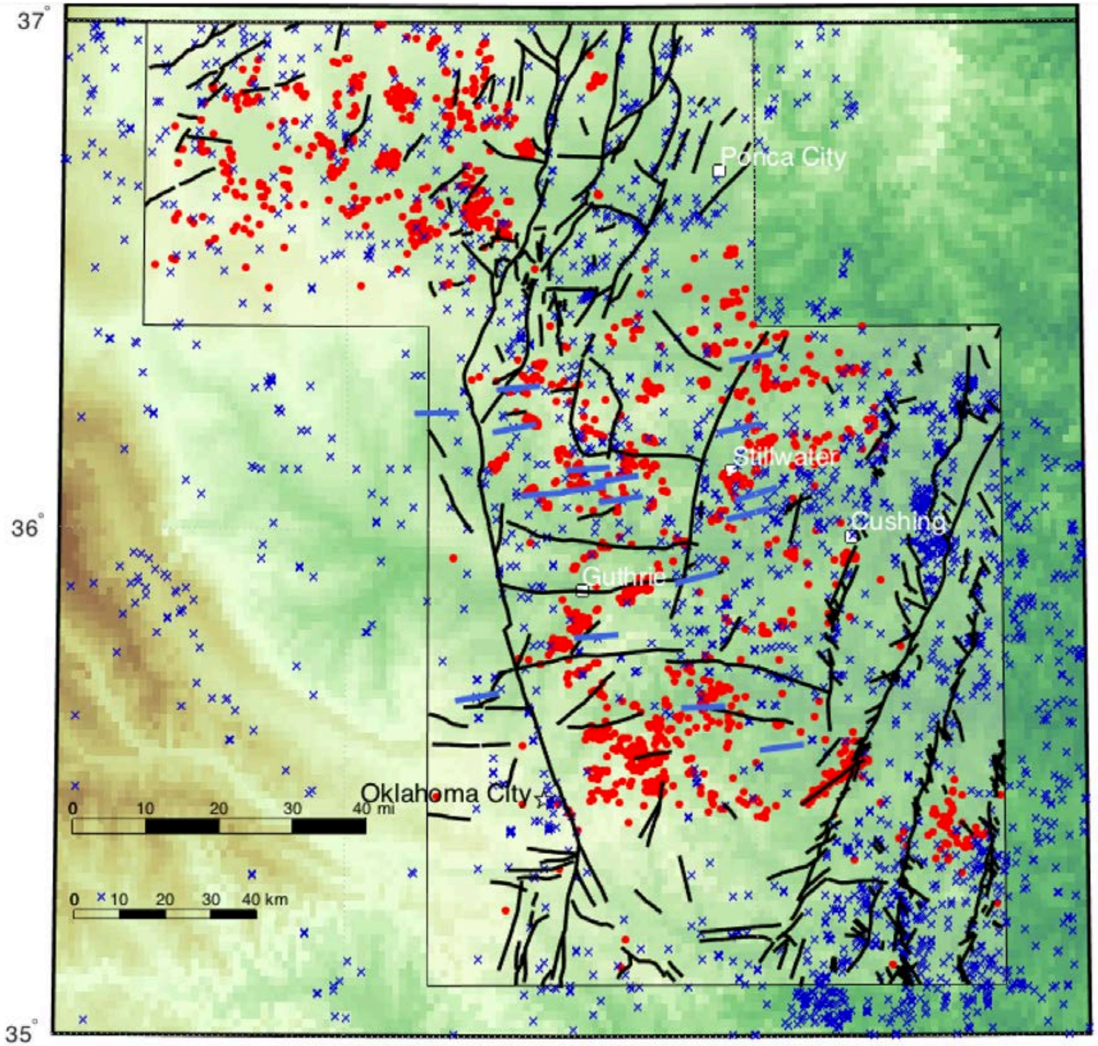


3 Areas with Few Earthquakes:



Map

Variable Distribution of Faults



<1 MPa Pressure Change Has Triggered Thousands of Earthquakes, Clustered in the Vicinity of (Unmapped) Critically-Stressed Faults