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

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<th>Well location</th>
<th>Regime</th>
<th>Depth (km)</th>
<th>Observation</th>
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<td>Cornwall HDR, England</td>
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<td>Pine et al. (1983)</td>
<td>Stress magnitudes; induced seismicity</td>
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<td>Fenton Hill HDR, New Mexico</td>
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<td>Barton et al. (1988)</td>
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<td>Dixie Valley, Nevada</td>
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<td>Cajon Pass, California</td>
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<td>Coyle and Zoback (1988)</td>
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<td>Lund and Zoback (1999)</td>
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<tr>
<td>KTB, Germany</td>
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<td>Huenges et al. (1997)</td>
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<td>Kola, Russia</td>
<td>R</td>
<td>12.2</td>
<td>SWC</td>
<td>Borevsky et al. (1987)</td>
<td>N.A.</td>
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*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)
I-We Live on a Critically-Stressed Crust

- 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”
Prior to 2009
M 4 Eqs 1/10 years

Walsh and Zoback (2015)

M 4 Eqs in 2015
1/11 days

Cumulative Number of Magnitude 2.5+ Earthquakes

Prior to 2009
M 4 Eqs 1/10 years

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

- Cherokee
- Perry
- Jones

3 Areas with Few Earthquakes:

- Enid
- Oklahoma City
- Ardmore

Map

Injection Rate in Millions of Barrels / Month

Earthquake Magnitude

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