Assessing Potential Magnitudes of Injection-Induced Seismicity

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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)

   
   Hiroki Sone, Arjun Kohli, Xiaodong Ma
   Fatemeh Rassouli, Shaochuan Xu
Strong Correlation Between Seismicity and SWD
\((\Delta P < 2 \text{ MPa see Poster P2-16})\)
Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA

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GEOLOGY

Data Repository item 2016334 | doi:10.1130/G38275.1
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What is the Probability That a Modest* $\Delta P_P$ Might Make a Known Pre-Existing Fault Slip (Prior to Injection)?

*Modest Means $\Delta P_P$ Small With Respect to Ambient Stresses
• Detailed Mapping of Stress Orientation and Relative Magnitudes
  • Wellbore Observations
  • Earthquake FM Inversions
  • Consistent $S_{H\text{max}}$ Dir.
  • Slowly Varying Relative Stress Magnitudes

• Utilize Information About Pre-Existing Faults (Darold and Holland, 2015)

• Can We Determine Which Faults are Potentially Problematic?
QRA - Prague Area Parameter Distributions

A. Coefficient of Friction

B. Fault Dip

C. Strike of faults in area 6

D. Response Surface

E. Pore Pressure at 5 km

F. S_{hmin}

G. Overburden Stress

H. S_{Hmax}

I. Stress Orientation Distributions

Walsh and Zoback, *Geology*, 2016

But there is uncertainty in every parameter.
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

Langenbruch and Zoback, 2016
Free, Online Software Released March 6, 2017
QRA to Assess Fault Slip Potential

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

- Normal Faulting or Stress States ($S_3 = S_{hmin}$)
- Elastic, Brittle
- Viscoplastic

\[ \mu = 0.6 \]
\( S_{\text{hmin}} / S_{V} \) Prediction

**Normal Faulting**

\( S_{V} > S_{\text{Hmax}} > S_{\text{hmin}} \)

- 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

\[
(t) = \frac{1}{B(1 - n)} t^n
\]

\[
S_1 - S_3 = \frac{E}{1 - n} t^n
\]

Xu and Zoback, in prep
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

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Rate and State Friction Experiments

Stable

<table>
<thead>
<tr>
<th>Coefficient of Friction</th>
<th>Slip Velocity (µm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>( V )</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>( V_0 )</td>
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</tbody>
</table>

Unstable

<table>
<thead>
<tr>
<th>Coefficient of Friction</th>
<th>Slip Velocity (µm/s)</th>
</tr>
</thead>
<tbody>
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<tr>
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</tr>
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</table>

\( D_e \) = Direct effect
\( a \) = Coefficient of friction
\( b \) = Evolution effect

\( a - b \) = Slip Displacement (µm)
Stable Sliding on Faults With High Clay

Kohli and Zoback (2013)
Rate and State Friction Experiments – Temperature Effects

Kohli & Zoback (2013)

Barnett
Eagle Ford
Haynesville

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

Assume that the crust is critically stressed
Increasing $\Delta P_P$ Can Makes Some Faults Slip
We assess likelihood of slip in terms of the $\Delta P_P$ needed to initiate slip.
Some Faults Can *Never* be Made to Slip

EXPLANATION
- Measured pore pressure
- Mud-weight pressure, MWX-1
- Mud-weight pressure, MWX-3
- Fracture gradient in shale and mudstone
- Fracture gradient in sandstone
- Fracture gradient in coal
- Interpreted pressure gradient

\( S_{hmin} \) (Shales)

\( S_{hmin} \) (Sands)

\( P_p \)

From Nelson (2003)
Multi-Well Experiment – Western Colorado

![Graph showing pressure vs. depth with various markers and lines representing different stress states and temperatures.](image-url)
Generalized Constitutive Law from Lab to Reservoir

\[ (t) = 0 \frac{1}{B(1+n)} t^n \]

\[ S_{1} - S_{3} = 0 \frac{E}{1} t^n \]

- $S_{1}$: maximum in situ principal stress
- $S_{3}$: minimum in situ principal stress
- $E$: Young’s modulus
- $t$: total geological time
- $\epsilon_0$: total tectonic strain
- $n$: dimensionless parameter that describes tendency for time-dependent deformation

*Sone and Zoback, 2013*