Limiting Slip on Basement Faults: The Rocks Matter

Mark Zoback
Professor of Geophysics
Stanford University

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What Makes a Good Bottom Seal?
Analogous Question Arises with CCS - Decatur, Illinois

- Injection of 1 million tons of CO$_2$ over a 3 year period into the Mt. Simon (8 million barrels, 1.3 million m$^3$)
- Small earthquakes define faults in Precambrian basement
- Pressure change less than 1 MPa
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)
Viscoplastic Creep in Unconventional Reservoirs

- 39% clay
- 25% clay, 22% clay, 33%

Sone and Zoback (2013b)

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Finding a Creep Constitutive Law

- Most creep experiments were 3 hours long, and suggested logarithm function
  \[ \text{creep} = A \log(t) \]
- Longer experiments show that it is closer to a power-law in the long term
  \[ \text{creep} = B t^n \]
- Furthermore, the total response (elastic + creep) can be described by a power law

![Graph showing creep strain over time with logarithm and power-law fits](image)
The concept of stress relaxation associated with viscoplasticity helps us understand why traditionally, shales were considered frac barriers when reservoirs (sands) were hydraulically fractured.
Frac Gradient Prediction

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

Bn: Barnett
Hy: 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

$\sigma(t) = \varepsilon_0 \frac{1}{B(1-n)} t^{-n}$

$S_1 - S_3 = \varepsilon_0 \frac{E}{1-n} t^{-n}$

Xu and Zoback, in prep
Increase in $S_{h_{\min}}$ in High Clay + Kerogen Formations

Ma and Zoback (in review)
Predicted Values of $S_{h_{\text{min}}}$ Using Viscoplastic Creep
Increase in $S_{hmin}$ in High Clay + Kerogen Formations

Ma and Zoback (in review)
Predicted Values of $S_{\text{hmin}}$ Using Viscoplastic Creep

From Nelson (2003)
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Rate and State Friction Experiments

Stable

- Coefficient of Friction
  - \( \mu \)
  - \( \mu_0 \)

- Slip Velocity (\( \mu \)m/s)
  - \( V \)
  - \( V_0 \)

- Slip Displacement (\( \mu \)m)
  - \( D_1 \)
  - \( (a - b) \)

Unstable

- Coefficient of Friction
  - \( \mu \)
  - \( \mu_0 \)

- Slip Velocity (\( \mu \)m/s)
  - \( V \)
  - \( V_0 \)

- Slip Displacement (\( \mu \)m)
  - \( D_1 \)
  - \( (a - b) \)

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Stable Sliding on Faults With High Clay

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

Kohli and Zoback, in prep

Kohli and Zoback, in prep
Aseismic Fault Slip Could Occur in a Bottom Seal
What Does this Mean for Leakage?
(see talk of Harry Lisabeth)