Strain accumulation across strike-slip faults: Investigation of the influence of laterally varying lithospheric properties

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The Problem

Can we use geodetic data to infer lateral variation in rigidity?
The Problem

Use gradients in velocity field to identify where active faults are locked and accumulating stress.

Gradients in velocity field can be attributed to:
1. Elastic distortion around locked faults
2. Lateral variations in lithospheric rigidity (thickness/stiffness)

Can we use geodetic data to infer lateral variation in rigidity?
Inferred Lateral Variations in Crustal Rigidity

Great Sumatra Fault

Elastic Half-Space Models

\( \text{e.g., Le Pichon (2005)} \)

Inferred rigidity ratio \( (\mu_1/\mu_2): 30 \)

Idealized bimaterial fault interface
Inferred Lateral Variations in Crustal Rigidity

Plate Models
e.g., Chéry (2008), Jolivet et al. (2008)

Flow underneath plates is not considered.
Inferred Lateral Variations in Crustal Rigidity

Finite Element Models
e.g., Lundgren et al (2009), Schmalze et al. (2005)

Inversions are difficult because models are computationally expensive.
Why revisit this problem?

• Elastic half-space and plate models neglect viscous flow – we show that this is important

• Finite Element models too slow to fully explore model space
Our Model:

- Displacement-discontinuity Boundary Element Method
- Elastic layers overlying viscoelastic half-space
- Lateral variation of rigidity: e.g. stiffness and thickness
- Earthquake cycle model

Analytical solution of an finite-width screw dislocation [e.g. Okada, 1992]
Our Model

Boundary conditions

\[ \tau_B \propto \exp \left( -t \frac{\mu_B}{\eta_B} \right) \]

Stress Relaxation time, \( t_R = 2(\eta_B / \mu_B) \)
**Our Model:**

For a purely elastic problem,

\[ b = Gs \]

\[ => s = G^{-1}b \]

\( b \) : a vector of boundary conditions  
\( s \) : a vector of corresponding displacements  
\( G \) : a matrix of Green's functions,
Our Model

Stresses vary with time, so do $s$ and $b$. 

\[ \tau_B = \tau^e * \exp\left(-t/t_R\right) \]

Stress Relaxation time, $t_R = 2(\eta_B/\mu_B)$
Our Model:

Stresses vary with time, so do $s$ and $b$.

At the $j$th increment, the displacement discontinuity distribution is

$$s_j = \sum_{j-1} G(t, t_R, s_1, s_2, \ldots, s_{j-1})^{-1} b$$
Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

\[ s_j = \sum_{k=0}^{j-1} G(t, t_R, s_1, s_2, \ldots, s_{j-1})^{-1} b \]
Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

\[
s_j = \sum_{k=0}^{j-1} G(t, t_R, s_1, s_2, \ldots, s_{j-1})^{-1} b
\]

T: earthquake recurrence interval
Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

\[ s_j = \sum_{k=0}^{j-1} G(t, t_R, s_1, s_2, ..., s_{j-1})^{-1} b \]

- Co-seismic:
  \[ t = n*T \text{ where } n = \infty + 1, \infty + 2, \infty + 3, ... \]

- Inter-seismic:
  \[ t \neq n*T \text{ where } n = \infty + 1, \infty + 2, \infty + 3, ... \]
Asymmetry of Deformation

Contrast in Elastic Thickness

Asymmetry varies with the time since last earthquake (t)

Asymmetry is more pronounced at early times
Asymmetry of Deformation

Contrast in Elastic Thickness

Asthenosphere viscosity is important:
Asymmetry is more pronounced for lower viscosities
Asymmetry of Deformation

Contrast in Elastic stiffness

Asymmetry varies with the time since last earthquake (t)

Asymmetry is more pronounced at later times
Asymmetry of Deformation

Contrast in Elastic stiffness

Asthenosphere viscosity is important:
Asymmetry is more pronounced for lower viscosities
Asymmetry of Deformation

Contrast in Elastic stiffness

Contrast in Elastic Thickness
Monte Carlo Inversion
-- Metropolis method

To sample the posterior distribution, we initiate a random walk through the model space that samples the a priori distribution.

\[ \mathbf{m}_j = \mathbf{m}_i + \sum_{k=1}^{d} \alpha_k \gamma_k \mathbf{e}_k \]

, where \( \mathbf{m} = [m^1 \ m^2 \ m^3 \ m^4 \ ... \ m^d] \)

\( \alpha_k \): scale factor
\( \gamma_k \): (-1, 1) uniform random deviate
\( \mathbf{e}_k \): the unit vector along the \( k \)th axis in parameter space
Markov Chain random walk

An example: samples projected to 2D

\[ \underline{m} = [m^1 \ m^2 \ m^3 \ m^4 \ldots \ m^q] \]

The walk moves to the next model with probability

\[ P_{ij} = \min \left(1, \frac{\rho_D(g(m_j))}{\rho_D(g(m_i))} \right) \]

\( \rho_D \): probability density function of the model parameters
Markov Chain random walk

Sample distribution

Probability contour
Great Sumatra Fault, Indonesia

Component of velocity parallel to the fault trace

(Genrich et al., 2000; Le Pichon, 2005)
Results

logarithmic ratio of stiffness

logarithmic ratio of thickness

Great Sumatra fault

Velocity (mm/yr)

Distance from fault trace (km)

95
Results

- For Great Sumatra fault, the inversion result shows eastern elastic layer must be stiffer than western one but there is no resolved a contrast in elastic thickness.

Consistent with the manifestation of geology
Results

- $\hat{S}$ (mm/yr):
  - 23, 24, 25, 26, 27

- $H_{NE}$ (km):
  - 20, 40, 60

- $H_{SW}$ (km):
  - 20, 40, 60

- $t_\alpha$ (years):
  - 0, 100, 200

- $T$ (years):
  - 100, 150, 200

- Locking depth:
  - 8.8 km
  - 97.5%
Carrizo segment of San Andreas Fault, USA

![Map of the Carrizo segment of the San Andreas Fault with velocity data graph. The map shows the fault line with arrows indicating movement and a graph plotting velocity against distance from the fault trace.]
Results

The inversion favors a thicker layer on the east side (2 times) but stiffer layer on west side (1.2 times); however, uniform thickness and stiffness cannot be ruled out.

SW block: thicker
NE block: thicker

10^{0.3} = 2

logarithmic ratio of thickness

logarithmic ratio of stiffness

Carrizo segment of San Andreas fault

Velocity (mm/yr)

Distance from fault trace (km)

95% confidence intervals (%)
Results

Plate Velocity

Thickness of Right Elastic Layer

Thickness of Left Elastic Layer

Stress Relaxation Time

Earthquake Recurrence Time

Locking Depth

- 2.5% to 97.5% range
- 15.5 km depth
- Uniform distribution
Conclusions

Can we use geodetic data to infer lateral variation in rigidity?  
Yes, we can  
(up to some degree).
Thank you for your attention!
Great Sumatra Fault
Results

ratio of $t_R$ to $T$ vs. rigidity ratio

ratio of $t_R$ to $T$ vs. thickness ratio

t_R: Stress relaxation time
t: earthquake recurrence time