3D Viscoelastic Earthquake Cycle Models
Estimating fault slip rates, locking distribution, elastic/viscous properites of lithosphere/asthenosphere

Kaj M. Johnson
Indiana University

In collaboration with: Paul Segall, Stanford; Ray Chuang, Indiana; Junichi Fukuda, Indiana University (now at ERI)
Conceptual Model of Lithosphere

Approach: develop forward model and inverse method to obtain joint estimation of

1. long-term fault slip rates
2. Interseismic creep rates
3. Location of locked patches
4. Lithosphere viscosity
5. Elastic thickness
Methodology/Philosophy

**Forward Model**
- Need fast models
- Semi-analytical methods
  - propagator matrix method
- boundary element methods for stress boundary conditions

**Inverse Method**
- Bayesian, probabilistic
- large number of unknown model parameters – no optimization – want posterior probability distributions
- Monte Carlo sampling
- need to compute 100 K’s of forward computations
Talk Outline

• Geologic/Geodetic fault slip rate discrepancy in southern California
  • model dependence on slip rate estimate
  • Illustration with 2D models (infinitely long faults)
  • Inversions with 2D and 3D models -- reconcile discrepancy

• San Francisco Bay Area interseismic deformation
  • inversion for:
    Fault slip rate
    Locking distribution
    Asthenosphere viscosity
    Earthquake repeat times
Slip Rate Discrepancies in Southern California

Becker et al. (2004), Meade et al. (2005)
Standard Elastic Block Model

e.g., Jim Savage, Rob McCaffrey, Brendan Meade

Rigid Body Rotation (no fault locking)

Elastic distortion due to fault locking
Viscoelastic Coupling Model
Savage and Prescott (1978)

\[ \frac{T}{t_R} = 4 \]
2D Models of Interseismic Deformation

Screw dislocation
Savage and Burford (1978)

Viscoelastic coupling model
Savage and Prescott (1983)

\[ \frac{T}{t_R} = 5 \]
\[ \frac{T_{eq}}{T} = 0.8 \]
2D Models of Interseismic Deformation

Viscoelastic coupling model
Savage and Prescott (1983)

\[ T/t_R = 5 \]
\[ T_{eq}/T = 0.8 \]
2D Models of Interseismic Deformation

Stress-driven creep model

Johnson and Segall (2004)
2D Models of Interseismic Deformation

Johnson et al (2007)
Viscosity Varies with Depth

Thatcher and Pollitz (2008)

$T = 250 \text{ yrs}$

Johnson et al. (2007)
Fault Slip Rates and Interseismic Deformation: Mojave Region

Johnson et al. (2007)
Data

**Paleoseismic record**

**GPS -- contemporary**

**triangulation**

**Landers postseismic GPS**
2D Viscoelastic Earthquake Cycle Model
Mojave segment of SAF system

Data:
- GPS
- Historical triangulation
- Paleoseismic data
- Landers postseismic

Estimate:
- slip rates
- viscosity

Johnson, Hilley, and Bürgmann (2007)
2D Viscoelastic Earthquake Cycle Model
Mojave segment of SAF system

Data:
- GPS
- Historical triangulation
- Paleoseismic data
- Landers postseismic

Result:
- Inversion: slip rate: 23-32 mm/yr
- Geology: 25-30 mm/yr
- Elastic block models: 10-15 mm/yr

Johnson, Hilley, and Bürgmann (2007)
2D Viscoelastic Earthquake Cycle Model

Inversion Results

[Diagram showing layers of the earth with different viscosities and recurrence plots for different equations.]

- recurrence Eq.4-Eq.3
- recurrence Eq.3-Eq.2
- recurrence Eq.2-Eq.1
- recurrence Eq.1-1812

- elastic thickness
- SAF slip rate
Lithosphere Viscosity

Thatcher and Pollitz (2008)
Faults are not 2D!
3D Earthquake Cycle Block Model

Interseismic Deformation = Steady State + Perturbation

paper in prep.
3D Earthquake Cycle Block Model

Interseismic Deformation = Steady State + Perturbation

earthquake cycle = forward slip + back-slip and earthquakes

slip vs. time

locked creeping elastic viscoelastic
Construction of Steady State Velocity Field

- Total deformation field
- Rigid block motion
- Cancel component of velocity discontinuity perpendicular to faults
- Steady slip on reverse faults
Fault Geometry
Based on SCEC Community Fault Model

Rupture Segments

recurrence time, time since EQ (years)
Interseismic Perturbation

15 km
Interseismic Perturbation

$tr = 25$ yr

15 km
Inversion Results: strike-slip rate (mm/yr)

Geologic rates

Elastic block model

15 km
Inversion Results: strike-slip rate (mm/yr)

Geologic rates

Viscoelastic block model

tr = 5 yr

tr = 250 yr
residual velocities (data - model)

5 mm/yr
- layered model
- elastic block model
San Francisco Bay Area

GPS and geologic data
San Francisco Bay Area
Triangulation data: post 1906 transient
Probabilistic Bayesian Inversion

Posterior distribution

$\mathbf{p(\Omega, n, w_{GPS}, w_{TRI} | d)} = k \cdot \mathbf{x}$

Likelihood

$\mathbf{p(d | \Omega, n, w_{GPS}, w_{TRI})}$

Prior distribution

$\mathbf{p(\Omega, n, w_{GPS}, w_{TRI})}$

geodetic data & model

geologic data

Euler poles (linear)

Relative weights on data

Nonlinear parameters
Algorithm
Monte Carlo with Metropolis Step

discrete samples

marginal
Mixed Linear/Nonlinear Inversion

\[ p(\Omega, n, w_{\text{GPS}}, w_{\text{TRI}} \mid d) = p(\Omega \mid d, n, w_{\text{GPS}}, w_{\text{TRI}}) \times p(n, w_{\text{GPS}}, w_{\text{TRI}} \mid d) \]
Inversion Result: Fault slip rates
Inversion Results:
Inversion Result: Earthquake Recurrence Times
Fit to GPS data
residual velocities
Conceptual Model of Lithosphere

Approach: develop forward model and inverse method to obtain joint estimation of

1. long-term fault slip rates
2. Interseismic creep rates
3. Location of locked patches
4. Lithosphere viscosity
5. Elastic thickness
Simultaneous Estimation of Long-term Slip Rates and Locking Distribution
Simultaneous Estimation of Long-term Slip Rates and Locking Distribution
Simultaneous Estimation of Long-term Slip Rates and Locking Distribution

assume steady asthenosphere flow – fault stressing rate is constant
The creep rate is linearly related to Euler poles and surface velocities. The total creep rate can be expressed as:

\[ \dot{d} = d_c + d_\ell = G_c \dot{s}_c + G_\ell \dot{s}_\ell \]

where \( d_c \) and \( d_\ell \) are the creeping and long-term contributions, respectively. The creeping rate can be calculated as:

\[ \dot{s}_c = (G'_\sigma)^{-1} G''_\sigma \dot{s}_\ell \]

boundary element

The total slip rate is given by:

\[ \dot{s} = V\Omega \]

and the total deformation can be expressed as:

\[ d = \left[ G_c (G'_\sigma)^{-1} G''_\sigma V_c + G_\ell V_\ell \right] \Omega \]

creeping contribution
locked contribution

The diagrams illustrate the long-term slip and interseismic slip with color-coded slip rates in units of (mm/yr).
Inversion Result

Distribution of locked and creeping patches

Interseismic creep rate
Distribution of locked and creeping patches

Locked and creeping seismicity rate

Locked

Creeping

Seismicity rate

Earthquakes/year
Creep Rate Varies with Time

Johnson and Segall (2004)

\[ T/l_R = 1 \]

\[ T/t_R = 10 \]

\[ t_{eq} = 0.8T \]
Creep Rate Below Locking Depth

different locking depths would be inferred
Incorporating Stress-driven Creep in Cycle Model

boundary condition: creep at constant stress (zero stressing rate)

\[ g_e^u(z,t) \dot{s}_L T + g_e^l(z,t)(\dot{s}_L - \dot{s}_i)T + g_c^l(z)\dot{s}_i = 0 \]

\( g \sim \) Green's functions  \( \dot{s}_L \sim \) long-term slip rate  \( \dot{s}_i \sim \) interseismic creep rate

\[ g_e^u(z,t)\dot{s}_L T + g_e^l(z,t)(\dot{s}_L - \dot{s}_i)T + g_c^l(z)\dot{s}_i T = 0 \]
Incorporating Stress-driven Creep in Cycle Model

boundary condition: creep at constant stress (zero stressing rate)

\[ g_e^u(z,t) \dot{s}_L T + g_e^q(z,t)(\dot{s}_L - \dot{s}_i) T + g_o(z) \dot{s}_i = 0 \]

\( g \sim \) Green's functions  
\( \dot{s}_L \sim \) long-term slip rate  
\( \dot{s}_i \sim \) interseismic creep rate

\[ g_e^u(z,t) \dot{s}_L T + g_e^q(z,t)(\dot{s}_L - \dot{s}_i) T + g_o(z) \dot{s}_i T = 0 \]

\[ \dot{s}_i = \dot{s}_L \frac{T[g_e^u(z,t) + g_e^q(z,t)]}{g_o(z) - g_e^q(z,t)T} \]

\[ (\dot{s}_L - \dot{s}_i)T = \dot{s}_L T \left\{ 1 - \frac{T[g_e^u(z,t) + g_e^q(z,t)]}{g_o(z) - g_e^q(z,t)T} \right\} \]
Incorporating Stress-driven Creep in Cycle Model

boundary condition: creep at constant stress (zero stressing rate)

\[ g_e(z,t)\dot{s}_L T + g_e(z,t)(\dot{s}_L - \dot{s}_i)T + g_c(z)\dot{s}_i = 0 \]

g \sim \text{Green's functions} \quad \dot{s}_L \sim \text{long-term slip rate} \quad \dot{s}_i \sim \text{interseismic creep rate}

\[ g_e(z,t)\dot{s}_L T + g_e(z,t)(\dot{s}_L - \dot{s}_i)T + g_c(z)\dot{s}_i T = 0 \]

\[ \dot{s}_i = \dot{s}_L \frac{T[g_e(z,t) + g_e^i(z,t)]}{g_c(z) - g_e^i(z,t)T} \]

\[ (\dot{s}_L - \dot{s}_i)T = \dot{s}_L T \left\{ 1 - \frac{T[g_e(z,t) + g_e^i(z,t)]}{g_c(z) - g_e^i(z,t)T} \right\} \]
boundary condition: creep at constant stress (zero stressing rate)

\[ g^{\text{e}}(z,t) \dot{s}_L T + g^i(z,t)(\dot{s}_L - \dot{s}_i) T + g^c(z) \dot{s}_i = 0 \]

g \sim \text{Green's functions} \quad \dot{s}_L \sim \text{long-term slip rate} \quad \dot{s}_i \sim \text{interseismic creep rate}

\[ g^{\text{ui}}(z,t) \dot{s}_L T + g^{\text{ei}}(z,t)(\dot{s}_L - \dot{s}_i) T + g^c(z) \dot{s}_i T = 0 \]

\[ \dot{s}_i = \dot{s}_L \frac{T[g^{\text{ui}}(z,t) + g^{\text{ei}}(z,t)]}{g^c(z) - g^e(z,t) T} \]

\[ (\dot{s}_L - \dot{s}_i) T = \dot{s}_L T \left\{ 1 - \frac{T[g^{\text{ui}}(z,t) + g^{\text{ei}}(z,t)]}{g^c(z) - g^e(z,t) T} \right\} \]
Stress-driven Interseismic Creep
Inversion Result

Distribution of locked and creeping patches
approximate stress-drive creep model

creep rate (mm/yr)

0 5 10 15 20 25
We nearly have a method to simultaneously estimate:

1. Long-term fault slip rates
2. Interseismic creep rates
3. Location of locked patches
4. Lithosphere viscosity
5. Elastic thickness