Combining InSAR and GPS data to distinguish coseismic and postseismic slip in the 2003 San Simeon and 2004 Parkfield earthquakes

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Two Central California Earthquakes

- 10 months and 60 km apart
- 2003 San Simeon
  - $M_w 6.5$
  - Largest EQ in region in last 100 years
  - Little postseismic slip on multiple structures
- 2004 Parkfield EQ
  - $M_w 6.0$
  - Most recent in a series of M6 eqs since 1857.
  - Copious postseismic slip
- Both typify of their tectonic settings
The Parkfield Segment

- Transition Zone
  - Some steady creep
  - Some strain accumulation
  - Transient slip
    - 1993-1996 slow earthquake
    - Copious postseismic slip

- 2004 earthquake
  - Nearly as much (or more) aseismic slip as seismic
  - Occurred extremely rapidly following the earthquake
  - Typical of earthquake on creeping fault (?)
The Parkfield Segment

- **Transition Zone**
  - Some steady creep
  - Some strain accumulation
  - Transient slip
    - 1993-1996 slow earthquake
    - Copious postseismic slip

- **2004 earthquake**
  - Nearly as much (or more) aseismic slip as seismic
  - Occurred extremely rapidly following the earthquake
GPS Displacements

Coseismic ($d_{pk}$)

Postseismic ($A_{ps}$)

Displacements relative to station ORES
The Parkfield Segment

- Transition Zone
  Heterogeneous distribution of fault frictional regimes
- 2004 earthquake
  Good separation of seismic vs. aseismic slip:
  - How transition is accommodated
  - What can we expect on other faults
ENVISAT Interferograms

7/3/03-9/30/04

4/14/04-10/6/04

5/19/04-10/6/04

9/14/04-11/23/04

6/23/04-12/15/04

ENVISAT Interferograms

8/26/04-12/9/04

6/19/04-12/28/04

RADARSAT Interfs.

5/19/04-10/6/04

8/26/04-12/9/04

6/19/04-10/17/04

6/19/04-12/28/04

Small earthquake → low signal to noise

SAFOD

Parkfield EQ epicenter

San Simeon EQ epicenter
Time History from GPS

Fit time-series with...
Steady Interseismic rate
Offset at San Simeon EQ (12/22/2003)
Offset at Parkfield EQ ($d_{pk}$)
Exponential after Parkfield EQ

$$A_{ps} \left( 1 - e^{-\frac{t - t_{pk}}{\tau}} \right)$$

$A_{ps}$ = Amplitude
$\tau$ = decay time constant
$t$ = time
$t_{pk}$ = date of Parkfield earthquake
Geodetic Data for Parkfield EQ

- 8 Interferograms
  - co-, post-intermixed
- 2 sets GPS displacements
  - co-, post-separate
- 1 model
  - BOTH co-, post-slip
Inversion Formulation

\[ \begin{align*}
\alpha G_{sl} & \quad \alpha G_{sl} \quad 1 - e^{-t_{ps1} - t_{pk}/\tau} \\
M & \quad M \\
\alpha G_{sN} & \quad \alpha G_{sN} \quad 1 - e^{-t_{psN} - t_{pk}/\tau} \\
G_{gc} & \quad 0 \\
G_{gp} & \quad \beta \nabla^2 \\
\beta \nabla^2 & 
\end{align*} \]

\[ \begin{align*}
R^1 & \quad \begin{bmatrix} r \\ \nabla d_{sl} \end{bmatrix} \\
M & \quad M \\
R & \quad r \\
\beta \nabla^2 & \\
\beta \nabla^2 & \\
0 & \quad 0 \\
0 & \quad 0 \\
0 & \quad 0 \\
R & 
\end{align*} \]

\[ \begin{align*}
d_{sN} & = \text{InSAR data} \\
r & = \text{r} \\
d_{pk}, d_{ps} & = \text{coseismic and postseismic GPS data} \\
\alpha & = \text{InSAR data weight} \\
G_{sN}, G_{gc}, G_{gp} & = \text{Green's functions for InSAR, co- and postseismic GPS} \\
\tau & = \text{decay time constant} \\
t_{psN} & = \text{Enddate of Interferogram} \\
t_{pk} & = \text{date of Parkfield earthquake} \\
\beta & = \text{weight of Laplacian smoothing operator (\nabla^2)} \\
s_{cs} & = \text{coseismic slip} \\
A_{ps} & = \text{amplitude of postseismic exponential} \\
\tau & = \text{tilt across each interferogram} \\
xy_N & = \text{Green's functions for tilt} \]
Inversion Formulation

\[ \begin{align*}
\alpha G_{sN} & \quad M \\
\alpha G_{sN} & \quad G_{gc} \\
0 & \quad \beta \nabla^2 \\
\end{align*} \]

\[ \begin{align*}
\alpha G_s & \\
G_{gp} & \quad 0 \\
0 & \quad \beta \nabla^2 \\
\end{align*} \]

\[ \begin{align*}
R^1 & \\
& \quad r \\
& \quad xy_1 \\
& \quad \alpha d_{sN} \\
& \quad 0 \\
& \quad 0 \\
& \quad 0 \\
& \quad 0 \\
\end{align*} \]

\[ \begin{align*}
& \quad r \\
& \quad xy_N \\
& \quad \alpha d_{sN} \\
& \quad 0 \\
& \quad 0 \\
& \quad 0 \\
& \quad 0 \\
& \quad 0 \\
\end{align*} \]

**Equations and Definitions:**

- \( d_{sN} \) = InSAR data
- \( d_{pk}, d_{ps} \) = coseismic and postseismic GPS data
- \( \alpha \) = InSAR data weight
- \( \beta \) = weight of Laplacian smoothing operator (\( \nabla^2 \))
- \( \gamma_{gs} \) = coseismic slip
- \( A_{ps} \) = amplitude of postseismic exponential
- \( t \) = tilt across each interferogram
- \( xy_N \) = Green’s functions for tilt

\[ R^1 \quad r \quad xy_1\]

\[ R \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]

\[ R \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]

\[ R \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]

\[ R \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]
Inversion Formulation

\[ \begin{align*}
\alpha G_{s1} & \quad \alpha G_{s2} \\
M & \quad G_{gc} \\
0 & \quad \beta \nabla^2
\end{align*} \]

\[ \begin{align*}
\alpha G_{sN} & \quad 0 \\
G_{gp} & \quad \beta \nabla^2
\end{align*} \]

\[ \begin{align*}
R^1 & \quad r \\
x y_1 & \quad \alpha d_{s1} \\
M & \quad r \\
x y_N & \quad \alpha d_{sN}
\end{align*} \]

\[ \begin{align*}
0 & \quad d_{pk} \\
d_{ps} & \quad 0 \\
0 & \quad R
\end{align*} \]

\[ \tau = \text{decay time constant} \]

\[ t_{psN} = \text{Enddate of Interferogram} \]

\[ t_{pk} = \text{date of Parkfield earthquake} \]
Slip during the Parkfield Earthquake

Coseismic Slip (seismic)

Postseismic Slip (aseismic)

Two slip patches

~Inverse relationship

M\textsubscript{w}6.2

M\textsubscript{w}6.1

2004 hypocenter

Double-Difference relocated seismicity (Thurber et al., 2006)
Postseismic slip and Aftershocks

Coseismic Slip (seismic)

Postseismic Slip (aseismic)

$M_w \sim 5.6$

2004 hypocenter

Double-Difference relocated seismicity (Thurber et al., 2006)

$M_w 5.0$
San Simeon Earthquake

December 22, 2003; Mw6.5

Occurred on northern edge of Los Osos Domain

Oceanic fault: low slip rate and non-creeping

Postseismic slip ~14% of coseismic with complex spatial pattern.

Example of Coast range building event
2 Postseismic Interferograms

Descending ERS

1/20/2004 - 4/1/2004
Ascending Radarsat

1 cycle = 2.8 cm
2 Postseismic Interferograms

Descending ERS

1/20/2004 - 4/1/2004
Ascending Radarsat

1 cycle = 2.8 cm
2 Postseismic Interferograms

Descending ERS

1/20/2004 - 4/1/2004
Ascending Radarsat

Extra slip sometime before 1/20/2004

1 cycle = 2.8 cm
Geodetic Data for San Simeon EQ

- 4 Interferograms
  - Intermixed
  - Postseismic only

- 1 set GPS displacements
  - Coseismic only

- 1 model
  - BOTH co-, post- slip

Coseismic ($d_{pk}$)

7/9/2003 - 4/14/2004
12/9/2003 - 9/14/2004
1/20/2004 - 4/1/2004
Inversion Formulation

\[ \begin{bmatrix} W \nabla^2 \beta \end{bmatrix}^{-1} \begin{bmatrix} Wd \end{bmatrix} = r \]

\[ m = \begin{bmatrix} \begin{bmatrix} r \end{bmatrix} A_{P1} \end{bmatrix} \]

\[ G = \begin{bmatrix} G_{Ca} & G_{P1a} \left( 1 - e^{-t_{a2}/\tau} \right) & G_{P2a} & xy_a \end{bmatrix} \]

\[ \begin{bmatrix} G_{Cb} & G_{P1b} \left( 1 - e^{-t_{b2}/\tau} \right) & G_{P2b} & xy_b \end{bmatrix} \]

\[ \begin{bmatrix} 0 & G_{P1c} \left( e^{-t_{c1}/\tau} - e^{-t_{c2}/\tau} \right) & G_{P2c} & xy_c \end{bmatrix} \]

\[ \begin{bmatrix} 0 & G_{P1d} \left( e^{-t_{d1}/\tau} - e^{-t_{d2}/\tau} \right) & 0 & xy_d \end{bmatrix} \]

\[ G_{Cgps} \]

\[ 0 \]

\[ 0 \]

\[ 0 \]

\[ 0 \]
San Simeon Slip Model

Coseismic Slip
$M_w=6.5$

Exponentially decaying slip
$M_w=5.8$ (9% of coseismic)

Extra slip
$M_w=5.7$ (5% coseismic)
ΔCoulomb Failure Stress
(San Andreas Parallel)

ΔCFS = µ´ (normal stress) + (shear stress)
µ´ = 0.4 (from Toda and Stein, 2002)

0.1 bars is observed threshold for significant aftershock triggering (e.g. Harris, 1998)
Summary

• Coseismic and postseismic slip can be separated in the modeling stage in cases where
  - the data contains deformation from both periods
  - Some *a priori* info on the time history is available

• Doing so reveals important features of the EQ
  - Prevalence of aseismic slip relative to seismic
  - Distribution and decay of postseismic slip
  - Can calculate relative effects of each period on other structures
The Parkfield Earthquake Prediction Experiment

Quasi-regular series of M~6 earthquakes:
- Next was predicted for 1988 (Bakun & Lindh, 1985)
- Earthquake occurred 16 years “late”

Goals:
- Detect precursory slip
- Test the characteristic earthquake hypothesis
- Get the best records all aspects of an earthquake

http://quake.usgs.gov/research/parkfield
Fault Behavior Spectrum

**Locked Fault**
- Slip occurs primarily in large earthquakes

**Mixed Behavior**
- Some Creep
- Some strain accumulation
  - “slow earthquakes”

**Block Offset**
- No strain accumulation
- No large earthquakes

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Steinbrugge Collection, EERC, UC Berkeley

Calaveras Fault, Hollister
Key Observations

• Location at transition zone may control some of its behavior
  - Produces regular, similar earthquakes
  - Transient slip events, such as rapid postseismic slip
  - Sensitive to outside stresses.
• Stress decreased near 1966 hypocenter
  - 1983 Coalinga Earthquake (Toda and Stein, 2002)
  - 1993-1996 slow earthquake (Murray and Segall, 2005)
• Stress increased throughout Parkfield segment
  - 2003 San Simeon earthquake