Lecture 20: Slow Slip Events and Stress Transfer

GEOS 655 Tectonic Geodesy
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Slow Slip Events

From Kristine Larson
What is a Slow Slip Event?

• Slip on a fault, like in an earthquake, BUT
  – Slow: hours to years rather than seconds
  – Releases little high-frequency seismic energy, so it is sometimes called a type of aseismic slip.
  – However, many or most of these events do produce a tremor-like seismic signal.
  – Discrete events, rather than continuous creep/slip

• Probably frictionally controlled slip, but not unstable like seismic slip
  – conditional stability from rate and state friction?

• Now known to be very common at and below base of main seismogenic zone at subduction zones.
Older Slow Slip Events

- Not generally accepted as real until ~15-20 years ago.
- Suggestion of a slow precursor before 1960 Chile earthquake (a few minutes prior)
- Slow Slip Before 1944 Tonankai, 1946 Nankaido earthquakes
  - Survey misclosures, tide gauges, water well level changes prior to each earthquake
  - Investigated as possible earthquake precursors
  - Linde and Sacks (2002) showed that observations were consistent with slow slip on plate interface below main seismogenic zone.
- Some “Silent Earthquakes” identified through normal modes; some did not correspond to regular quakes
San Juan Bautista 1993

M. Johnston, USGS
“Mostly Silent” Earthquake

- Significant fault creep and near-fault strain accompanied swarm of small earthquakes
- Creep and strain too large to explain by earthquakes
- Interpretation is that a patch on the fault was creeping
- What triggered what?
Kenai

- Combination of
  - locked subduction zone (NNW)
  - postseismic deformation (SSE)
- Up to 55 mm/yr relative to NOAM
- Up to ~75 mm/yr relative motions
- Along-strike changes in seismogenic zone
Kenai Detail

- Obvious transition between western and eastern Peninsula
- Look at sites same distance from trench
- Edge of plate coupling toward western edge of Peninsula
  - Edge of PWS asperity
Regional Plate Coupling

Plate Coupling Model for 1992-1999 GPS Data

Zweck et al. (2002)
Suito and Freymueller (2009)
1993-1997 and 1997-2000 velocities relative to NOAM
Comparison of Time Series

![Graph showing data points for TALKEETNA, ATWC, REEDY, and TRAIL LAKES over a period from 1995 to 2002. The graph displays the trend of North (mm) values over time.](image-url)
Afterslip Model for Time Series

Non-linear inversion to fit each time series

- \( n(t) = a + bt + c\log(1+(t-t_0)/\tau) \)
- Logarithmic decay characteristic of afterslip (Marone et al., 1991)
  - Rate and state-dependent friction law
  - Velocity-strengthening
  - Subjected to sudden stress step

\( t_0 = 1998.3 \) to 1998.6
\( \tau = 0.3 \) to 0.6 years
  (120-220 days)
Hutton et al. (2001) found 100-150 days for Jalisco
Campaign vs. Continuous
1993-1997 and 1997-2000 velocities relative to NOAM
Summary of Observations

- Velocities over an area >15,000 km$^2$ changed dramatically at ~1998.5
- Large southward component, decaying with time
- Anomalous displacement $\sim \log(1+t/0.6)$
  - Functional form for afterslip in velocity-strengthening material obeying rate and state dependent friction law
- Preceded by decrease in seismicity rate within slab
Interpretations

• Most compatible with a creep-type process on the plate interface downdip of seismogenic zone
  – NOT a transition from locked to creep, but from one rate of creep to a faster rate
• Trigger for event not clearly understood
  – NO significant (M > 5.5) earthquakes
  – NO apparent offset in time series = no sudden creep
• Possible link to continuing post-1964 slip transient
  – Did postseismic creep on adjacent segment trigger faster creep on this segment?
• Tide gauge observations at Anchorage suggest complex creep events have occurred in the past
Non-linear Deformation

Location of Selected Sites

Timeseries with log fit

1998.5
Three Time Periods

1998-2001
Velocities measurably different over area >100x200 km²
Before and After
Data and Model
Comparison of Slip Models
Slip Models through Time

Ohta et al. (2006)
Slip Models through Time

Ohta et al. (2006)
Slip Models through Time

- The only difference between the two time periods is accelerated slip in one patch during SSE
- Located downdip of 1964 earthquake rupture
- Also associated with seismic tremor.

*Ohta et al. (2006)*
Tokai Slow Slip Event
Guerrero Slow Slip Events

- From Kristine Larson
- Wide variety of events from Guerrero, Mexico
- Variety of spatial scales, durations, magnitudes
- Some events propagated along strike for a considerable distance.
Introduction to Stress Transfer

How does slip change stresses in surrounding area?

BEFORE

Locked

Creeping
Introduction to Stress Transfer

How does slip change stresses in surrounding area?

AFTER

Locked

Creeping
Effect of Slip

- Slip reduces shear stress in region that slipped, increases shear stress in surrounding region
- Slip may also change normal stresses.
- Postseismic deformation also changes stresses.
- Stress changes from one earthquake may bring another part of the fault or another fault closer to failure – triggering.
Stress Transfer, or “Conversations between Earthquakes”

Ross S. Stein, Aykut A. Barka and James H. Dieterich
Geophysical Journal International (March 1, 1997)
Sequence Has Repeated

North Anatolian fault often ruptures in progressive earthquakes. Mean repeat time ~450±220 yr.
Bay area shocks during the 75 years before 1906

Earthquakes from Bakun [1999] and Ellsworth [1990]
Bay area shocks during the 75 years after 1906

1911 M=6.2 shock from Bakun [BSSA, 1999]
Bay area is a system of roughly parallel faults.
Bay area faults may have fallen under a stress shadow in 1906

Stress change is correlated with seismicity rate change for 1994 M=6.7 Northridge shock

from Stein (Nature, 1999)
Stress change is correlated with seismicity rate change for 1994 M=6.7 Northridge shock

from Stein (Nature, 1999)
Coulomb Failure Criterion

- Slip on a fault will occur if the shear stress resolved on the fault plane exceeds the force of friction retarding slip:
  \[ \tau \geq \mu (\sigma - p) \]

- Define the Coulomb stress change as:
  \[ \Delta CFS = \Delta \tau - \mu \Delta (\sigma - p) \]
  \[ \Delta CFS = \Delta \tau - \mu' \Delta \sigma \]
How to Calculate

• Start with a model of source of deformation
  – Usually slip on a fault using Okada’s formulation of dislocation theory
• Calculate strain tensor at desired points by calculating strain components at a depth of choice
• Convert strain tensor to change in stress tensor using linear elasticity
• Resolve delta-stress tensor onto desired fault plane(s) based on geometry of fault
Effect Depends on Orientation of “Receiver fault”

- Stress tensor changes depend on the “source fault”
- Coulomb stress also depends on the geometry of “receiver fault”
  - Fancy graphics for Coulomb stress change assume receiver fault
  - Specific fault or “optimally-oriented strike slip”
Calculated shear stress imposed by Coalinga on planes parallel to the San Andreas fault at 8 km depth

from Toda & Stein (JGR, 2003)
Fault creep was retarded or reversed by Coalinga earthquake

![Map of fault lines with markers for Coalinga, Parkfield, Cholame, XSC1, XMM1, XPK1, WKR1, XGH1.]

![Graph showing right-lateral creep over years from 1980 to 1990. The Coalinga shock is marked by a vertical line in 1983, with data points for XSC1, XMM1, XPK1, WKR1, XGH1.]}
Stress accumulated since great 1857 shock loads Coast Ranges thrust faults.

Interseismic stress accumulation, 1857-1983

Interseismic stress accumulation, 1857-2003

Coulomb stress change (bars) at 10 km depth on Coalinga (left) and San Simeon (right) rupture planes, for $\mu=0.8$

Modified from Lin & Stein (JGR, 2004)
1992 M=7.3 Landers shock increases stress at Big Bear

First 3 hr of Landers aftershocks plotted

from Stein (2003)
1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hr later.

First 3 hr of Landers aftershocks plotted from Stein (2003)
...and promotes the M=7.1 Hector Mine shock 7 yr later

Los Angeles

First 7 yr of aftershocks plotted

from Stein (2003)
North Anatolian fault

- Stress changes calculated for right-lateral faults paralleling the North Anatolian fault due to the entire 20th century sequence of earthquakes
- Each earthquake releases stress where it slips, and brings adjacent segment closer to failure
2003 M=6.5 San Simeon earthquake ratcheted up stress at Parkfield

Calculation by Shinji Toda on 31 Mar 2004
(a similar plot by Bob Simpson appears in Hardebeck et al, 2004)
Stress Transfer at Subduction Zones

[Diagrams and graphs illustrating stress transfer at subduction zones, with annotations and color-coded fault zones.]
Effect of Large vs. Small Quakes

- Compares effect of 1960 Chile with 1995 Antofagasta earthquakes
  - Note difference in color scale
Now what?

Creep (no large shocks)

28 Sept 2004
M = 6.0

9 Jan 1857
M = 7.9
Now what part 2?
Now what part 2?

2005 + 2007