Inferring fault friction and their spatial variability from the joint analysis of geodetic and seismological data

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Conceptual framework

Some outstanding questions:

- What are the frictional properties of faults?
- How do these properties vary in space and time?
- How do they influence individual earthquakes or the long term seismic behavior of a fault?
Conceptual framework

Rate&state friction:

\[
\frac{\tau}{\sigma} = \mu = \mu_* + a \ln\left(\frac{V}{V_*}\right) + b \ln\left(\frac{\theta}{\theta_*}\right)
\]

\[
d\theta/dt = 1 - V\theta/D_c
\]

At steady state

\[
\mu_{ss} = \frac{\tau}{\sigma} = \mu_* + (a-b) \ln\left(\frac{V}{V_*}\right)
\]

\[
\frac{\partial \mu_{ss}}{\partial \ln V} = a - b
\]

\[a-b < 0\]
Rate Weakening
(seismic slip)

\[a-b > 0\]
Rate Strengthening
(aseismic slip)
Conceptual framework

Interseismic

Postseismic

Coseismic
Fault Frictional Properties

Afterslip governed by rate strengthening friction should obey:

\[ \delta(t) = \delta_i + \frac{1}{c} \log \left[ 1 + d \frac{V_i}{V_0} \left( \exp \left( \frac{t}{t_r} \right) - 1 \right) \right] \]

Postseismic

(Perfettini and Avouac, 2004)
The 2007 Mw 8.0 Pisco Earthquake

(Sladen et al, JGR, submitted)
Coseismic slip model of the 2007 Mw 8.0 Pisco Earthquake

(Sladen et al, JGR, submitted)
Aftershocks of the 2007 Mw 8.0 Pisco Earthquake

(Sladen et al, JGR, submitted)
Postseismic displacements following the 2007 Mw 8.0 Pisco Earthquake

(Perfettini et al, submitted)
Afterslip following the 2007 Mw 8.0 Pisco Earthquake

Postseismic displacements reveal two aseismic patches with limited overlap with the coseismic asperities.

(Perfettini et al, submitted)
**Afterslip following the 2007 Mw 8.0 Pisco Earthquake**

- The temporal evolution of afterslip is consistent with rate-strengthening frictional sliding:

\[
\delta(t) = \delta_i + \frac{1}{c} \log \left[ 1 + d \frac{V_i}{V_0} (\exp(t/t_r) - 1) \right]
\]

- The extent of the coseismic rupture is probably partly controlled by rate-strengthening barriers

\[
\sigma \frac{\partial \mu_{ss}}{\partial \ln V} = (a - b)\sigma = 0.2 - 0.6 MPa
\]

(Perfettini et al, submitted)
Interseismic Coupling before the 2007 Mw 8.0 Pisco Earthquake

The seismic ruptures of 1974 and 2007 correlate with patches which remain locked in the interseismic period.

Coupling model from Perfettini et al, (submitted)
Rate-strengthening patches can act as barriers to the propagation of seismic rupture.

Rupture extent of Historical earthquakes from Dorbath (1990)
INTERSEISMIC DEFORMATION

Vert. Velocities (coral, 1962-present)

Horizontal Velocities (SuGAr + Campaign GPS)
Between 1962 and 2005, this pattern of locking has lead to a moment deficit accumulation of about $2-8 \times 10^{20}\text{Nm/yr}$.

(Chlieh et al, 2008)
The 2005 Mw 8.7 Nias Earthquake

Postseismic displacements reveal aseismic creep on patches on the megathrust surrounding the seismic rupture.
Time evolution of afterslip is consistent with rate strengthening frictional afterslip yielding:

\[ \sigma \frac{\partial \mu_{ss}}{\partial \ln V} = (a - b)\sigma = 0.2 - 0.7\, \text{MPa} \]
Afterslip vs. Aftershocks

Earthquakes before 03/28/05
Earthquakes after 03/28/05

Postseismic Obs. 0.3 m
Postseismic slip (m)
0.0 0.5 1.0

Diagram showing seismic activity with locations marked and distances indicated.
Postseismic displacement and the cumulative number of aftershocks follow the same time evolution

\[ U(t) = U_{t=0} + a f(t) \]
\[ N(t) = N_{t=0} + b f(t) \]
LHWA

Displacement

Aftershocks
(Chlieh et al., 2008)
Source Models of the 2007, Mw8.4 & 7.9 Mentawai Islands Earthquakes

Data used:
- GPS (SuGAr)
- InSAR
  - Field measurements
  -- Teleseismic waveforms

(Konca et al, 2008)
Postseismic Deformation

Postseismic displacements reveal aseismic creep on patches on the megathrust surrounding the seismic rupture.

(Kositsky et al, in prep.)
Neither Time Predictable nor Slip Predictable

- **Time predictable**: stress drop of last earthquake & stress rate => can tell the time of the next event (we know at what stress level the fault will break)

- **Slip predictable**: given the stress drop of the last event and stress rate, if an earthquake happens today=> can tell the amount of slip (we know the postearthquake stress level)
(Sieh et al, 2008)
Seismic ruptures tend to be confined within patches that remain locked in the interseismic period.

A nearly ‘characteristic’ behavior is suggested for Nias area.

In the Mentawai area the behavior is neither time- nor slip-predictable.
Dynamic modeling

Narrow rate-strengthening barrier of width D

Rate\&state friction:

$$\frac{\tau}{\sigma} = \mu = \mu_*(T) + a \ln\left(\frac{V}{V_*}\right) + b \ln\left(\frac{\theta}{\theta_*}\right)$$

$$\frac{d\theta}{dt} = 1 - V\theta / D_c$$

Boundary Integral Method in 3-D of Lapusta and Liu (JGR, 2009)

(Kaneko et al, in prep)
Dynamic modeling

3-D simulations

(Kaneko et al, in prep)
Intereiseismic coupling and the probability that an earthquake propagates across a rate-strengthening barrier are both linearly dependent on the 'strength' of the barrier:

\[ B = (a - b)\sigma D \]

(Kaneko et al, in prep)
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\[ B = (a - b)\sigma D \]

(Kaneko et al, in prep)
Time- and slip-predictable behavior in our model
Conclusions

• A variety of observation suggest that Megathrust consist of a patchwork of RS and RW areas.
• The topology of this patchwork and the frictional parameters can be inferred from combined analysis of co-seismic, interseismic and postseismic deformation.
• This conceptual model explains some of the systematic and non-systematic patterns observed in Nature.
• The physical parameters determining the patchiness of interseismic strain remain unclear.
Conclusions