Megathrust Earthquakes

Susan Schwartz
University of California Santa Cruz
The largest megathrust events are not uniformly distributed at all subduction zones.
M>8 since 1900, blue events between 2004-2014

- 2013 Sea of Okhotsk, Mw 8.3
- 2006/2007 Kuril, Mw 8.4, 8.1
- 2011 Japan, Mw 9.0
- 2007 Solomon Is., Mw 8.2
- 2013 Santa Cruz Is., Mw 8.0
- 2009 Samoa, Mw 8.1, 8.0
- 2006 Tonga, Mw 8.0
- 2007 Peru, Mw 8.0
- 2014 Chile, Mw 8.1
- 2010 Chile, Mw 8.8

2004, 2005, 2007 Sumatra, Mw 9.2, 8.7, 8.5

2012 Indo-Australia, Mw 8.7, 8.2

Lay, 2014
Goals of this talk

• Synthesize what has been learned from seismic studies of the numerous, well recorded recent megathrust earthquakes

• Discuss some outstanding questions and directions for future research
Earthquakes are Controlled by Friction

The seismogenic zone is defined by the transitions from stable to unstable frictional deformation

Marone & Scholz, 1988
Friction

\[ \tau = \mu \sigma_n \]

proposed that stick-slip behavior in laboratory friction experiments might be analogous to earthquake rupture.
Stick Slip Behavior

\[ \tau = \mu_s \sigma_n \]

Sliding initiates at static friction coefficient but frictional resistance falls once sliding starts resulting in a dynamic instability or slip.

Condition for Instability:

\[ \frac{\delta \tau}{\delta u} > K \] (K- elastic properties of the medium)

Frictional stability is determined by the combination of:
1) fault zone frictional properties and
2) elastic properties of the surrounding material.
Further work on physics of rock friction revealed:

1. Time dependence of friction

\[ \mu_s = \mu_0 + A \ln (Bt+1) \]  

(Dietrich)

2. Velocity dependence of friction

\[ \mu_D = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]

**Diagram:**
- Slips on \( y \)-axis
- Velocity on \( x \)-axis
- Initial velocity \( V_0 \)
- Slip rate: \( V_1 = eV_0 \)
- Instantaneous effect
- Evolutionary effect

- Velocity weakening: \( b-a > 0 \)
Rate and State Dependent Friction Law

\[ V_o \quad V_1 = e V_o \quad \text{Slip rate} \]

\[ a \quad b \quad V_1 = e V_o \quad \text{Velocity Weakening} \]

\[ D_c \quad b-a > 0 \]

\[ \text{Slip} \]

\[ \begin{align*} 
  a-b < 0 & \quad \text{velocity weakening- STICK-SLIP INSTABILITY} \\
  a-b \geq 0 & \quad \text{velocity strengthening and STABLE} 
\end{align*} \]
Friction Laws and Their Application to Seismic Faulting

(a-b) > 0  Always Stable, No Earthquake Nucleation, Dynamic Rupture Arrested

(a-b) < 0 Unstable, Earthquakes May Nucleate, Dynamic Rupture Will Propagate

(a-b) \sim 0  Conditionally Stable, No Earthquakes Nucleate, Dynamic Rupture May Propagate
Seismogenic Zone

Up-Dip Stable/Unstable Frictional Transition

1) Clay mineral transformation

2) Consolidation/lithification state of fault gouge and accretionary prism materials
   - Poorly consolidated granular gouge exhibits velocity strengthening
   - Lithified materials and highly localized shear exhibit velocity weakening
Seismogenic Zone

Moore et al., 2007
Seismogenic Zone

Down-Dip Seismic/Aseismic Transition

Temperature
Contact with serpentinized mantle
If $a \sim b$ we have conditionally stable conditions where earthquakes do not nucleate but slip propagates.

At frictional transitions slow slip that occurs at velocities between steady creep and dynamic earthquake rupture can occur.
Main Asperity Regions

First Order Observations

1. Segmentation of the megathrust-rupture areas tend to abut one another
2. Megathrust events tend to have a characteristic recurrence interval

Ye et al., 2016
\[ S(t) \ast G(t) \ast I(t) = U(t) \]
\[ S(t) \times G(t) \times I(t) = U(t) \]

Source \( x(t) \)

\[ * \]

Structure \( q(t) \)

\[ * \]

Instrument \( i(t) \)

Seismogram \( u(t) \)

P-wave take-off angle and azimuth projected on P-wave focal mechanisms

Grid points

- hr-GPS stations
- Strong motion stations
- Campaign GPS stations

Cocos Plate

Effective depth

Yue et al., 2013
Finite Fault Inversions

Yue et al., 2013
2004 M=9.2 Sumatra Earthquake GPS Inversion

Chileh et al., 2007
Variation in Earthquake rupture - Due to various asperity distributions

- 2011 Tohoku-oki ($M_w$ 9.0)
- 1964 Alaska ($M_w$ 9.2)
- 2004 Sumatra–Andaman ($M_w$ 9.2)
- 2010 Chile ($M_w$ 8.8)
- 2003 Hokkaidō ($M_w$ 8.3)

**SEISMIC MOMENT RATE ($\times 10^{20}$ Nm/sec)**

**TIME FROM START OF RUPTURE (seconds)**
Inversion of GPS Velocity for Locking on the Plate Interface
2010 Maule Earthquake

Fig. 2

Moreno et al., 2010
Geodetic plate locking Vs. 3 Coseismic Rupture modes- 2010 Maule Earthquake

Moreno et al., 2010
Geodetic Locking Vs. Coseismic Slip for 2012 Nicoya Earthquake

Yue et al. 2014

Protti et al. 2014
Deformation At Subduction Zone

Backslip model (Savage, 1983)

- Shallow part of fault slips only in earthquakes
- Deeper part slips steadily at long-term rate
- Superposition of steady slip on entire interface and backslip (*slip deficit*)
- Earth deforms as elastic or linear viscoelastic body
  - Viscoelasticity of mantle introduces time dependence!
Nicoya, Costa Rica

April 2012

EARTHQUAKE-
September 2012

September 2014
Afterslip and plate boundary aftershocks tend to occur outside coseismic slip.
Main Asperity Regions - From Coseismic Slip Distribution

Slip distributions from megathrust earthquakes Also bring surprises.

Lay et al., 2011
Future Directions- Asperities

• Continued improvement of coseismic slip inversions integrating all available data sets-seismic, geodetic, tsunami earthquakes.

• What do slip patches (asperities) represent? Are they controlled by upper or lower plate, both, or neither?

• Do asperities persist through many earthquake cycles?
Down-dip Transition and Slow Slip

Domain A
Large Slip
Very weak shaking
Strong tsunami

Domain B
Large slip
Low frequency shaking

Domain C
Moderate slip
High frequency shaking

Domain D
Slow slip/Seismic tremor

Lay et al., JGR (2012).
What is Slow Slip?
How do we Detect Slow Slip?
Cascadia Slow Slip Earthquakes- or Episodic Tremor and Slip (EPS)

Modified from Dragert and Rogers [2004]
A  Tremor

Gomberg et al., 2013
Shelly et al., 2006
Up-dip Transition and Slow Slip

Domain A
Large Slip
Very weak shaking
Strong tsunami

Domain B
Large slip
Low frequency shaking

Domain C
Moderate slip
High frequency shaking

Domain D
Slow slip/Seismic tremor

Aseismic
Seismic
Conditionally Stable

Lay et al., JGR (2012).
Is the Shallow Megathrust Locked?

**Peru Trench**

*Gagnon et al. (2005)*

**Continental Megathrust (Nepal)**

*Galetzka et al. (2015)*

---

(a) [Graph showing vertical displacement with depth and horizontal distance from the trench.]

(b) [Map highlighting the megathrust zone, with labels for subducting plates and offshore/onshore regions.]

---

*Seafloor geodesy arrays, Land GPS stations (Norabuena, 1998), Temporary shore stations, PUCU, SALI.*
Jiang et al., 2017
Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip
HOBITSS

Wallace et al., 2016
Seafloor moves up ~2-5 cm

Wallace et al.,
2016
\[ M_0 = \mu A x \]

\[ M_0 \sim L^3 \]

\[ L = V_r d \]

\[ V_r \text{ is quasi-constant controlled by seismic velocity} \]

\[ L \sim d \]

\[ M_0 \sim d^3 \]

\[ d \sim (M_0)^{1/3} \]
Does Slow Slip Precede Megathrust Earthquakes?  
2011 Tohoku Earthquake

Kato et al., 2012

Ito et al., 2013
Does Slow Slip Precede Megathrust Earthquakes?
2011 Tohoku Earthquake

Mavrommatis et al., 2014

Acceleration from 1996-2011 interpreted as up-dip migration of slow slip
Does Slow Slip Precede Megathrust Earthquakes?
2014 Iquique, Chile Mw 8.1

Kato & Nakagawa, 2014
2014 Iquique, Chile Mw 8.1

Kato & Nakagawa, 2014
2014 Iquique, Chile Mw 8.1

Kato & Nakagawa, 2014
2014 Iquique, Chile Mw 8.1

From Brodsky and Lay (2014)

From Ruiz et al. (2014)
Fig. 3. Global distribution of slow earthquakes.

Obara & Kato, 2016
The subduction interface is more complex than we usually draw

(Bebout, and Penniston-Dorland, 2015)
Future Directions-Slow Slip

• Can seismic and aseismic processes occur at the same locations at different times?
• Are the mechanisms of slow slip different at different locations along the plate interface (up dip vs. down dip of the seismogenic zone)?
• Does slow slip commonly precede megathrust earthquakes?
• What is the strain budget at the megathrust boundary?