Earthquakes and Plate tectonics

Sinking oceans and rising mountains, earthquakes that shape the Earth

Jean-Philippe Avouac
California Institute of Technology
Talk outline

• Earthquakes phenomenology: from ground shaking to earthquakes source.

• Some key features of worldwide seismicity well explained by ‘Plate Tectonics’.

• Some features not well explained by ‘Plate Tectonics’.

• The seismic cycle - Three case examples.

• Earthquake forecasting: a modern perspective.
Seismometer
Techniques used:

- **Remote Sensing (SAR&Optical)**
- **GPS**
- **Seismology**
- **Field investigations**
- **Modeling**
EX: The Mw 2005, 7.6, Kashmir Earthquake

Surface rupture measured from cross-correlation of ASTER satellite images

NS displacements

(Avouac et al., EPSL, 2006)
The Mw 2005, 7.6, Kashmir Earthquake

Slip distribution and isochrons of rupture propagation

Source time function

(Avouac et al., EPSL, 2006)
The Earthquake Machine

Spring and Slider Model

1. Elastic strain over time (\(\sigma_s\), \(\sigma_d\))
2. Slip over time
Moment & Magnitude

• **Seismic Moment** (N.m)

\[
M_0 = \int \int S(x, y) \, dx \, dy = \left\langle S \right\rangle A
\]

where \( <S> \) is average slip,
\( A \) is fault area and
\( \mu \) is elastic shear modulus (30 to 50 GPa)

• **Moment Magnitude** (where \( M_0 \) in N.m):

\[
M_w = \frac{2}{3} \log_{10} M_0 - 6
\]
The Gutenberg-Richter law

Let $N (\geq M)$ be the number of EQs per year with magnitude $\geq M$

Here the seismicity catalogue is global. Every year we have about 1 $M \geq 8$ event, 10 $M > 7$ events ... 

This empirical law holds at any scale.
• Montessus de Ballore, 1906 (see Cisternas, EPSL, 2009)
  – Seismic waves are generated by slip on faults (BSSA, 1912)
  – World distribution of seismicity (1906, 1911)

(Christ distribution of seismicity: ‘La sismologie moderne’, Montessus de Ballore, 1911)

• Hugo Benioff and Kiyoo Wadati: the Wadati-Benioff zone

Tonga-Kermadec Seismicity
(‘Fault origin of oceanic deeps’, Benioff, 1949)
World seismicity (data source USGS) and velocities relative to ITRF1997 (Sella et al., 2000)

(McKenzie et al., 2005)

(Yamasaki et al., 2003)
• Megathrust have released 90% of the global moment release over the last century (Pacheco and Sykes, 1992).
• All Mw > 8.5 (except for the 2012 Wharton Basin EQ) have occurred at megathrust.
The ‘Seismic Cycle’ at a Megathrust

PS: The notion refers to how earthquakes initiate, grow and arrest (in reality all EQs are different, because of the different environments in which they are born (the stress distribution in particular).
• **H1:** ‘Seismic Gap’ hypothesis (e.g., Fedotov, 1965; Sykes, 1971; Kelleher et al, 1973; Nishenko & Sykes, 1993)

• **H2:** The earthquake rate is proportional to fault slip rate (e.g., Brune, 1968)

• **H3:** The maximum magnitude on a megathrust depends on the age of the subducting plate and on the convergence rate (e.g., Ruff and Kanamori, 1980, 1983; Uyeda and Kanamori, 1979)
(Ruff & Kanamori, 1980, 1983)
The moment conservation principle & Seismic Coupling

→ Sum up all events over time period $T$ over a fault of area $A$, to get the seismic slip rate, $V_s$

→ If all slip is seismic for ageological slip rate, $V$, and fault area, $A$, the moment release rate is

$$M_0 = \frac{\sum M_0}{T} = \mu V A_s$$

→ In fact within fault of area $A$ some of the slip is aseismic. The ‘coupling’ coefficient needs to be estimated:

$$s = \frac{A_s}{A} = \frac{M_0}{AVT}$$
Relating seismicity rate and moment deficit rate based on the moment conservation principle

Frequency of largest EQ in the GR distribution

\[
\frac{1}{T(M_0)} = \frac{\dot{M}_0}{M_0}
\]

\[
M_w = \frac{2}{3} \log_{10} M_0 - 6
\]

\[
\log_{10} \left( \frac{1}{T} \right) = \log_{10} (\dot{M}_0) - \frac{3}{2} M_w - 9
\]

\[
\frac{1}{T(M_{\text{max}})} = (1 - \frac{2b}{3}) (1 - \alpha) \frac{\dot{M}_0}{M_{\text{max}}}
\]

\[
\dot{M}_0 = \mu V A_{\text{locked}}
\]

(Avouac, AREPS, 2015)
Interseismic coupling

**Definition:**
\[ \chi_i = \text{deficit of slip/long term slip} \]
(assigned to a fault, varies in time and space)

**Determination:**
Elastic Dislocation Modeling of Interseismic geodetic displacements
Example 1: The South America Megathrust
Ecuador-North Peru

(Nocquet et al, NGEO, 2014)

-> No large earthquake is expected to fill this gap!
Example 2: The Sumatra Megathrust

The Sumatra Megathrust

- Interseismic coupling

Comparison of Interseismic Coupling (deficit of slip in the interseismic period) with seismic and aseismic transient slip.

(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)
Comparison of Interseismic Coupling (deficit of slip in the interseismic period) with seismic and aseismic transient slip.
The Sumatra Megathrust

- Interseismic coupling
- Mw 8.6, 2005, Nias EQ
- Mw 8.4, 2007, Bengkulu EQ
- Mw 7.9, 2007, Bengkulu EQ

Comparison of Interseismic Coupling (deficit of slip in the interseismic period) with seismic and aseismic transient slip.

(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)
The Sumatra Megathrust

- Interseismic coupling is highly heterogeneous
- Slip is mostly aseismic (50-60%) in the 0-40km ‘Seismogenic’ depth range
- Seismic ruptures seem confined to ‘locked’ areas. Creeping zones tend to arrest seismic ruptures.
- The gap offshore Padang should fail at some point.

(Source: Chlieh et al, JGR, 2008; Konca et al. 2008, Hsu et al., 2006...)

The slip budget is balanced (seismic+aseismic slip=long term slip)
Strain accumulation and release at the Sumatra Megathrust from coral-reef paleogeodesy

(Philibosian et al., 2017)
Variable ruptures/quasi stationnary coupling

(Philibosian et al., 2017)
The Seismic Cycle, a Conceptual framework

(Avouac, 2015)
Dynamic modeling

Rate & state friction:
(Dieterich, 1979; Ruina, 1983)

\[
\mu = \mu_* + a \ln \frac{V}{V_*} + b \ln \frac{\theta}{\theta_*}
\]
\[
\frac{d\theta}{dt} = 1 - \frac{V \theta}{D_c}
\]

Numerical Method: Boundary Integral Method
(Lapusta and Liu (JGR, 2009))

(Kaneko, Avouac and Lapusta, 2010)
Example 3: The Himalayan Megathrust
Example 3: The Himalayan Megathrust
April, 24, 2015

Dharahara Tower

April, 25, 2015
Mwc Depth 7km

2.72 +/- 0.13 km/s

Back projection of ~1Hz teleseismic waves (Lingsen Meng & Pablo Ampuero) (Avouac et al., 2015)

Bandpass filtered 0.5-2 Hz
Model of the Mw7.8 Gorkha earthquake

Near-field records show a smooth rupture beneath Kathmandu which generated only modest ground acceleration <20\%g).

(Avouac et al., 2015; Galetzka et al., 2015)
Predicted Ground Motion

Mw7.8 Nepal Earthquake

(Shengji Wei, Rob Graves et al. 2018)
Dynamic Modeling: a Gorkha-like rupture

Year: 975  Days: 299  Sec after nucleation: -212742559.9

Event 12

(Michel et al., GRL, 2017)
Dynamic Modeling of full ruptures

Event 13

(Michel, Lapusta & Avouac, GRL, 2017)
Conclusions

- Seismic gaps can be either zones of aseismic creep or of high slip deficit.

- The seismic potential of subduction zone can be assessed based on interseismic geodetic strain and seismicity.

- Seismic ruptures tend to be confined within locked fault patches.

- Dynamic models of the earthquake cycle could be designed and calibrated based on geodetic and seismological observations.

- Such models might be used in the future to forecast earthquakes (estimate the probability of $> M$ earthquakes over the ‘$n$’ coming years).

PS: Animations, graphics and outreach material available from my webpage and from the Tectonics Observatory webpages.
Thank You
Thank You
Paleoseismology

[Map of South Asia with seismic activity indicators]

Compilation by Bollinger et al. JGR (2014) 
[Kondo et al., 2008; Kumar et al., 2001, 2006, 2010; Kumahara in Sapkota, 2011; Lavé et al., 2005; Malik et al., 2010; Mugnier et al., 2011; Sapkota et al., 2013; Upreti et al., 2000; Yule et al., 2006]

Sapkota et al (NGEO, 2012)
Paleoseismology

Ruptures in 1255AD and 1934, with 12-18m of slip

Sapkota et al (NGEO, 2012)
Interseismic Coupling-Slip rate on MHT

Moment deficit accumulation in the interseismic period of $18 \times 10^{19}$ Nm/yr needs to be released by transient slip events on the locked portion of the MHT.

(Stevens and Avouac, GRL, 2015)
Aseismic slip dominant where $T > 350^\circ C$.

consistent with laboratory experiments which show that stable frictional sliding is promoted at temperatures higher than about 300$^\circ$C (for Quartzo-felspathic rocks).

(Blanpied et al., 1991; Marone, 1998)
Application to the Mw 9.0 Tohoku Oki Earthquake

Interseismic coupling (Loveless&Meade, JGR, 2010)
Coseismic rupture (Ozawa et al., Nature, 2011)