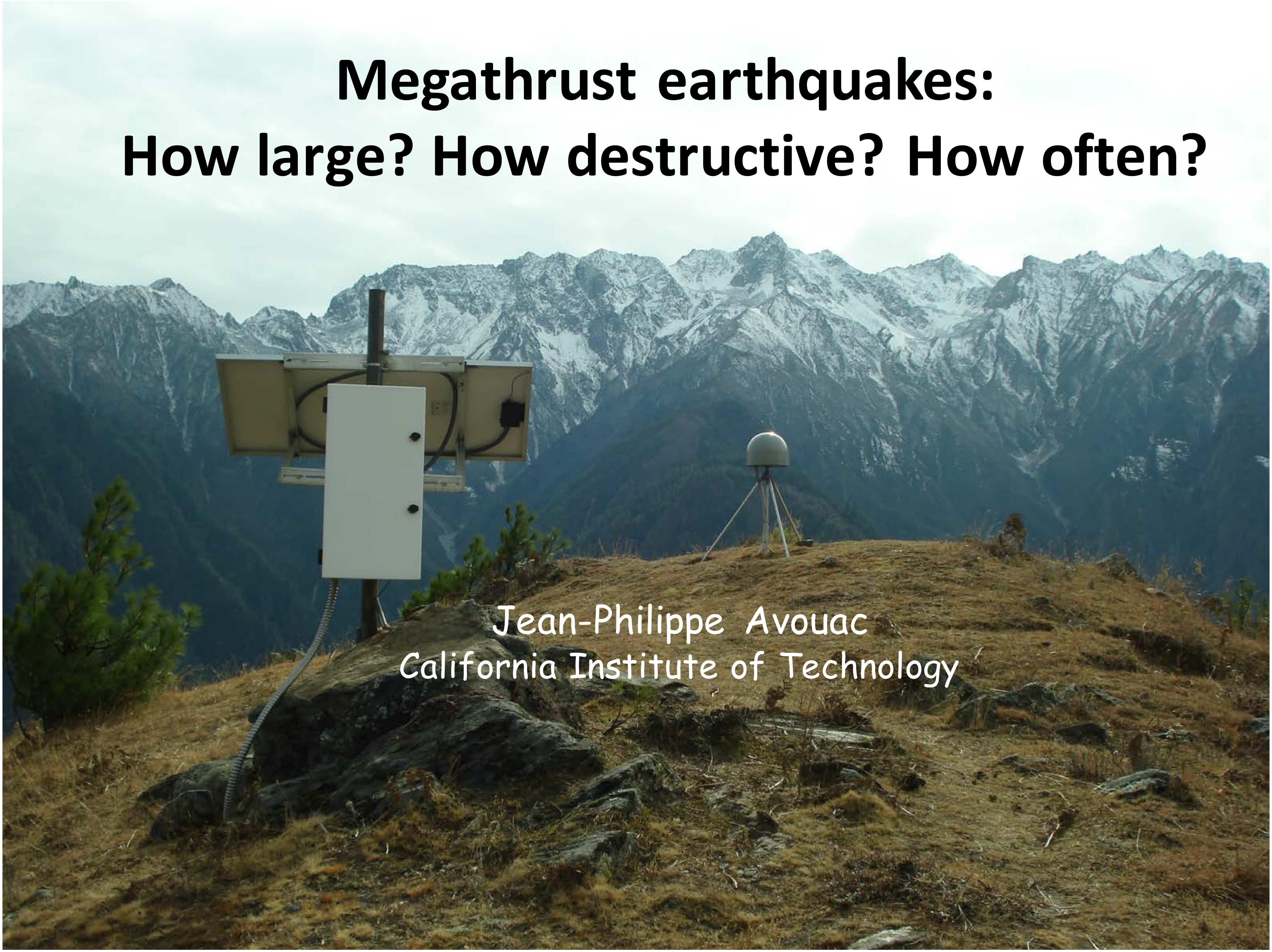
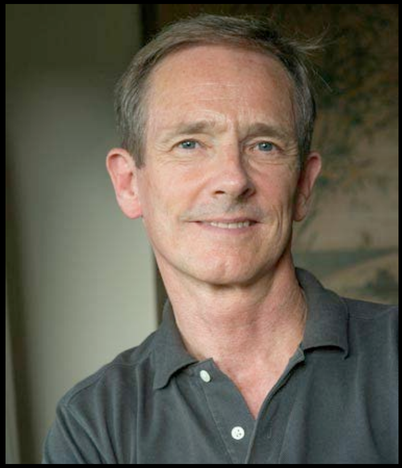
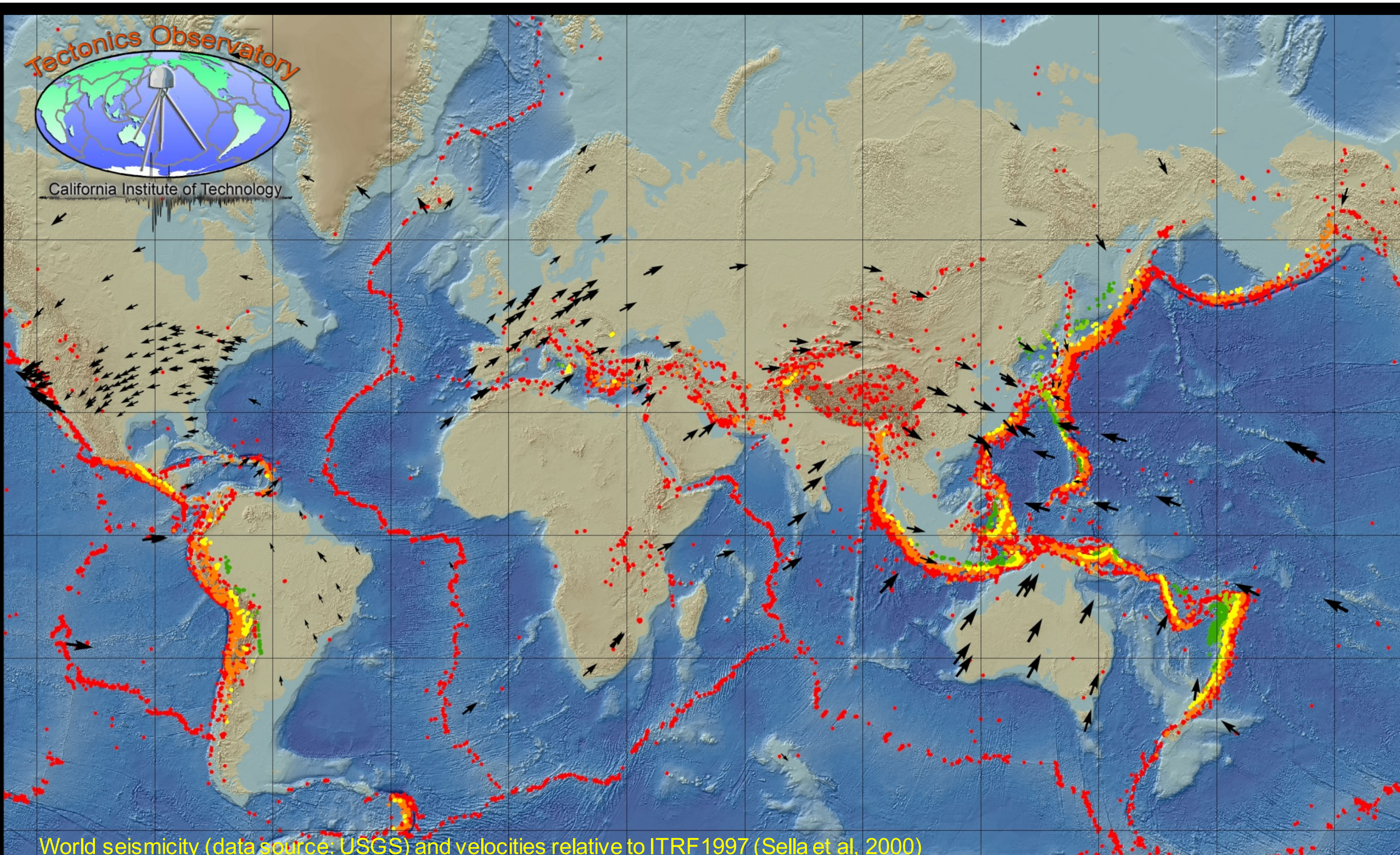
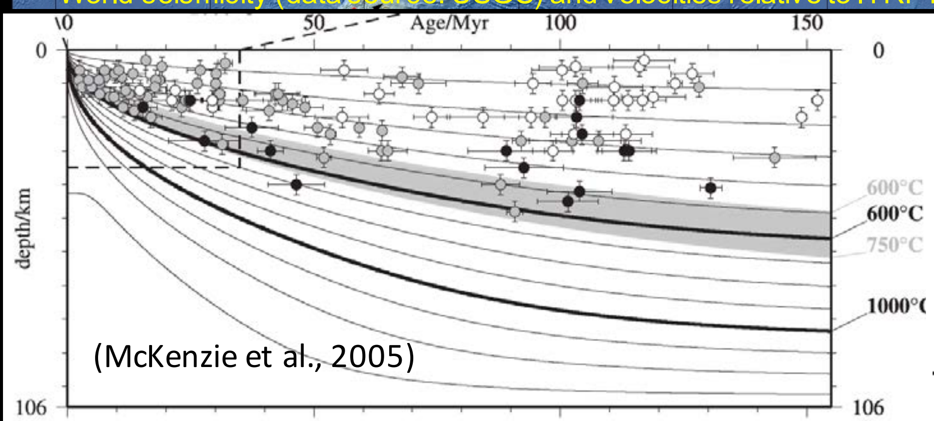
Megathrust earthquakes:
How large? How destructive? How often?

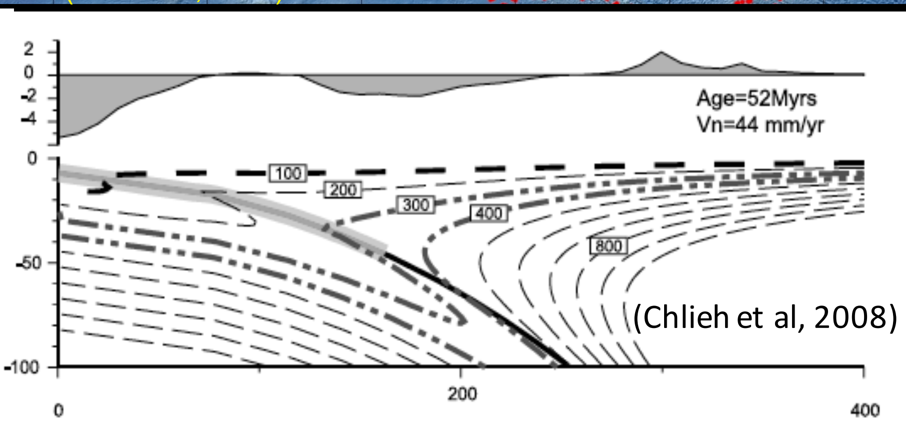


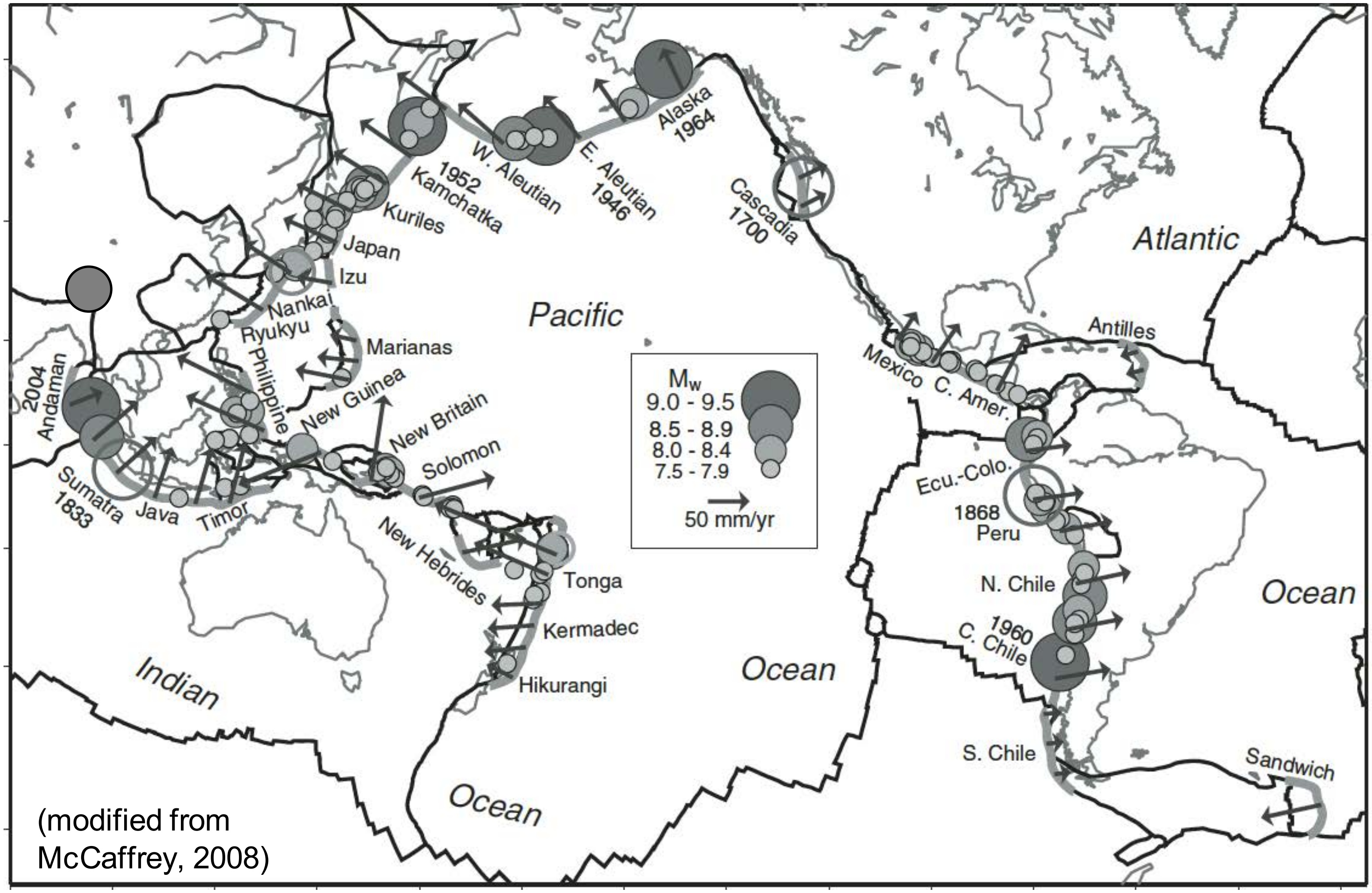
Jean-Philippe Avouac
California Institute of Technology



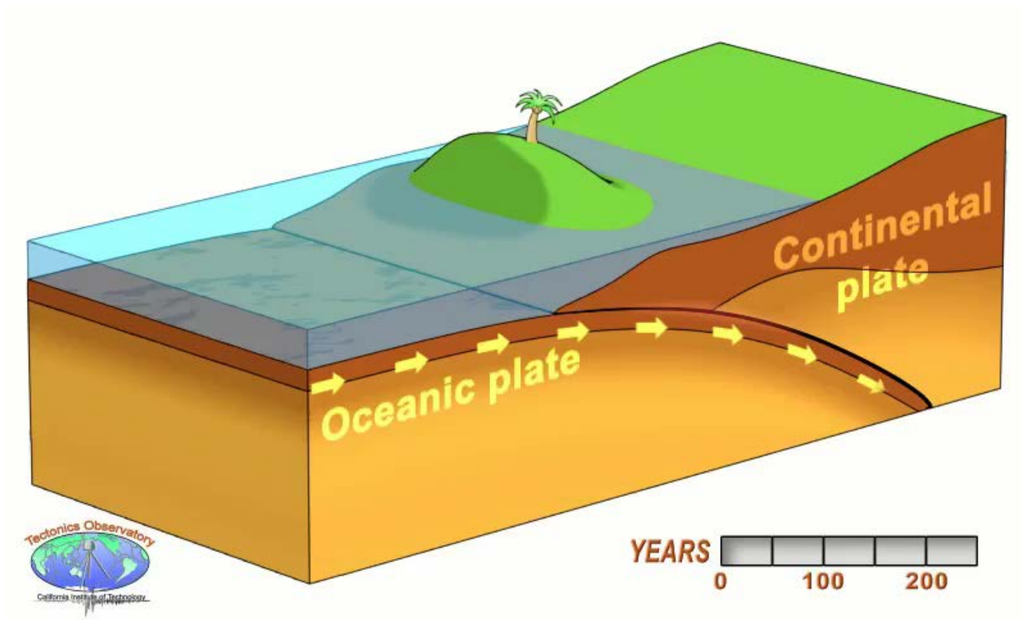

Tectonics Observatory
California Institute of Technology
World seismicity (data source: USGS) and velocities relative to ITRF1997 (Sella et al, 2000)

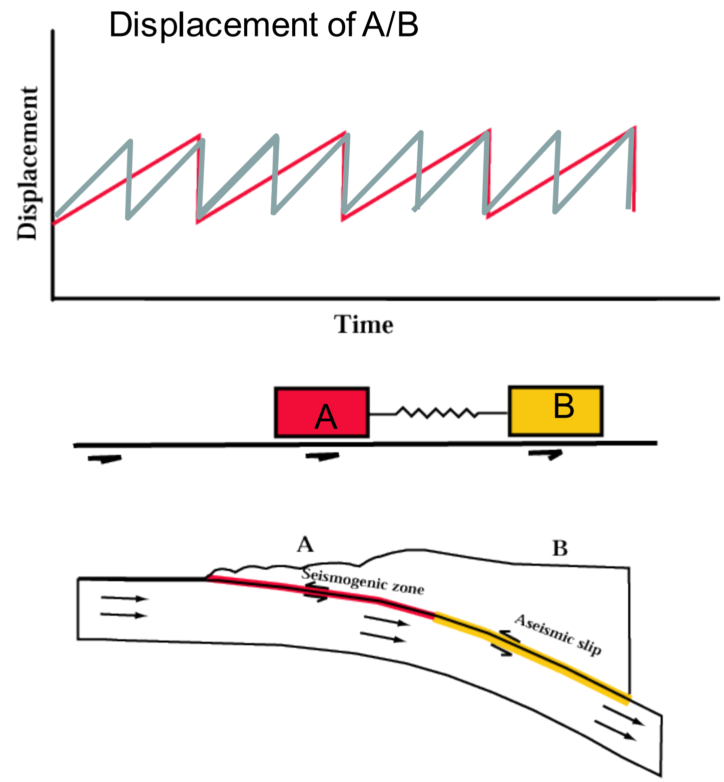

Age/Myr
0
50
100
150
depth/km
0
106
600°C
600°C
750°C
1000°C
(McKenzie et al., 2005)


2
0
-2
-4
Age=52Myrs
Vn=44 mm/yr
0
-50
-100
100
200
300
400
800
0
200
400
(Chlieh et al, 2008)

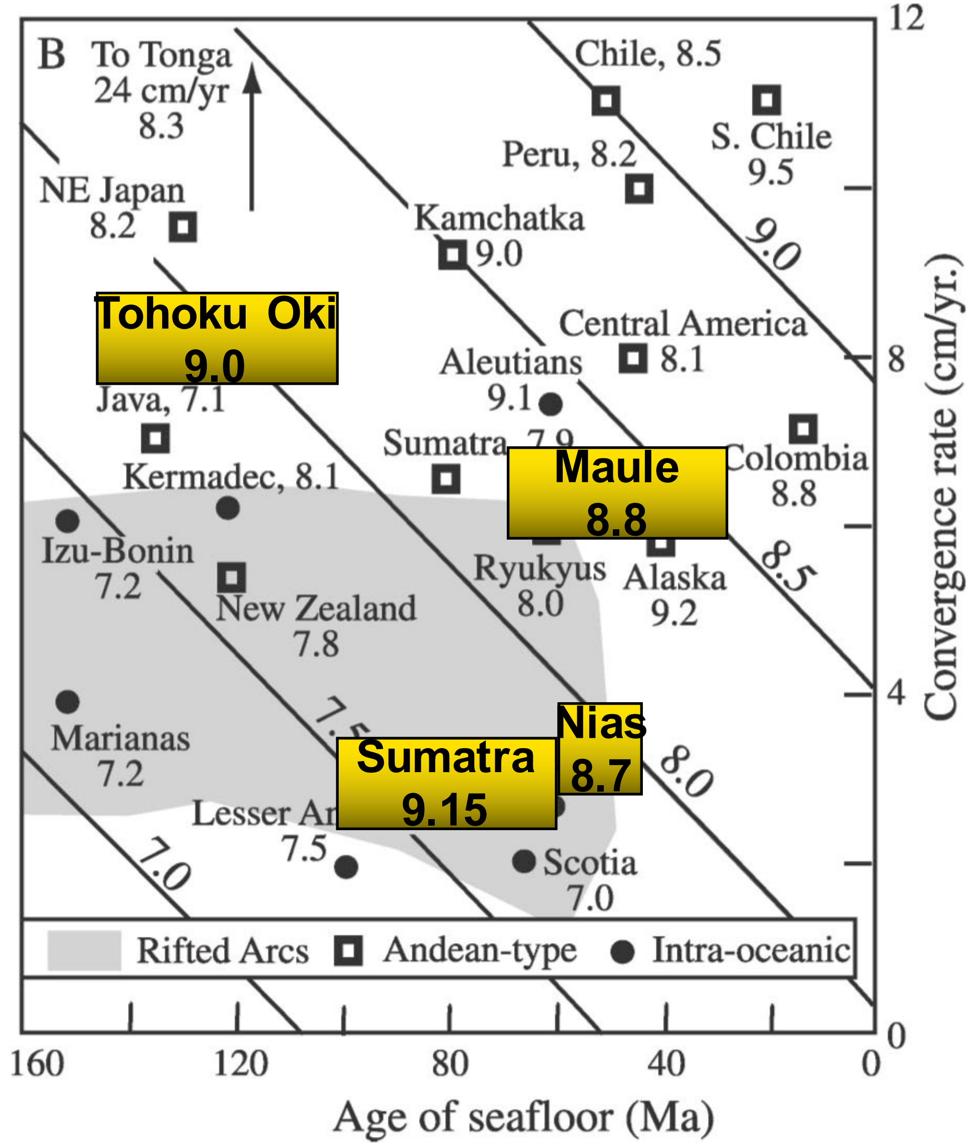


- Megathrust have released 90% of the global moment release over the last century (Pacheco and Sykes, 1992).
- All Mw>8.5 (except for the 2012 Wharton Basin EQ) have occurred at megathrust.





- **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)

Moment & Magnitude

- **Seismic Moment** (N.m)

$$M_0 = \iint_{Fault\_area} \mu S(x,y)\,dx\,dy = \mu \langle S \rangle A$$

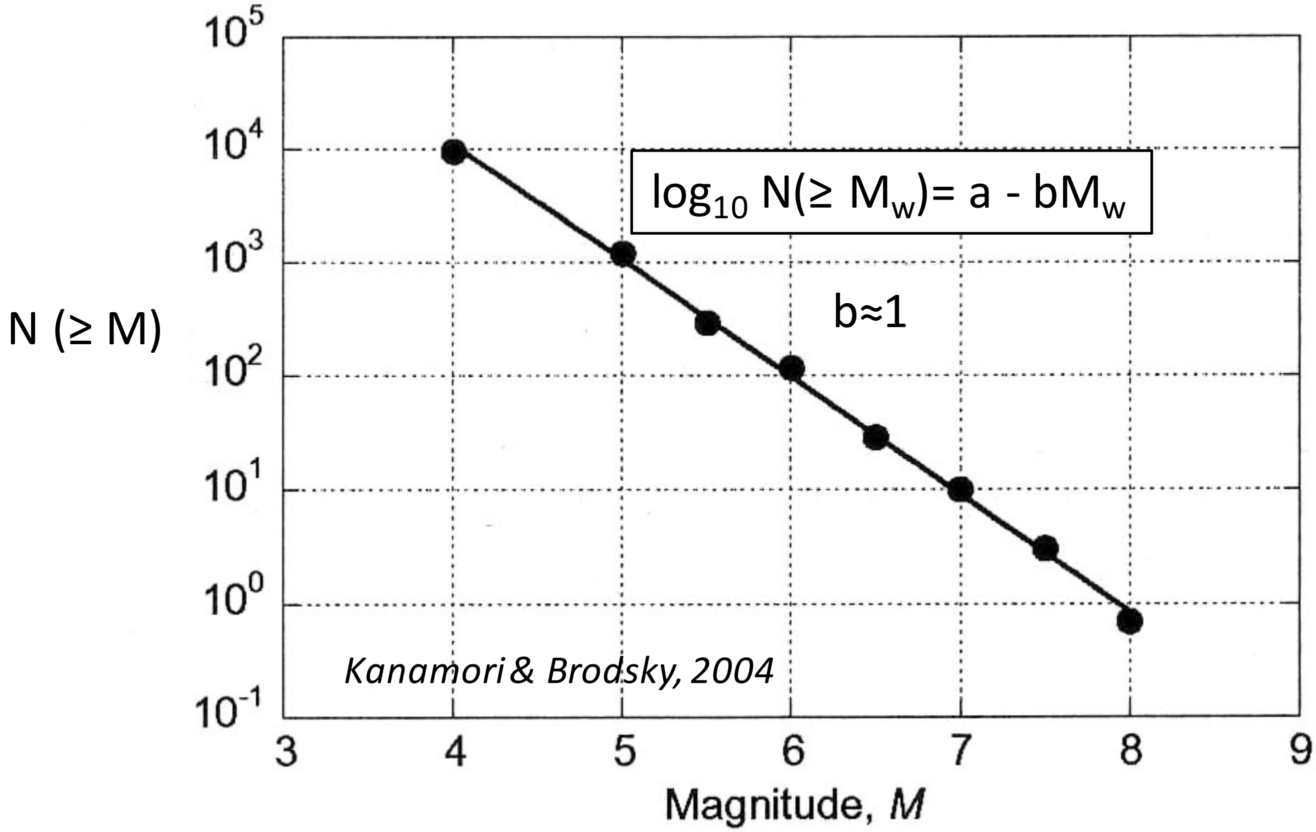
where <*S*> is average slip,
A is fault area and
μ is elastic shear modulus (30 to 50 GPa)

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

$$\mathrm{M_w} = \frac{2}{3}\log_{10} M_0 - 6$$

The Gutenberg-Richter law

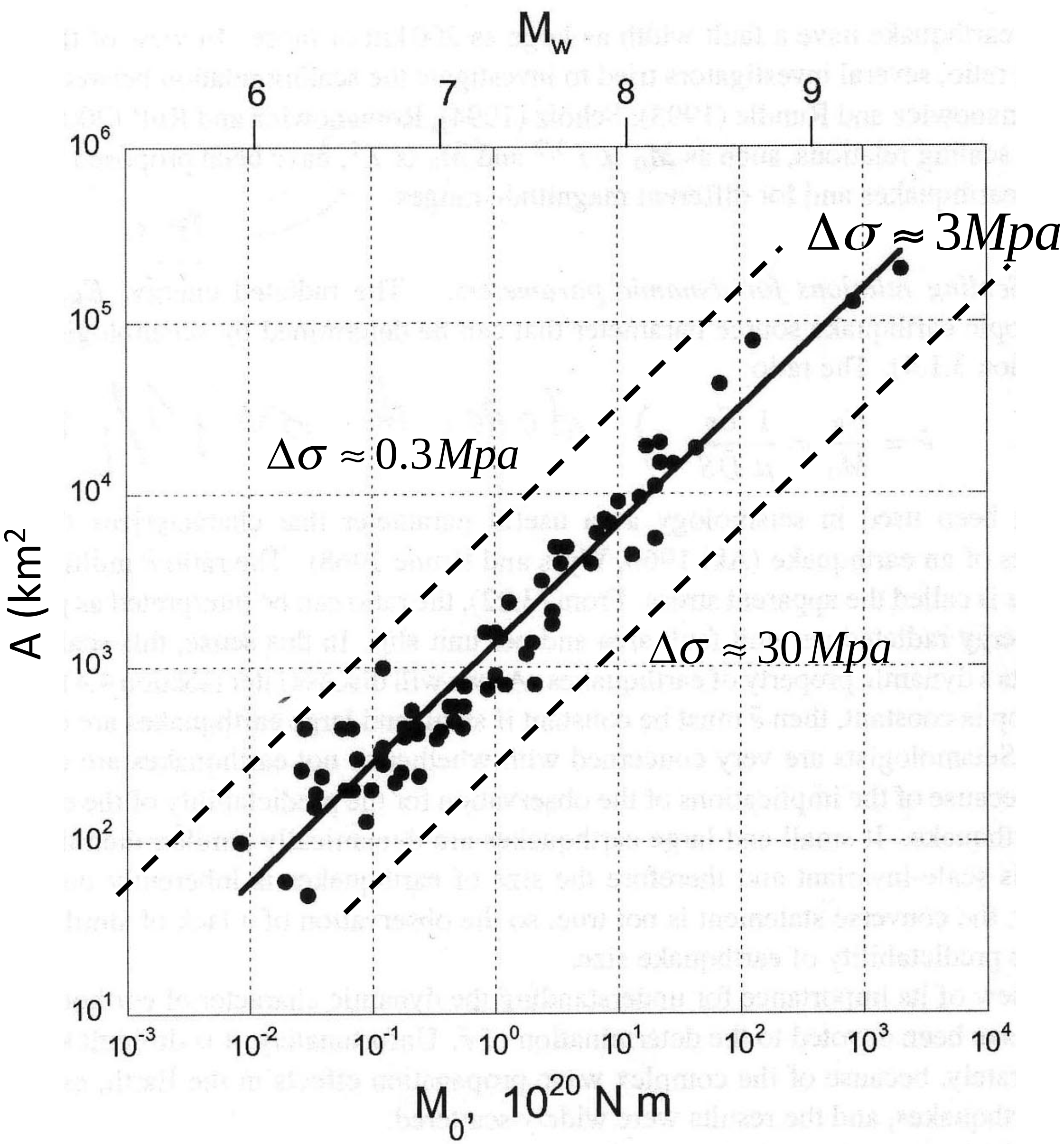
Let N (≥ M) be number of EQs per year with magnitude ≥ M



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

This empirical law holds at any scale.

Moment-Rupture area scaling



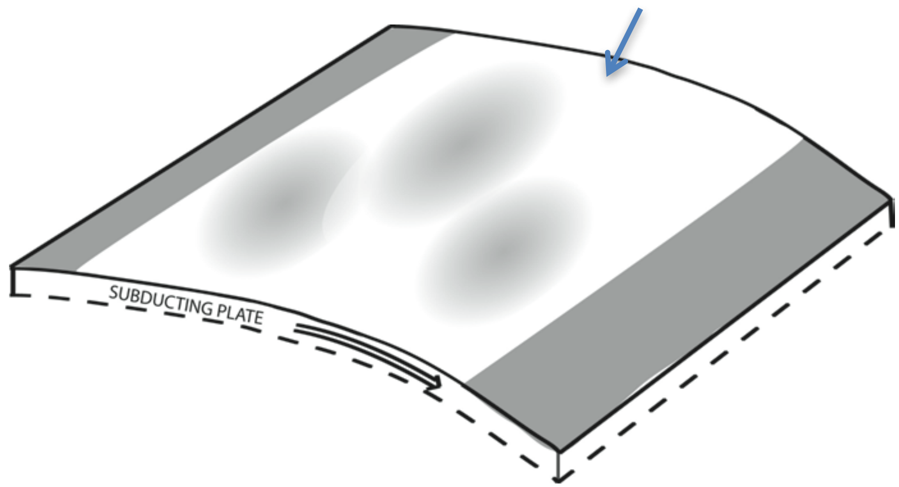
Modified from Kanamori & Brodsky, 2004

M_0 scales with $A^{3/2}$
(Wyss, 1979).
This is expected from a simple crack model (*e.g.*, Eshelby, 1957) if **stress drop is constant**.

$$\Delta\sigma \approx C\mu\frac{\langle S\rangle}{\sqrt{A}} = C \cdot M_0 \cdot A^{-3/2}$$

The moment conservation principle & Seismic Coupling

Brune (1968) relates **accumulated moment** to the **total fault slip**



Average seismic slip, <S> is a function of seismic moment, M_0 and of the seismogenic fault zone area, A

$$\langle S \rangle = \frac{M_0}{\mu A}$$

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

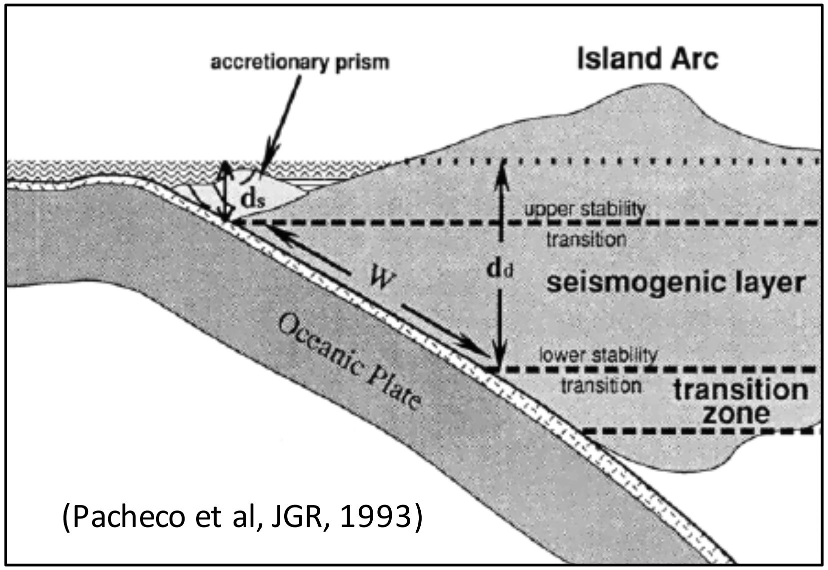
$$V_s = \frac{\sum M_0}{\mu A T} = \frac{\dot{M}_0}{\mu A}$$

→ Estimate the average moment release rate from the geologial slip rate, *V*, and fault area, *A*

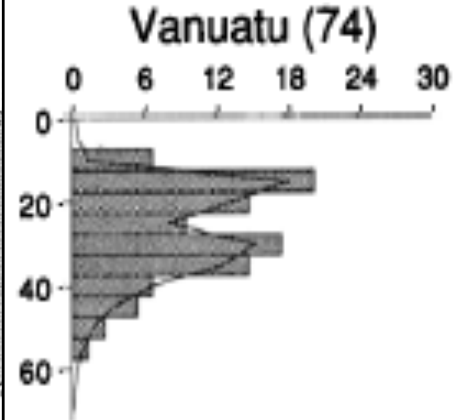
$$\dot{M}_0 = \mu V A$$

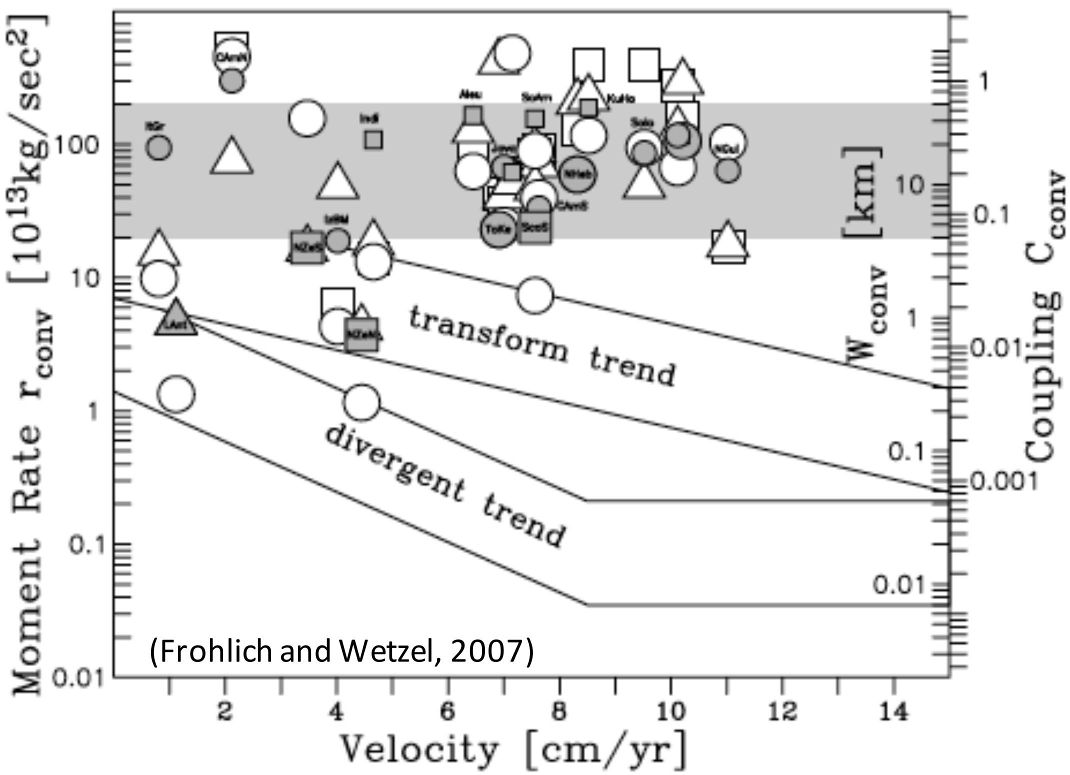
→ Seismic coupling

$$\chi_s = \frac{V_s}{V} = \frac{\sum M_0}{\mu A V T}$$



(Pacheco et al, JGR, 1993)





(Frohlich and Wetzel, 2007)

Seismic Coupling at converging plate boundaries is ~0.6 on average.

→ A fraction of slip within the seismogenic zone is aseismic

→ or a global deficit of subduction earthquakes

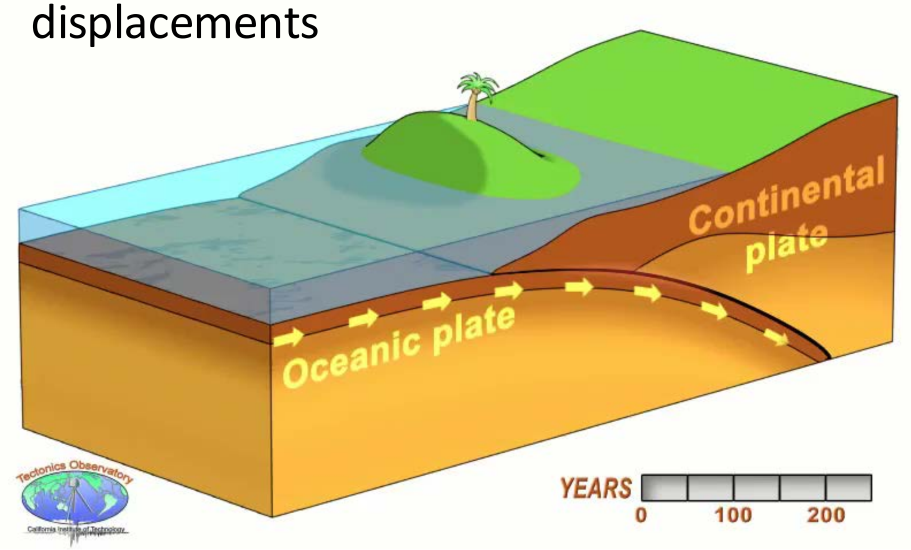
Interseismic coupling

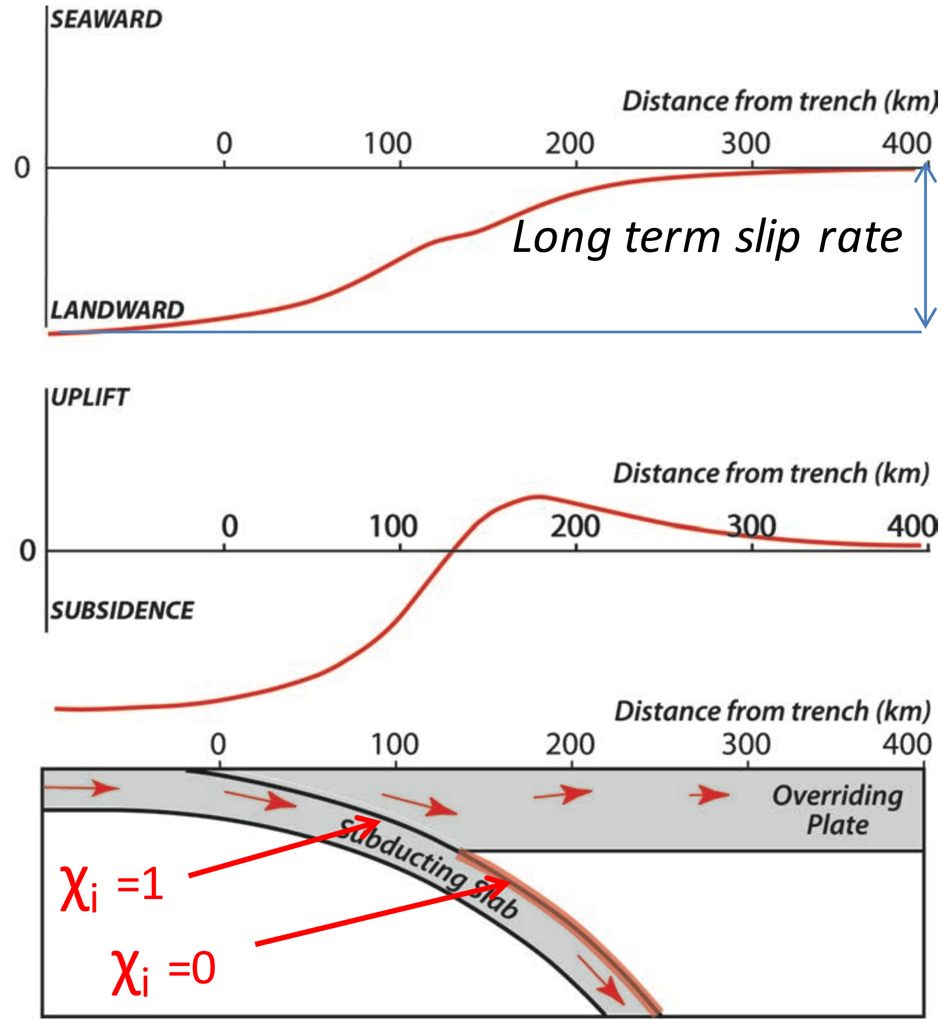
Definition:

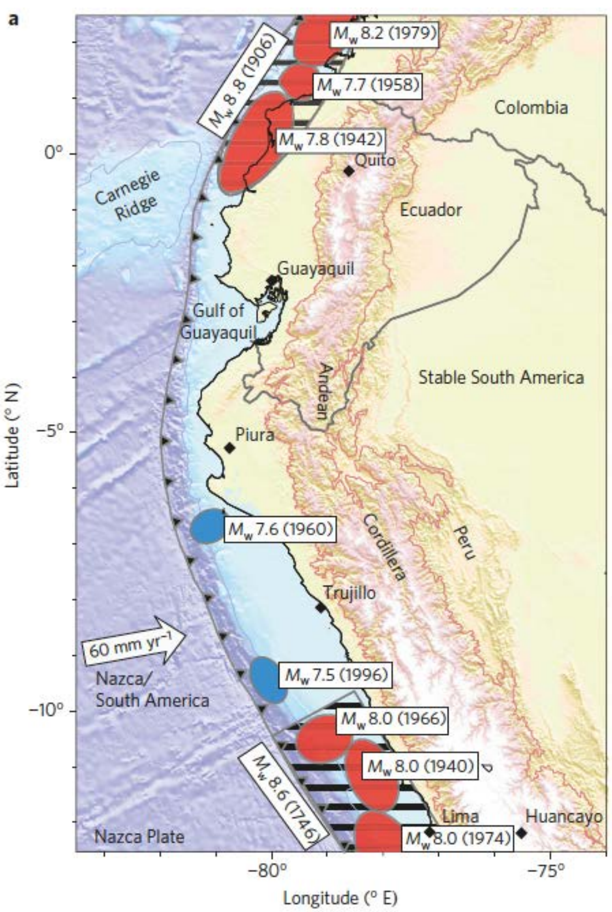
χ_i =deficit of slip/long term slip
(assigned to a fault,
varies in time and space)

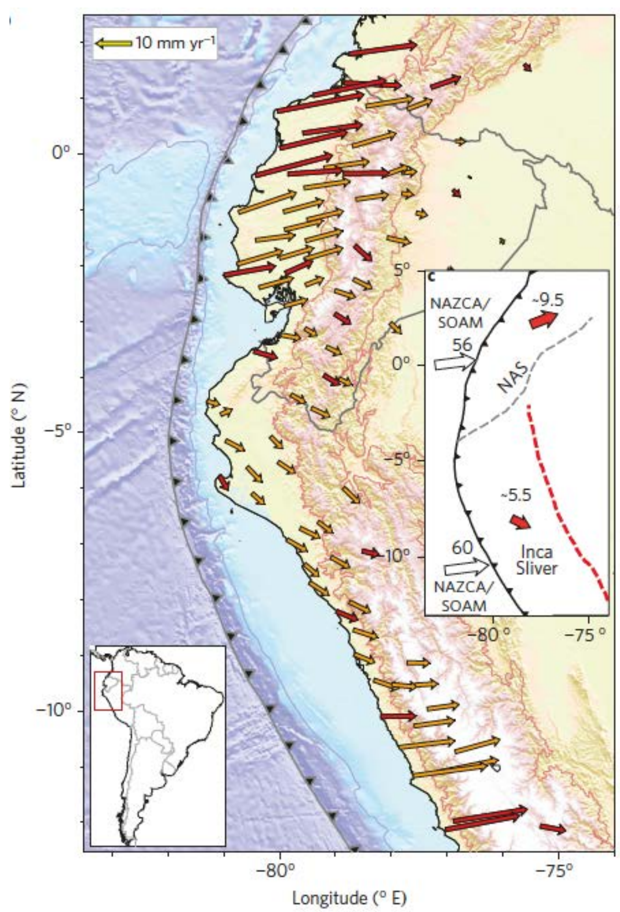
Determination:

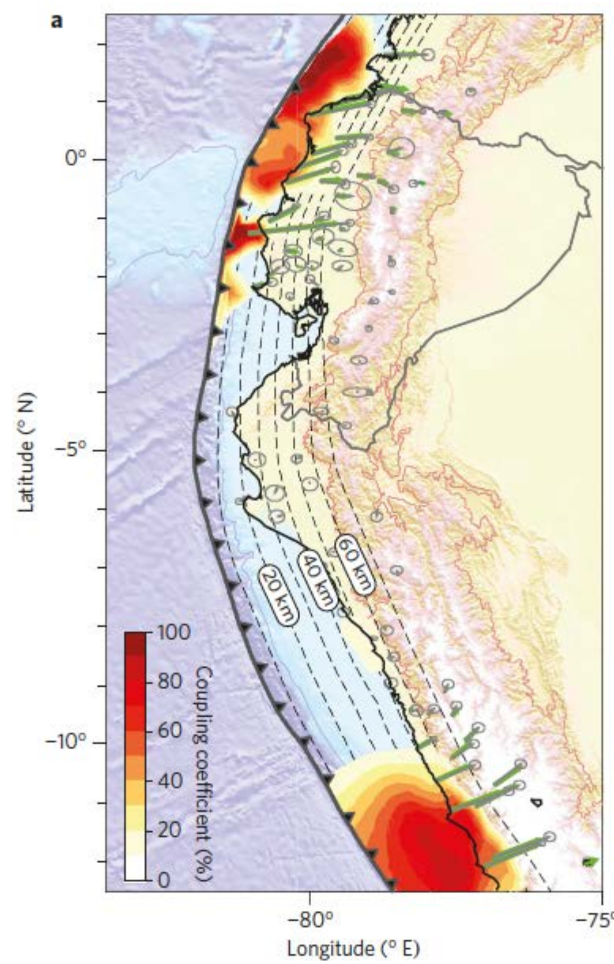
Elastic Dislocation Modeling of Interseismic geodetic displacements





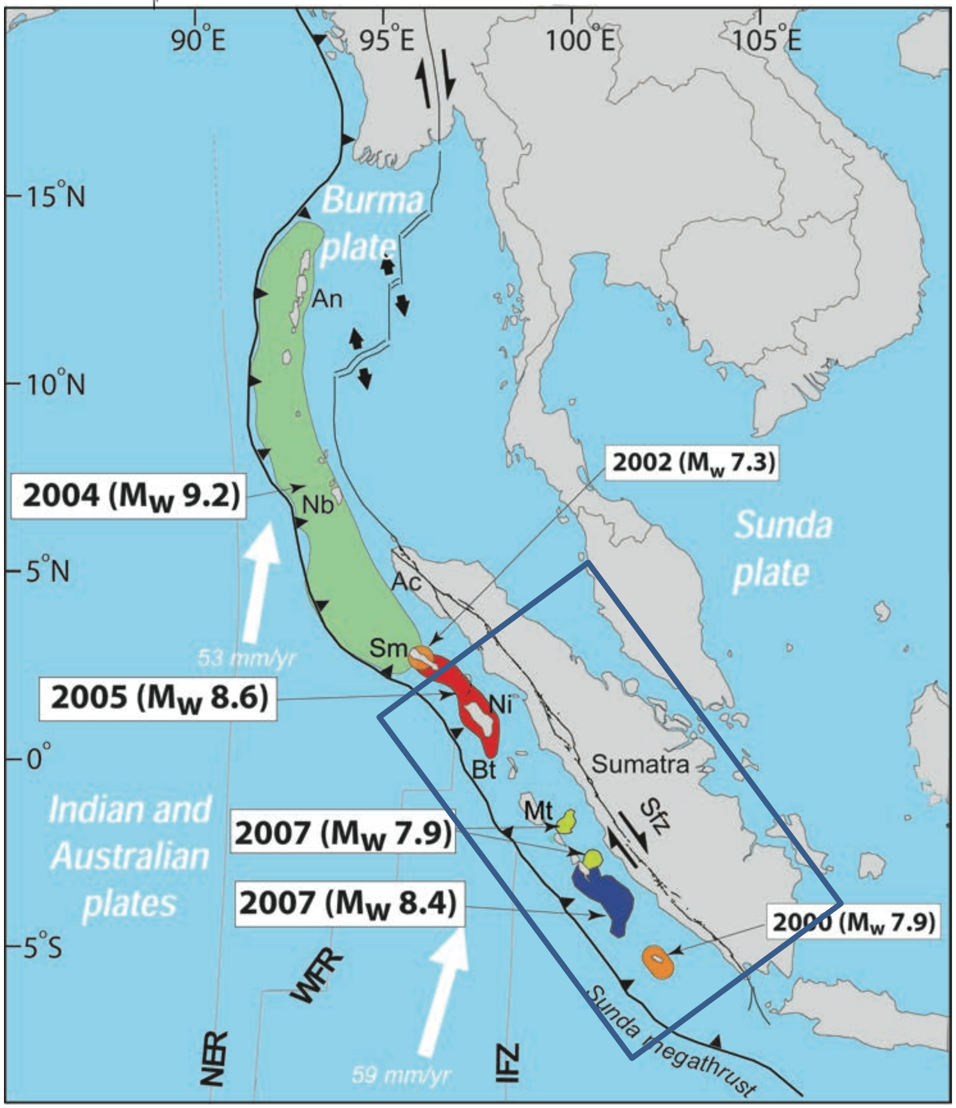


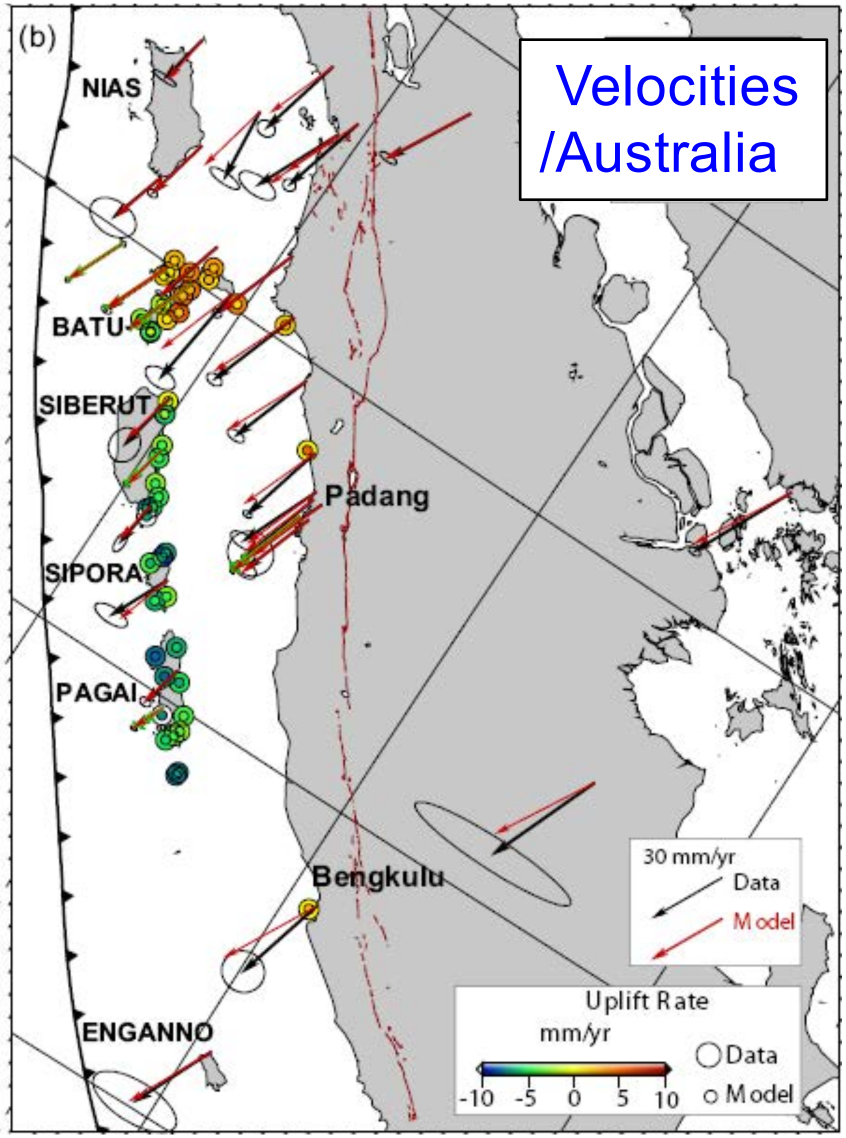




(Nocquet et al, NGEO, 2014)

The Sumatra Megathrust

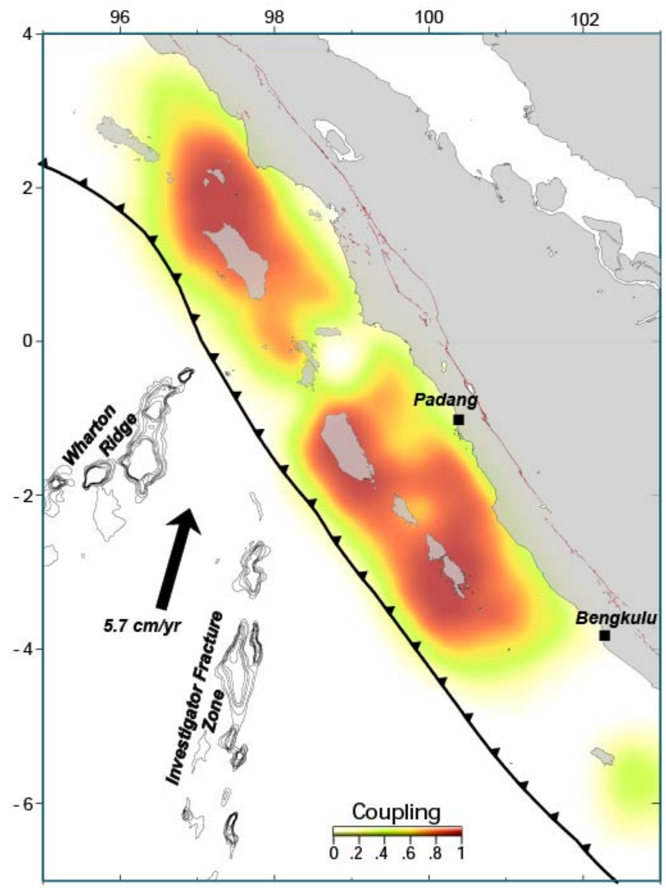




Sources: Natawidjaja et al, (2004),Chlieh et al, (2008); Briggs et al (2006); Hsu et al (2006); Konca et al (2006, 2008)

The Sumatra Megathrust

- Interseismic coupling

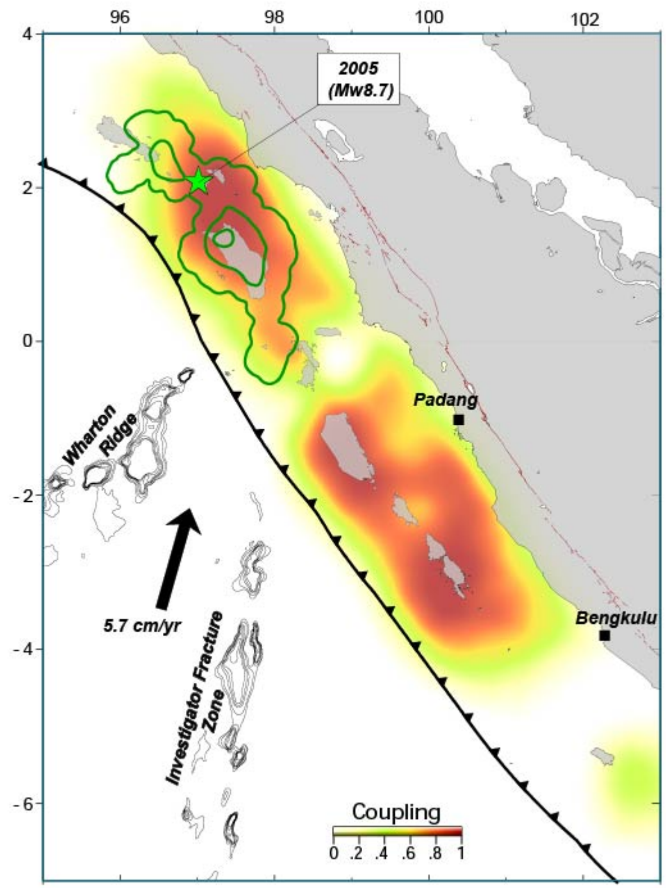


(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)

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

The Sumatra Megathrust

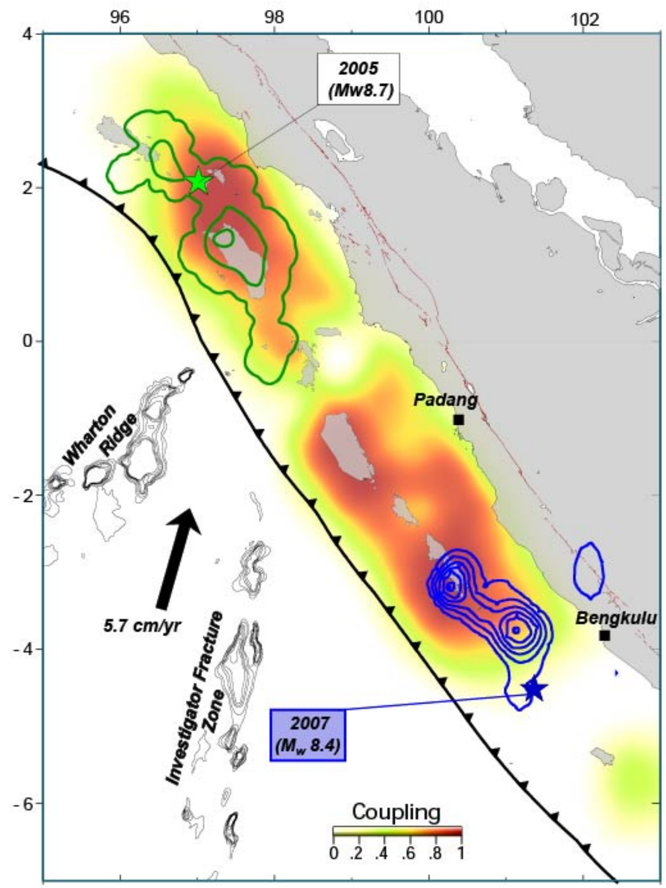
- Interseismic coupling
- Mw, 8.6, 2005, Nias EQ



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

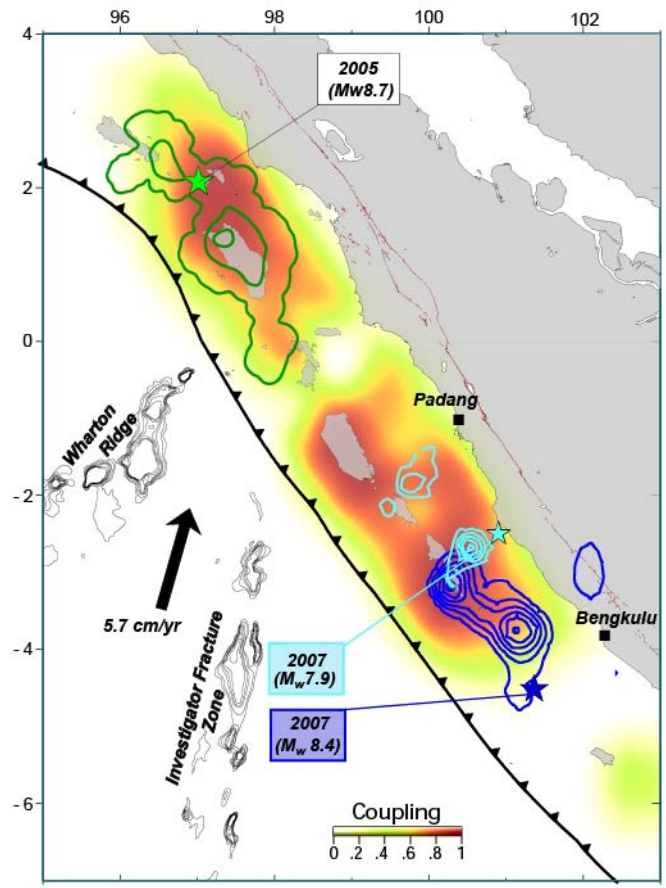


(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)

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

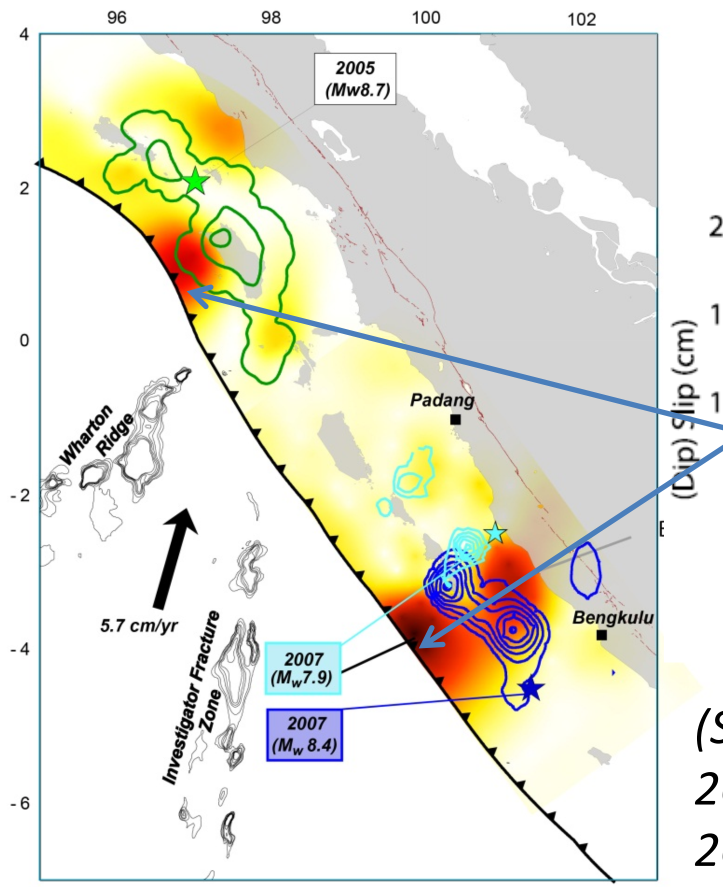


(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)

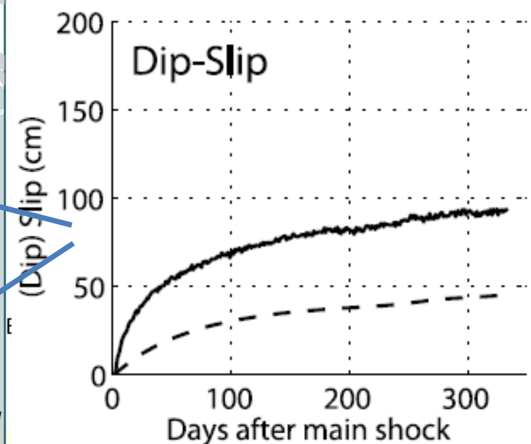
Comparison of Interseismic Coupling (deficit of slip in the interseismic period) with seismic and aseismic transient slip.

The Sumatra Megathrust

- Mw 8.6, 2005, Nias EQ
- Mw 8.4, 2007, Bengkulu EQ
- Mw 7.9, 2007, Bengkulu EQ
- 1 yr afterlip following Nias EQ
- 1 yr afterlip following Bengkulu EQs



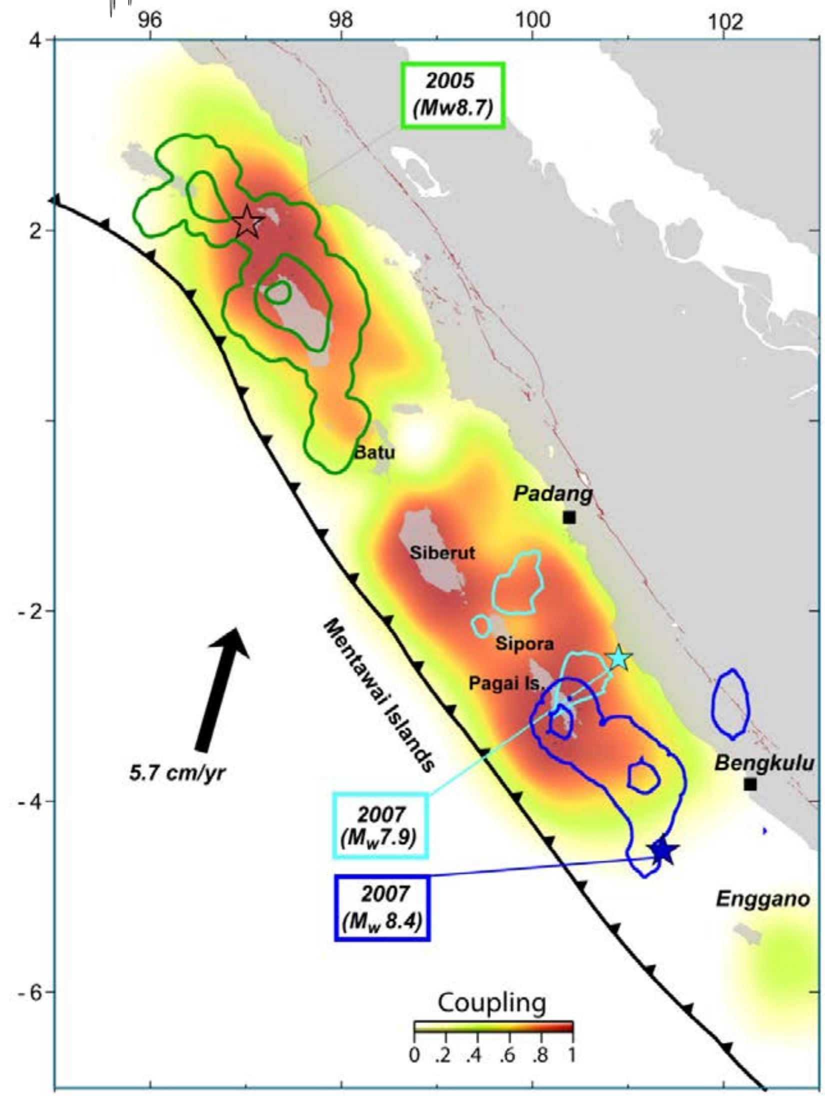
Afterslip: 30% of coseismic moment release over 1 yr



(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.

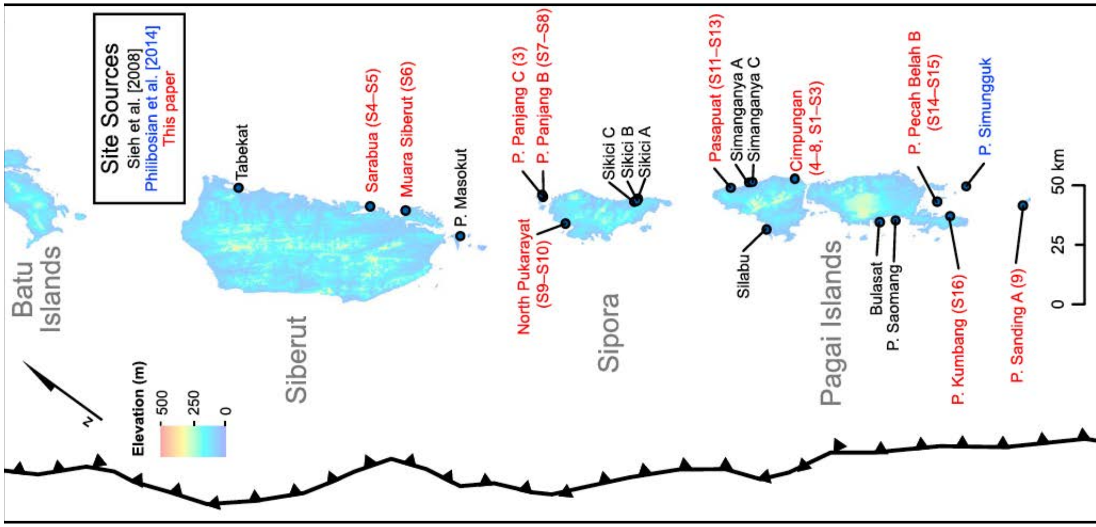
The Sumatra Megathrust

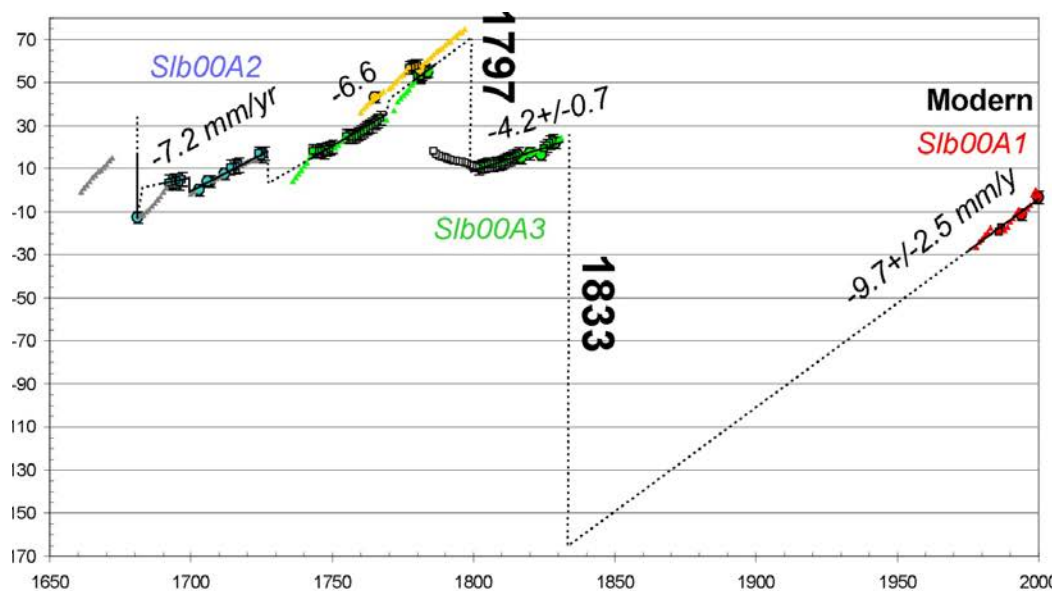


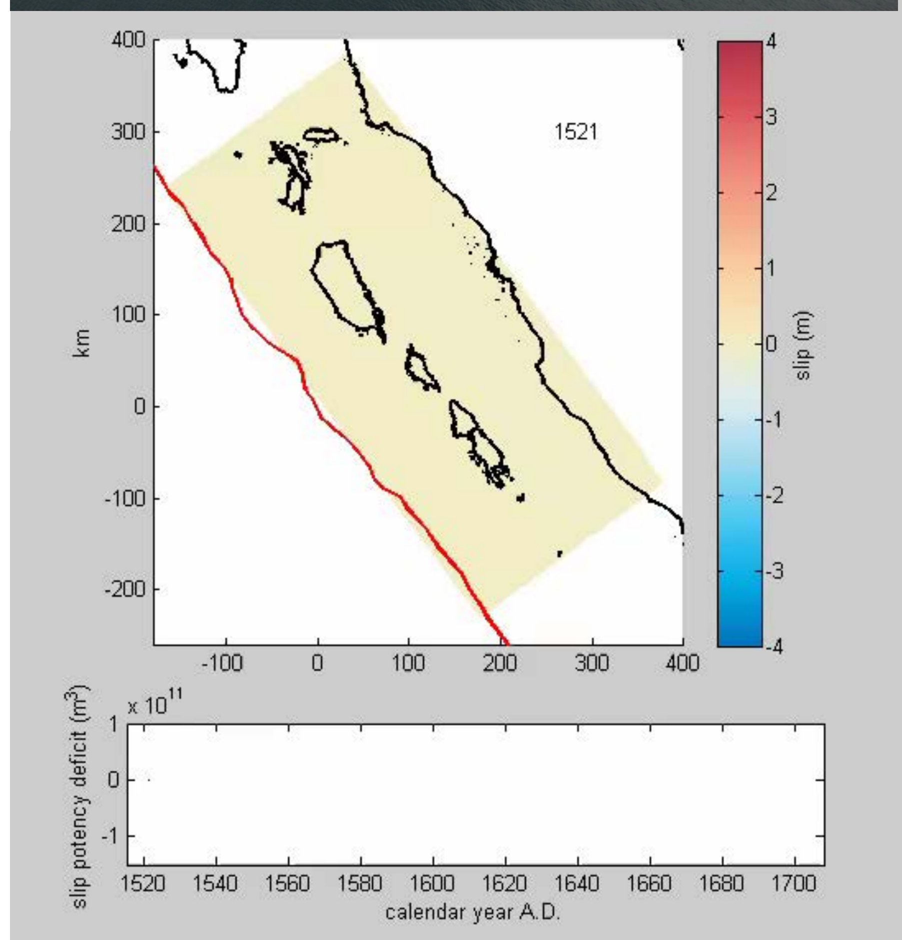
- Interseismic coupling is highly heterogeneous
- Slip is mosty aseismic (50-60%) in the 0-40km 'Seismogenic' depth range
- Seismic ruptures seem confined to 'locked' areas. Creeping zones tend to arrest seismic ruptures.
- Afterslip increases as a logarithmic function of time.

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

Strain accumulation and release at the Sumatra Megathrust from coral-reef paleo-geodesy

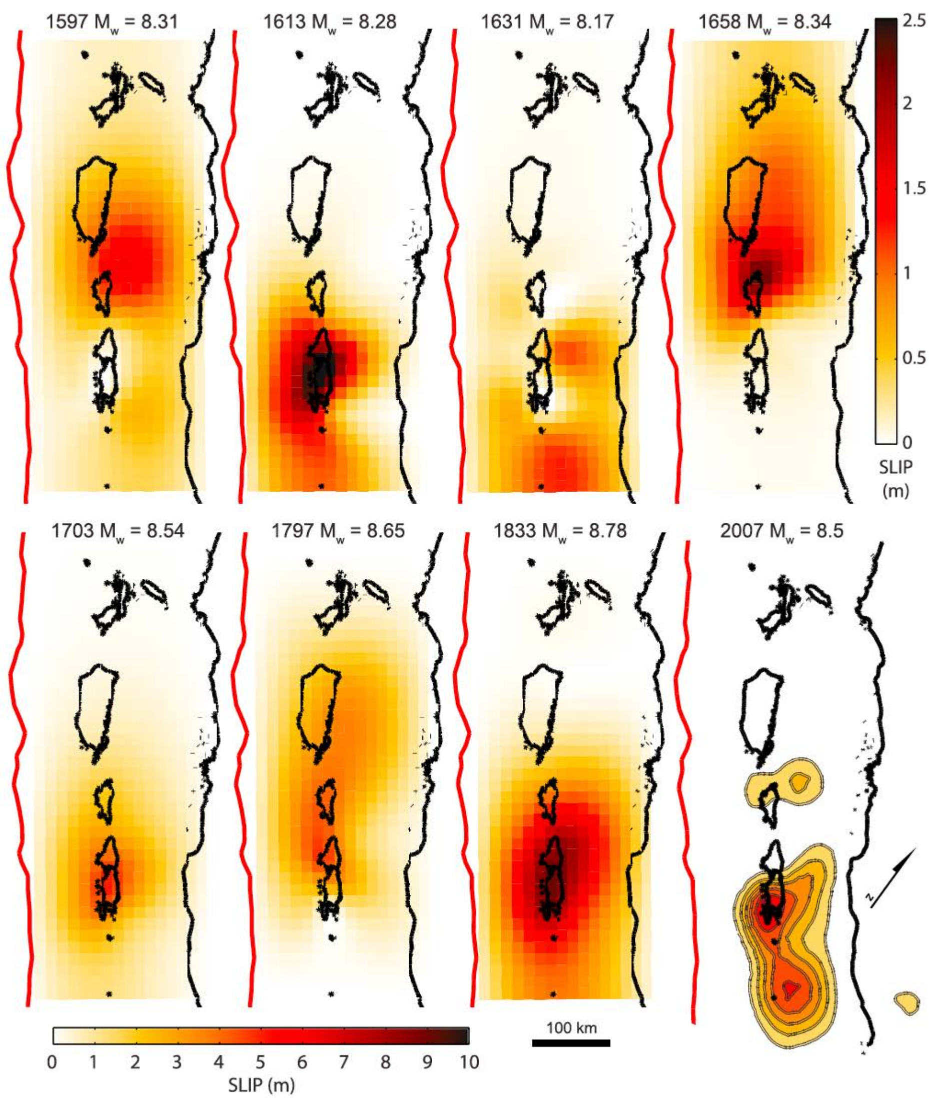


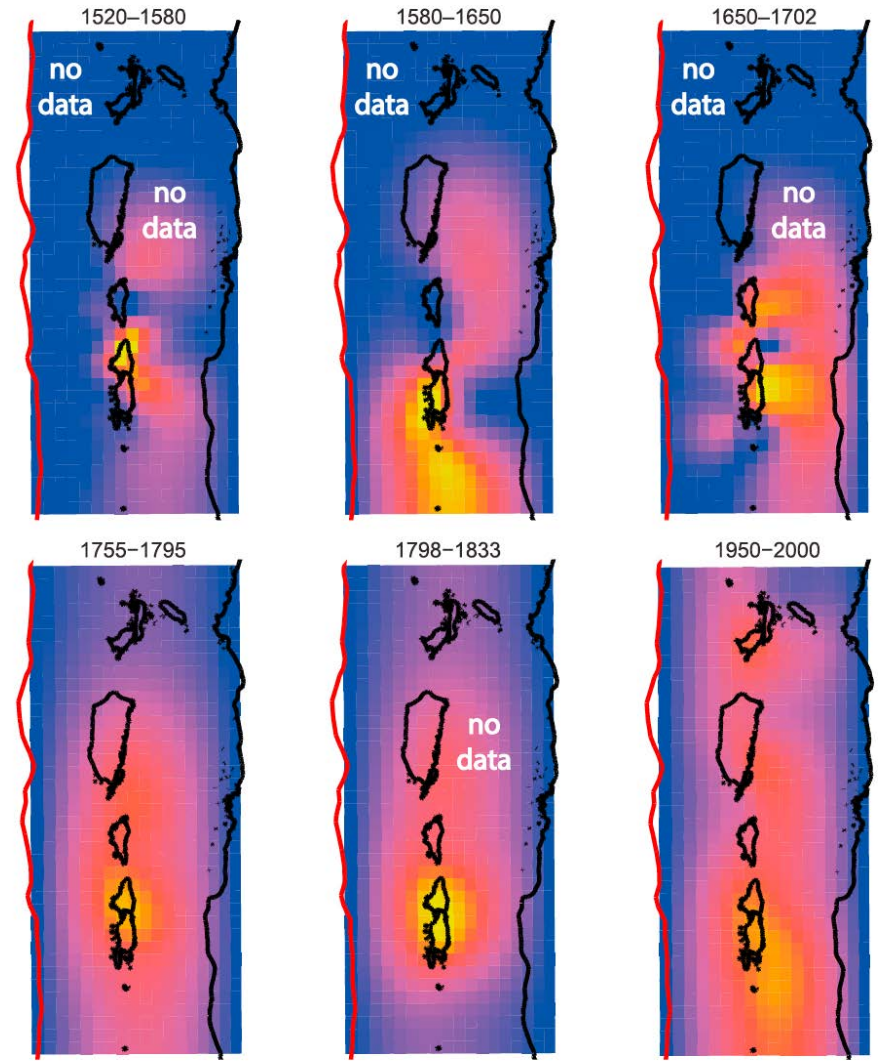




(Philibosian et al., 2017)

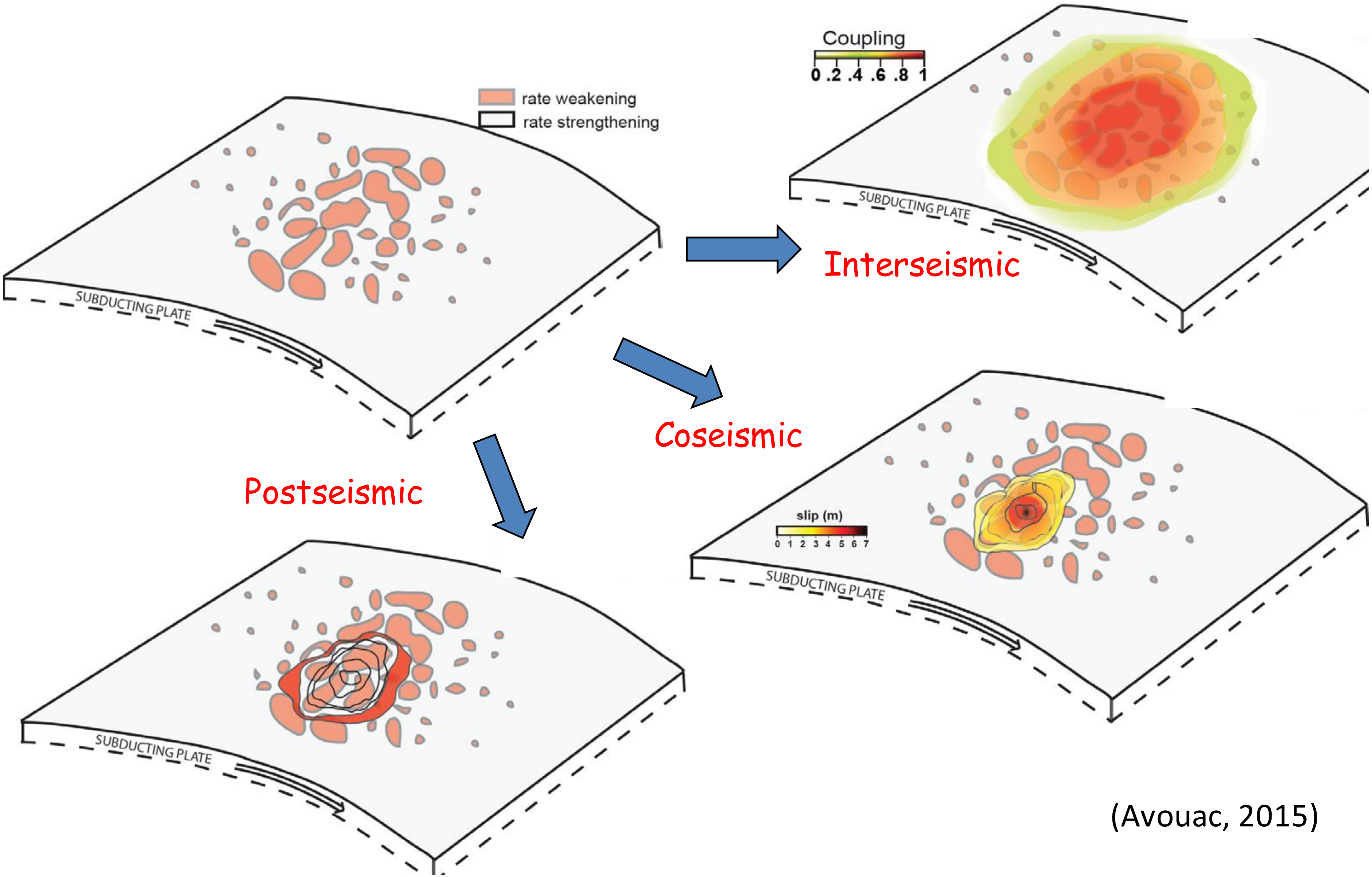
Variable ruptures/quasi stationnary coupling





(Philibosian et al., 2017)

The Seismic Cycle, a Conceptual framework

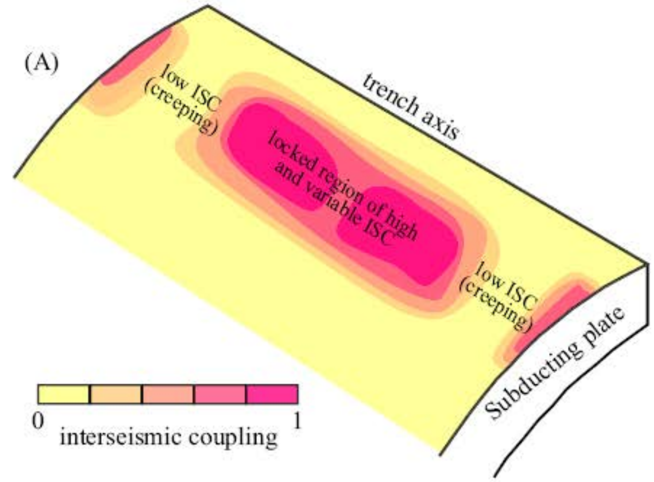


(Avouac, 2015)

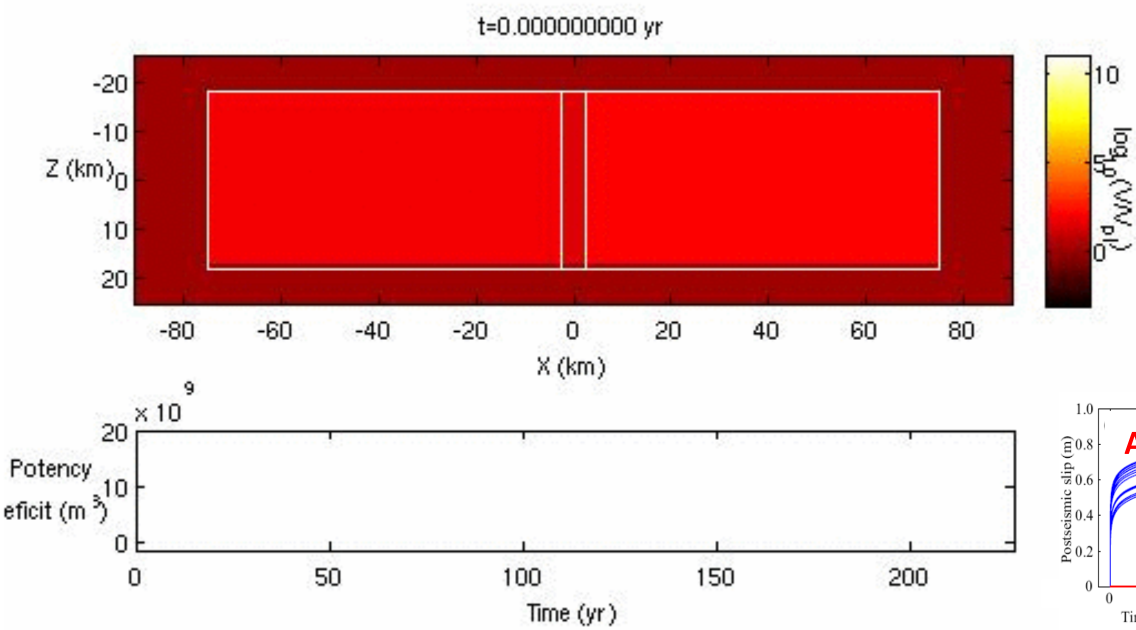
Dynamic modeling

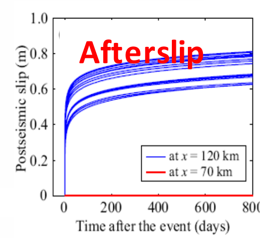
Rate & state friction:
(Dieterich, 1979;
Ruina, 1983)

$$\begin{cases} \mu = \mu_* + a \ln \dfrac{V}{V_*} + b \ln \dfrac{\theta}{\theta_*} \\ \dfrac{d\theta}{dt} = 1 - \dfrac{V\theta}{D_c} \end{cases}$$



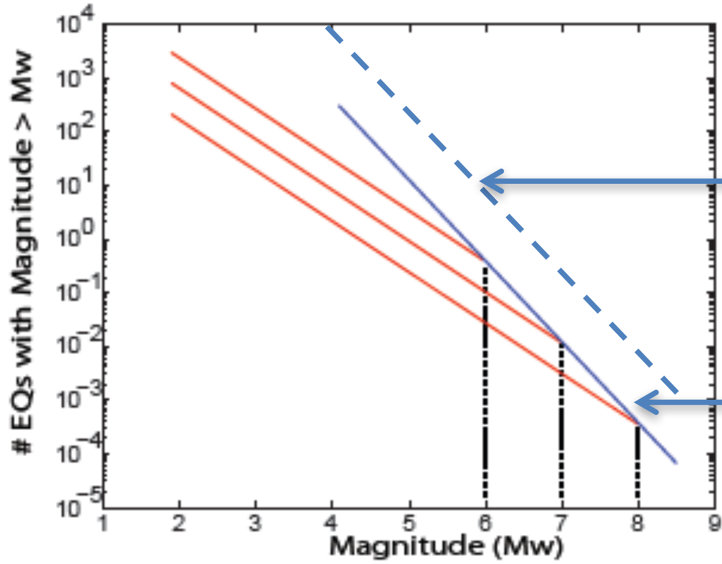
Numerical Method: Boundary Intregral Method
(Lapusta and Liu (JGR, 2009)





(Kaneko, Avouac and Lapusta, 2010)

Relating seismicity rate and moment deficit rate

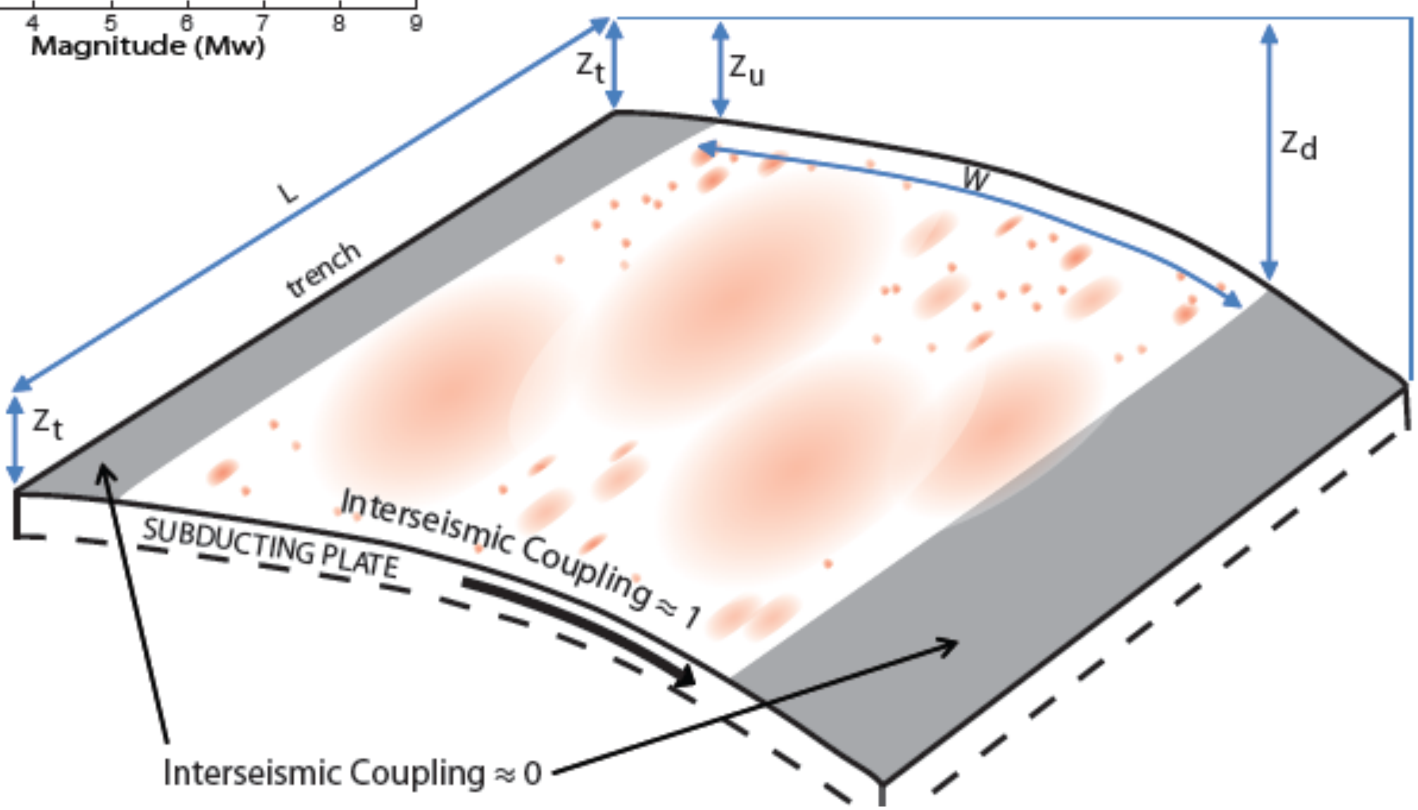


Frequency of largest EQ in the GR distribution

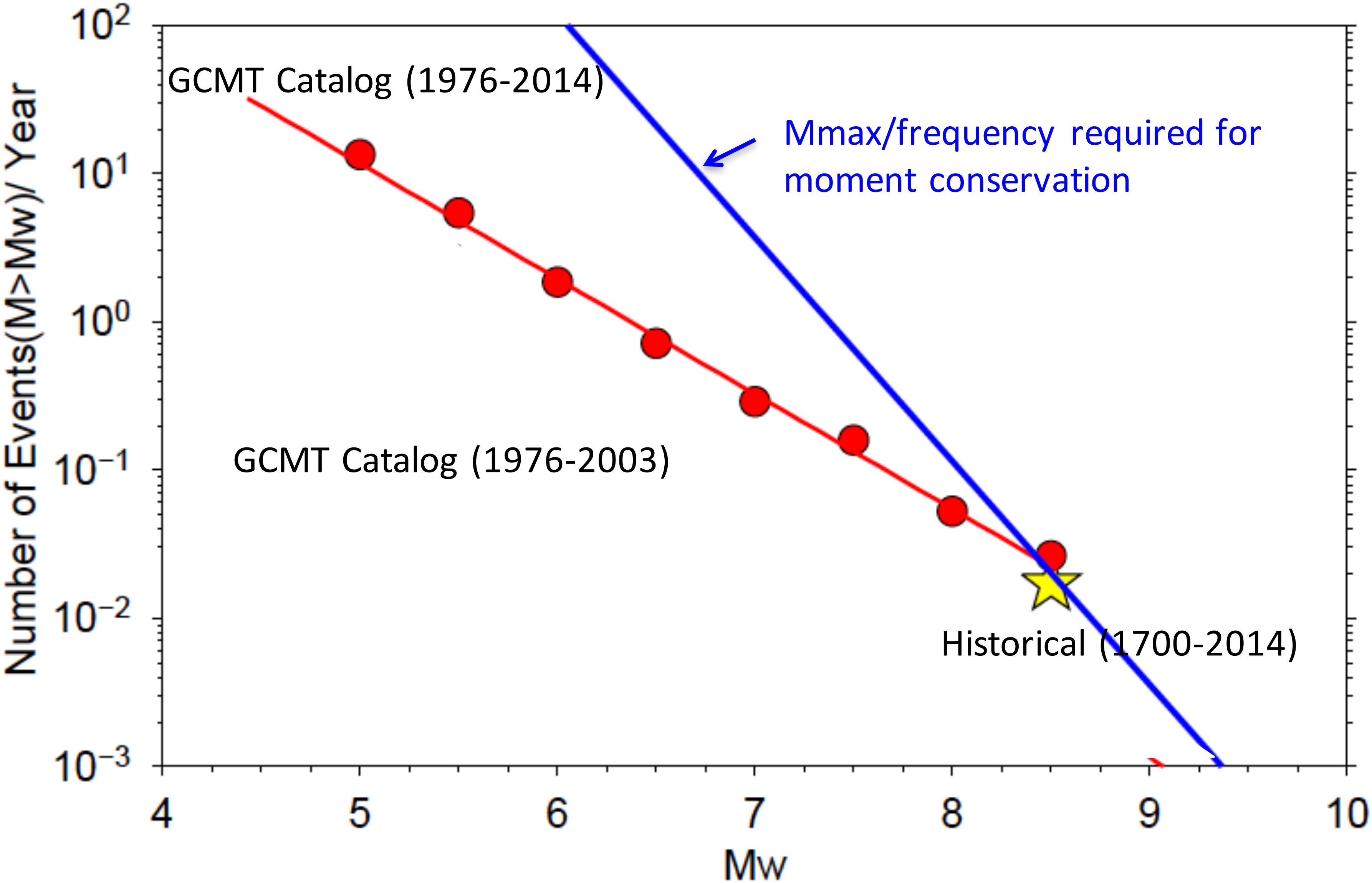
$$\frac{1}{T(M_0)} = \frac{\dot{M}_0}{M_0}$$

$$\frac{1}{T(M_{max})} = (1 - \frac{2b}{3})\frac{\dot{M}_0}{M_{max}}$$ (Molnar, 1979)

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

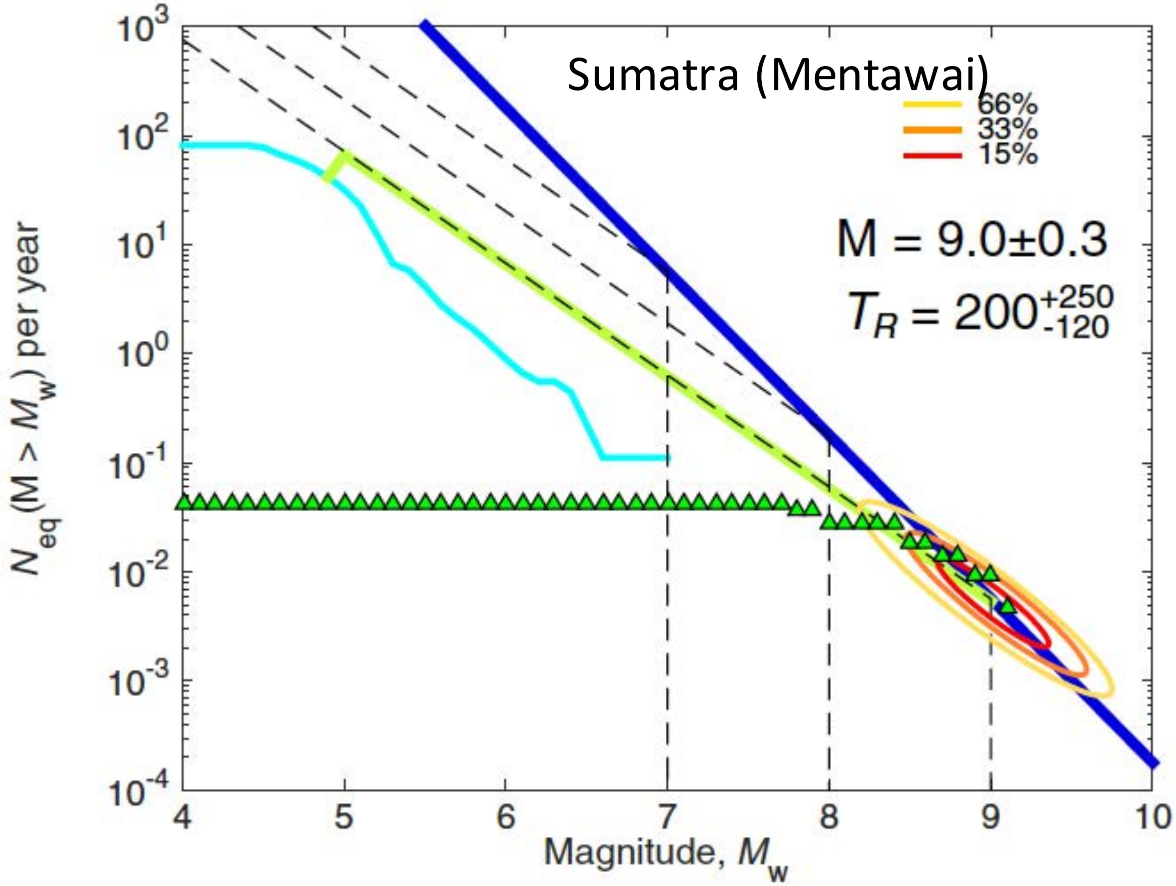


Testing the moment conservation principle



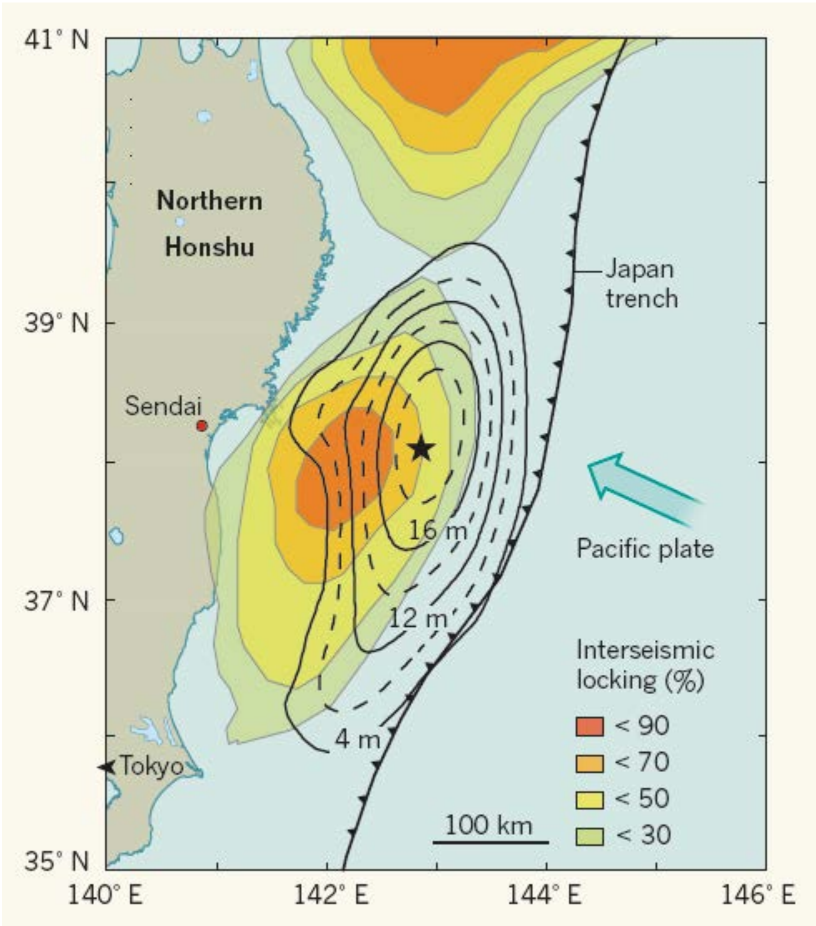
Estimation of Mmax and its frequency

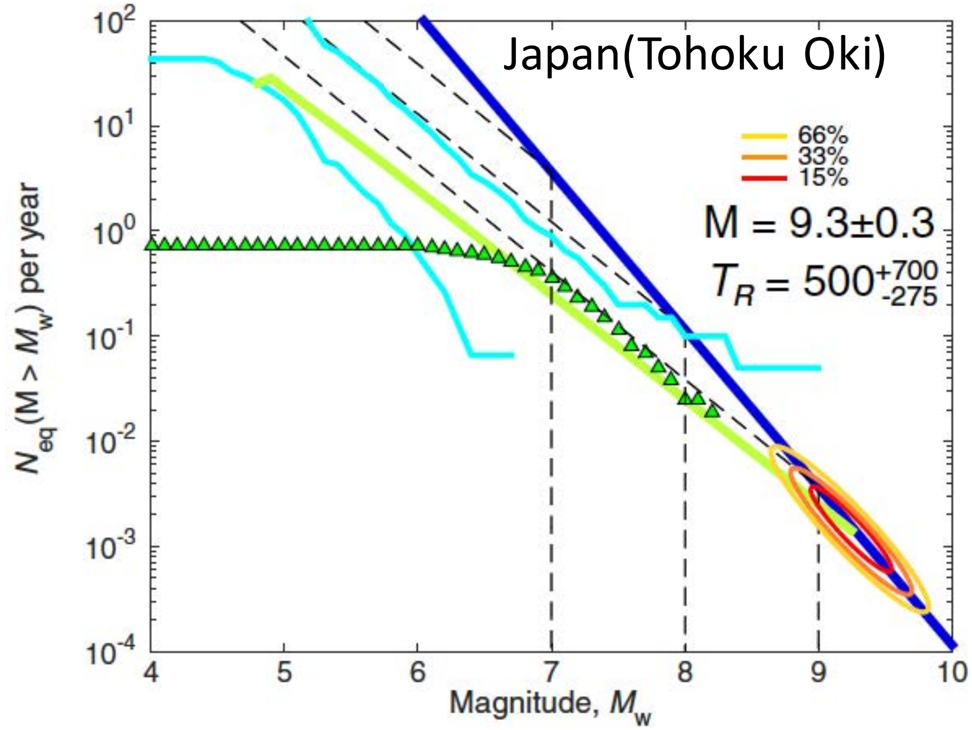
Long term seismicity model, so M_{max} and $1/T(M_{max})$, can be estimated based on interseismic coupling and 'interseismic' seismicity using the moment conservation principle



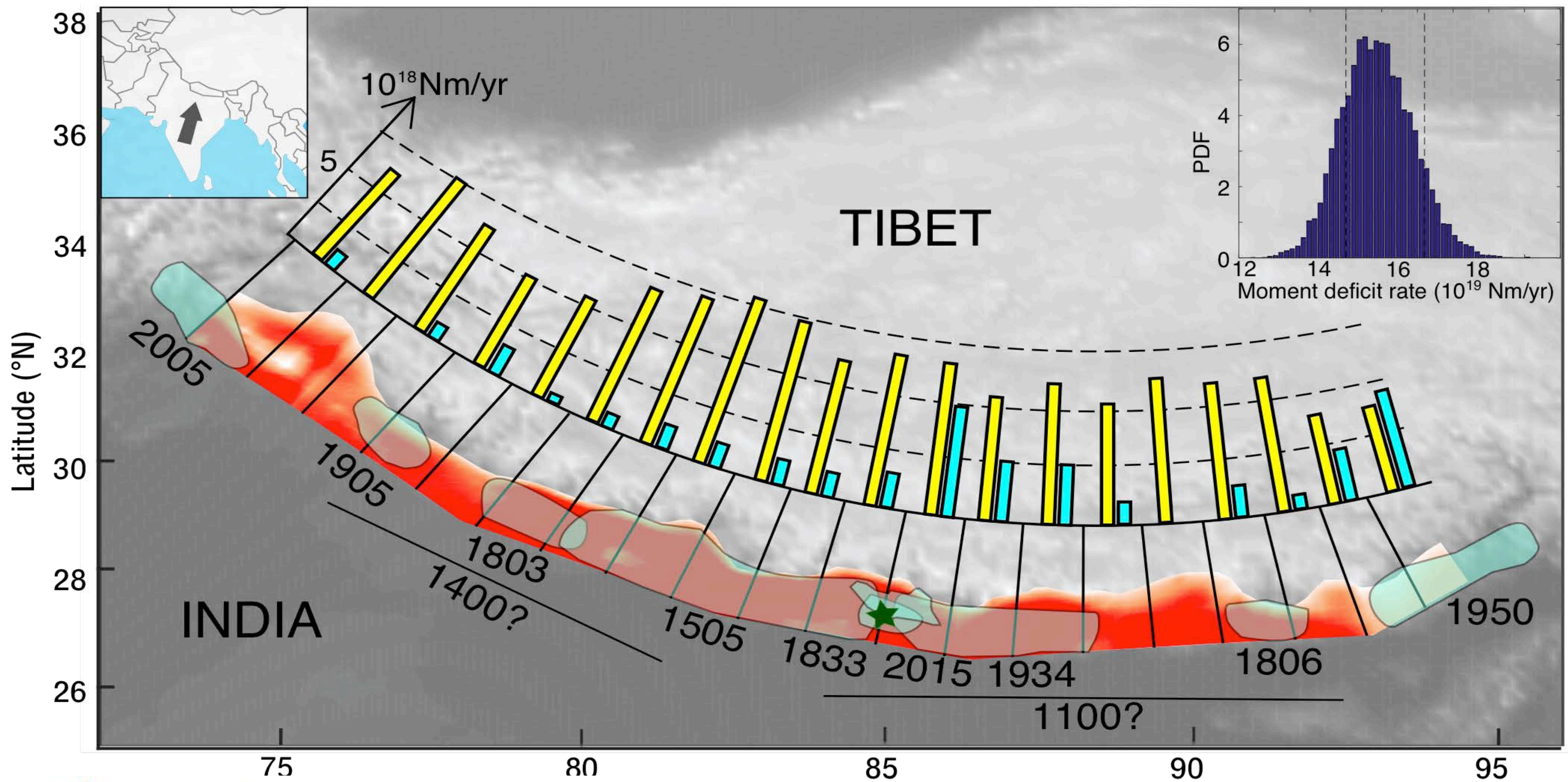
(Stevens and Avouac, BSSA, 2018)

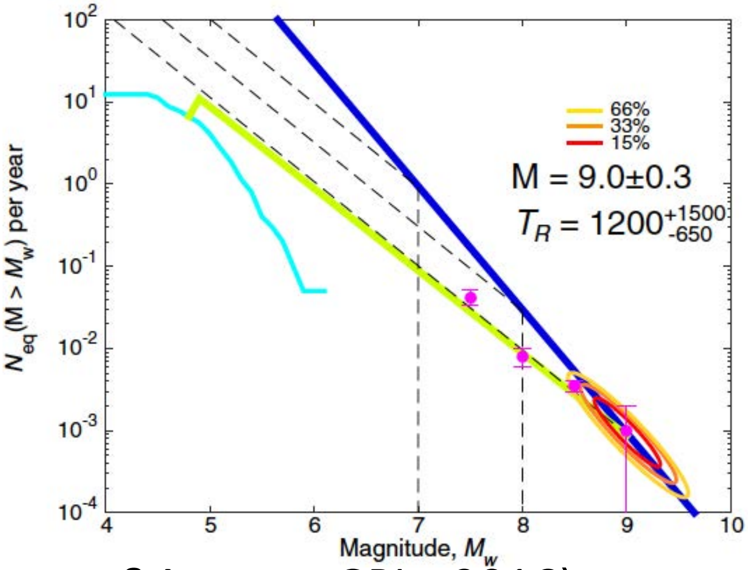
Application to the Mw 9.0 Tohoku Oki Earthquake



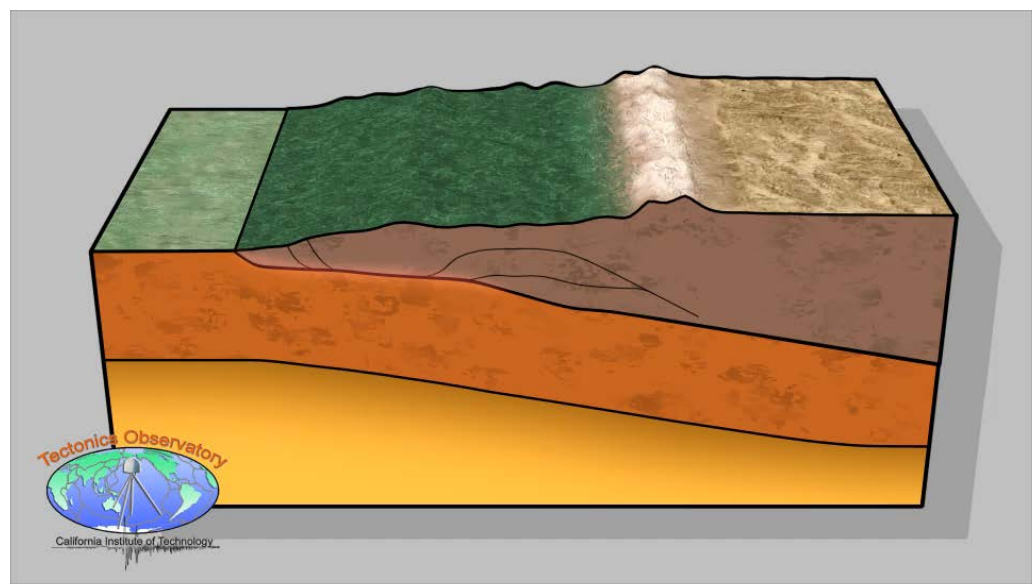


Interseismc coupling (Loveless&Meade, JGR, 2010) (Stevens&Avouac, BSSA, 2017)
Coseismic rupture (Ozawa et al., Nature, 2011)

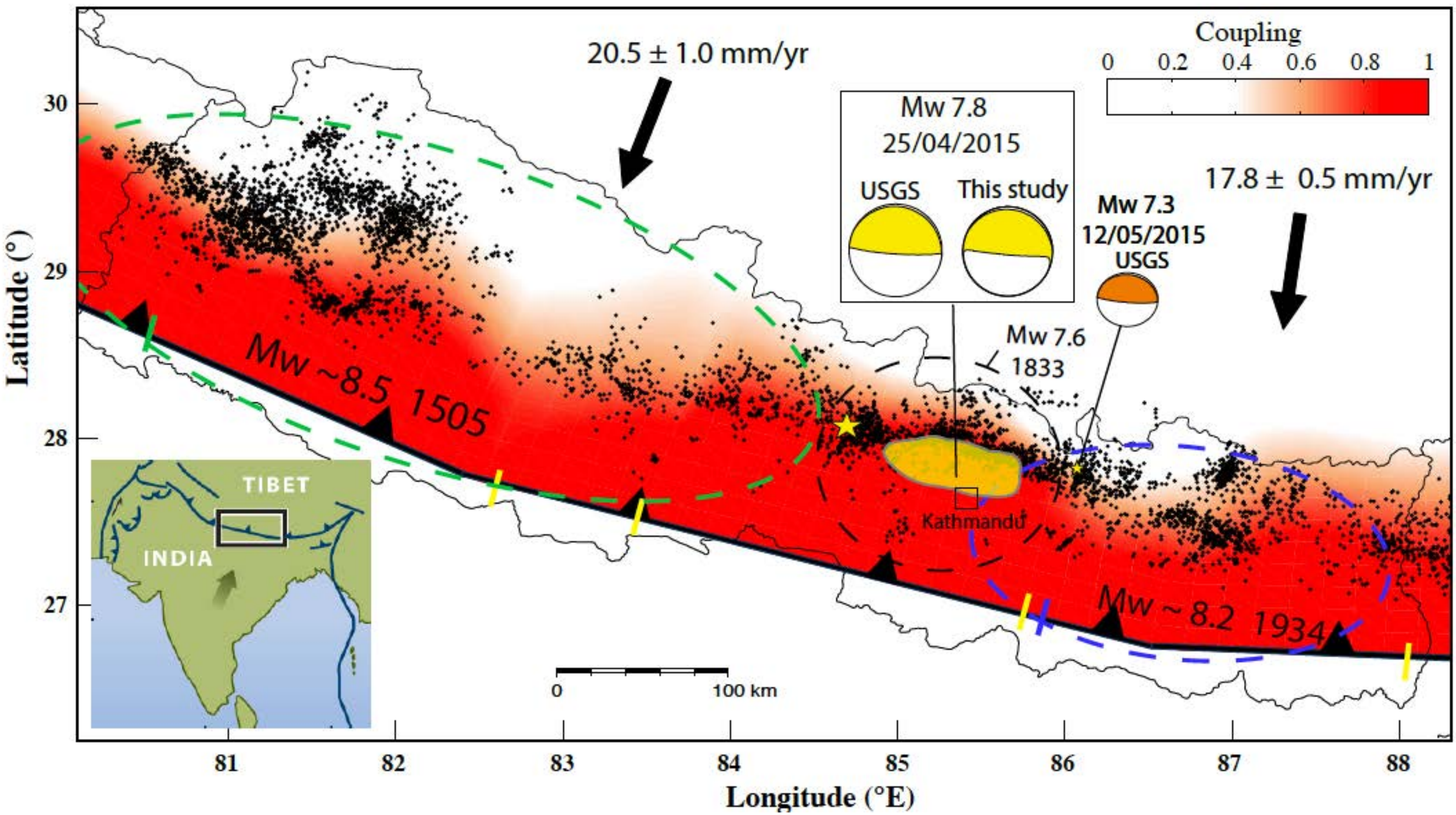




(Stevens&Avouac, GRL, 2016)



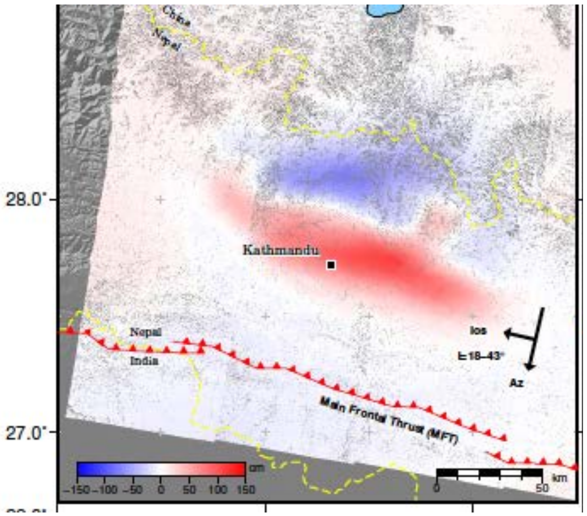
The 2015 Mw7.8 Gorkha Earthquake

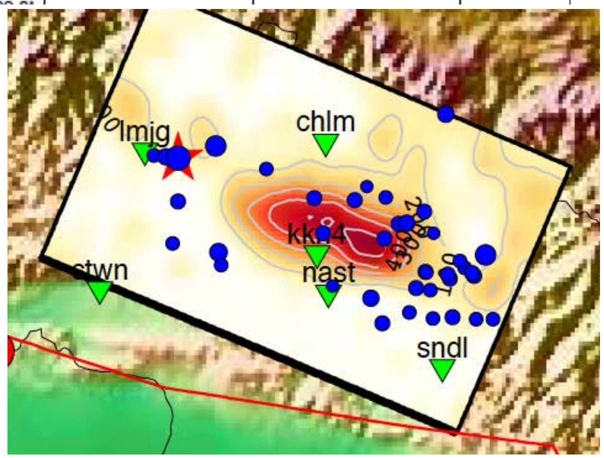


Dharahara Tower

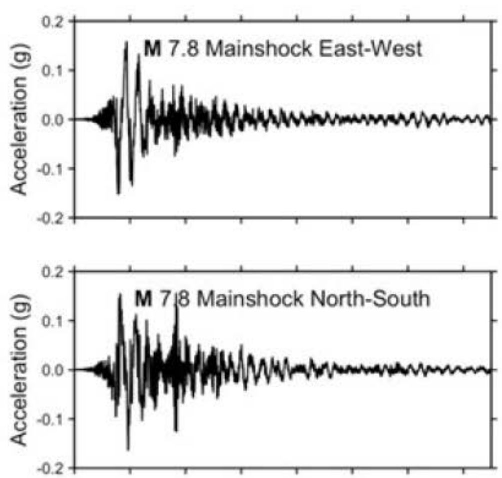
April, 24, 2015

April, 25, 2015



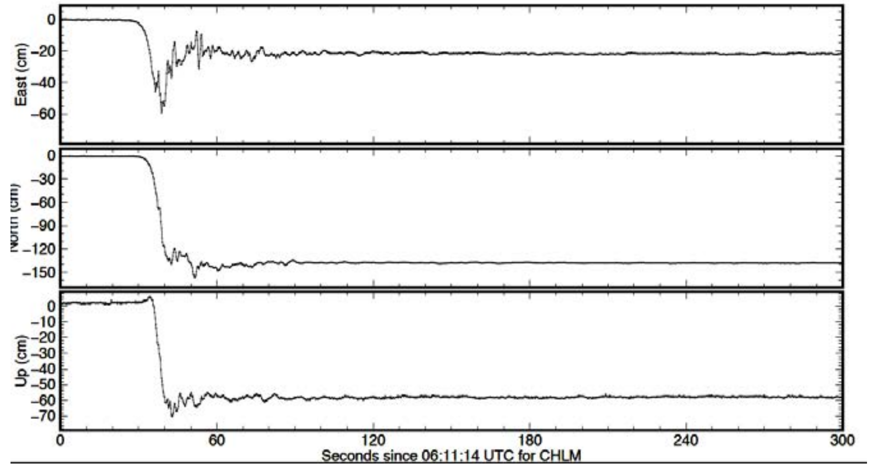


KATNP

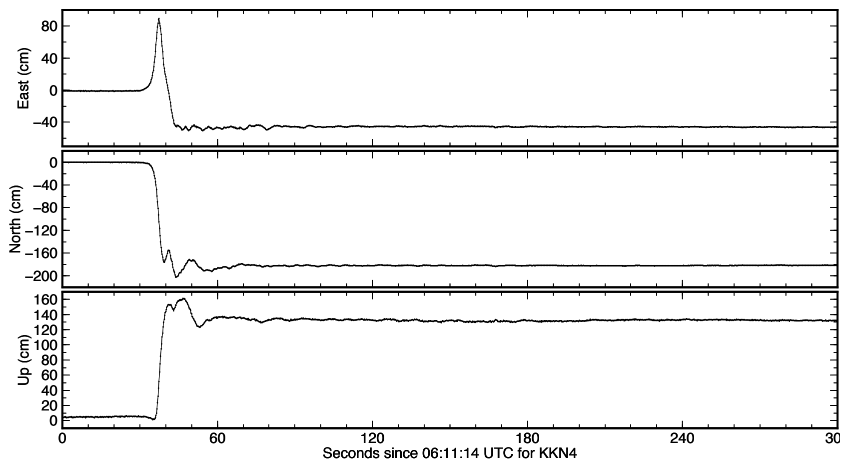


Accelerometric records (PGA<20%g)

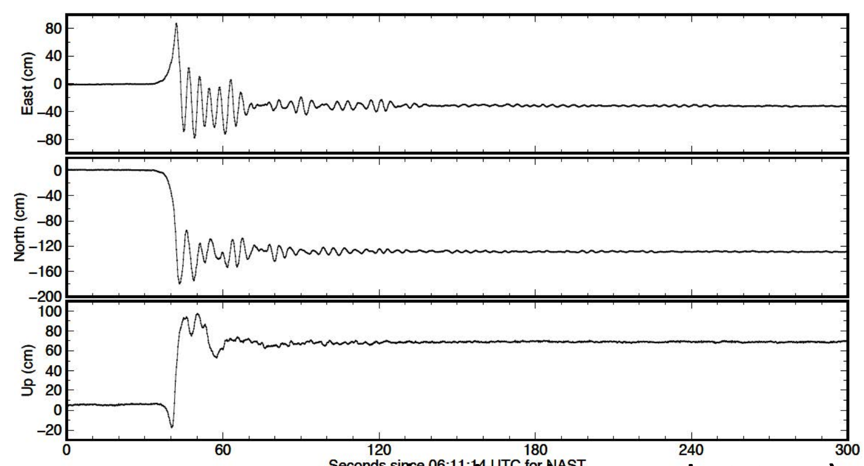
CHLM



KKN4

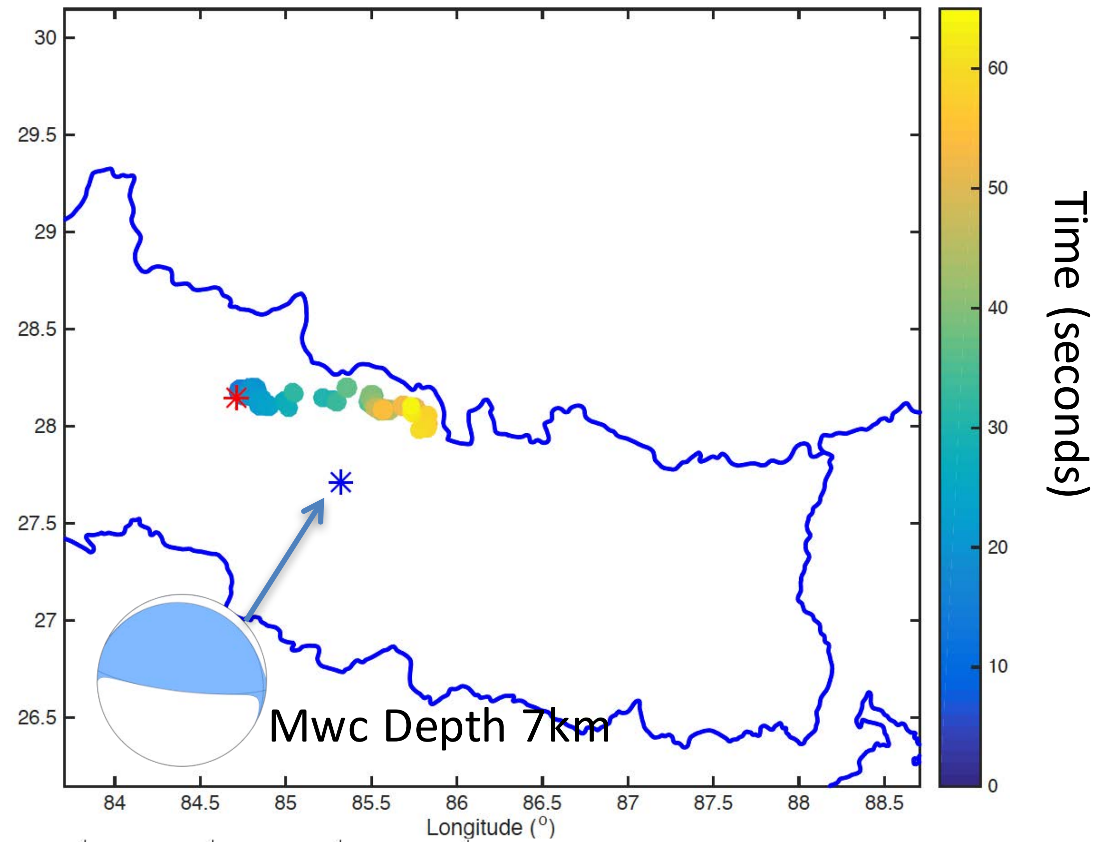


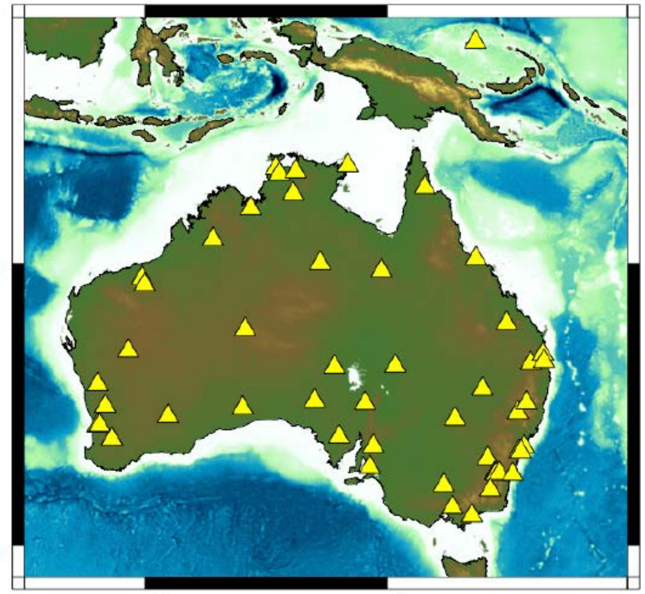
NAST

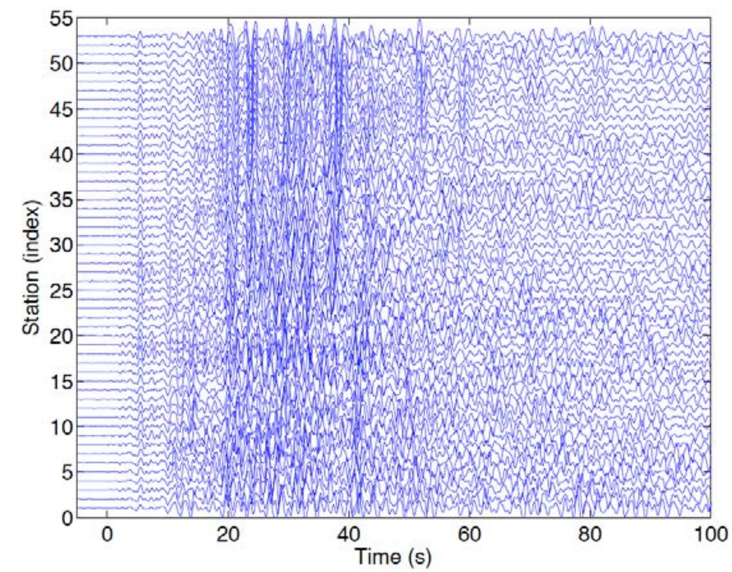


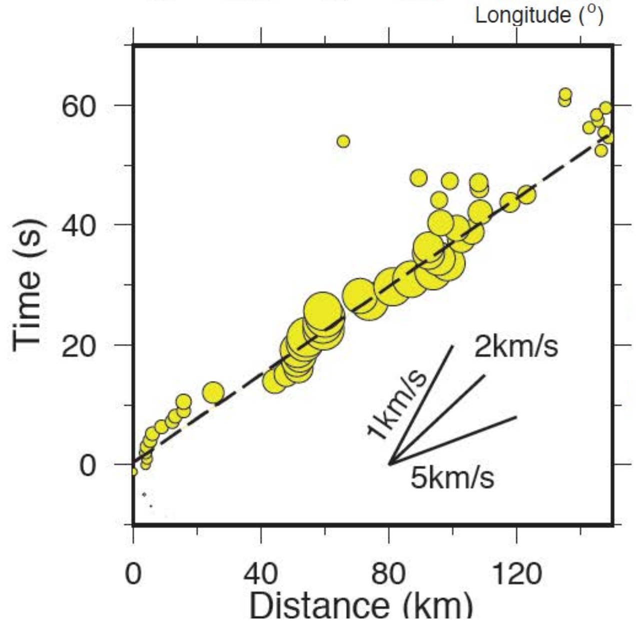
High rate GPS records

(Galetzka et al, 2015)









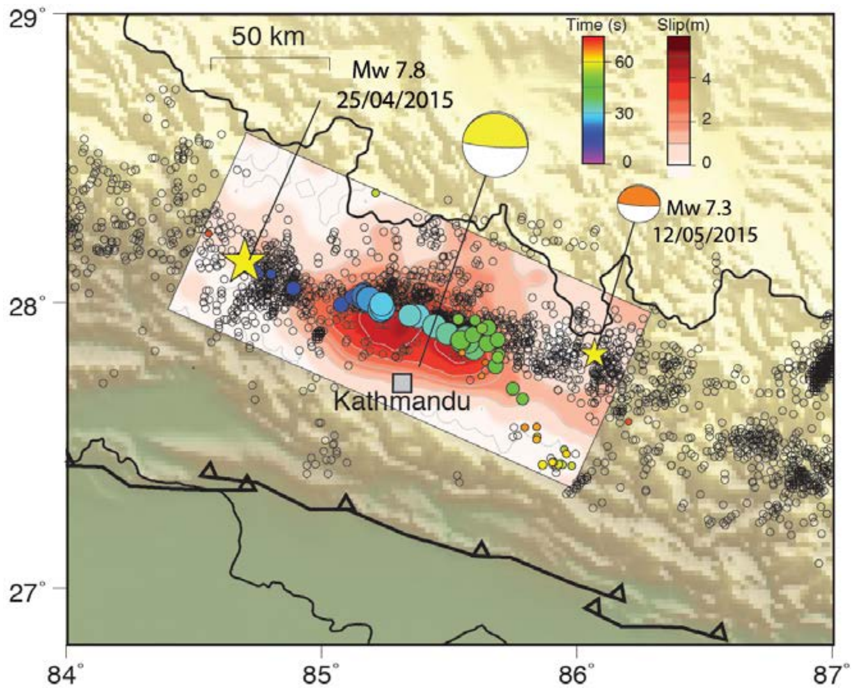
2.72+/-0.13km/s

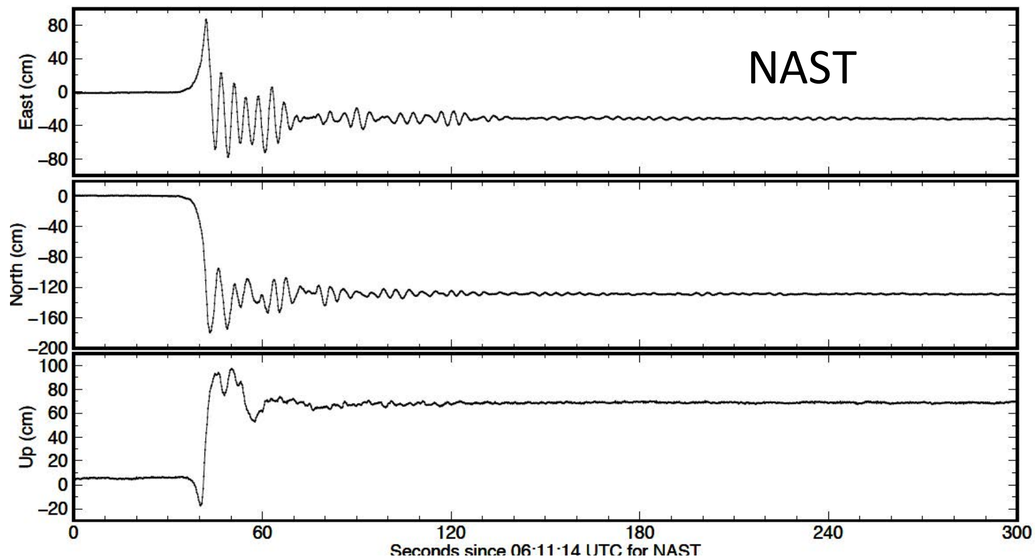
Bandpass filtered 0.5-2Hz

Back projection of ~1Hz teleseismic waves (Lingsen Meng&Pablo Ampuero)

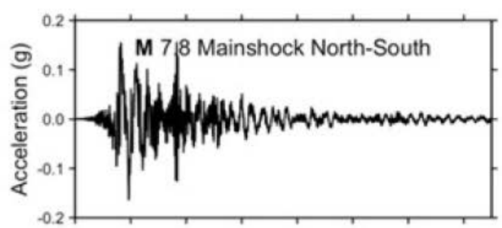
(Avouac et al., 2015)

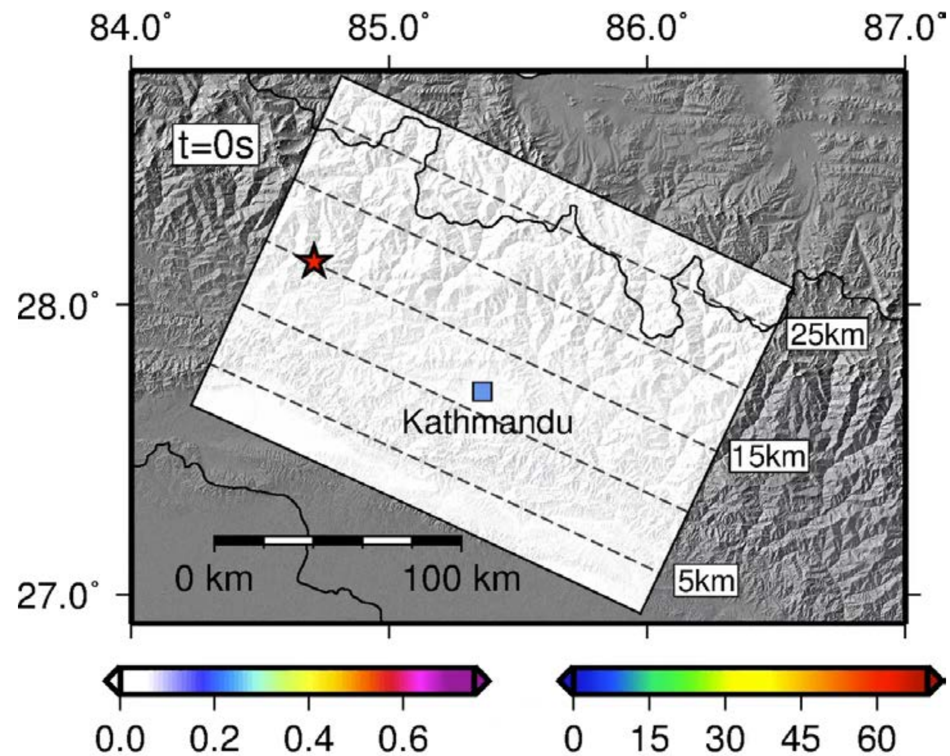
Model of the Mw7.8 Gorkha earthquake





Acc. rec/.
KATNP



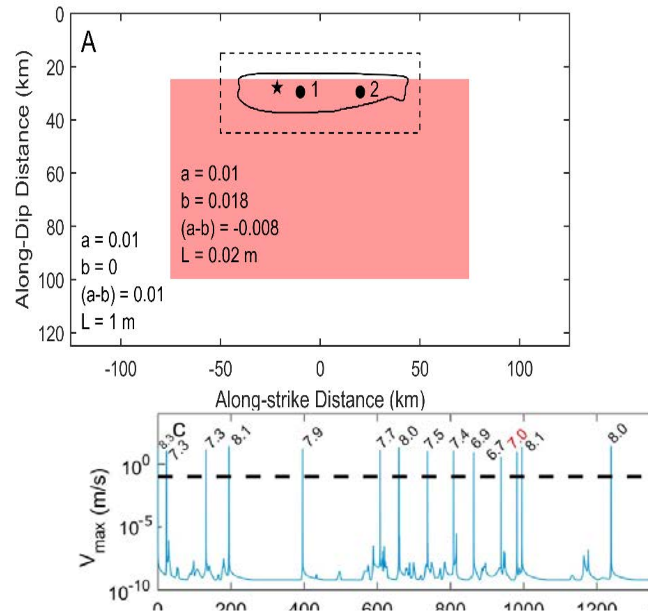


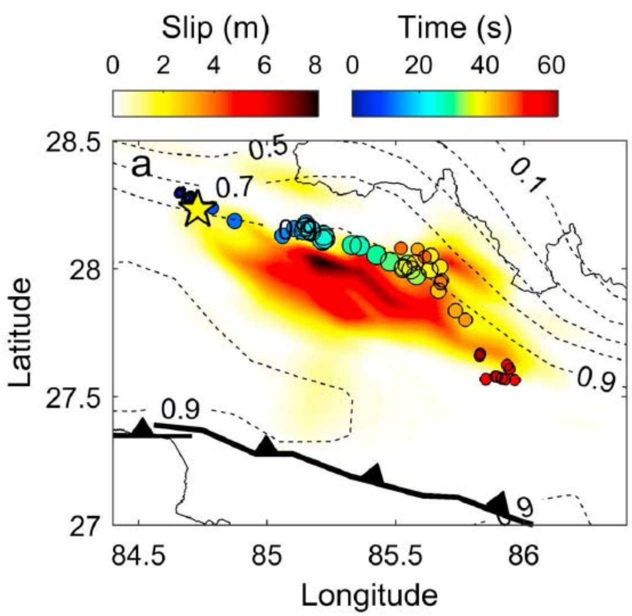
Near-field records show a smooth rupture beneath Kathmandu which generated only modest ground acceleration <20%g).

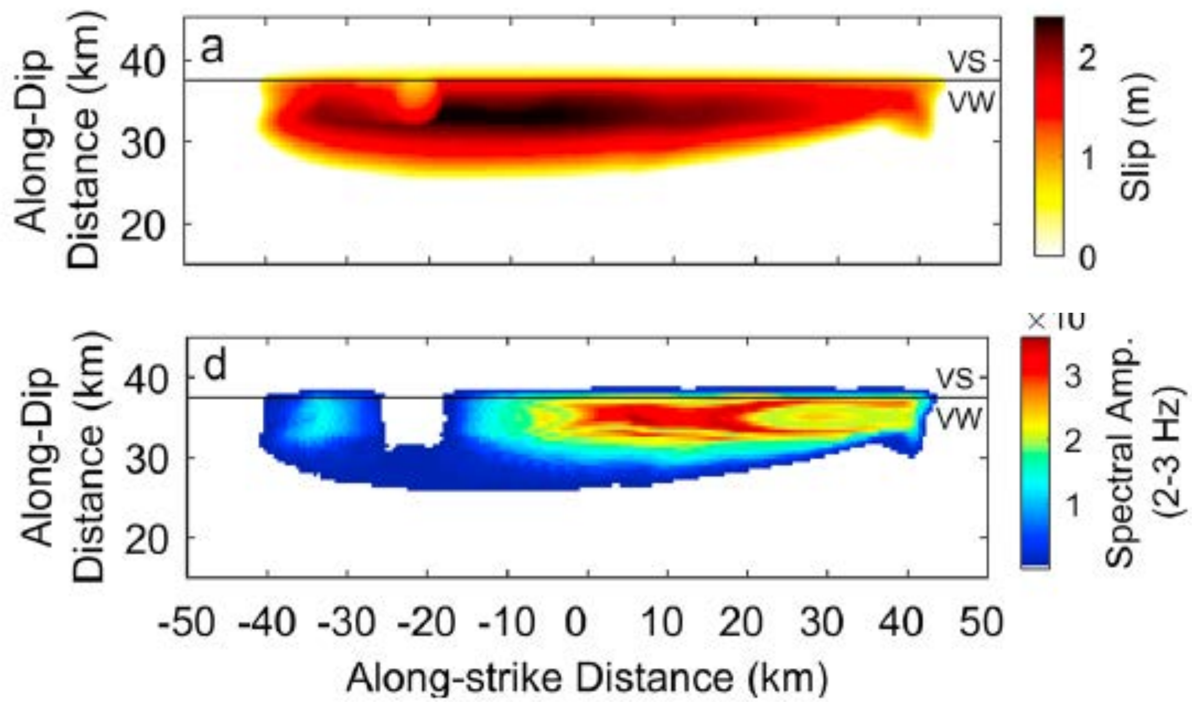
(Avouac et al., 2015; Galetzka et al., 2015)

Dynamic Modeling: a Gorkha-like rupture

Event 12







(Michel et al., GRL, 2017)

Conclusions

- Interseismic coupling is highly heterogeneous and relatively stationnary.
- Seismic ruptures tend to be confined within locked fault patches.
- Seismic gaps cab be eitherzones of aseismic creep or of high slip deficit
- The seismic potential of subduction zone can be assessed based on interseismic geodetic strain and seismicity.
- 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 predict the full range of possible EQs scenario and their probability of occurrence.


Thank You