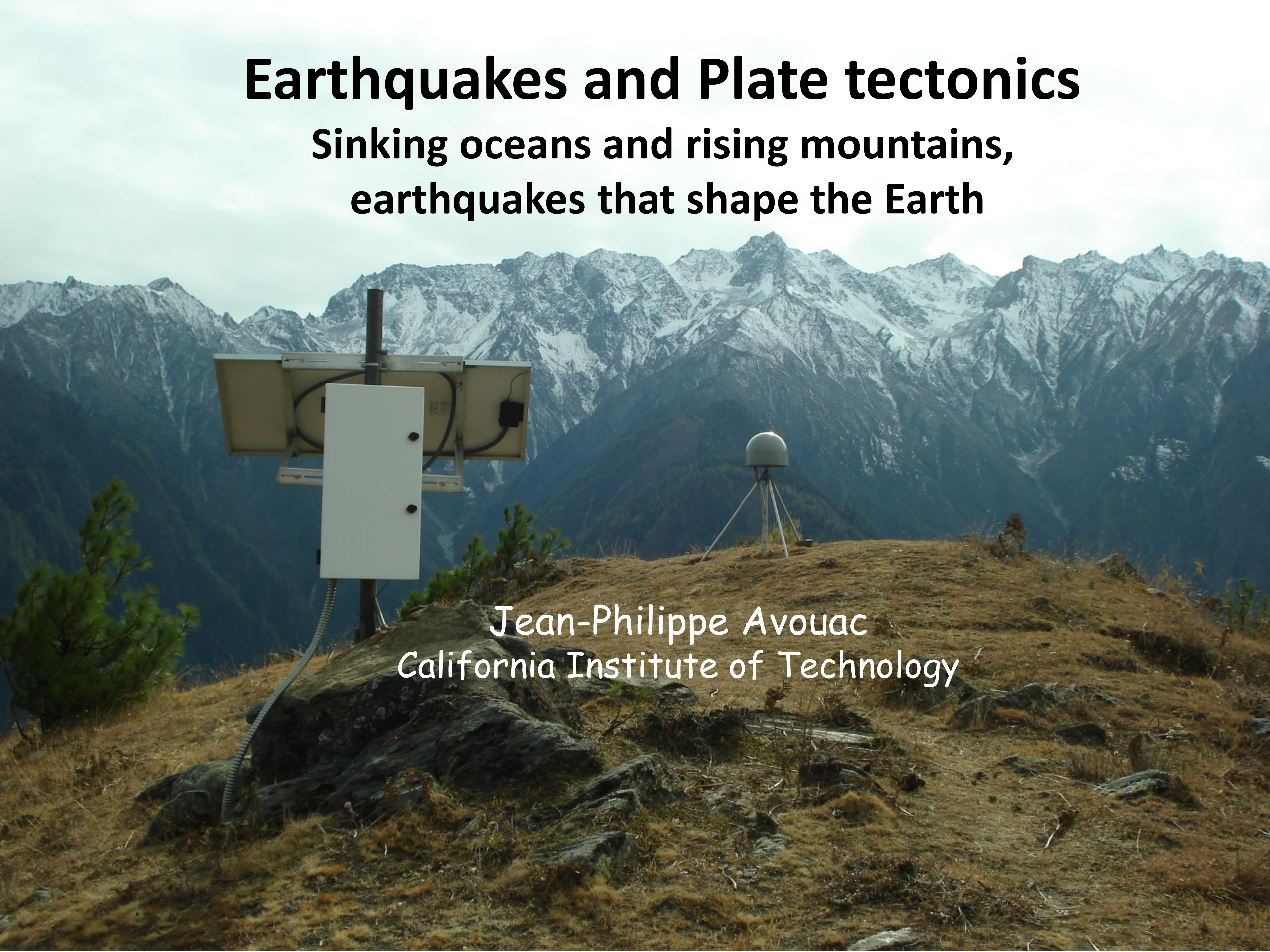
Earthquakes and Plate tectonics

Sinking oceans and rising mountains, earthquakes that shape the Earth

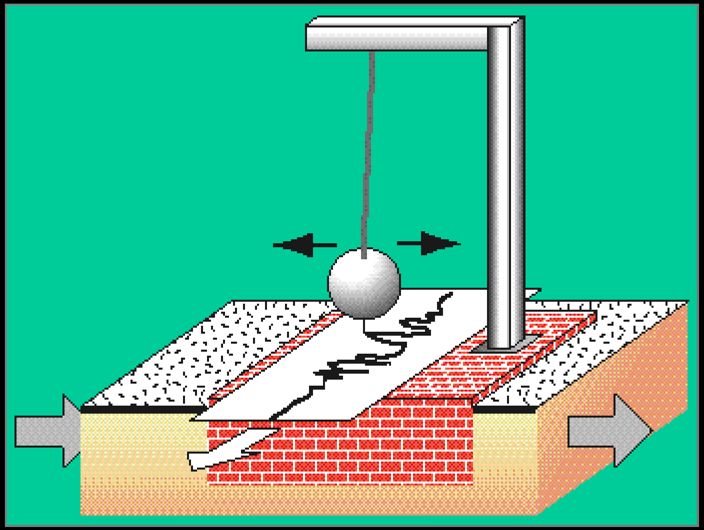


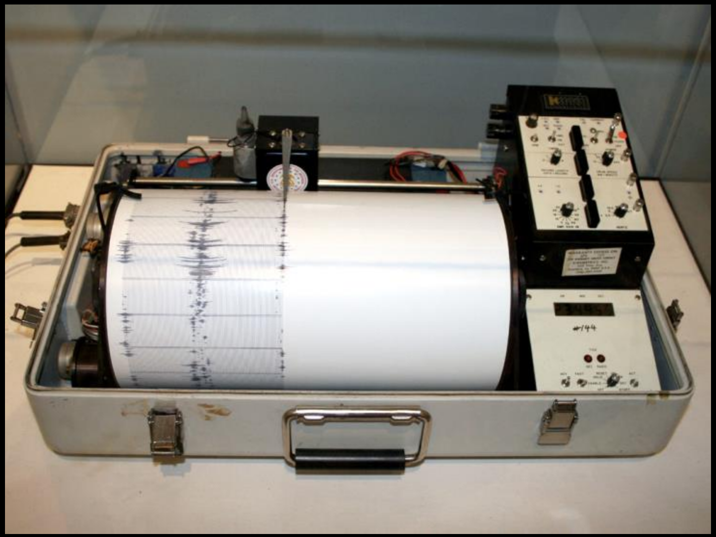
Jean-Philippe Avouac
California Institute of Technology

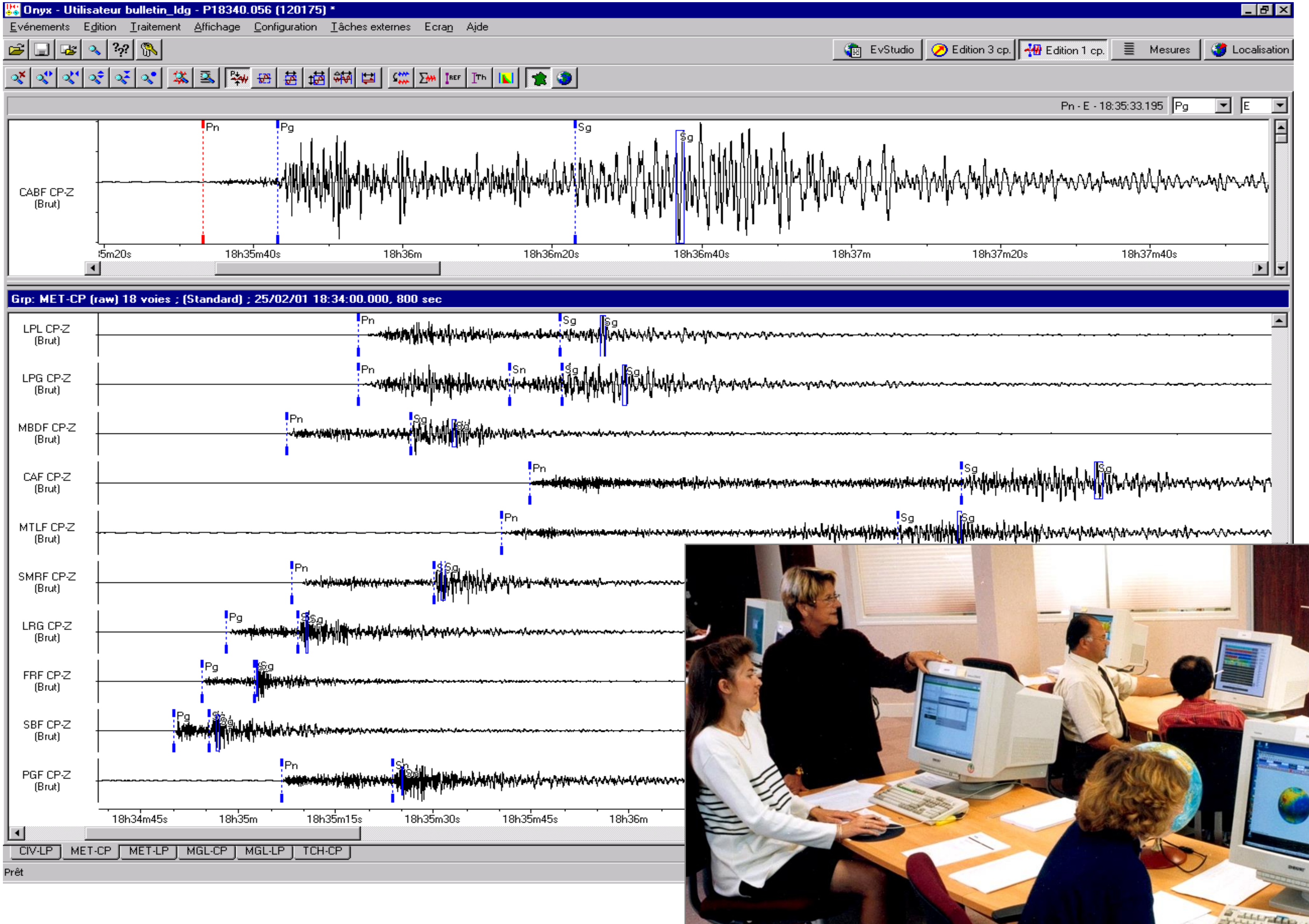
Talk outline

- 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



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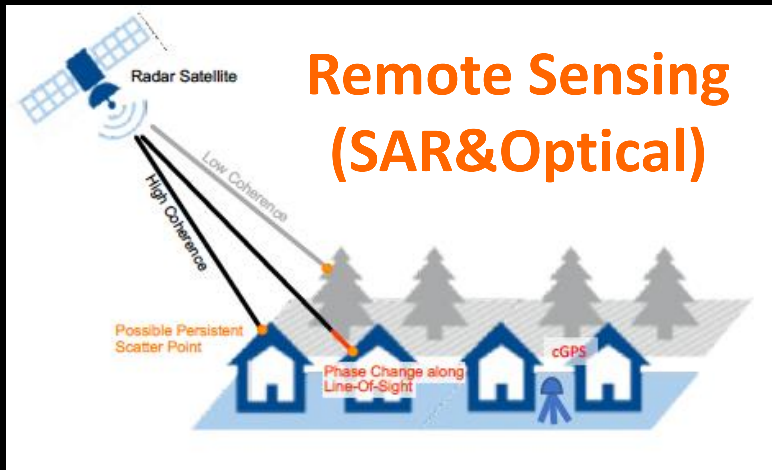
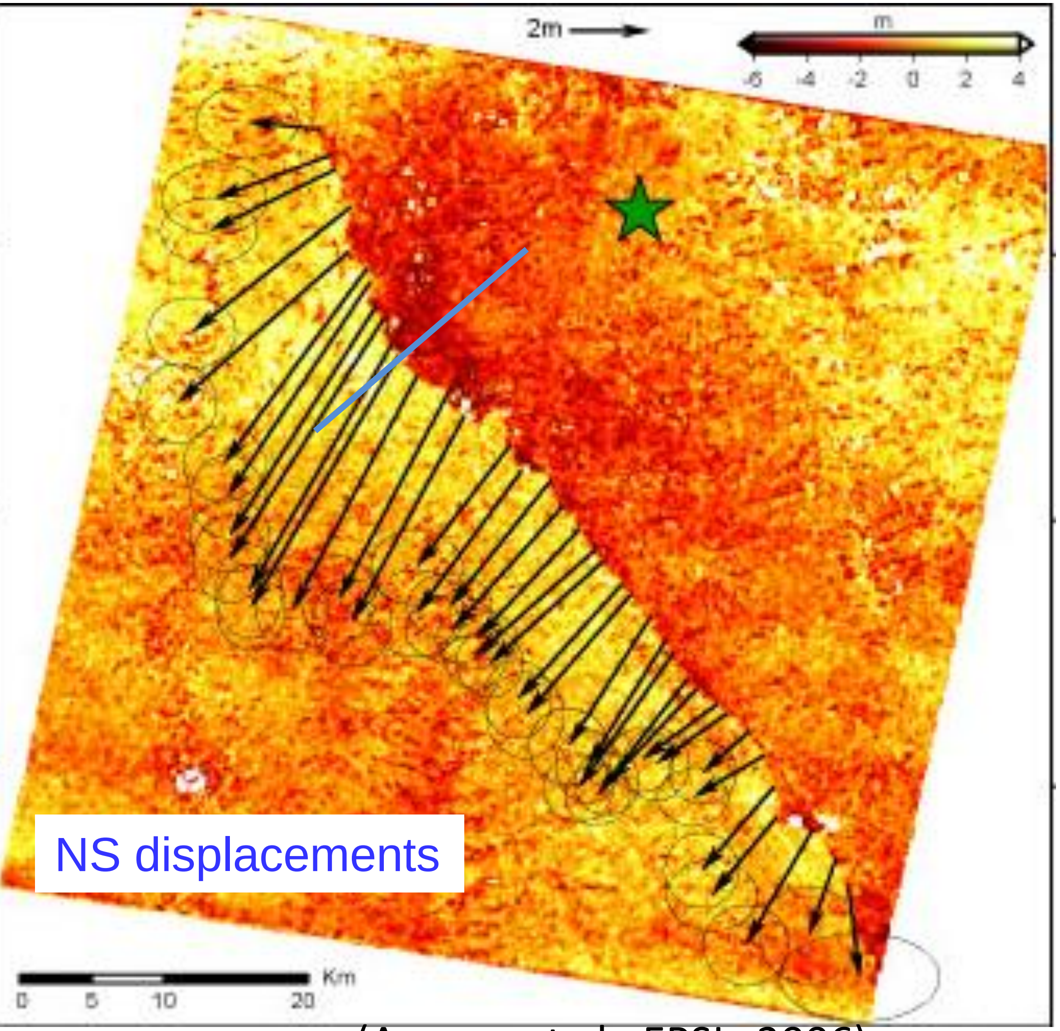


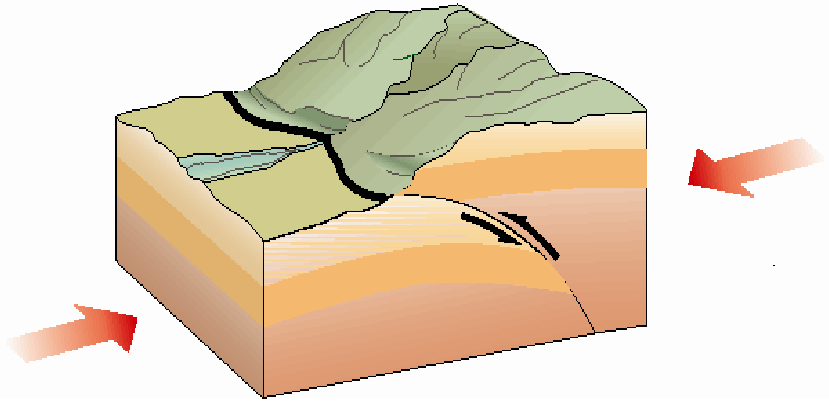
Techniques used

EX: The Mw 2005, 7.6, Kashmir Earthquake

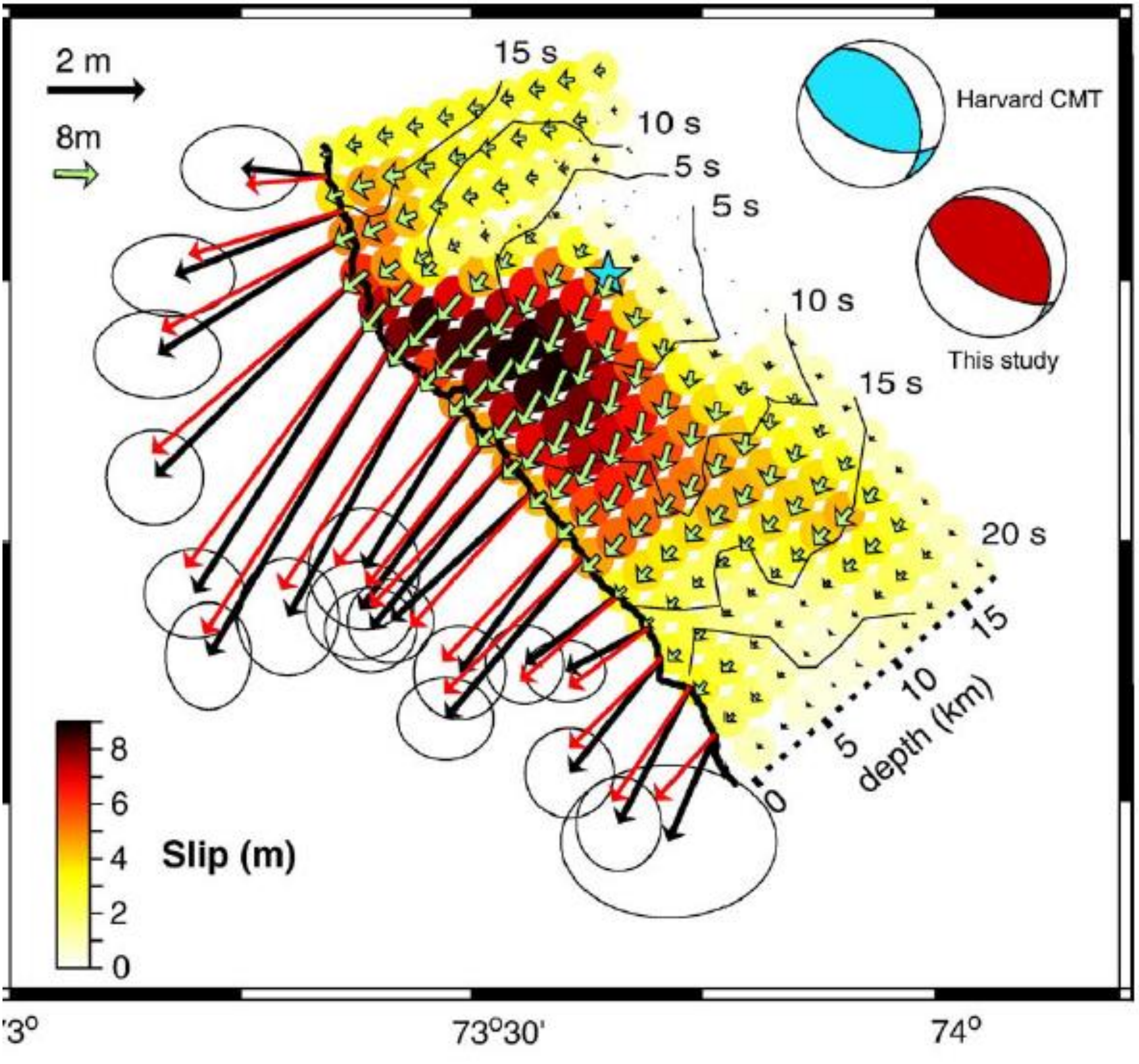
Surface rupture measured from cross-correlation of ASTER satellite images



(Avouac et al., EPSL, 2006)

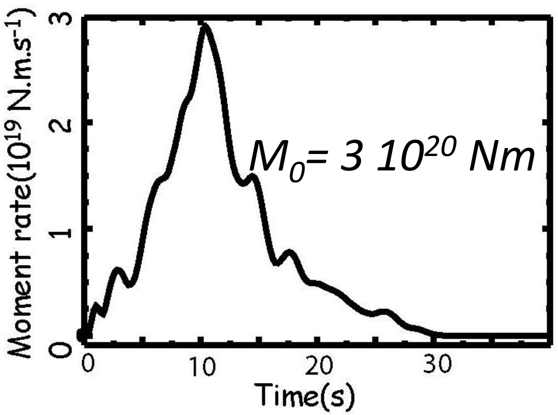


The Mw 2005, 7.6, Kashmir Earthquake

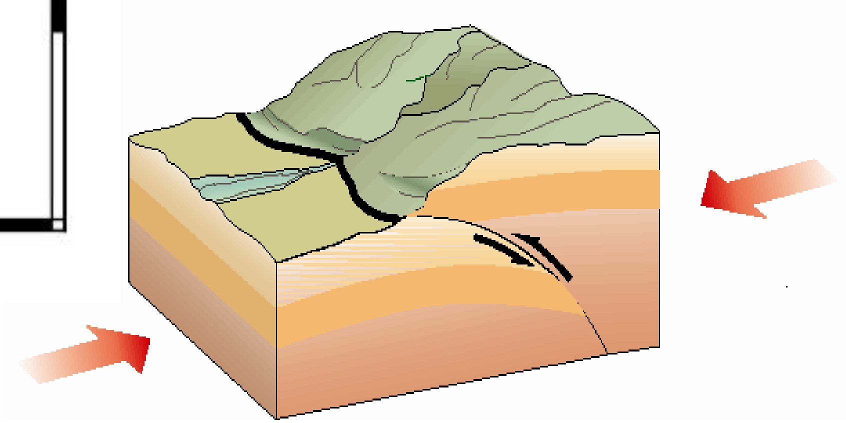


(Avouac et al., EPSL, 2006)

Slip distribution and isochrons of rupture propagatation

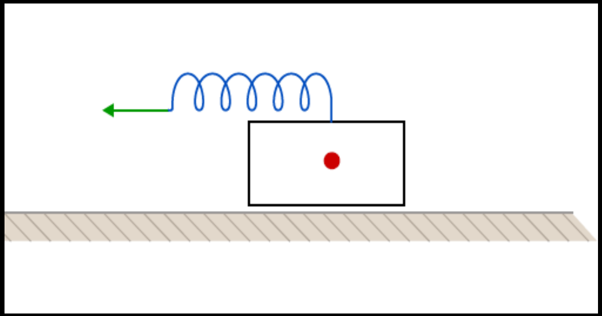


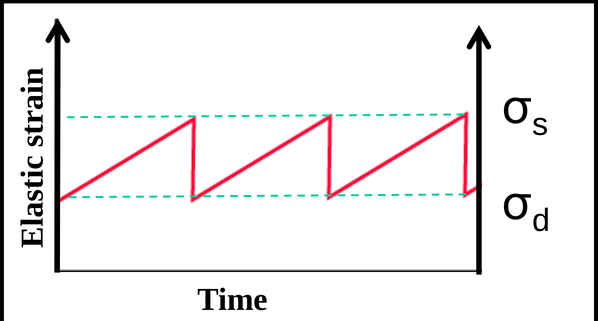
Source time function

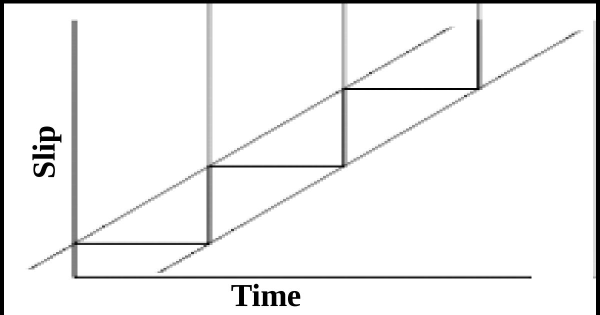


The Earthquake Machine

Spring and Slider Model







Moment & Magnitude

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

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

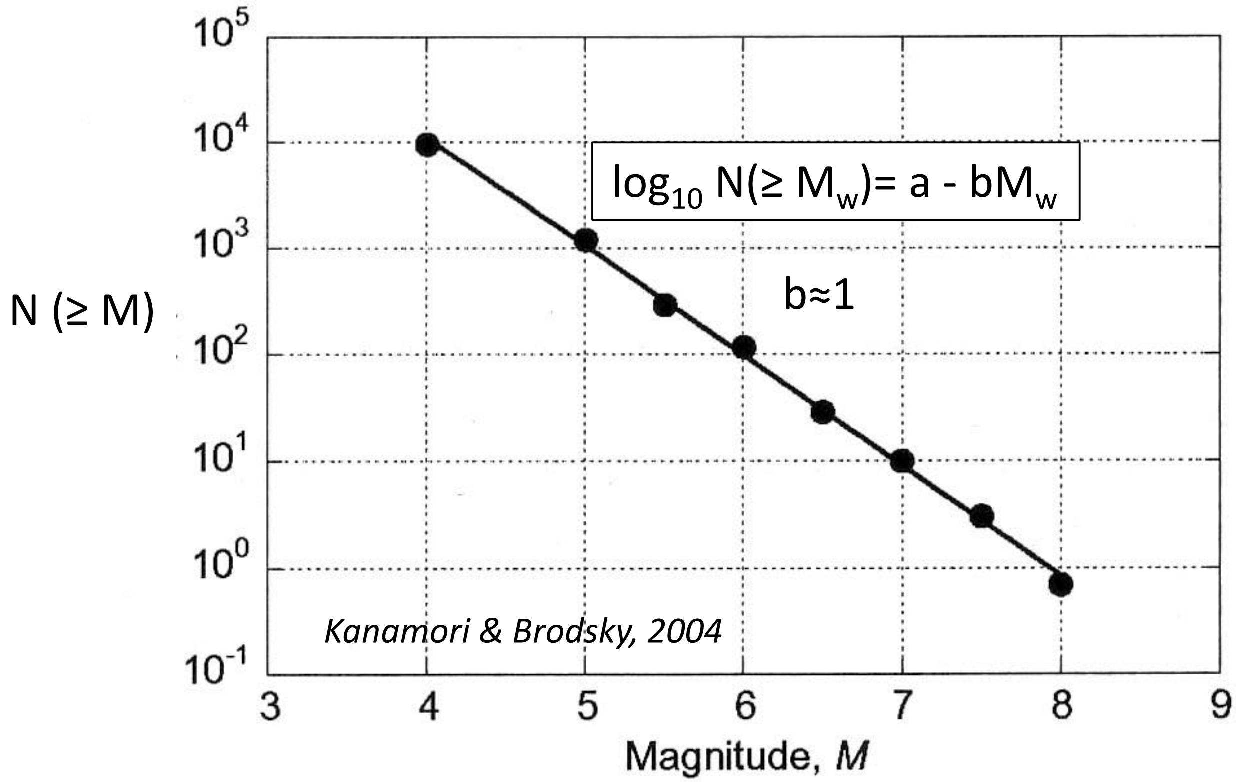
where <*S*> is average slip,
A is fault area and
μ is elastic shear modulus (30 to 50 GPa)

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

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

The Gutenberg-Richter law

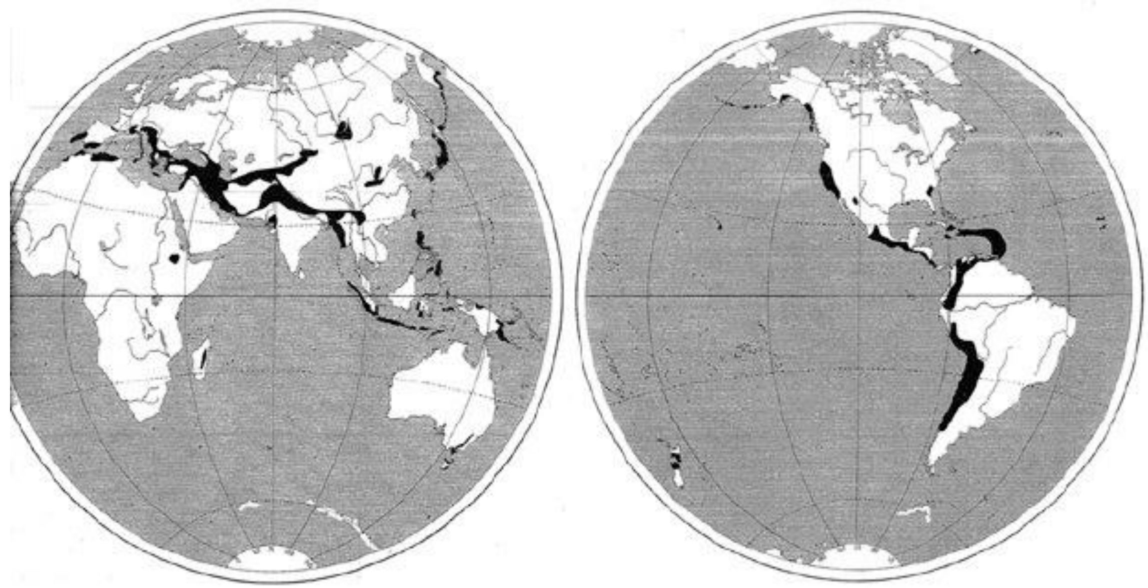
Let N (≥ M) be number of EQs per year with magnitude ≥ M



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

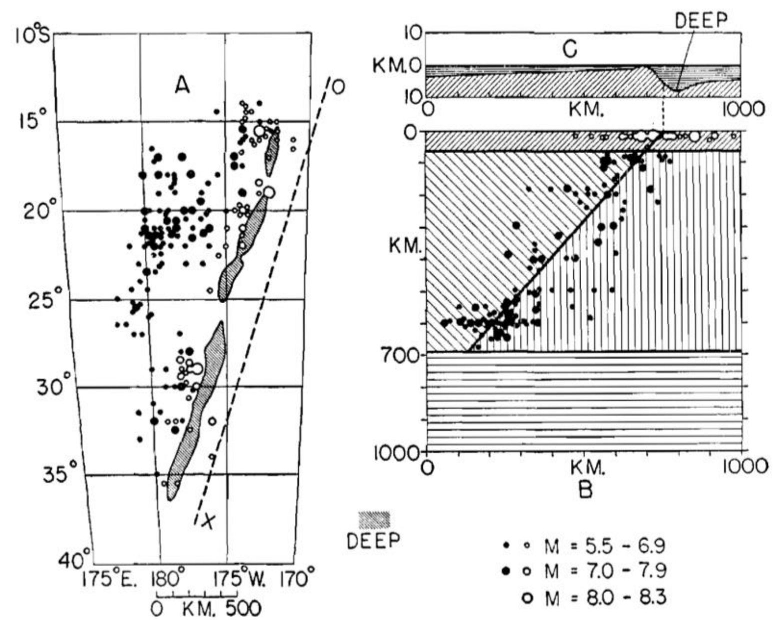
This empirical law holds at any scale.

- Montessus de Ballore, 1906 (see Cisternas, EPSL,2009)
  - Seismic waves are generated by slip on faults (BSSA, 1912)
  - World distribution of seismicity (1906, 1911)



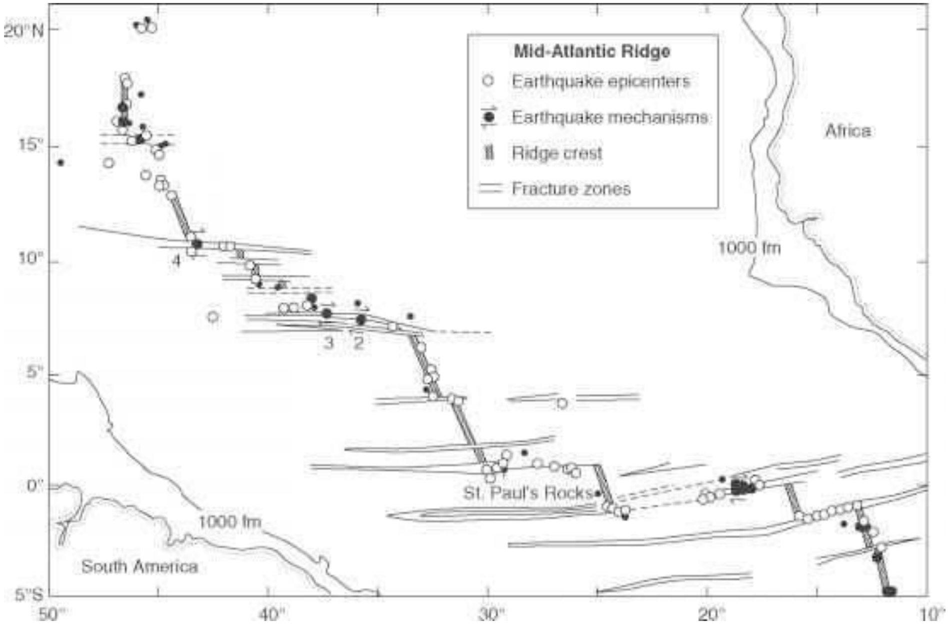
(World distribution of seismicity :‘La sismologie moderne’, Montessus de Ballore, 1911)

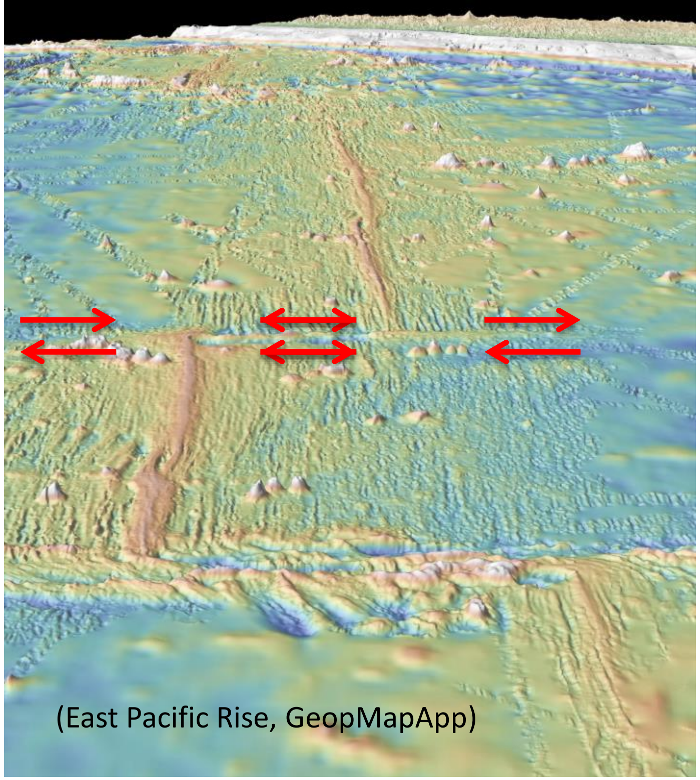
- Hugo Benioff and Kiyoo Wadati: the Wadati-Benioff zone

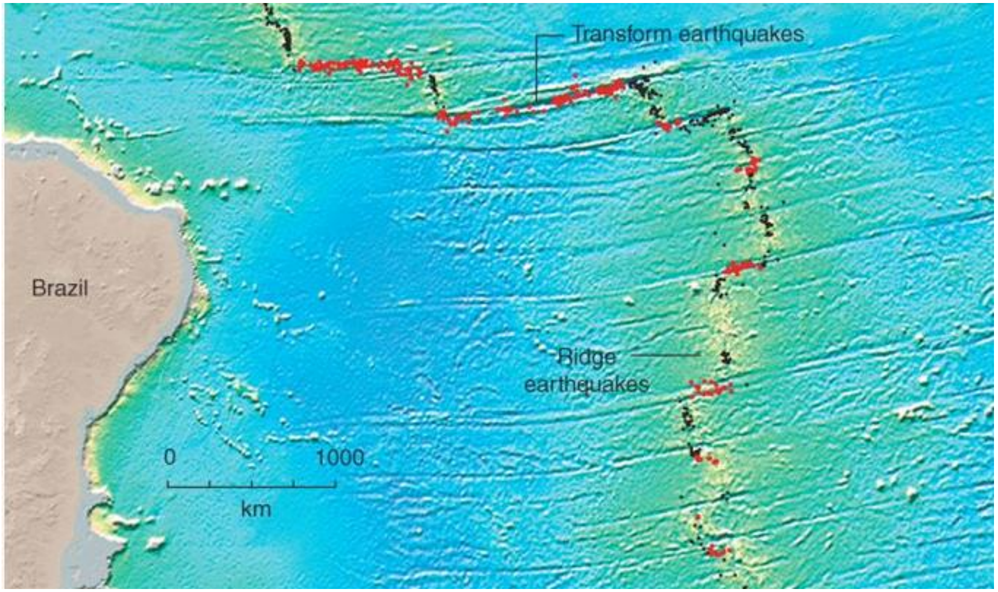


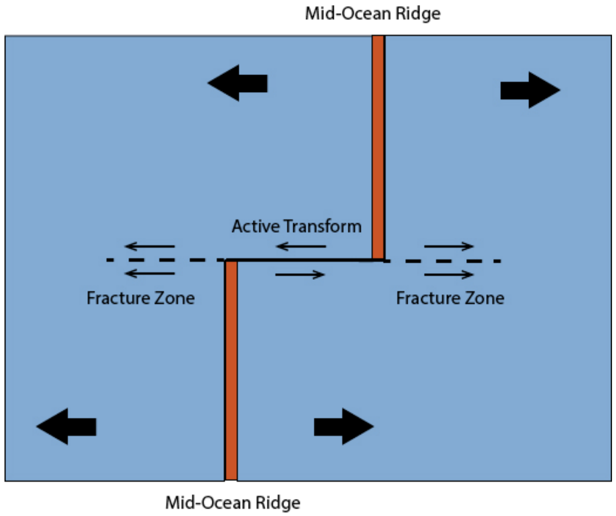
Tonga-Kermadec Seismicity
(‘Fault origin of oceanic deeps’, Benioff, 1949)

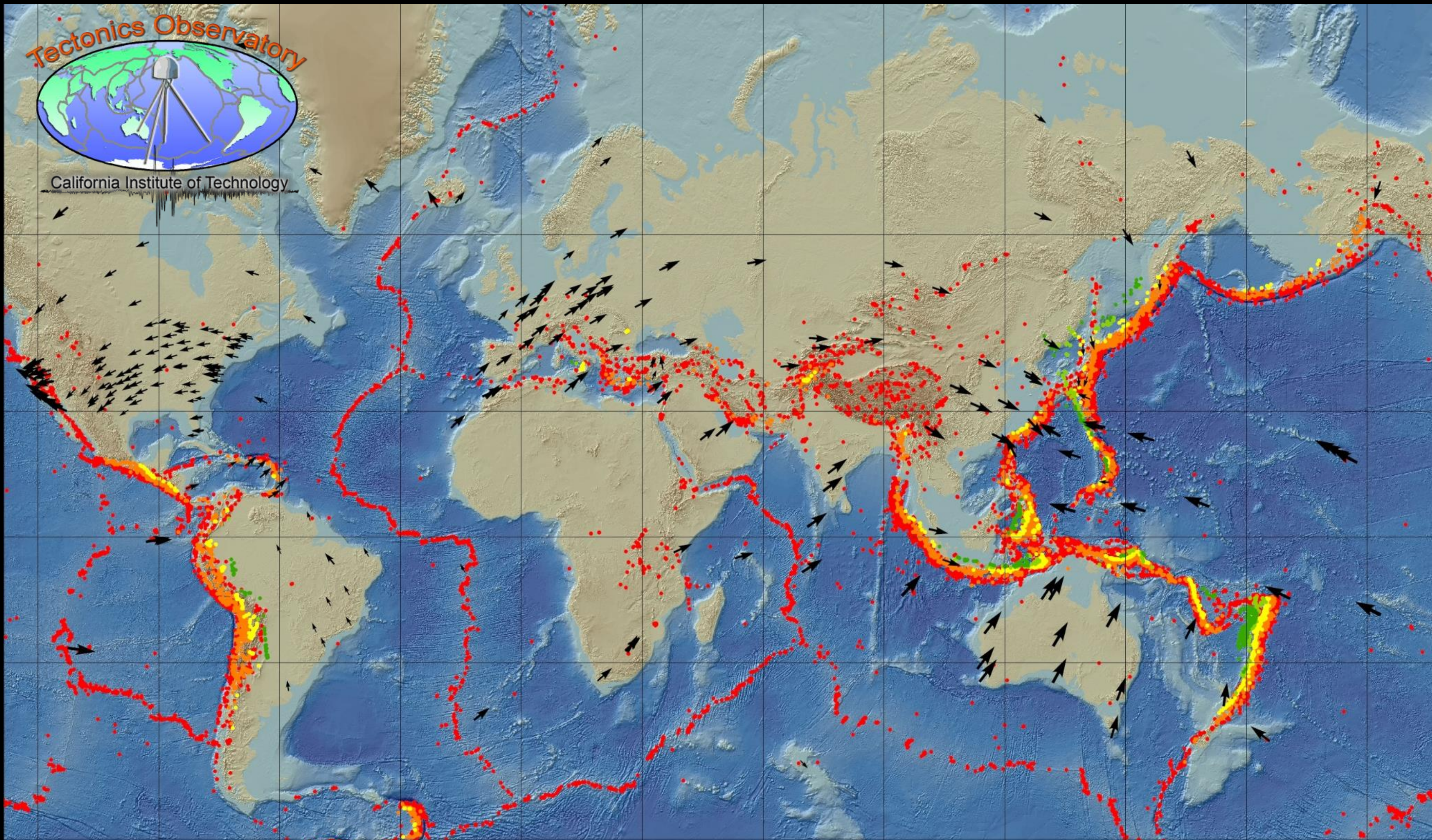
- Lynn Sykes (1967): Strike-slip earthquakes along oceanic transform faults prove sea-floor spreading



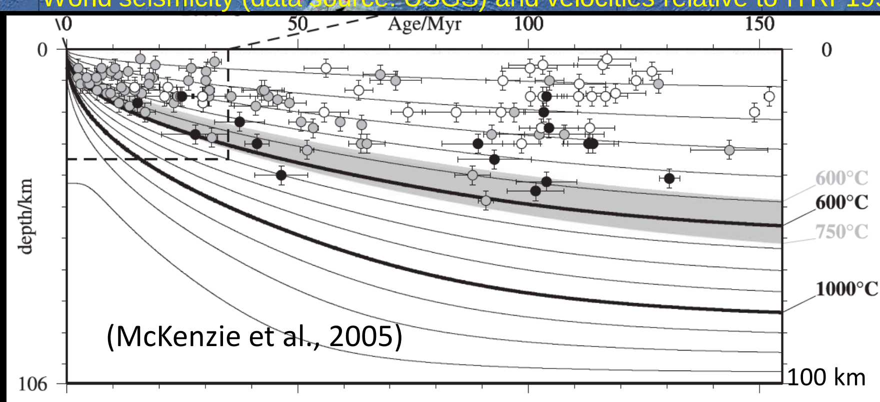




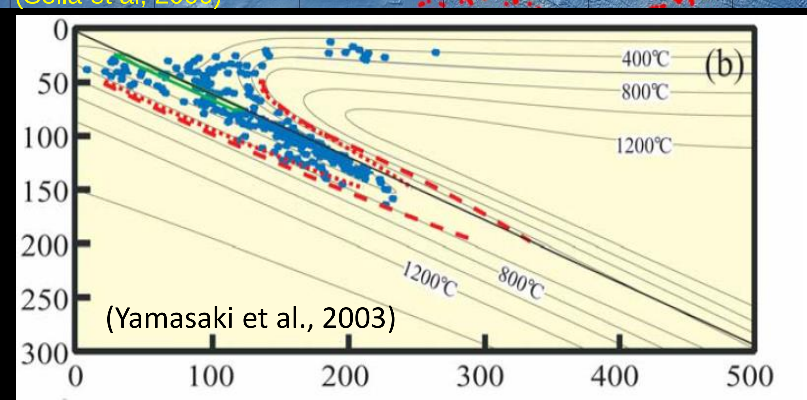




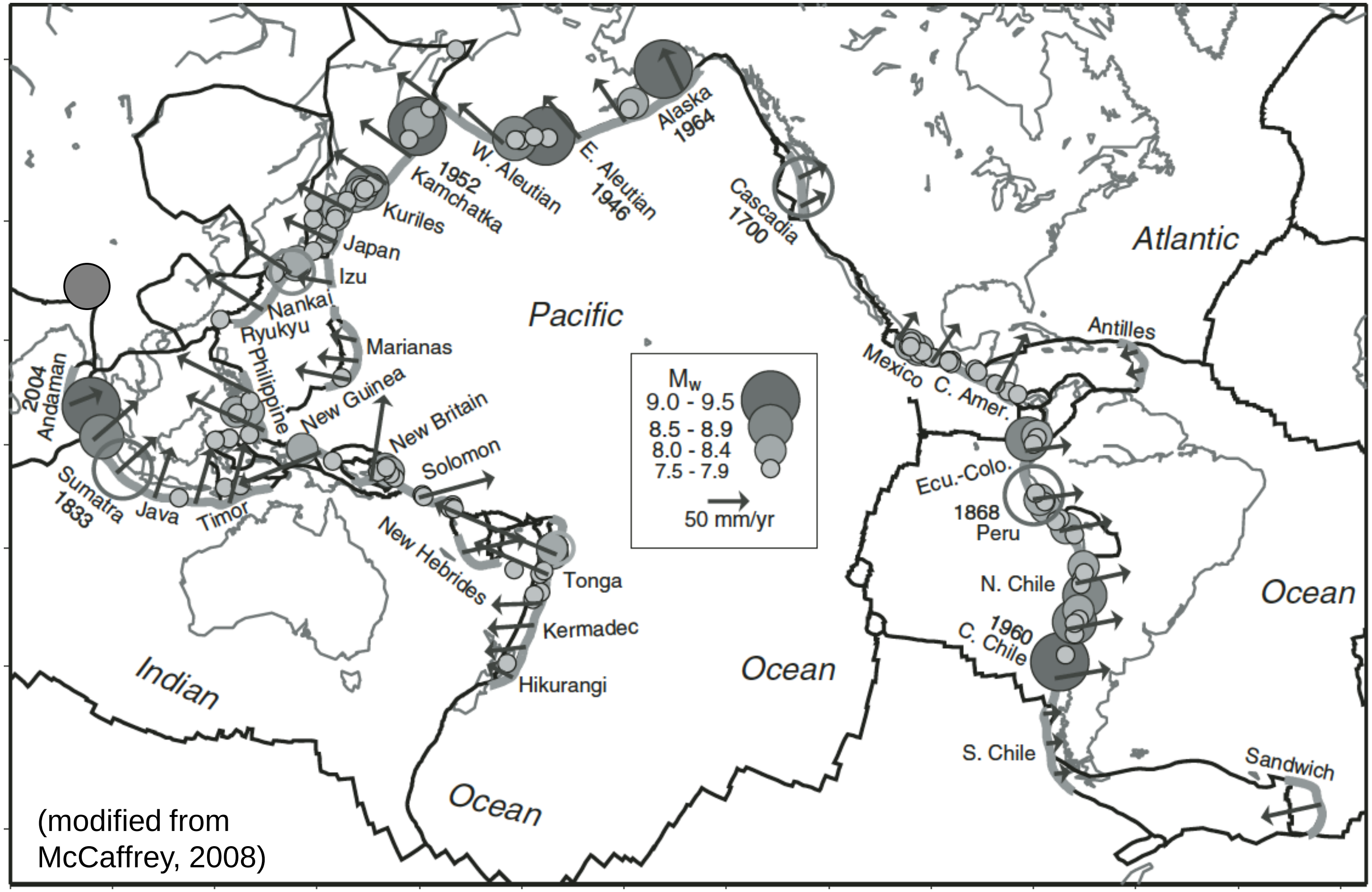
World seismicity (data source: USGS) and velocities relative to ITRF1997 (Sella et al, 2000)



(McKenzie et al., 2005)

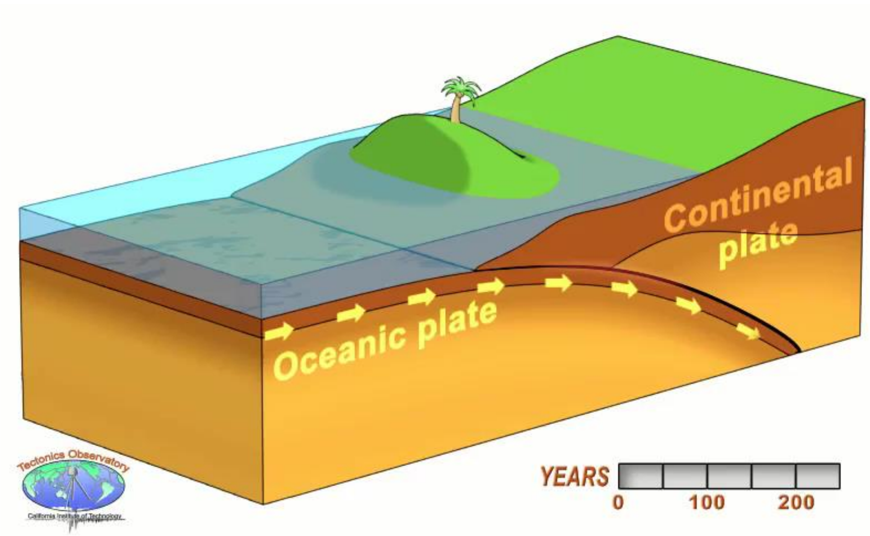


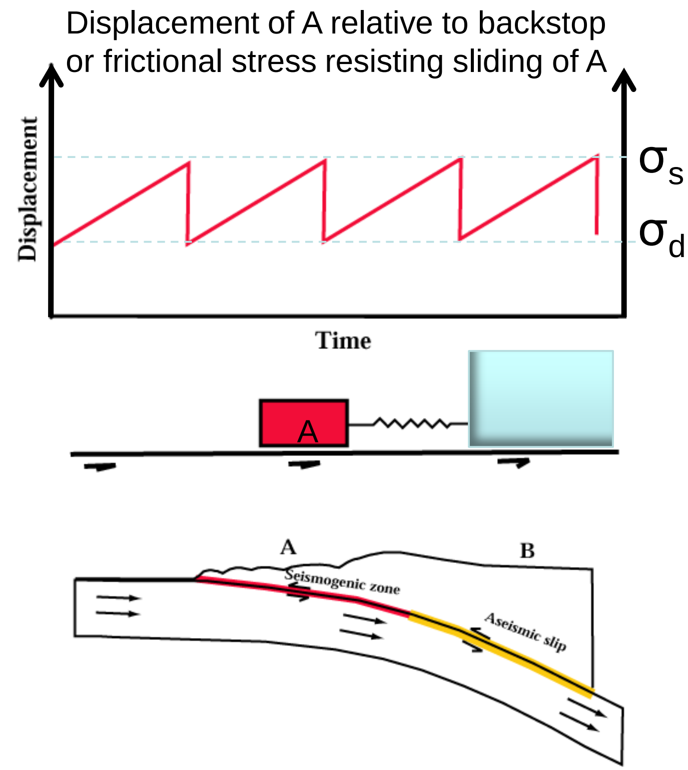
(Yamasaki et al., 2003)



- 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.

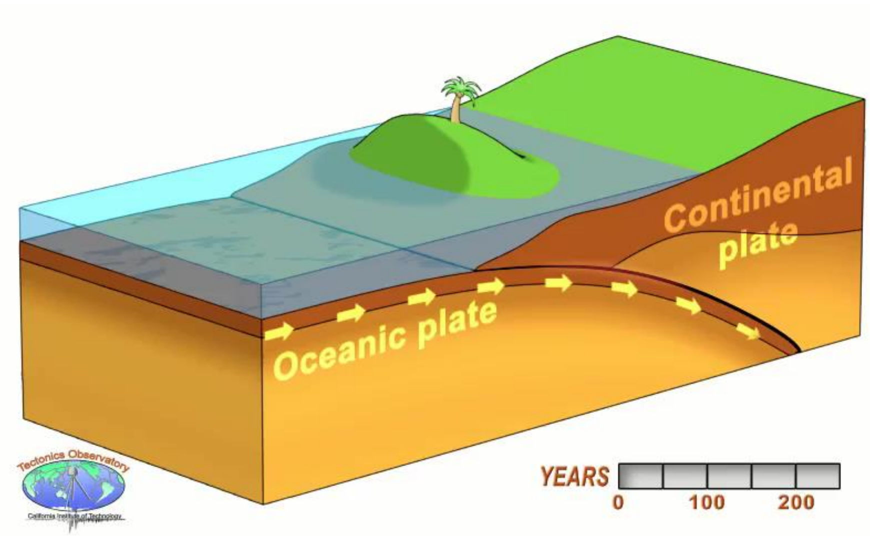
The ‘Seismic Cycle’ at a Megathrust

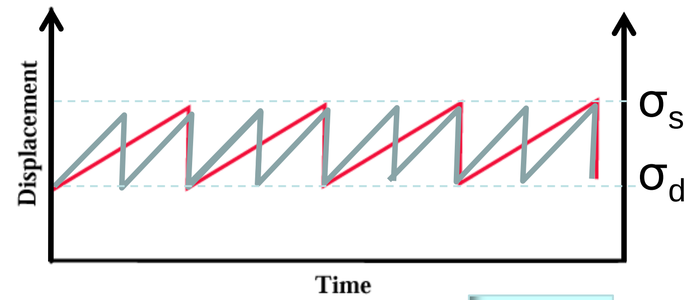


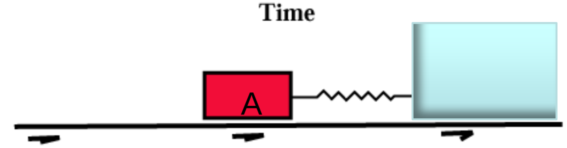


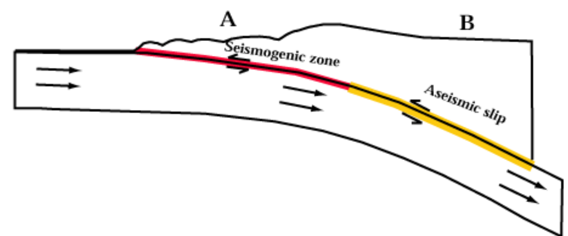
PS: The notion refers to how earthquakes initiate, grow and arrest (in reality all EQs are different, because of the different environments in which they are born (the stress distribution in particular).

Implications of Plate Tectonics for EQ forecasting

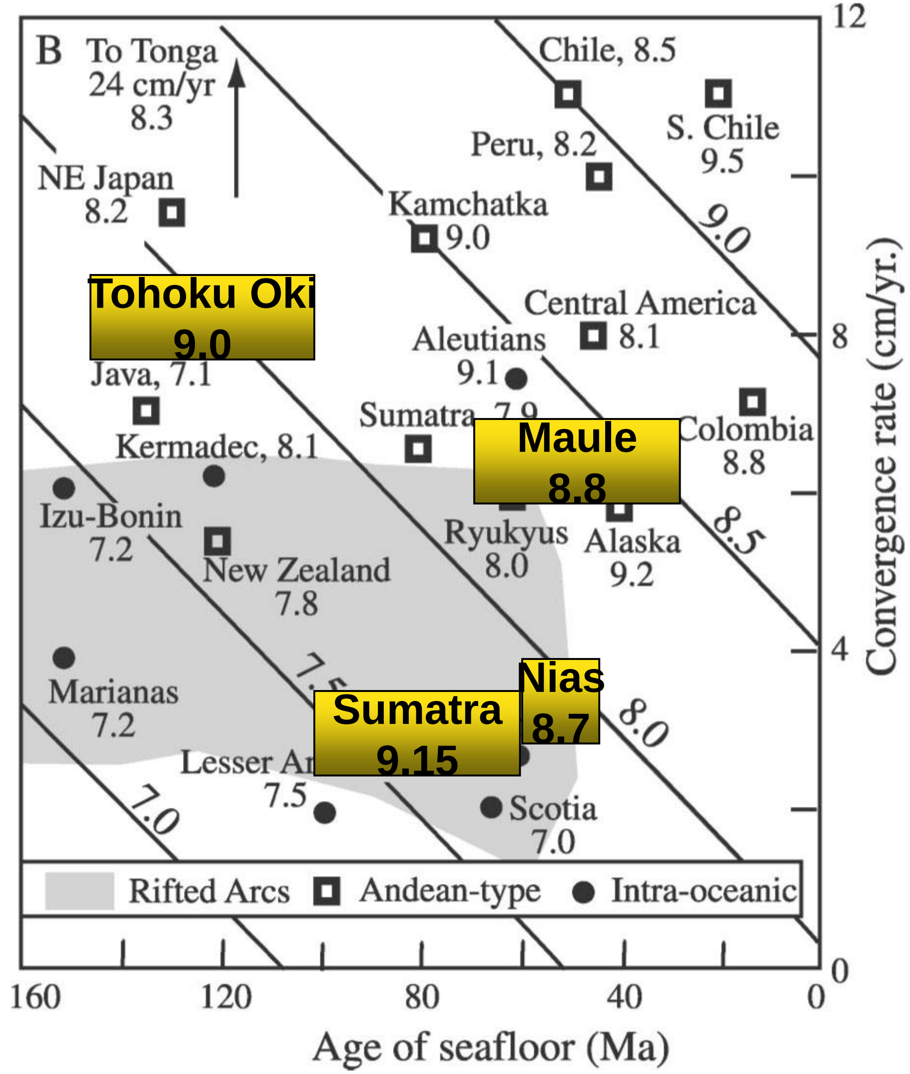






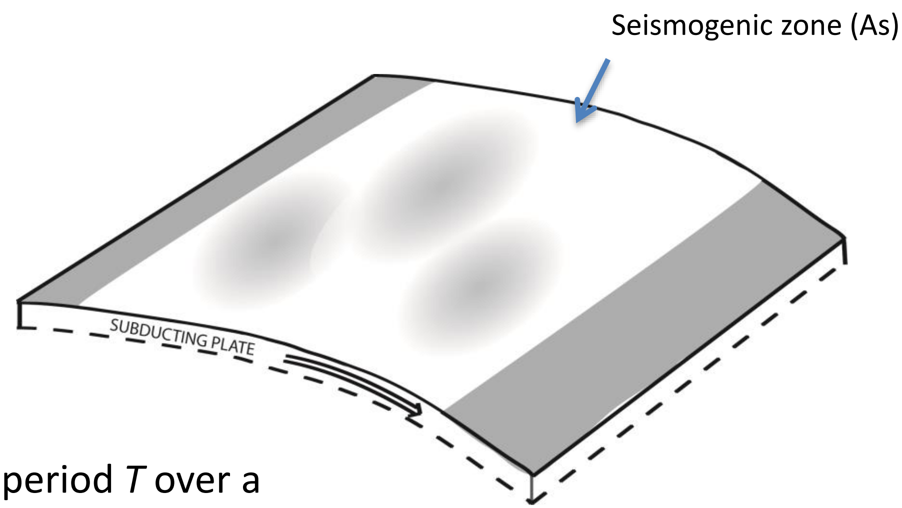


- **H1:** ‘Seismic Gap’ hypothesis (e.g., Fedotov, 1965; Sykes, 1971; Kelleher et al, 1973; Nishenko&Sykes, 1993)
- **H2:** The earthquake rate is proportional to fault slip rate (e.g., Brune, 1968)
- **H3:** The maximum magnitude on a megathrust depends on the age of the subducting plate and on the 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

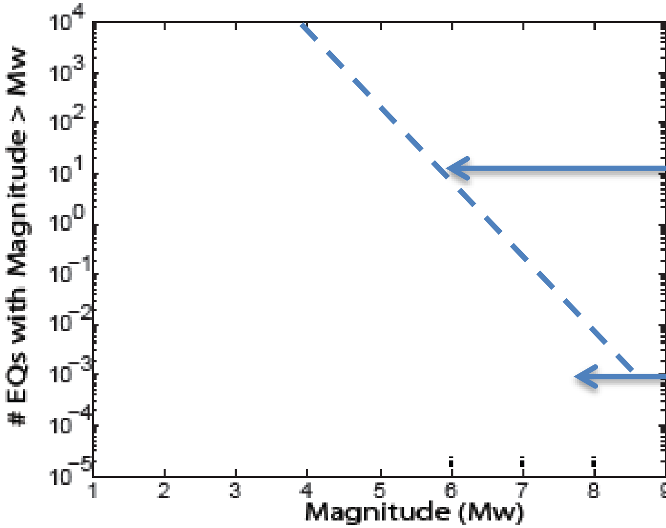
→ If all slip is seismic for ageologial slip rate, *V*, and fault area, *A,* the moment release rate is

$$\dot{M}_0 = \frac{\sum M_0}{T} = \mu V A_s$$

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

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

Relating seismicity rate and moment deficit rate based on the moment conservation principle



Frequency of largest EQ in the GR distribution

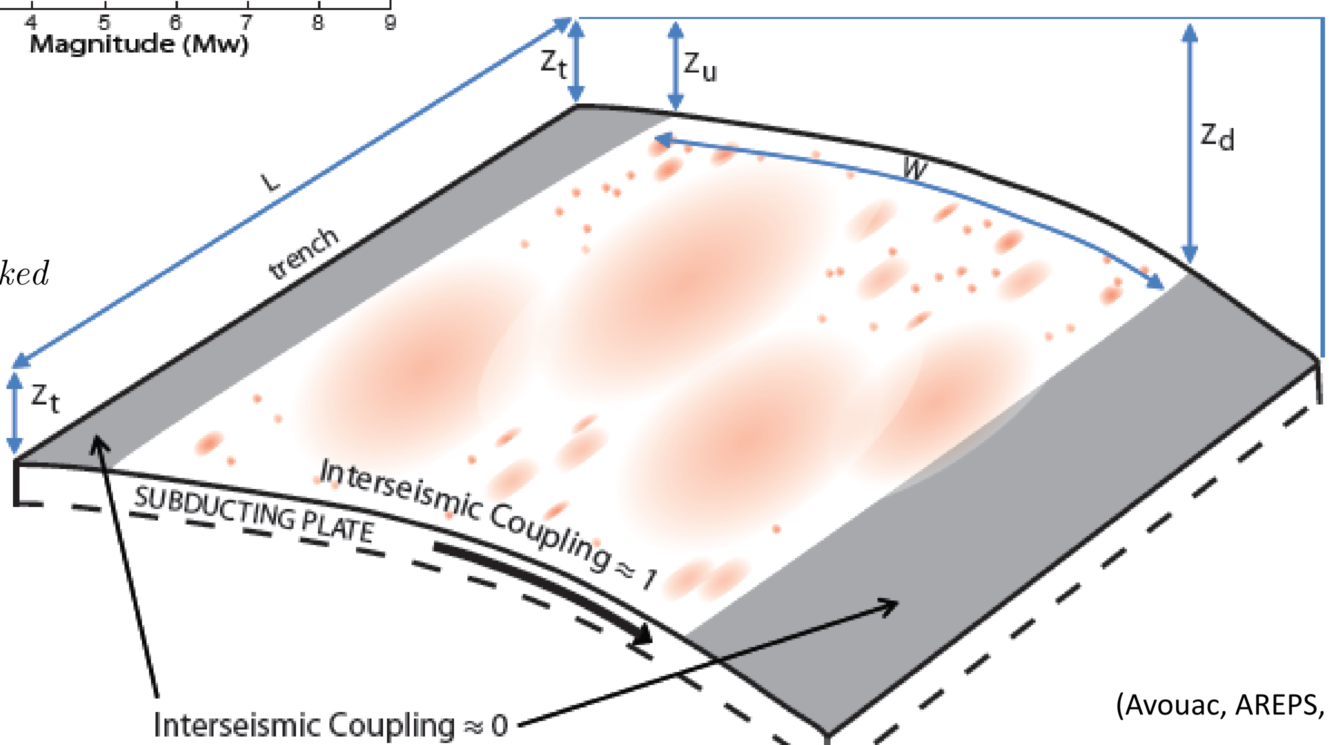
$$\frac{1}{T(M_0)} = \frac{\dot{M}_0}{M_0}$$

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

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

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

$$\dot{M}_0 = \mu V A_{locked}$$



(Avouac, AREPS, 2015)

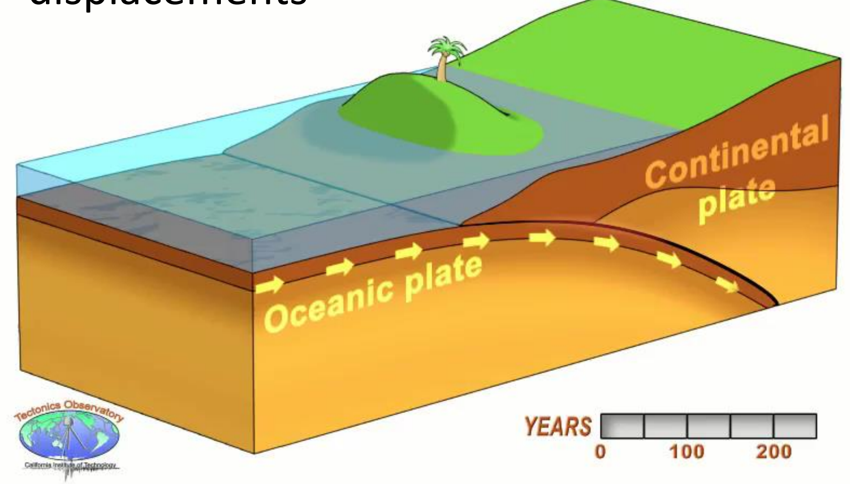
Interseismic coupling

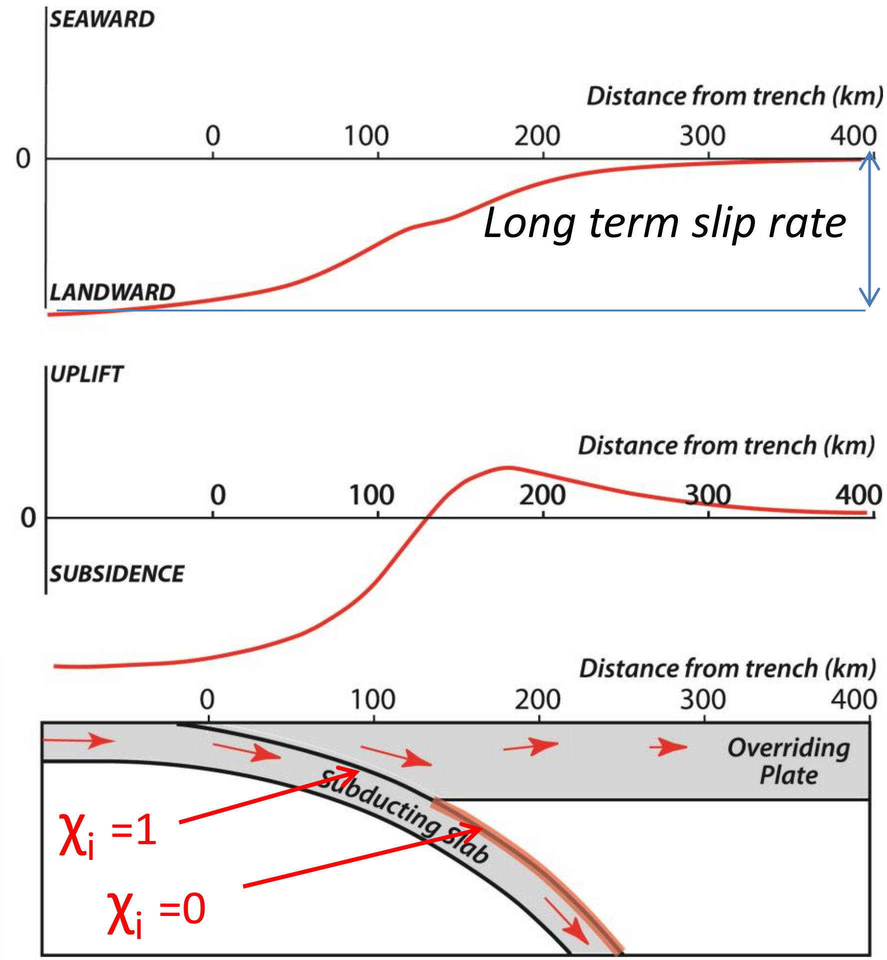
Definition:

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

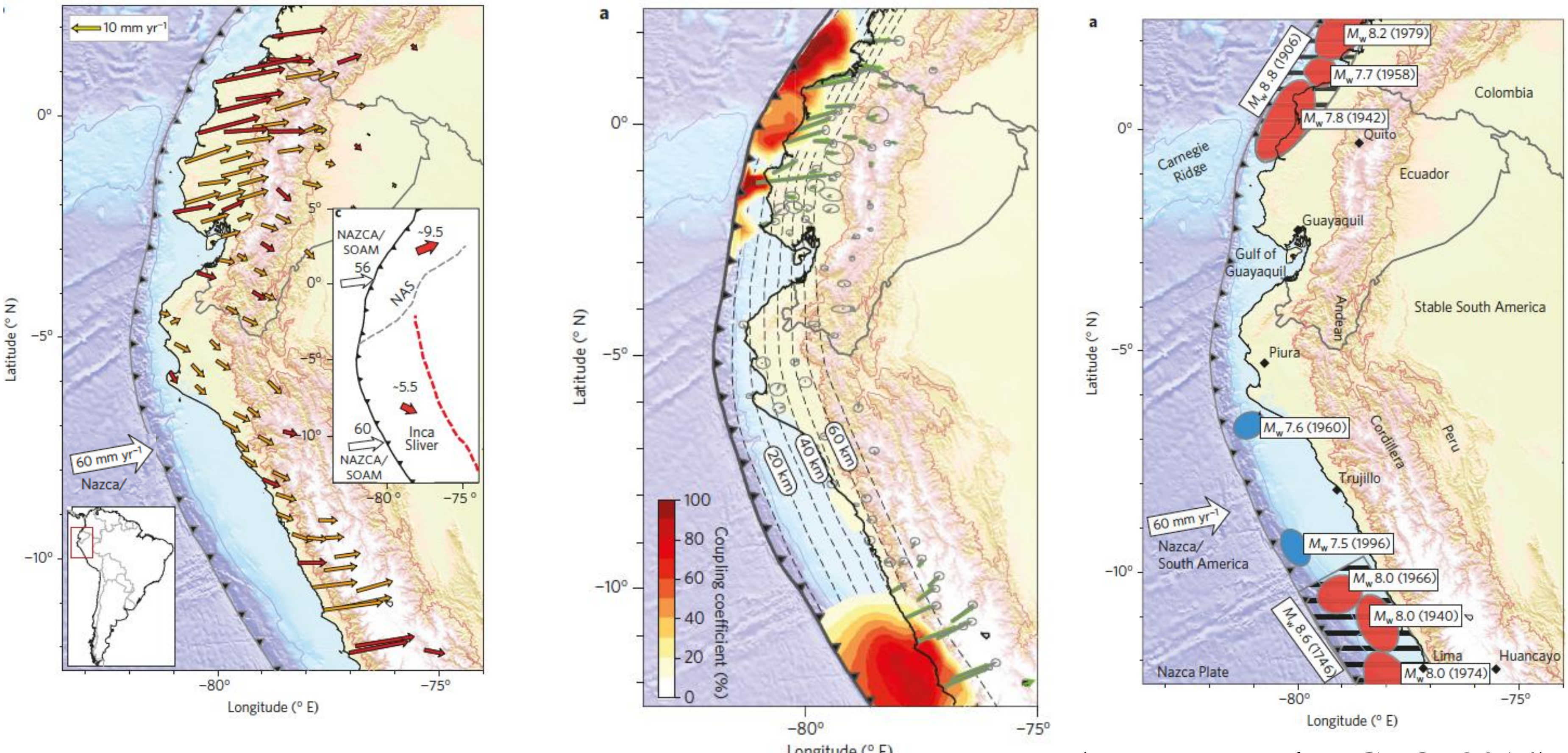
Determination:

Elastic Dislocation Modeling of Interseismic geodetic displacements





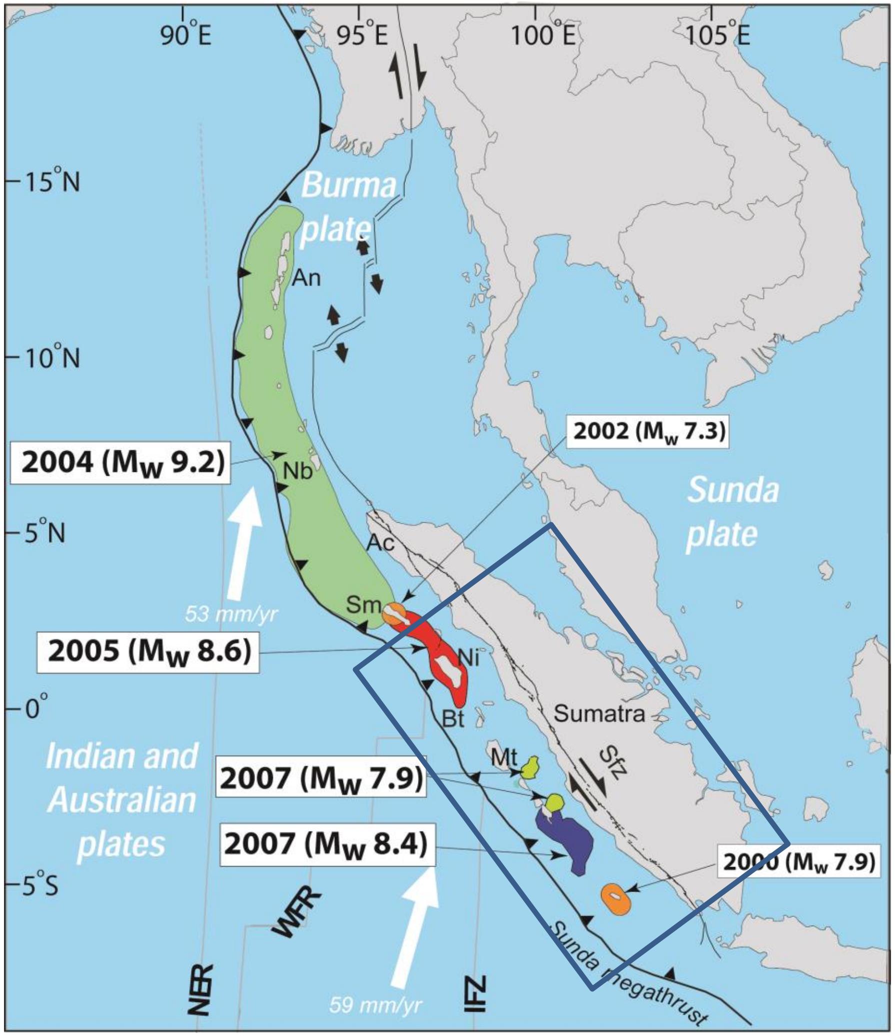
Example 1: The South America Megathrust Ecuador-North Peru

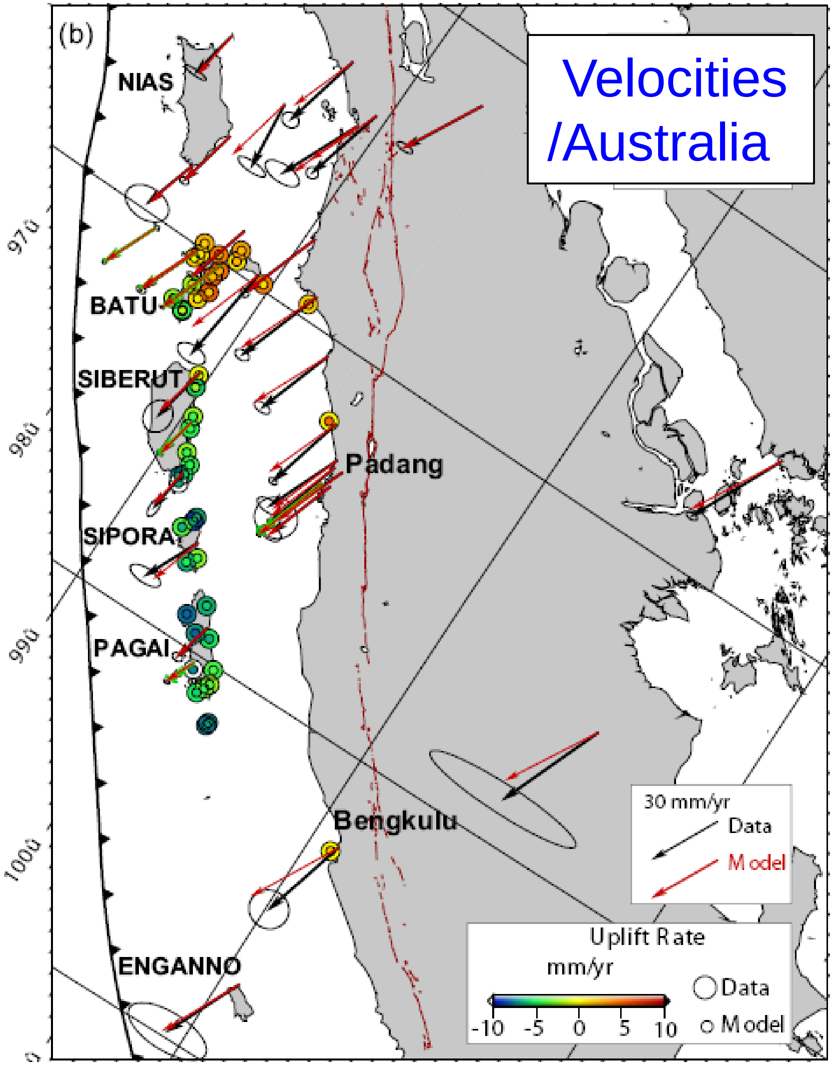


(Nocquet et al, NGEO, 2014)

-> No large earthquake is expected to fill this gap!

Example 2: The Sumatra Megathrust

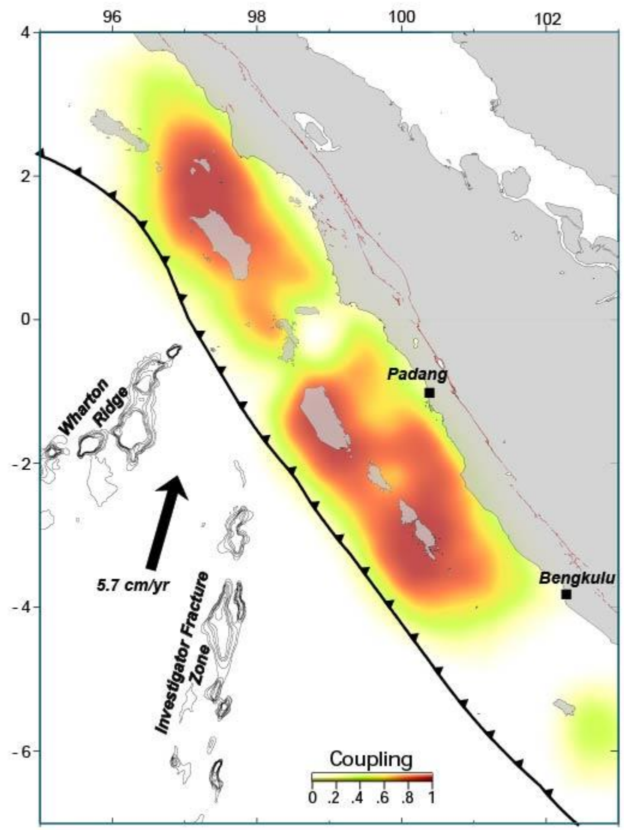




Sources: Natawidjaja et al, (2004),Chlieh et al, (2008); Briggs et al (2006); Hsu et al (2006); Konca et al (2006, 2008)

The Sumatra Megathrust

- Interseismic coupling

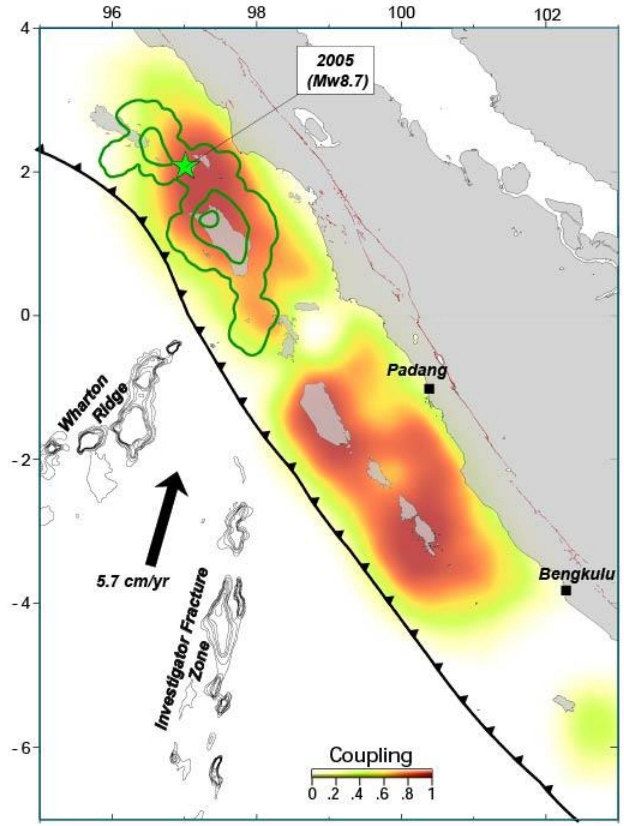


(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)

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

The Sumatra Megathrust

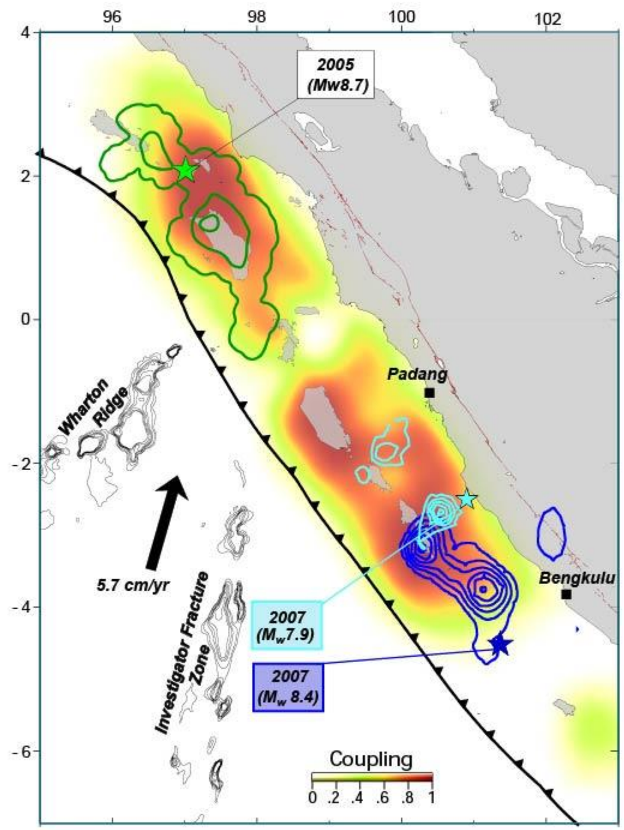
- Interseismic coupling
- Mw, 8.6, 2005, Nias EQ



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

The Sumatra Megathrust

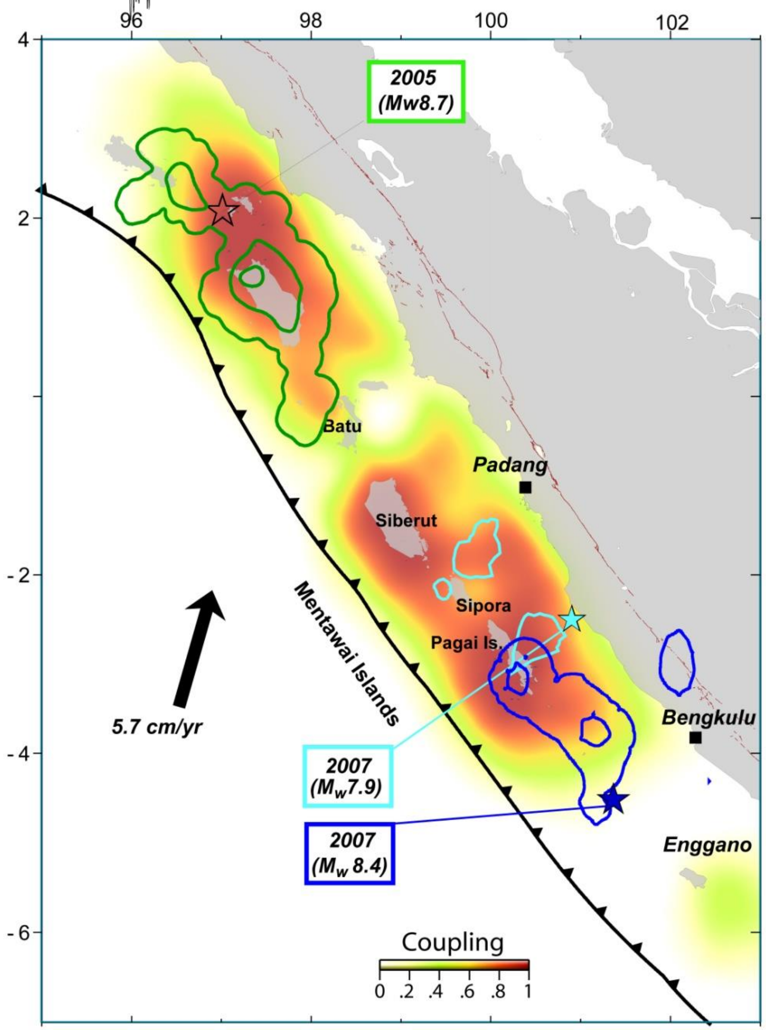
- Interseismic coupling
- Mw 8.6, 2005, Nias EQ
- Mw 8.4, 2007, Bengkulu EQ
- Mw 7.9, 2007, Bengkulu EQ



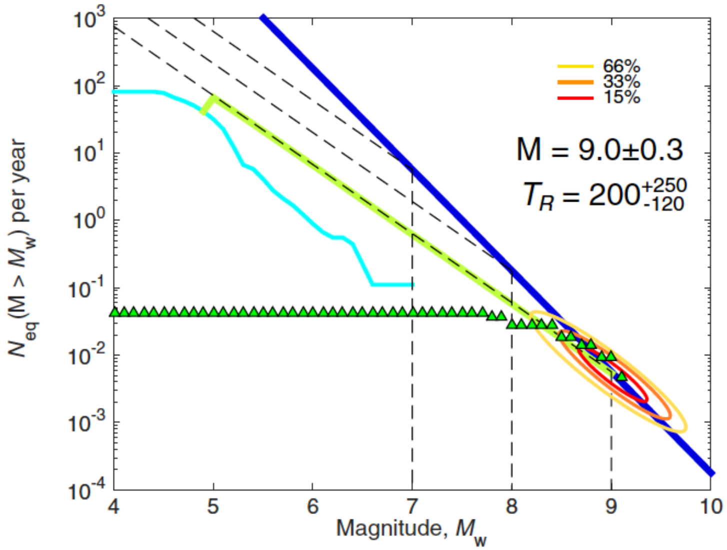
(Source: Chlieh et al., 2008; Konca et al. 2008, Hsu et al., 2006)

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

The Sumatra Megathrust



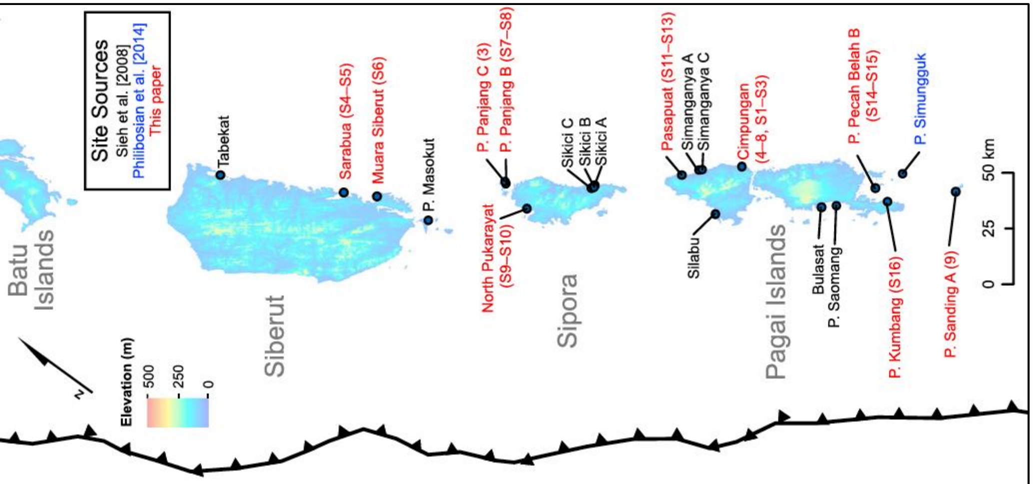
- Interseismic coupling is highly heterogeneous
- Slip is mosty aseismic (50-60%) in the 0-40km 'Seismogenic' depth range
- Seismic ruptures seem confined to 'locked' areas. Creeping zones tend to arrest seismic ruptures.
- The gap offshore Padang should fail at some point.

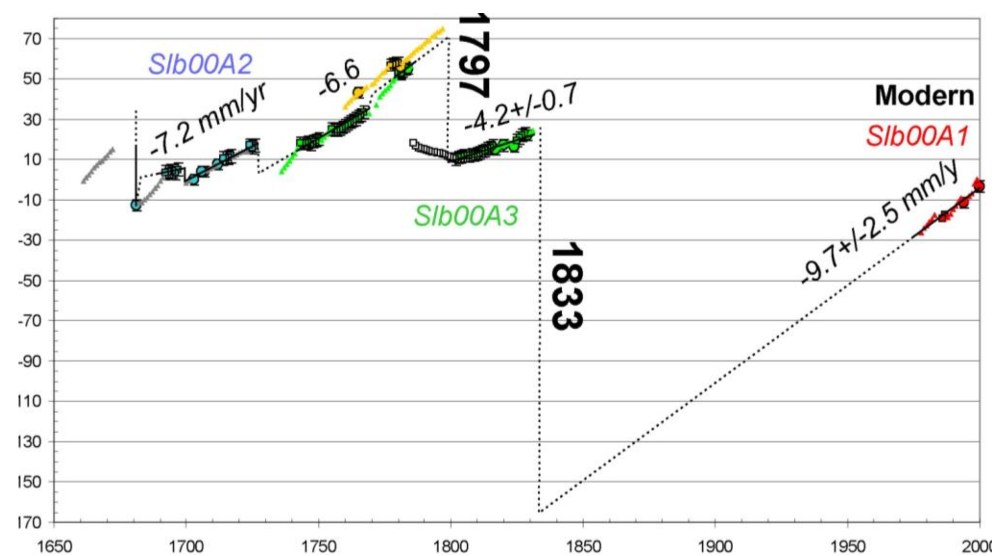


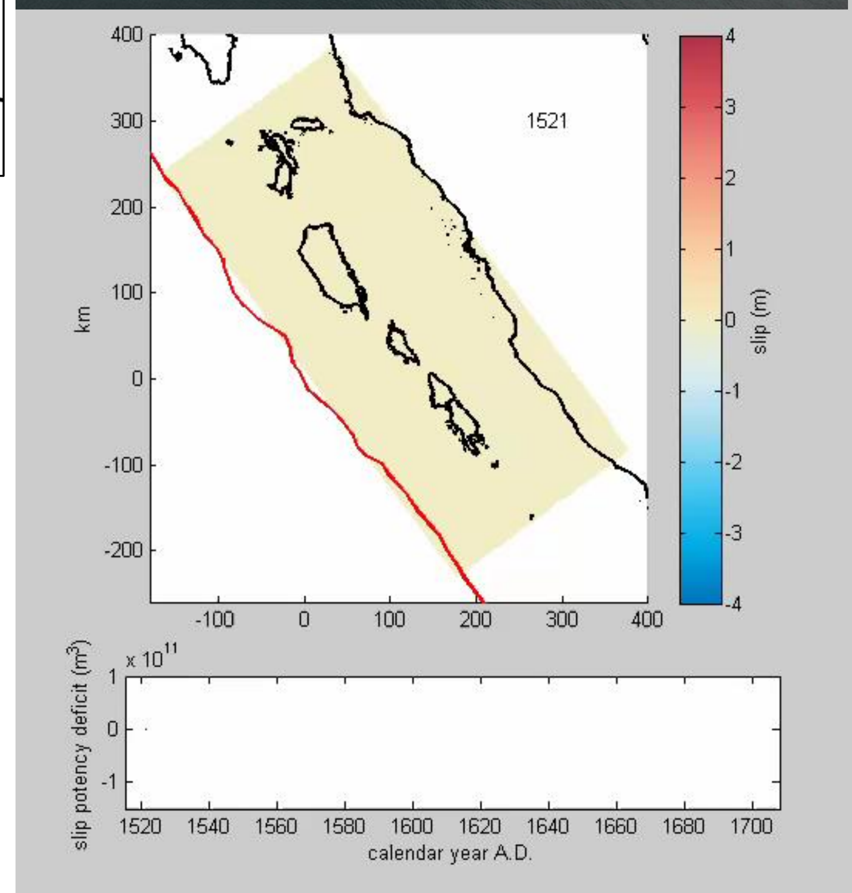
The slip budget is balanced (seismic+aseismic slip=long term slip)

(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

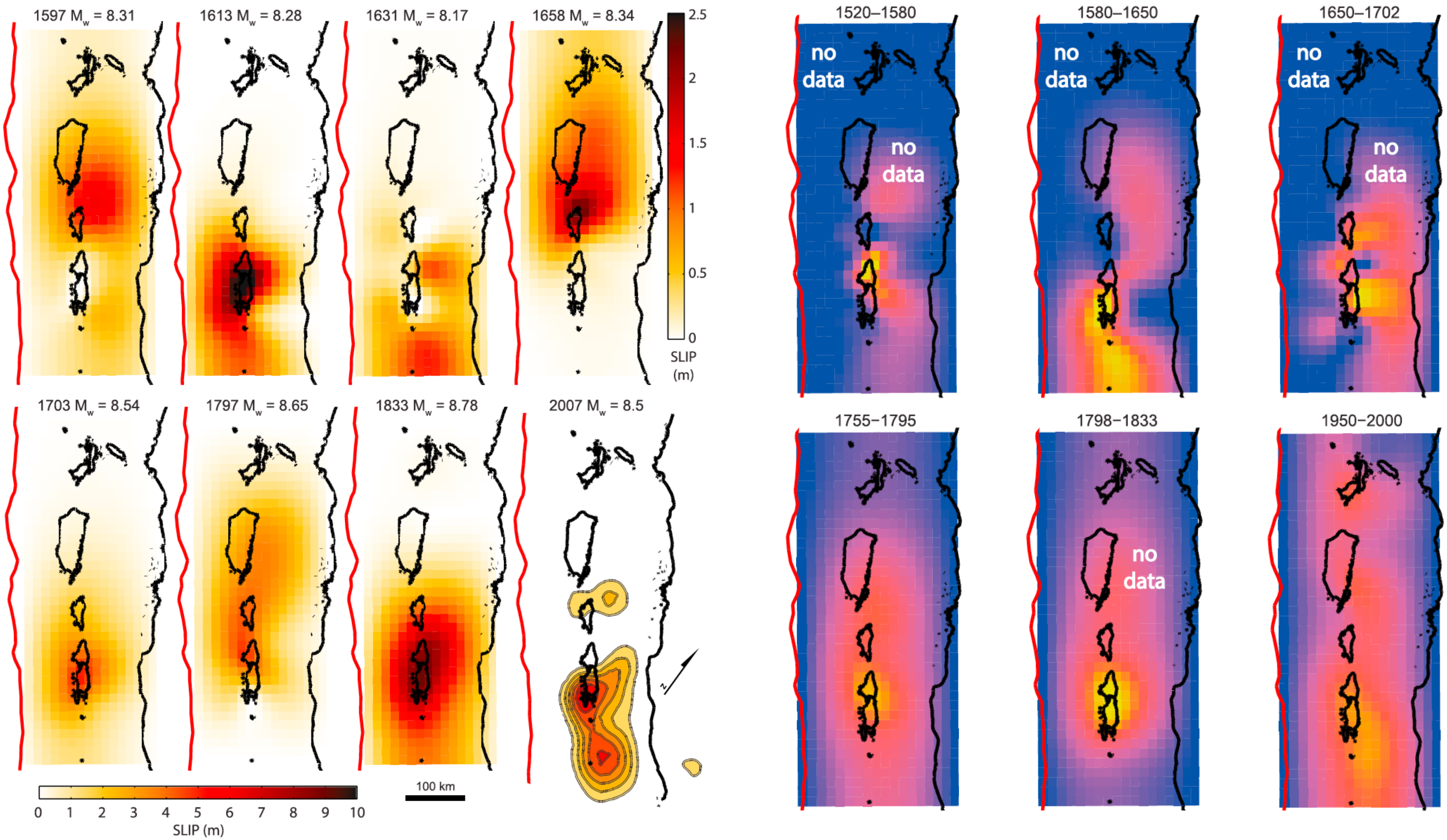






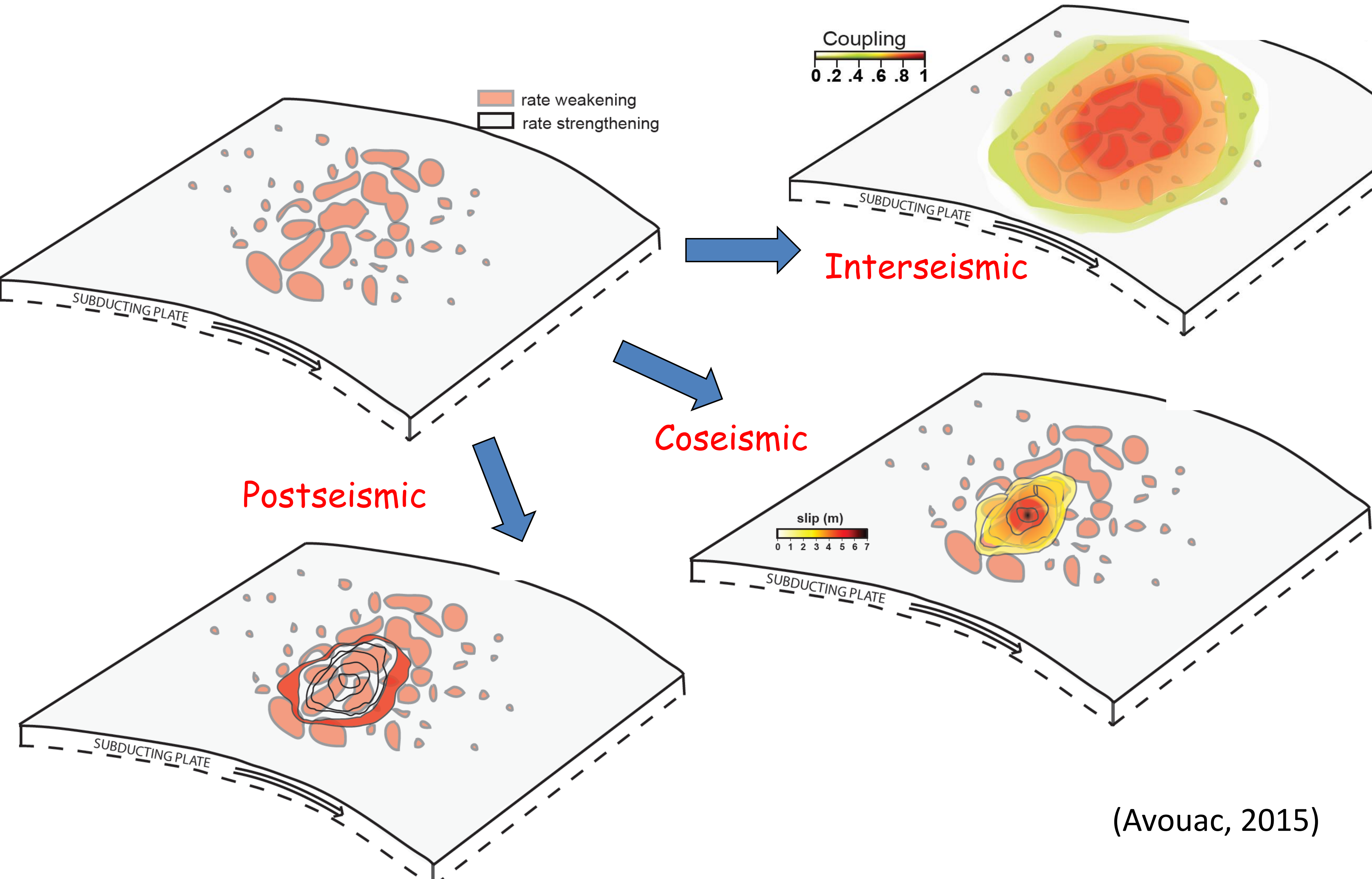
(Philibosian et al., 2017)

Variable ruptures/quasi stationnary coupling



(Philibosian et al., 2017)

The Seismic Cycle, a Conceptual framework

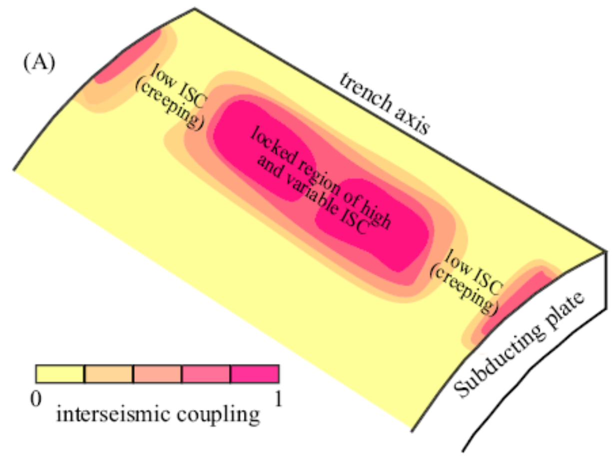


(Avouac, 2015)

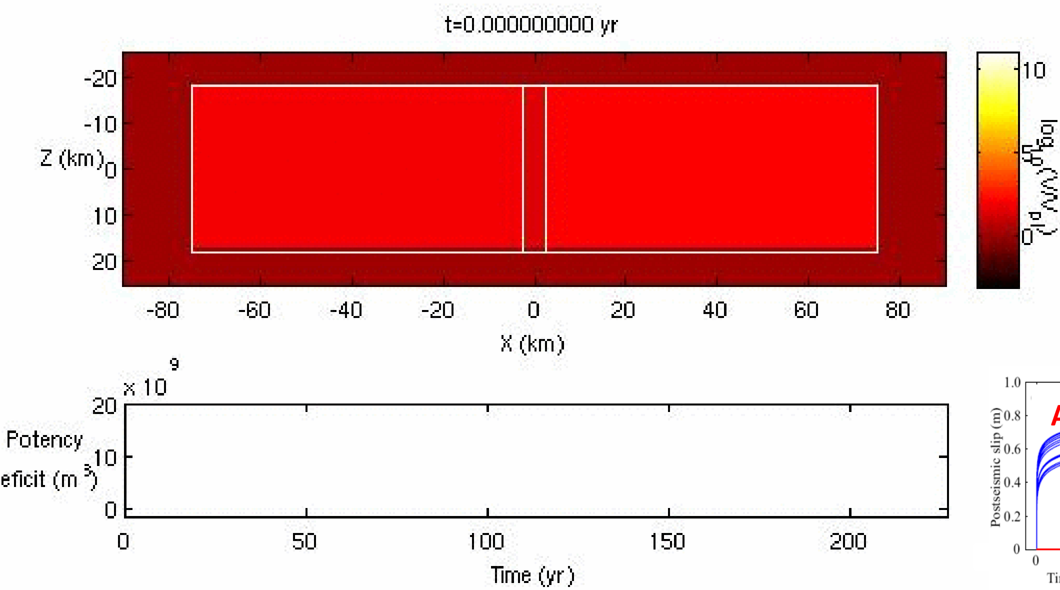
Dynamic modeling

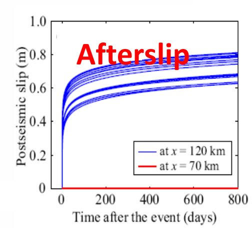
Rate & state friction:
(Dieterich, 1979;
Ruina, 1983)

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



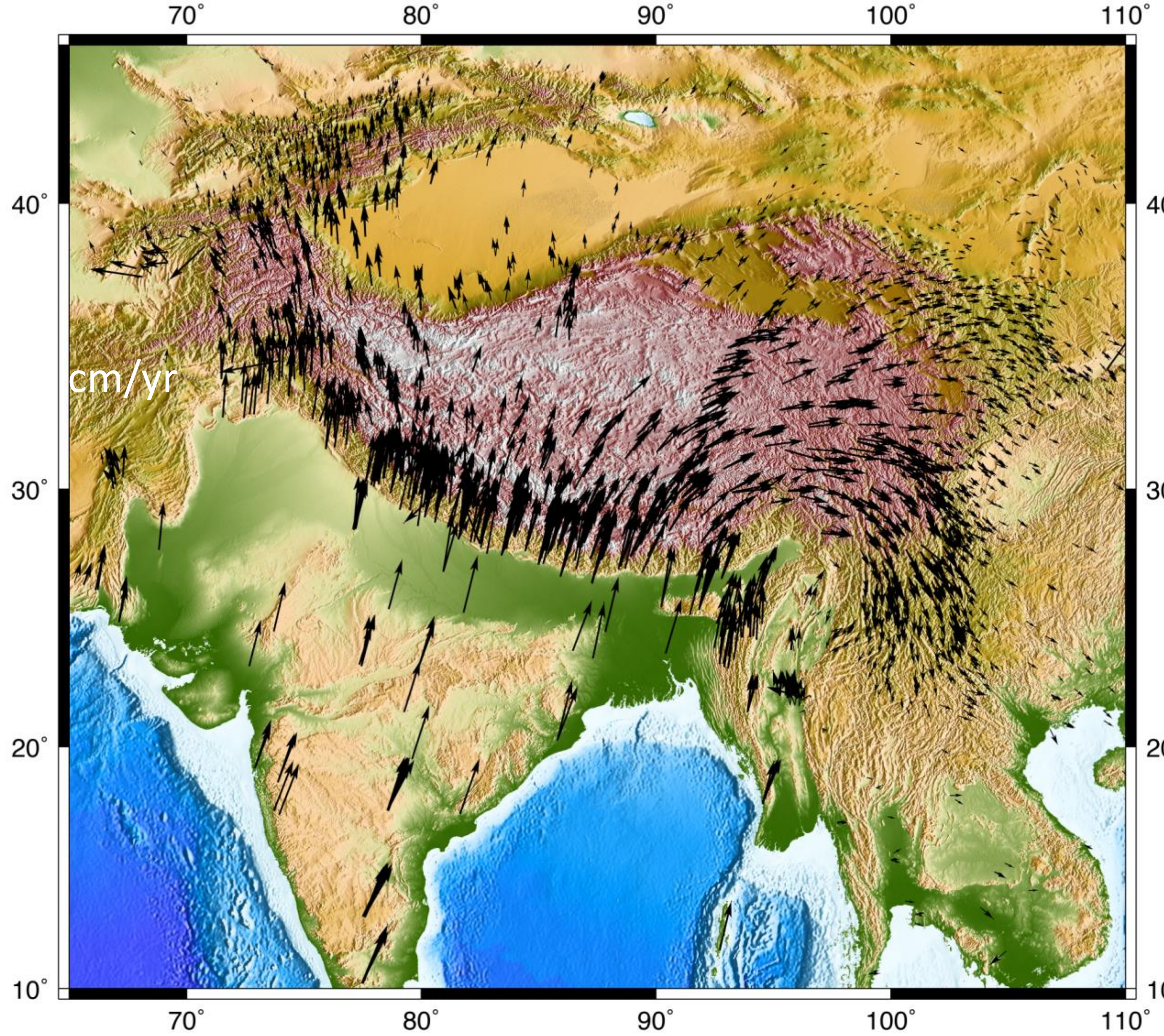
Numerical Method: Boundary Intregral Method
(Lapusta and Liu (JGR, 2009)



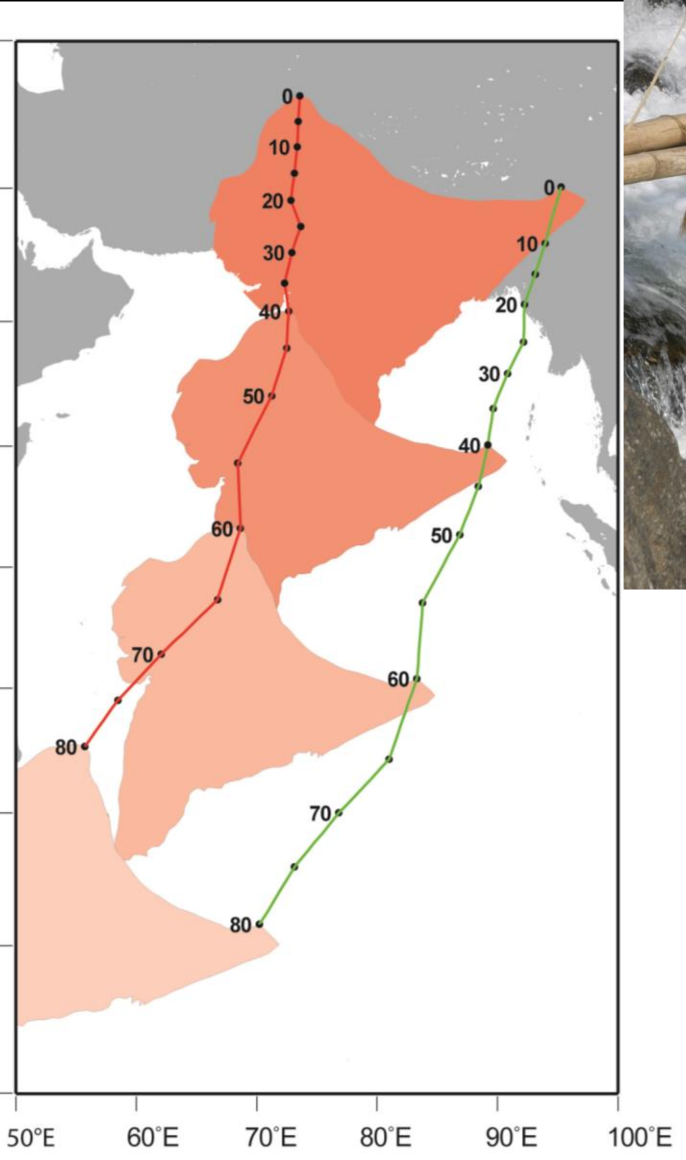


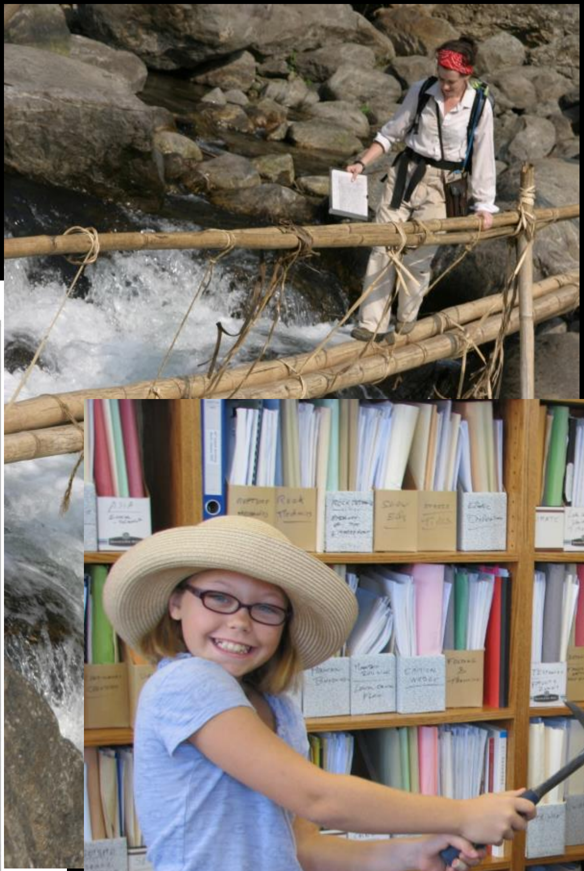
(Kaneko, Avouac and Lapusta, 2010)

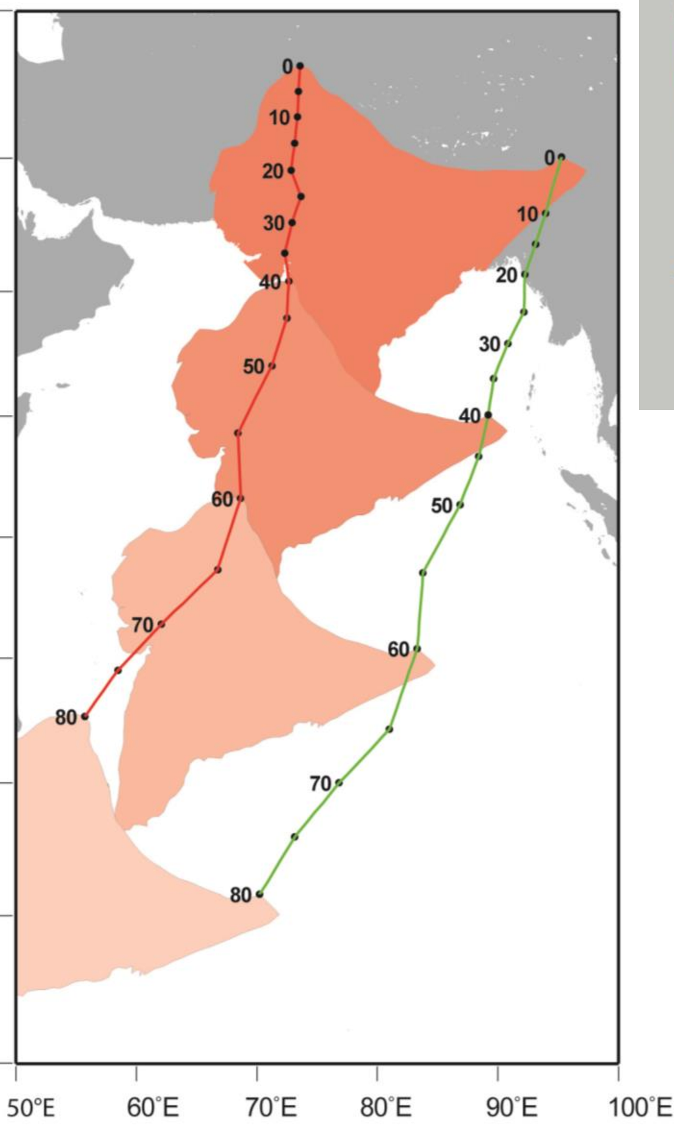
Example 3: The Himalayan Megathrust



Tectonics Observatory
California Institute of Technology






0
10
20
30
40
50
60
70
80
0
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80
50°E
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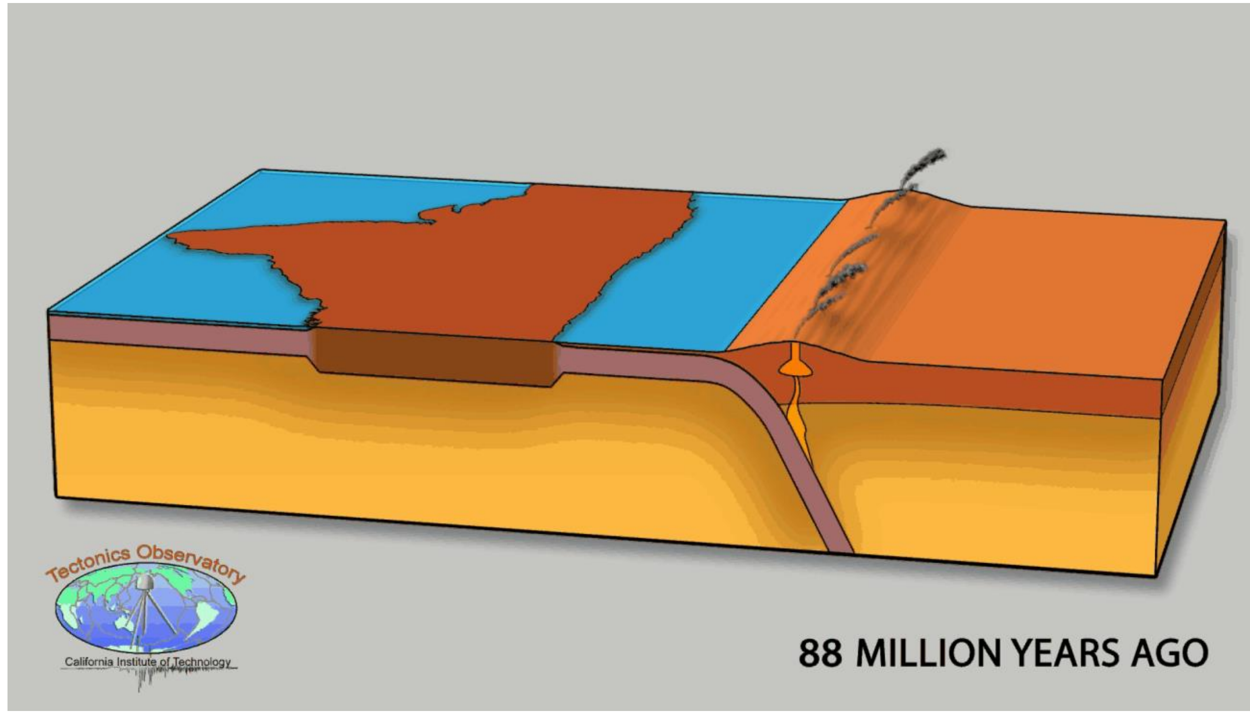
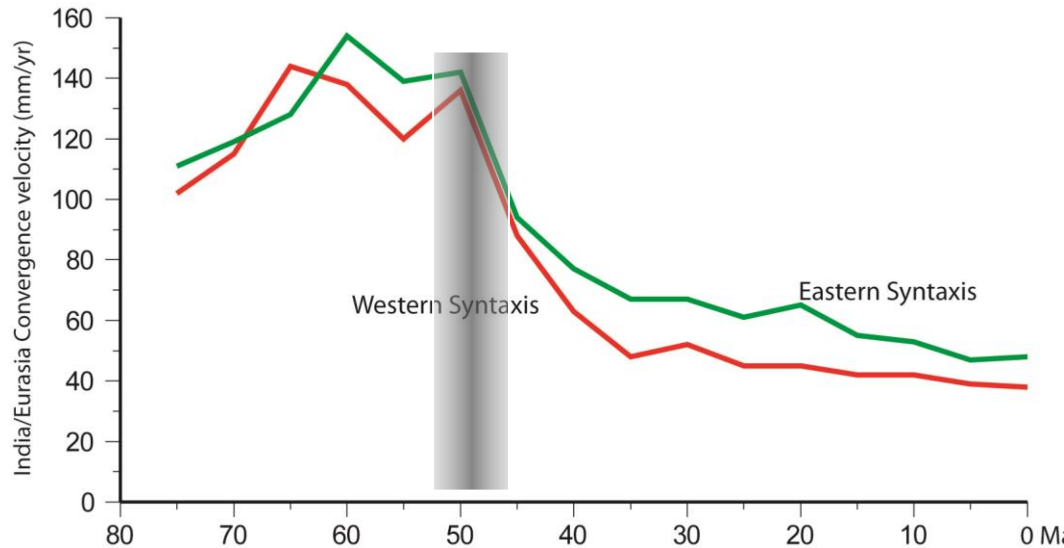
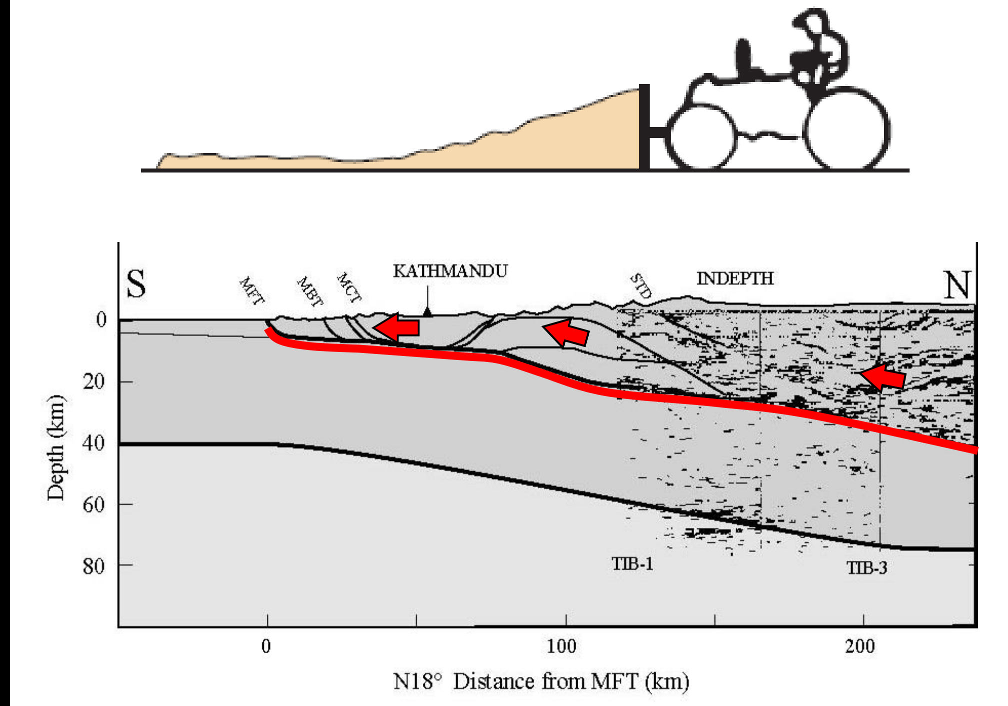
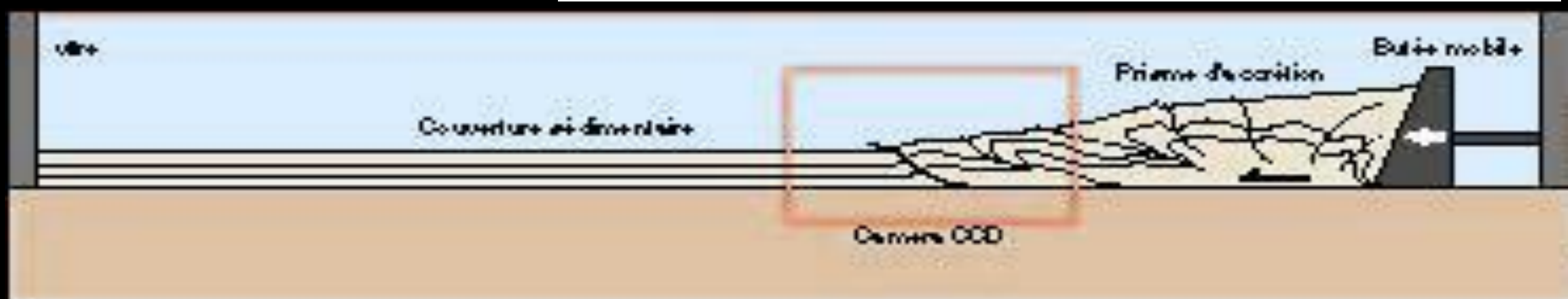
70°E
80°E
90°E
100°E


Tectonics Observatory
California Institute of Technology
88 MILLION YEARS AGO

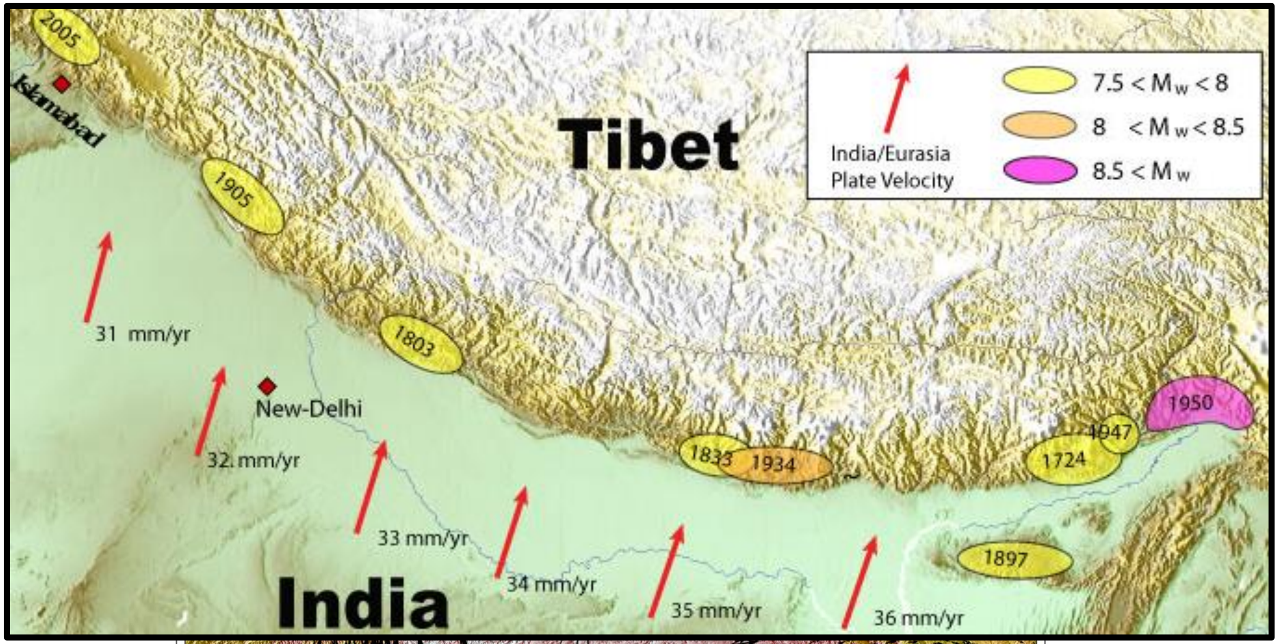

India/Eurasia Convergence velocity (mm/yr)
160
140
120
100
80
60
40
20
0
Western Syntaxis
Eastern Syntaxis
80
70
60
50
40
30
20
10
0 Ma

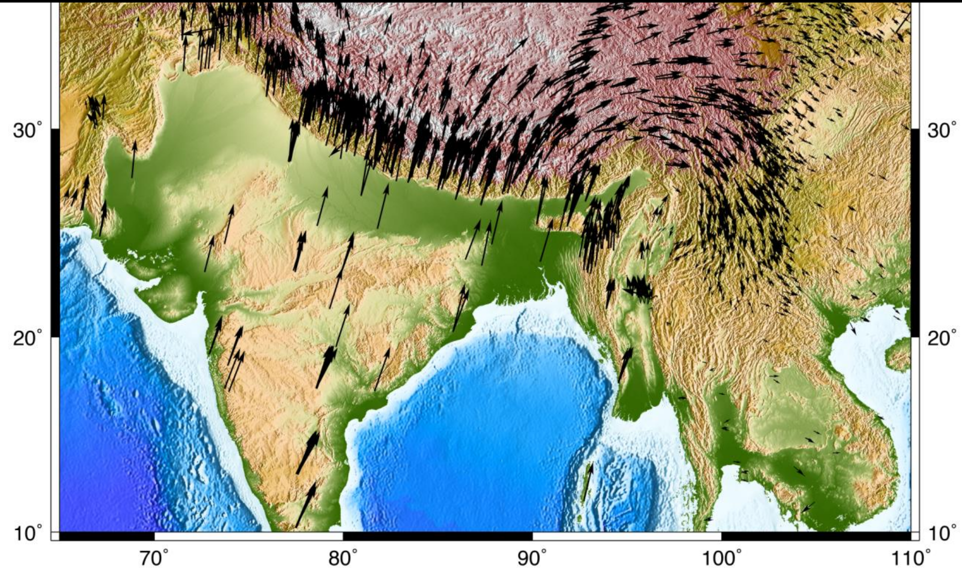
Tectonics Observatory
California Institute of Technology

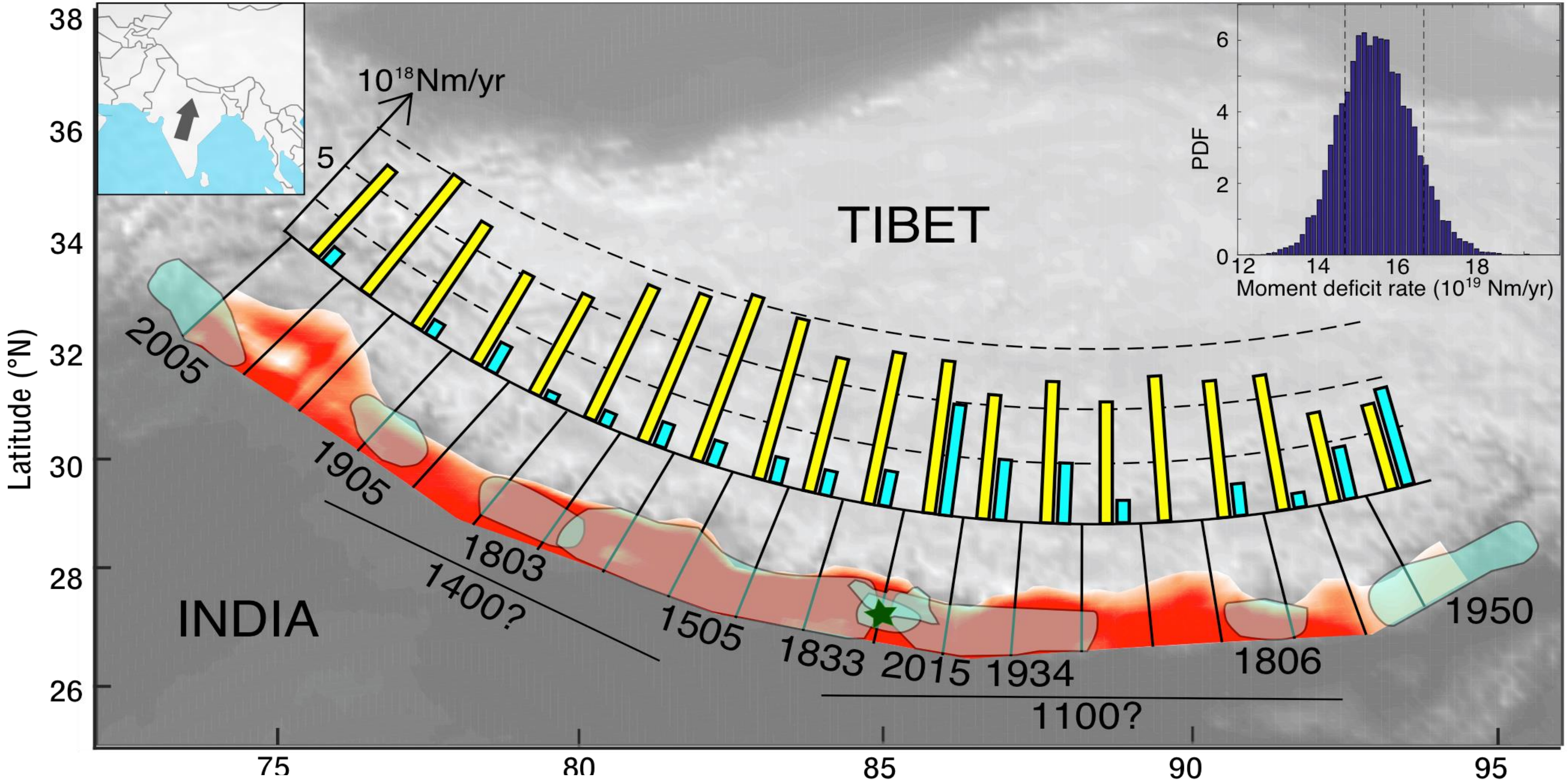


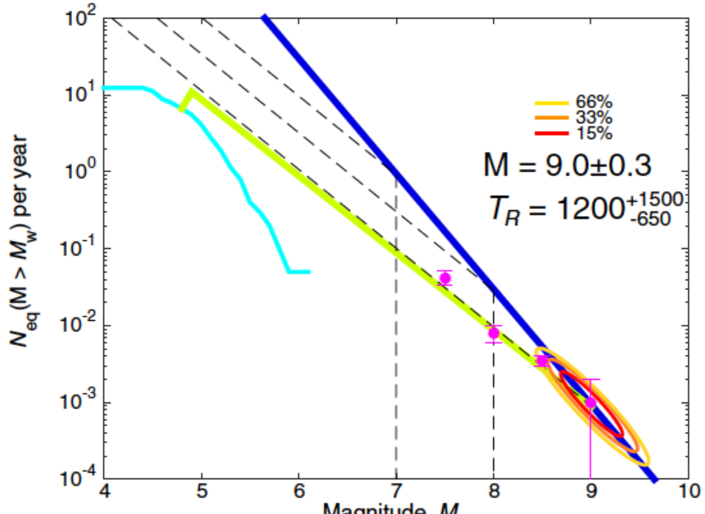


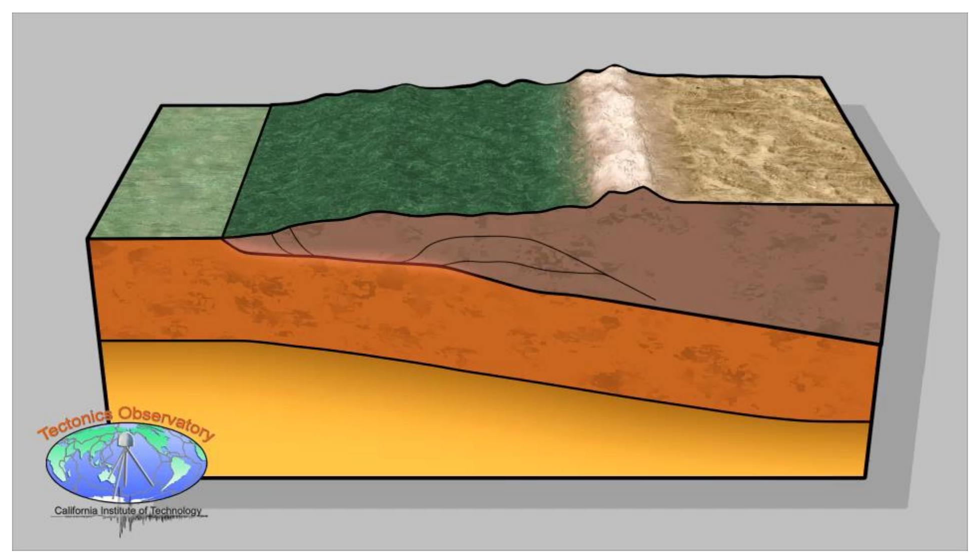
Example 3: The Himalayan Megathrust





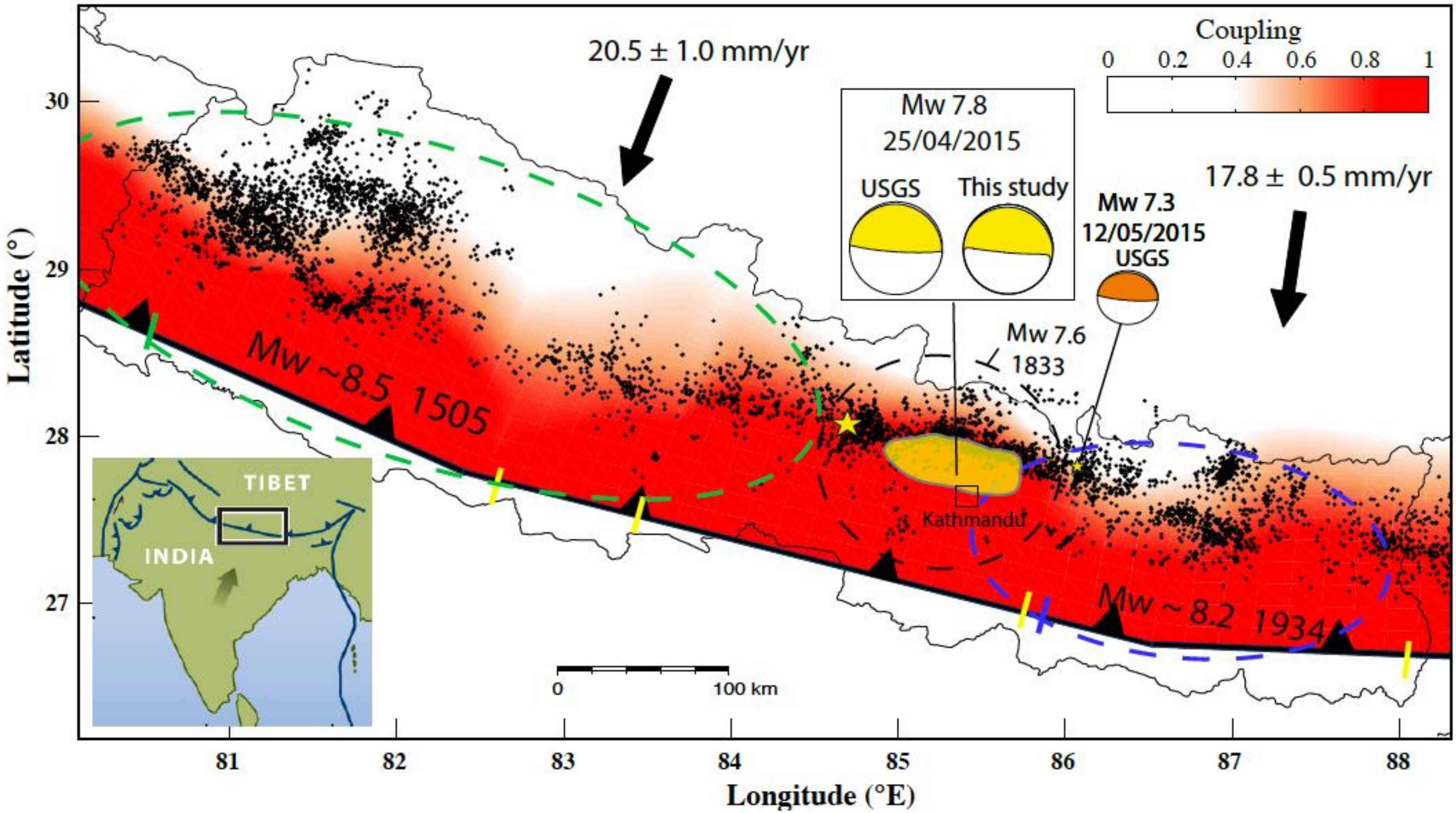






(Stevens&Avouac, GRL, 2016)

The 2015 Mw7.8 Gorkha Earthquake



Dharahara Tower

April, 24, 2015

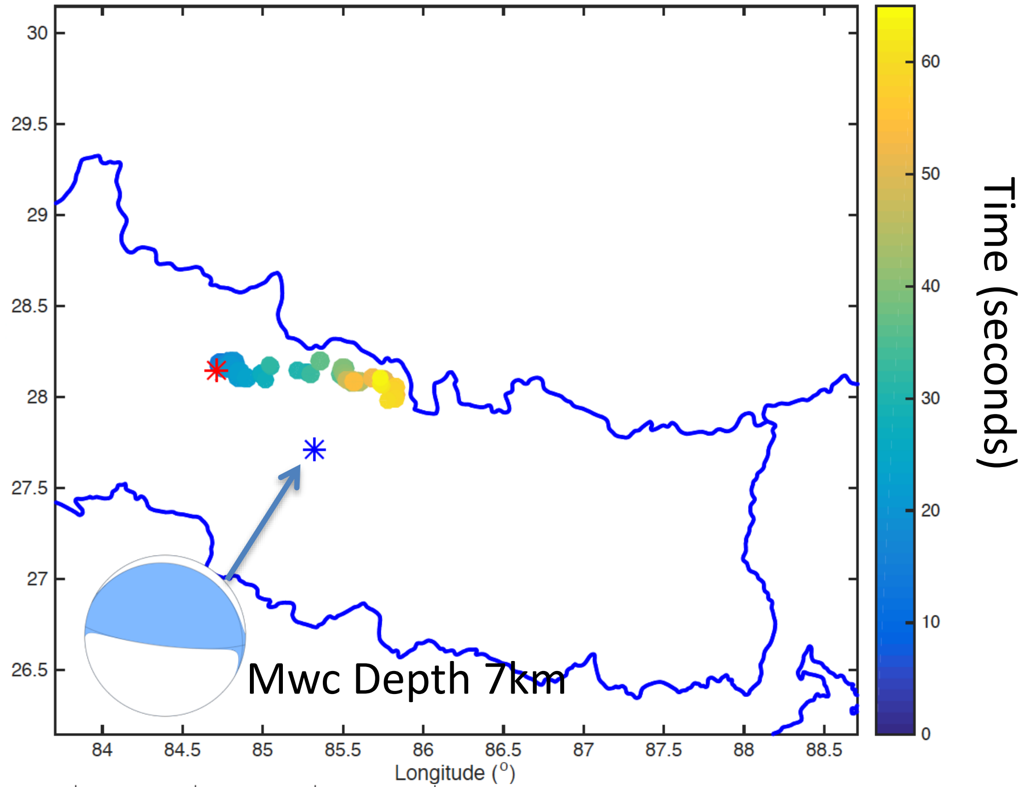
April, 25, 2015

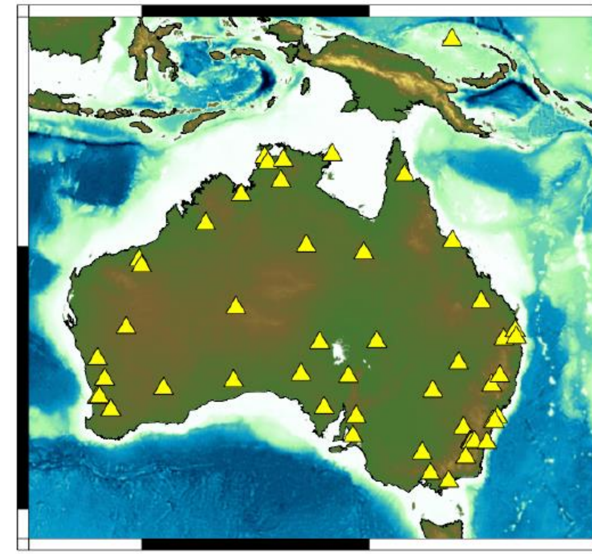
National Seismological Centre
Lainchaur, Kathmandu, Nepal

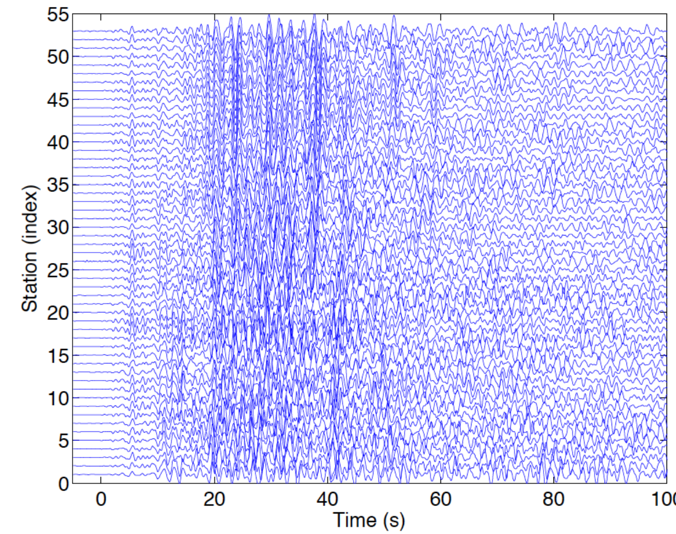
NASA

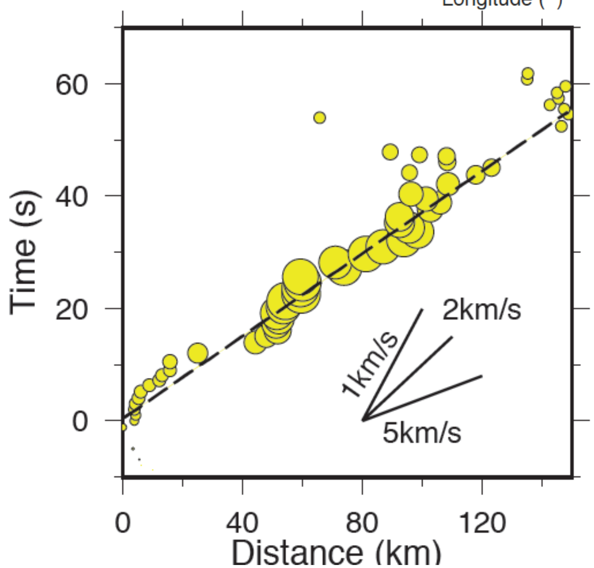
NSF

UNAVCO









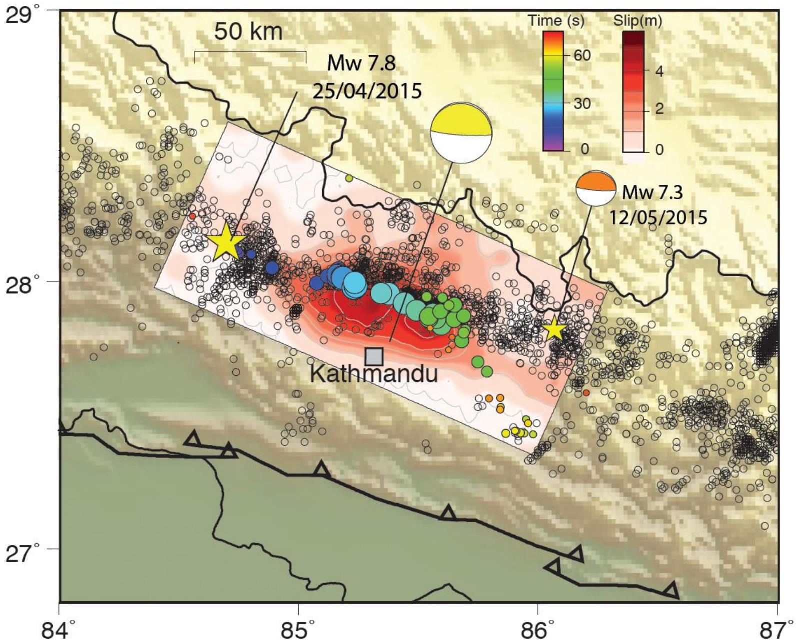
2.72+/-0.13km/s

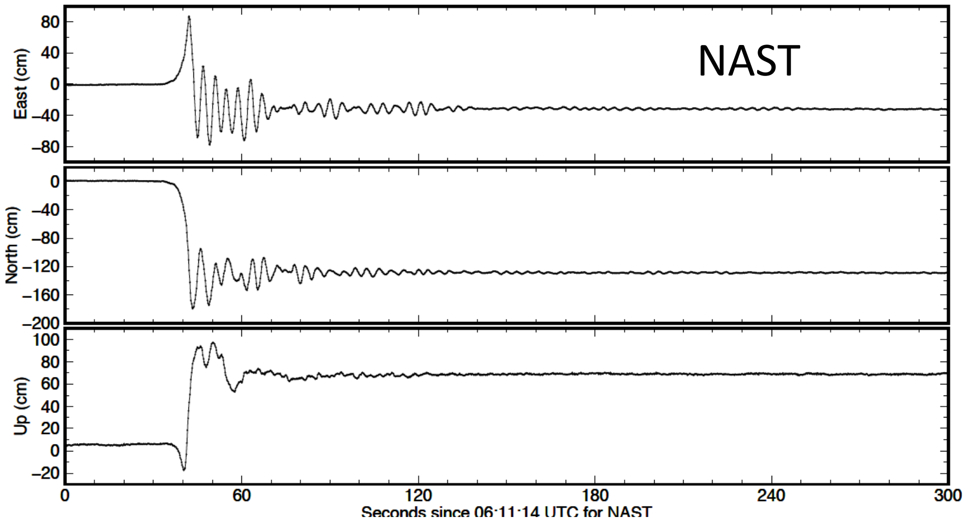
Bandpass filtered 0.5-2Hz

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

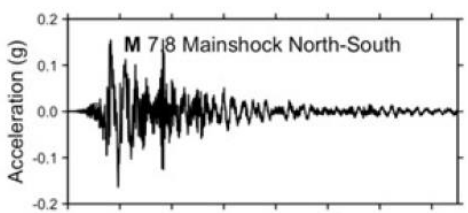
(Avouac et al., 2015)

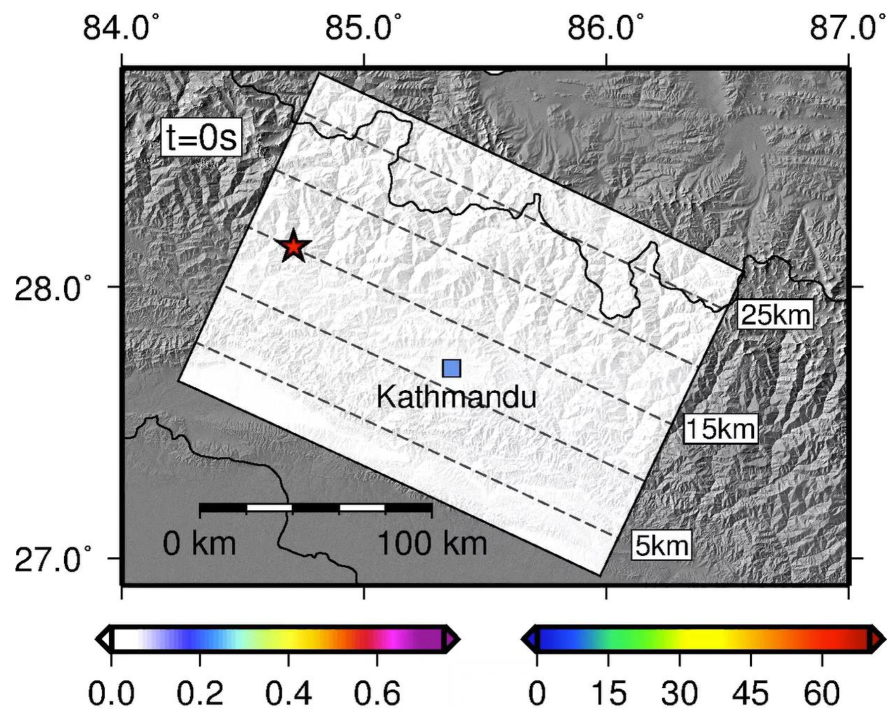
Model of the Mw7.8 Gorkha earthquake





Acc. rec/.
KATNP

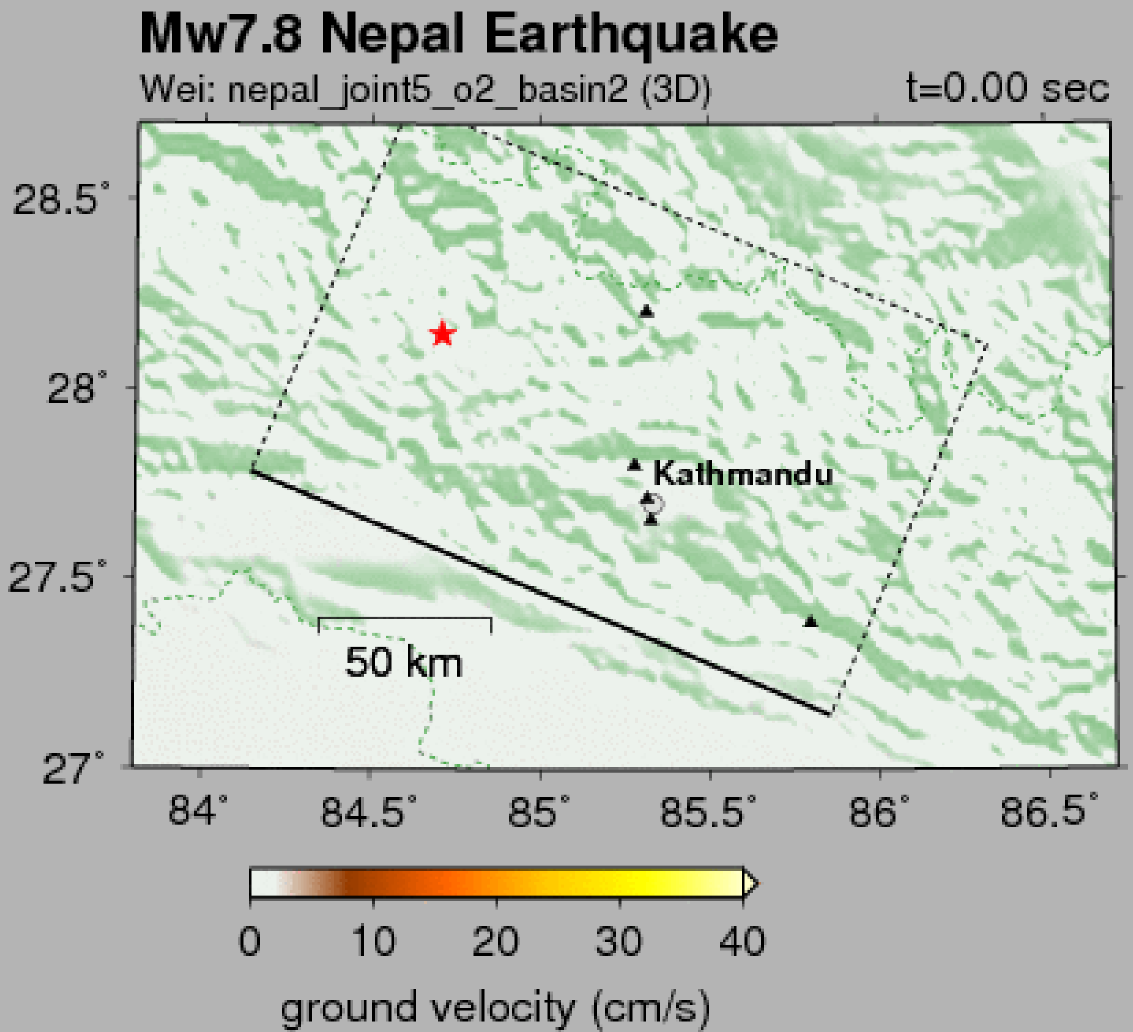




Near-field records show a smooth rupture beneath Kathmandu which generated only modest ground acceleration <20%g).

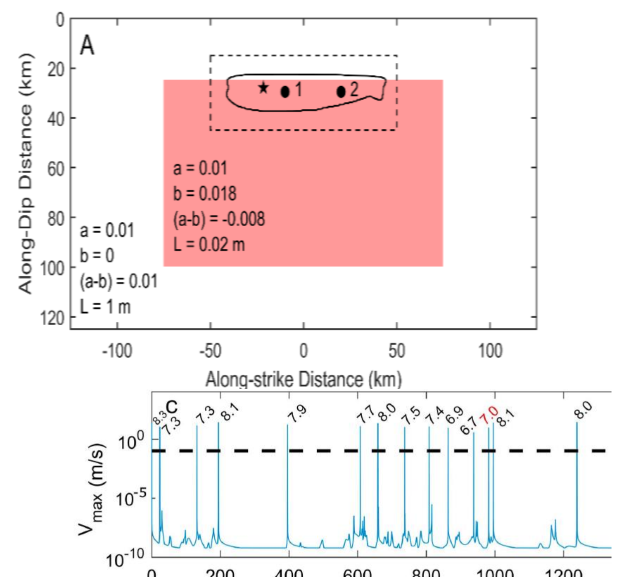
(Avouac et al., 2015; Galetzka et al., 2015)

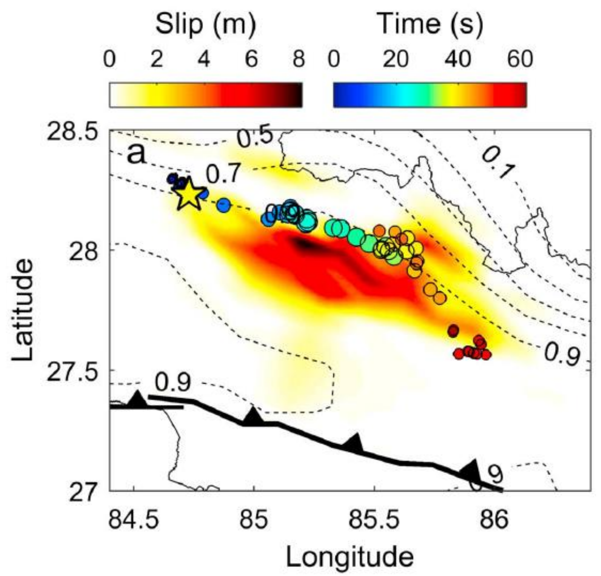
Predicted Ground Motion

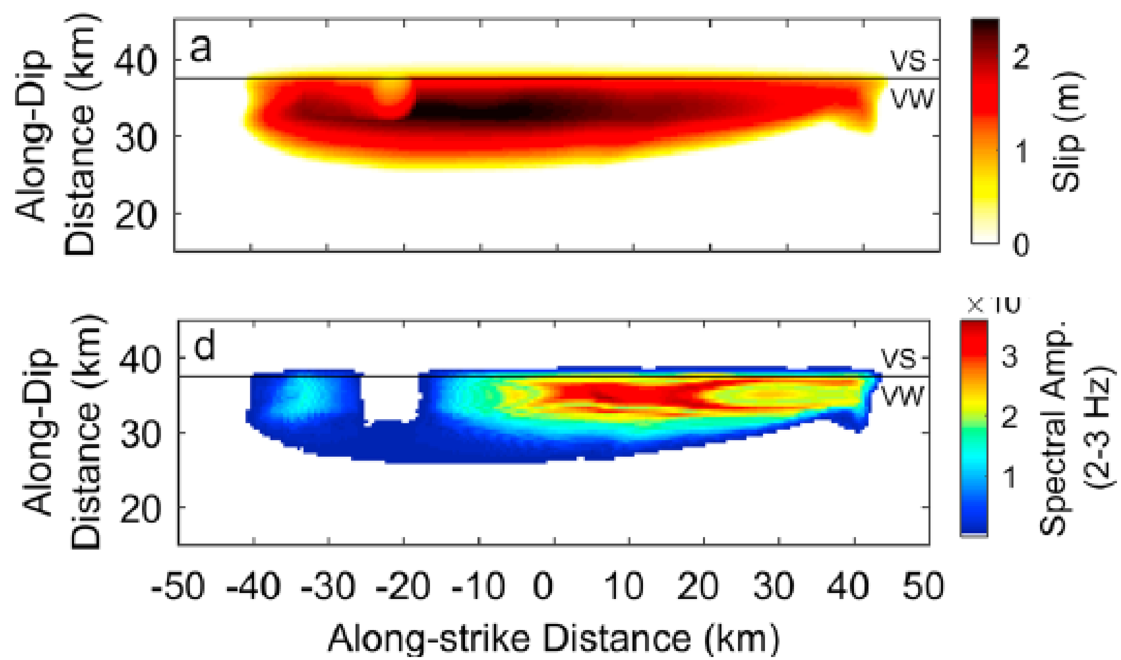


(Shengji Wei, Rob Graves et al. 2018)

Dynamic Modeling: a Gorkha-like rupture



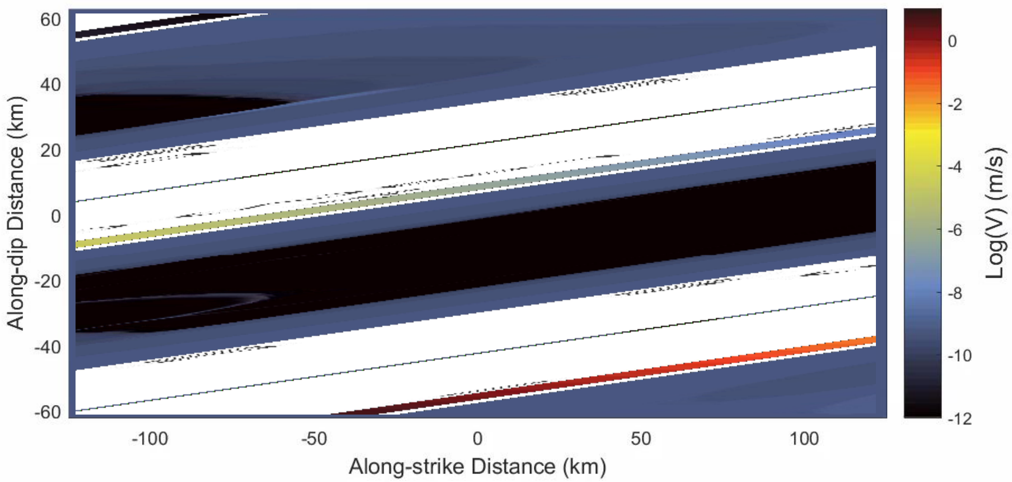


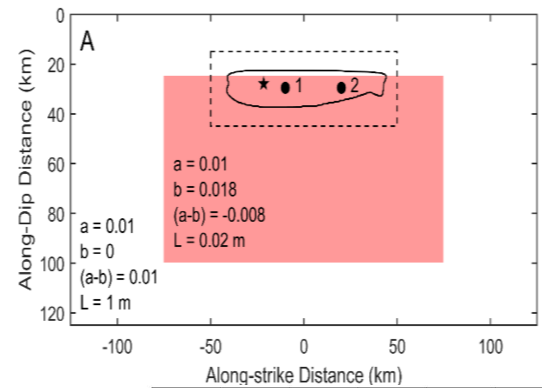


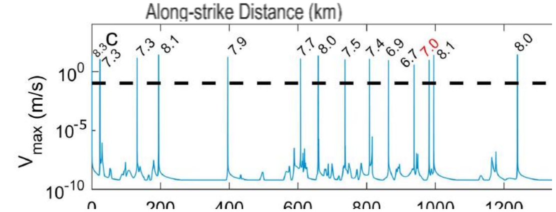
(Michel et al., GRL, 2017)

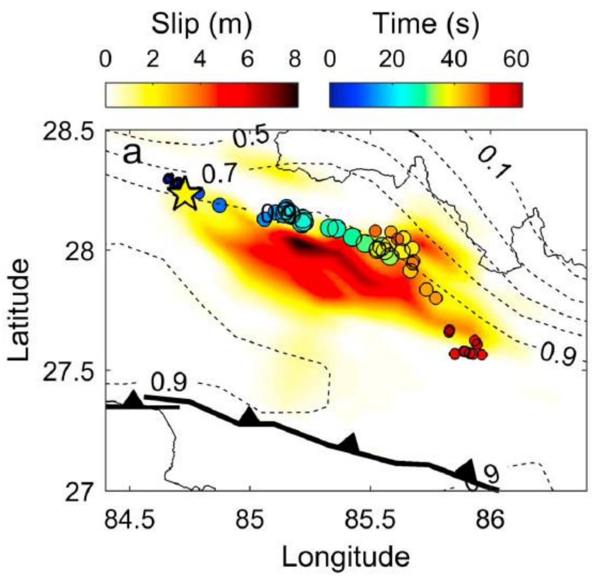
Dynamic Modeling of full ruptures

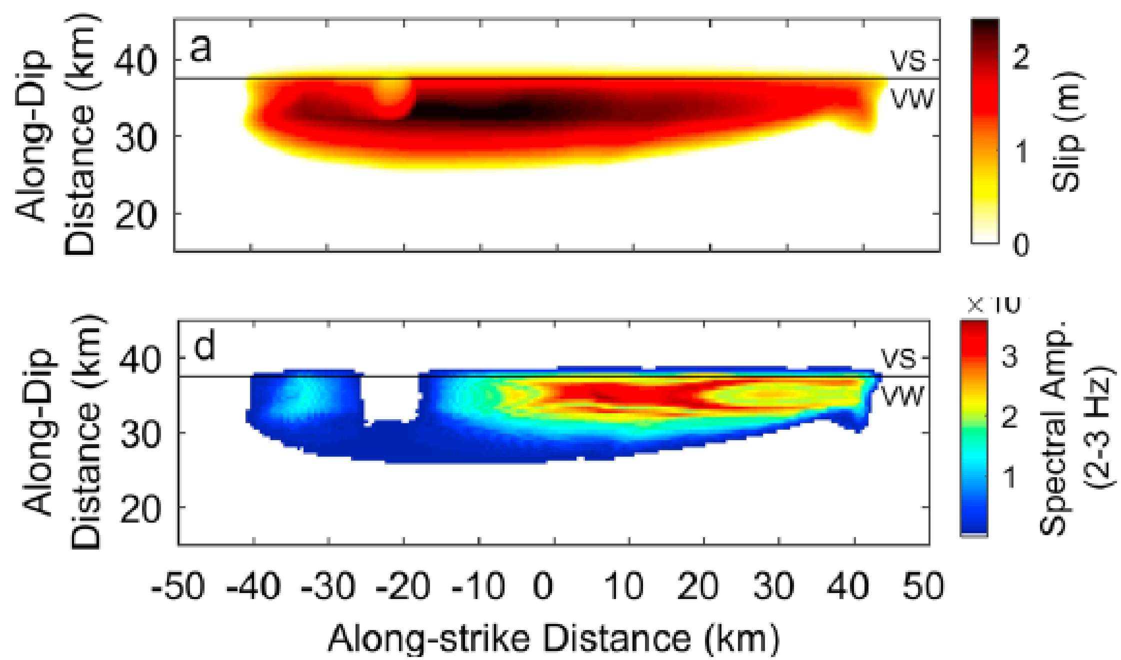
Event 13











(Michel, Lapusta&Avouac, GRL, 2017)

Conclusions

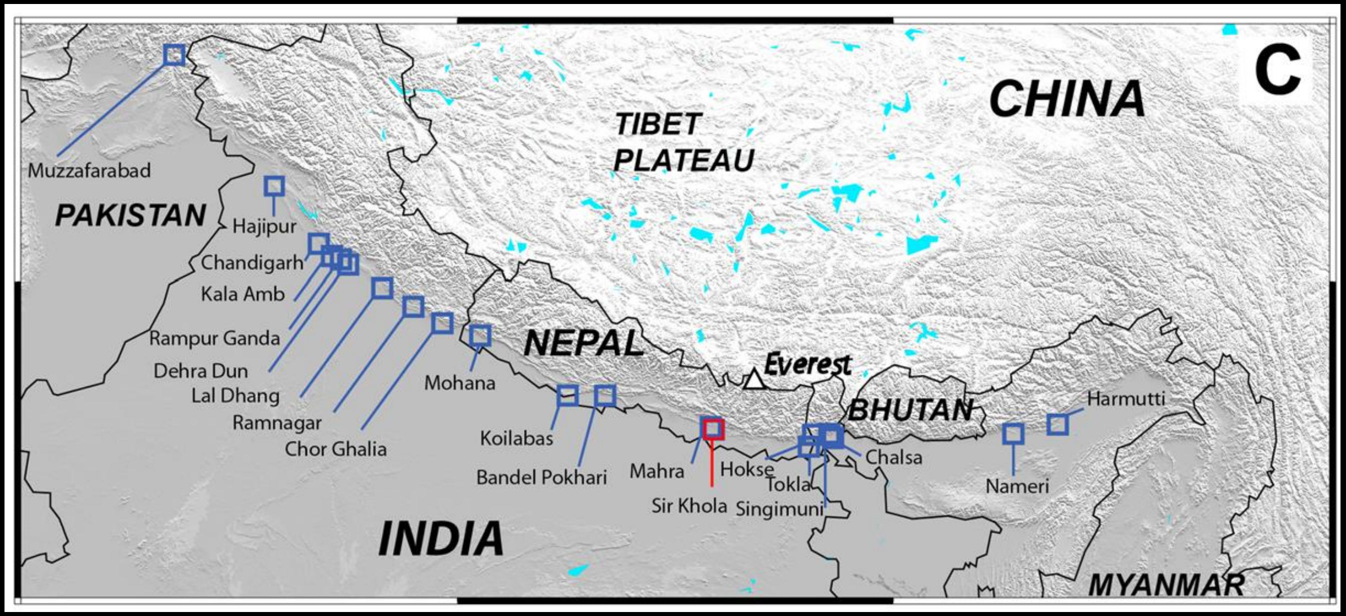
- Seismic gaps can be either zones of aseismic creep or of high slip deficit
- The seismic potential of subduction zone can be assessed based on interseismic geodetic strain and seismicity.
- Seismic ruptures tend to be confined within locked fault patches.
- Dynamic models of the earthquake cycle could 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 material available from my webpage and from the Tectonics Observatory webpages.


Thank You

Thank You

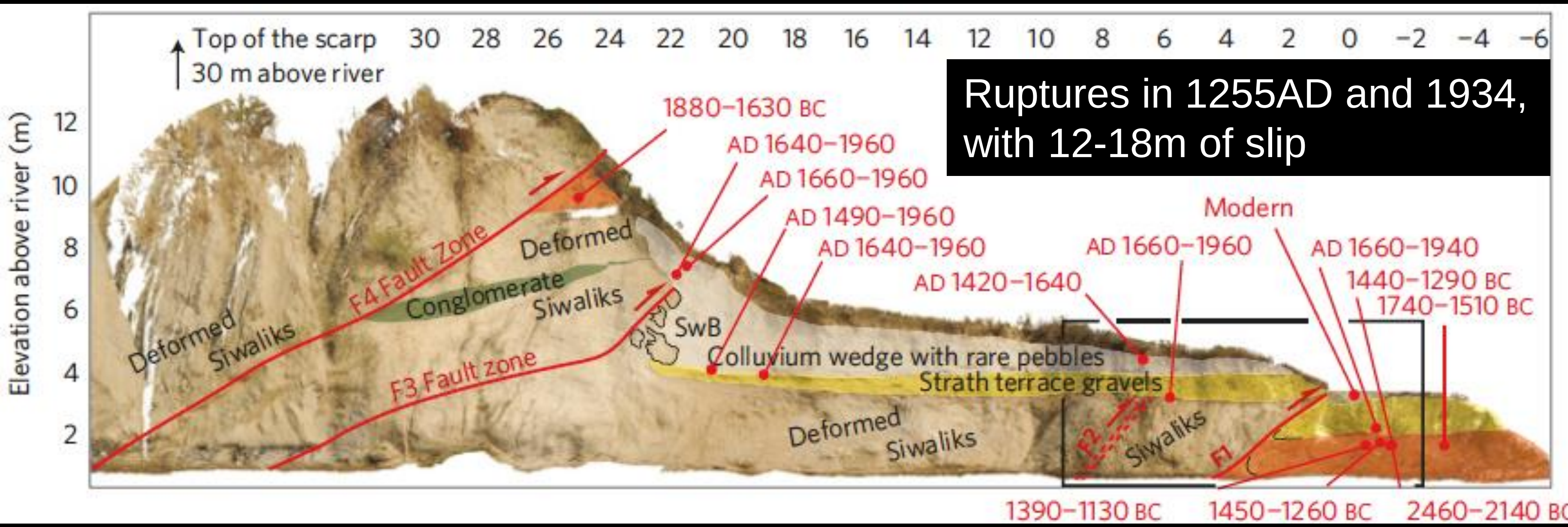
Paleoseismology



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)

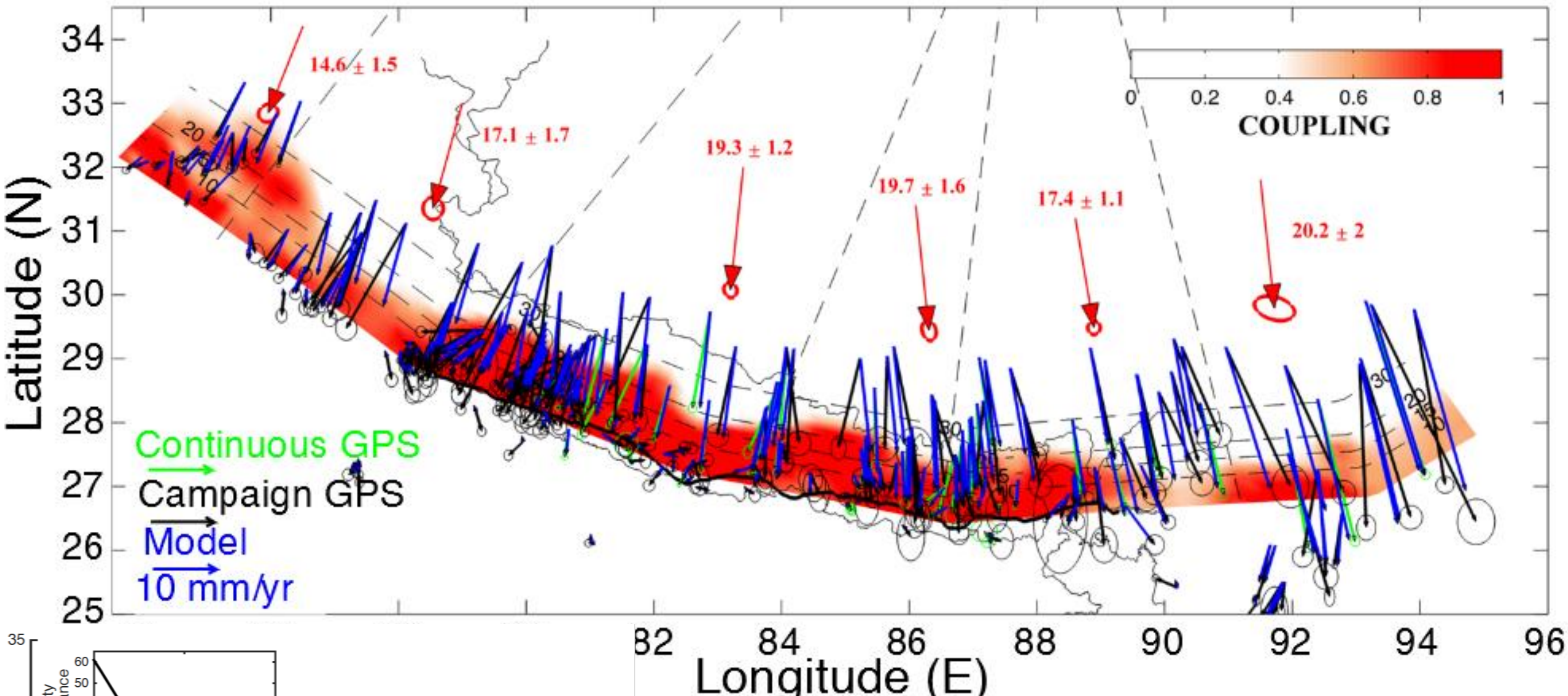
Paleoseismology

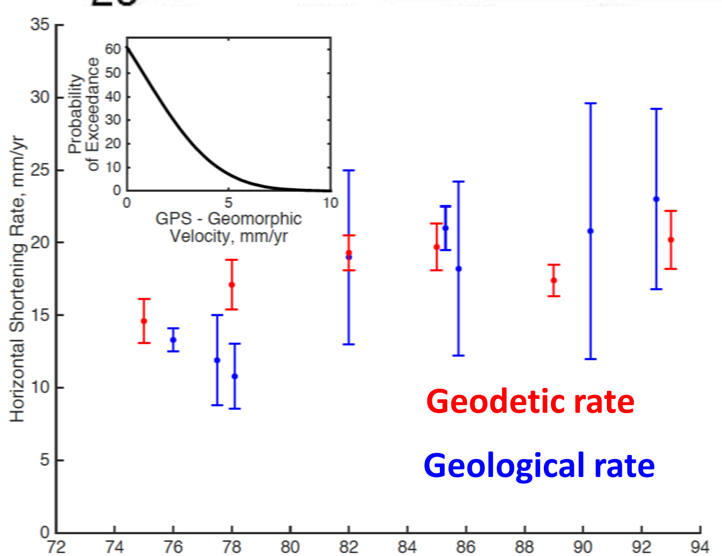


Ruptures in 1255AD and 1934, with 12-18m of slip

Sapkota et al (NGEO, 2012)

Interseismic Coupling-Slip rate on MHT

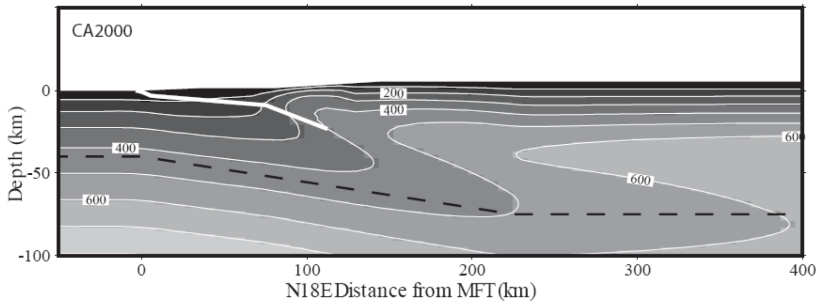


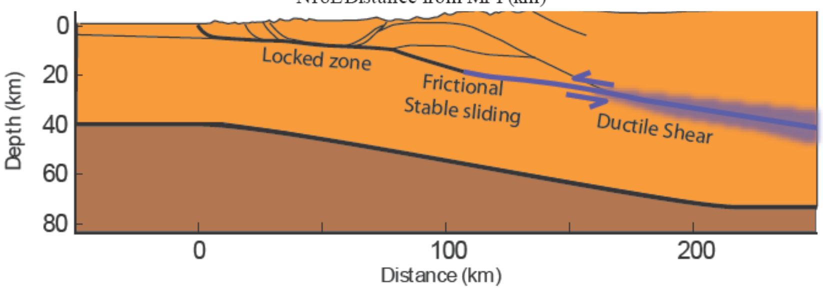


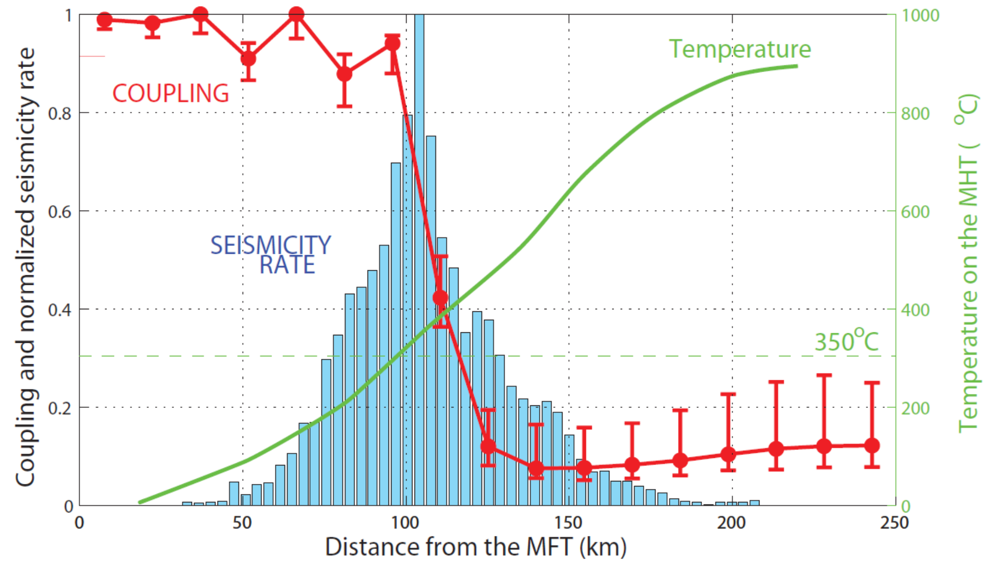
Moment deficit accumulation in the interseismic period of **18 x10^{19} Nm/yr needs to be released by transient slip events on the locked portion of the MHT**

(Stevens and Avouac, GRL, 2015)

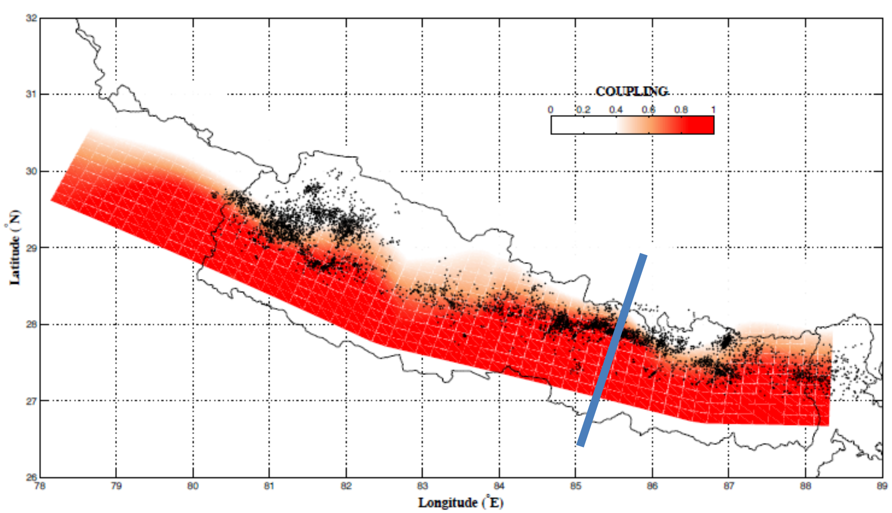
Role of Temperature







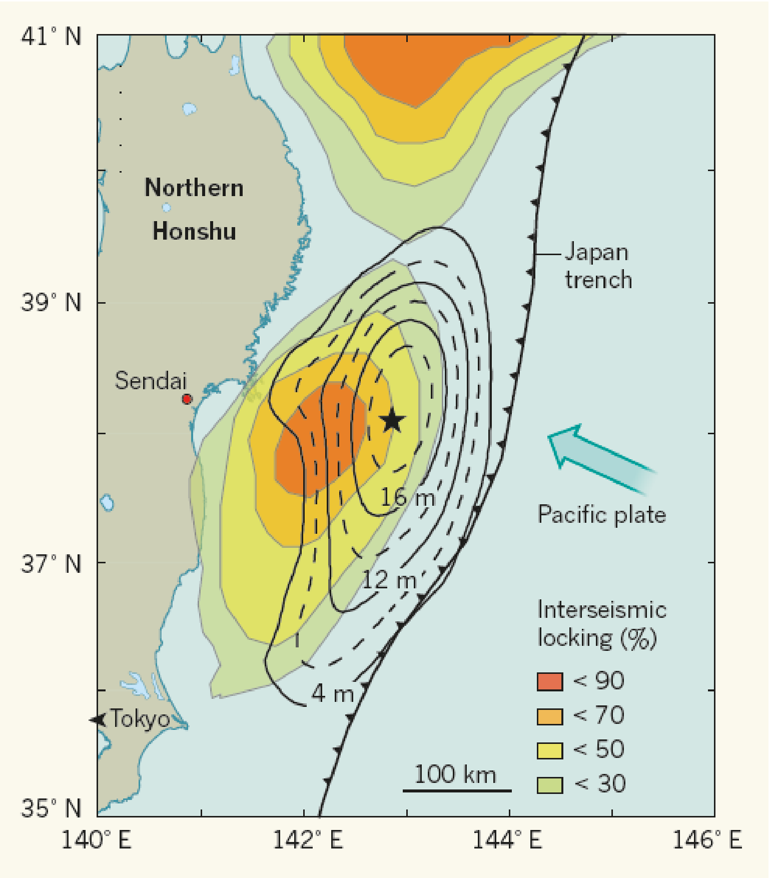
(Ader et al., 2012)

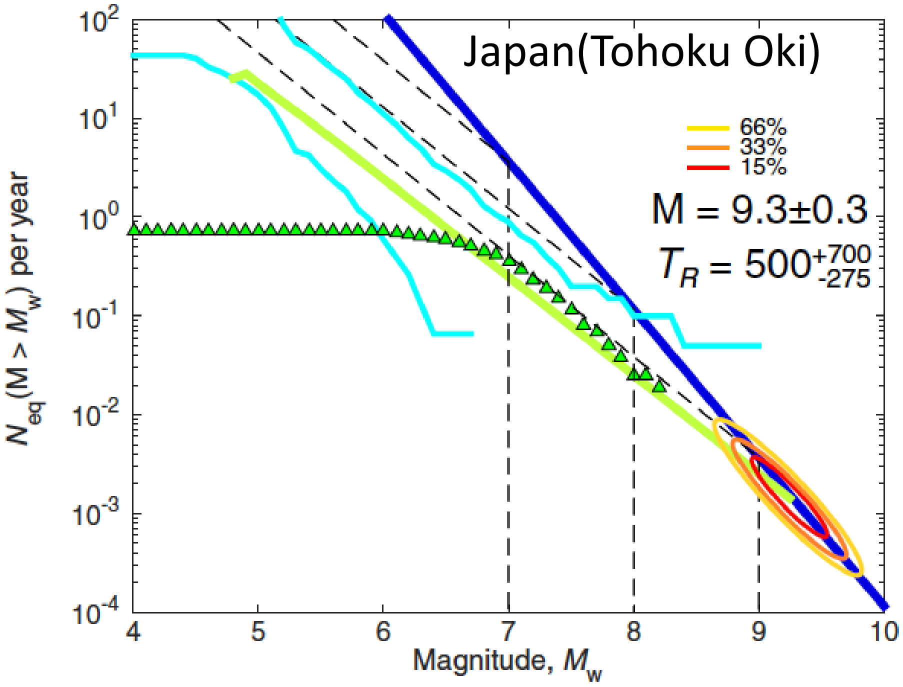


Aseismic slip dominant where T > 350°C.

consistent with laboratory experiments which show that stable frictional sliding is promoted at temperatures higher than about 300°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)

(Stevens&Avouac, BSSA, 2017)