Creep or Stick?

Spatial variations of fault friction, implications for earthquake hazard

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Collaborators

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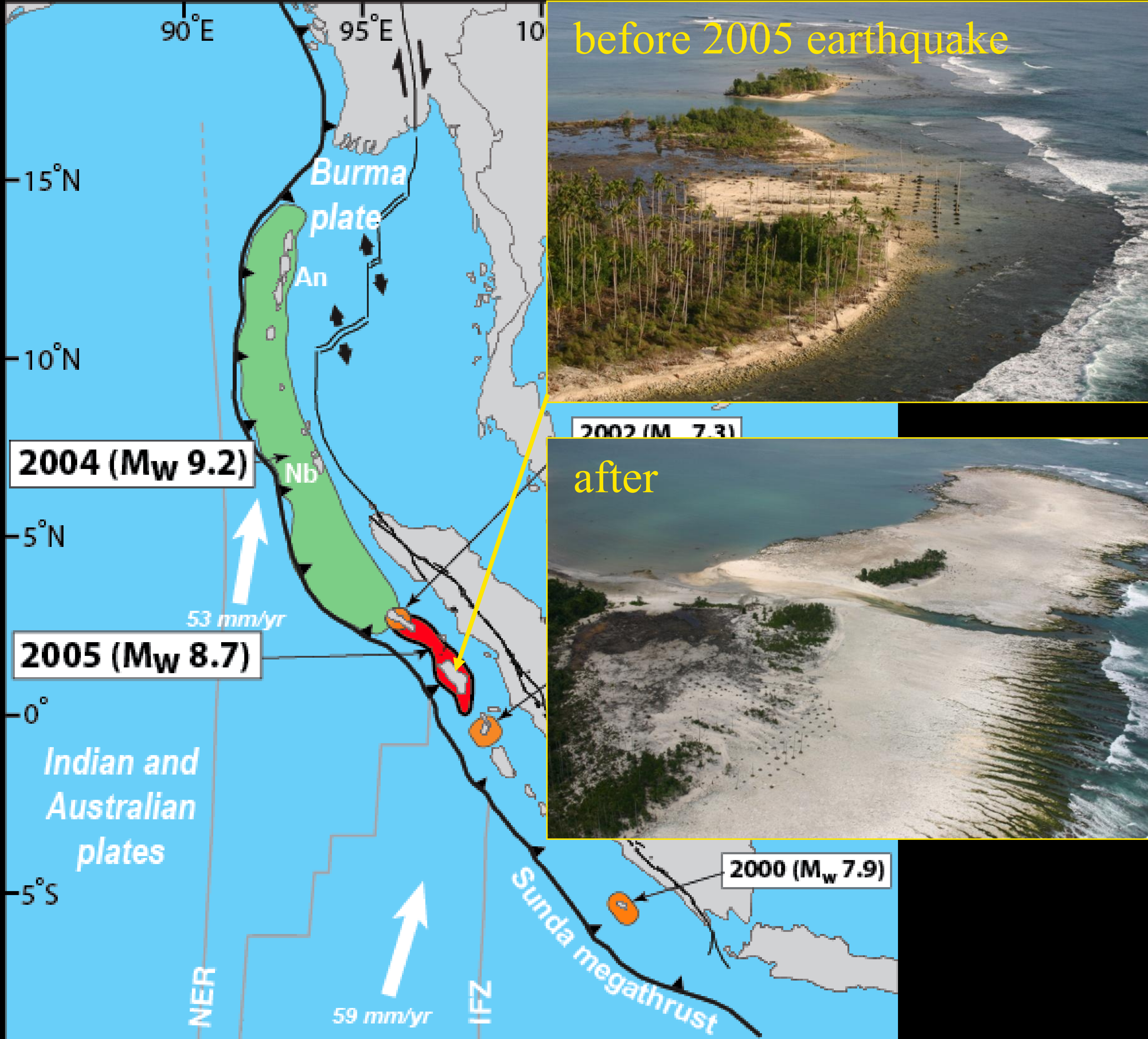
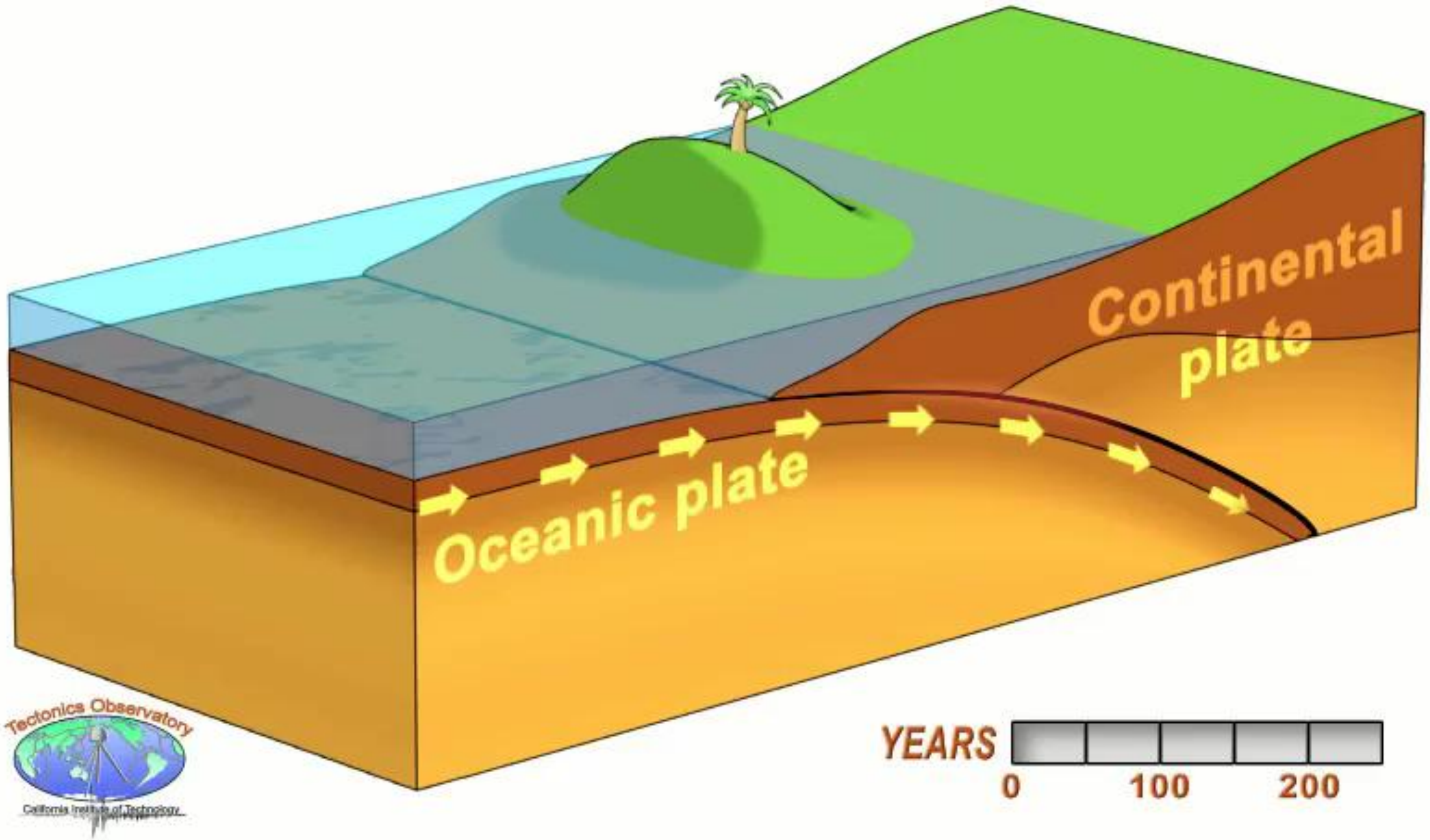
Talk Outline

- Interseismic coupling
- The Sumatra megathrust
- The Longitudinal Valley Fault, Taiwan
- The Himalayan megathrust
- Dynamic modeling: Parkfield, SAF
- What makes fault stick or creep?



before 2005 earthquake
after
90°E
95°E
15°N
10°N
5°N
0°
5°S
Burma plate
An
Nb
2004 (Mw 9.2)
2005 (Mw 8.7)
2000 (Mw 7.9)
53 mm/yr
59 mm/yr
Indian and Australian plates
Sunda megathrust
NER
IFZ


Continental
plate
Oceanic plate
YEARS
0
100
200
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Interseismic coupling

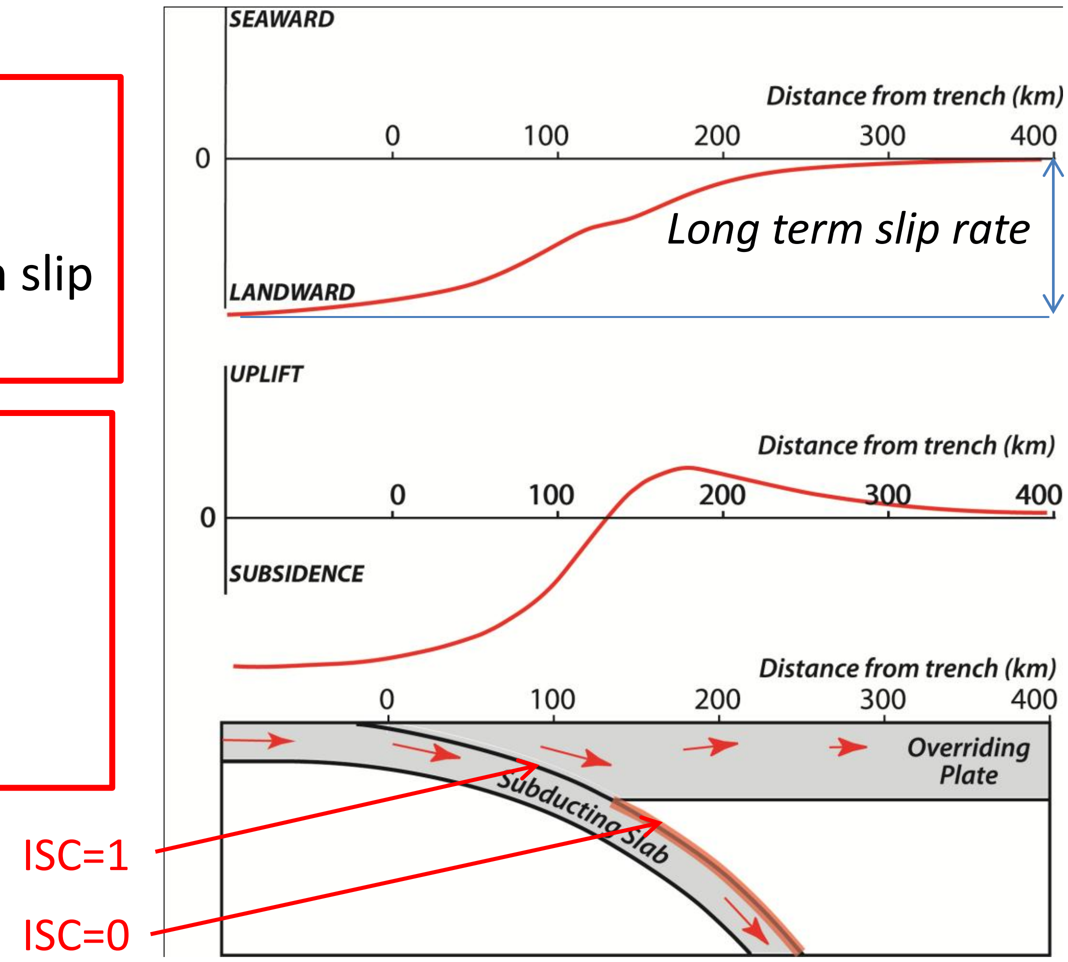
Definition:

ISC

χ_i =deficit of slip/long term slip

Determination:

Elastic Dislocation Modeling of Interseismic geodetic displacements



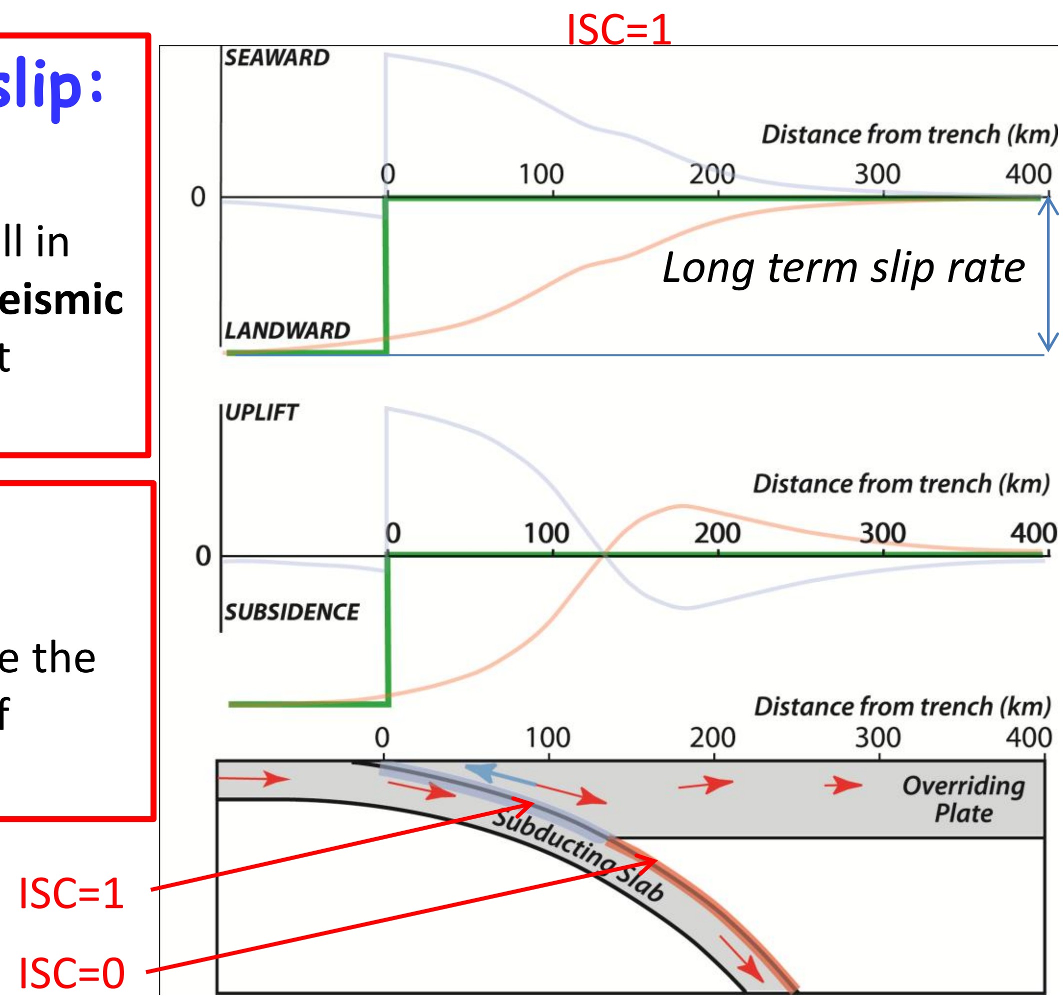
Interseismic coupling

Relation to Seismic slip:

If deformation of the hanging wall in the long term is negligible then **seismic slip and aseismic transients** must balance ISC

Implication:

The ISC pattern should determine the location, amplitude/frequency of seismic and aseismic transients.



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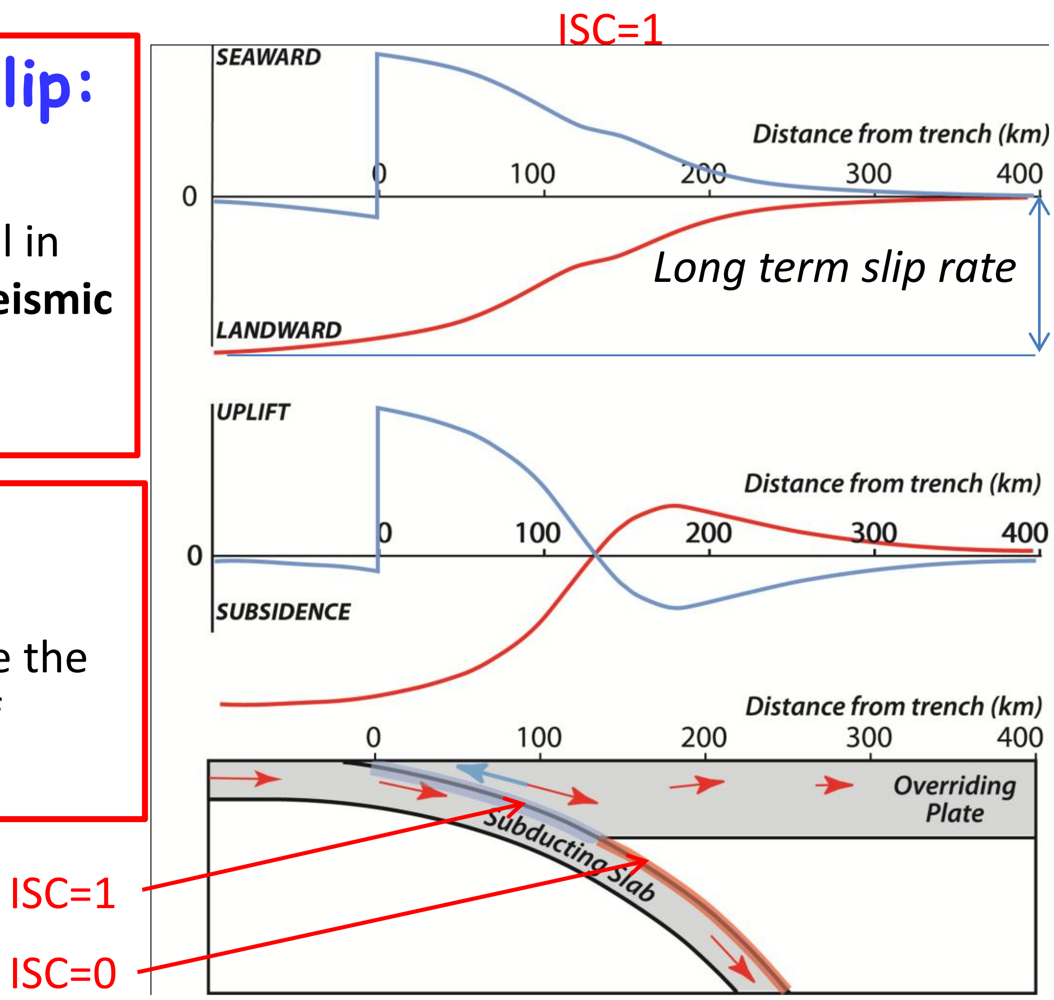

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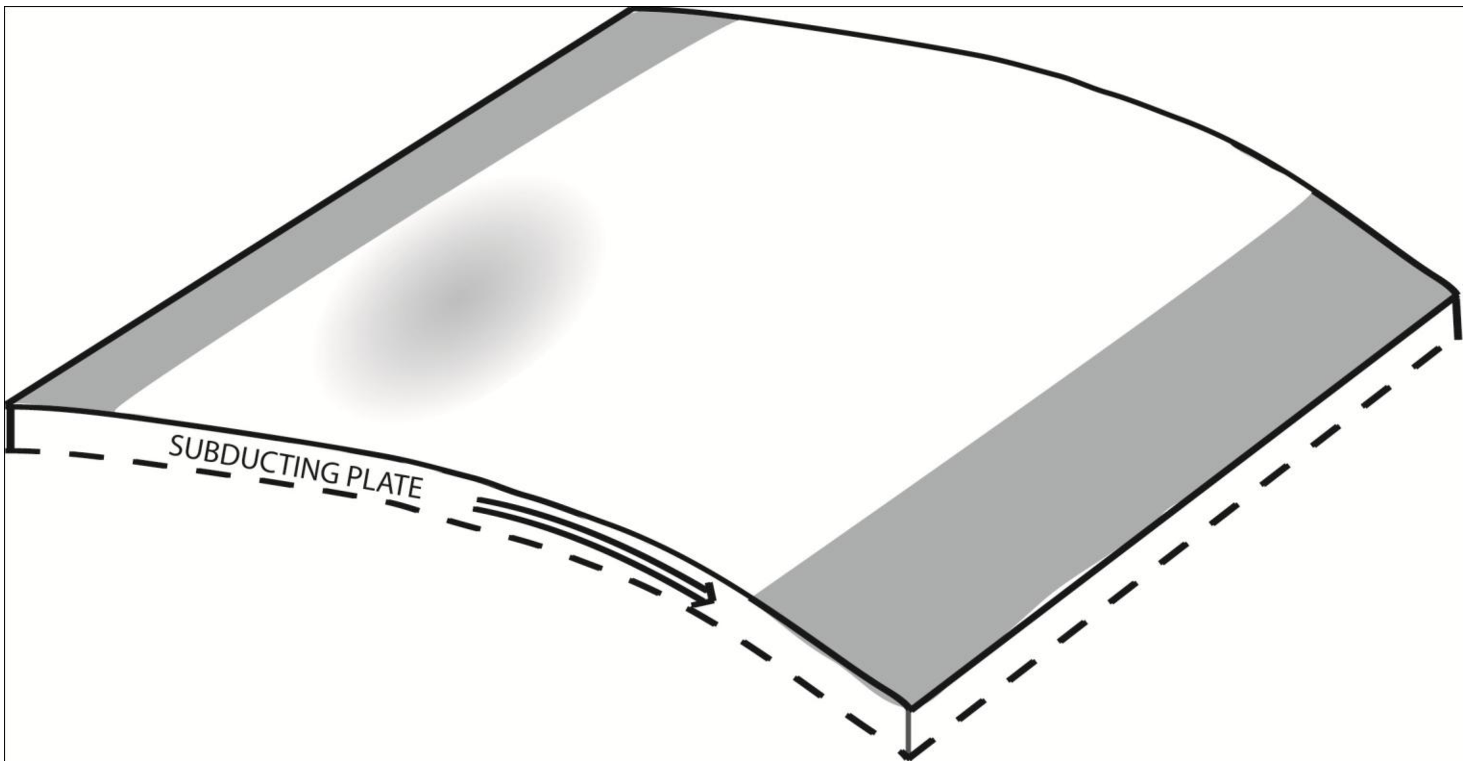
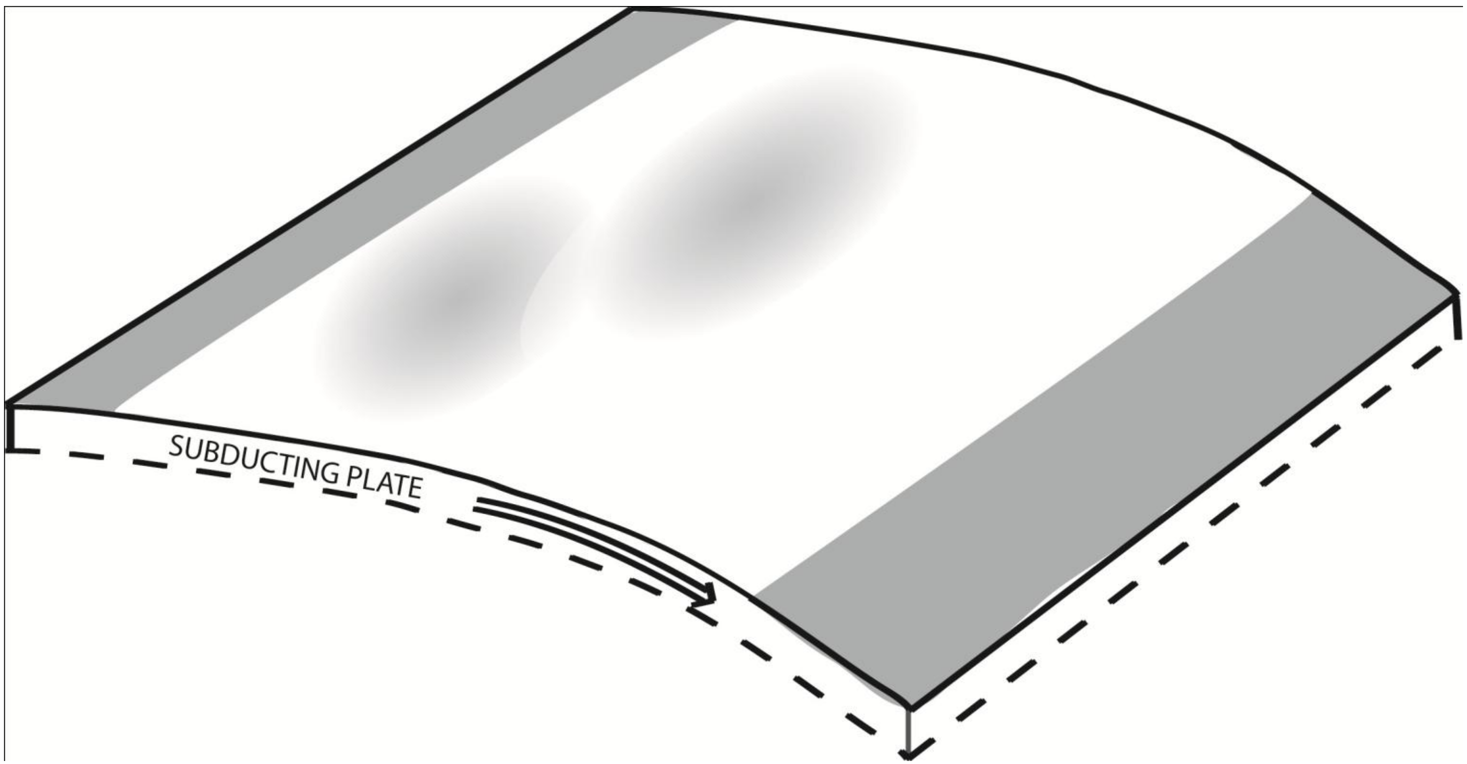
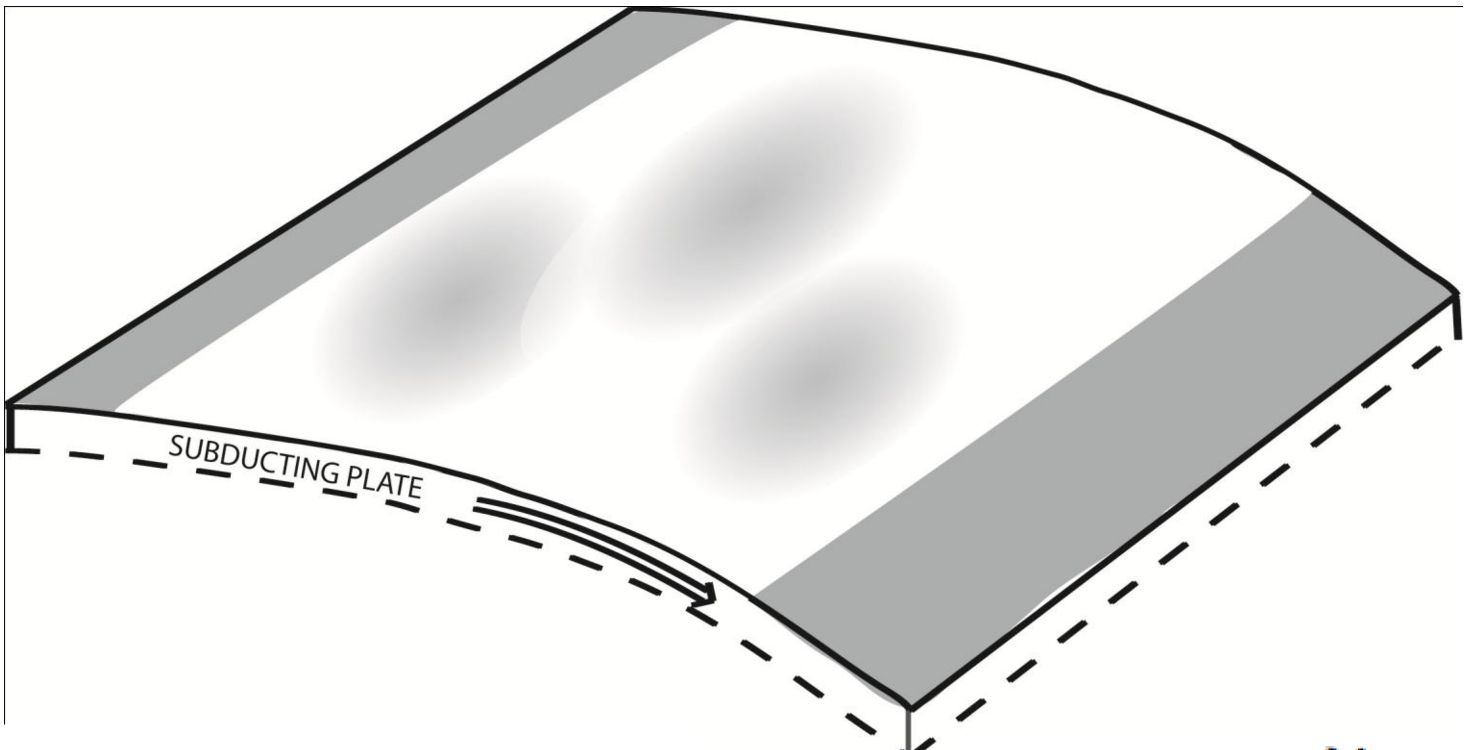
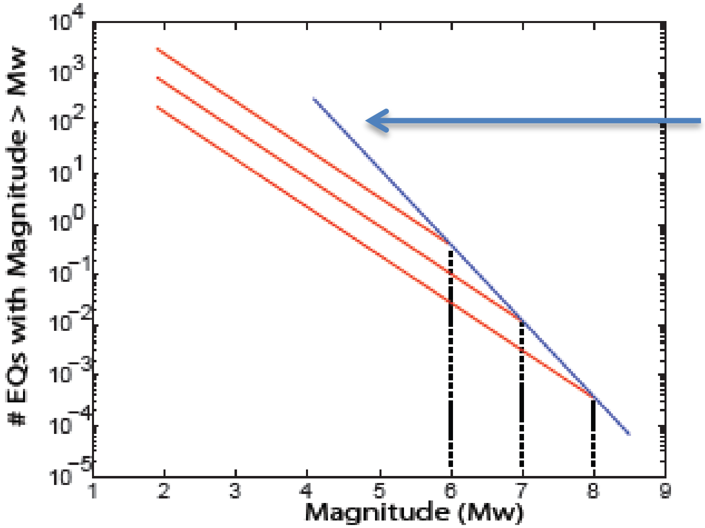



SUBDUCTING PLATE

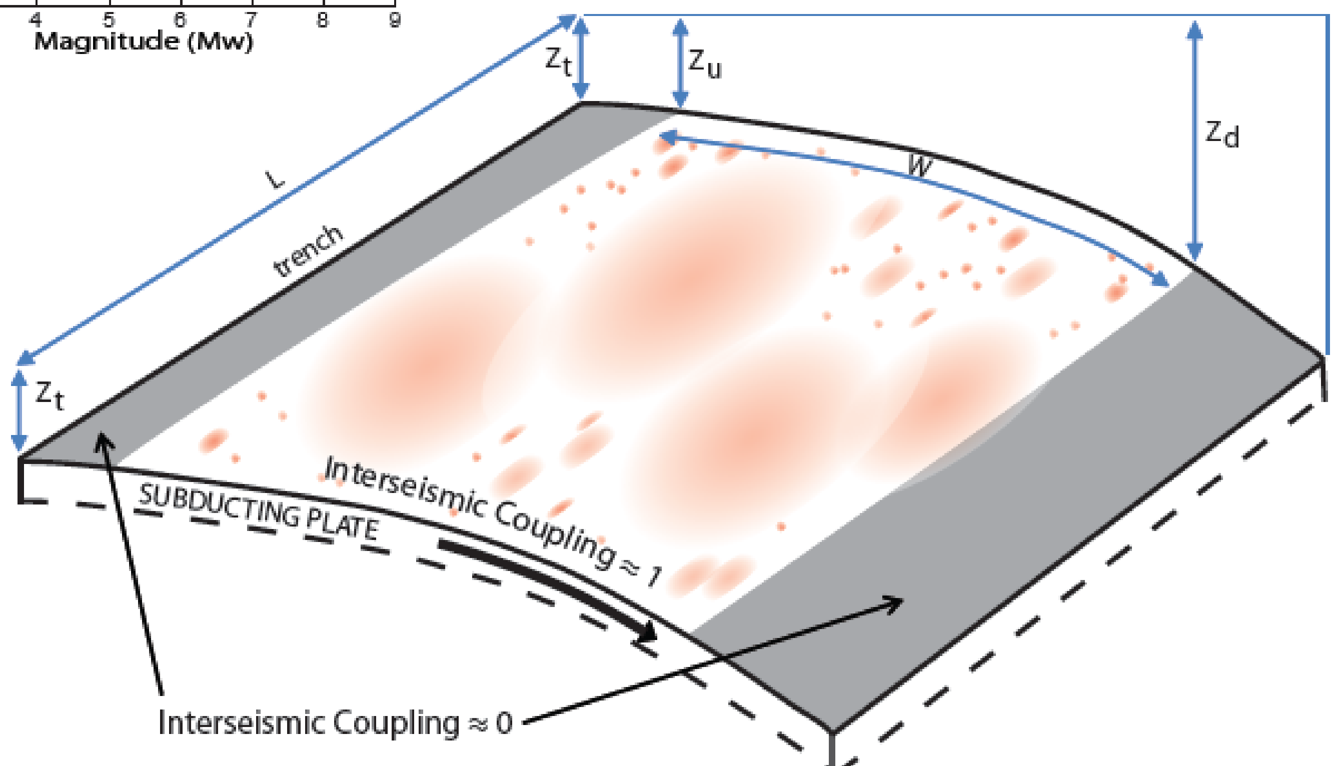


$$\dot{\mathcal{M}}_0 = \int_{Megathrust} \mu V \chi_i ds \,,$$

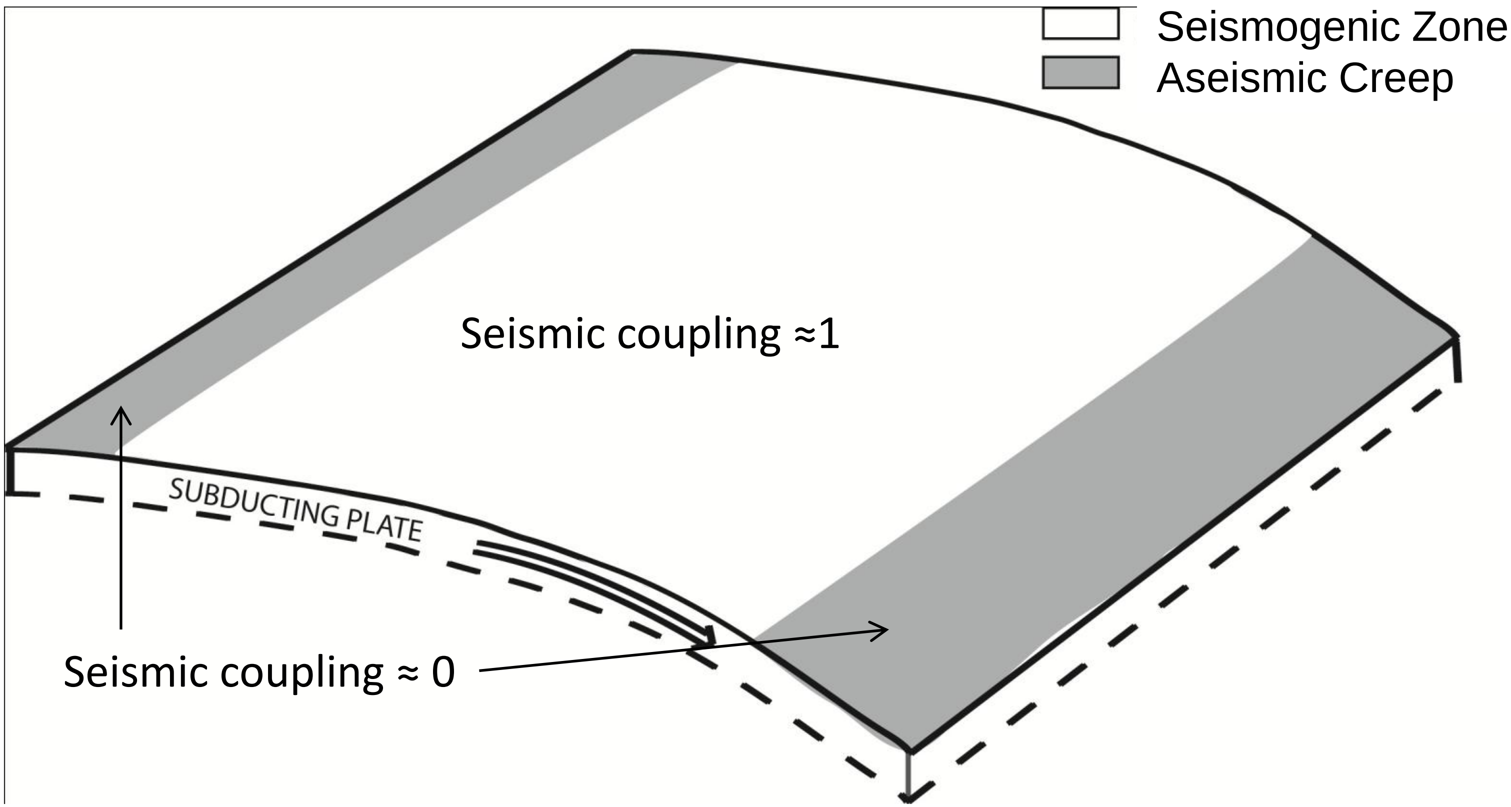
$$T(\mathcal{M}_{char}) = \frac{\mathcal{M}_{char}}{\dot{\mathcal{M}}_0}$$



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



Dynamic Modeling



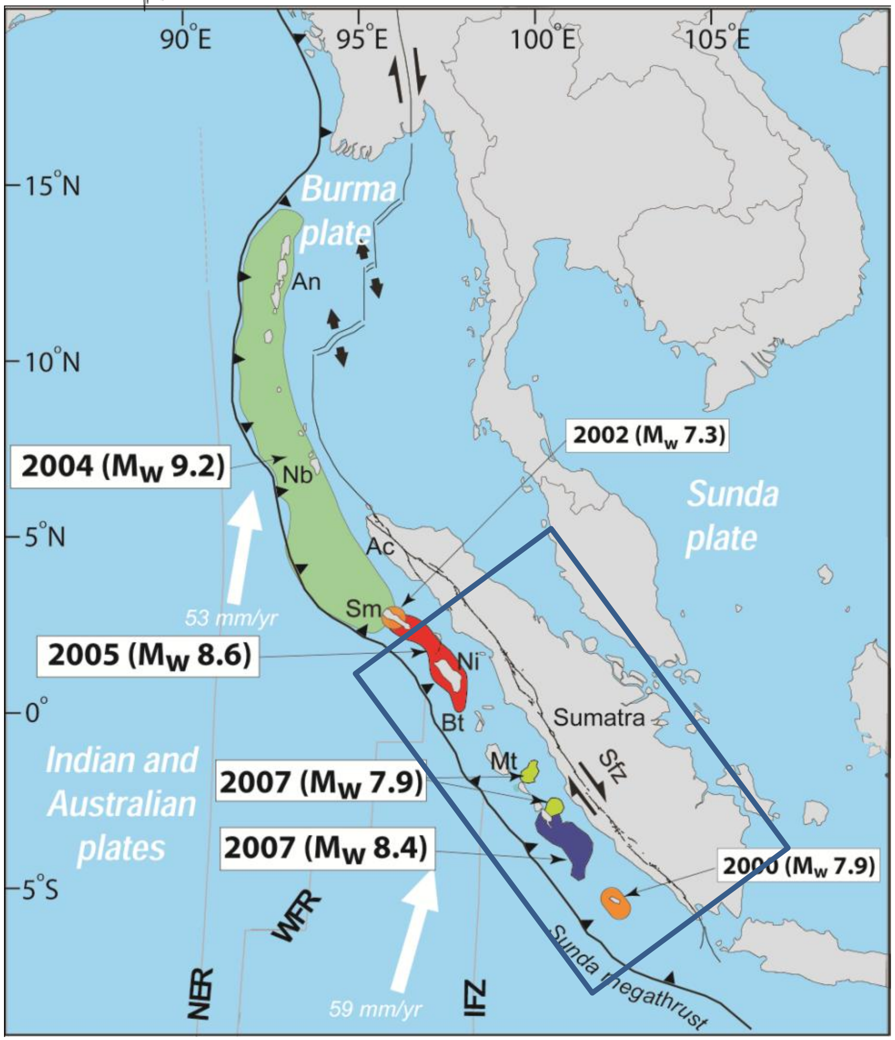
Seismogenic Zone : Rate Weakening (RW) $\mu_s > \mu_d$

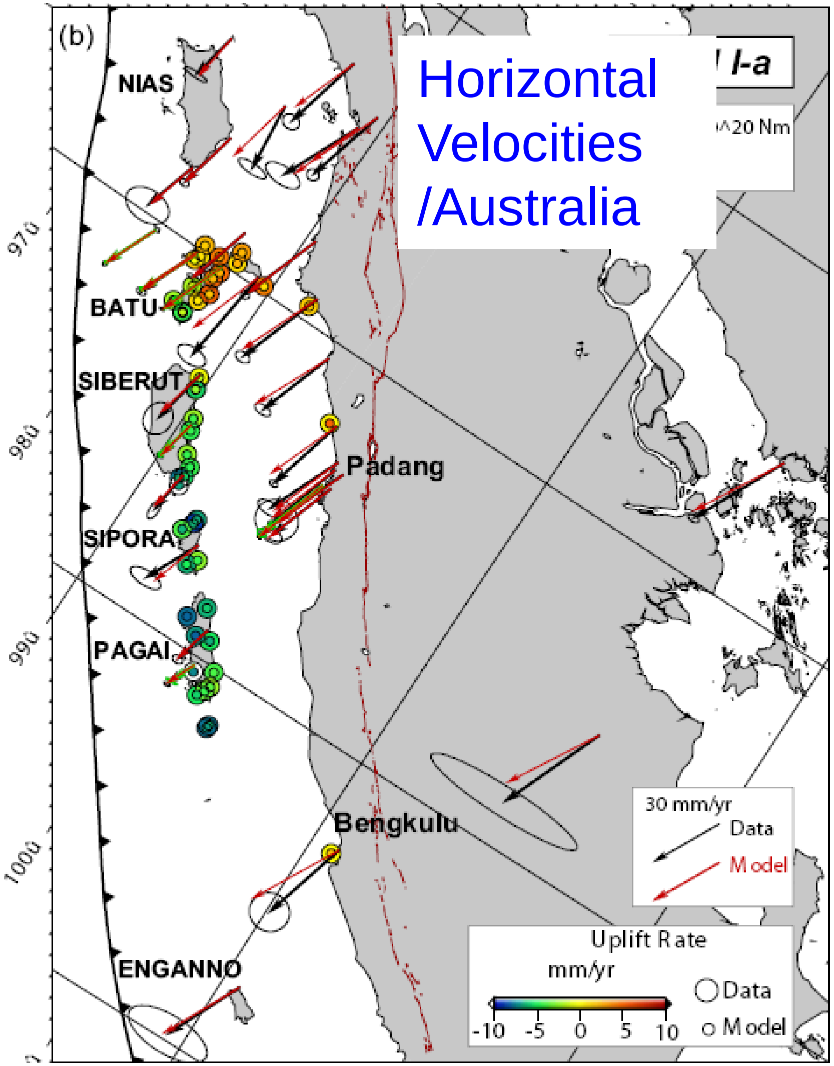
Aseismic Creep : Rate Strengthening (RS) $\mu_s < \mu_d$

μ_s : Static friction

μ_d : Dynamic friction

The Sumatra Megathrust

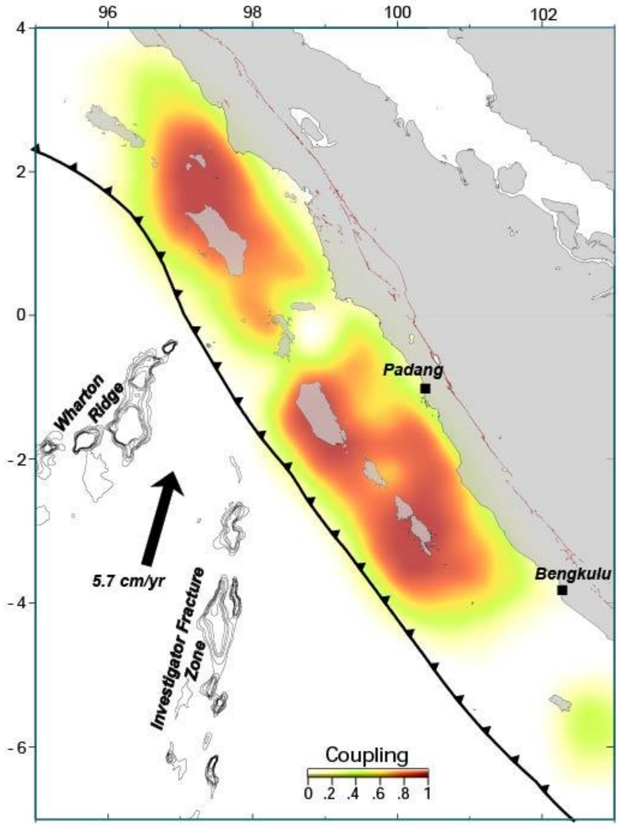




Sources: Natawidjaja et al, (2004), Chlieh et al, (2008); Briggs et al (2006); Hsu et al (2006); Konca et al (2006, 2008)

The Sumatra Megathrust

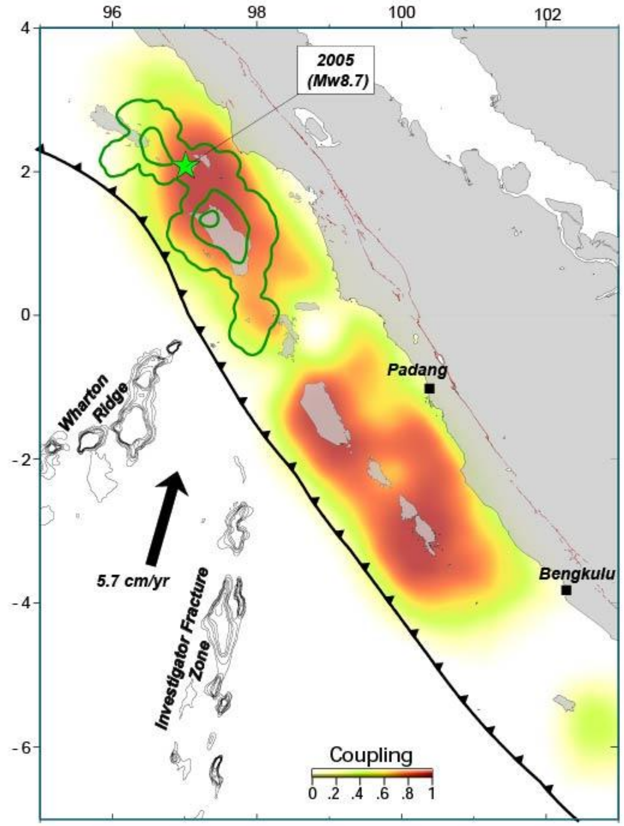
- Interseismic coupling



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



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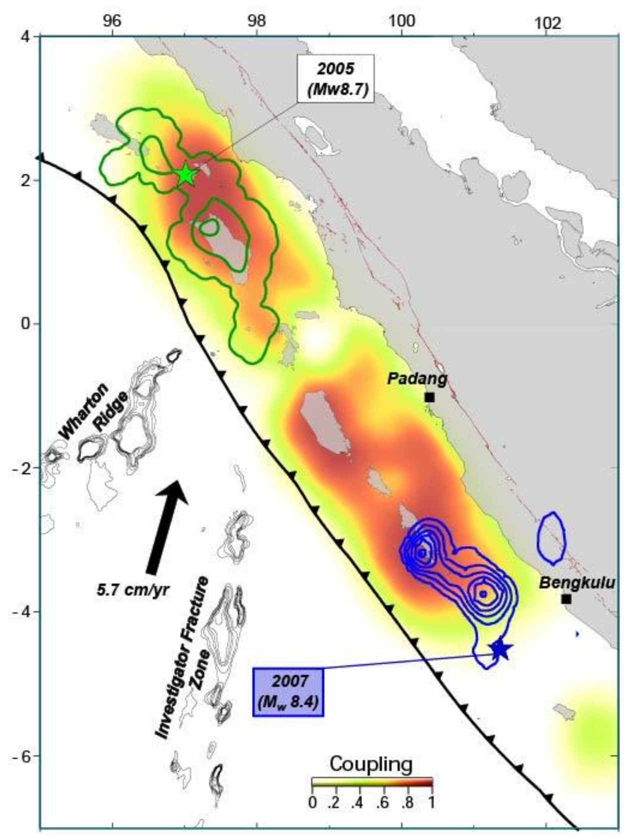

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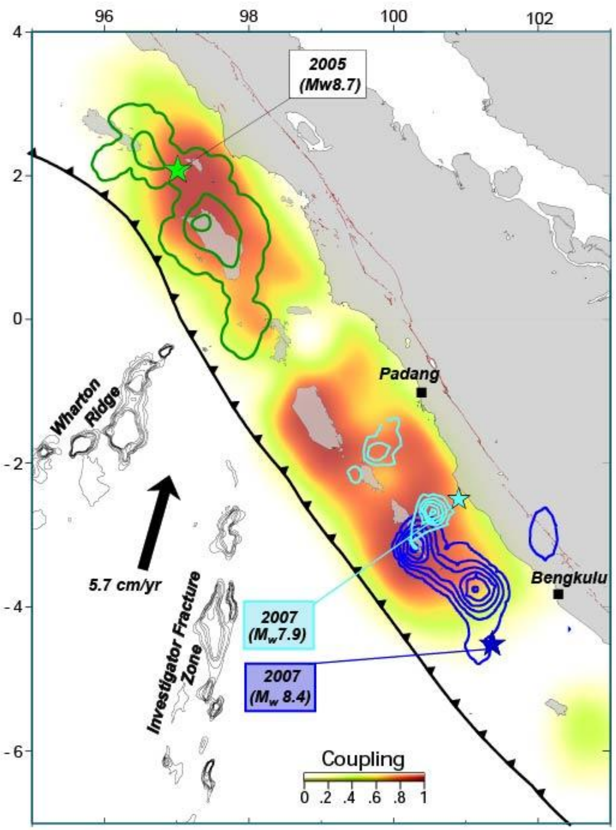
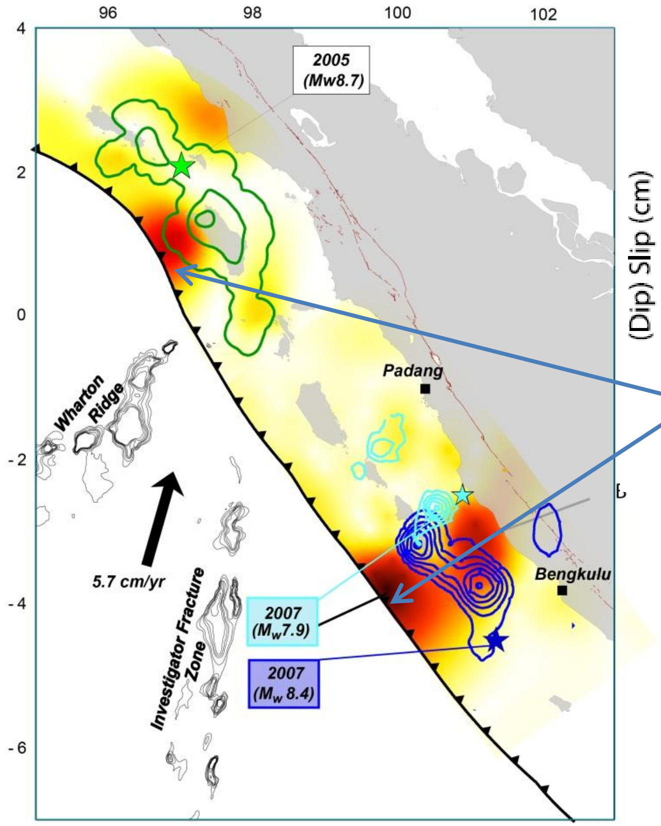


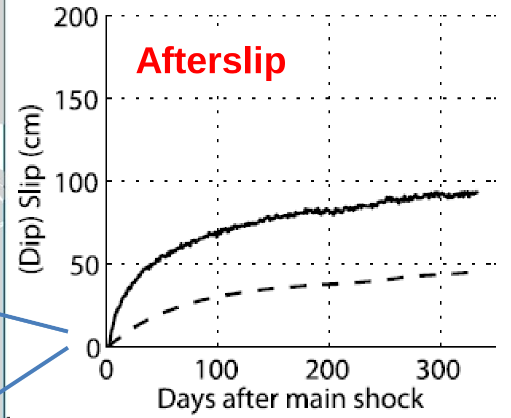
Comparison of Interseismic Coupling (deficit of slip in the interseismic period) with seismic and aseismic transient slip.

The Sumatra Megathrust

Afterslip: 30% of coseismic moment release over 1 yr

- 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





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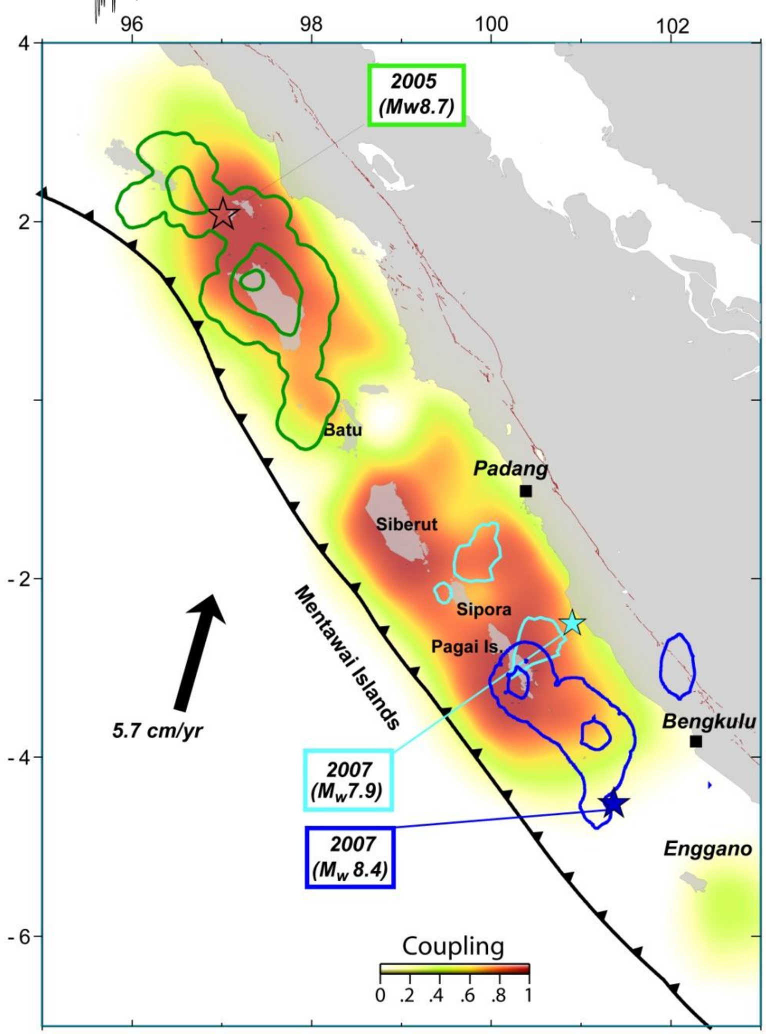
The Sumatra Megathrust

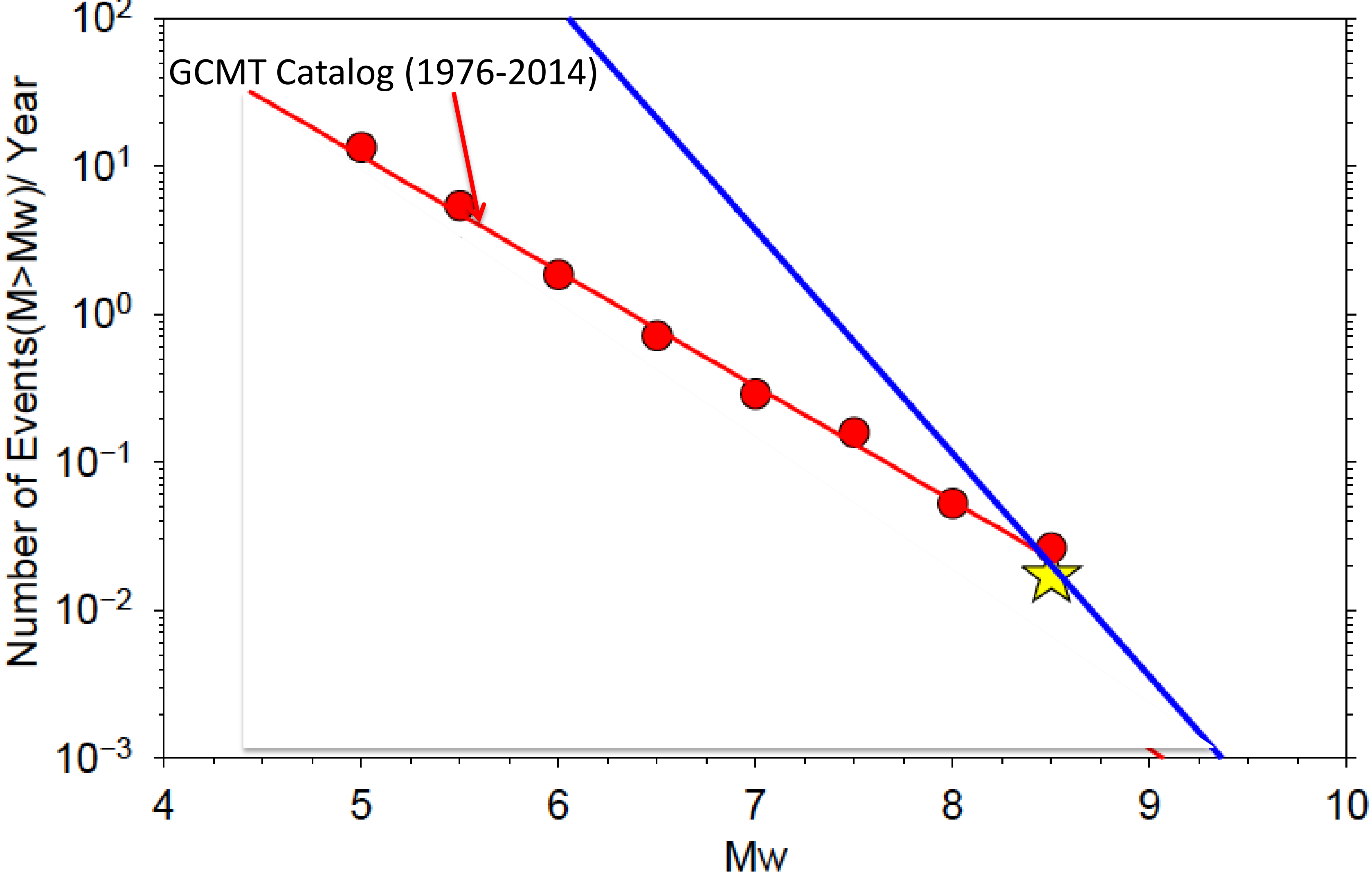


- Interseismic coupling is highly heterogeneous
- Slip is mosty aseismic (50-60%) in the 0-40km 'Seismogenic' depth range
- Seismic ruptures seem confined to 'locked' areas. Creeping zones tend to arrest seismic ruptures.
- Afterslip increases as a logarithmic function of time.

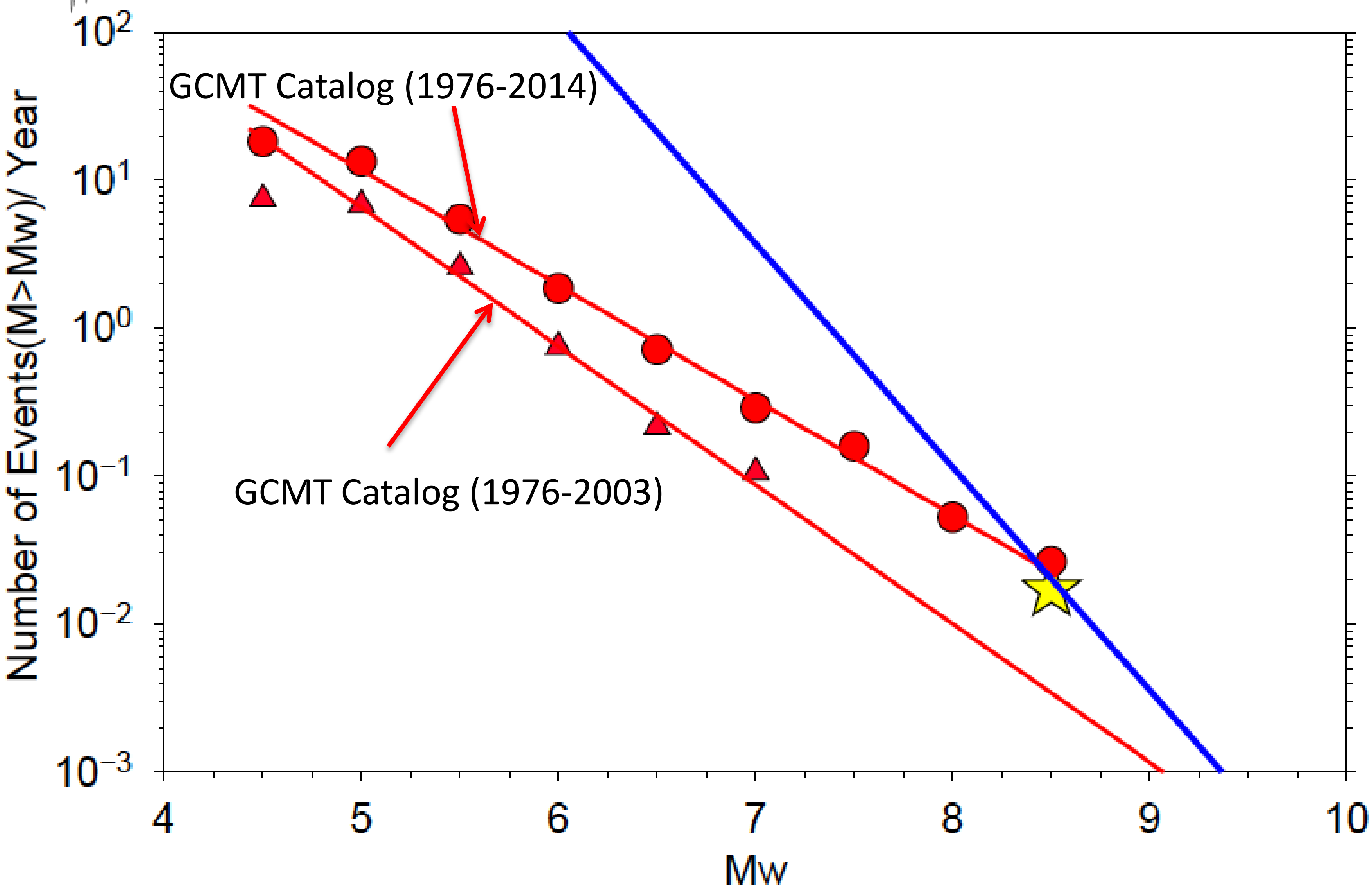
Does the slip budget close (seismic +aseismic slip=long term slip)?

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

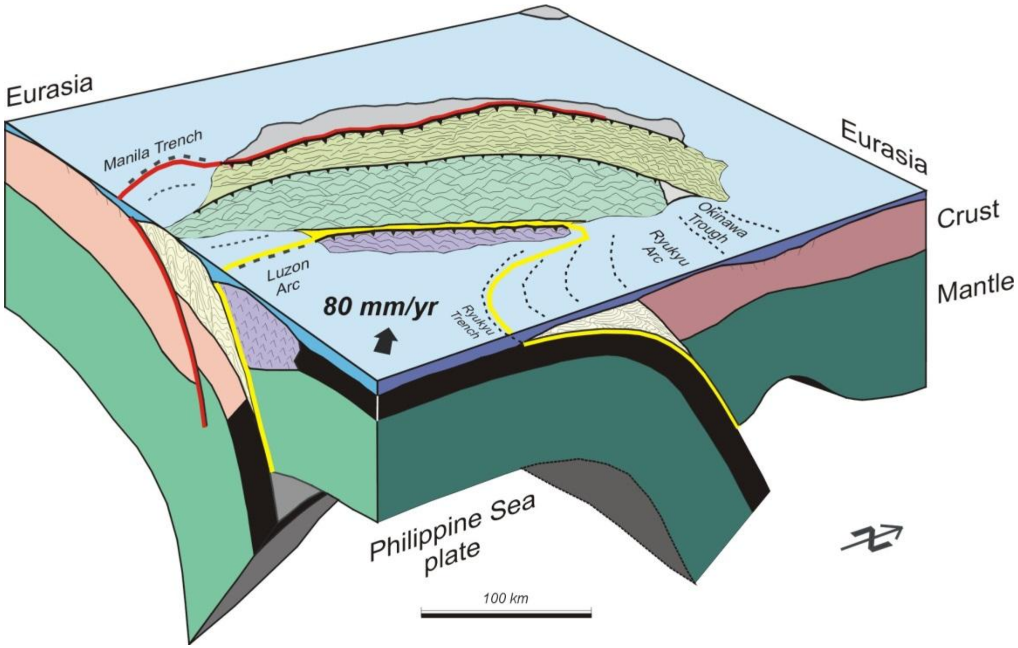
The Sumatra Megathrust

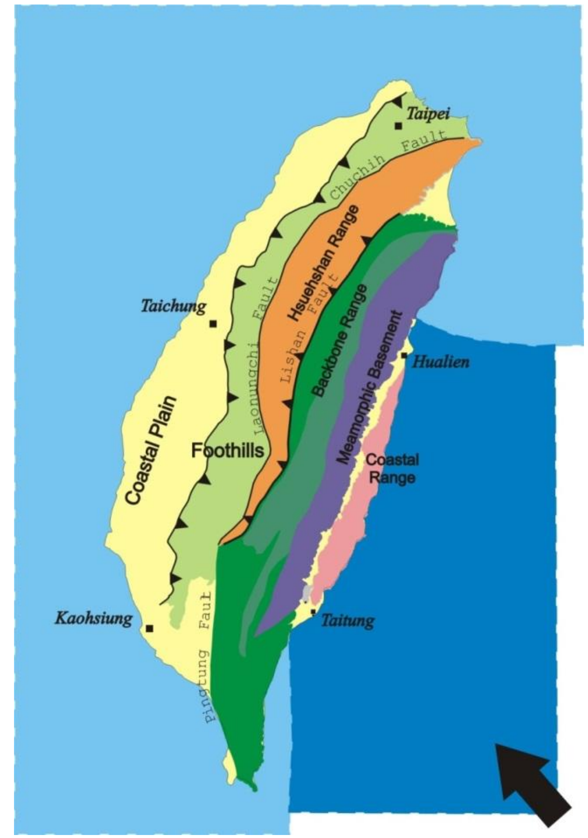


The Sumatra Megathrust

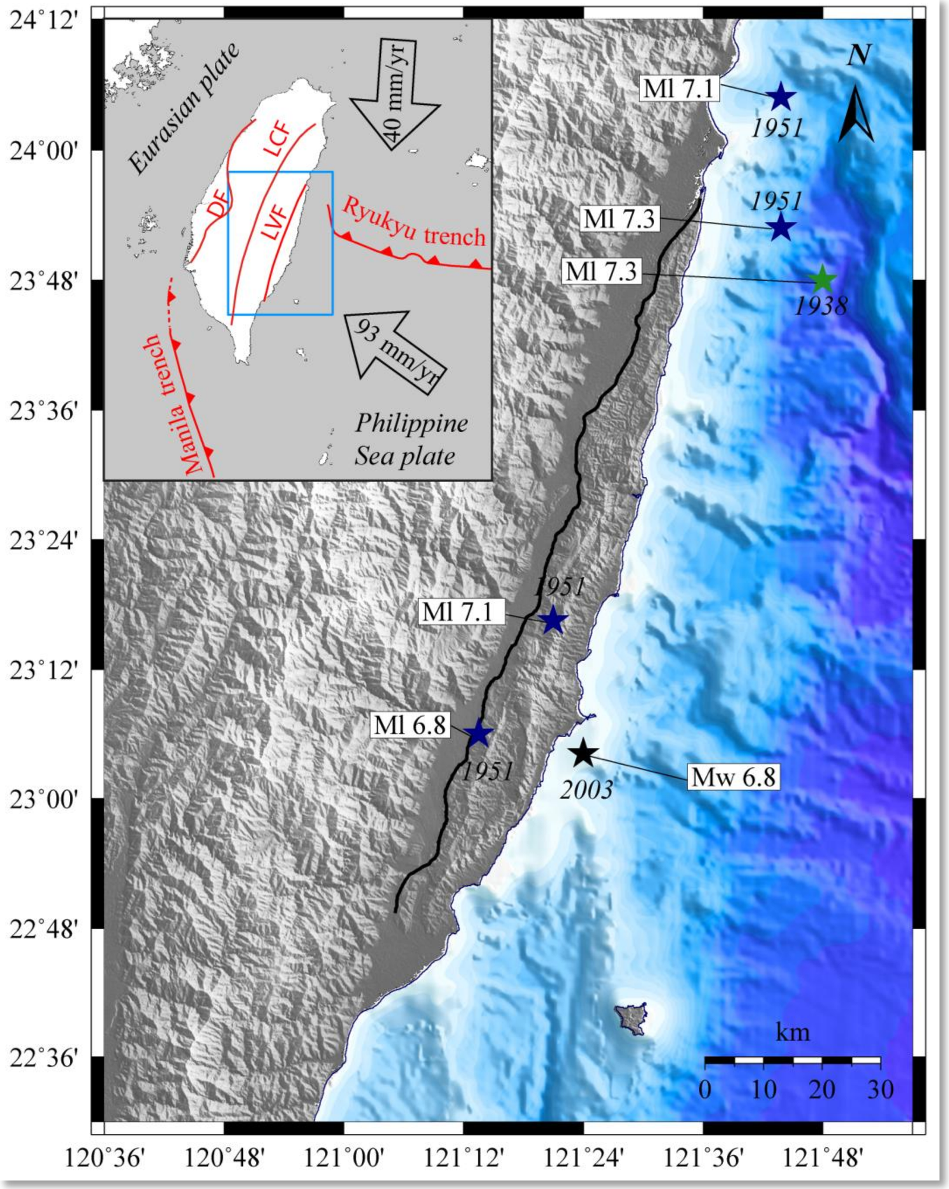


The Longitudinal Valley fault





(Thomas et al, JGR, 2014; Thomas et al, Tectonophysics, 2014))

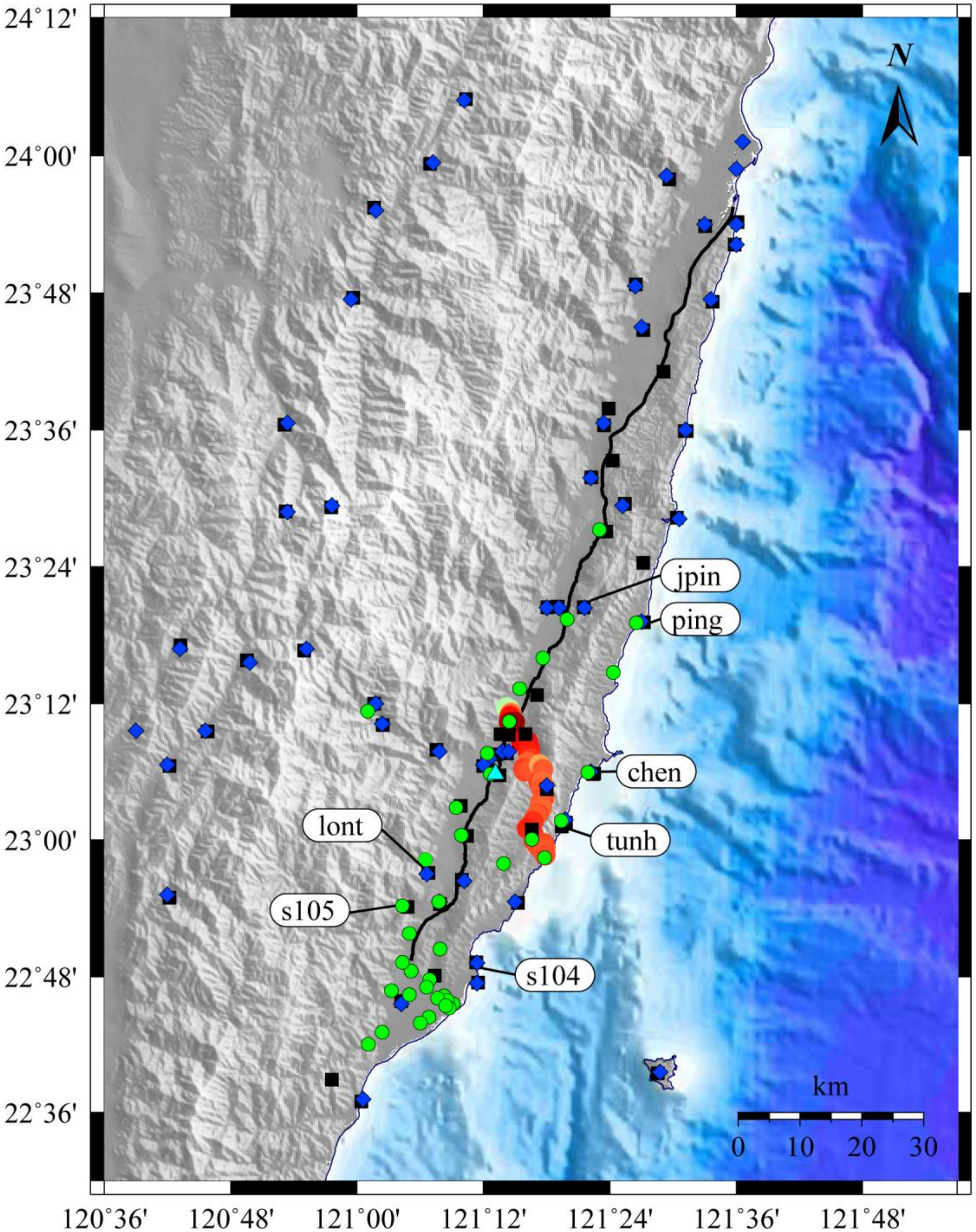


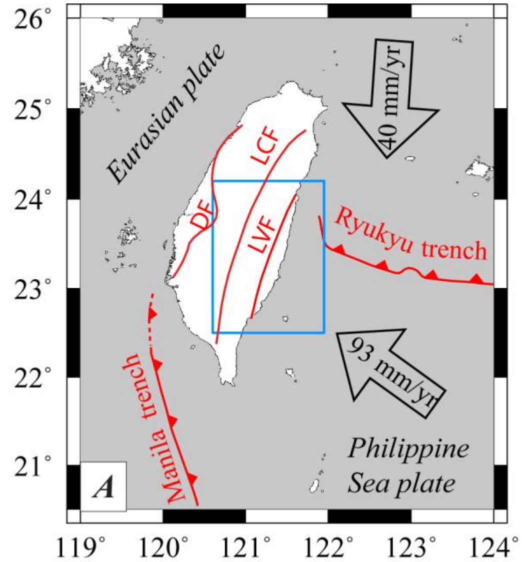
Why studying the longitudinal valley fault?

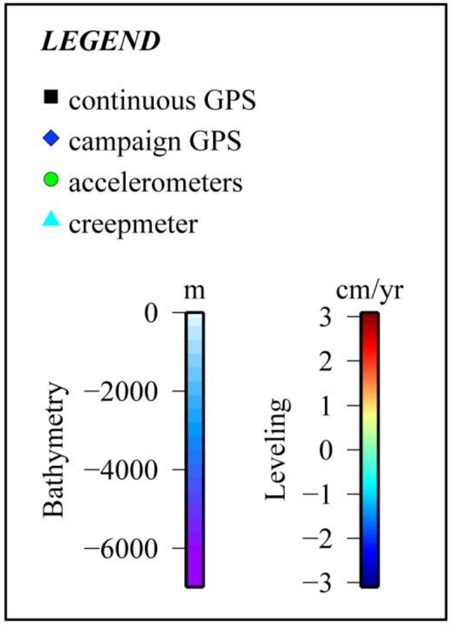
- LVF is part of very active plate boundary
- High slip rate: > 4 cm/yr
- Aseismic creep documented at the surface

- Large earthquakes : M>7 1951 ; Mw6.8 2003
- Thrust fault: an access to exhumed fault zone

THE LONGITUDINAL VALLEY FAULT (TAIWAN)







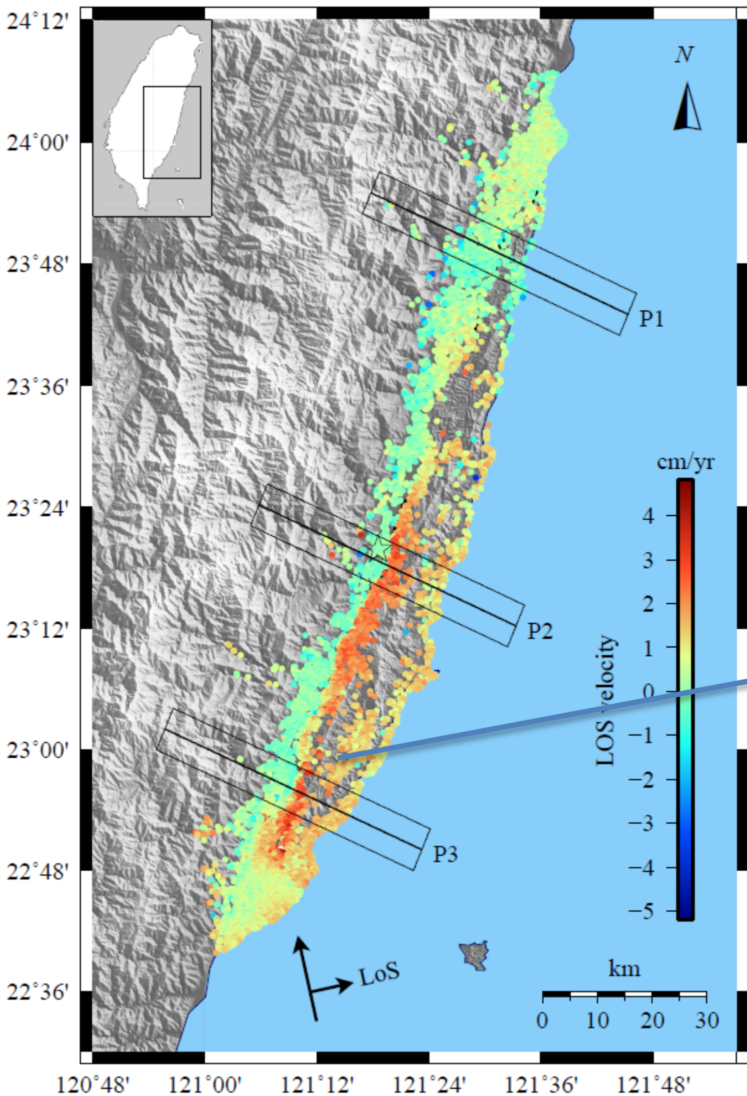
GPS times series
From 1994 to 2010
Tec websites
67 stations

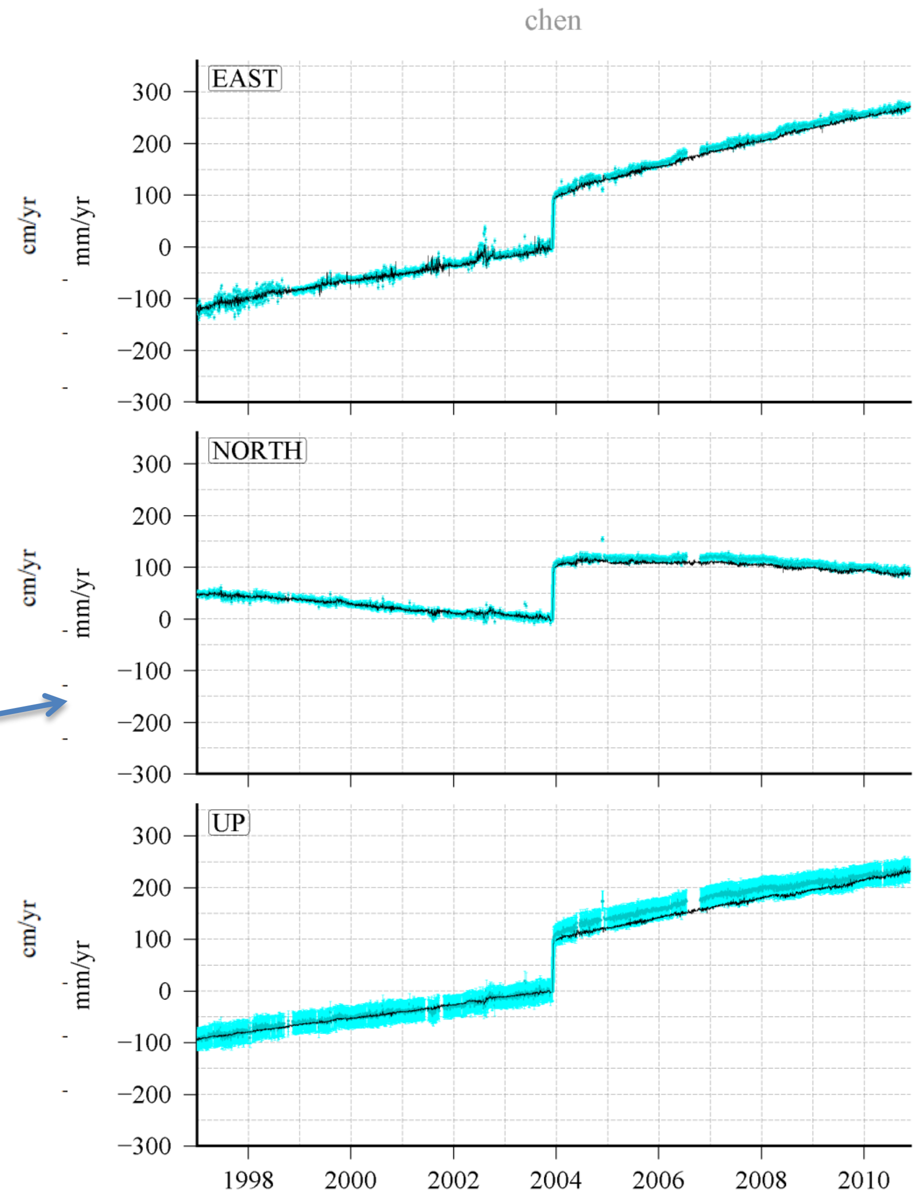
Accelerometers
2003 Chengkung EQ
Wu et al, 2006
38 stations

Campaign GPS
From 1992 to 1999
Yu et al, 2001
45 stations

Leveling
From 2007 to 2010
Chen et al, 2012

THE LONGITUDINAL VALLEY FAULT (TAIWAN)





Yohann Champenois

Principal Component Analysis based Inversion Method (PCAIM)

- Method based on the theory of dislocations in an elastic half space and Principal Component Analysis

$X = USV^t$

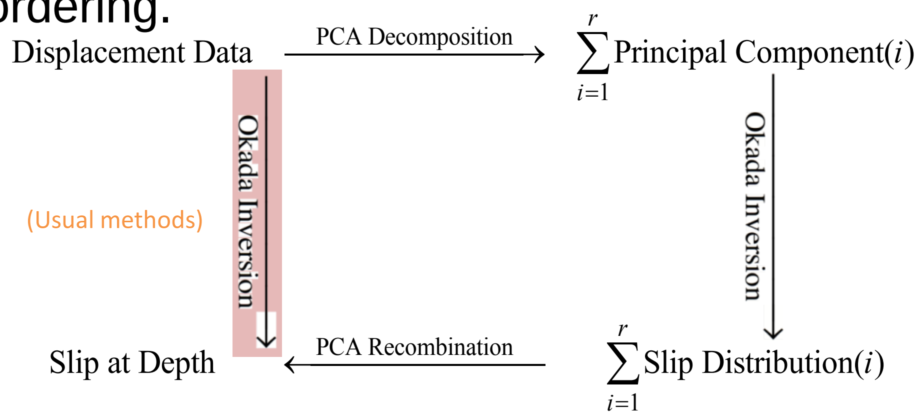
$U = GG \cdot L$

$X = (GG \cdot L)\,SV^t$

$X = GG\,(LSV^t)$

Singular Value Decomposition of surface displacement series
+
least-square inversion formulation
=
Slip decomposition

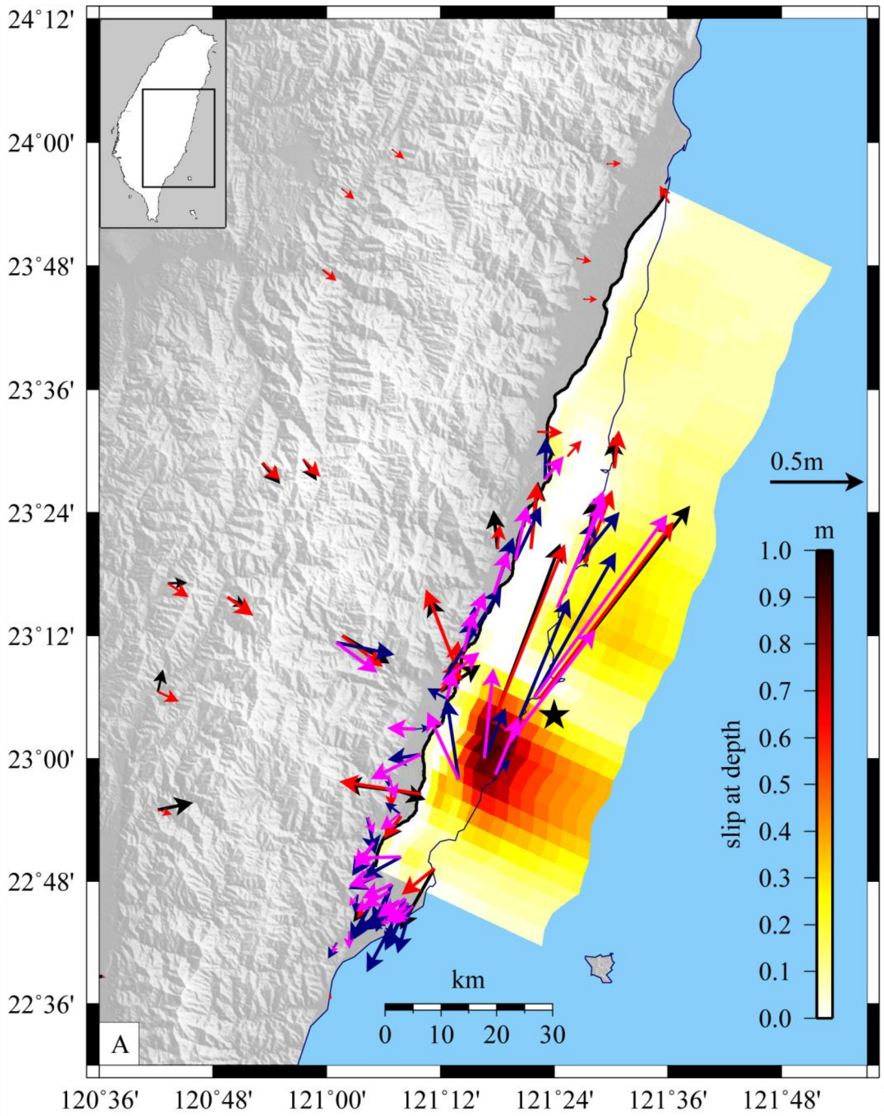
- PCA and theory of dislocations are linear and associative and thus you can switch their ordering.



- PCAIM can deal with any kind of time variation of fault-slip
- PCAIM can integrate simultaneously different geodetic measurement and remote sensing data.

(Kositsky and Avouac, JGR 2010, Perfettini et al, 2010)

THE LONGITUDINAL VALLEY FAULT (TAIWAN)

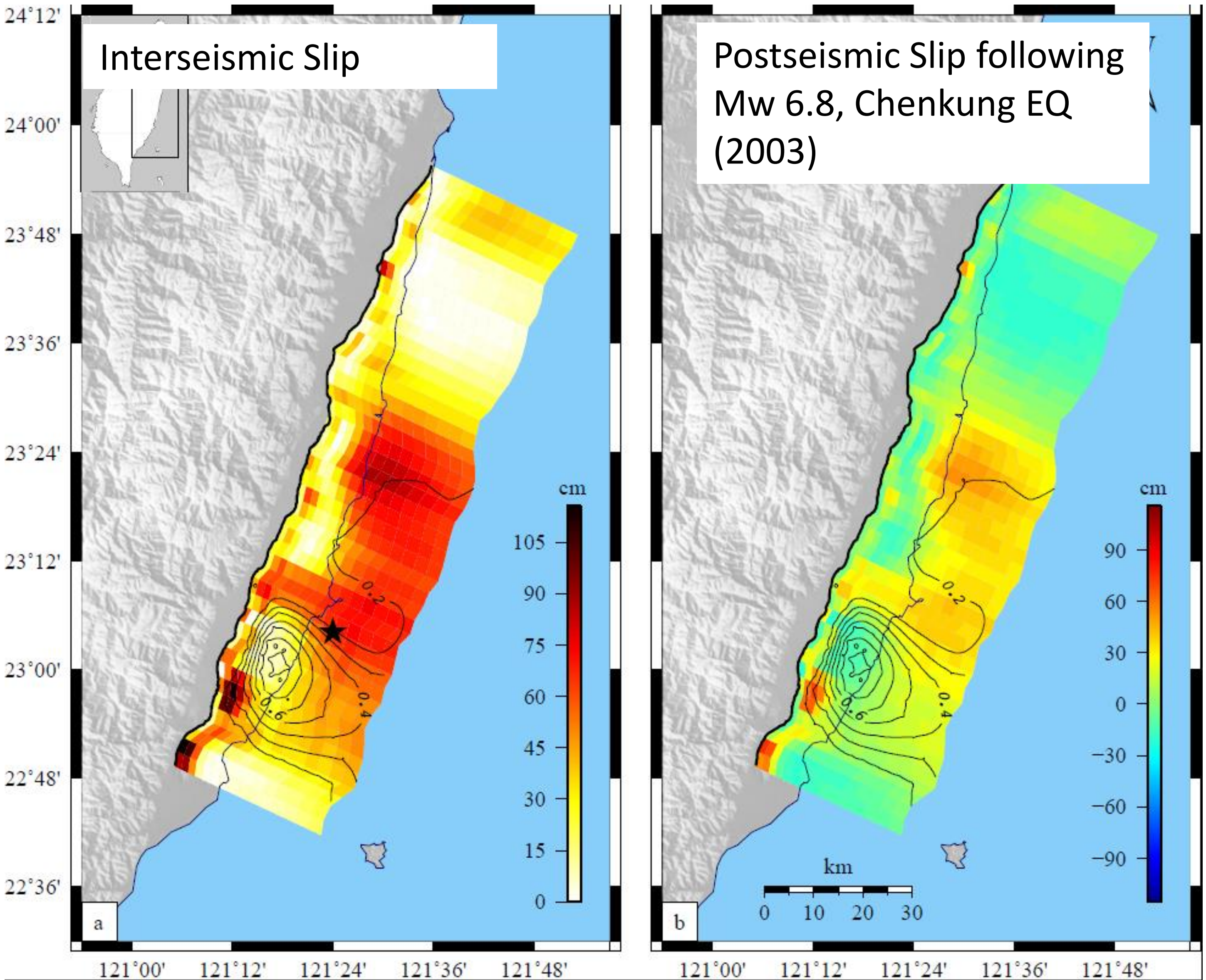


CO-SEISMIC MODEL

(2003, Mw 6.8, chengkung earthquake)

(Thomas et al, JGR, 2014)

THE LONGITUDINAL VALLEY FAULT (TAIWAN)



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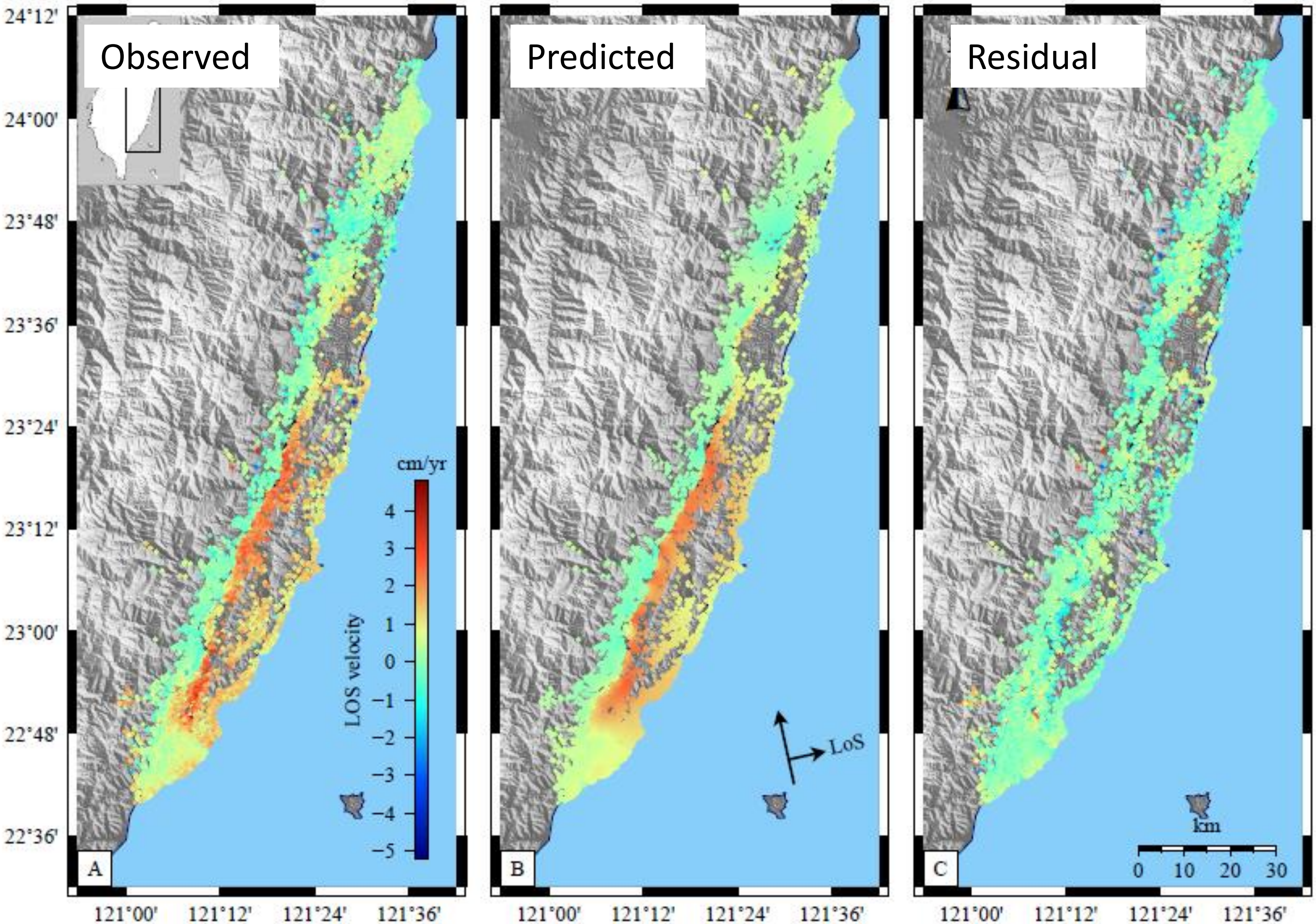
THE LONGITUDINAL VALLEY FAULT (TAIWAN)



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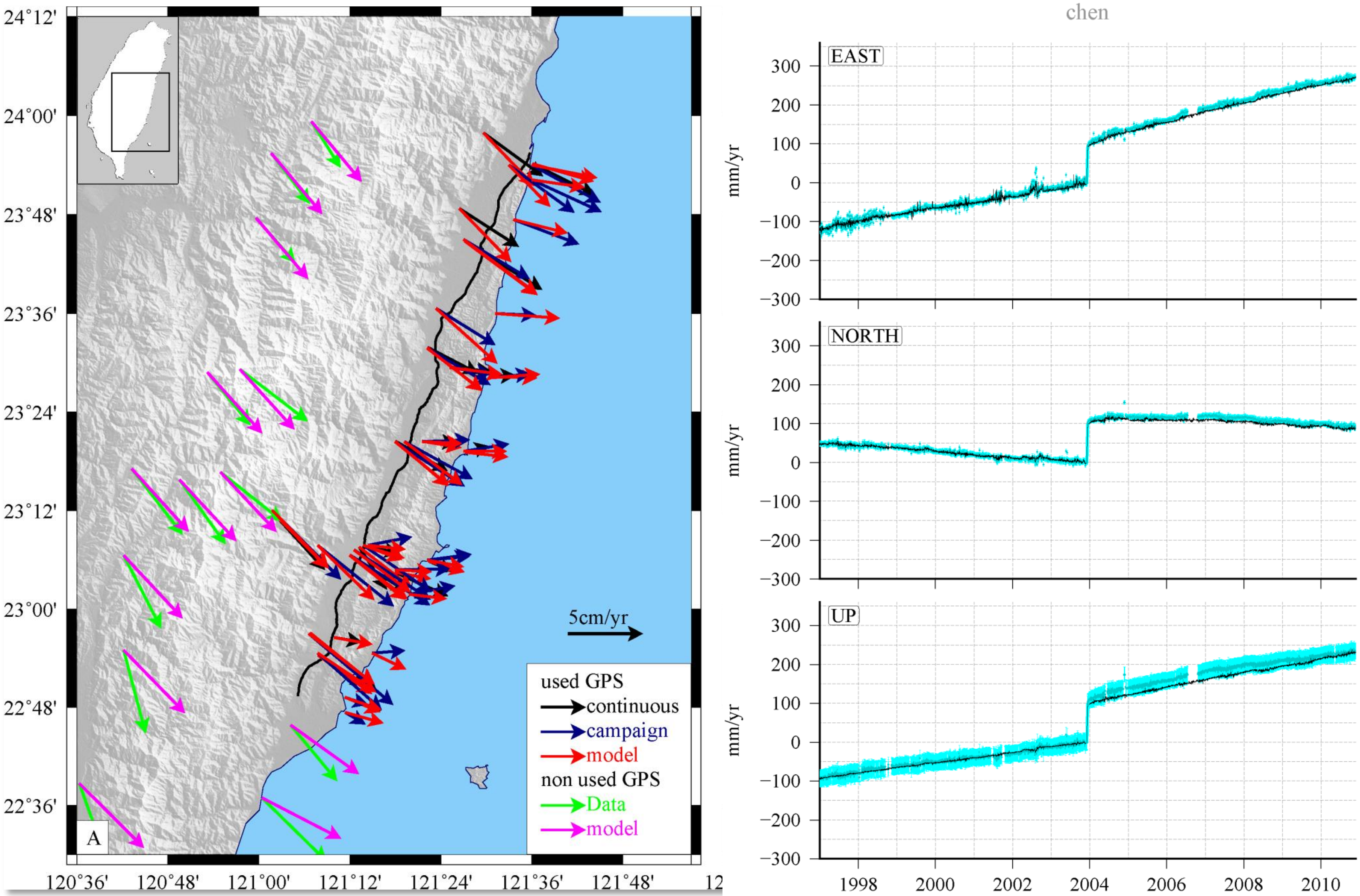

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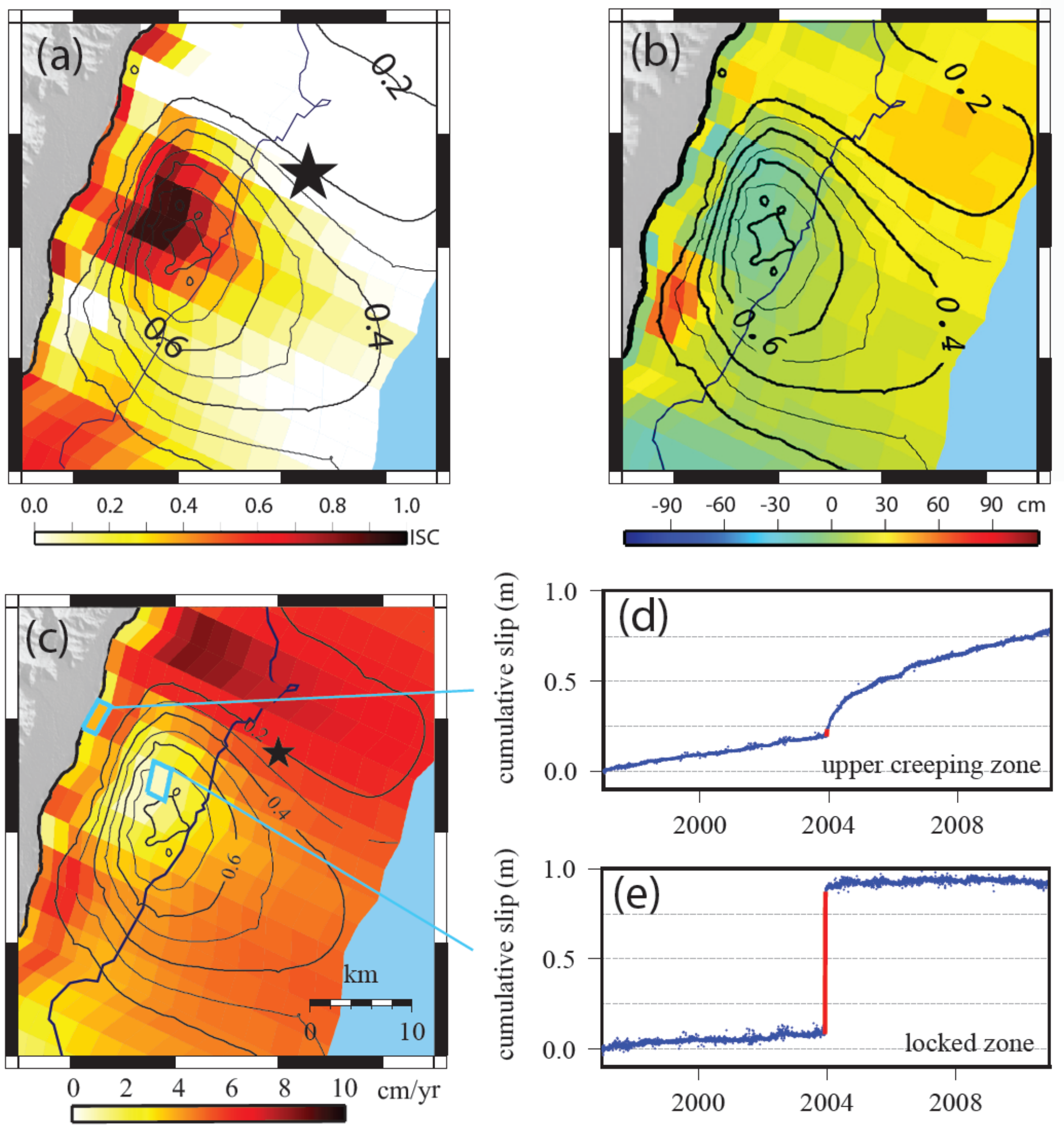
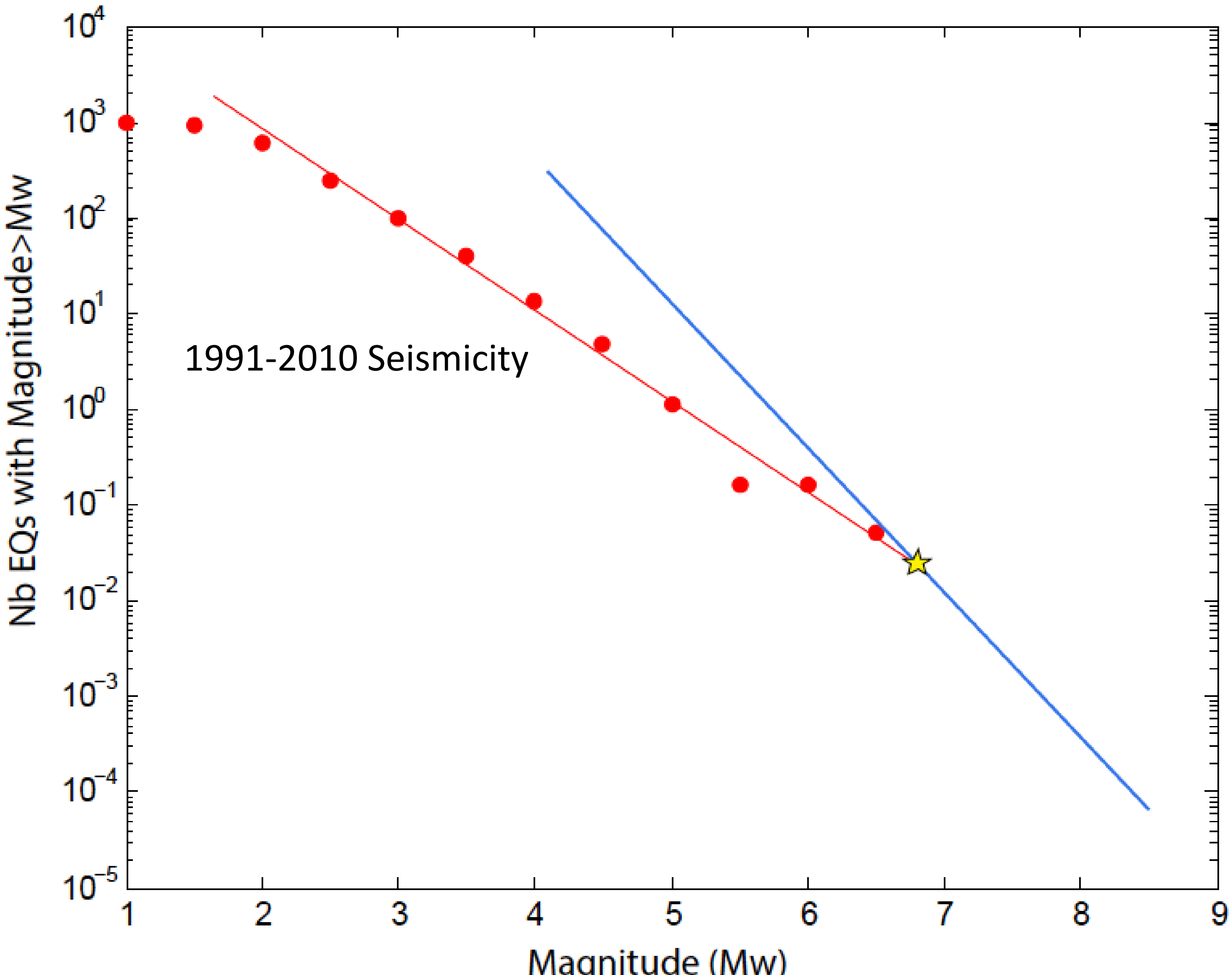


- Interseismic coupling is highly heterogeneous
- Slip is mosty (80%) aseismic in the 0-40km 'Seismogenic' depth range
- Seismic ruptures seem confined to 'locked' areas. Creeping zones tend to arrest seismic ruptures.

TIME EVOLUTION OF SLIP AT DEPTH

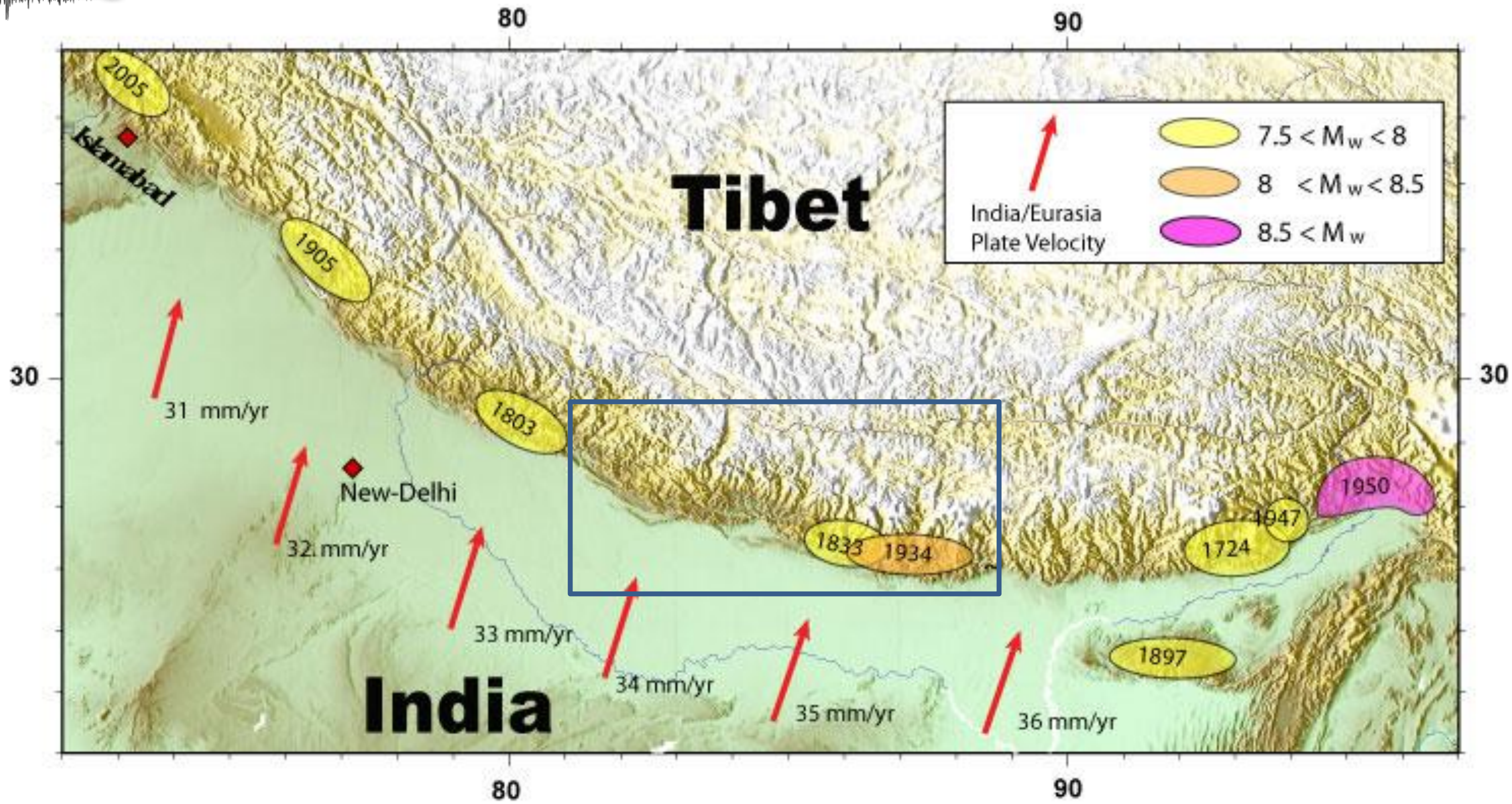
(Thomas et al, JGR, 2014)

THE LONGITUDINAL VALLEY FAULT (TAIWAN)



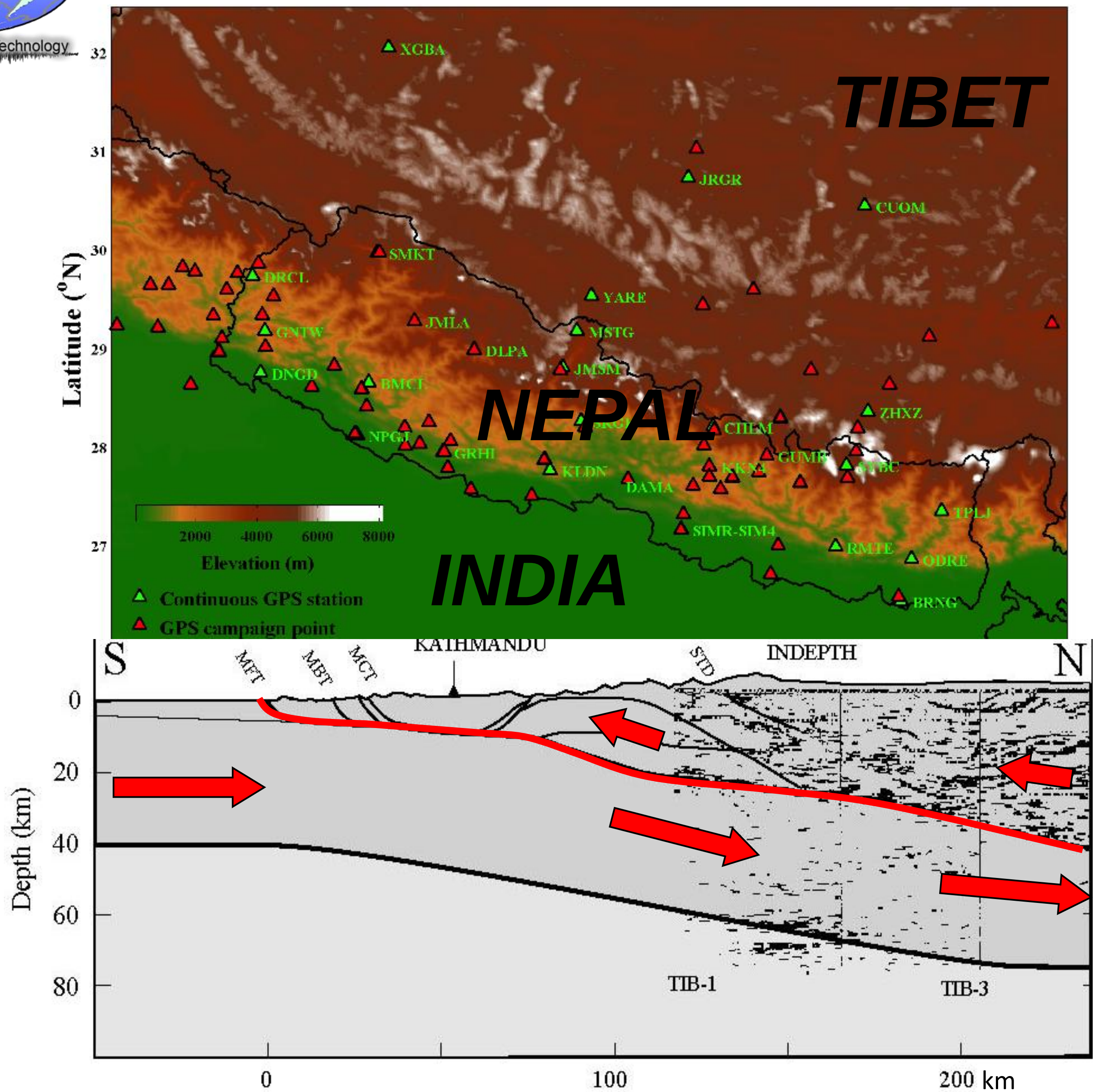
(Thomas et al, JGR, 2014)

The Himalayan Megathrust



Estimated rupture areas of major earthquakes in the Himalaya since 1700 (e.g., Ambraseys and Bilham, 2000; Hough et al, 2005).

The Himalayan Megathrust



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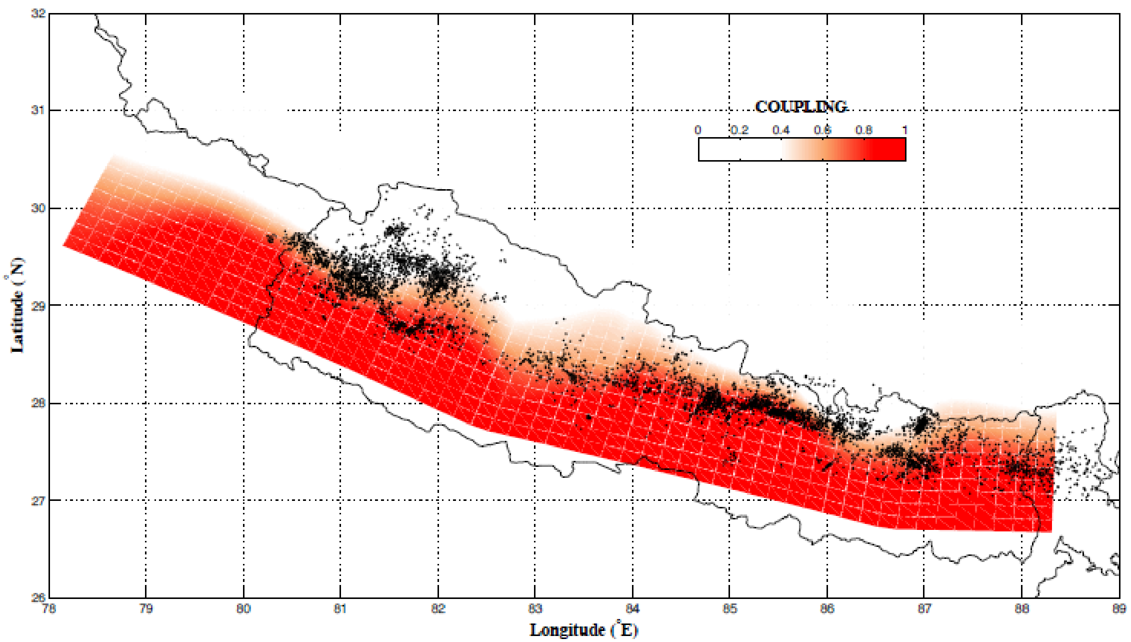


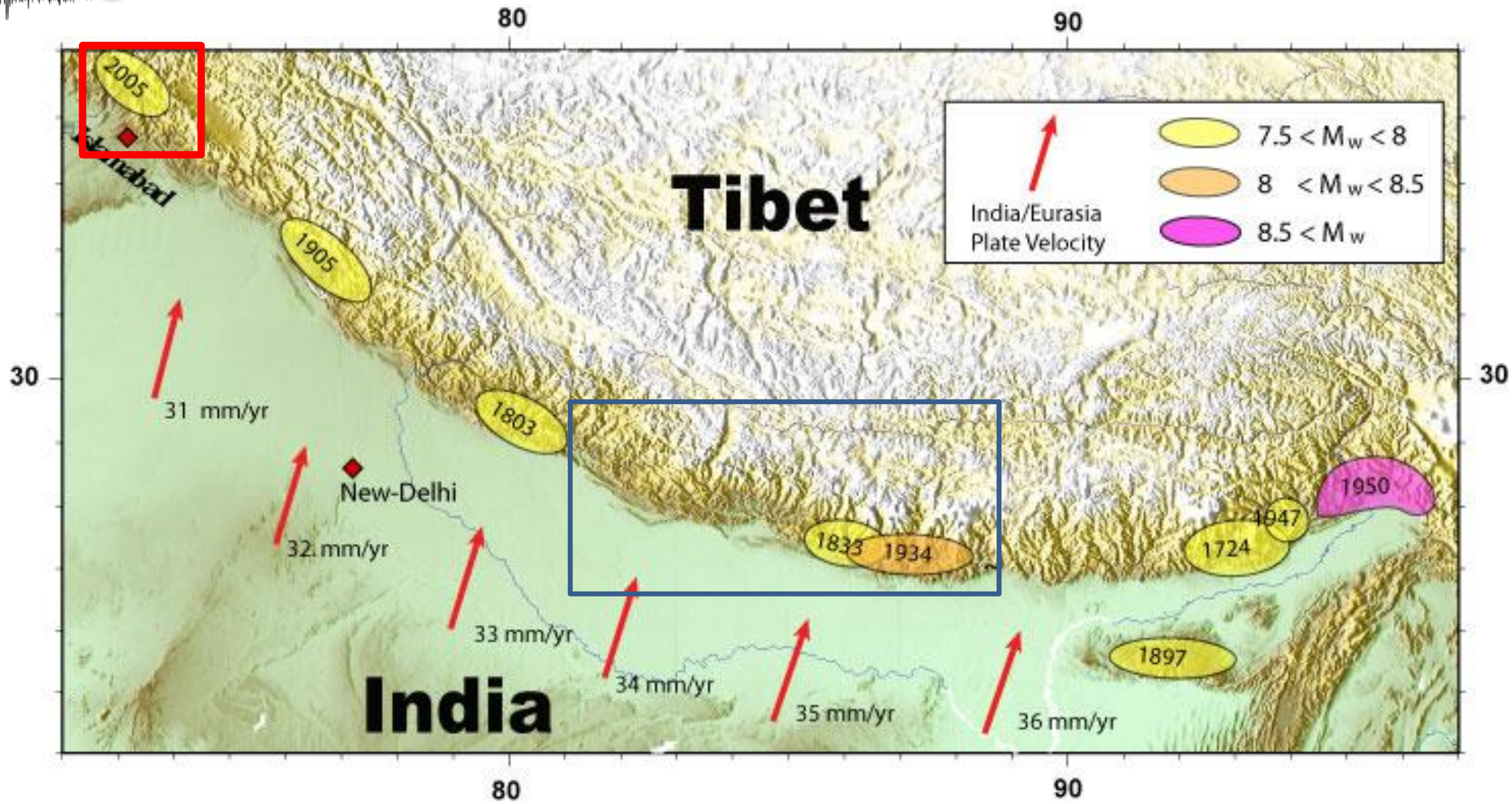
(Ader et al., 2012)

Seismicity follows the downdip end of Locked Fault Zone where shear stress increases in the interseismic period by > 4kPa/yr.

The moment deficit accumulates in the interseismic period at a rate of **6.6 10^{19} Nm/yr.**

How large and how frequent need the largest Himalaya earthquakes be?

The Himalayan Megathrust



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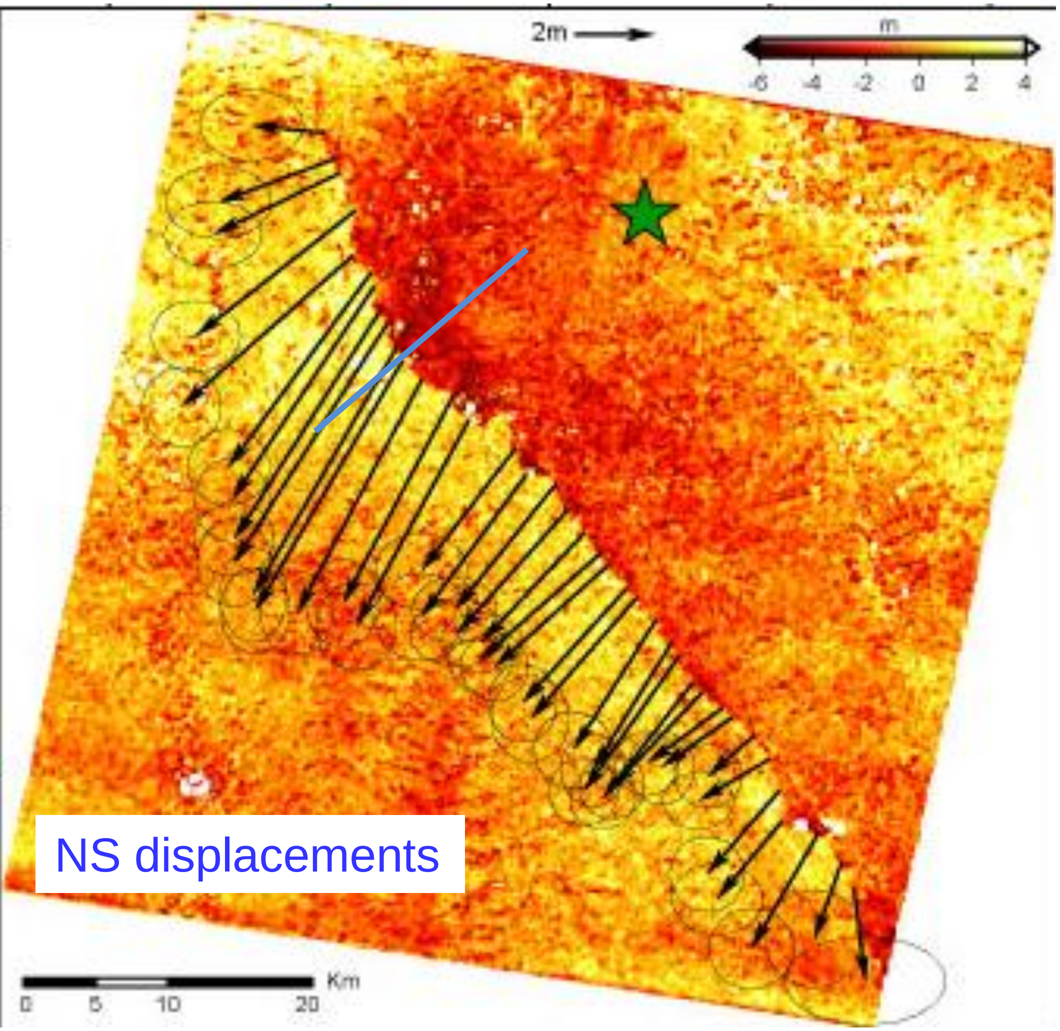
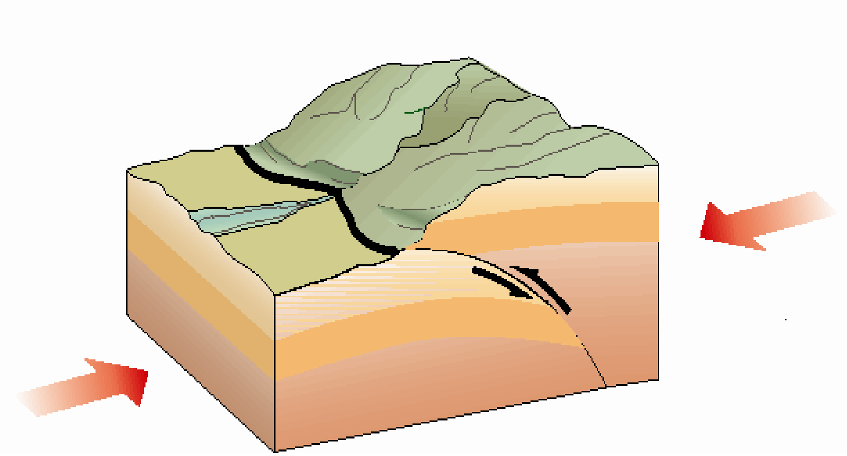
The Mw 2005, 7.6, Kashmir Earthquake



(Avouac et al., 2006)

Surface rupture measured from cross-correlation of ASTER satellite images



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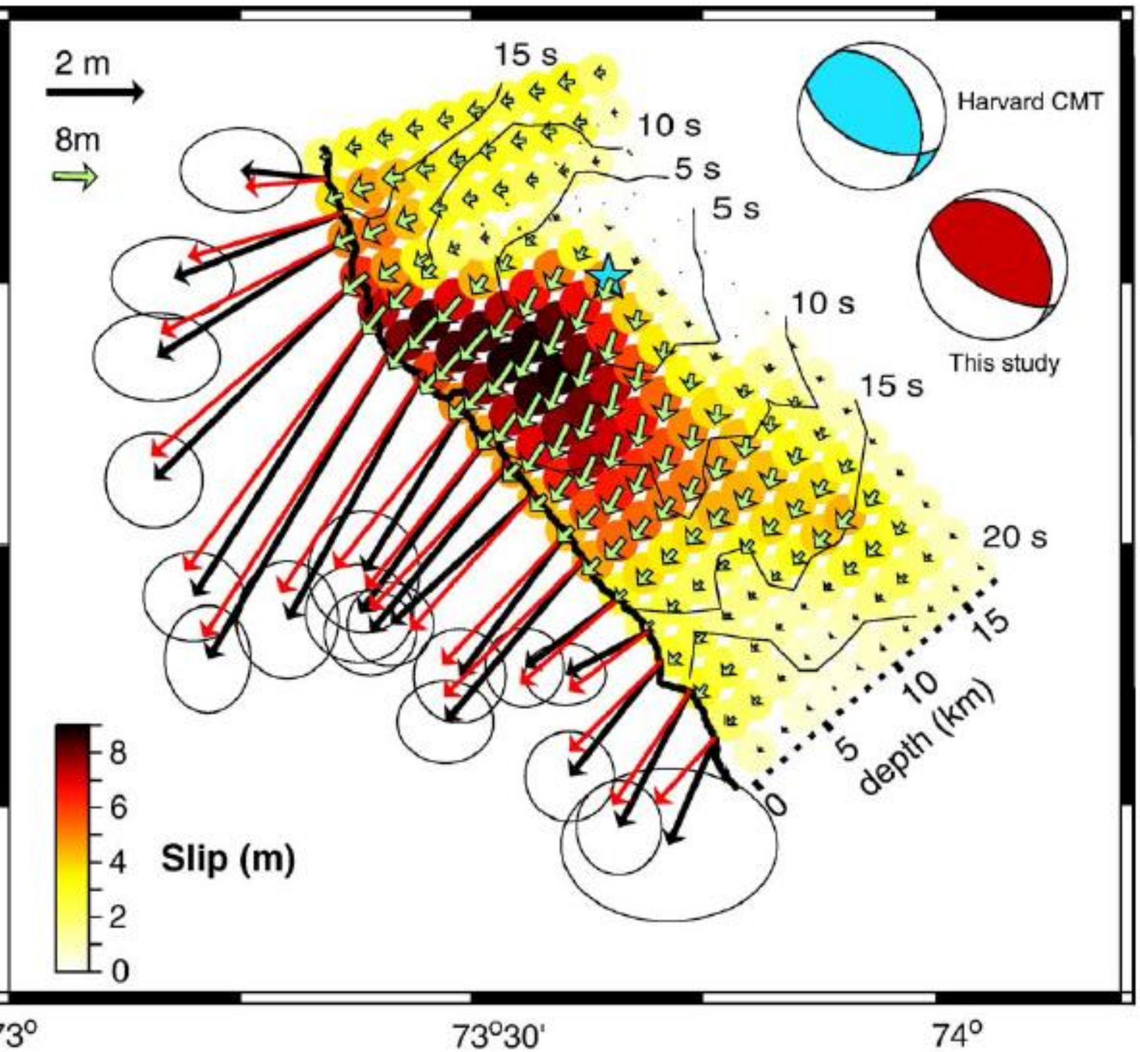
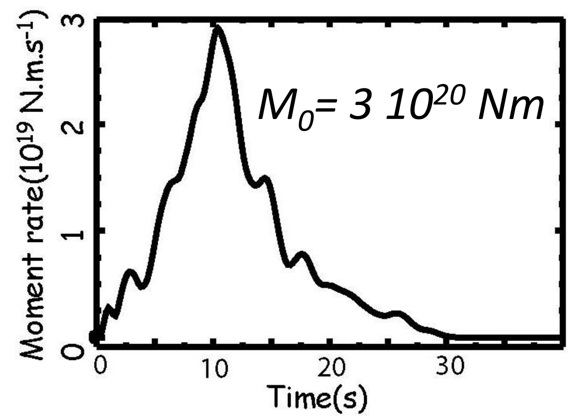
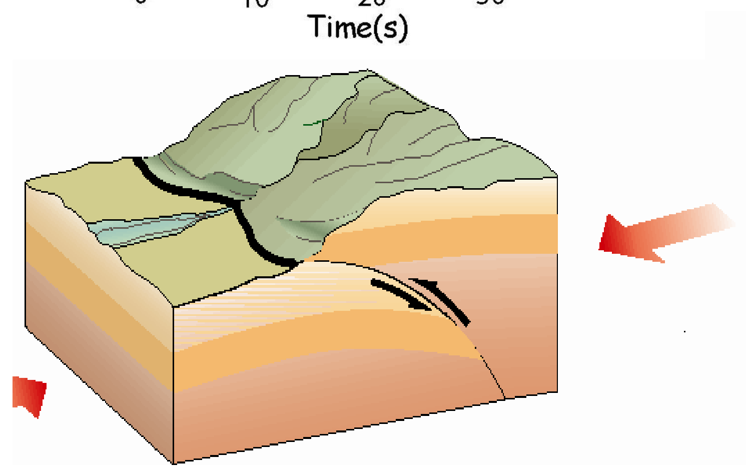


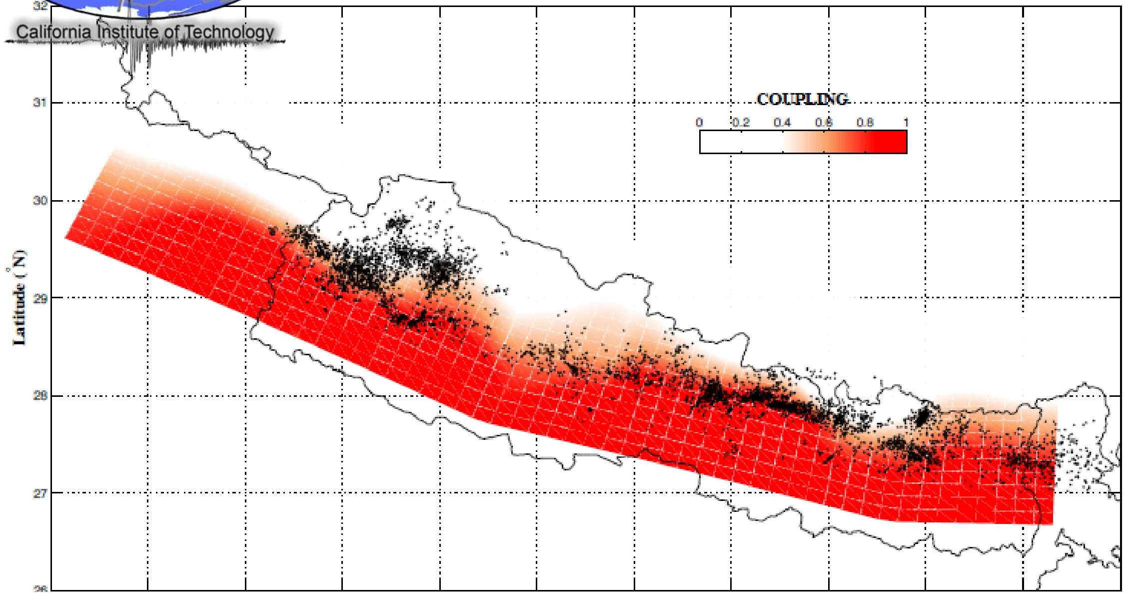
(Avouac et al., 2006))

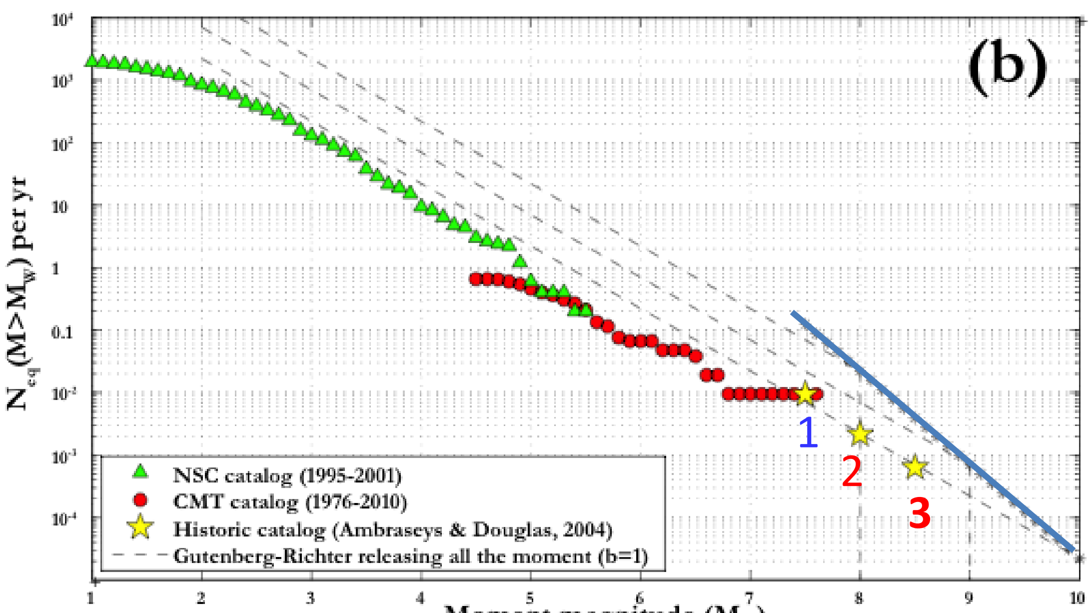
Source Model





The Himalayan Megathrust





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How large and how frequent need the largest Himalaya earthquakes be?

1-Mw 7.6 : 7 yr

2- Mw 8.2 : 50 yr

*3-**Mw >8.5** 300yr*

(Ader et al., 2012)

Key points so far

- Interseismic Coupling on subduction Megathrust is highly heterogeneous./ more homogeneous on the Himalayan Megathrust
- Seismic ruptures tend to be confined within locked fault patches and to nucleate at the edges of these patches.
- The frequency/magnitude of the largest earthquakes can in principl be constrained from the determination of ISC,… but uncertainties are large.

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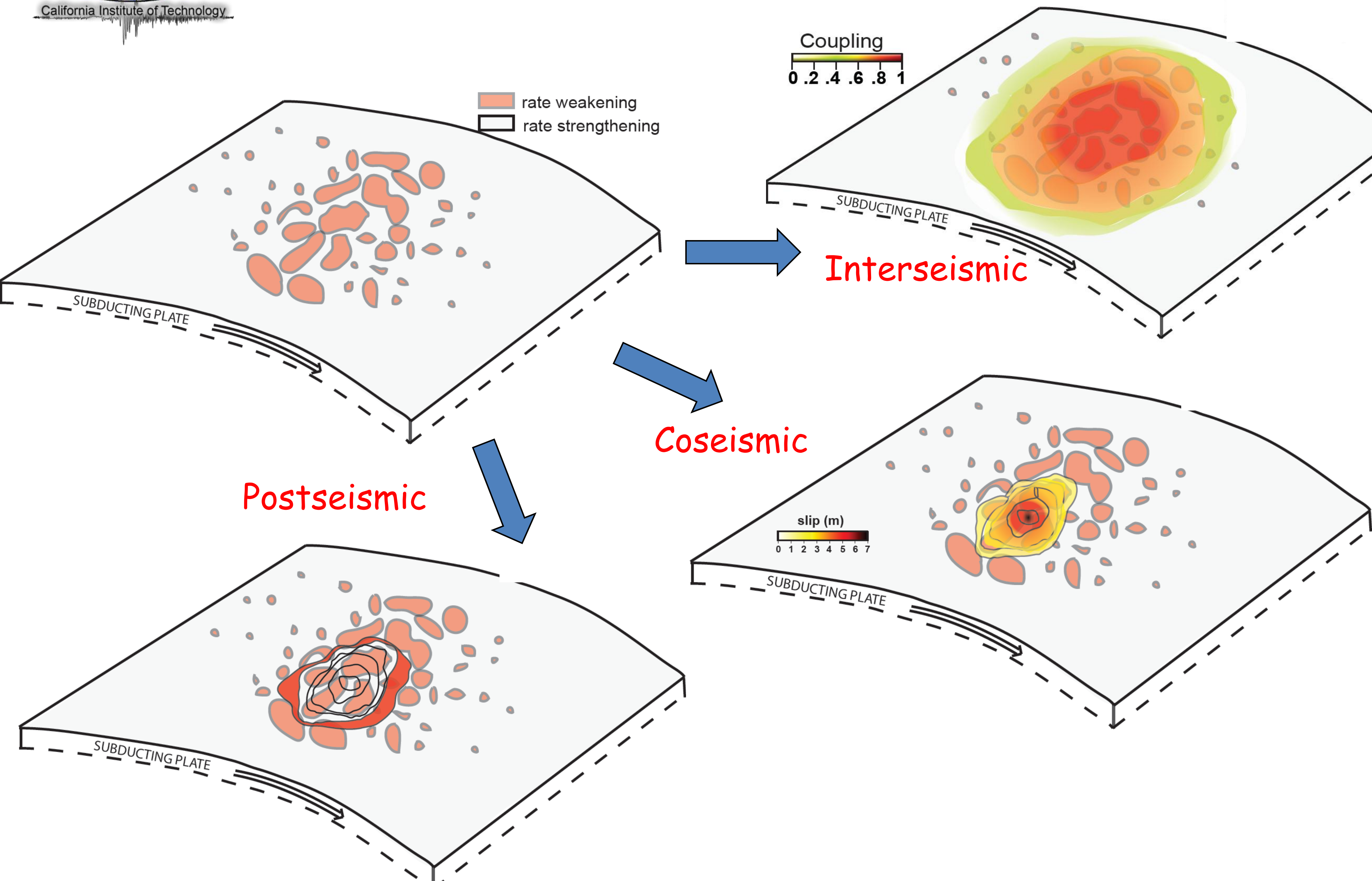
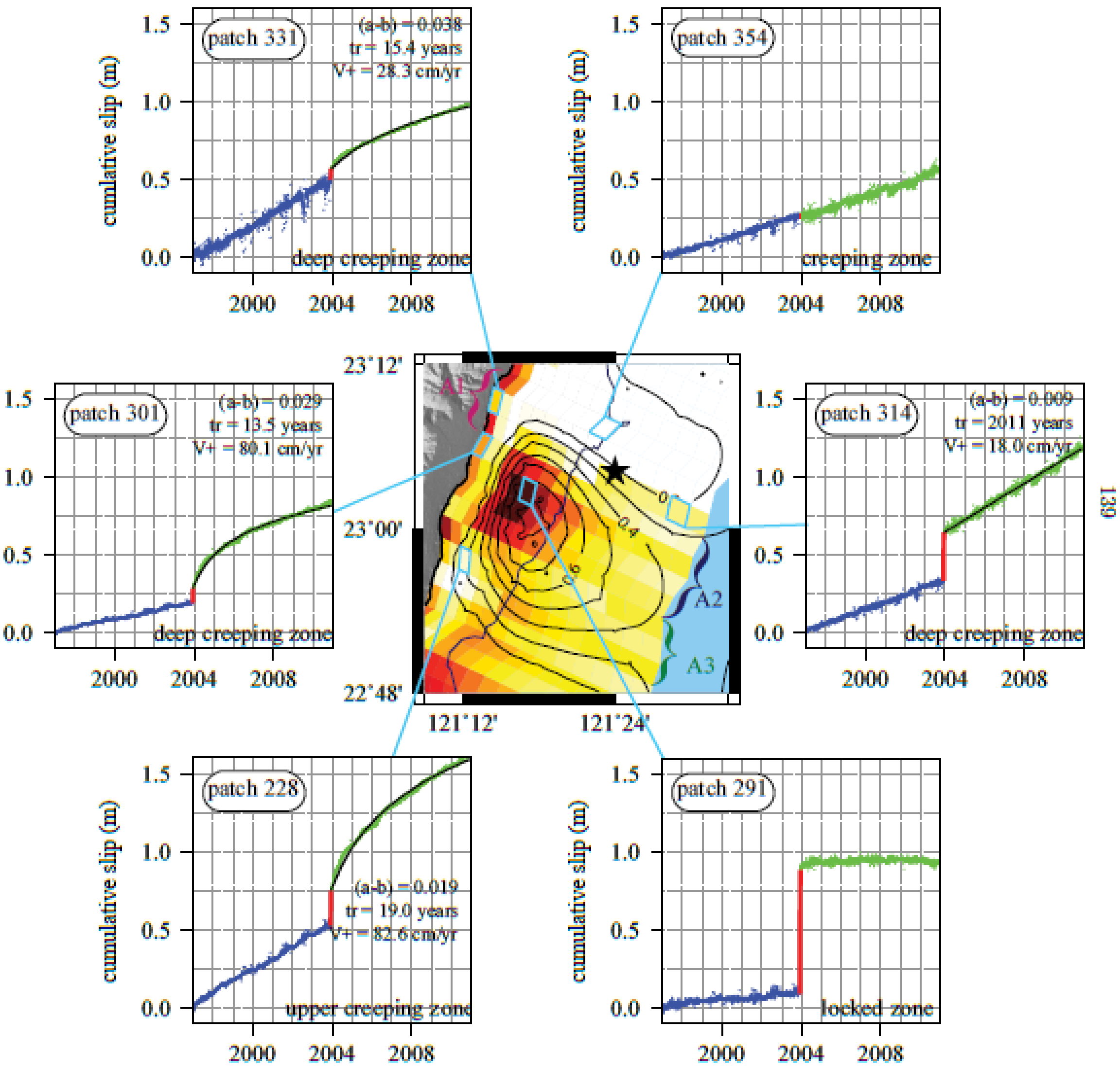
Conceptual Model

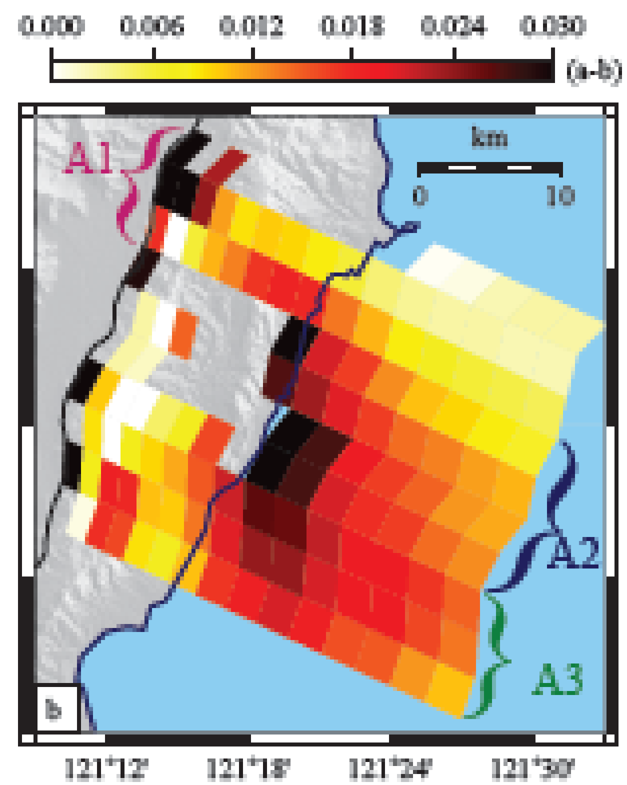


THE LONGITUDINAL VALLEY FAULT (TAIWAN)

INSIGHTS ON FRICTIONAL PROPERTIES

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

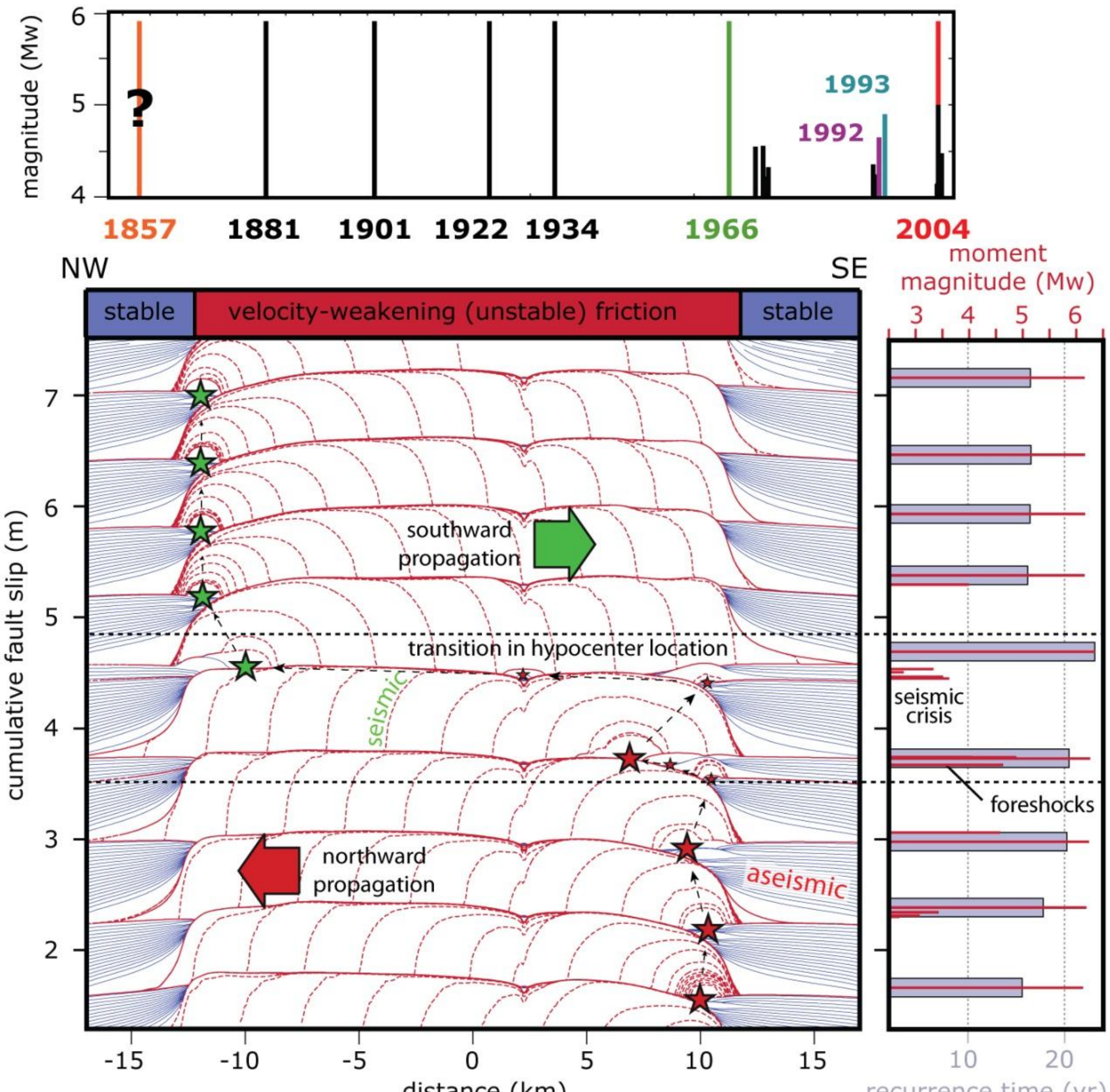


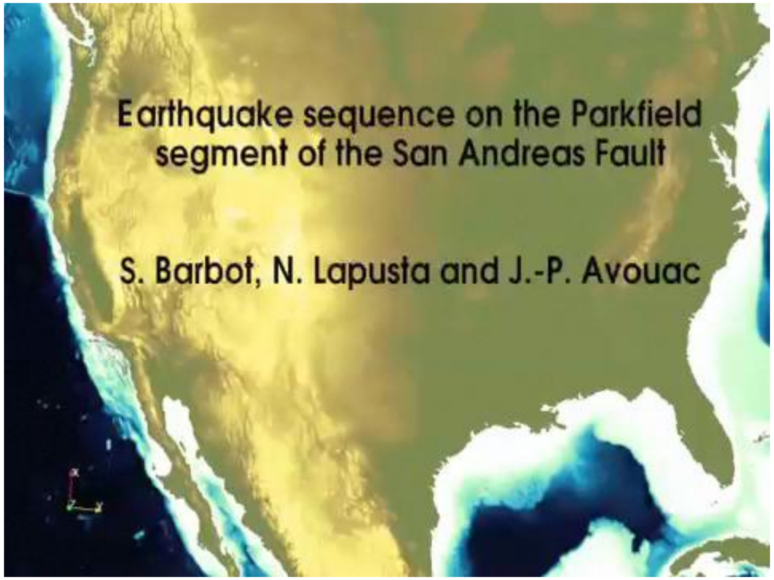


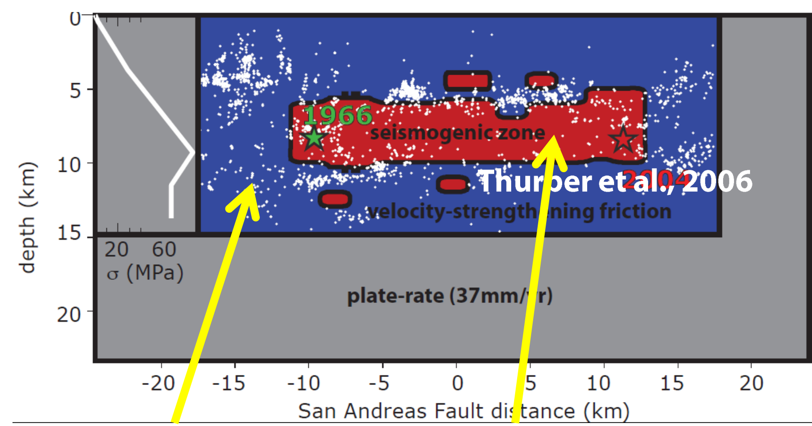
(Thomas et al., in prep)

Dynamic modeling

Modeling the Parkfield EQs Sequence on the SAF







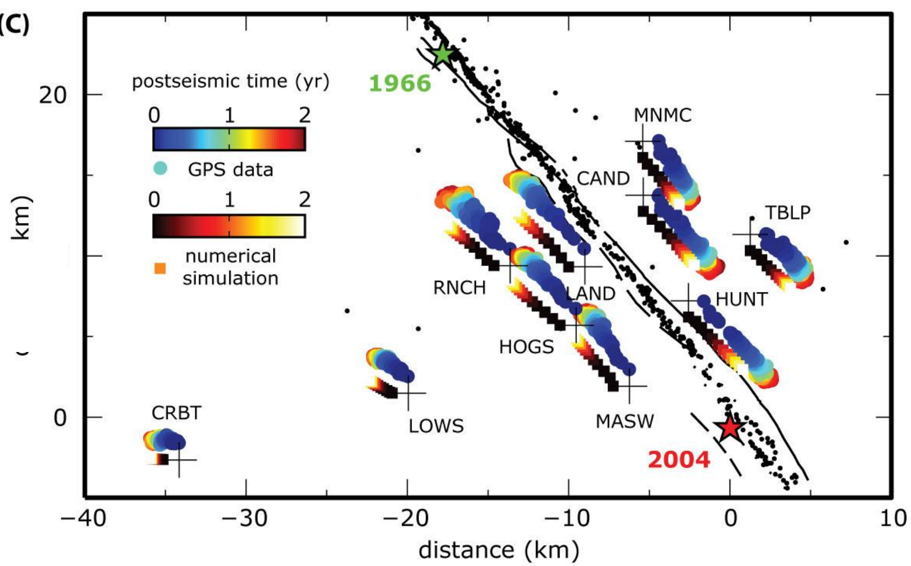
Rate Strengthening **Rate Weakening**

(Barbot et al, Science, 2012)

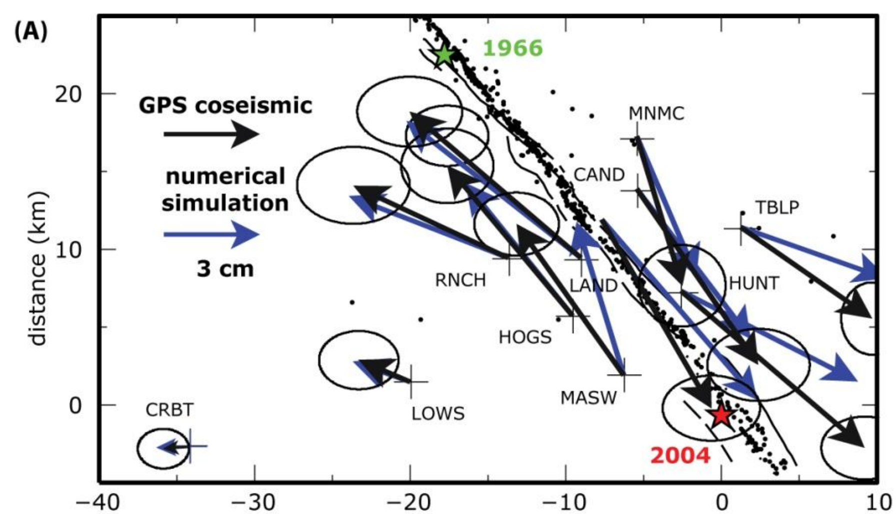
Dynamic modeling

Modeling the Parkfield EQs Sequence on the SAF

postseismic transient



coseismic displacements in 2004



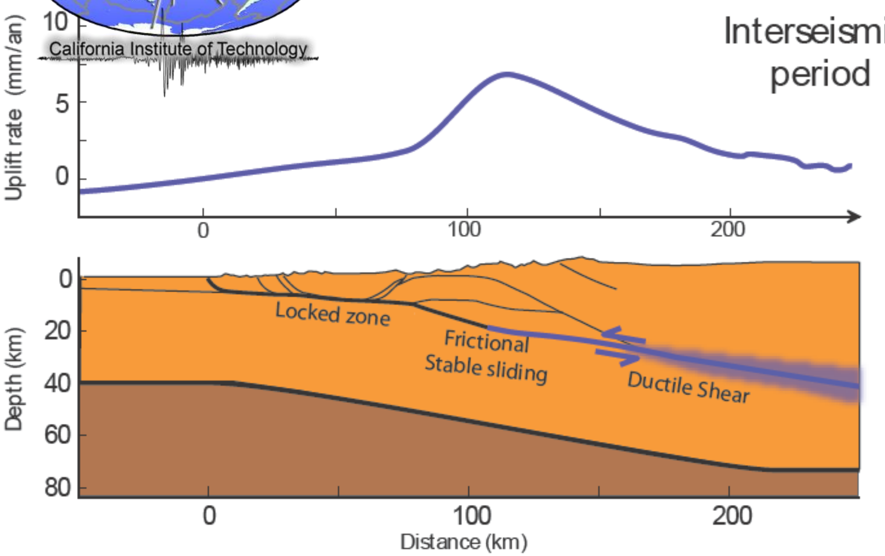
(Barbot et al, Science, 2012)

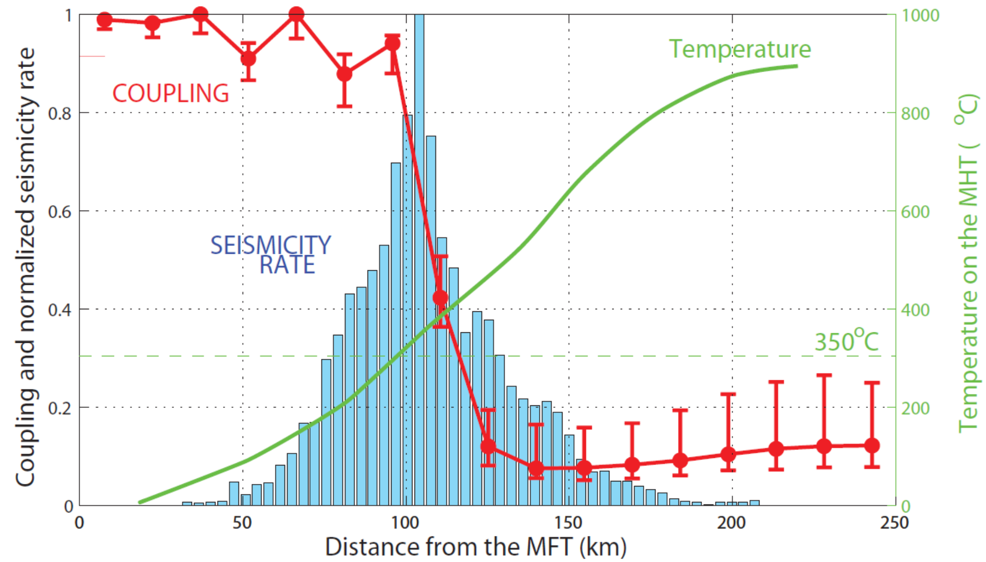
- How to constrain frictional properties in absence of large co- and post-seismic signal?
- Why makes fault creep (or stick)?

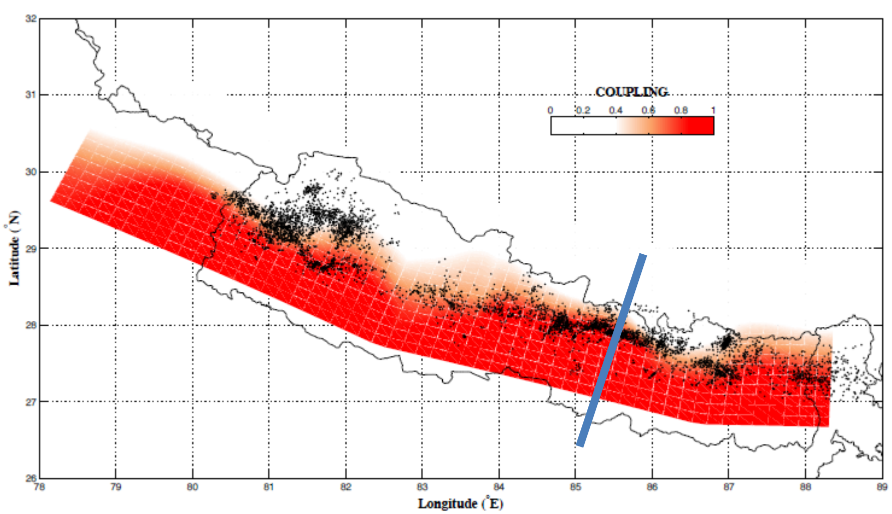
- How to constrain frictional properties in absence of large co- and post-seismic signal?
- Why makes fault creep (or stick)?
  - Lithology $a\text{-}b > 0$
  - Temperature
  - Water

$$b - a > \lambda \frac{GD_c}{L\sigma_n'}$$

The Himalayan Megathrust





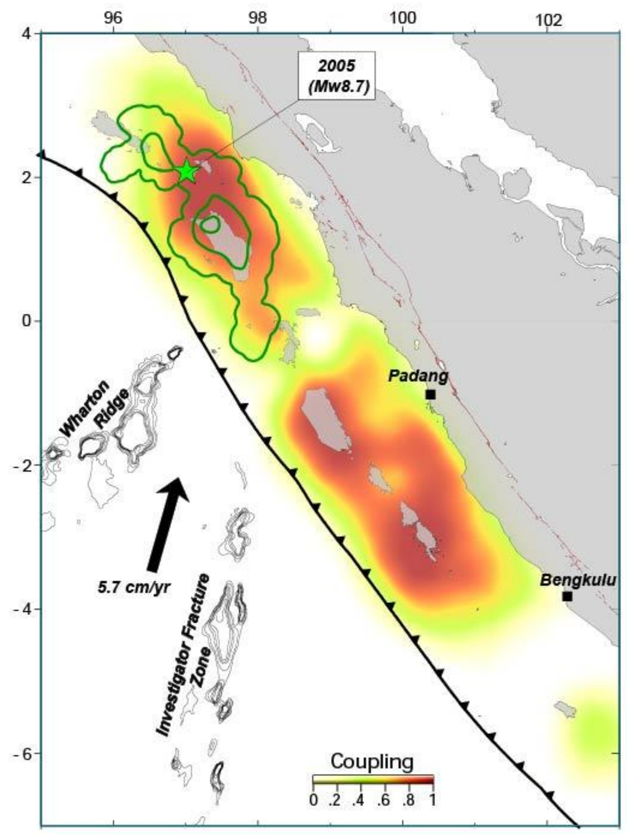


Aseismic slip dominant where T > 350°C.

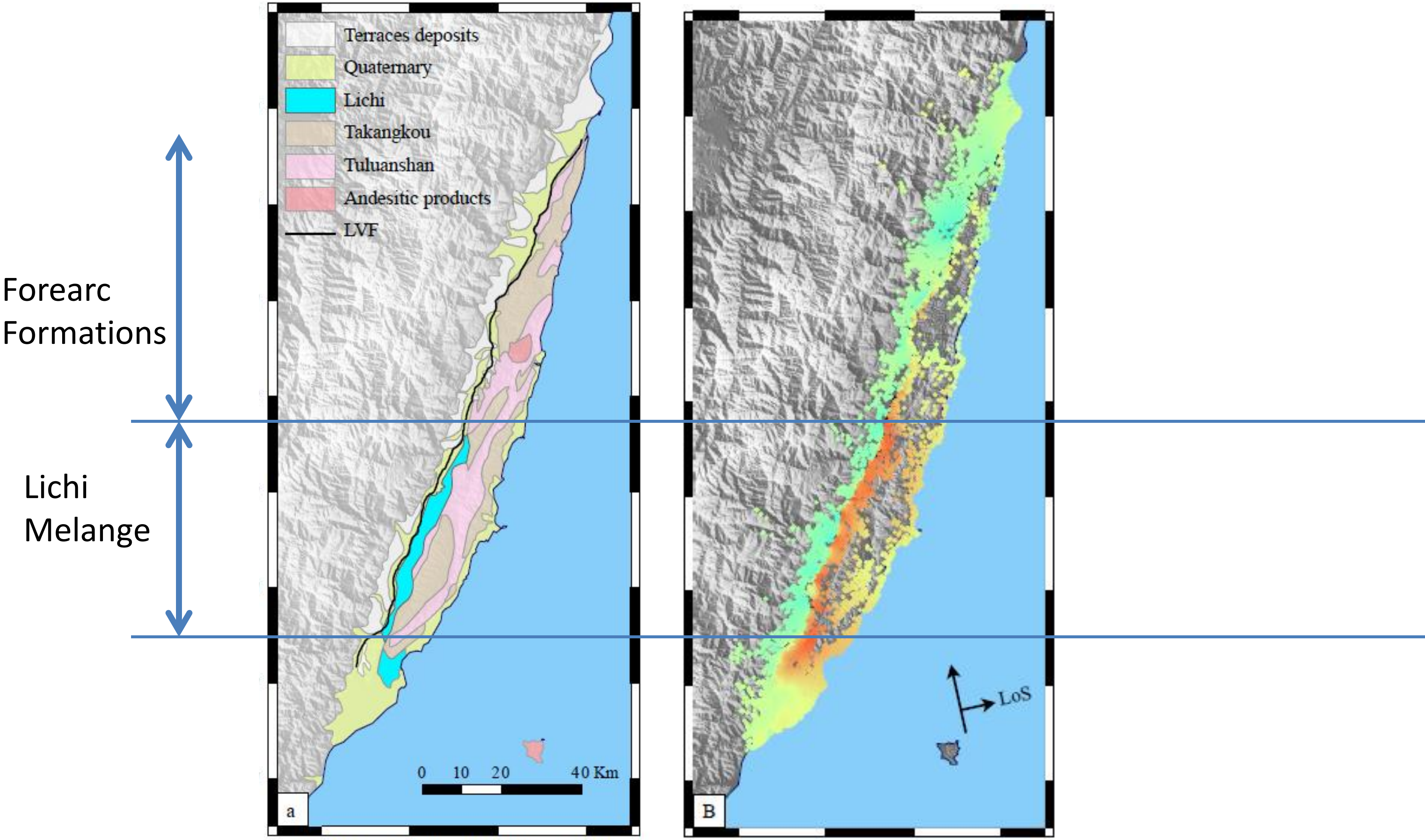
consistent with laboratory experiments which show that stable frictional sliding is promoted at temperatures higher than about 300°C (for Quartzo-felspathic rocks).
(Blanpied et al, 1991; Marone, 1998)

(Ader et al., 2012)

The Sumatra Megathrust

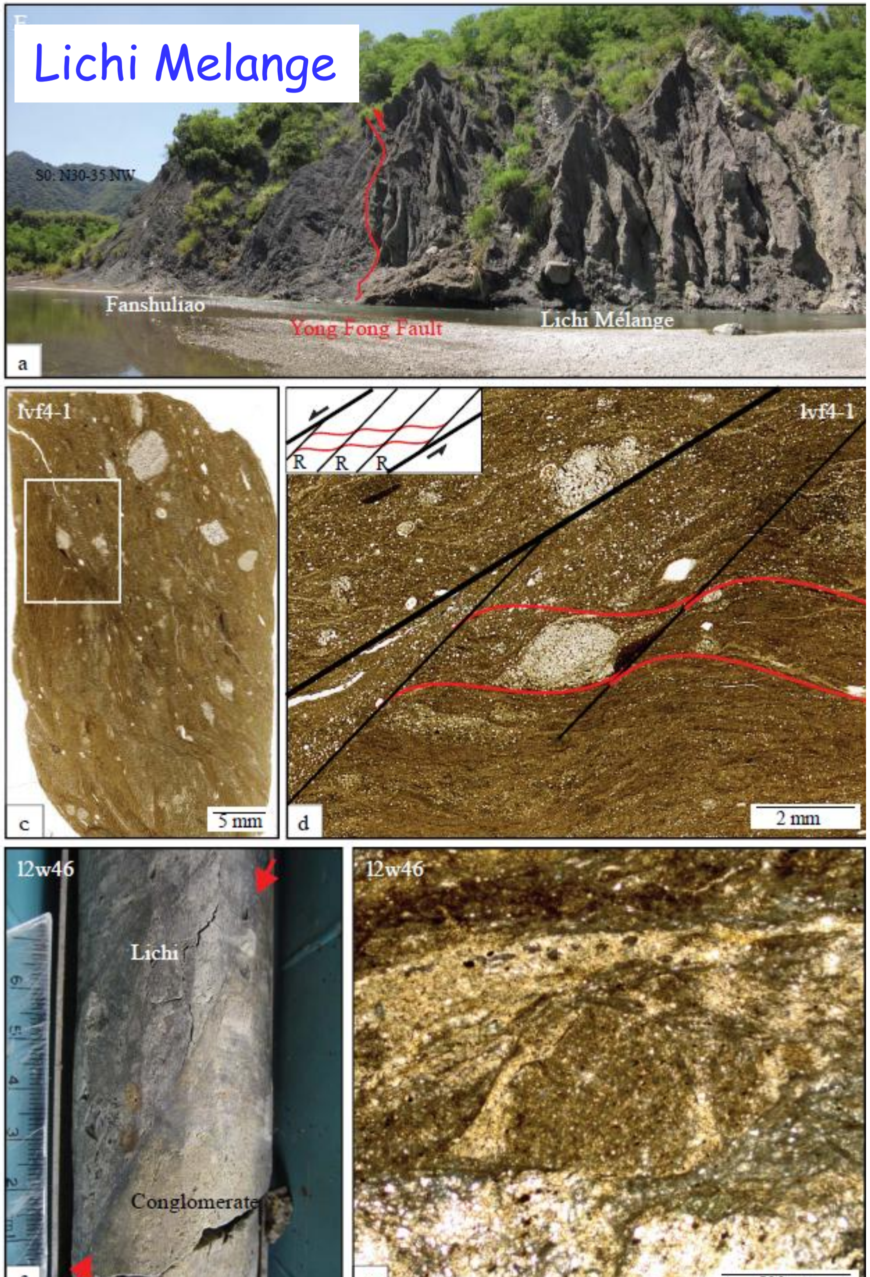


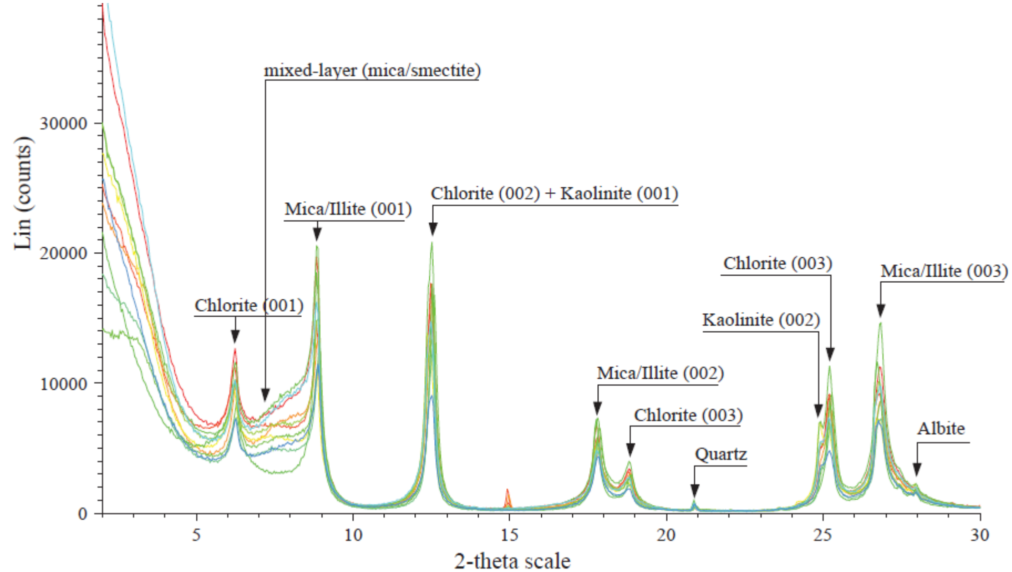
THE LONGITUDINAL VALLEY FAULT (TAIWAN)

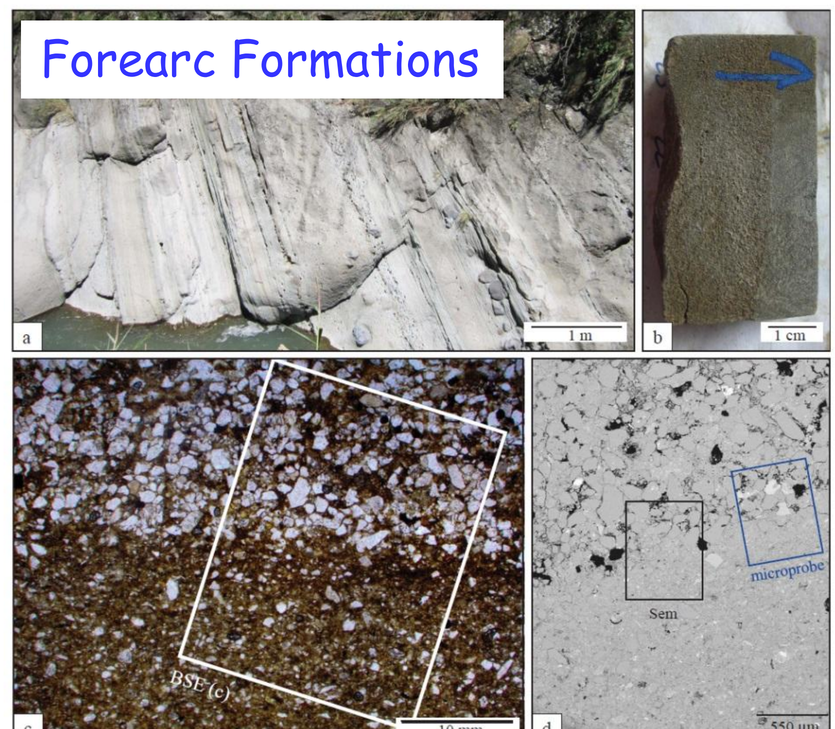


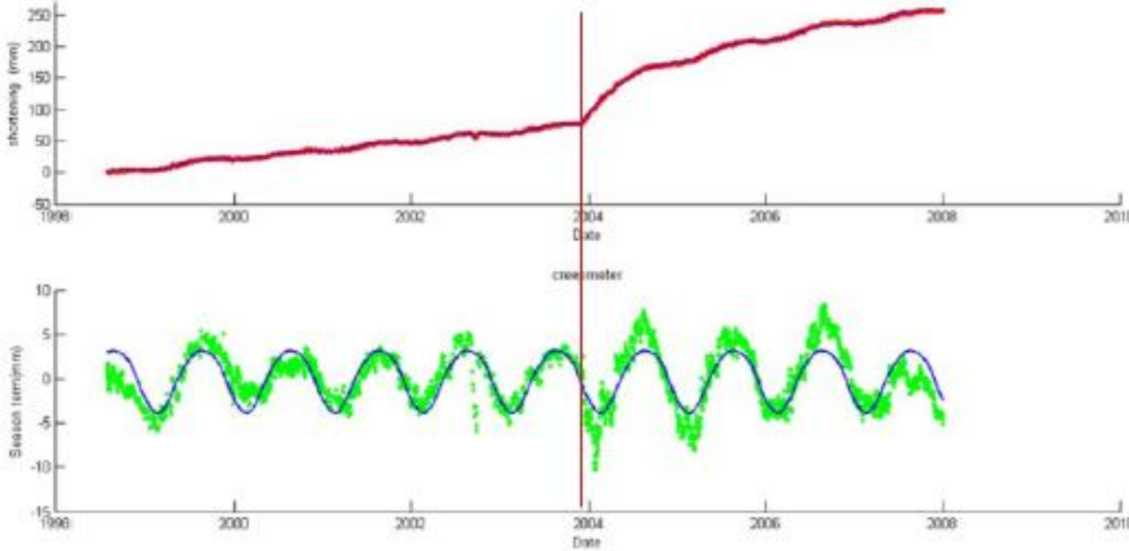
(Thomas et al, JGR, subm.)

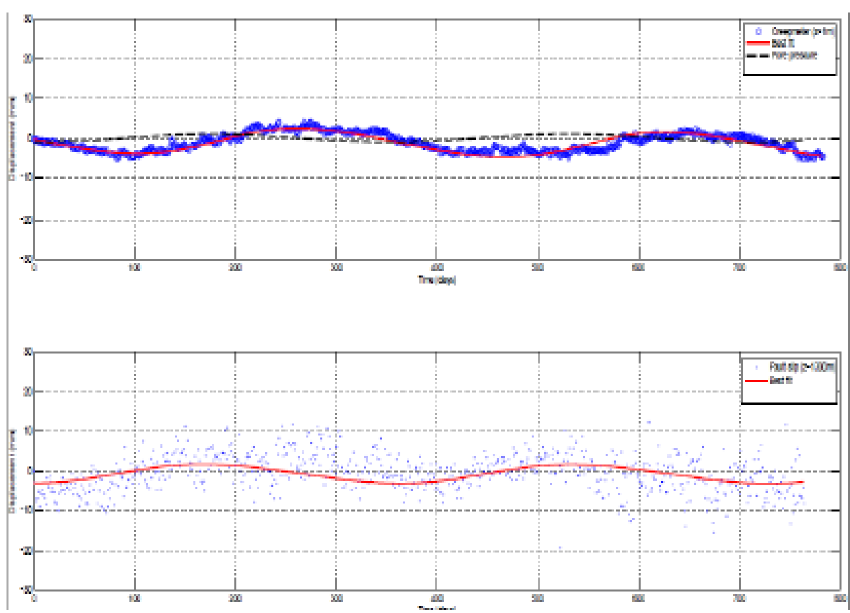
THE LONGITUDINAL VALLEY FAULT (TAIWAN)





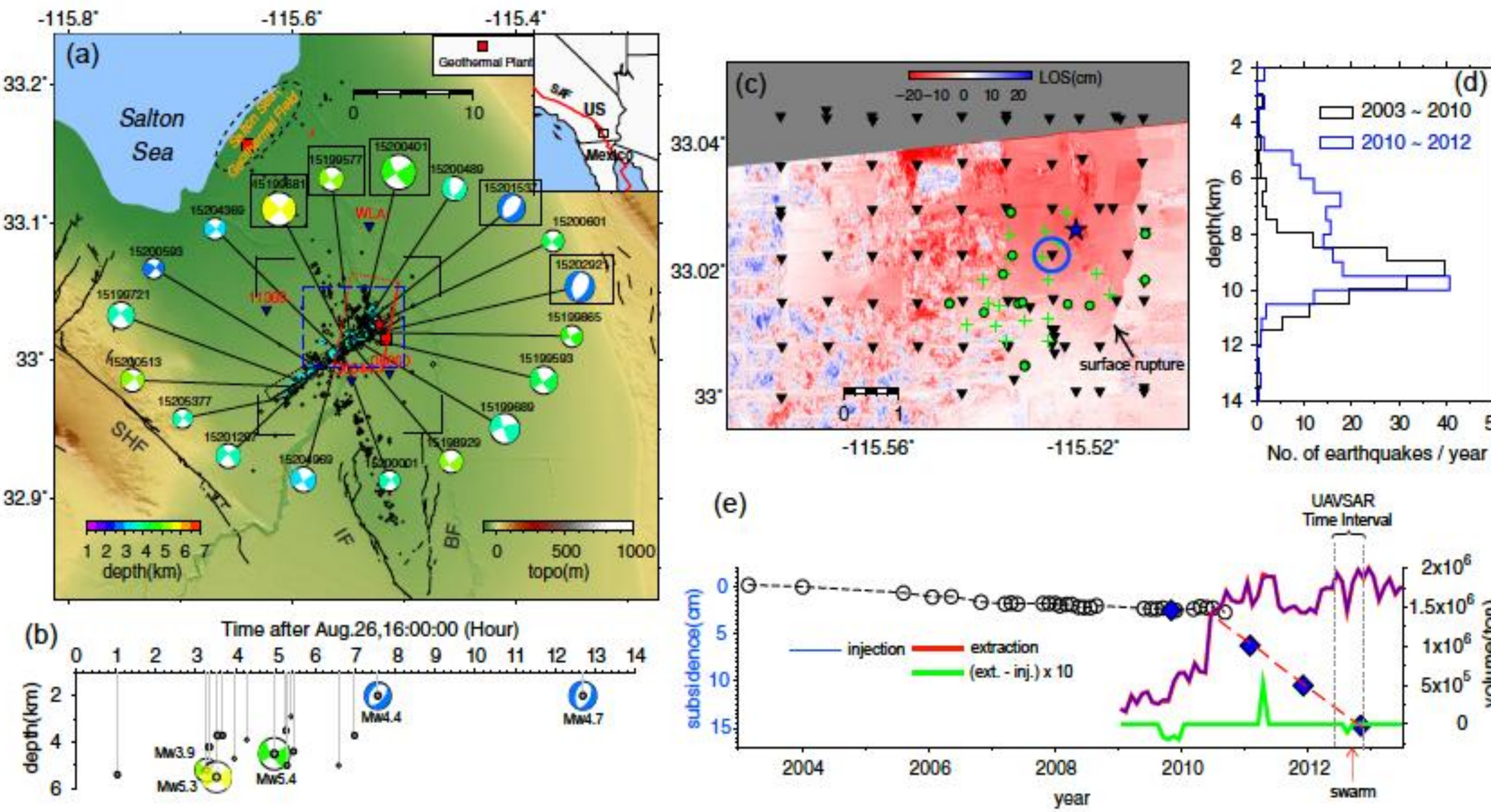


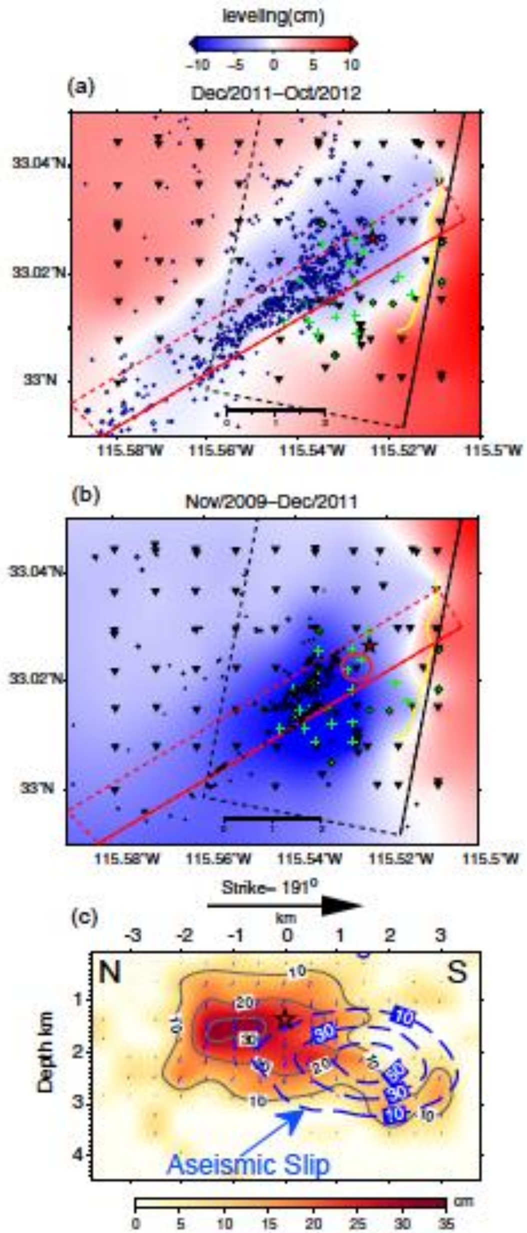

shortening (mm)
Date
creepmeter
Date


Time (days)

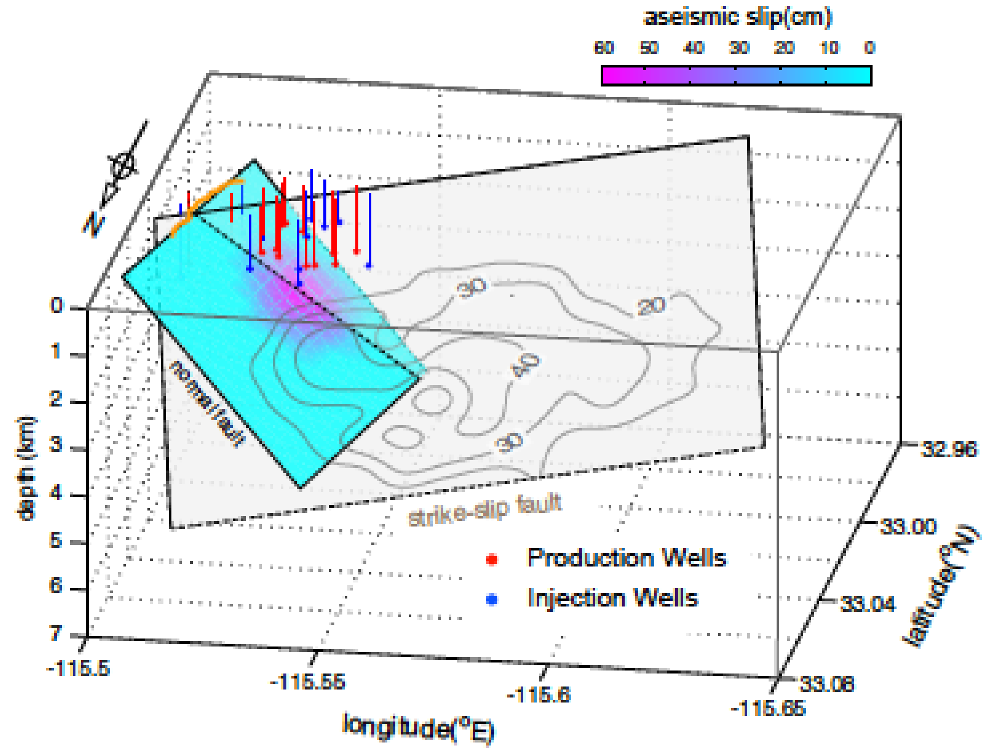
- Indications that fluids promote creep:
  - Soultz-la-foret experiment (e.g., Cornet et al, 1997; Bourrouis and Bernard,2007)
  - Correlation between swarms and creeping zone (e.g., Holtkamp and Brudzinski, 2014)
  - The Brawley example (Wei et al, in prep)
  - The LSBB expriment (Guglielmi, Cappa et al, in prep)

The Brawley Swarm





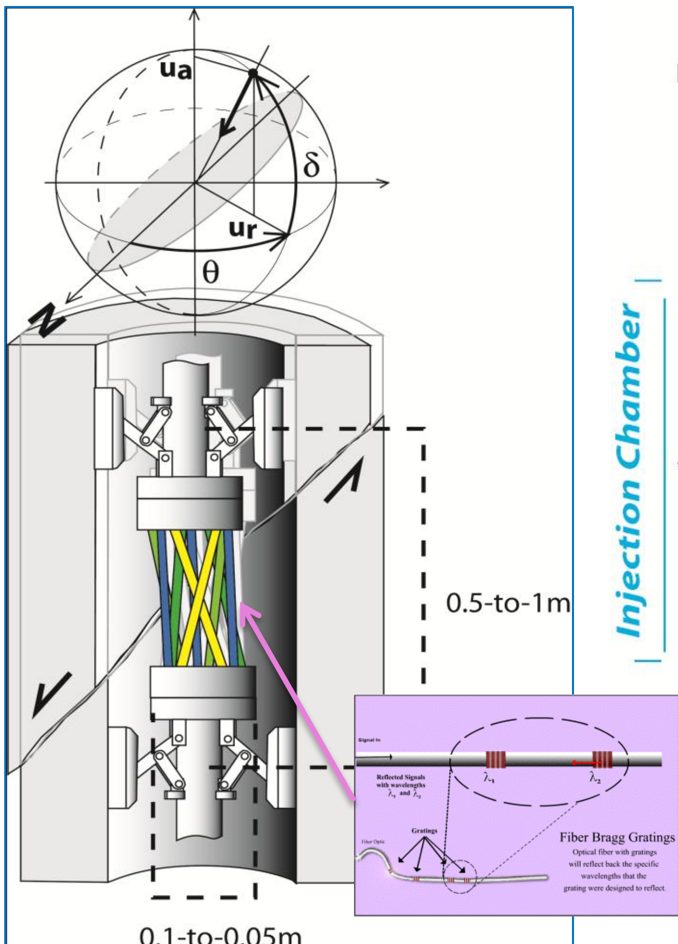
leveling(cm)
(a)
Dec/2011–Oct/2012
(b)
Nov/2009–Dec/2011
Strike= 191°
(c)
N
S
Depth km
Aseismic Slip
cm

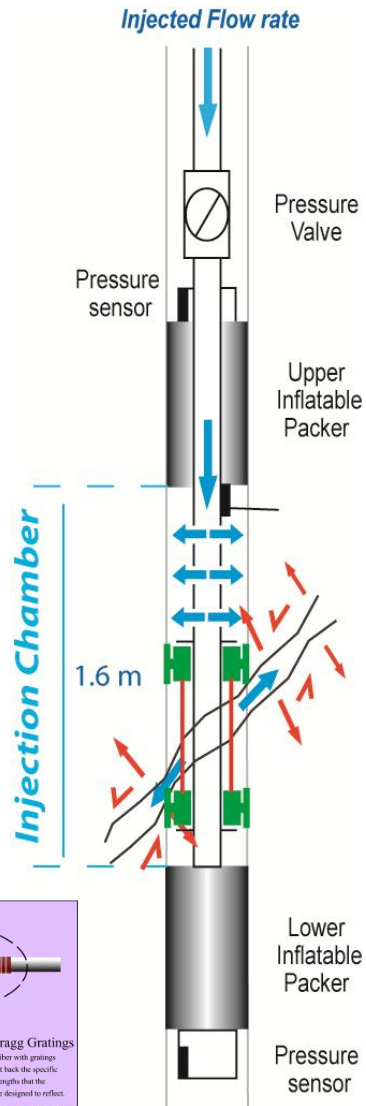


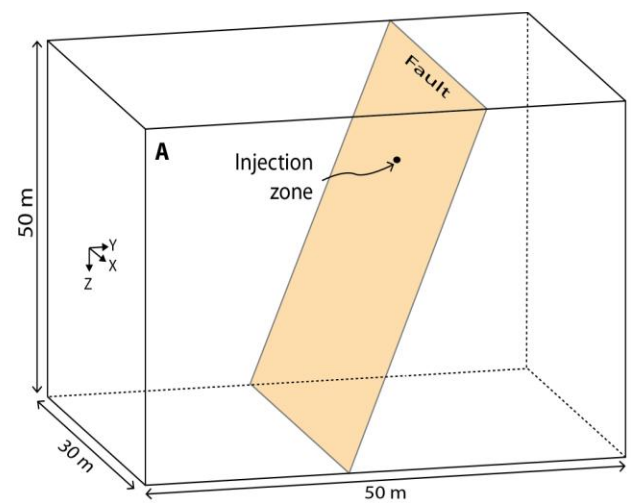
aseismic slip(cm)
N
normal fault
strike-slip fault
Production Wells
Injection Wells
depth (km)
longitude(°E)
latitude(°N)

In-Situ probing of fault friction from hydraulic stimulation

The HPPP probe

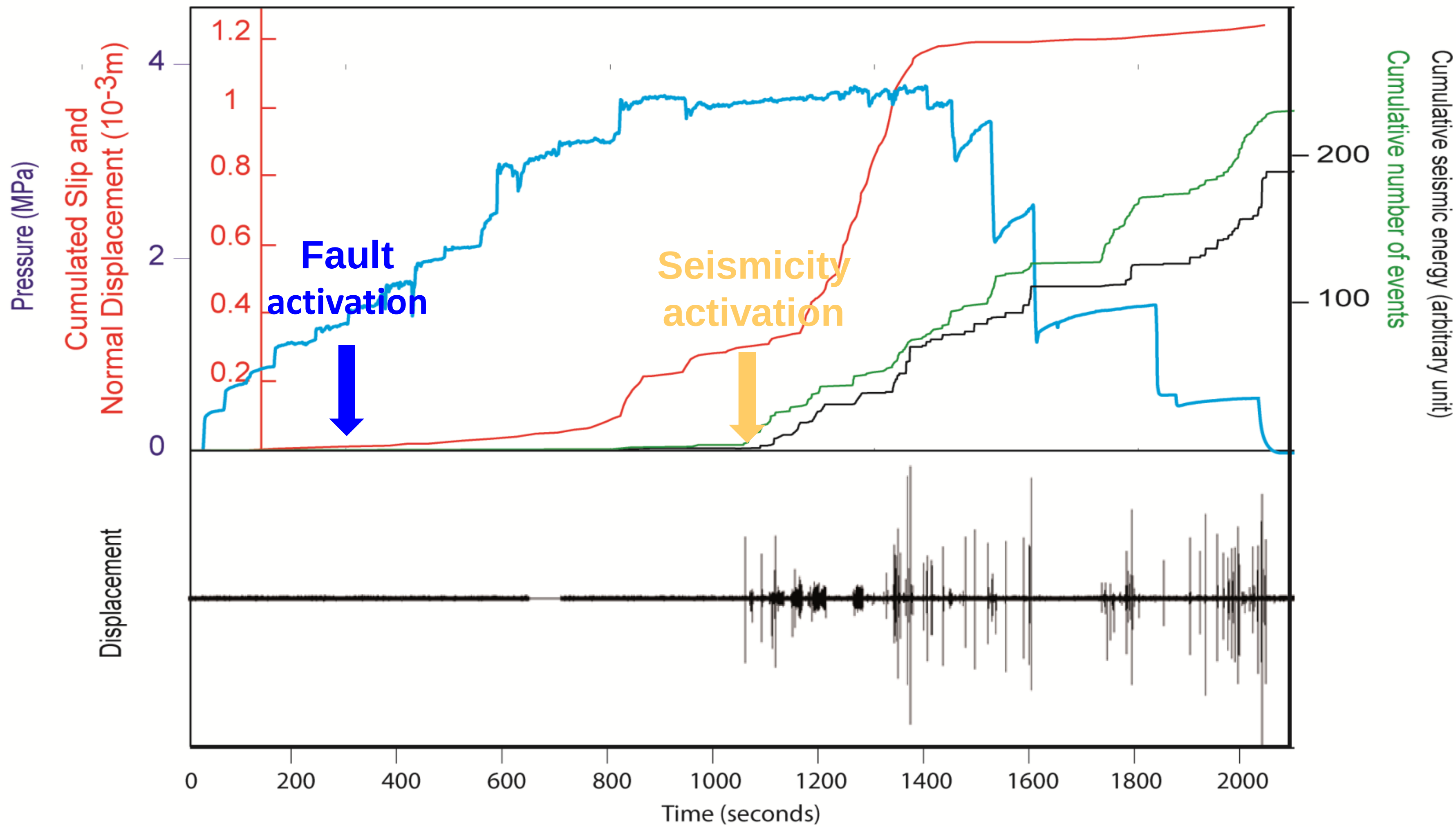




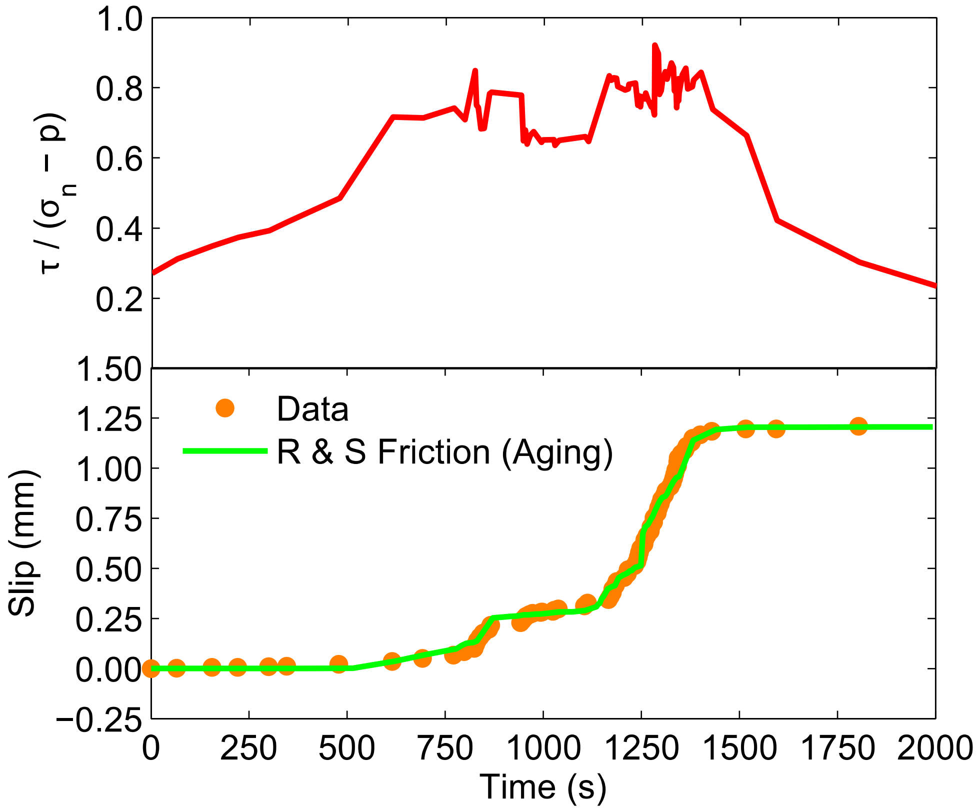


(Yves Guglielmi and Frederic Cappa)

In-Situ probing of fault friction from hydraulic stimulation



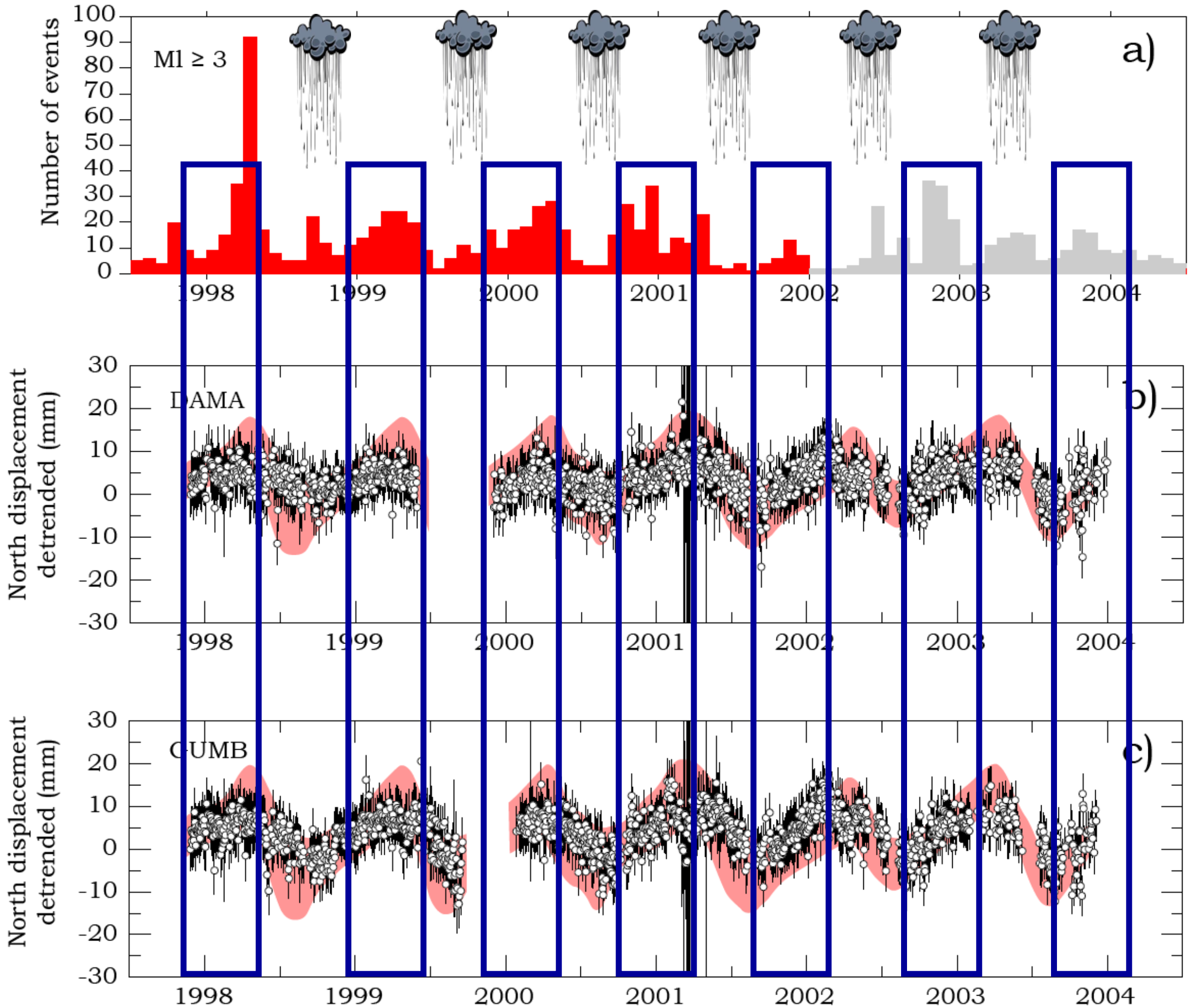
(Guglielmi, Cappa et al., in preparation)



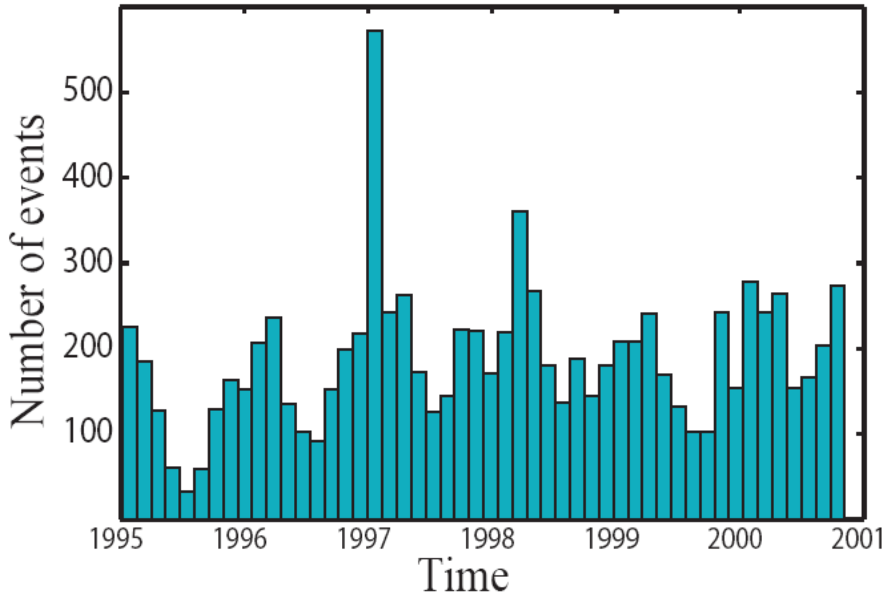
Comparison between measured and modelled slip on the fault (bottom) assuming rate-and-state friction (with the aging law), complete stress drop and uniform effective normal stress. Aseismic slip is induced when the ratio of the shear stress to the effective normal stress is around 0.7 (top panel). Friction parameters: **μ=0.6, a=0.056, b=0.001, dc= 1μm.**

Conclusions

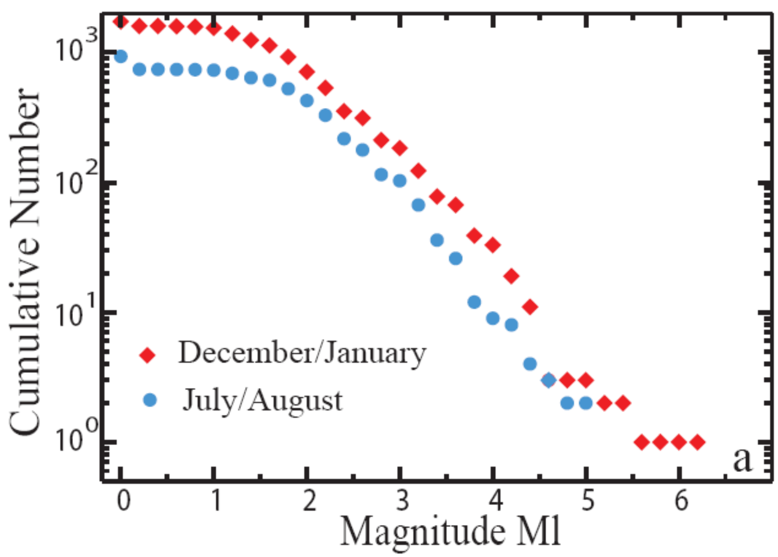
- Interseismic Coupling on subduction Megathrust is highly heterogeneous.
- Seismic ruptures tend to be confined within locked fault patches and to nucleate at the edges of these patches.
- Dynamic models of the earthquake cycle can be designed and calibrated based on ISC and past seismicity. Such models might be used in the future to predict the full range of possible EQs scenario and their probability of occurrence.
- **We have little understanding of the factors favoring aseismic creep and of the aseismic deformation mechanisms**
- **We would learn a lot from in situ probing of creeping and non creeping faults from fluid injection experiments.**

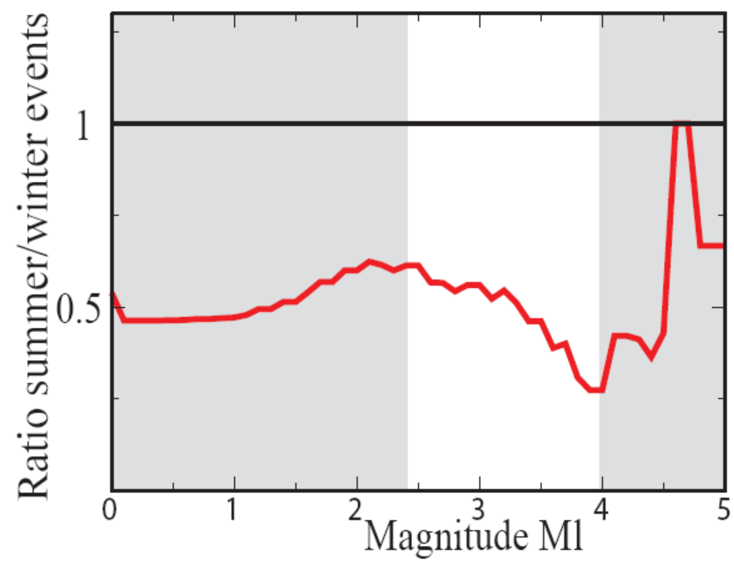


Seismicity is enhanced in the winter when shortening rate across the Himalayan is increased.



Winter seismicity rate is nearly twice as large as summer seismicity rate.

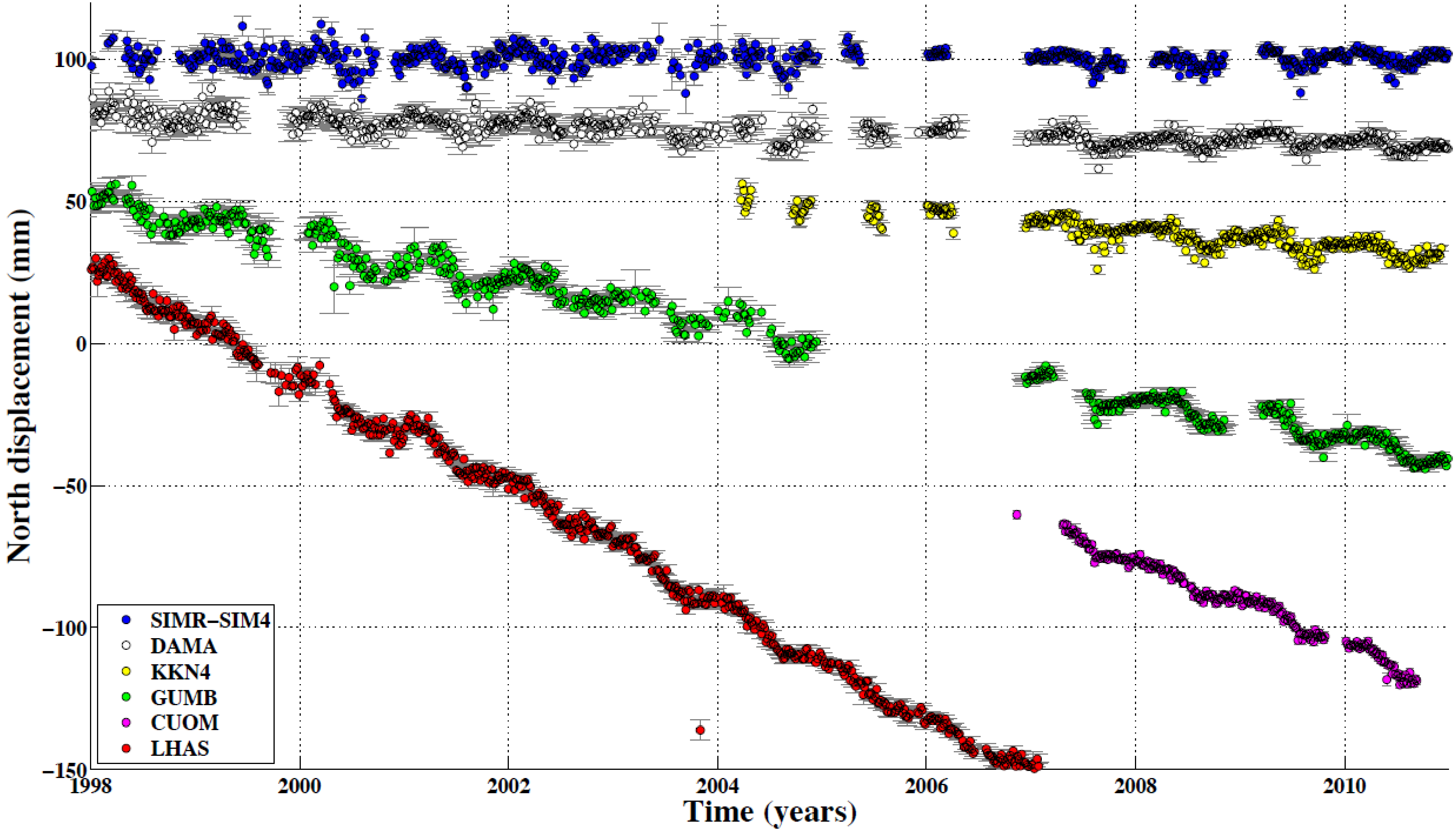




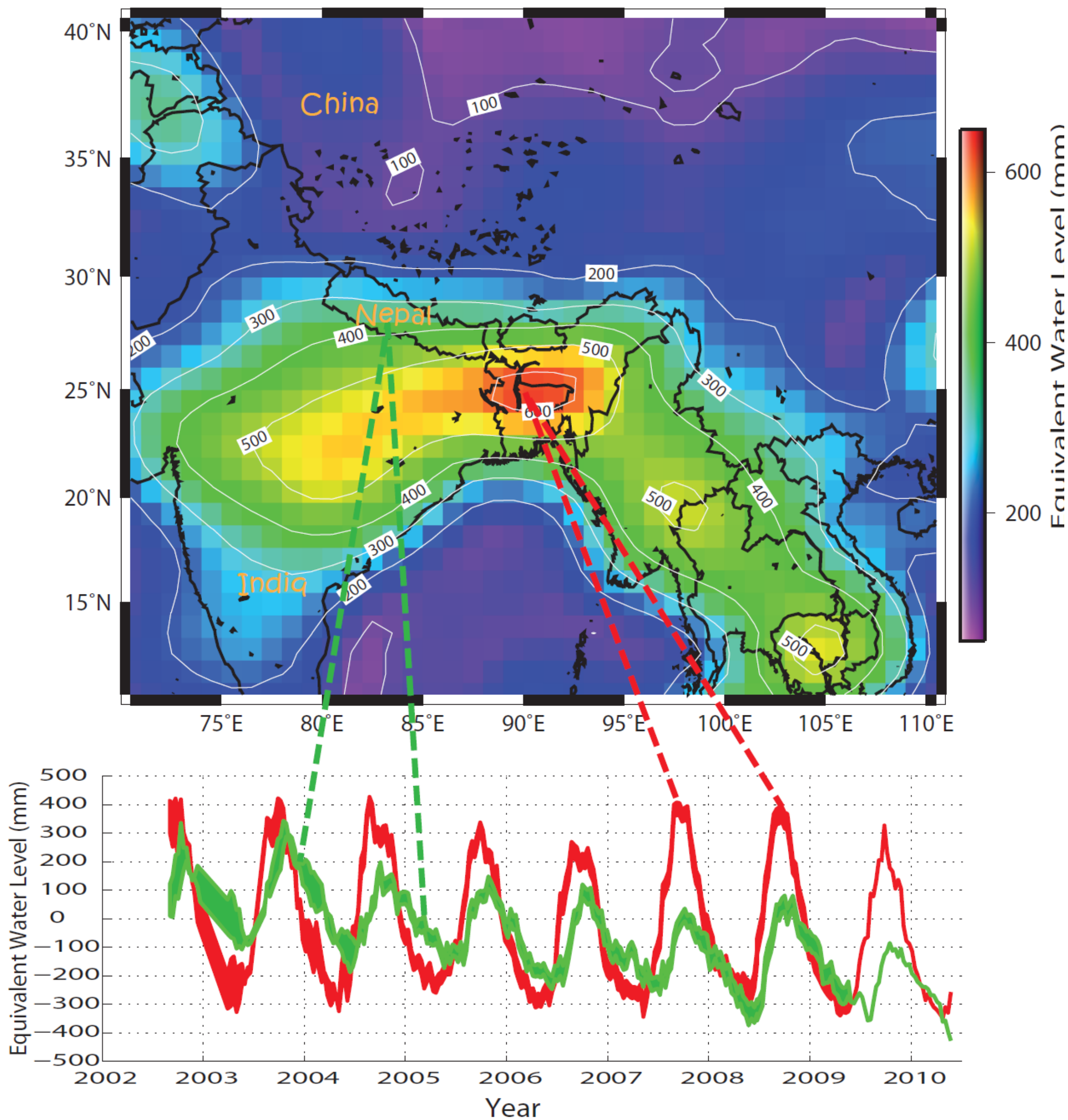
(Bolllinger et al, 2007)

Horizontal displacements relative to India

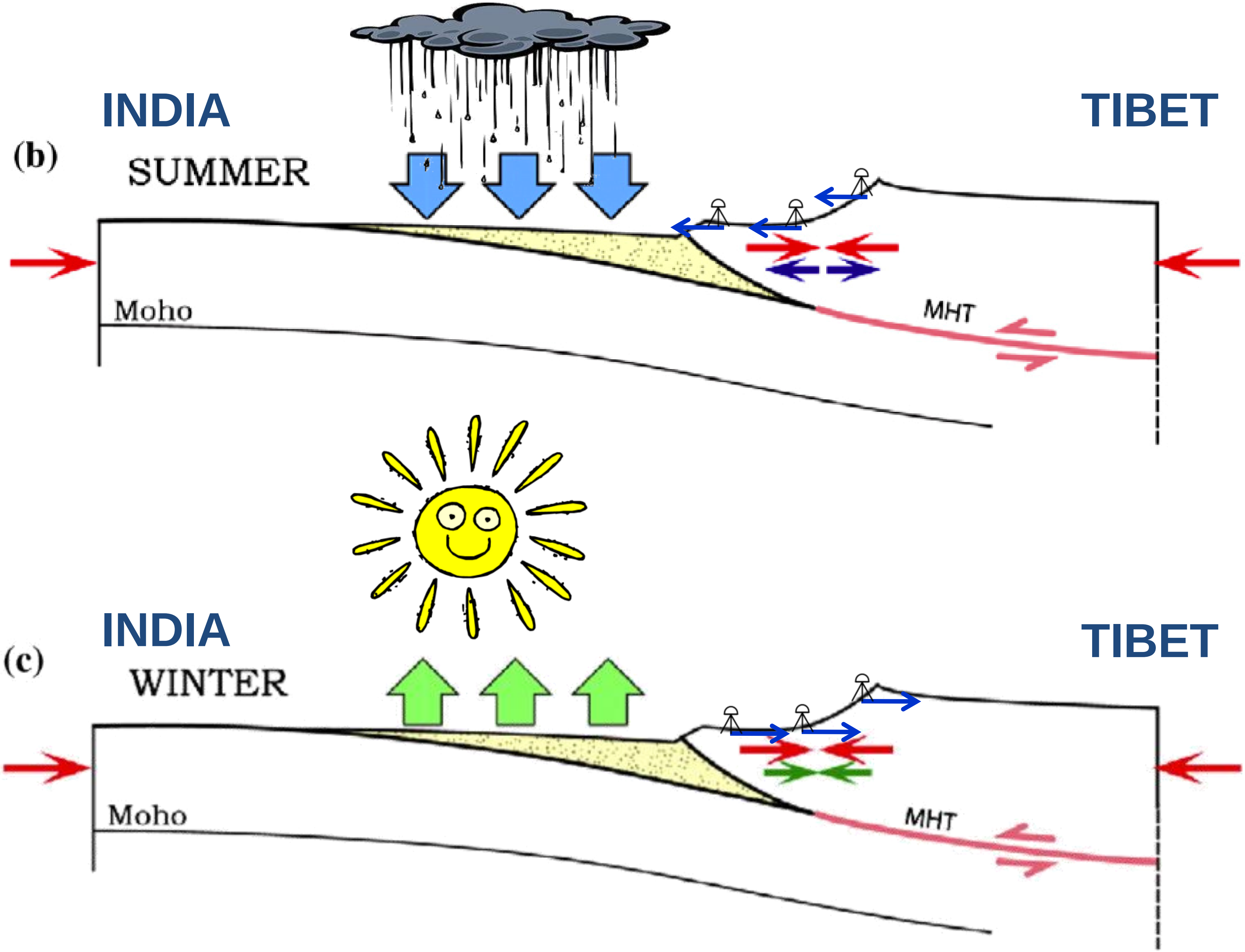
Note seasonal variations



Seasonal variations of surface load derived from GRACE

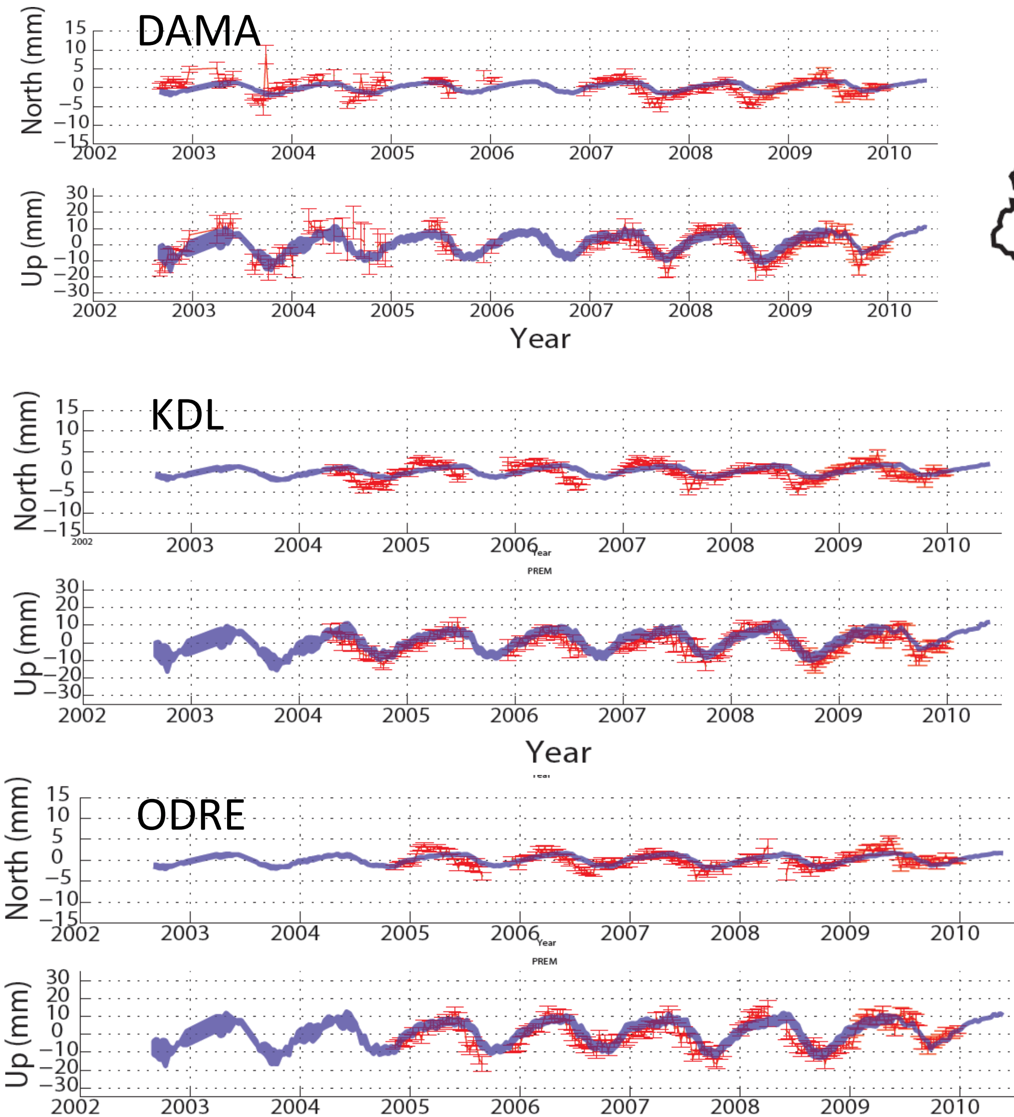


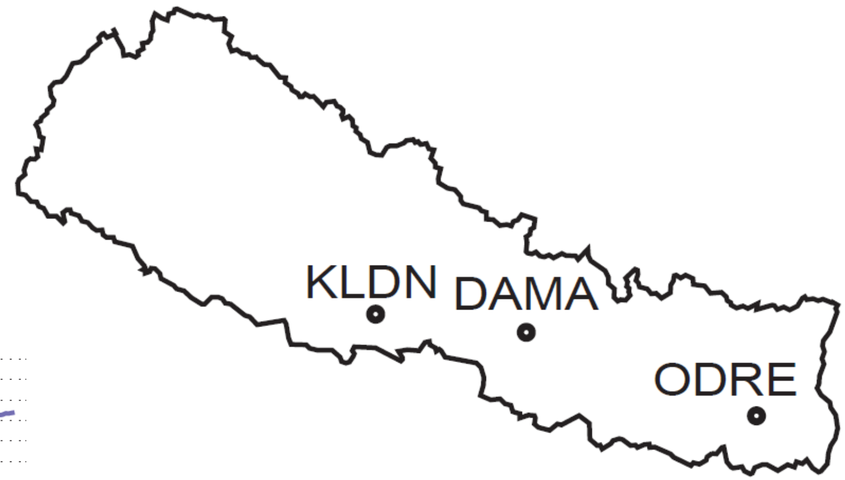
(Kristel Chanard)



Bettinelli et al. (2008)

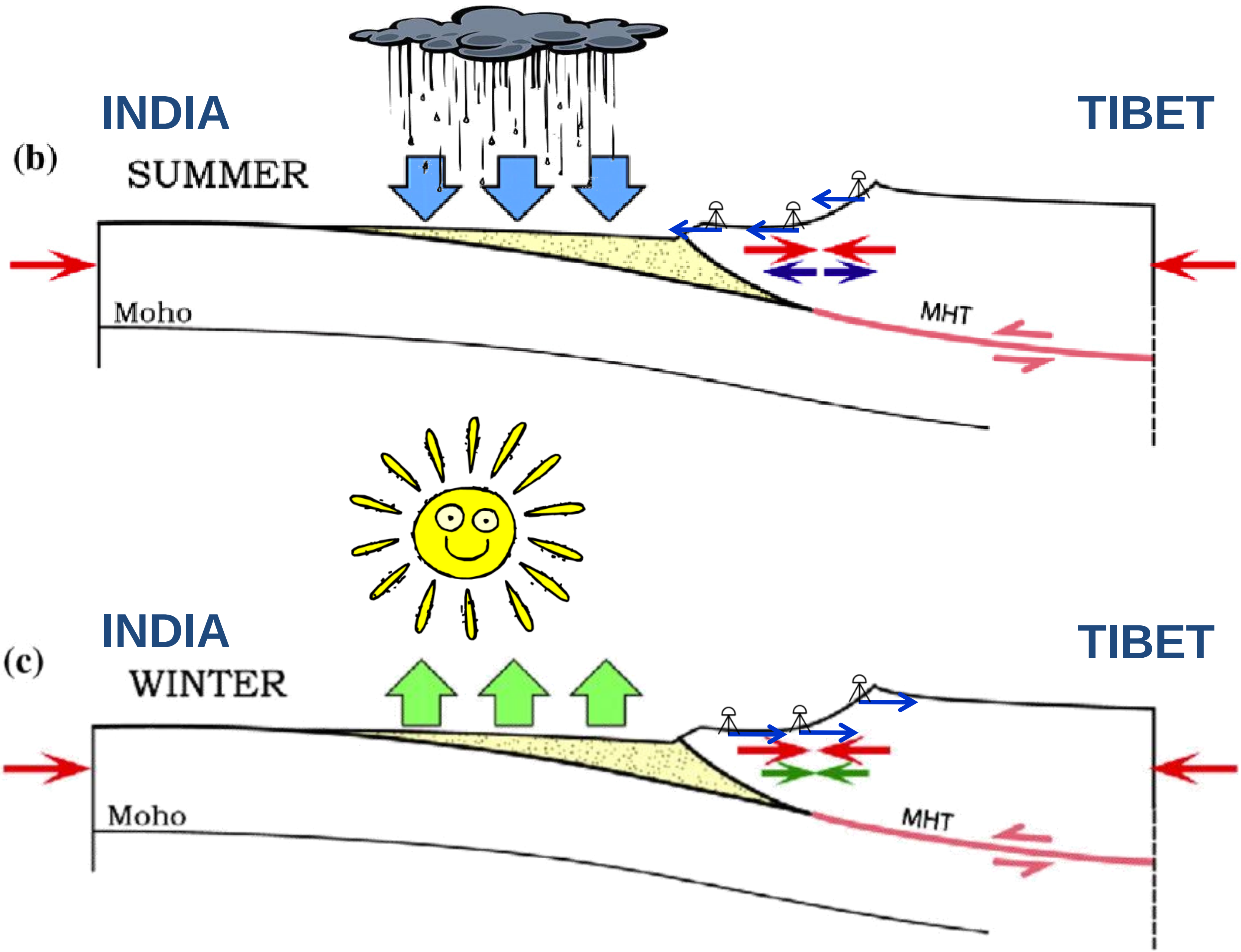
Observed seasonal displacements and predictions from surface load variation





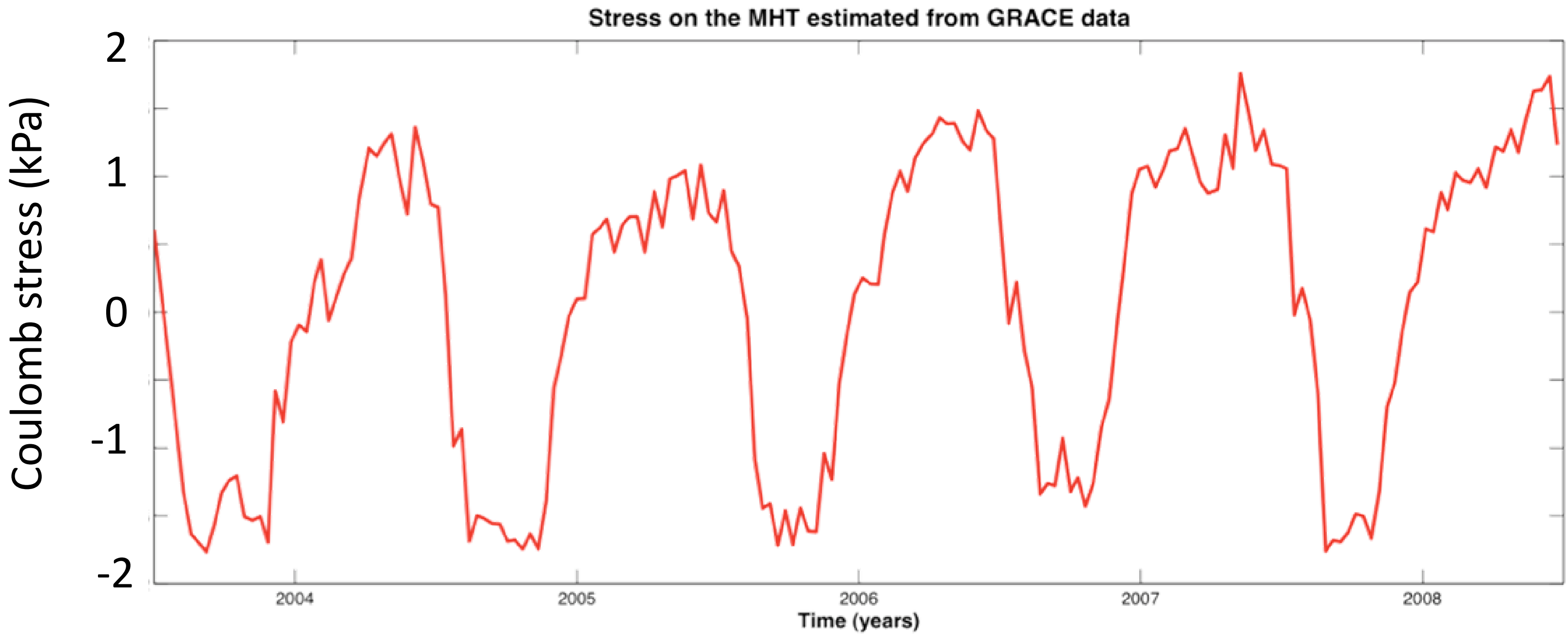
Model: Elastic response to surface load of a spherical Earth model (PREM)

(Kristel Chanard)

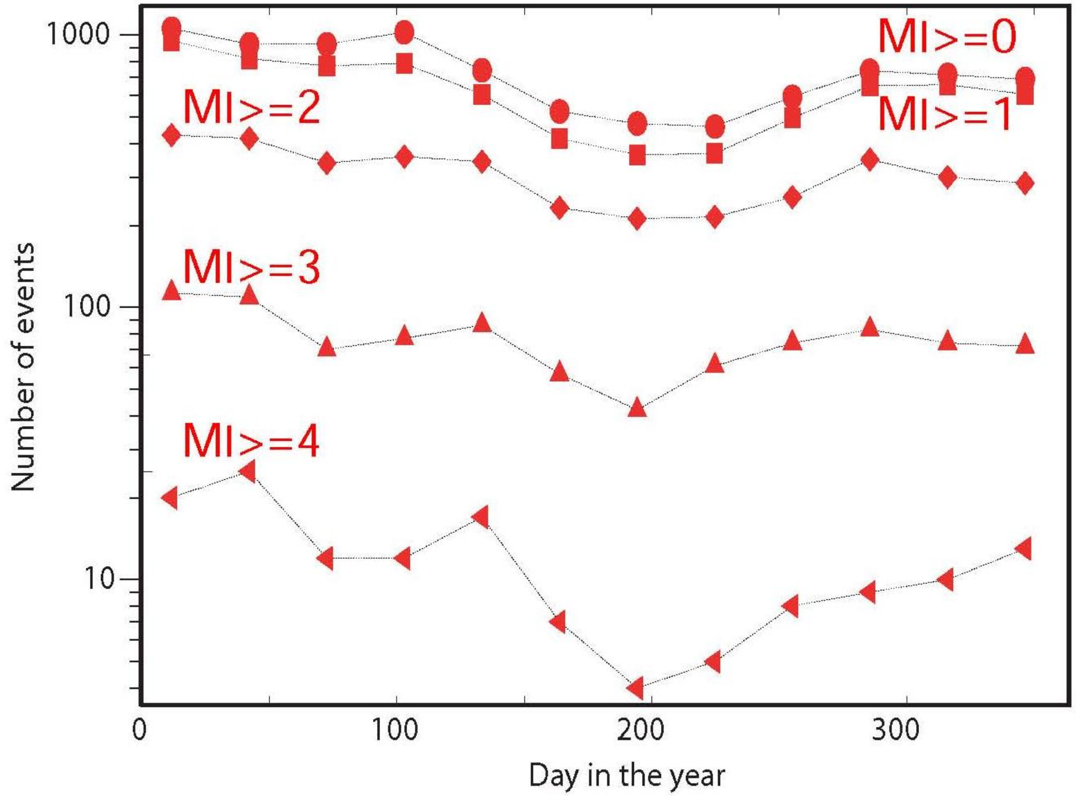


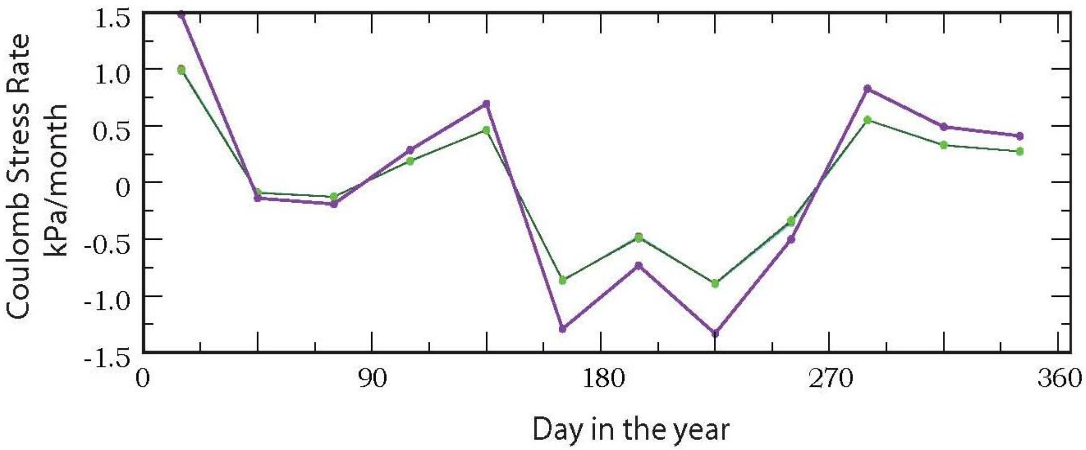
Bettinelli et al. (2008)

Variation of Coulomb stress due to seasonal surface loading



(Kristel Chanard)



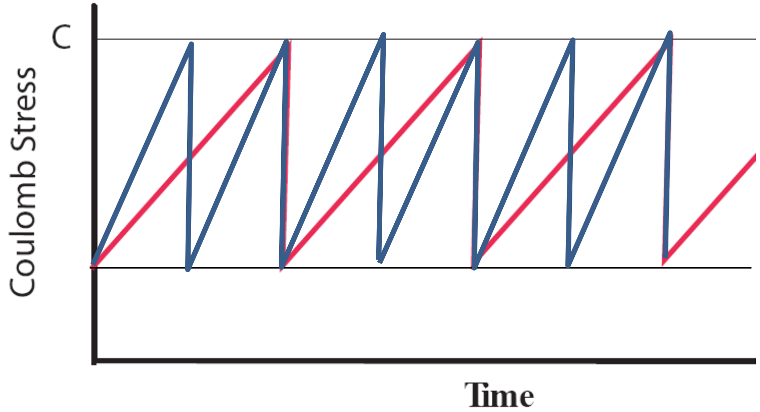


- Seismicity rate is approximately proportional to stress rate and no significant phase shift is observed

(Bettinelli et al, 2008)

Standard Coulomb Failure Model

$$S = \tau - \mu \cdot \sigma_n$$



Assuming $\dot{S} > 0$, seismicity rate obeys :

$$R = R_0 \frac{\dot{S}}{\dot{S}_0}$$

Seismicity rate is proportional to stress rate

For periodic loading :

$$\frac{\Delta R}{R_0} = 2\pi \frac{\tau_m}{T \cdot \dot{S}_0}$$

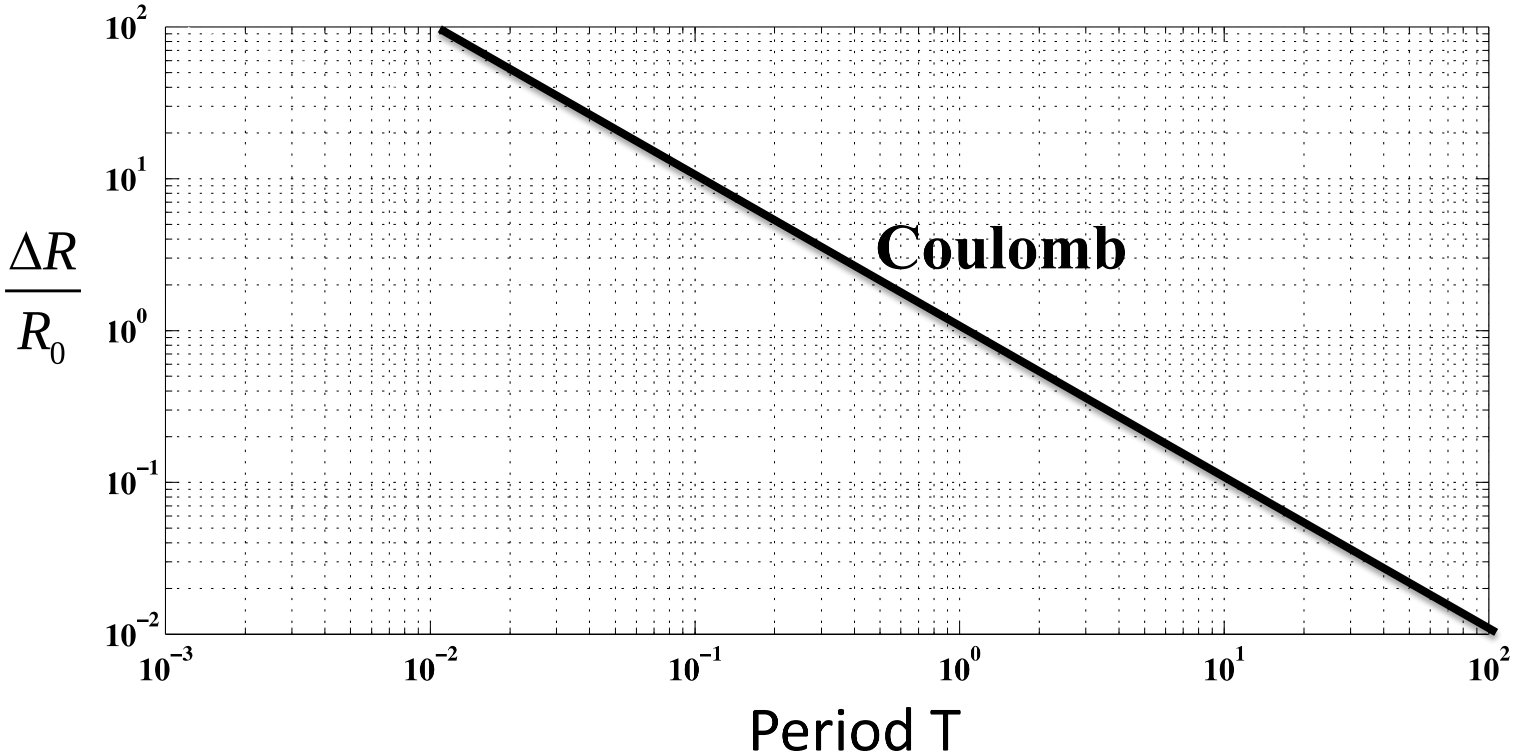
The amplitude of seismicity rate fluctuations scale as 1/T

Standard Coulomb Failure Model

Seismicity rate: $R(t) \propto \dot{\tau}(t)$

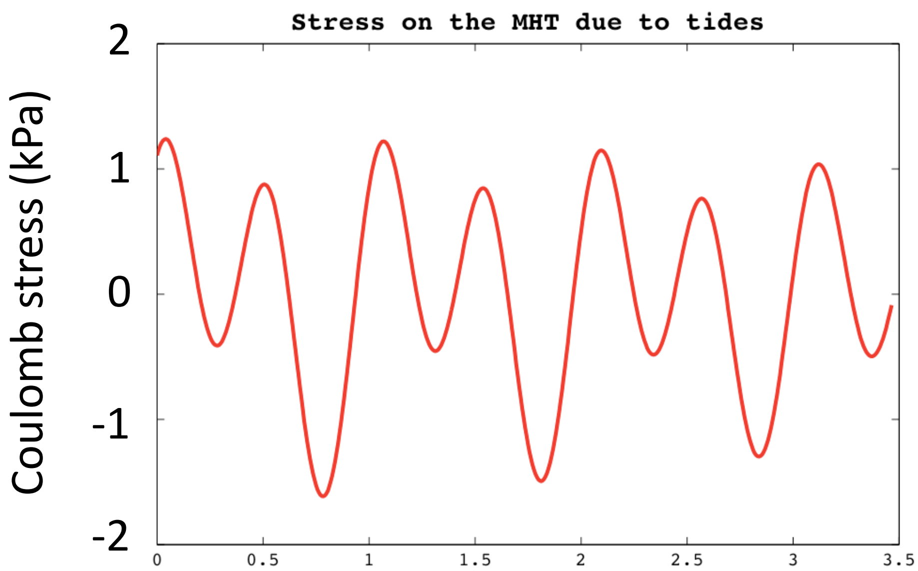
Stress: $\tau(t) = \Delta\tau \sin 2\pi t / T$

$$\frac{\Delta R}{R_0} = 2\pi \frac{\tau_m}{T \cdot \dot{S}_0}$$



The amplitude of seismicity rate fluctuations scale as 1/T

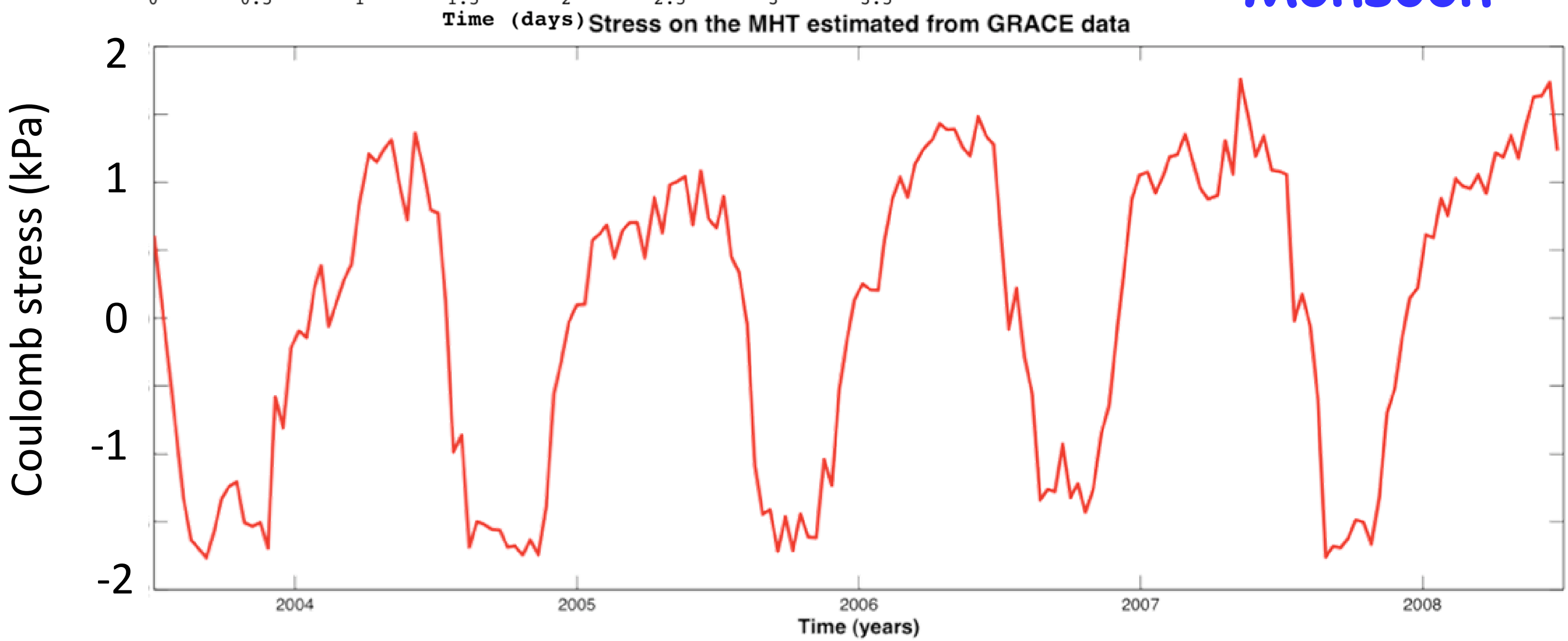
Variation of Coulomb stress



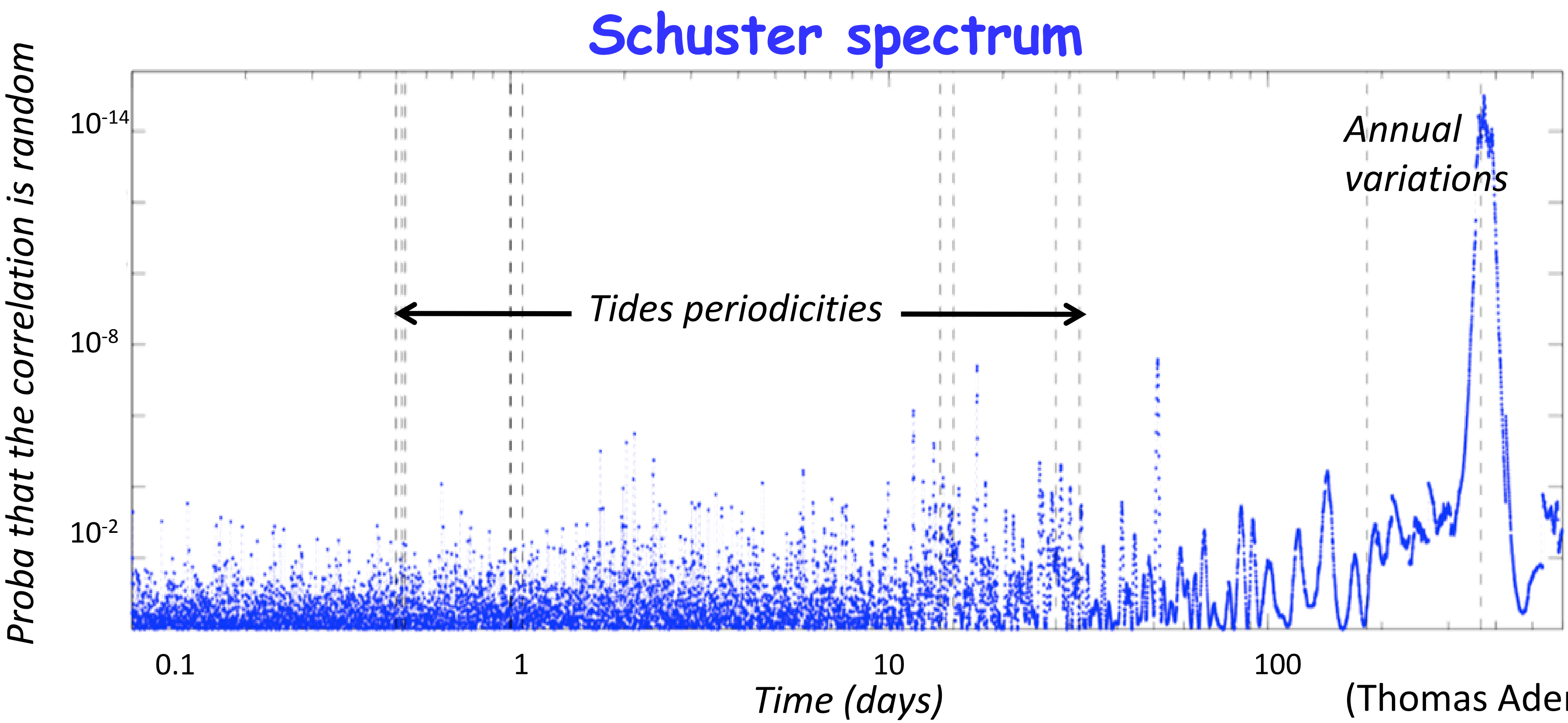
Tides

Same amplitude
Different periods

Monsoon



Periodicities of Himalayan Seismicity



(Thomas Ader)

No correlation with tides // Annual correlation

The absence of a detectable correlation with earth tides shows that rupture is a time-dependent process at the 12h scale (ta>12h)

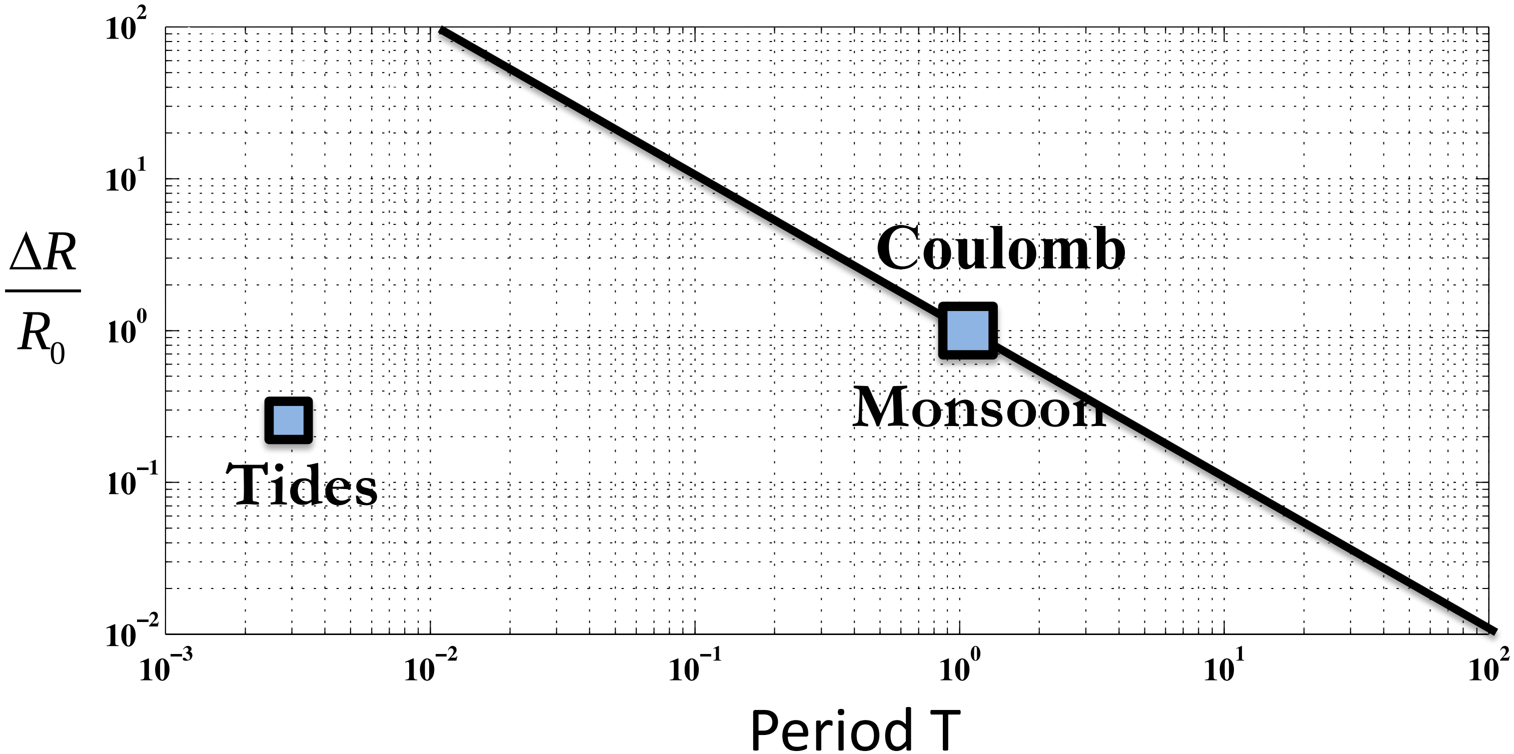
12 h << nucleation time << 1yr

Standard Coulomb Failure Model

Seismicity rate: $R(t) \propto \dot{\tau}(t)$

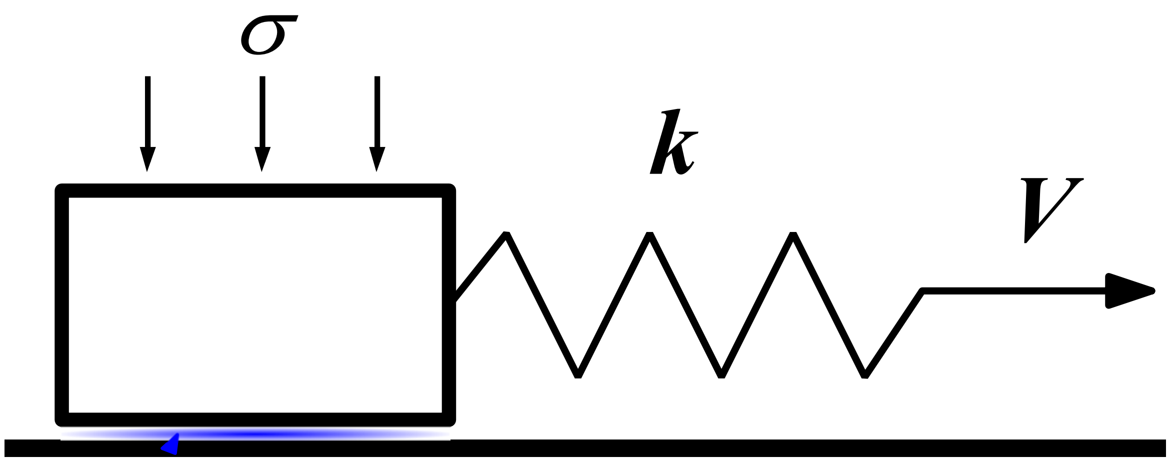
Stress: $\tau(t) = \Delta\tau \sin 2\pi t / T$

$$\frac{\Delta R}{R_0} = 2\pi \frac{\tau_m}{T \cdot \dot{S}_0}$$



Failure has to be a time-dependent process

Rate&State Friction Model

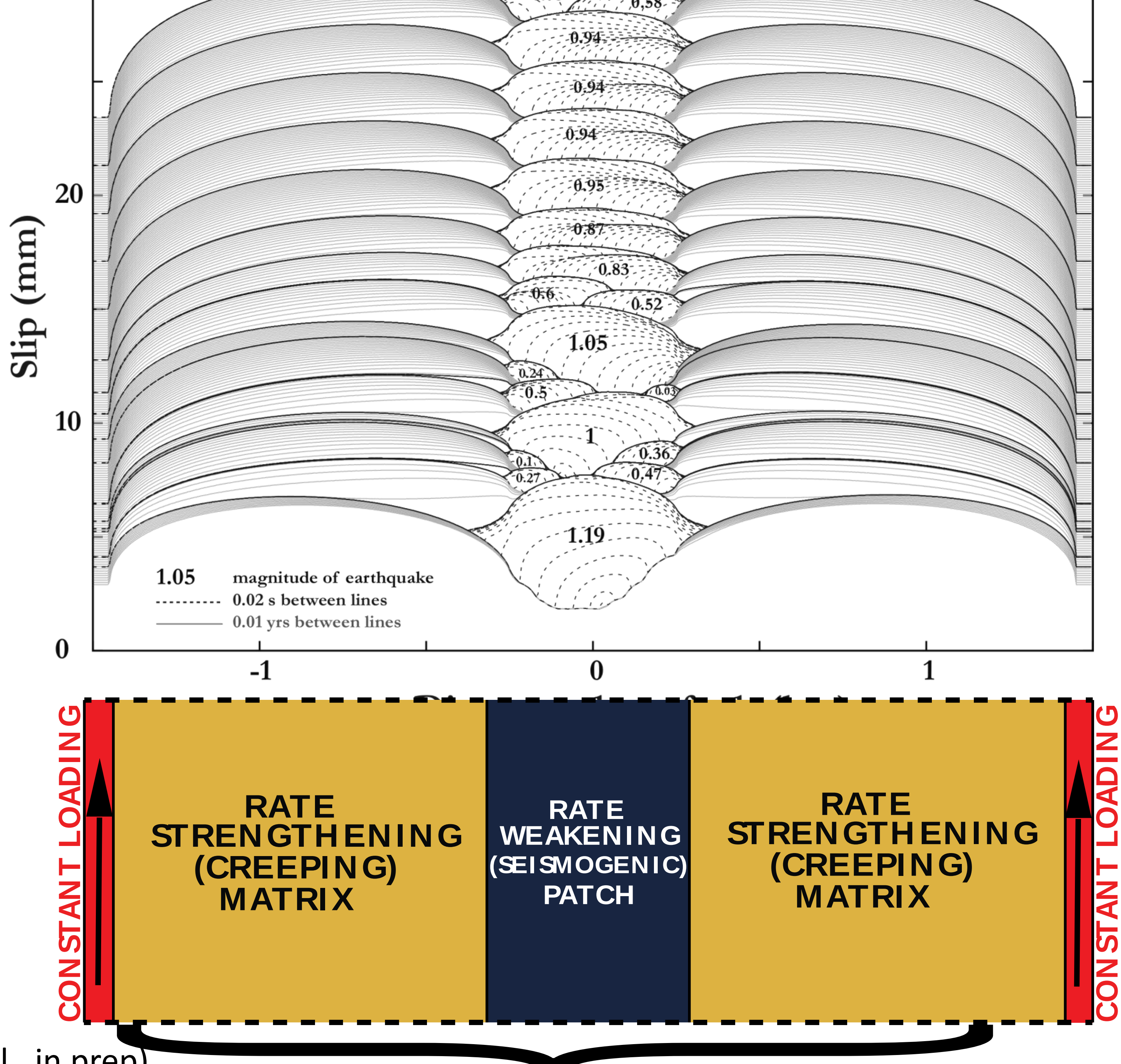


$$\dot{\tau}(t) = kV$$

$$\begin{cases} \tau(t) = \sigma\left(\mu^* + a\ln\dfrac{V}{V^*} + b\ln\dfrac{\theta V^*}{D_c}\right) \\ \dfrac{d\theta}{dt} = 1 - \dfrac{\theta V^*}{D_c} \end{cases}$$

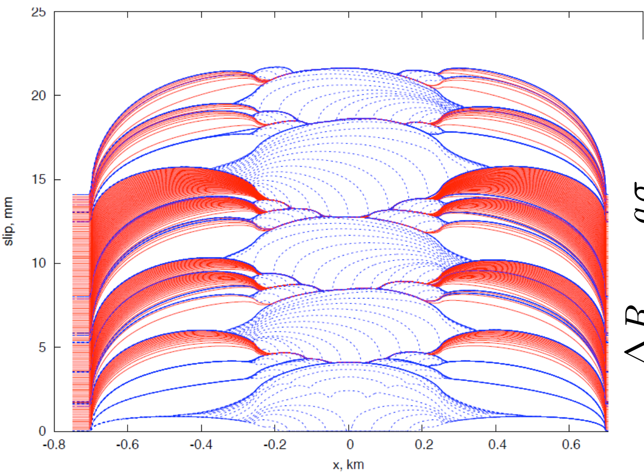
Stick-slip requires rate-weakening friction

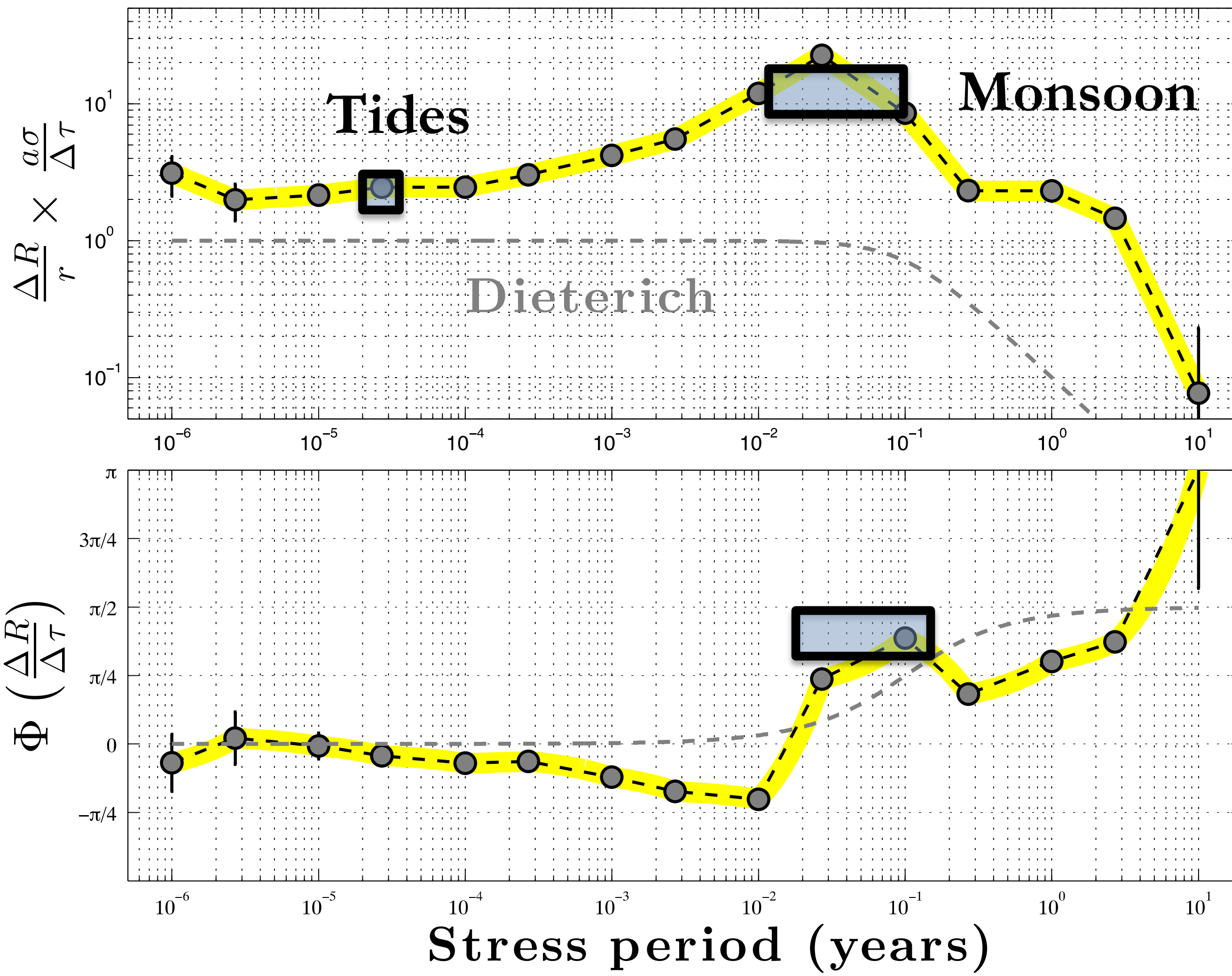
$a-b < 0$



(Ader et al., in prep)

Rate&State Friction Model





Model parameters:

σ_n = 5 MPa

a = 0.008

b = 0.004, RS

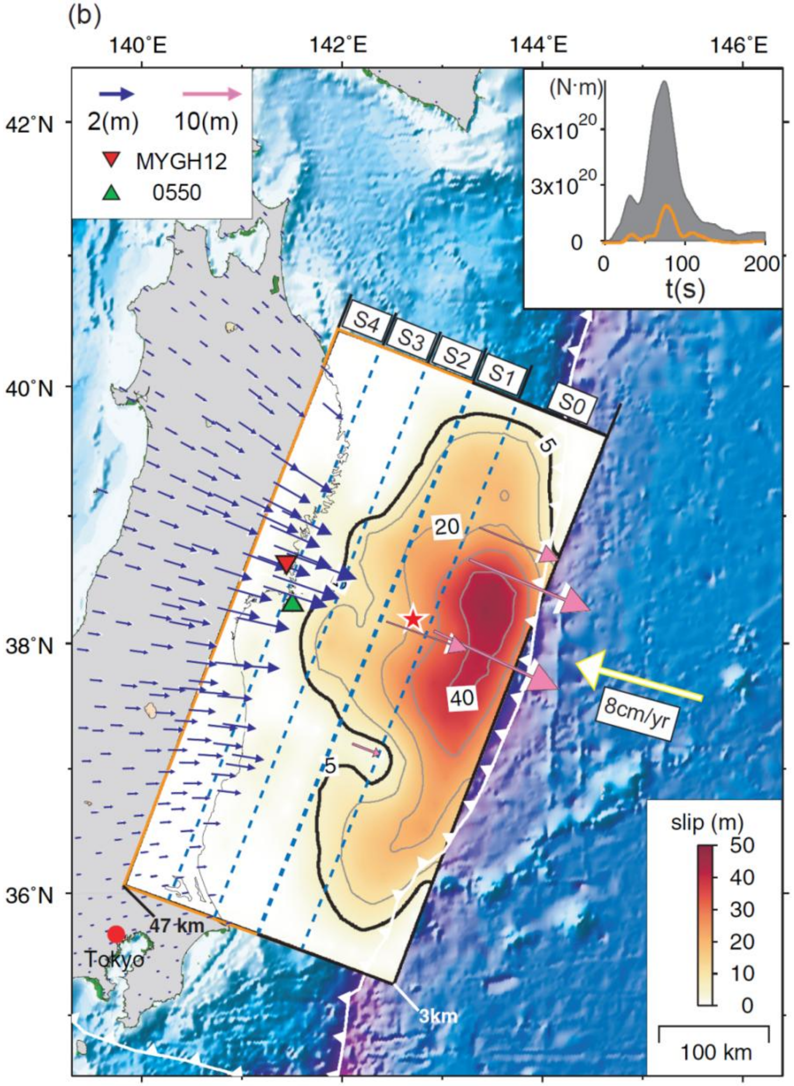
b= 0.012, RW

D_c = 5 μm.

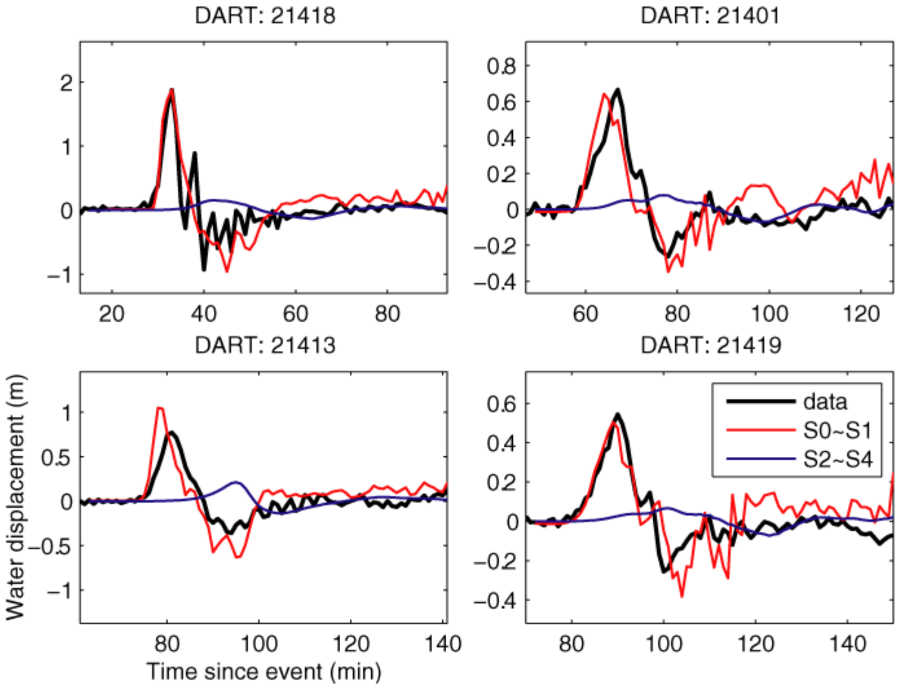
V_o = 1 cm/yr.

(Ader et al., in prep)

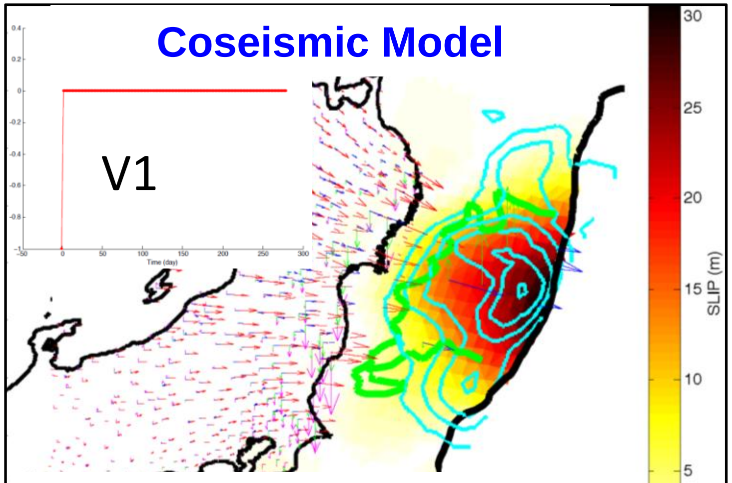
The 2011, M_w9.0 Tohoku-Oki Earthquake



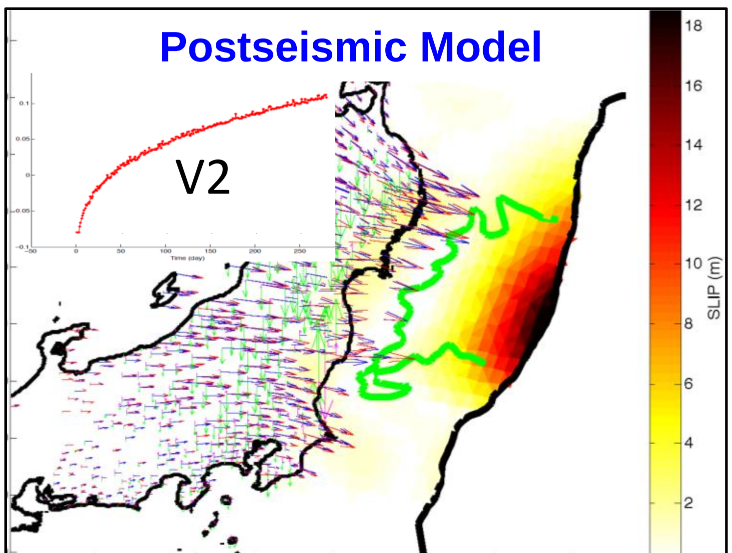
Source model determined from the joint inversion of CGPS, teleseismic and acclereometric records (Wei et al., EPSL, 2012)



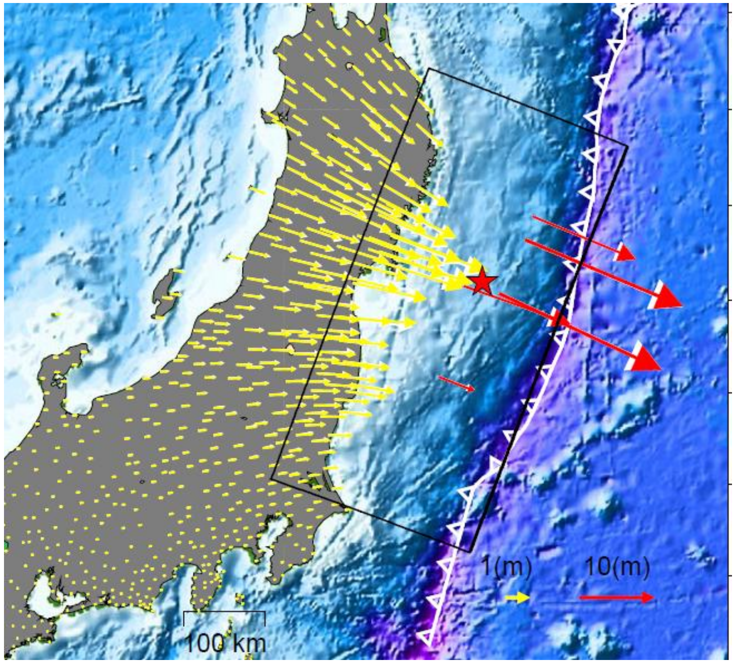
Co-, Post- and Inter-seismic Models of the 2011 M_w9.0 Tohoku-Oki Earthquake



Coseismic ruptures shown for reference:
Wei et al, 2010 (blue) Kato and Igarashi, 2012(Green)

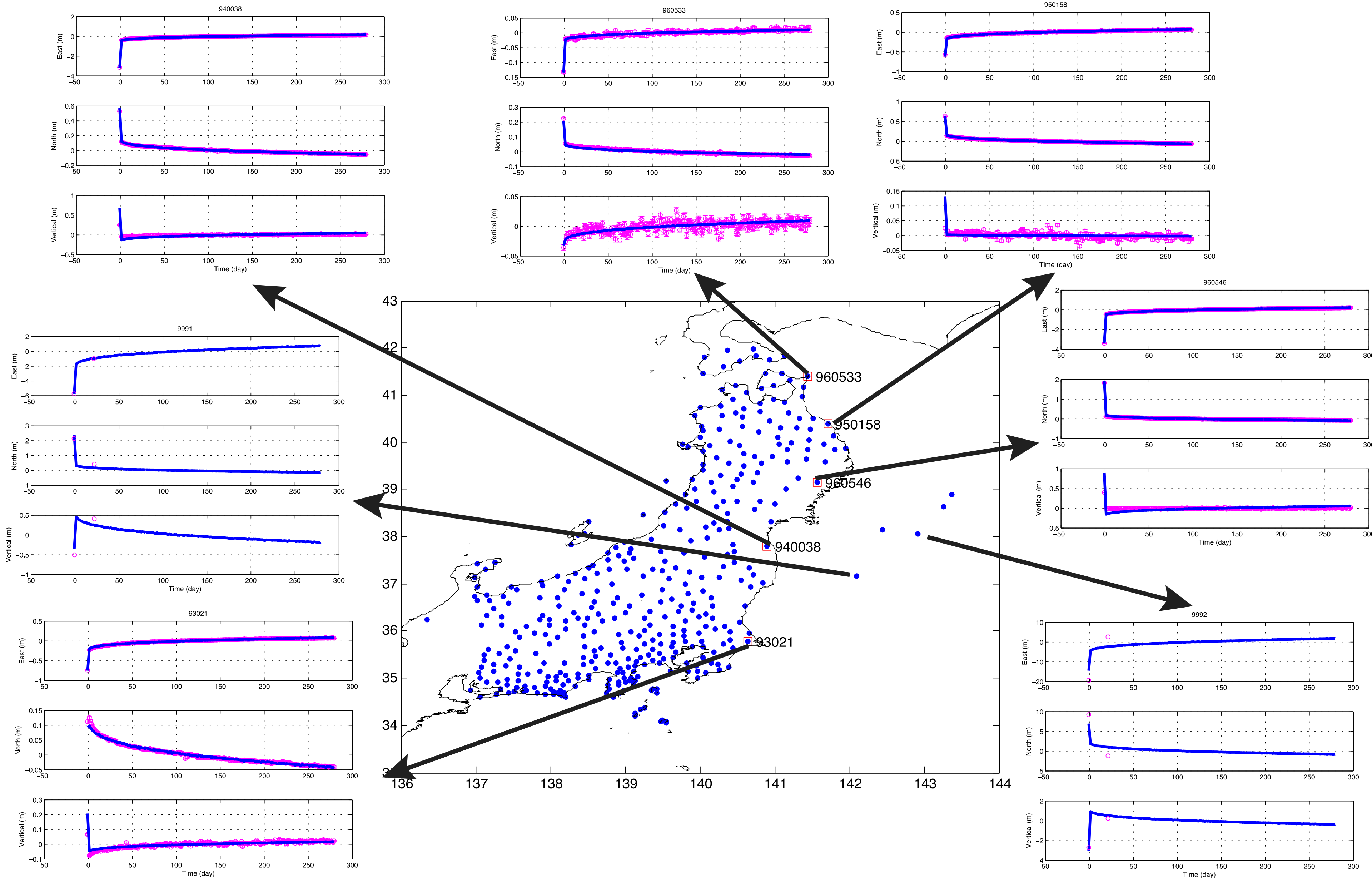


Method: Joint inversion of onshore GPS time series and offshore campaign data for co- and post-seismic slip using **PCAIM** (Kosistsky and Avouac, 2010)
Data: GEONET+ seabottom data (Inuma et al, JGR, 2012)



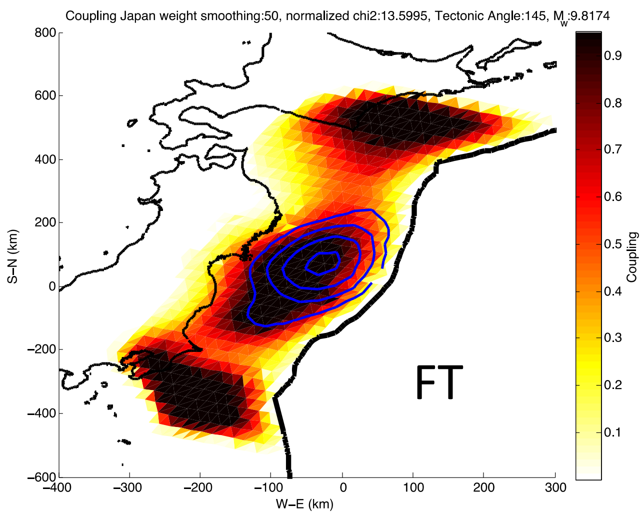
Tectonics Observatory
California Institute of Technology

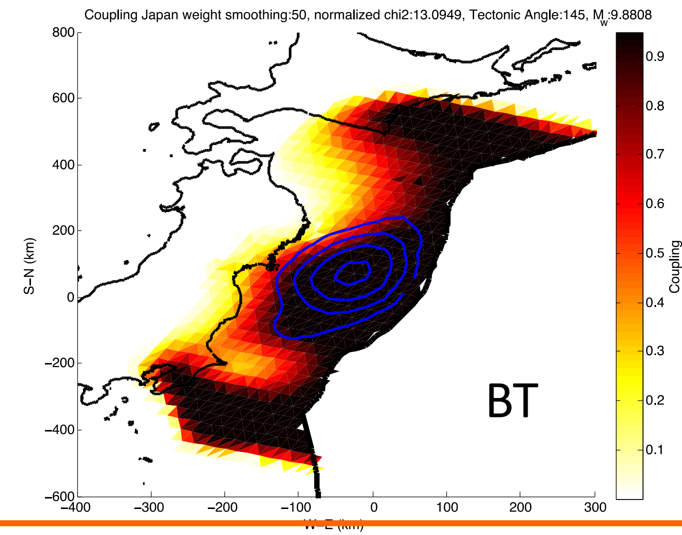
Co-, Post- and Inter-seismic Models of the 2011 M_w9.0 Tohoku-Oki Earthquake

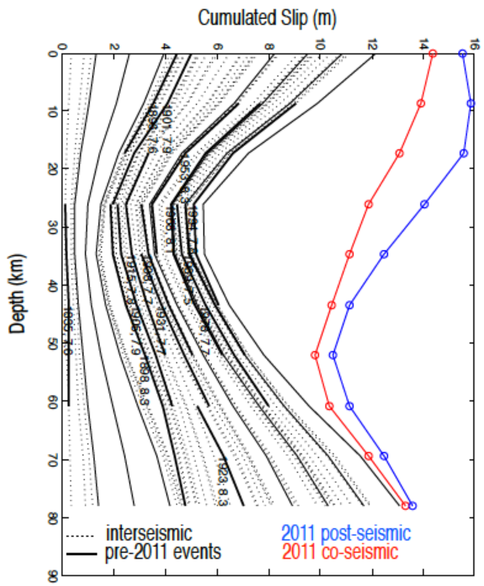


Co-, Post- and Inter-seismic Models of the 2011 M_w9.0 Tohoku-Oki Earthquake

Interseismic Coupling



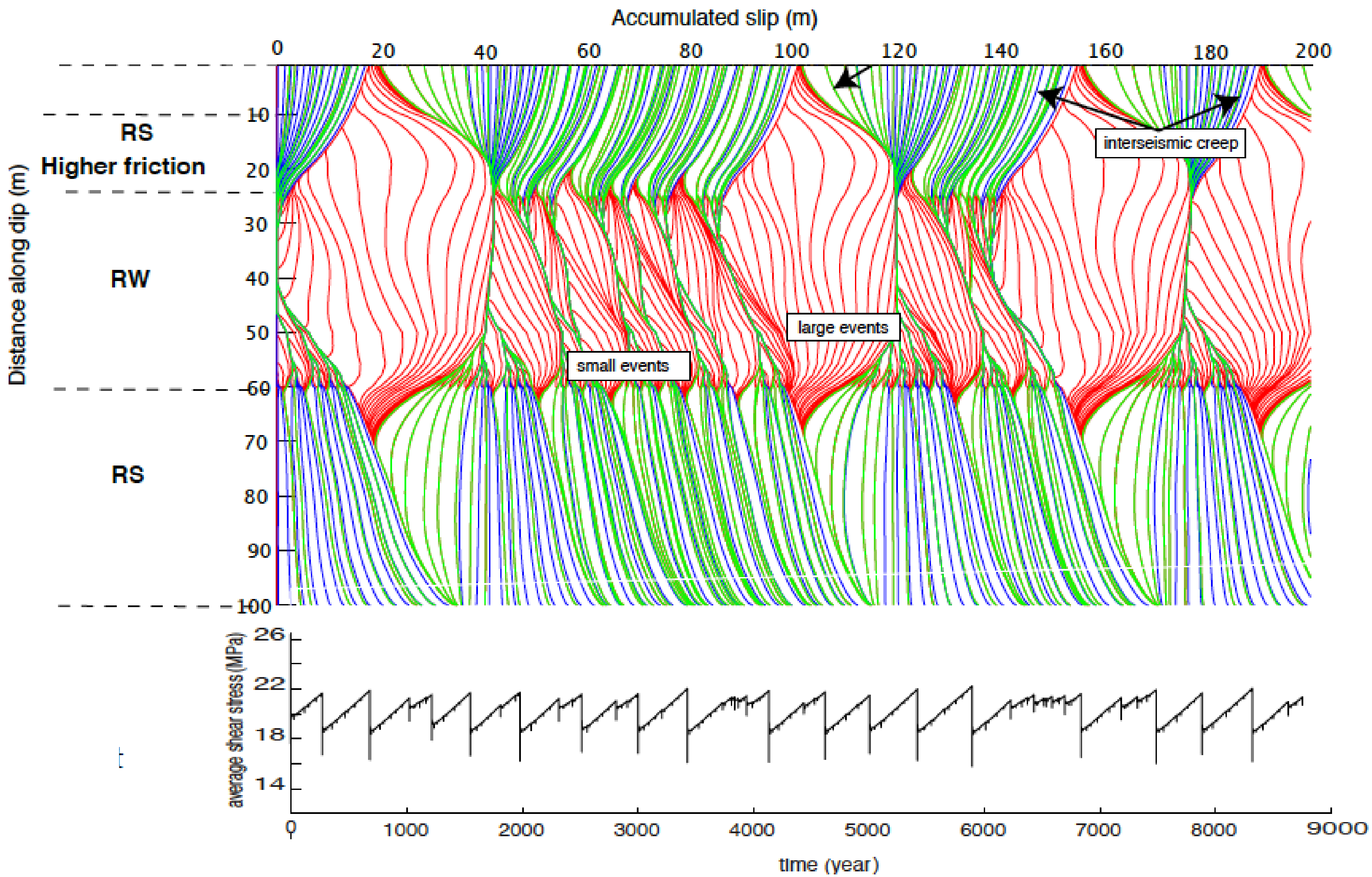




Data:
- Interseismic GPS velocities from GEONET (Loveless and Meade, 2010,2011)
- Sea bottom displacements (Matsumoto et al. EPS, 2008)

Implication
- Return Period of Tohoku Oki EQ estimate to 100yr (BT) - 300yr (FT)

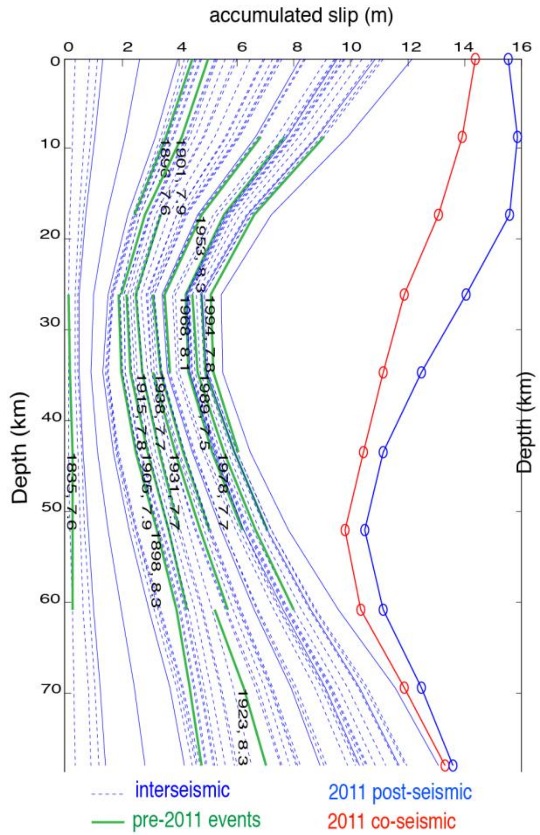
Dynamic Modeling

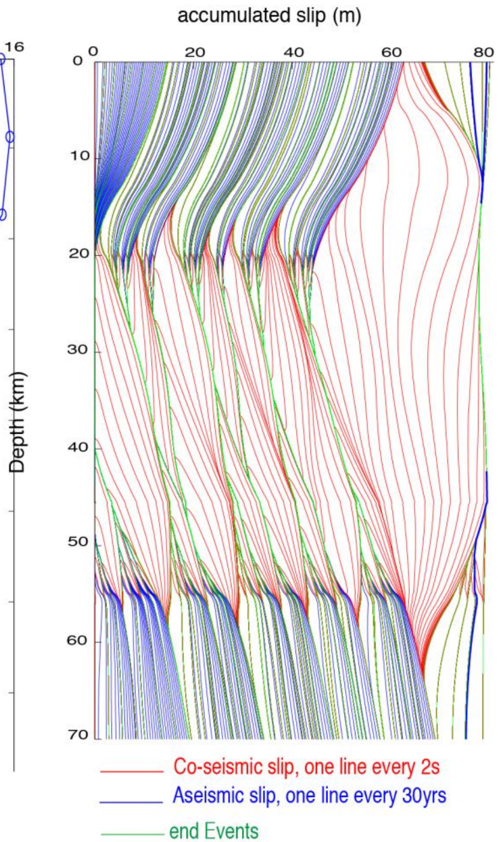


Thermal Pressurization allows overlapping seismic and aseismic slip (Noda and Lapusta, 2012)

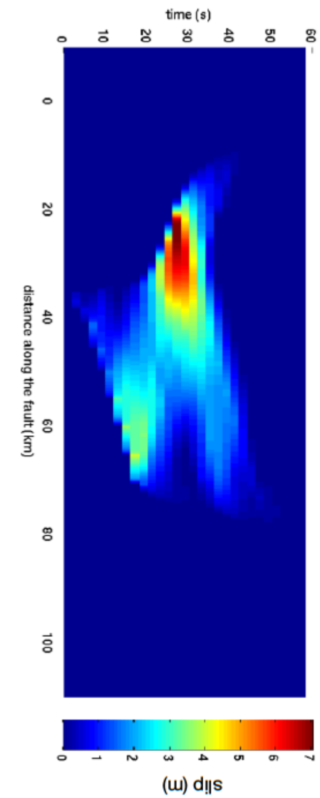
Dynamic Modeling

Observed and simulated slip during over the seismic cycle

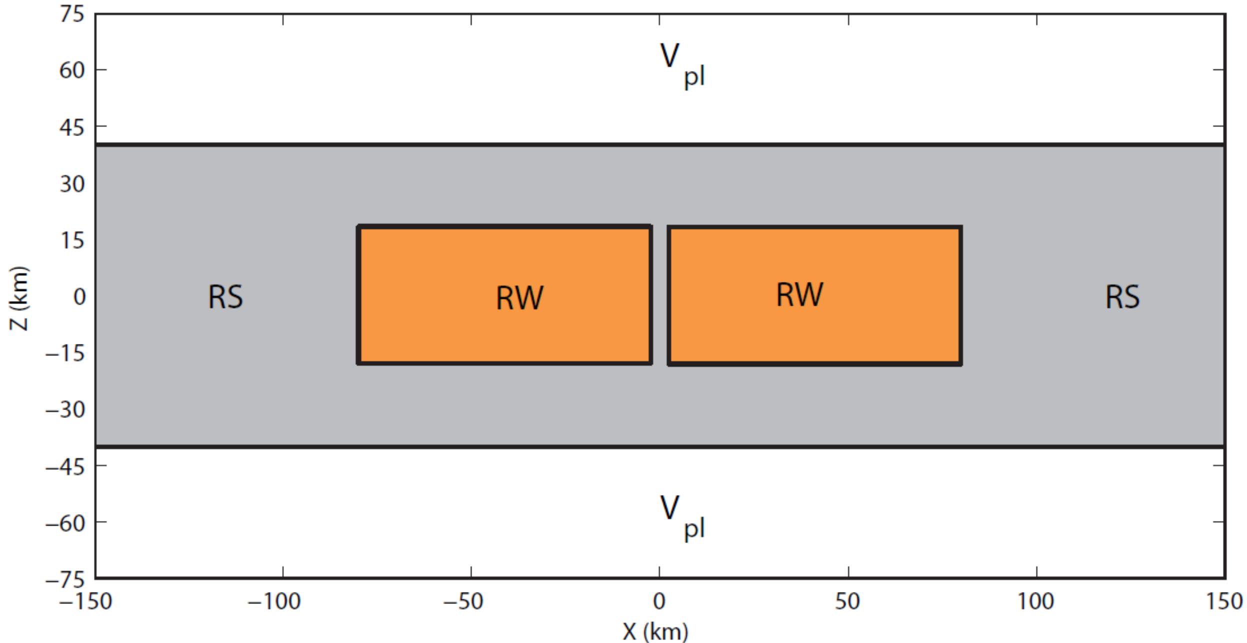


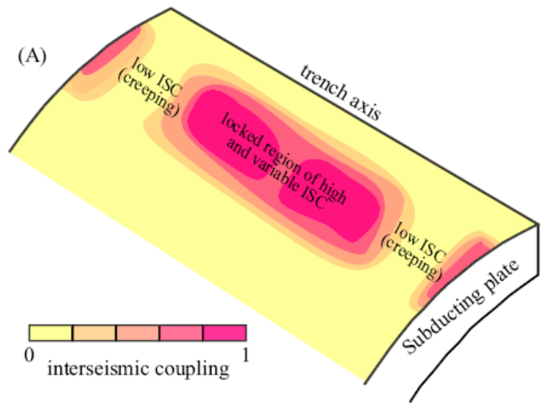


Rupture propagation



Dynamic modeling





Rate & state friction:

(Dieterich, 1979;Ruina, 1983)

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

Numerical Method: Boundary Intregral Method in 3-D

(Lapusta and Liu (JGR, 2009))

(Kaneko, Avouac and Lapusta, 2010)

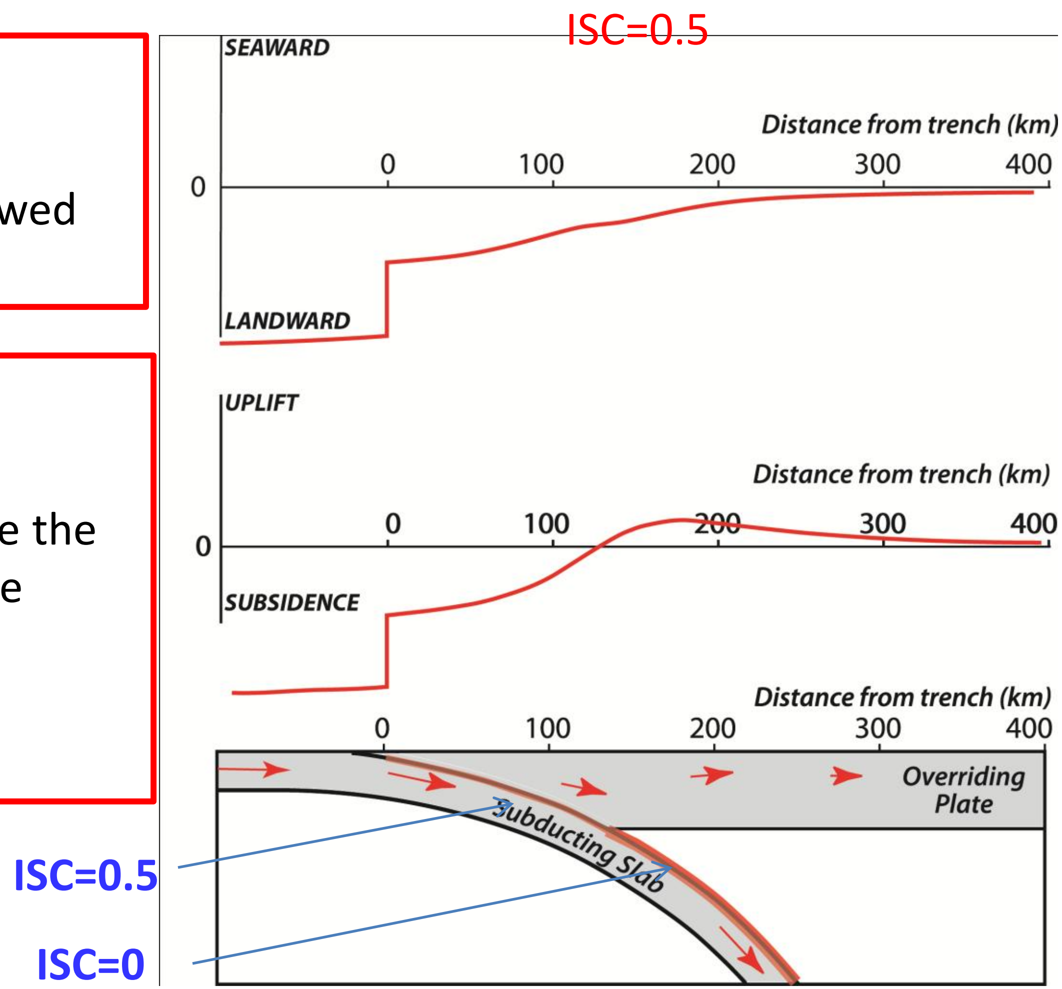
Interseismic coupling

Partial Coupling:

In kinematic inversions ISC is allowed to vary between 0 and 1.

Implication:

Seismic slip is required to balance the quantity ISC x Long Term Slip Rate



Interseismic coupling

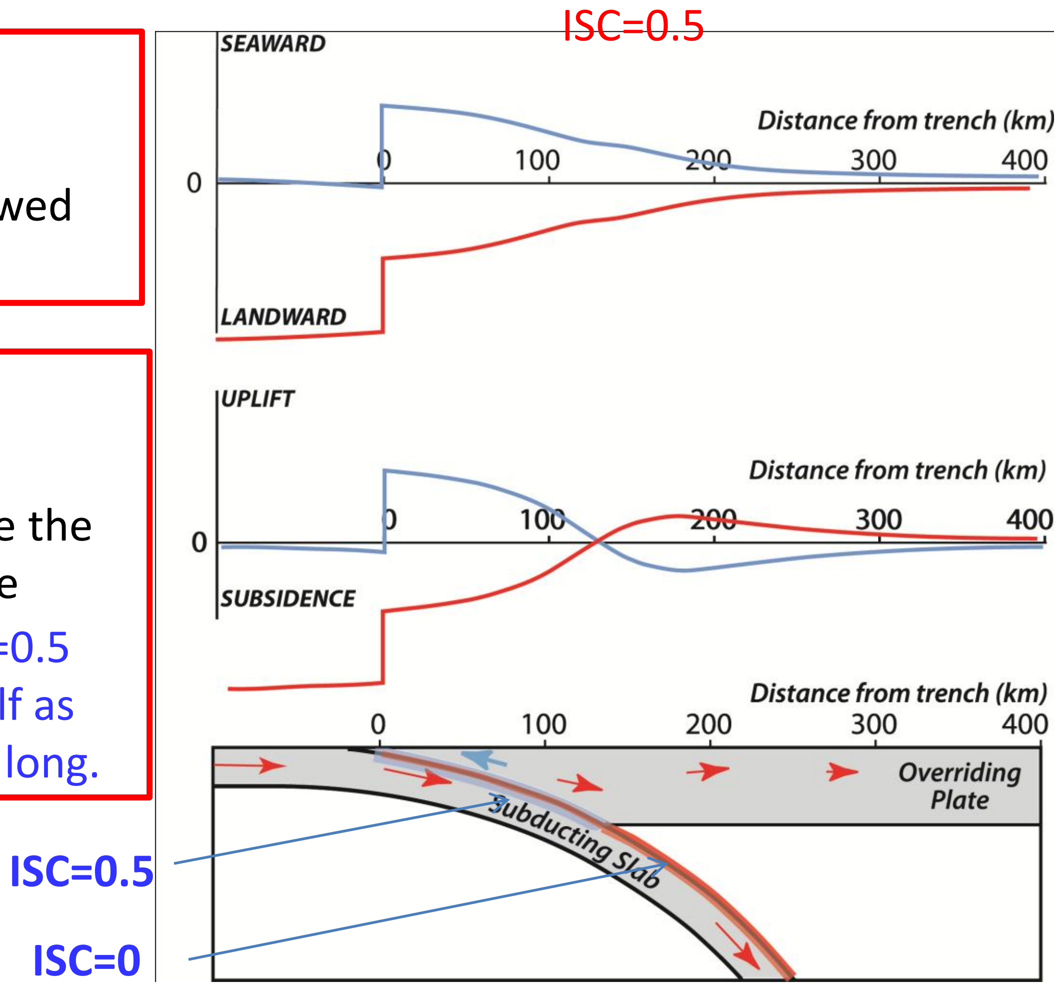
Partial Coupling:

In kinematic inversions ISC is allowed to vary between 0 and 1.

Implication:

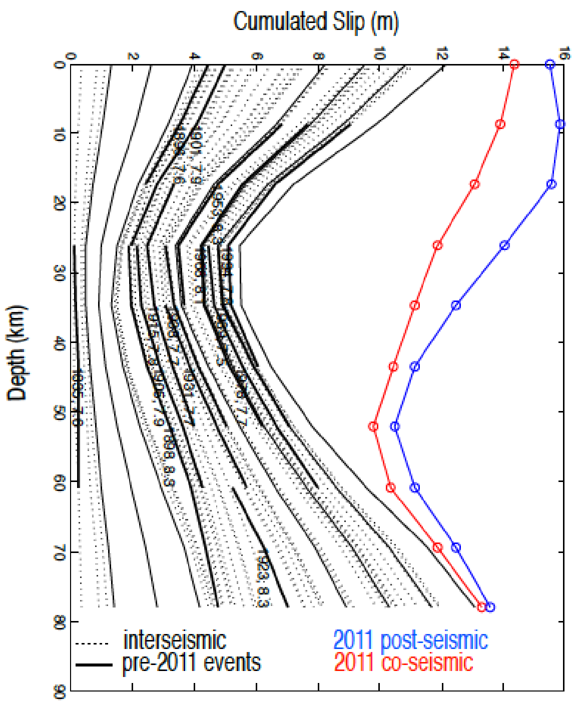
Seismic slip is required to balance the quantity ISC x Long Term Slip Rate

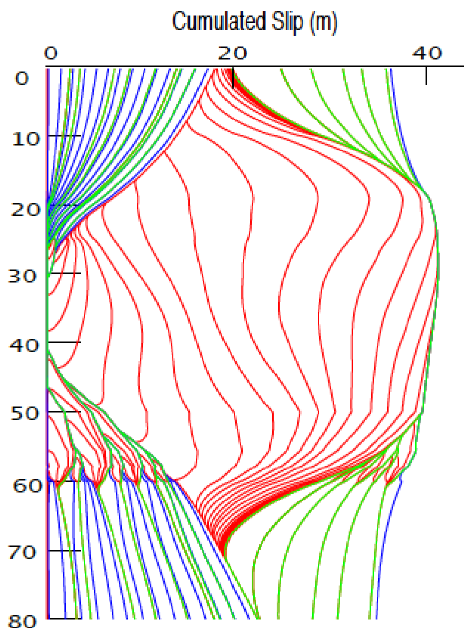
Compared to the case ISC=1, ISC=0.5 requires transients slip events half as large, or a return period twice as long.



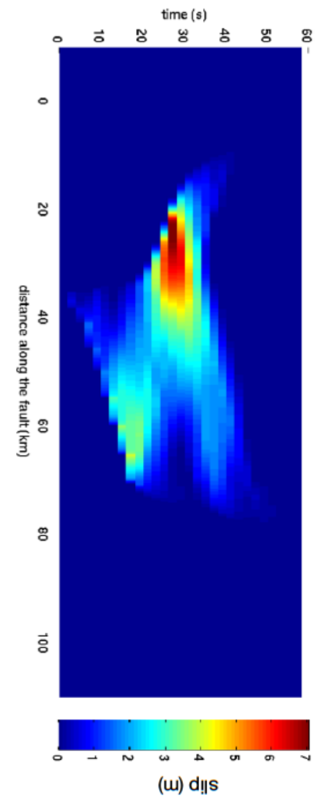
Dynamic Modeling

Observed and simulated slip during over the seismic cycle



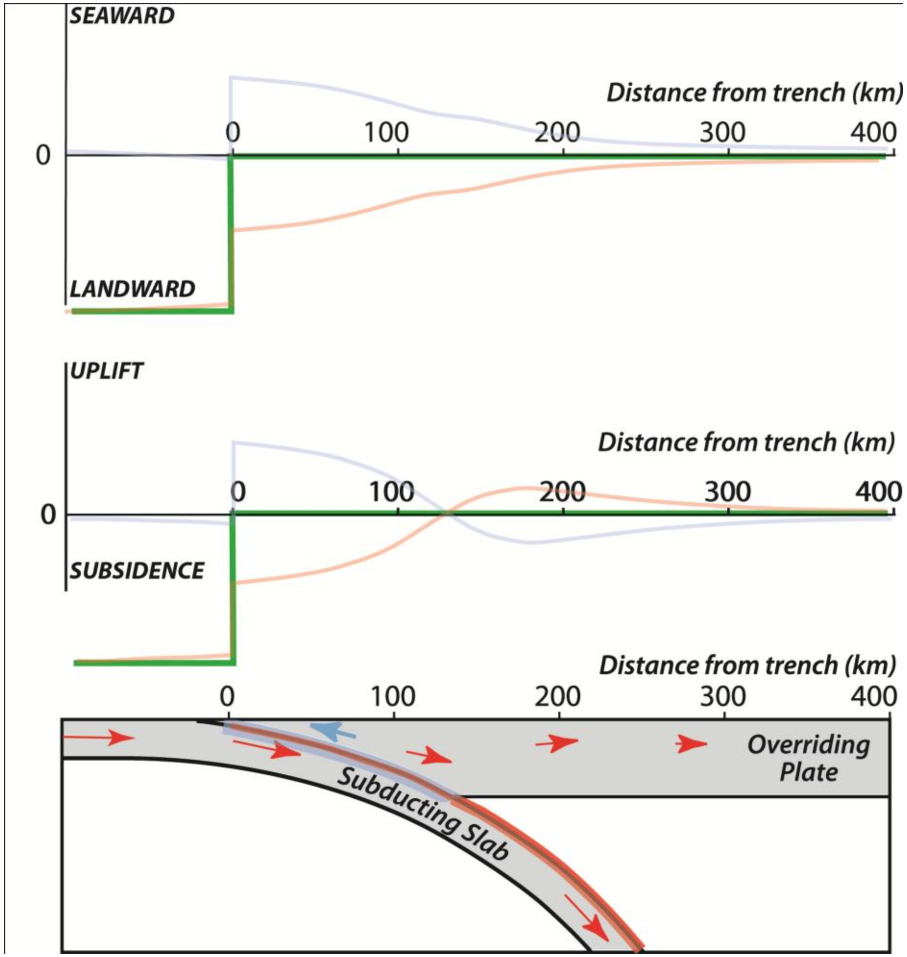


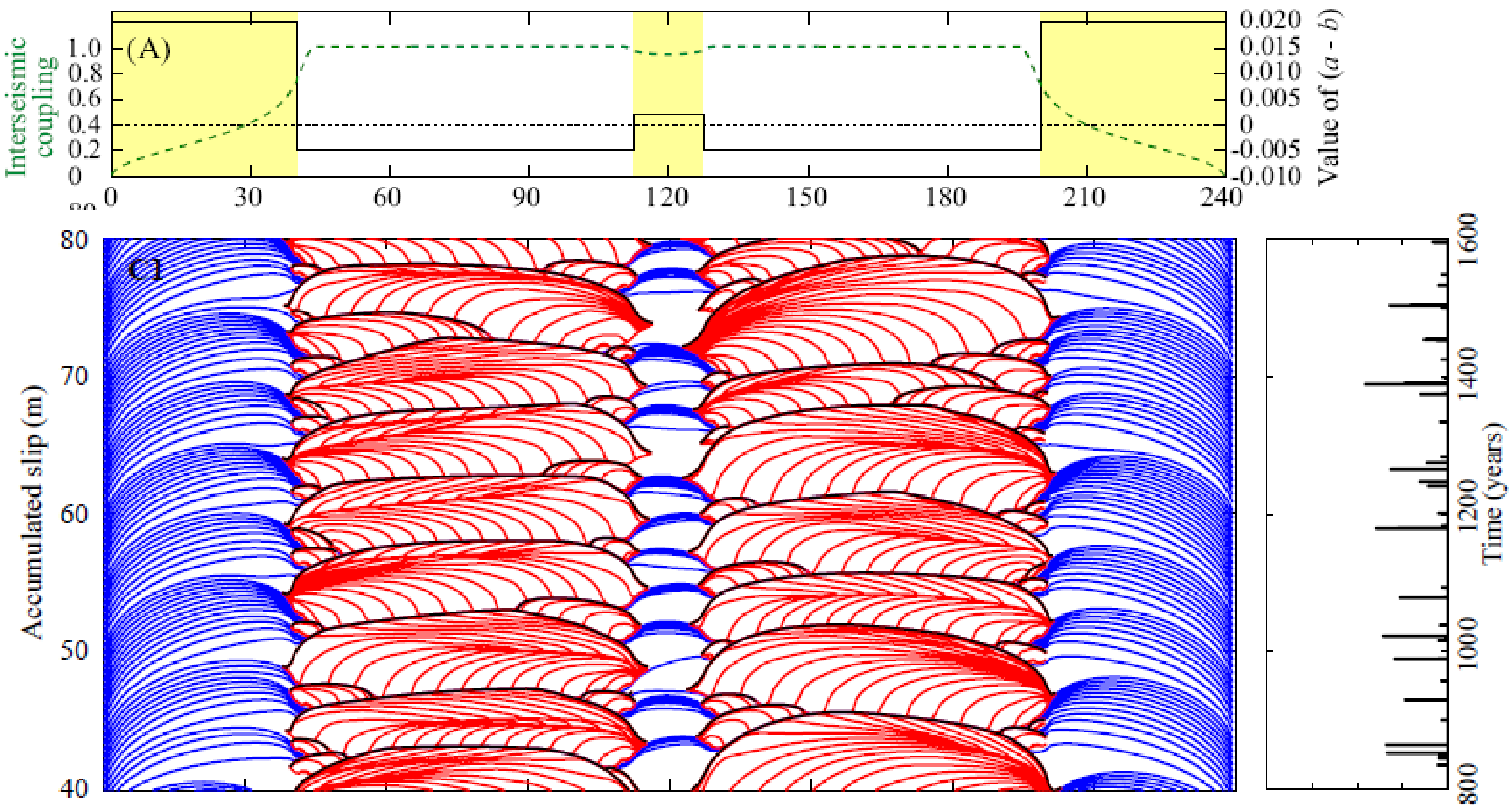
Backward propagation



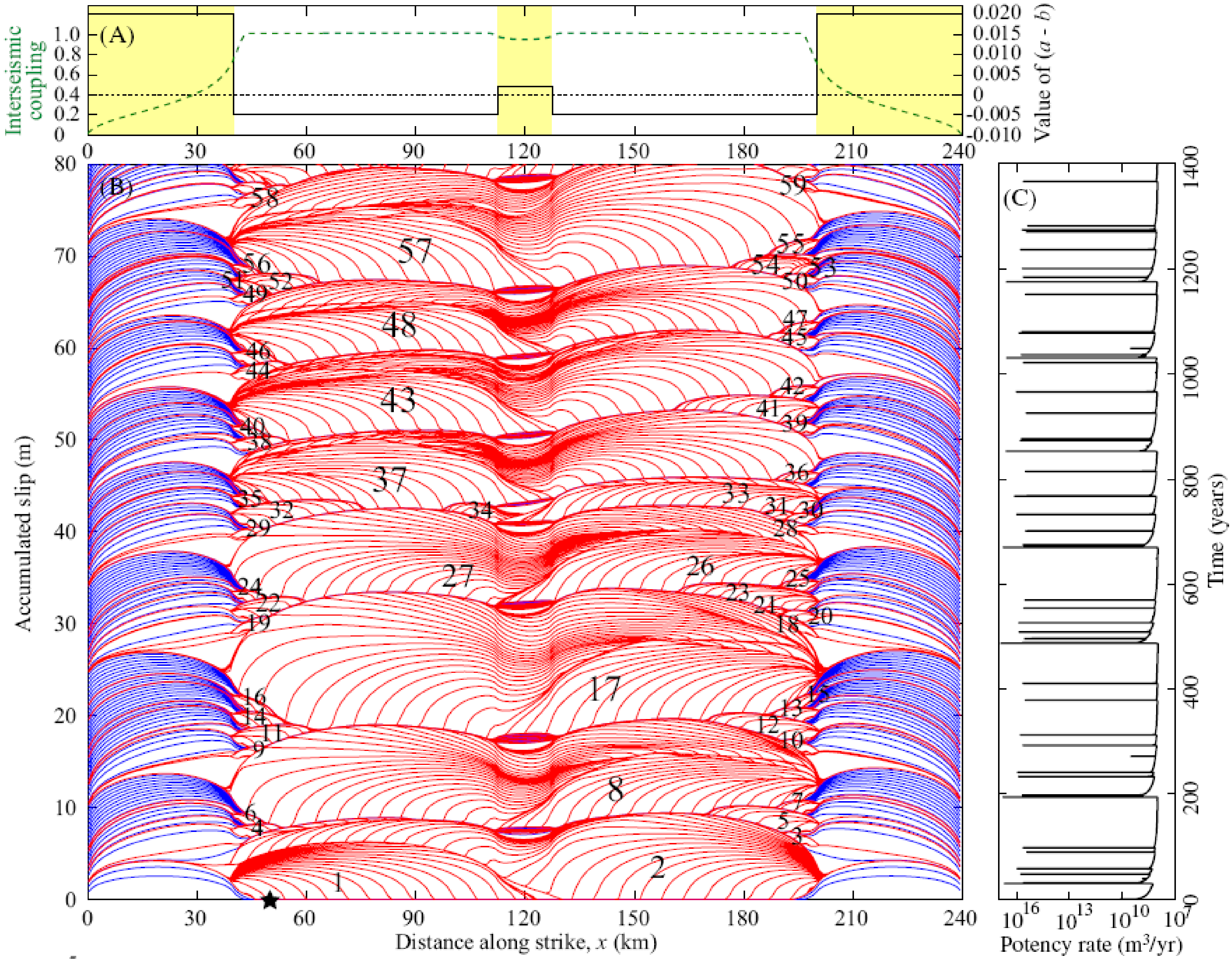
(**Nadaya Cubas** et al, T22C-08.*)*

Interseismic coupling



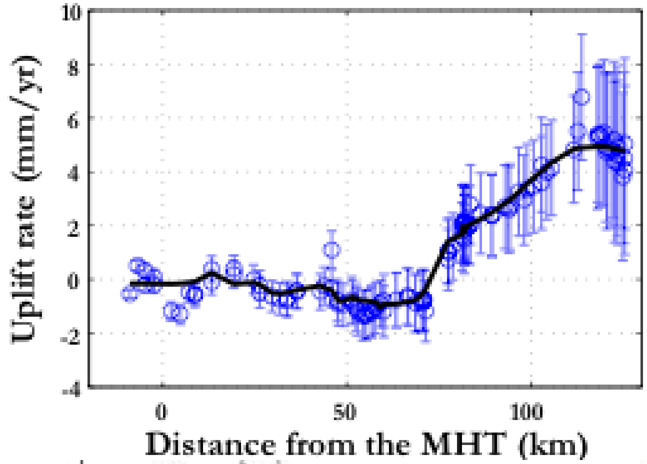


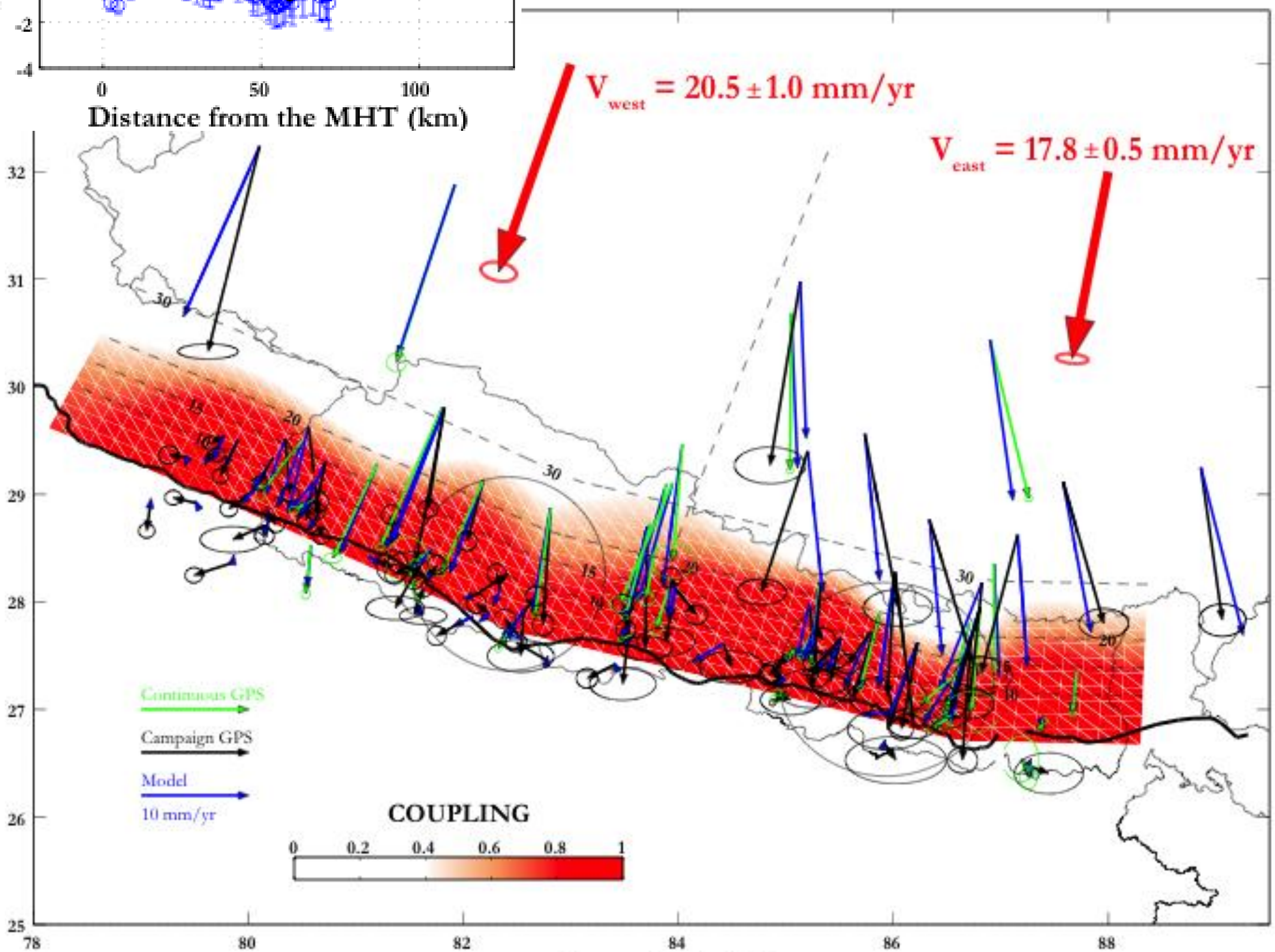
(Kaneko, Avouac and Lapusta, 2010)



(Kaneko, Avouac and Lapusta, 2010)

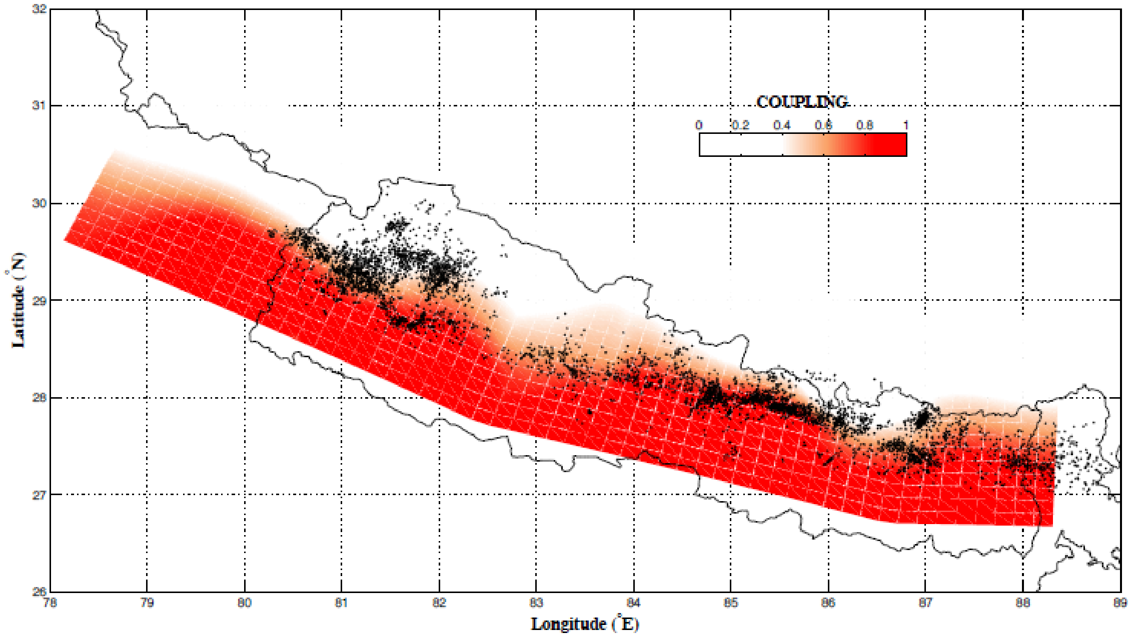
Interseismic Coupling derived from inversion of CGPS, campaign GPS and levelling data





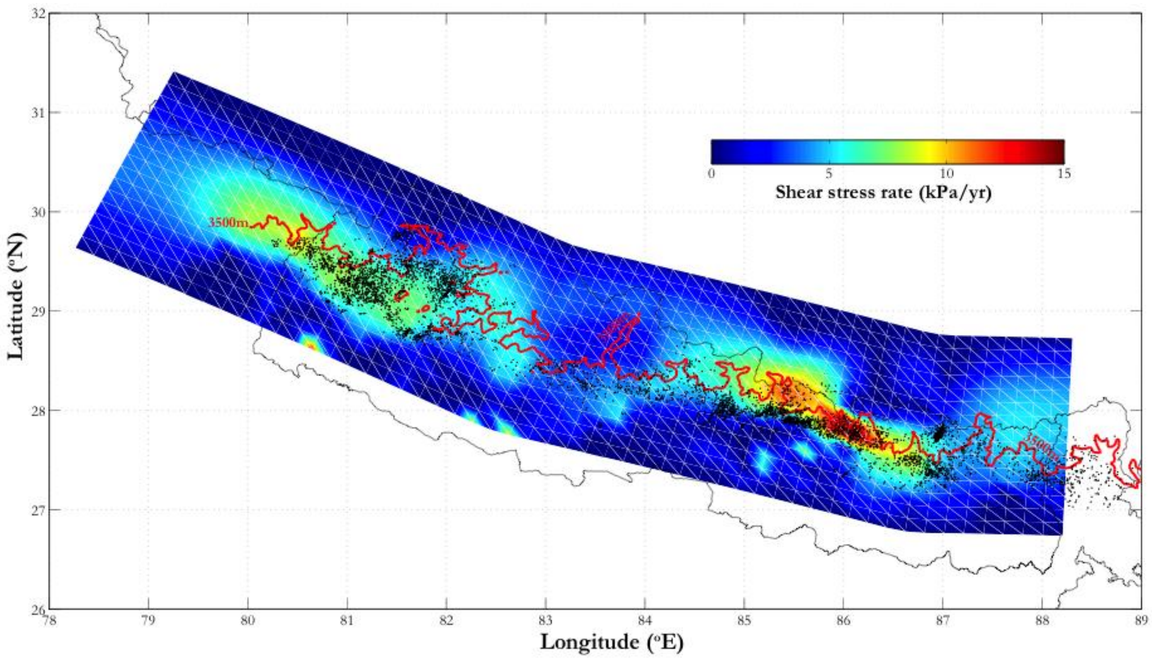
Ader et al. (2012)

Correlation of ISC with seismicity



Seismicity follows the downdip end of Locked Fault Zone where shear stress increases in the interseismic period by > 4kPa/yr.

The moment deficit accumulates in the interseismic period at a rate of 6.6 10^{19} Nm/yr.



How large and how frequent need the largest Himalaya earthquakes be?