Inferring fault friction and their spatial variability from the joint analysis of geodetic and seismological data

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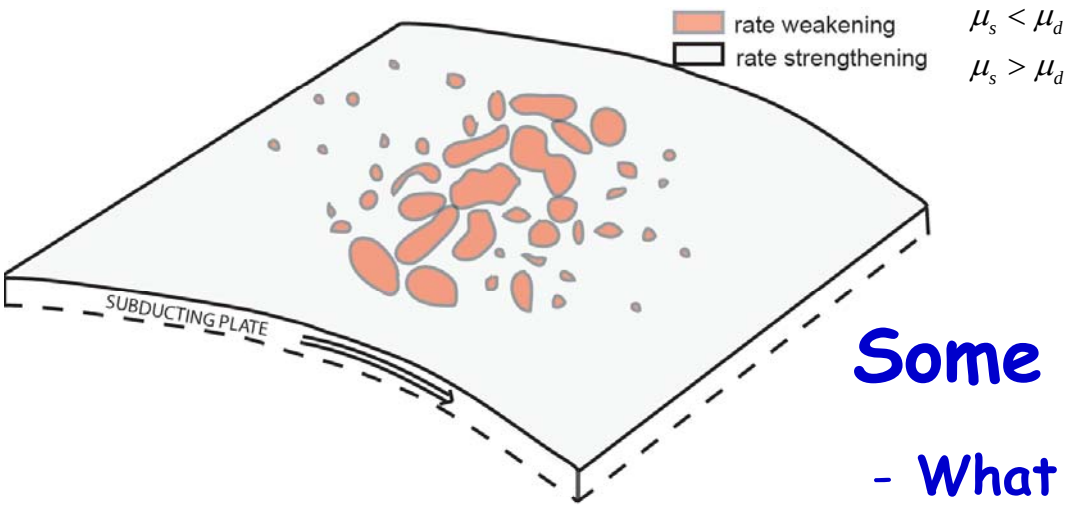
Conceptual framework



$\mu_s < \mu_d$

$\mu_s > \mu_d$

μ_s Static friction

μ_d Dynamic friction

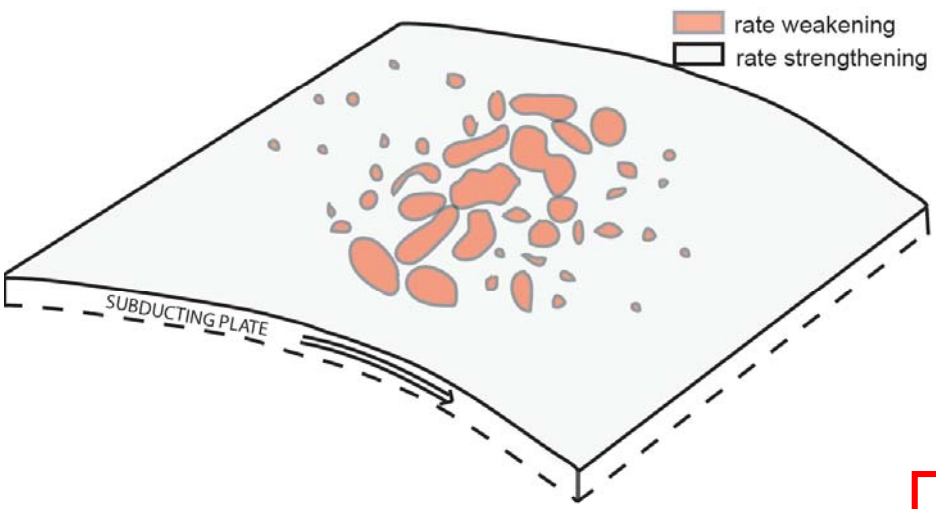
Some outstanding questions:

- What are the frictional properties of faults?

- How do these properties vary in space and time?

- How do they influence individual earthquakes or the long term seismic behavior of a fault?

Conceptual framework



Rate&state friction:

$$\tau/\sigma=\mu=\mu_*+a\ln(V/V_*)+b\ln(\theta/\theta_*)$$

$$d\theta/dt=1-V\theta/D_c$$

At steady state

$$\mu_{ss}=\tau/\sigma=\mu_*+(a-b)\ln(V/V_*)$$

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

a-b < 0

Rate Weakening

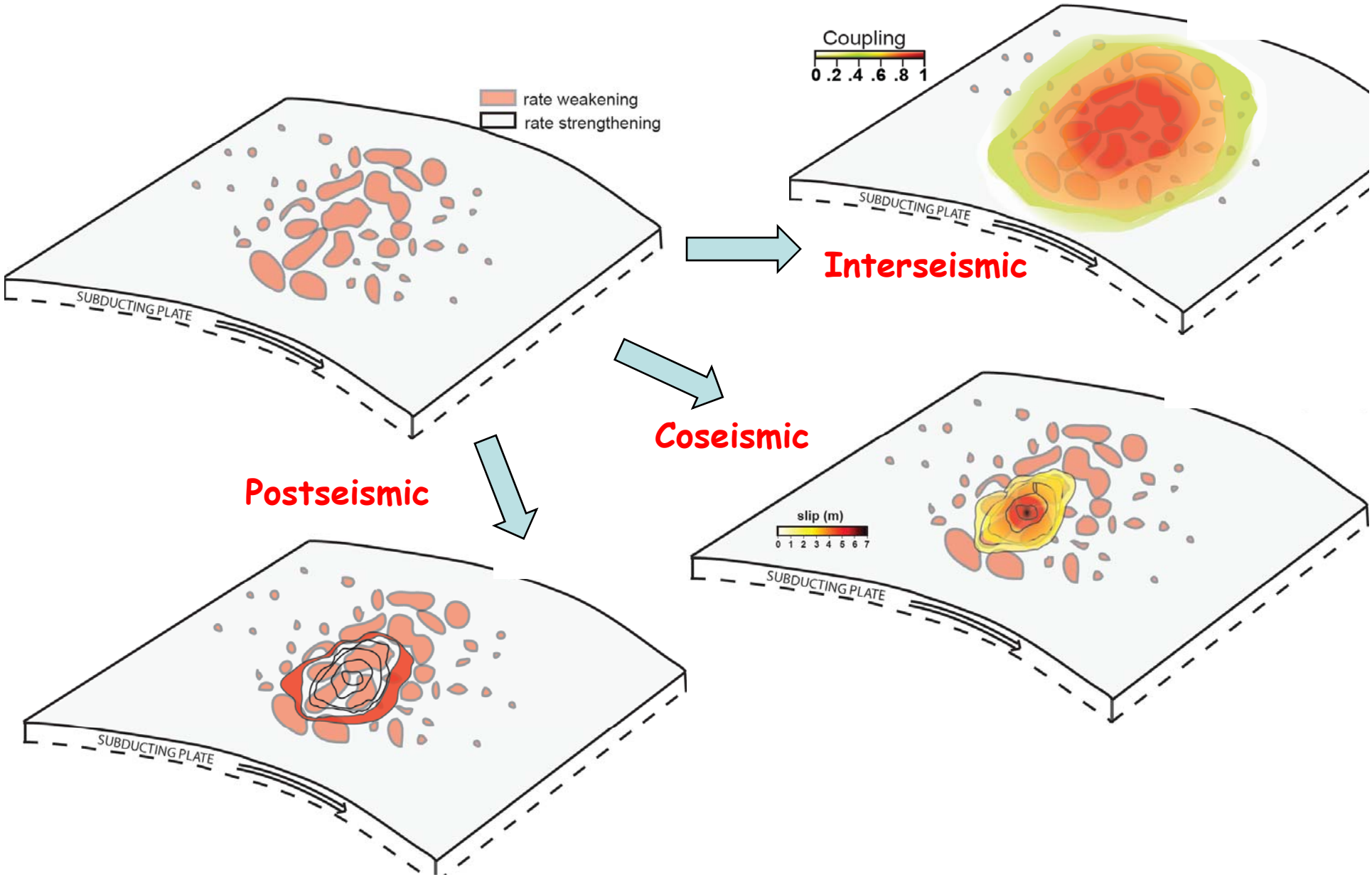
(seismic slip)

a-b > 0

Rate Strengthening

(aseismic slip)

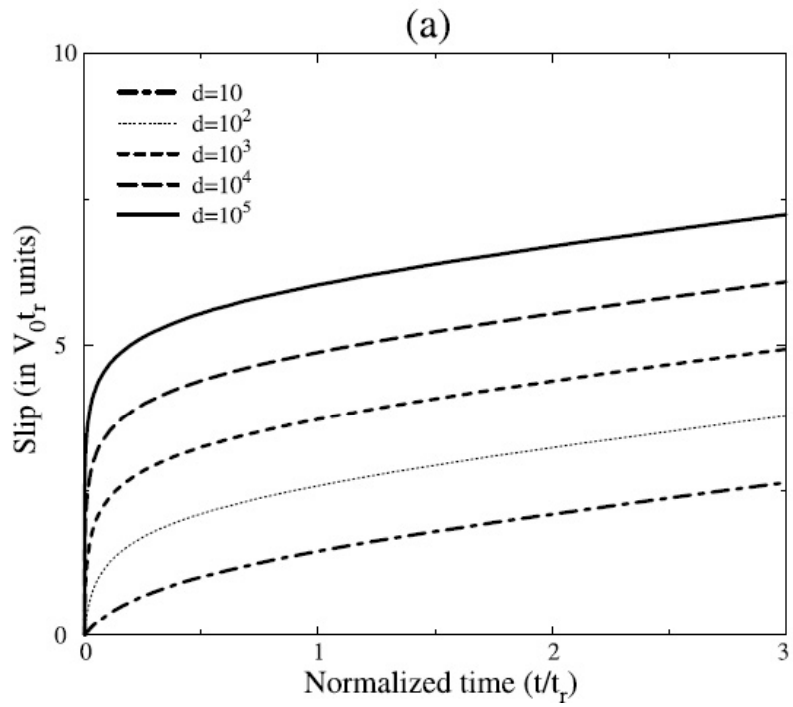
Conceptual framework



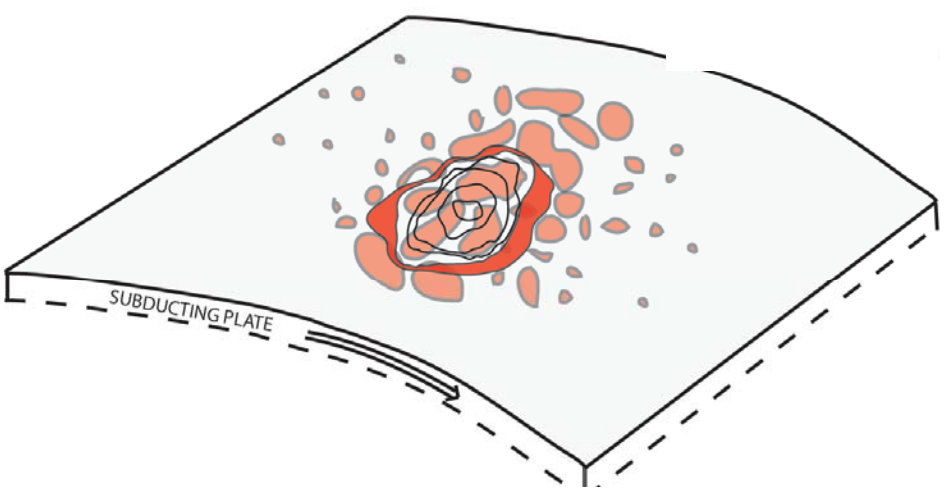
Fault Frictional Properties

Afterslip governed by rate strenghtening friction should obey:

$$\delta(t) = \delta_i + \frac{1}{c}\log\left[1 + d\frac{V_i}{V_0}\left(\exp\left(t/t_r\right) - 1\right)\right]$$

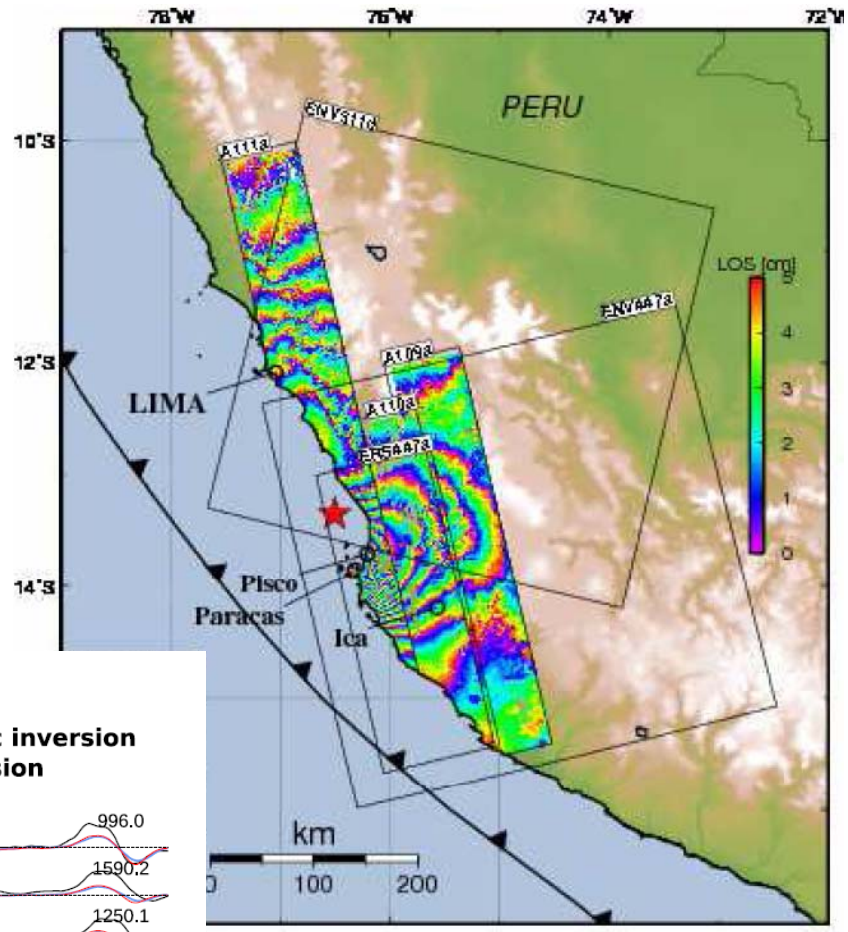


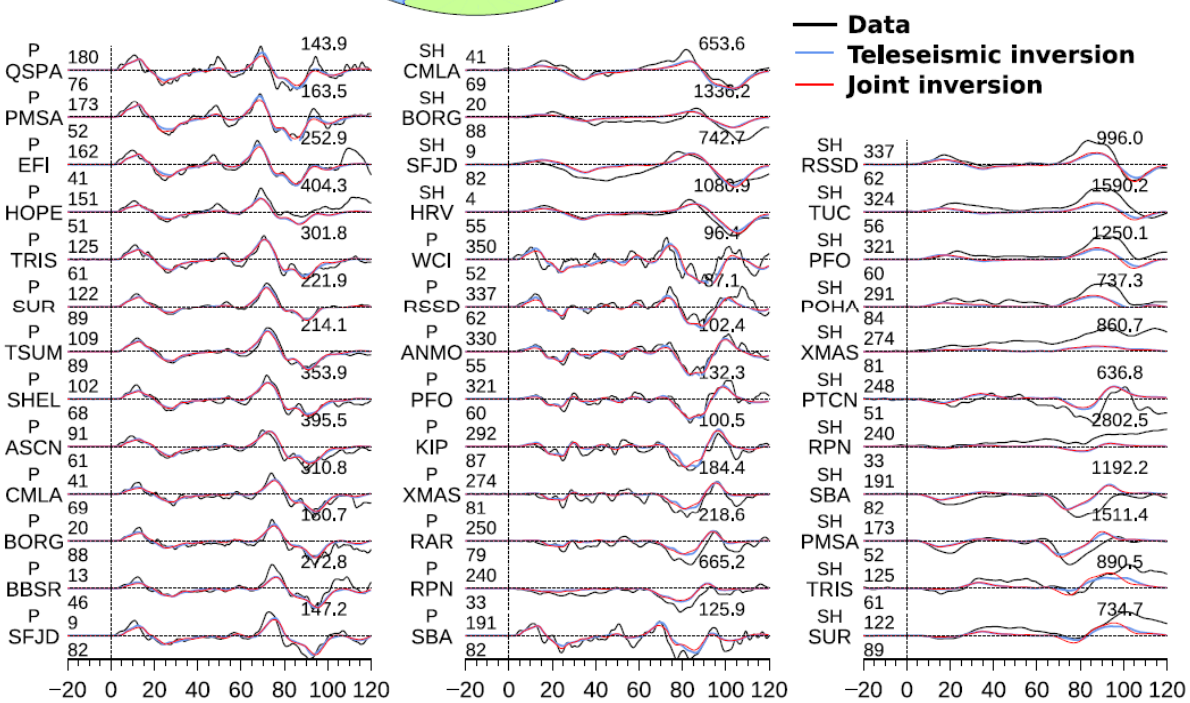
Postseismic



(Perfettini and Avouac, 2004)

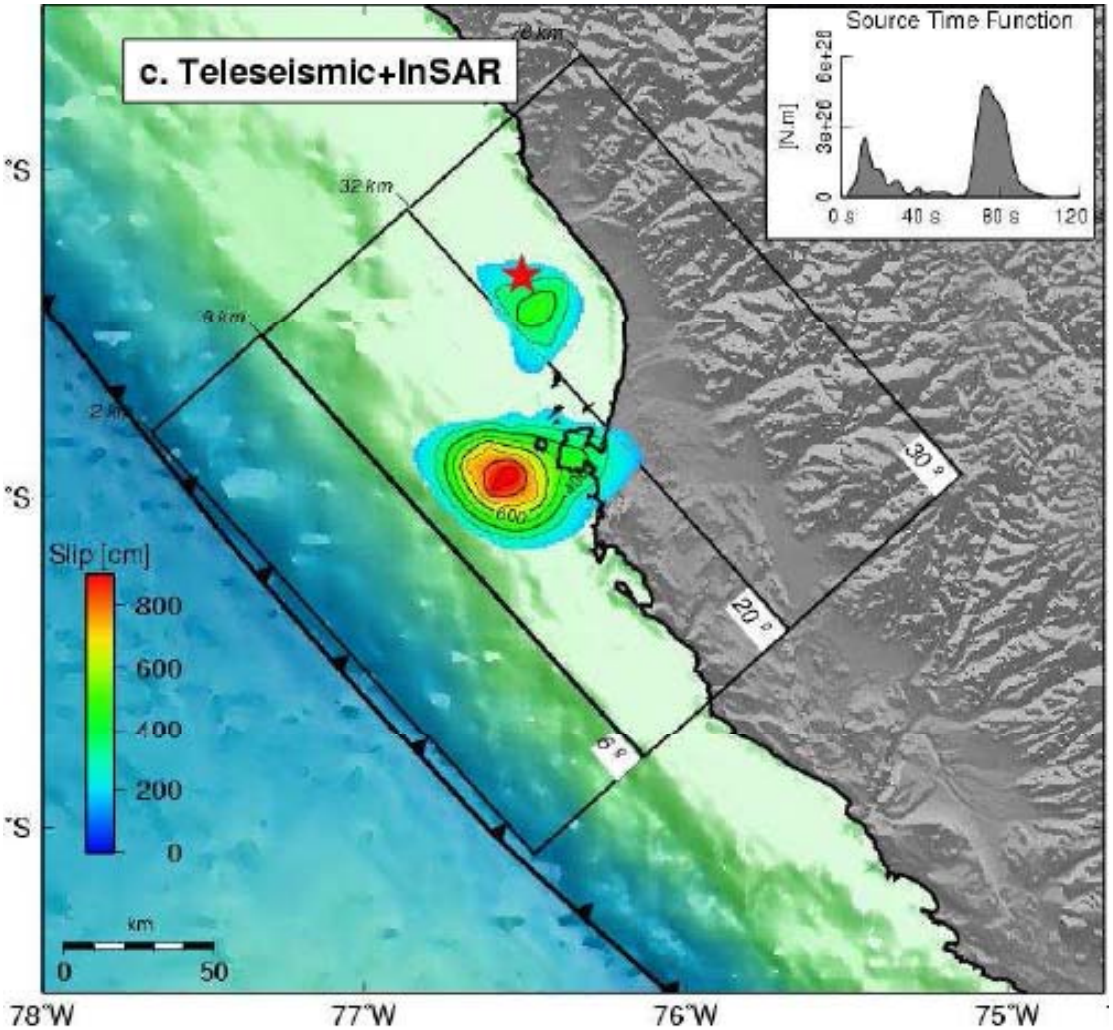
The 2007 Mw 8.0 Pisco Earthquake





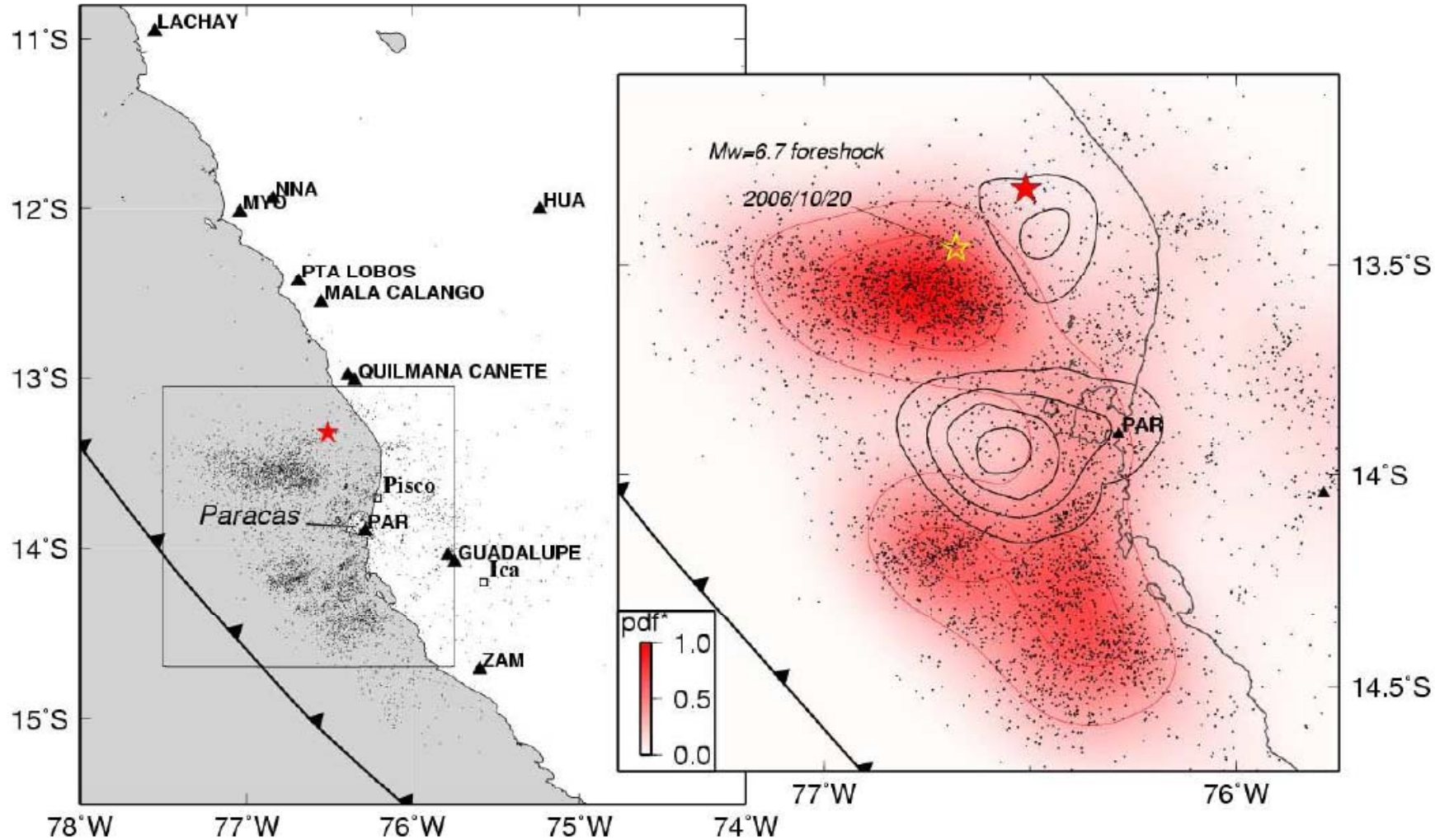
(Sladen et al, JGR, submitted)

Coseismic slip model of the 2007 Mw 8.0 Pisco Earthquake



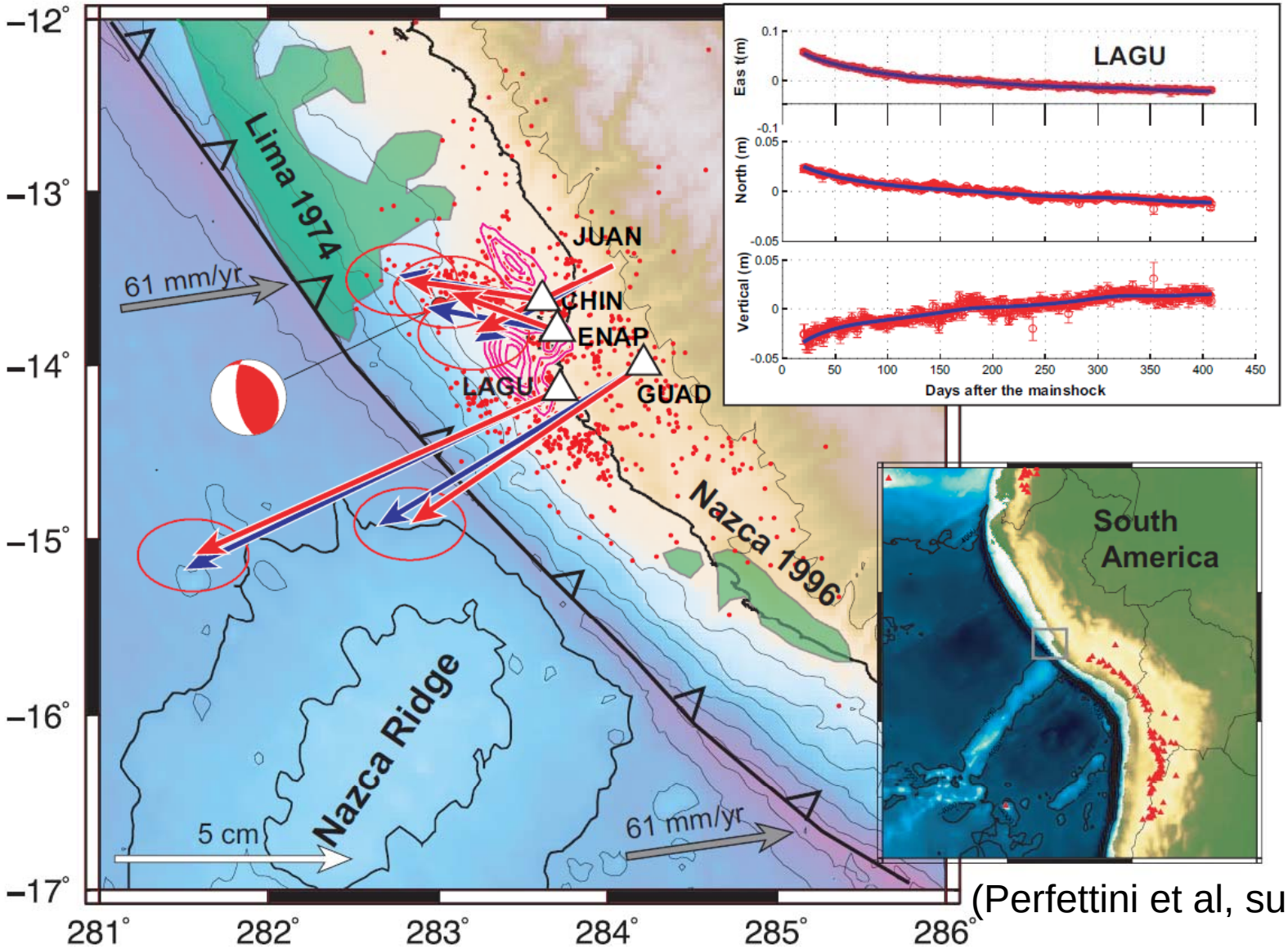
(Sladen et al, JGR, submitted)

Aftershocks of the 2007 Mw 8.0 Pisco Earthquake



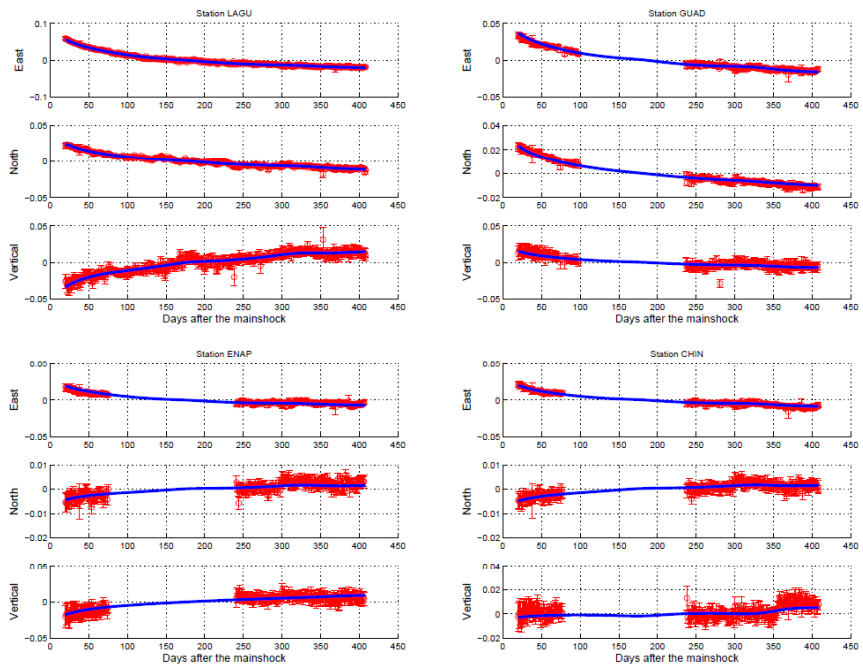
(Sladen et al, JGR, submitted)

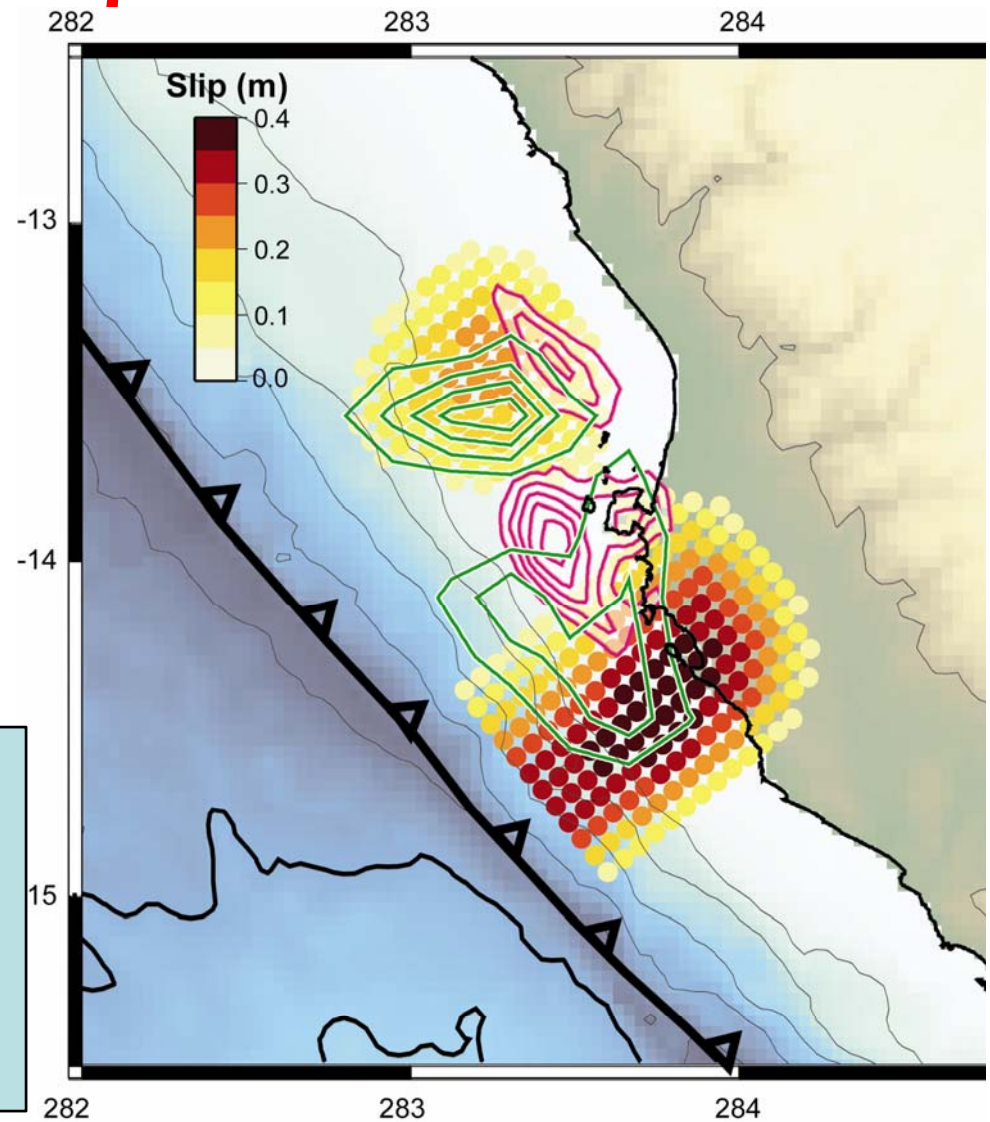
Postseismic displacements following the 2007 Mw 8.0 Pisco Earthquake



(Perfettini et al, submitted)

Afterslip following the 2007 Mw 8.0 Pisco Earthquake





- Postseismic displacements reveal two aseismic patches with limited overlap with the coseismic asperities.

(Perfettini et al, submitted)

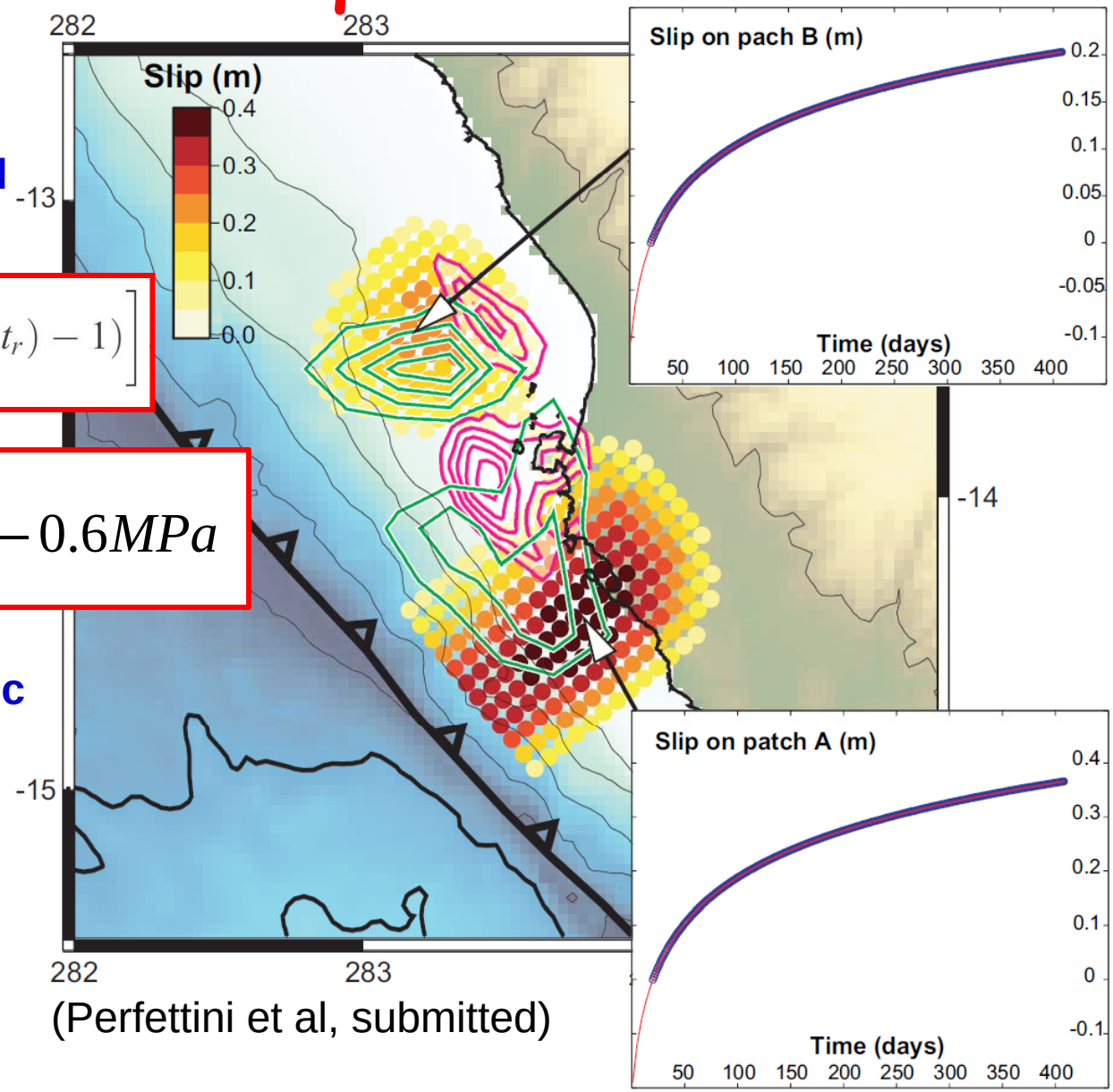
Afterslip following the 2007 Mw 8.0 Pisco Earthquake

-The temporal evolution of afterslip is consistent with rate-strengthening frictional sliding:

$$\delta(t) = \delta_i + \frac{1}{c}\log\left[1 + d\frac{V_i}{V_0}\left(\exp\left(t/t_r\right) - 1\right)\right]$$

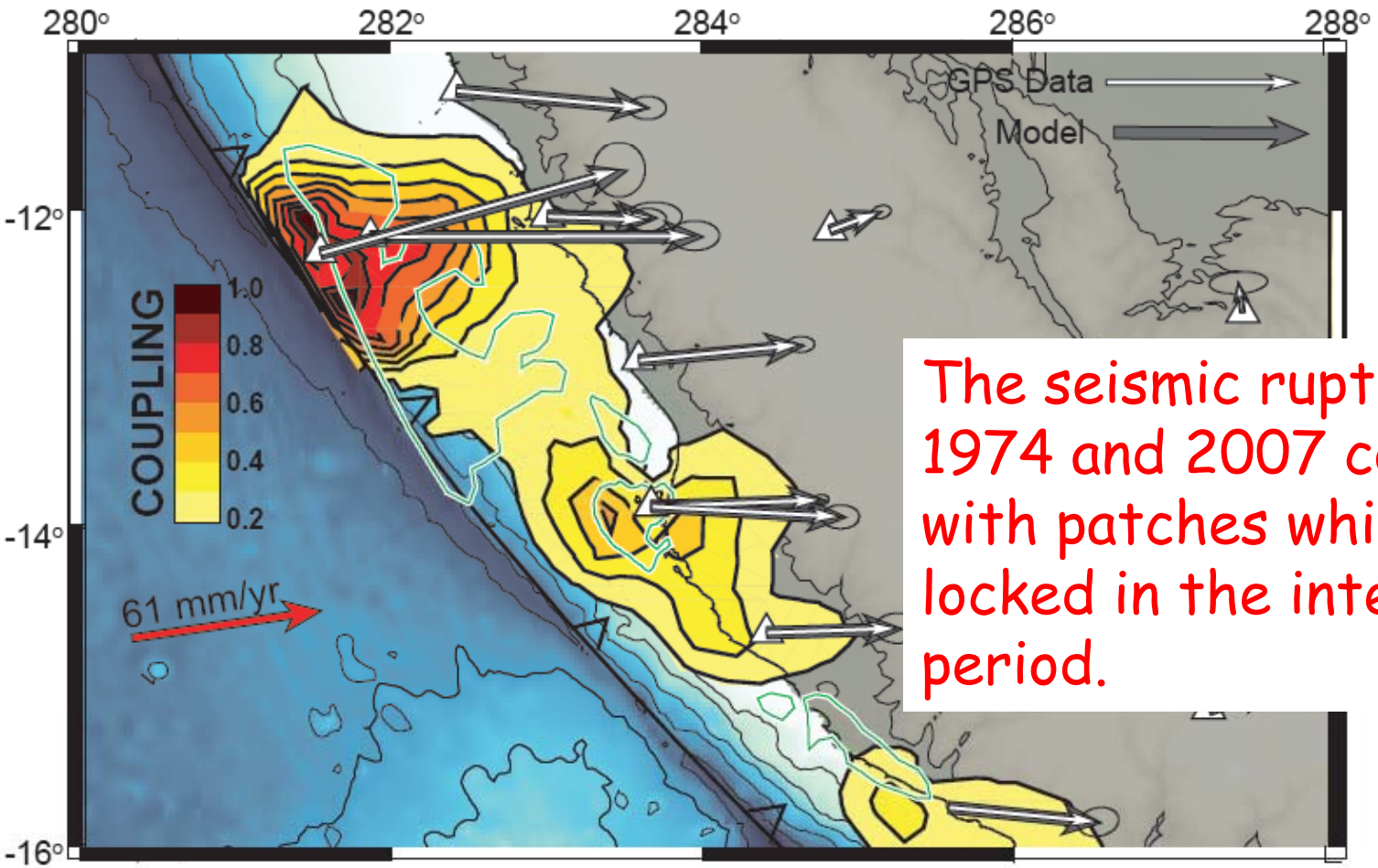
$$\sigma\frac{\partial\mu_{ss}}{\partial\ln V} = (a-b)\sigma = 0.2 - 0.6MPa$$

- The extent of the coseismic rupture is probably partly controlled by rate-strengthening barriers



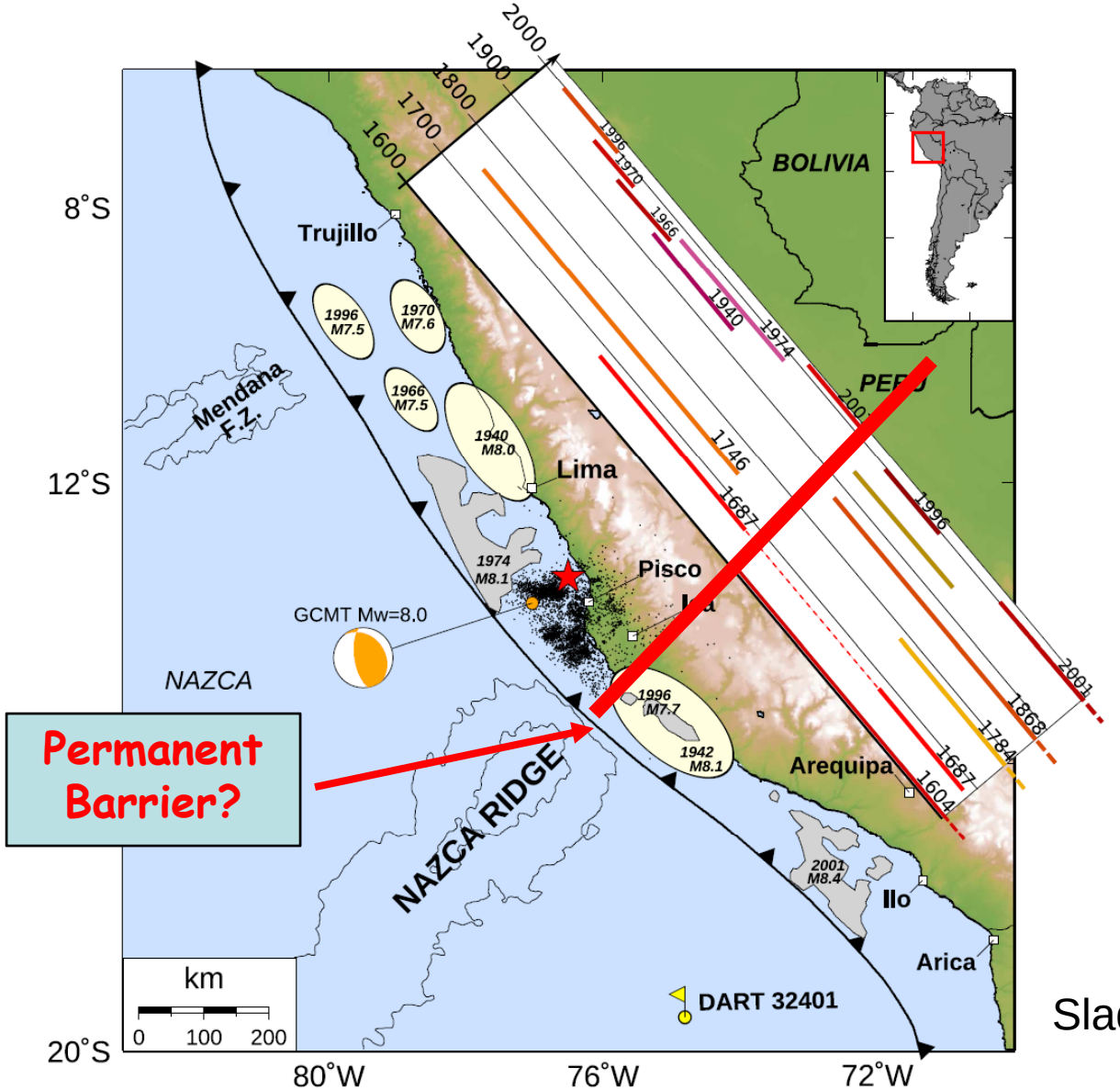
(Perfettini et al, submitted)

Interseismic Coupling before the 2007 Mw 8.0 Pisco Earthquake



The seismic ruptures of 1974 and 2007 correlate with patches which remain locked in the interseismic period.

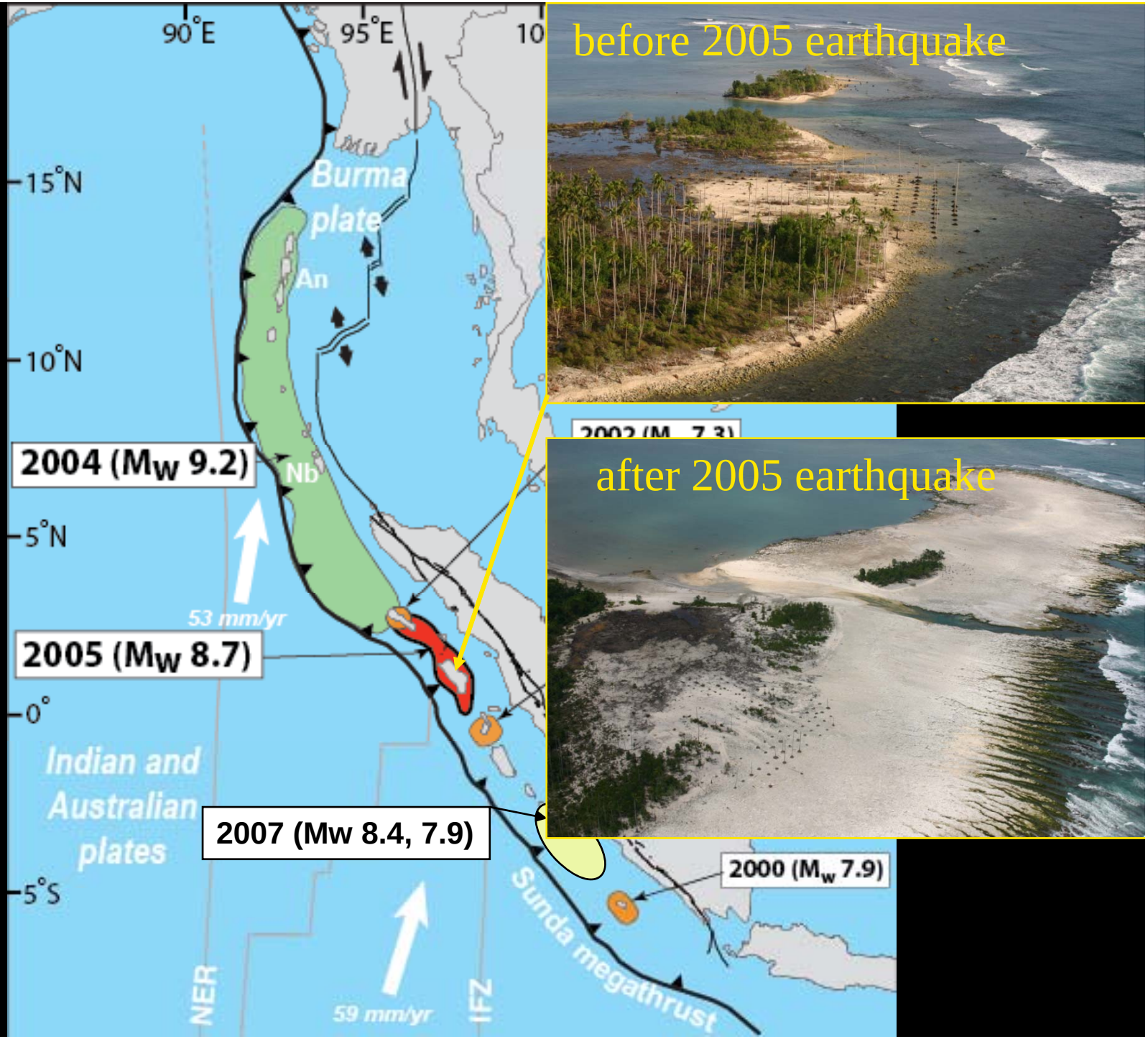
GPS data from Bevis et al (2001), Kendrick et al (2001), Gagnon et al (2005)
Coupling model from Perfettini et al, (submitted)



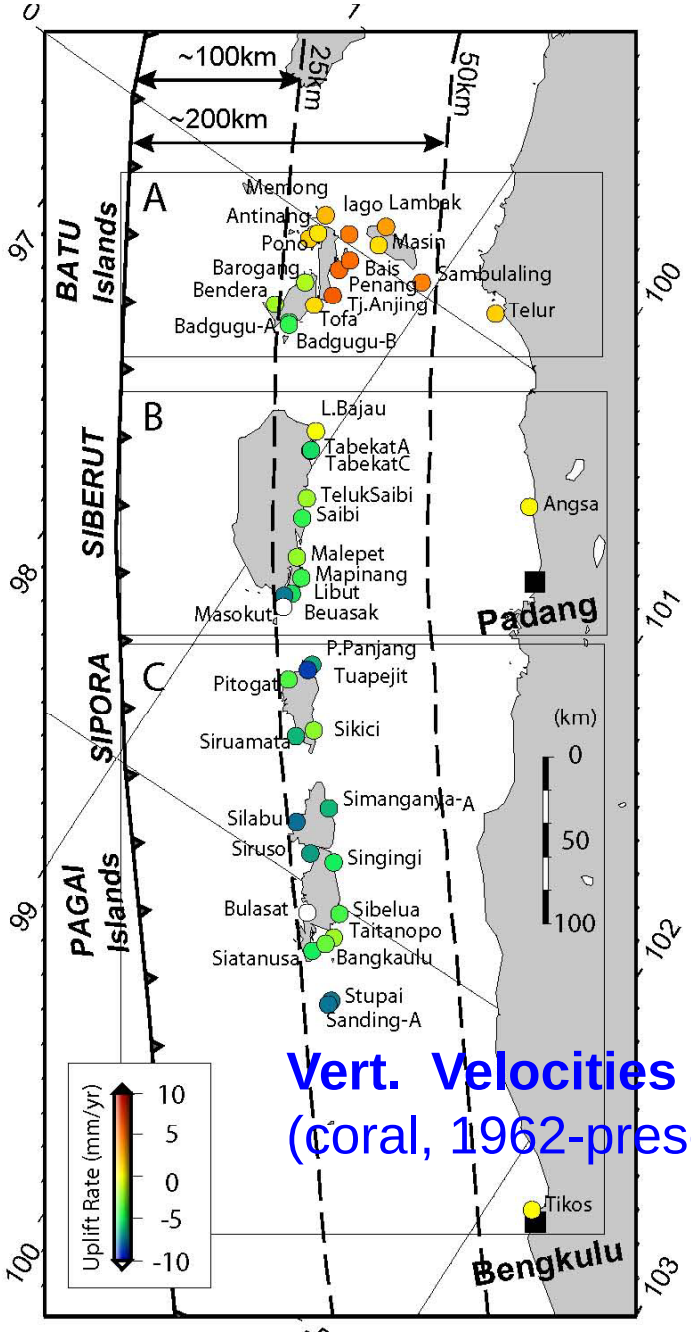
Rate-strengthening patches can act as barriers to the propagation of seismic rupture.

Sladen et al, JGR, submitted)

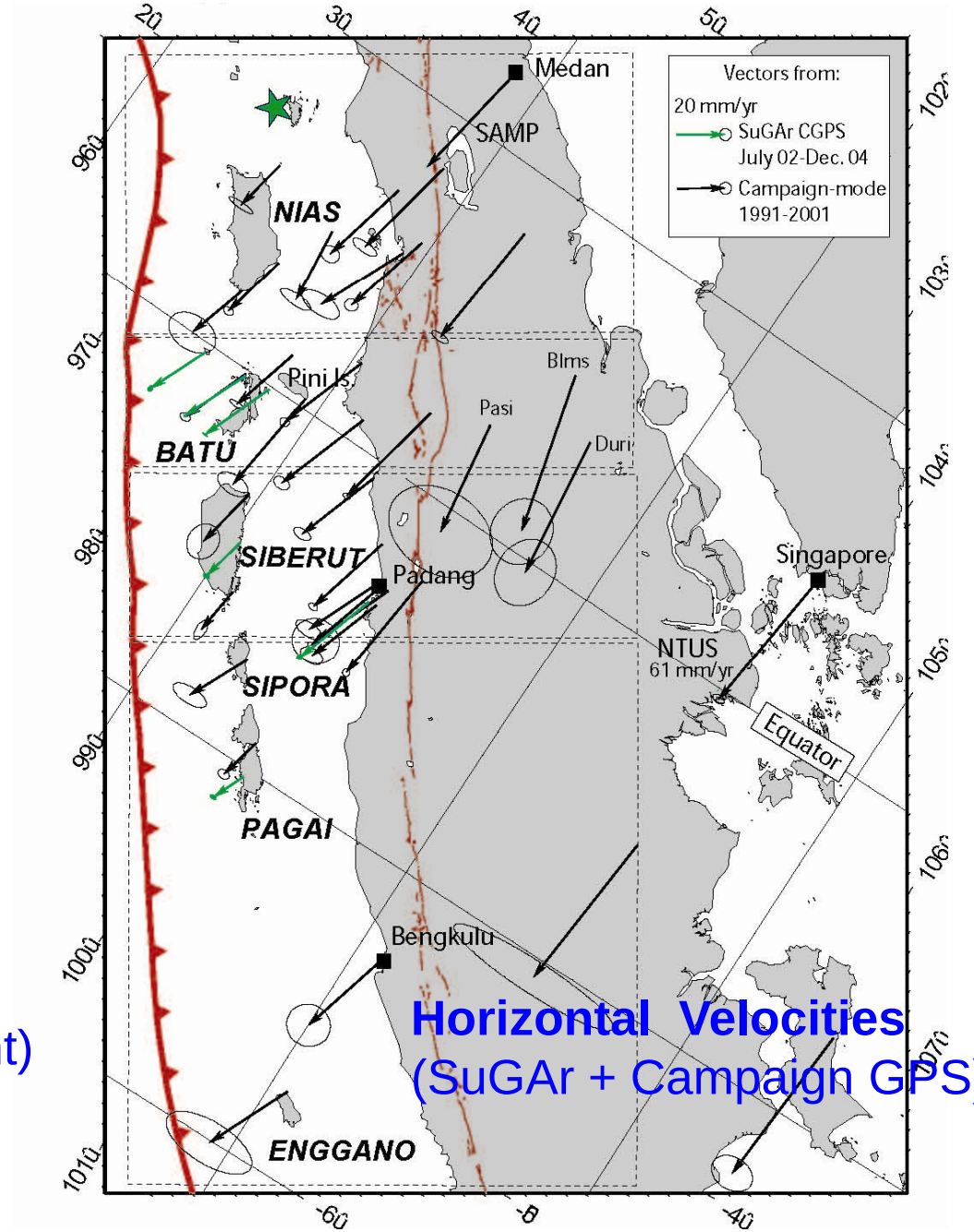
Rupture extent of Historical earthquakes from Dorbath (1990)


90°E
95°E
15°N
10°N
5°N
0°
5°S
Burma plate
An
Nb
2004 (Mw 9.2)
53 mm/yr
2005 (Mw 8.7)
Indian and Australian plates
2007 (Mw 8.4, 7.9)
59 mm/yr
NER
IFZ
Sunda megathrust
2000 (Mw 7.9)
before 2005 earthquake
after 2005 earthquake

INTERSEISMIC DEFORMATION

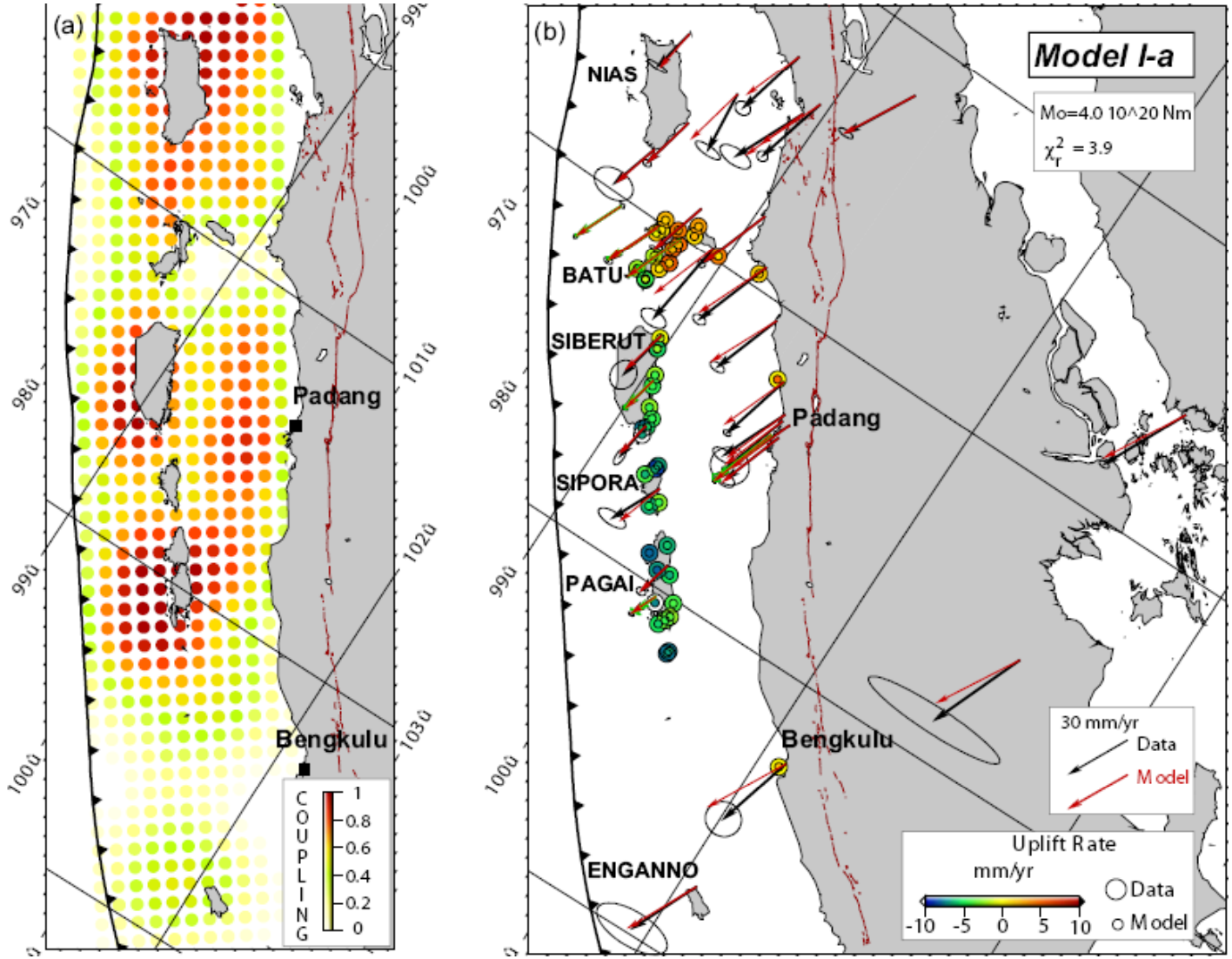


Vert. Velocities
(coral, 1962-present)



Horizontal Velocities
(SuGAr + Campaign GPS)

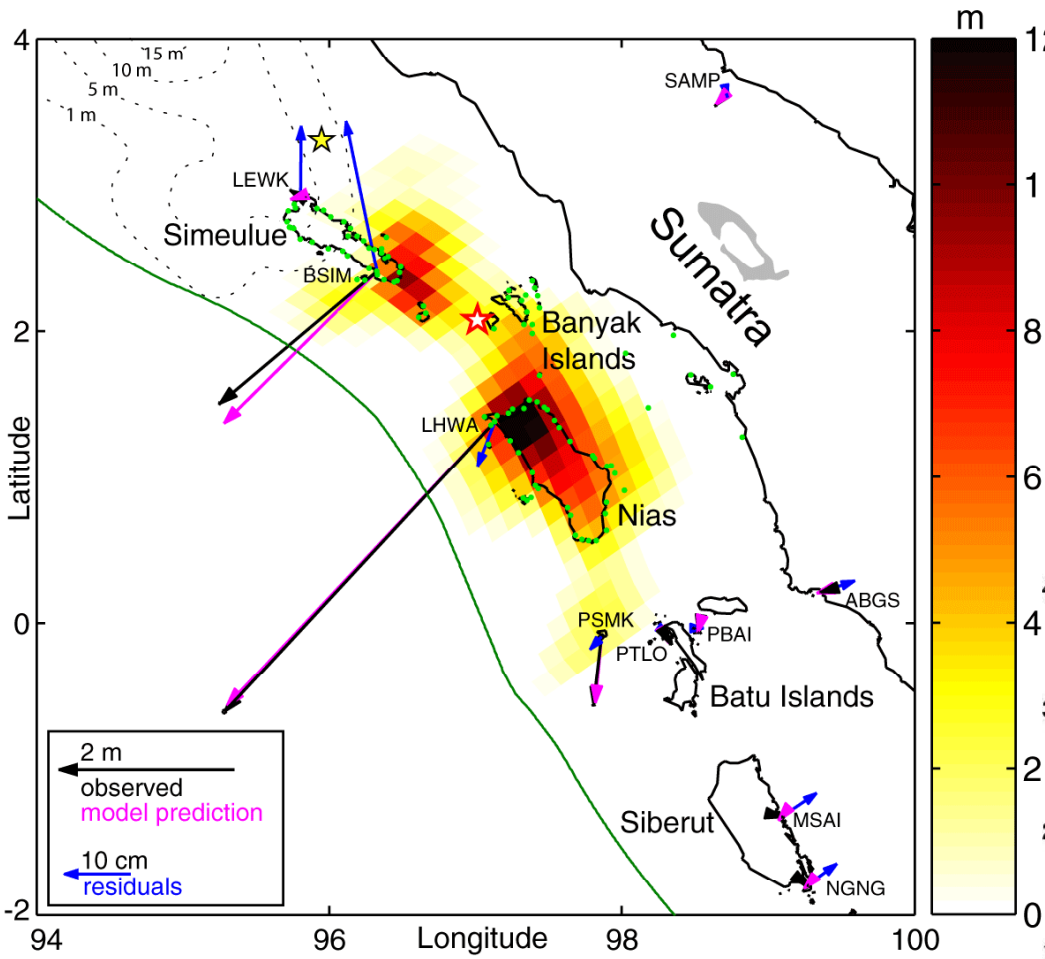
INTERSEISMIC DEFORMATION

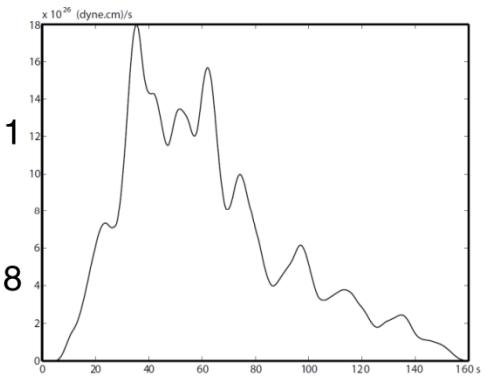


Between 1962 and 2005, this pattern of locking has lead to a moment deficit accumulation of about 2-8 10^{20}Nm/yr.

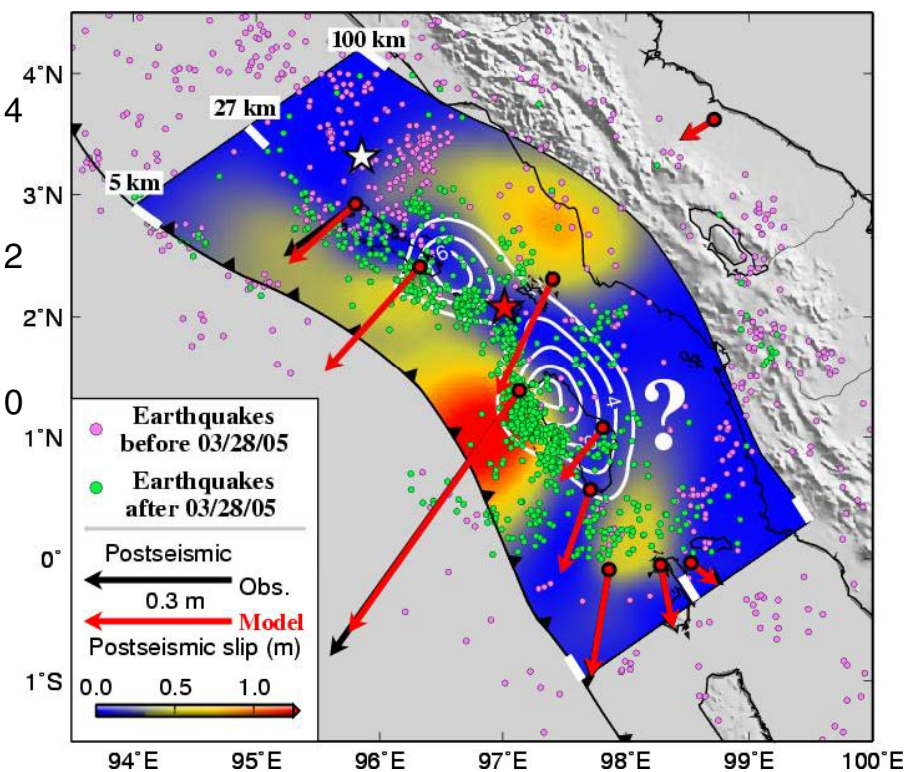
(Chlieh et al, 2008)

The 2005 Mw 8.7 Nias Earthquake

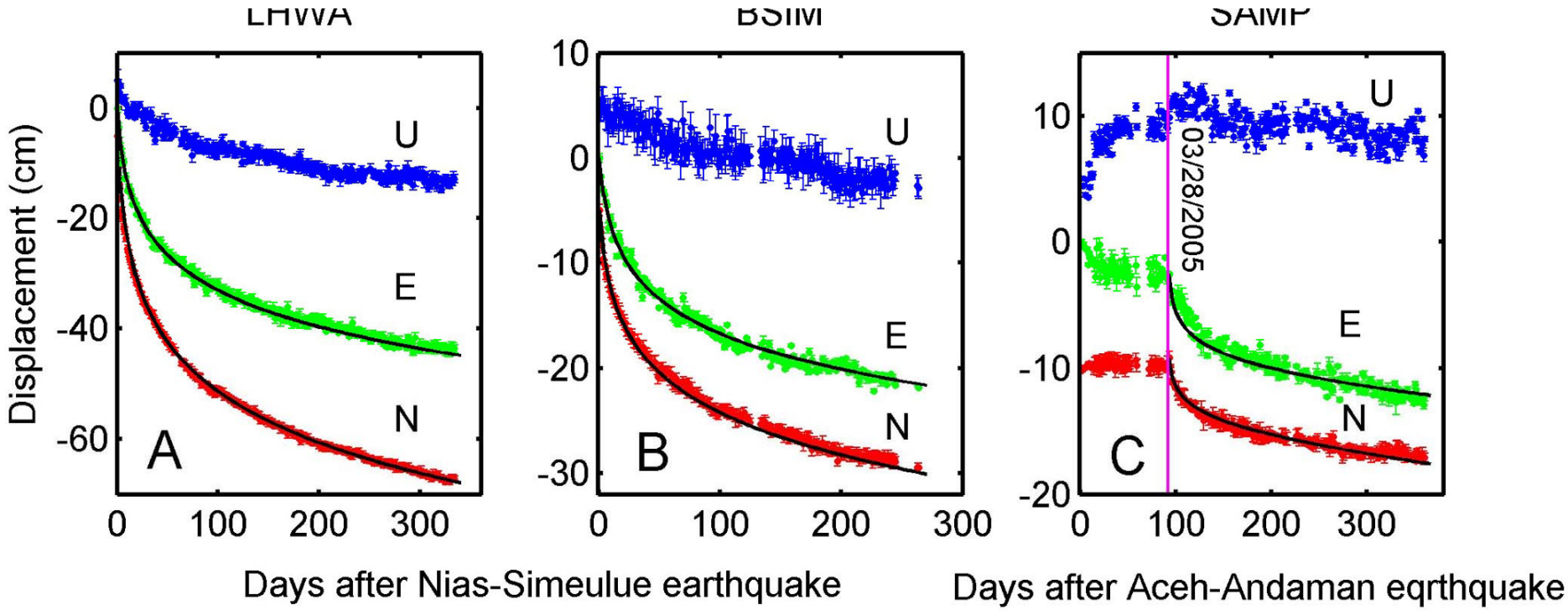




(Briggs et al, 2006, Hsu et al, 2007)



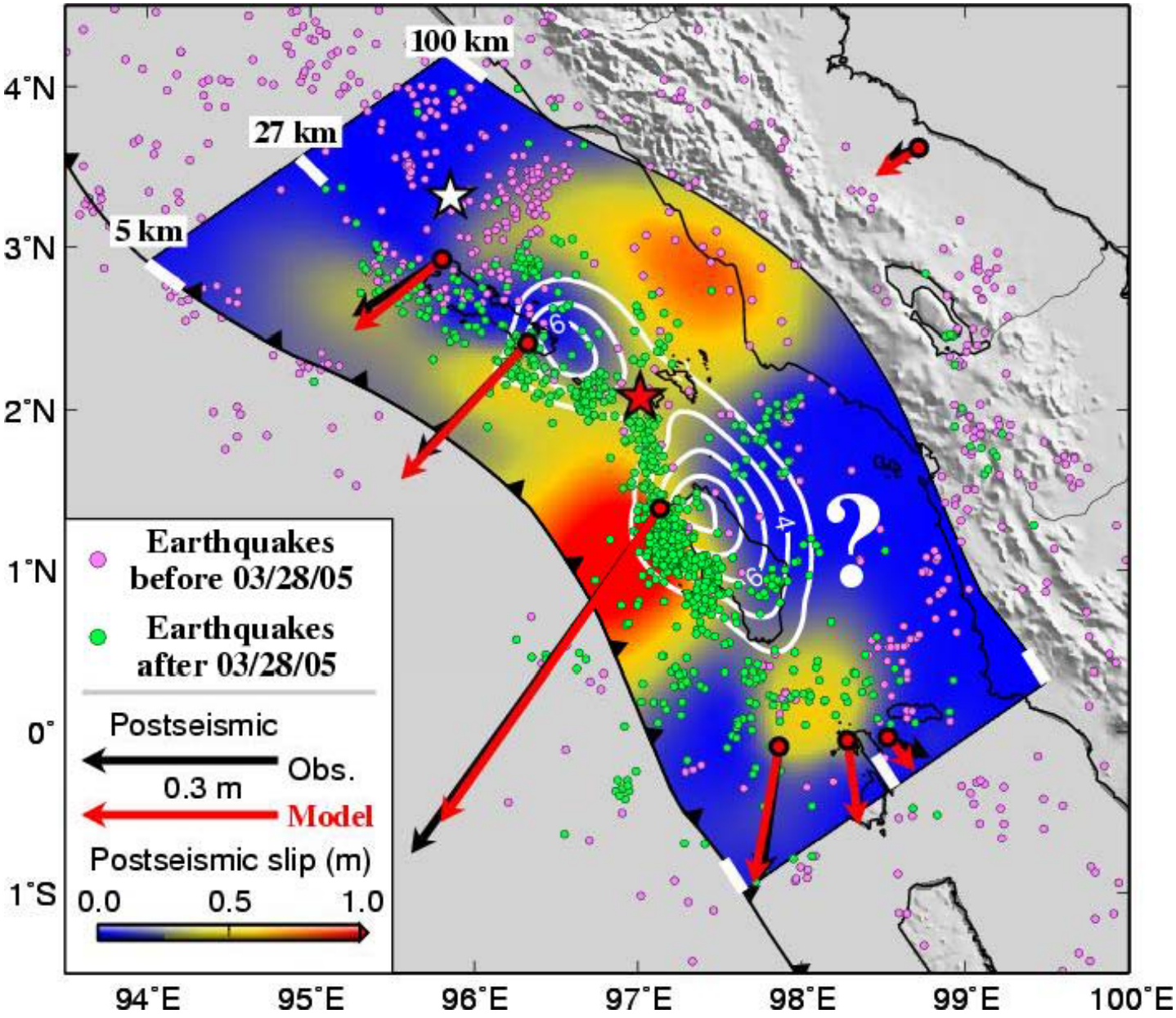
Postseismic displacements reveal **aseismic creep on patches** on the megathrust surrounding the seismic rupture.

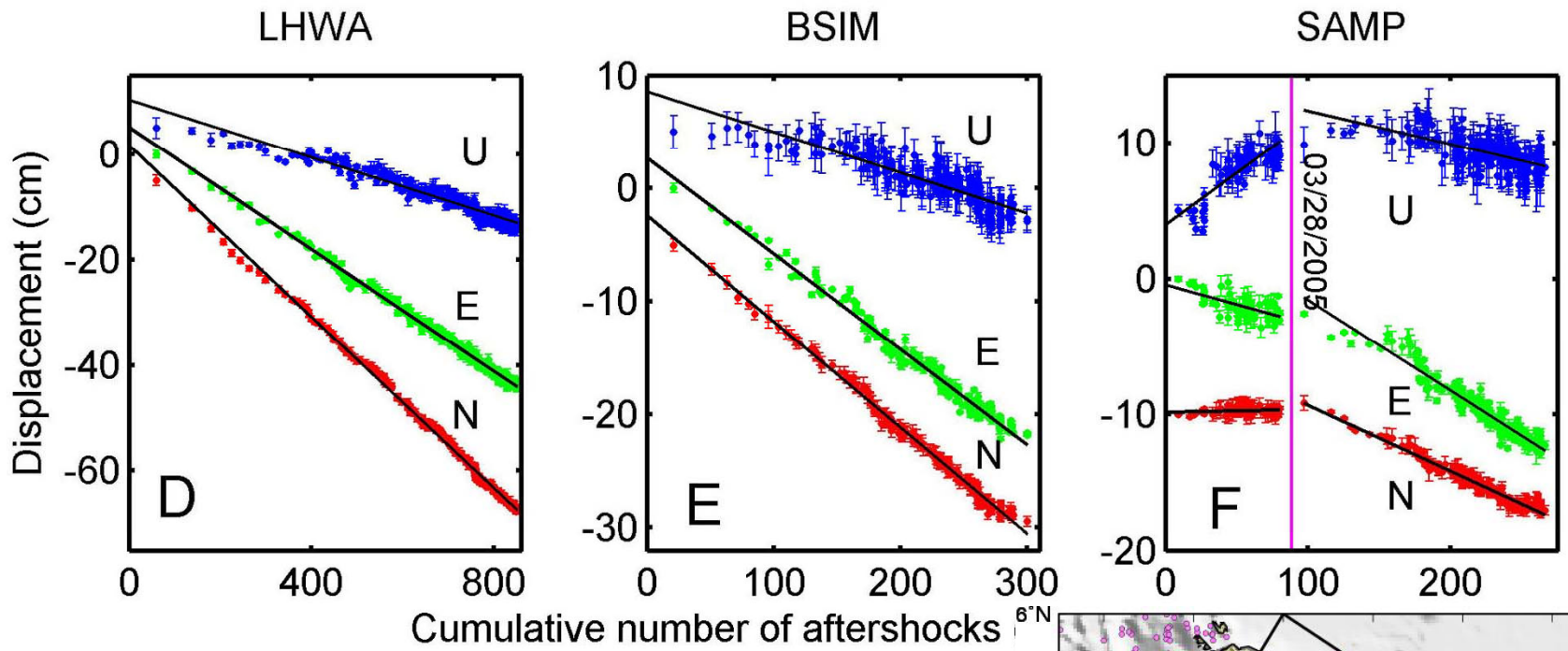


Time evolution of afterslip is consistent with rate strengthening frictional afterslip yielding:

$$\sigma \frac{\partial \mu_{ss}}{\partial \ln V} = (a-b)\sigma = 0.2 - 0.7 MPa$$

Afterslip vs. Aftershoks

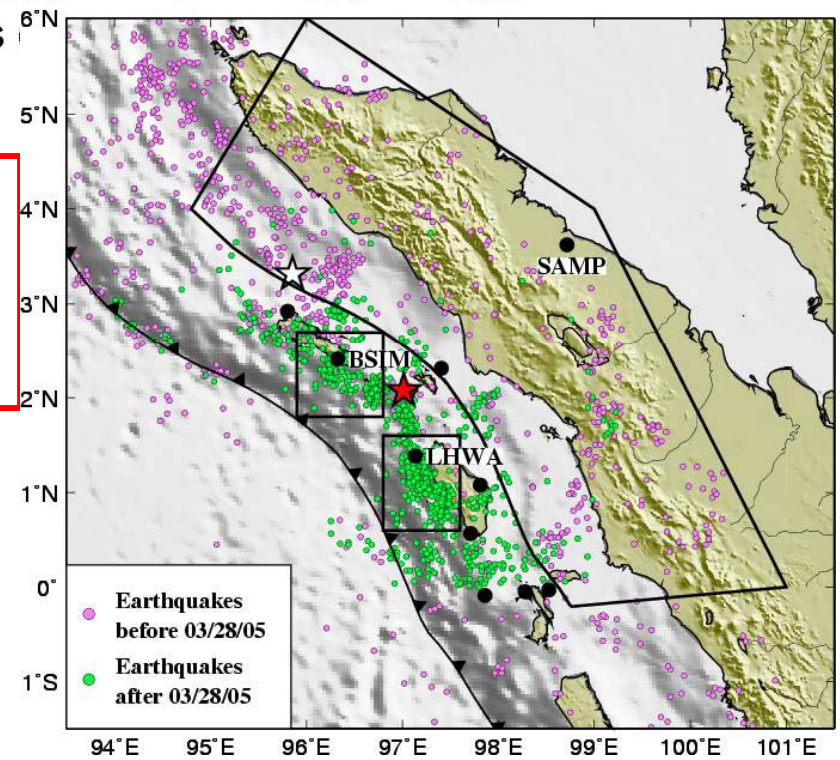




Postseismic displacement and the cumulative number of afetrshocks follow the same time evolution

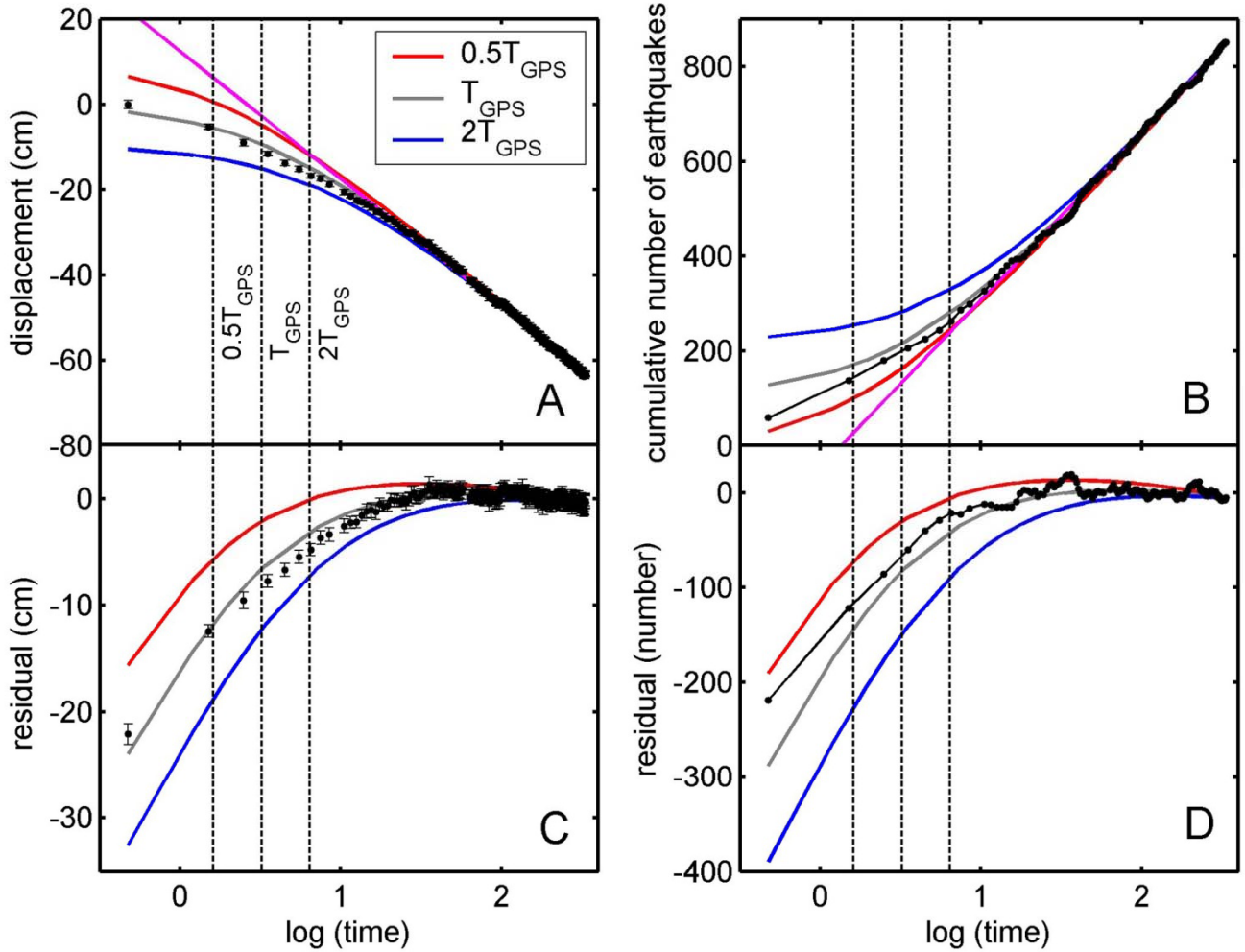
$$U(t) = U_{t=0} + a\ f(t)$$

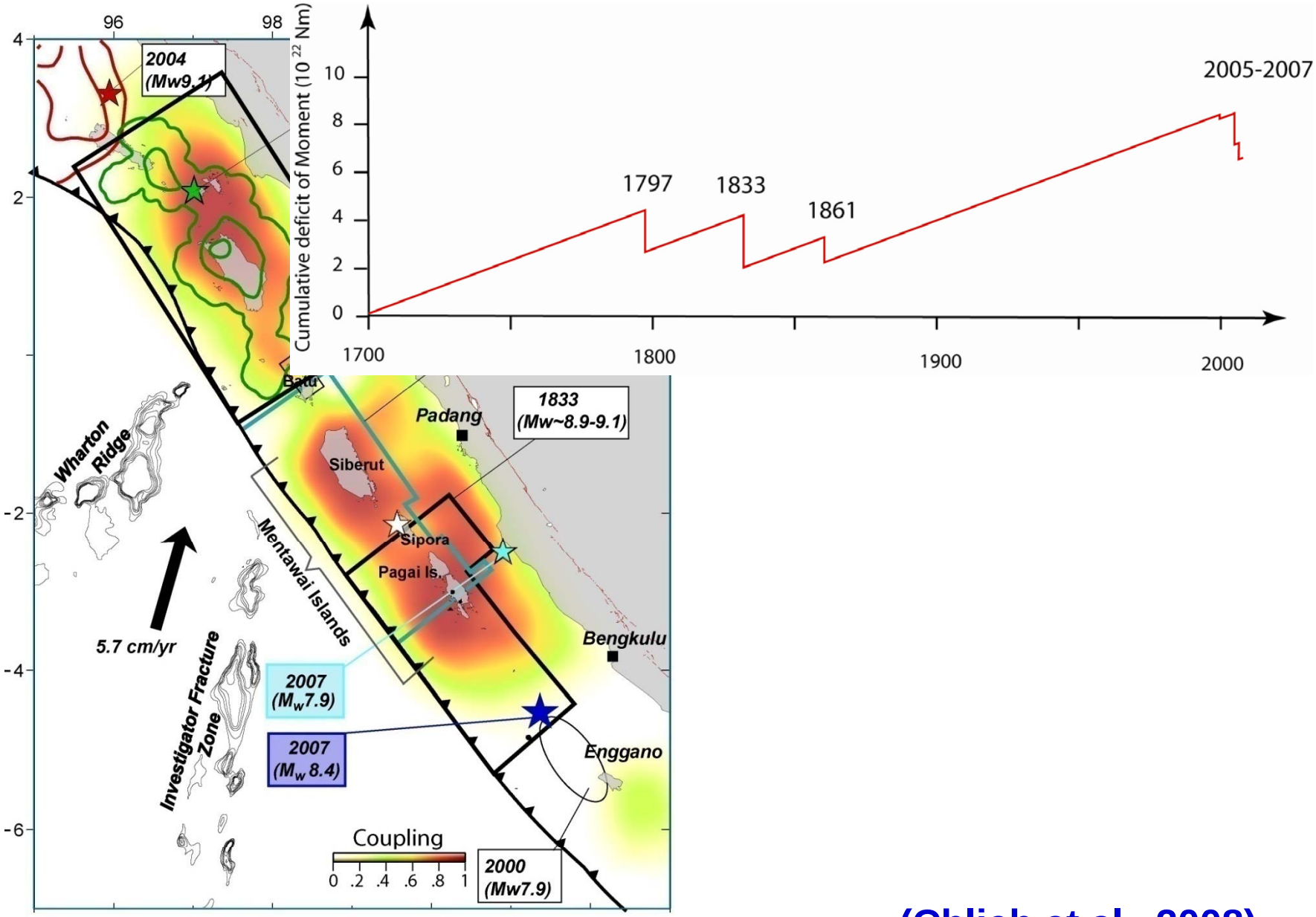
$$N(t) = N_{t=0} + b\ f(t)$$



LHWA

⇩ Displacement ⇩ Aftershocks

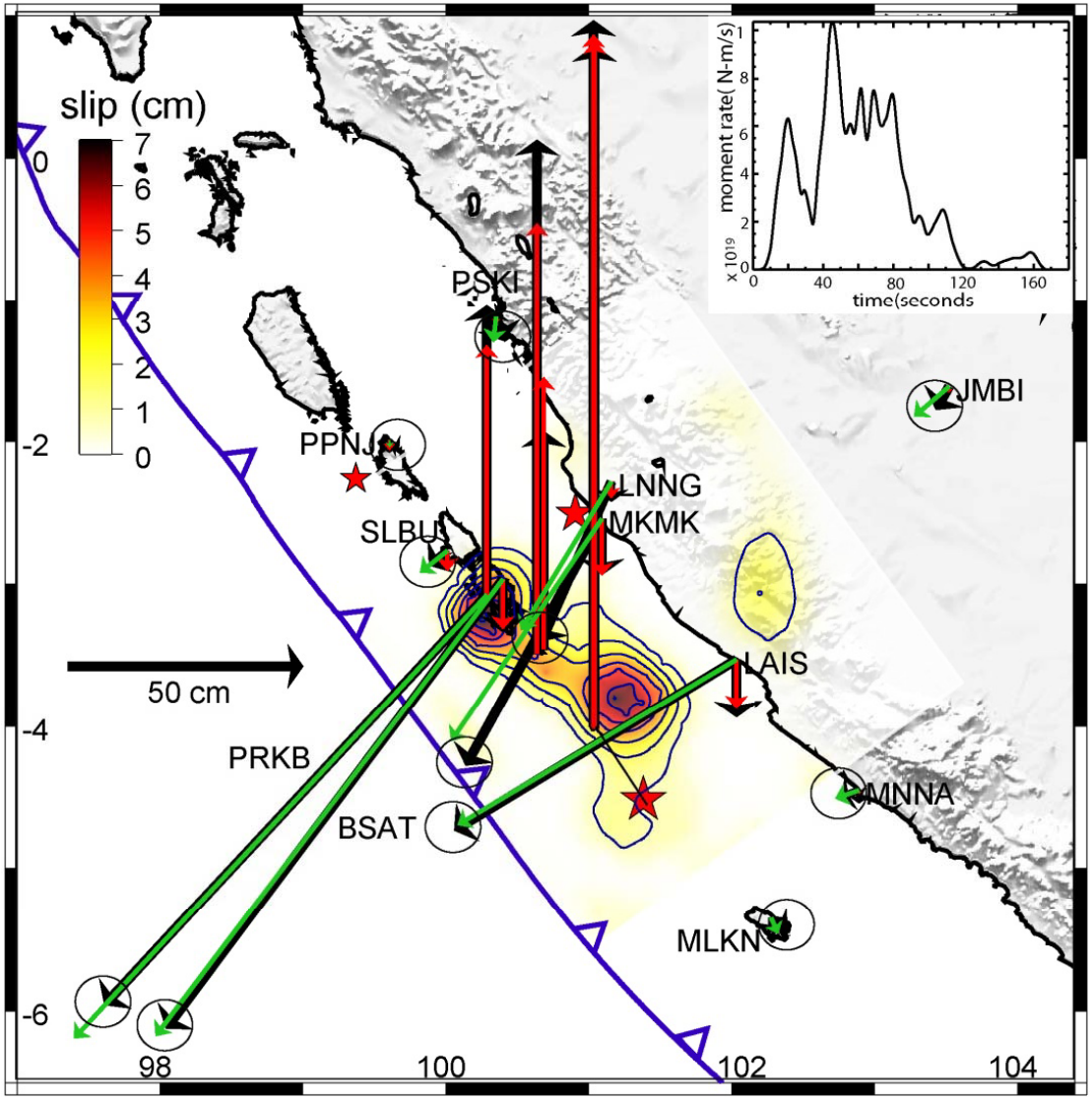




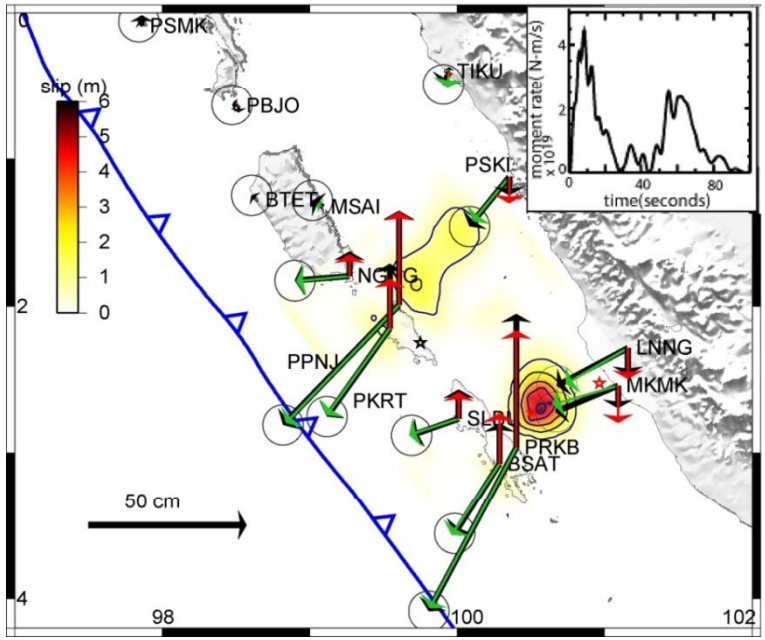
(Chlieh et al., 2008)

Source Models of the 2007, Mw8.4 & 7.9 Mentawai Islands Earthquakes

M_w8.4



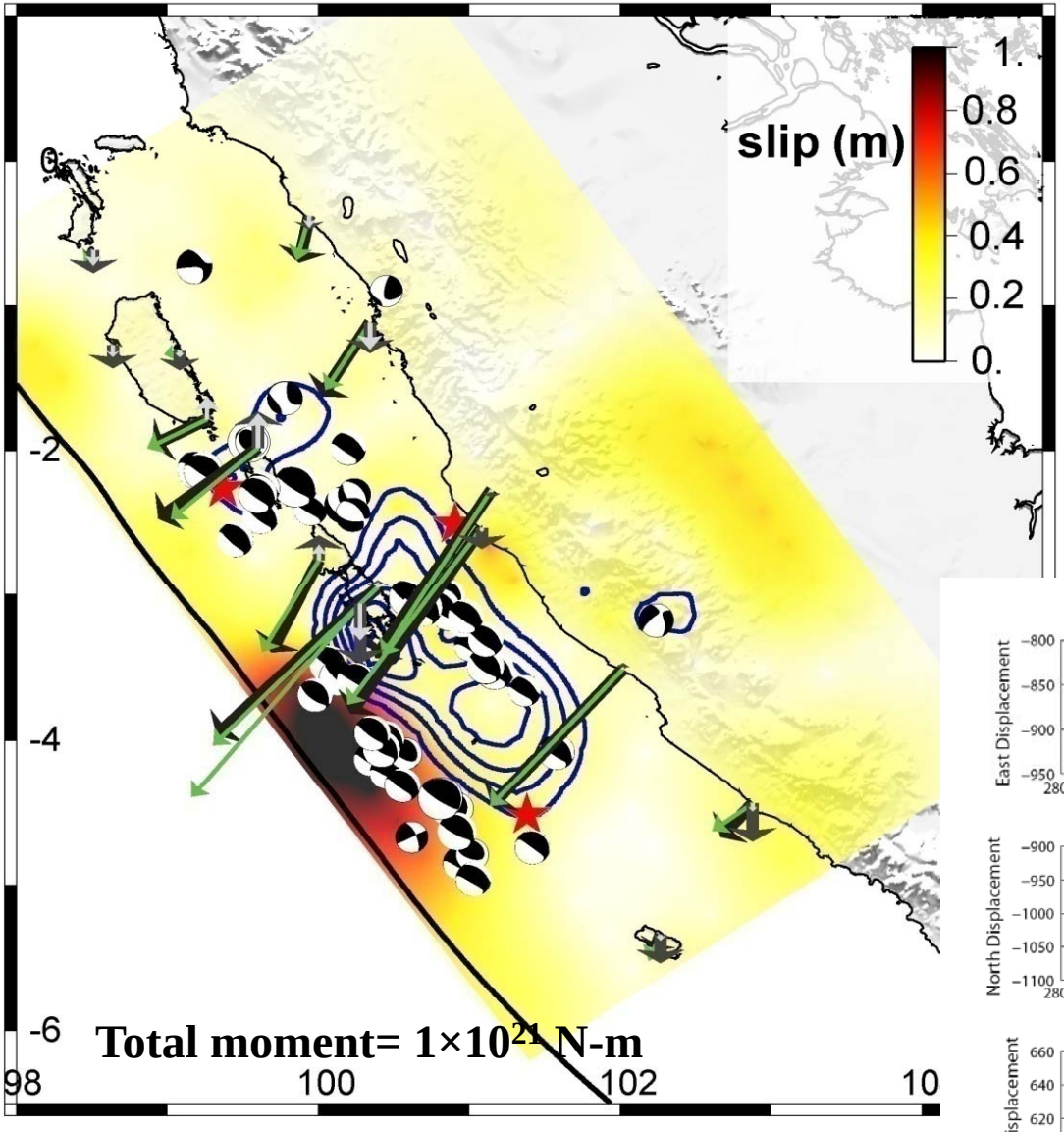
M_w7.9



Data used:
-GPS (SuGAr)
-InSAR
- Field measurements
--Teleseismic waveforms

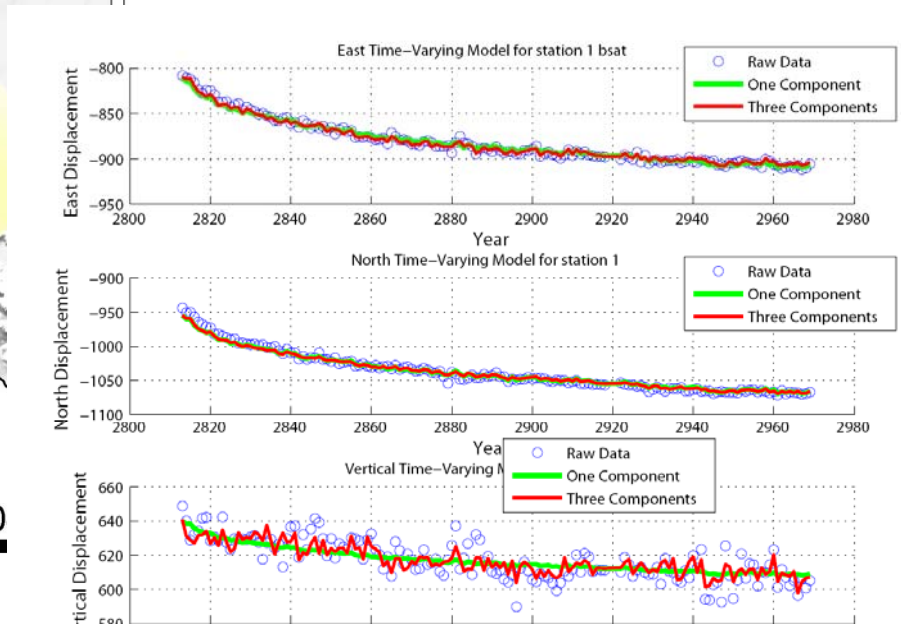
(Konca et al, 2008)

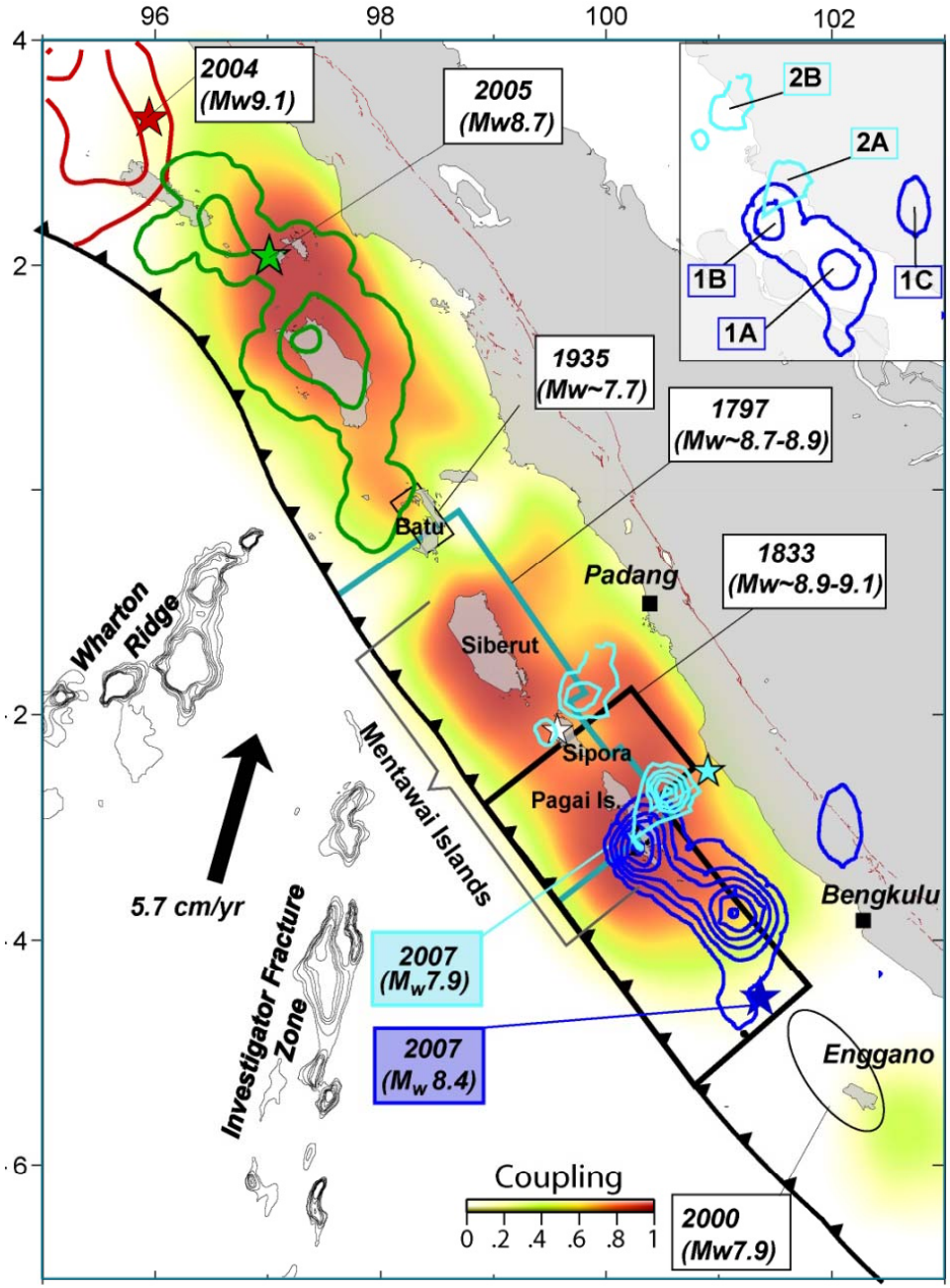
Postseismic Deformation



Postseismic displacements reveal **aseismic creep on patches** on the megathrust surrounding the seismic rupture.

(Kositsky et al, in prep.)

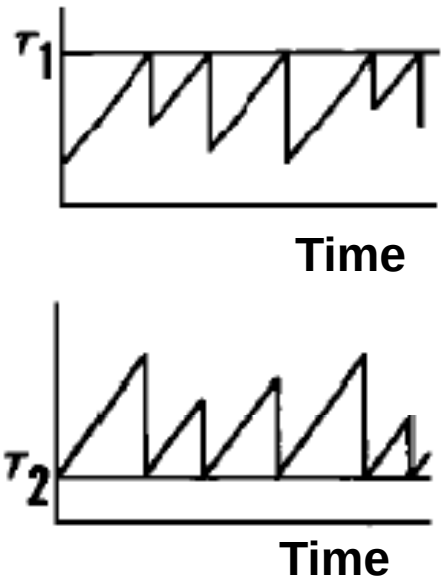


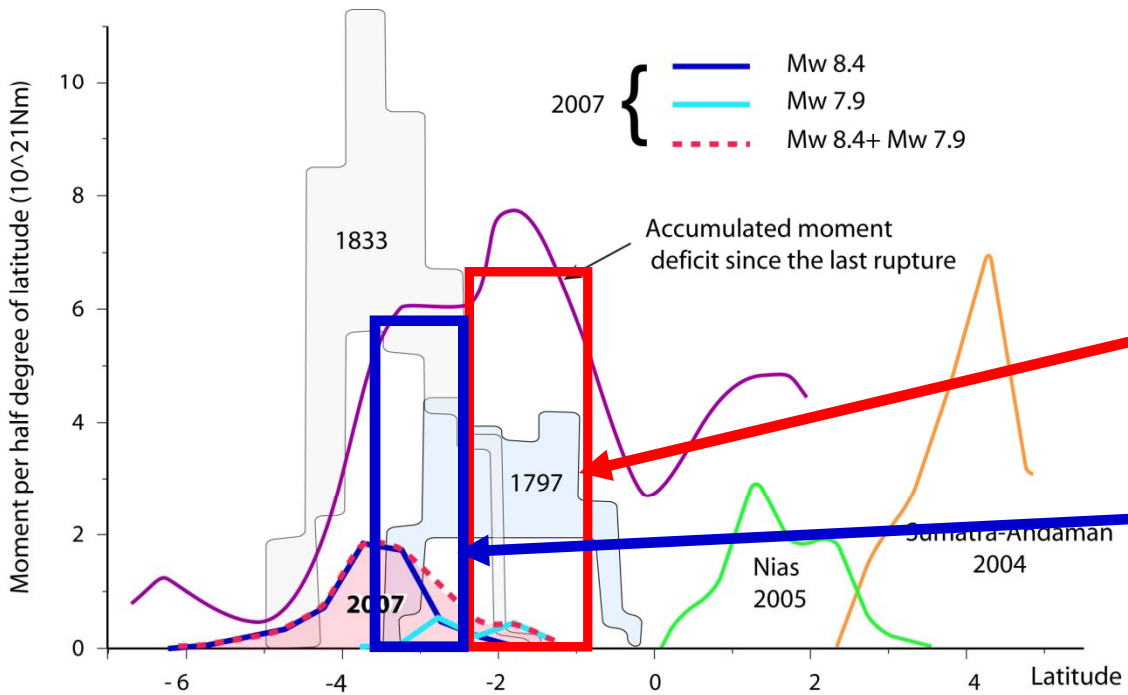

96
98
100
102
4
2
-2
-4
-6
2004
(Mw9.1)
2005
(Mw8.7)
2B
2A
1B
1C
1A
1935
(Mw~7.7)
1797
(Mw~8.7-8.9)
Batu
Padang
1833
(Mw~8.9-9.1)
Wharton
Ridge
Siberut
Sipora
Pagai Is.
Mentawai Islands
5.7 cm/yr
Bengkulu
2007
(Mw7.9)
2007
(Mw 8.4)
Investigator Fracture
Zone
Enggano
Coupling
0 .2 .4 .6 .8 1
2000
(Mw7.9)

Neither Time Predictable nor Slip Predictable

- **Time predictable:** stress drop of last earthquake & stress rate => can tell the time of the next event (we know at what stress level the fault will break)

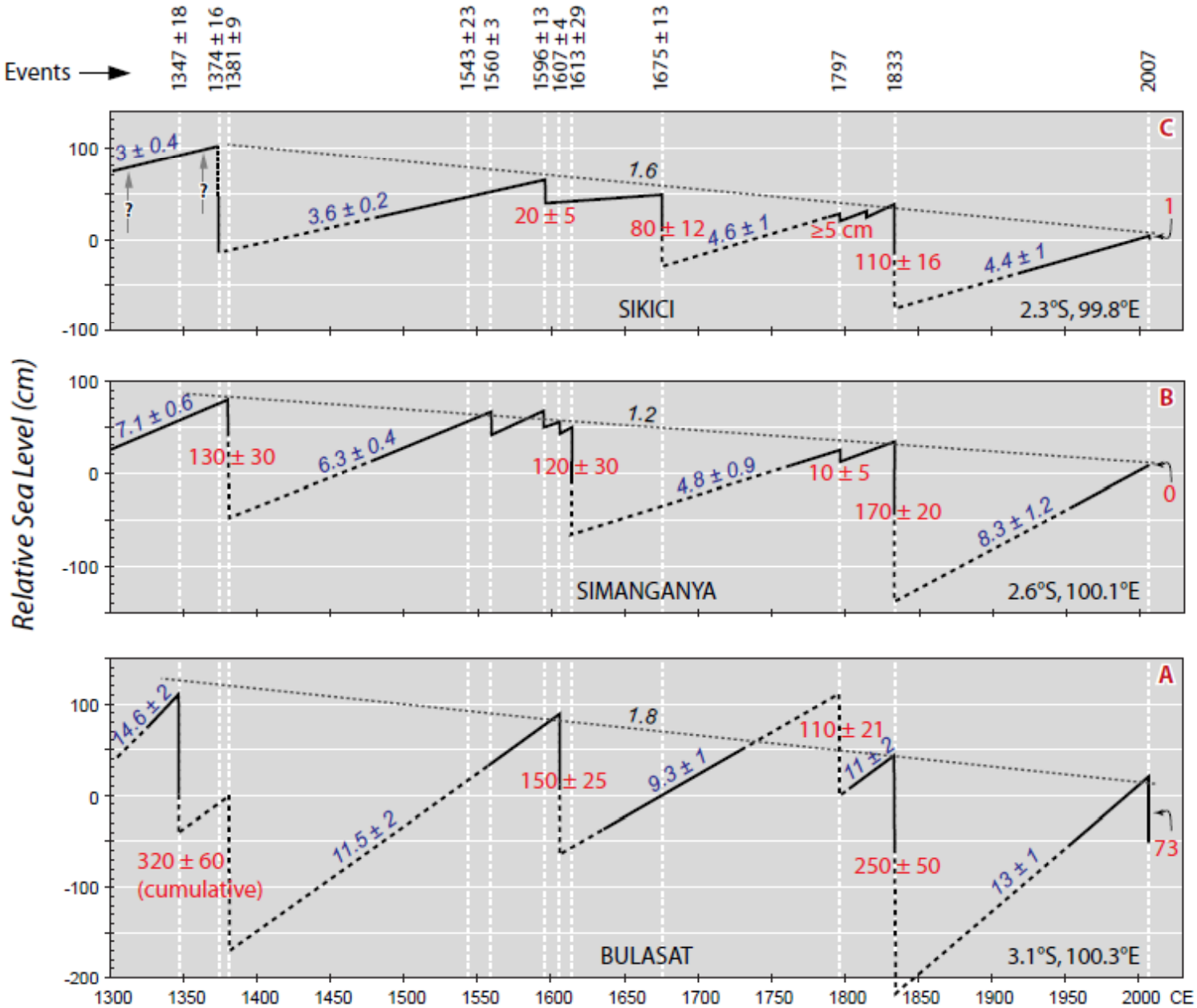
- **Slip predictable:** given the stress drop of the last event and stress rate, if an earthquake happens today=> can tell the amount of slip (we know the postearthquake stress level)





This portion should have ruptured already.

This portion should have slipped much more in 2007

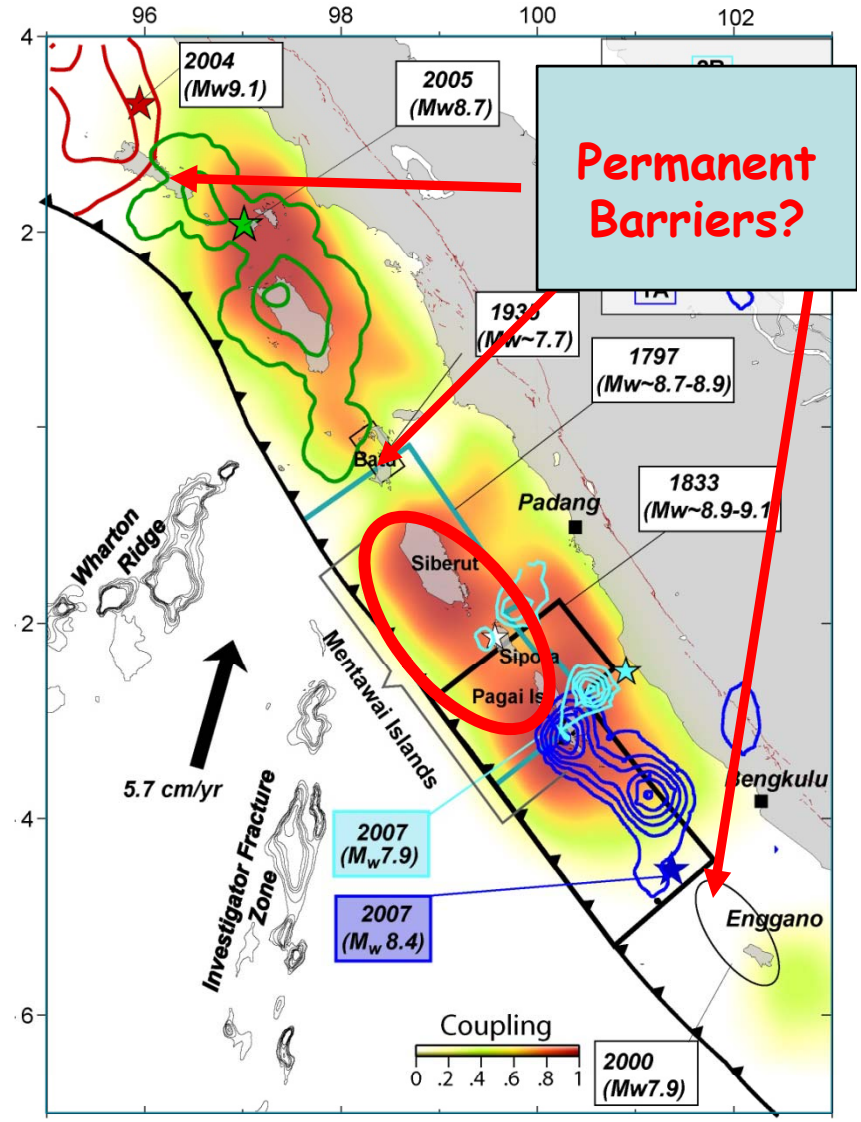


(Sieh et al, 2008)

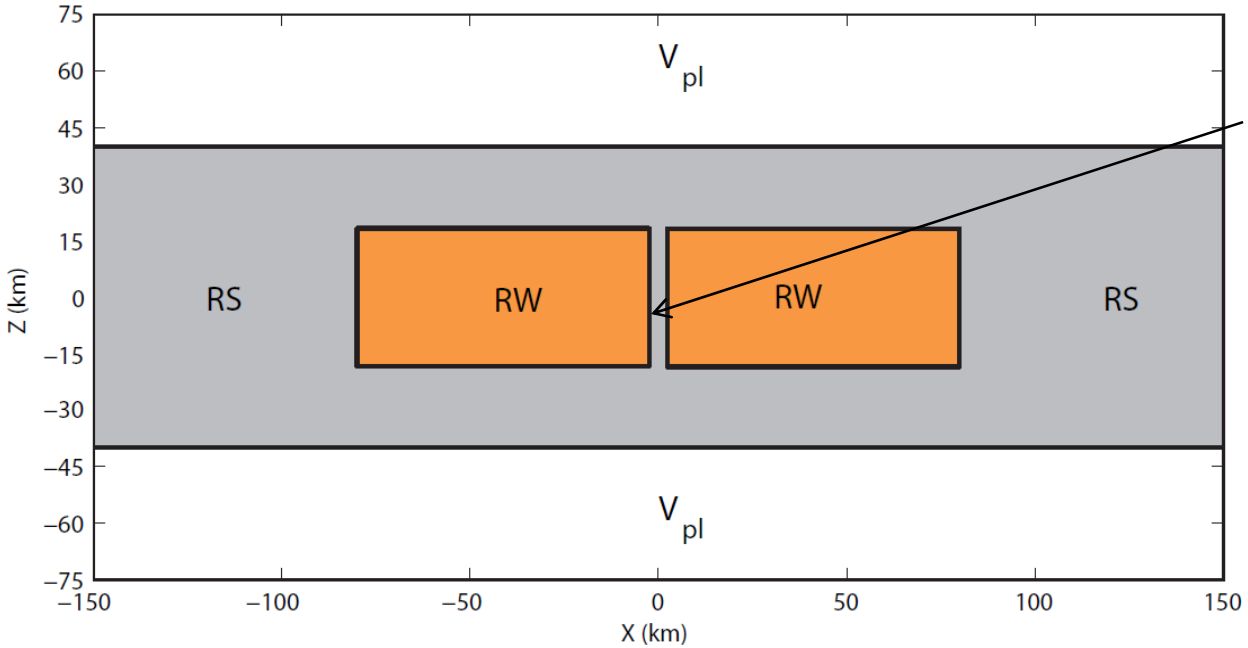
Seismic ruptures tend to be confined within patches that remain locked in the interseismic period.

A nearly 'characteristic' bevavior is suggested for Nias area.

In the Mentawai aera the behavior is neither time- nor slip-predictable.



Dynamic modeling



Narrow rate-strengthening barrier of width D

Rate&state friction:

$$\tau/\sigma=\mu=\mu_*(T)+a\ln(V/V_*)+b\ln(\theta/\theta_*)$$

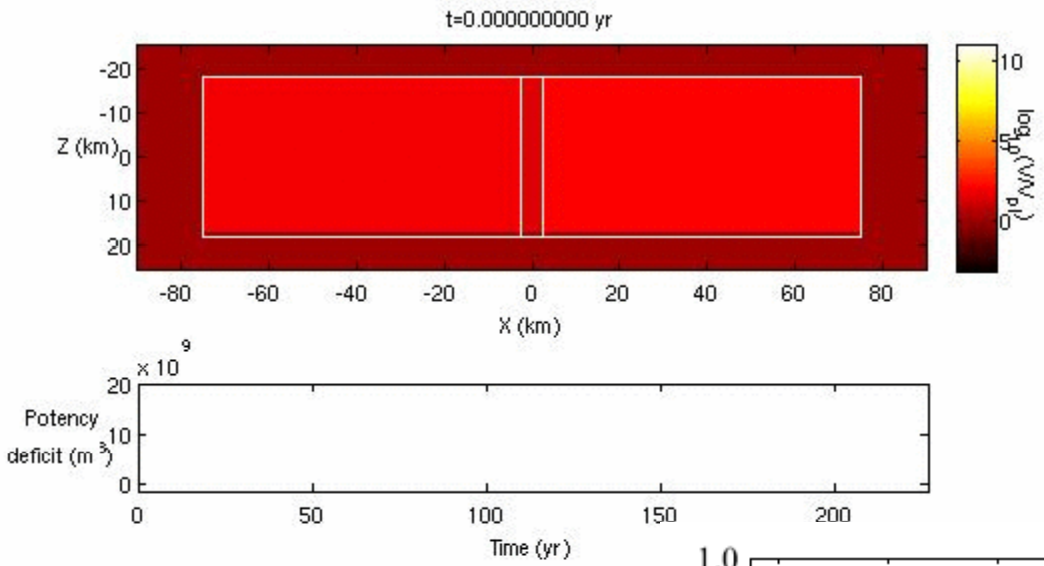
$$d\theta/dt=1-V\theta/D_c$$

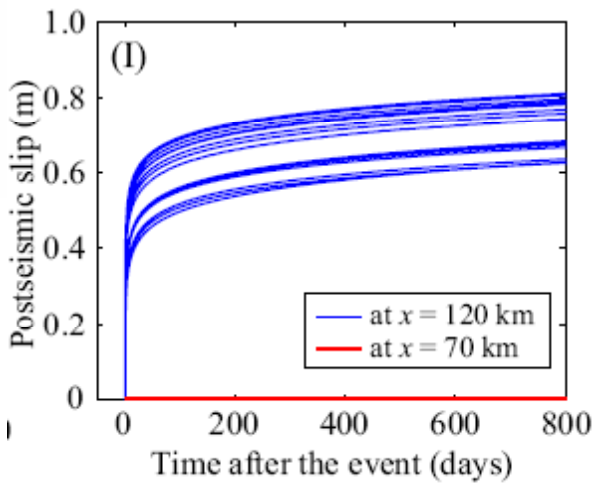
Boundary Intregral Method in 3-D of Lapusta and Liu (JGR, 2009)

(Kaneko et et al, in prep)

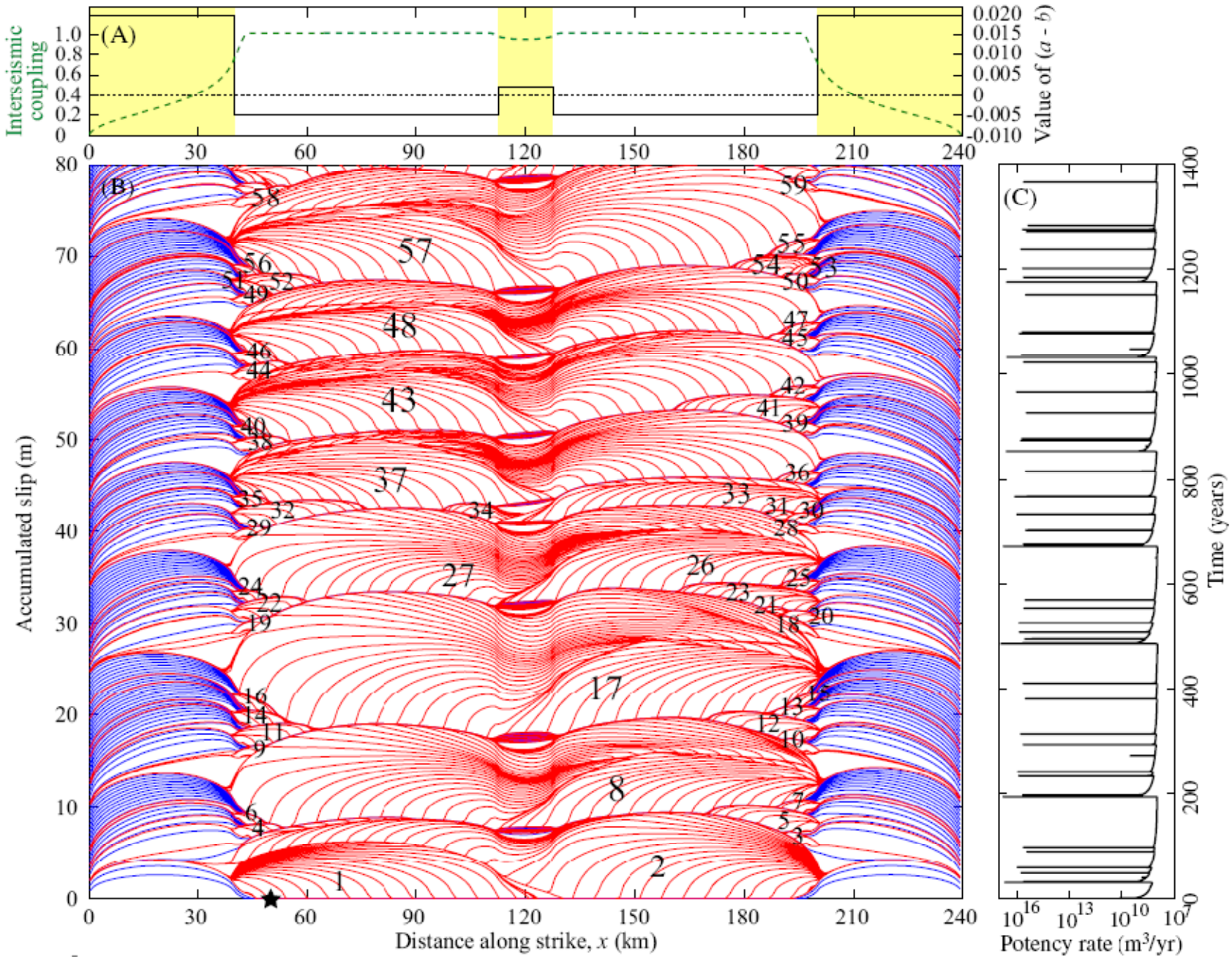
Dynamic modeling

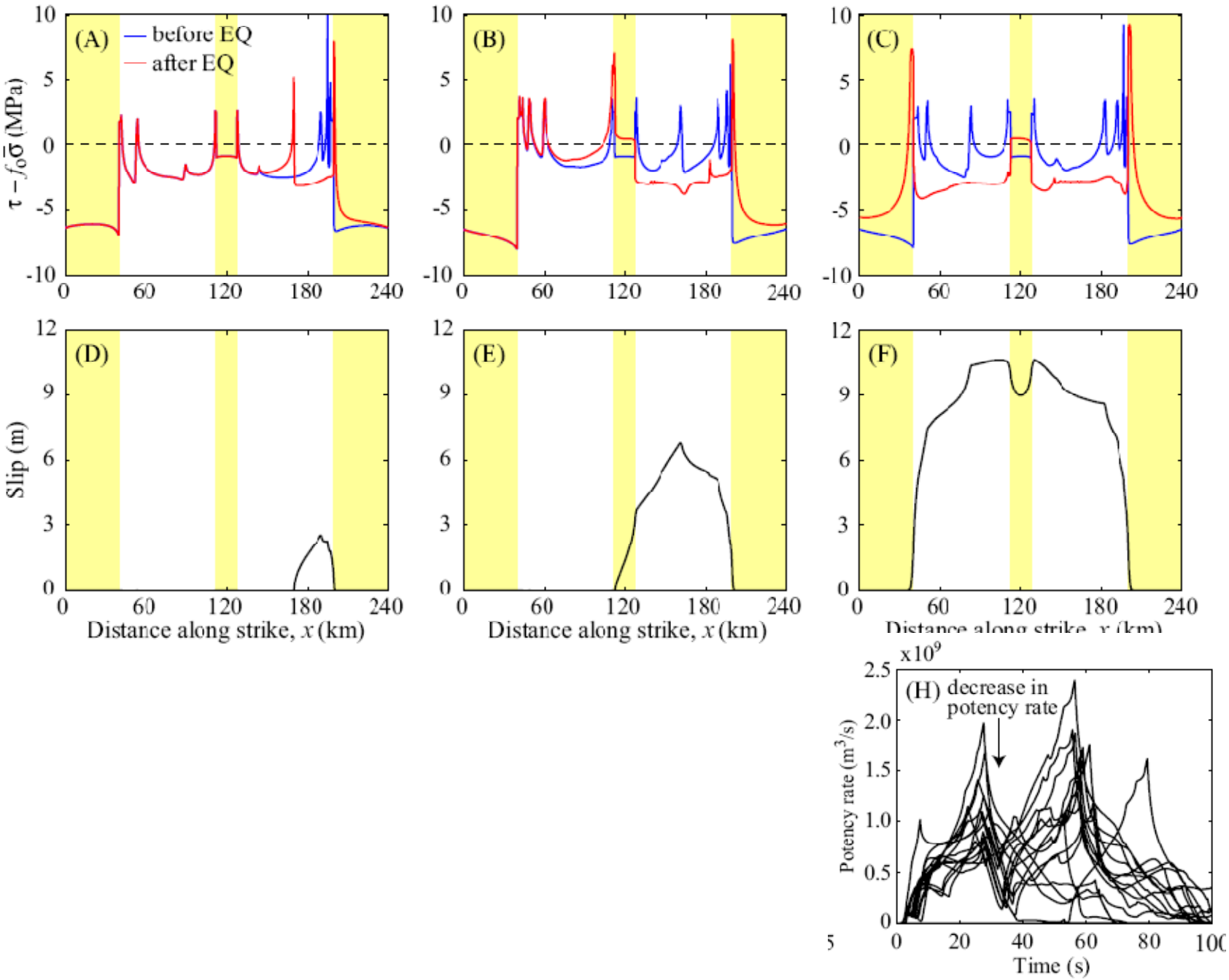
3-D simulations

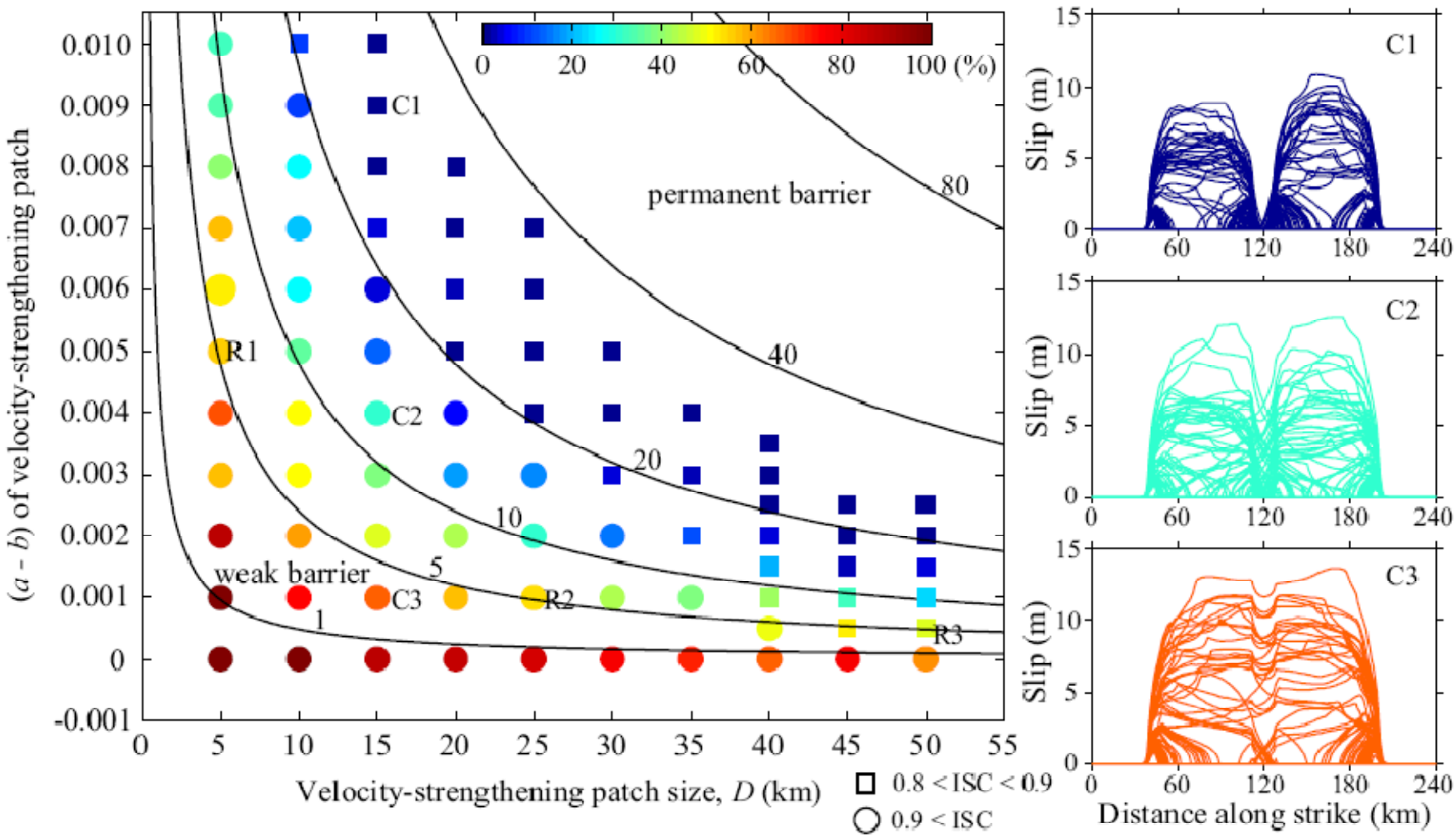




(Kaneko et et al, in prep)


(A)
Interseismic coupling
Value of (a - b)
(B)
Accumulated slip (m)
Distance along strike, x (km)
(C)
Time (years)
Potency rate (m³/yr)

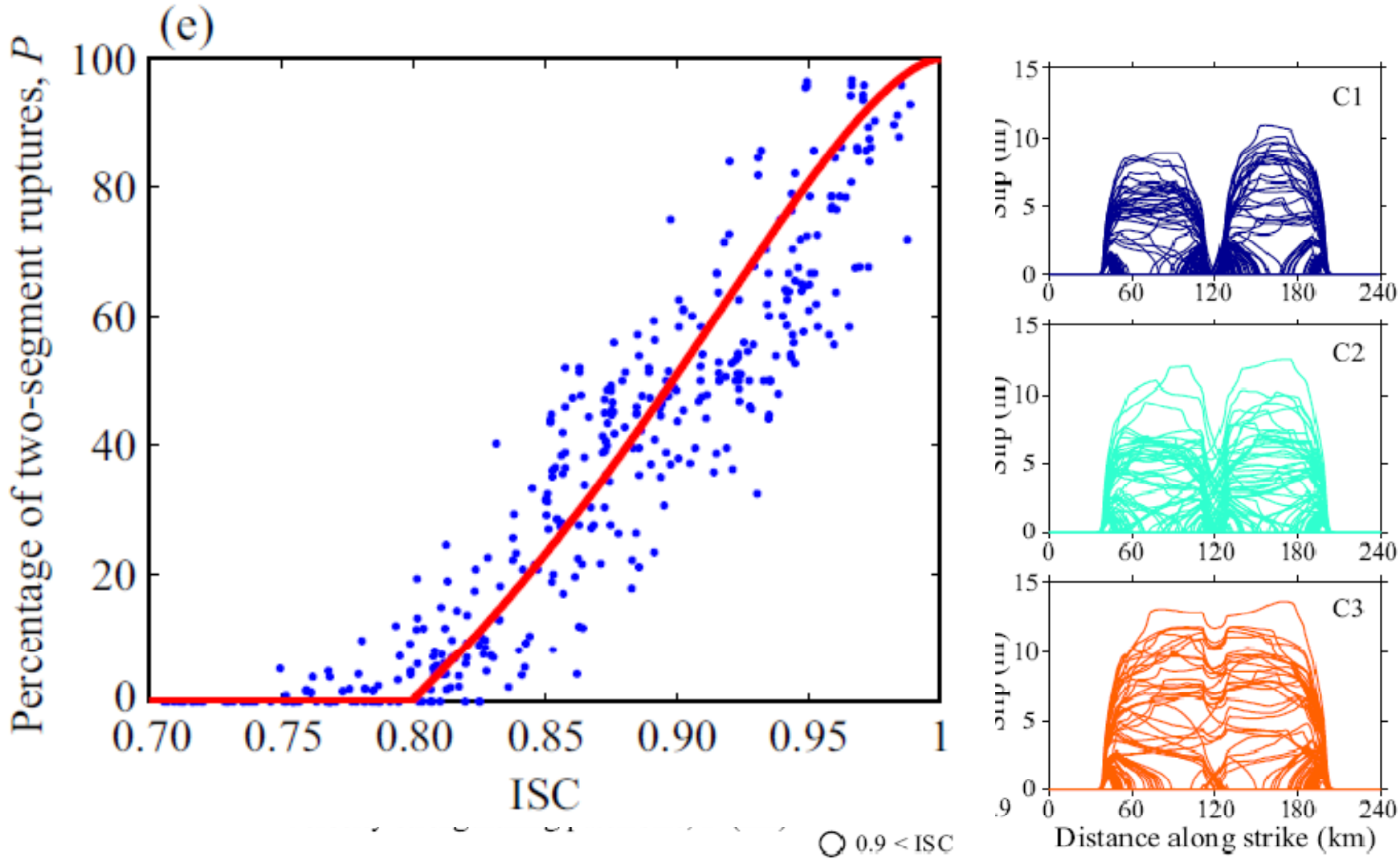

(A)
before EQ
after EQ
(B)
(C)
$\tau - f_0\bar{\sigma}$ (MPa)
(D)
(E)
(F)
Slip (m)
Distance along strike, x (km)
(H) decrease in potency rate
x10^9
Potency rate (m^3/s)
Time (s)



Intreseismic coupling and the probability that an earthquake propagates across a rate-strenthening barrier are both linearly dependent on the 'strength' of the barrier:

$$B = (a - b)\sigma D$$

(Kaneko et et al, in prep)



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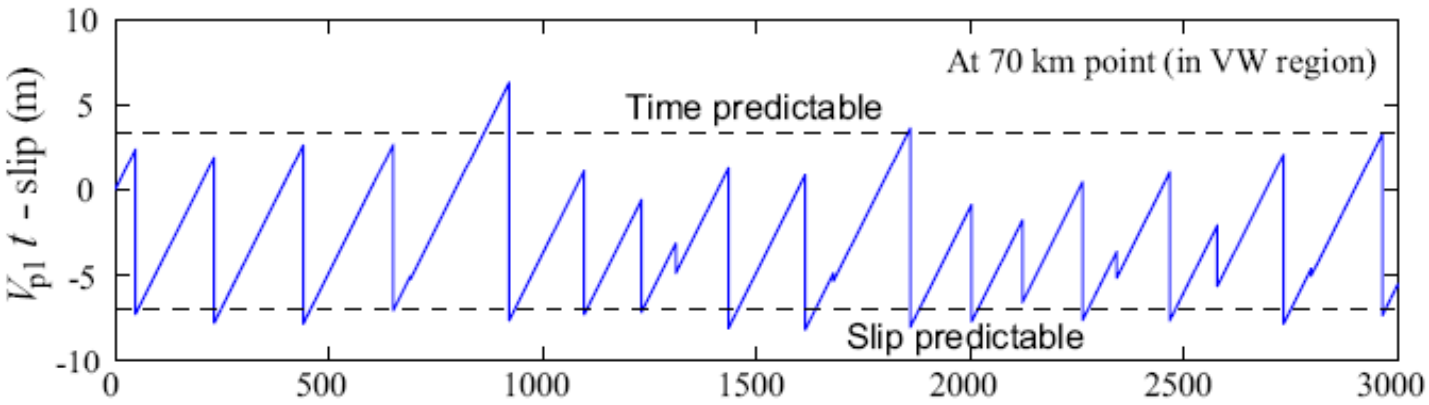
(Kaneko et et al, in prep)

Time- and slip-predictable behavior in our model



Conclusions

- A variety of observation suggest that Megathrust consist of a patchwork of RS and RW areas.
- The topology of this patchwork and the frictional parameters can be inferred from combined analysis of co-seismic, interseismic and postseismic deformation.
- This conceptual model explains some of the systematic and non-systematic patterns observed in Nature.
- The physical parameters determining the patchiness of interseismic strain remain unclear.

Conclusions