Megathrust Earthquakes

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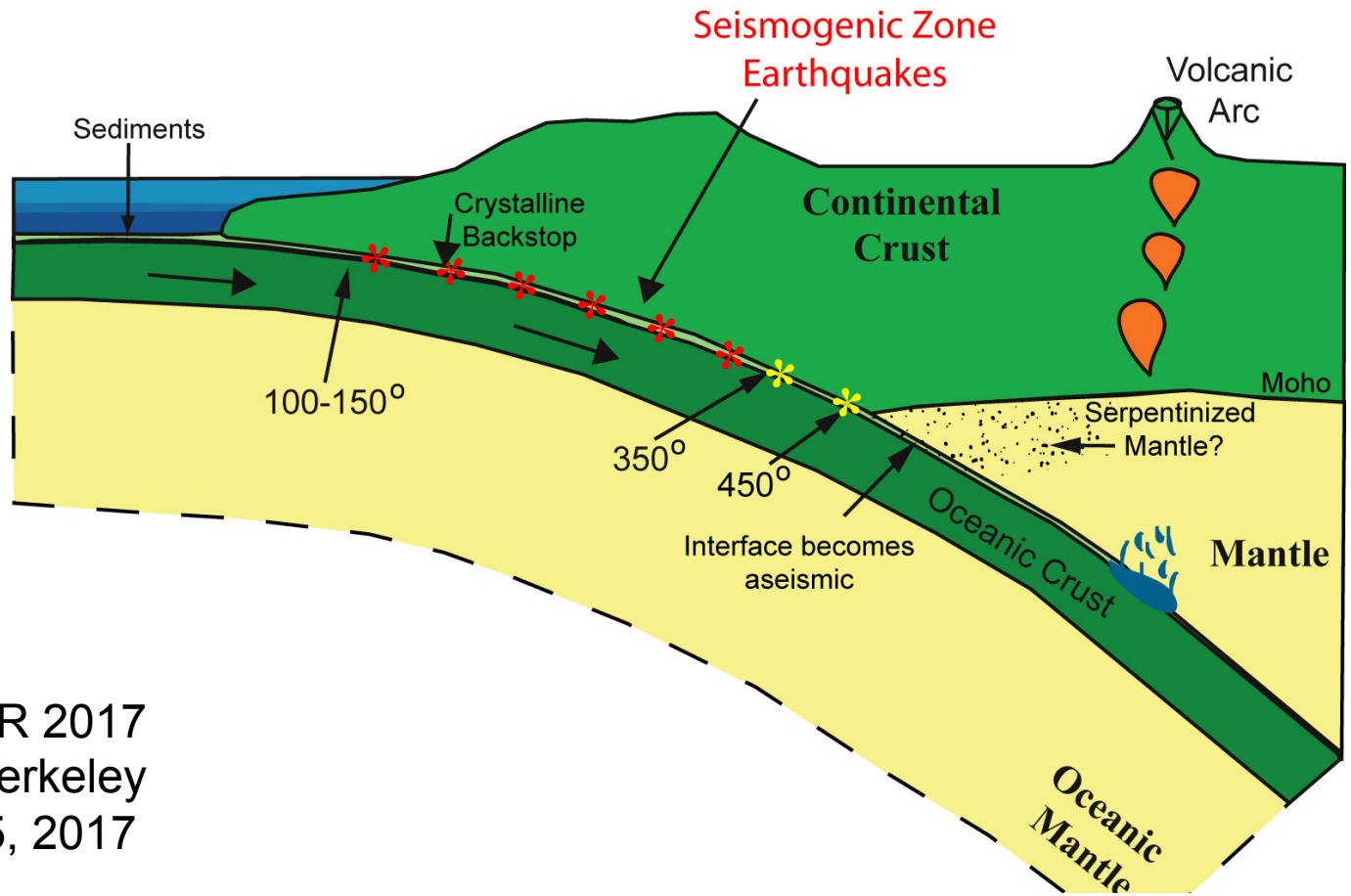
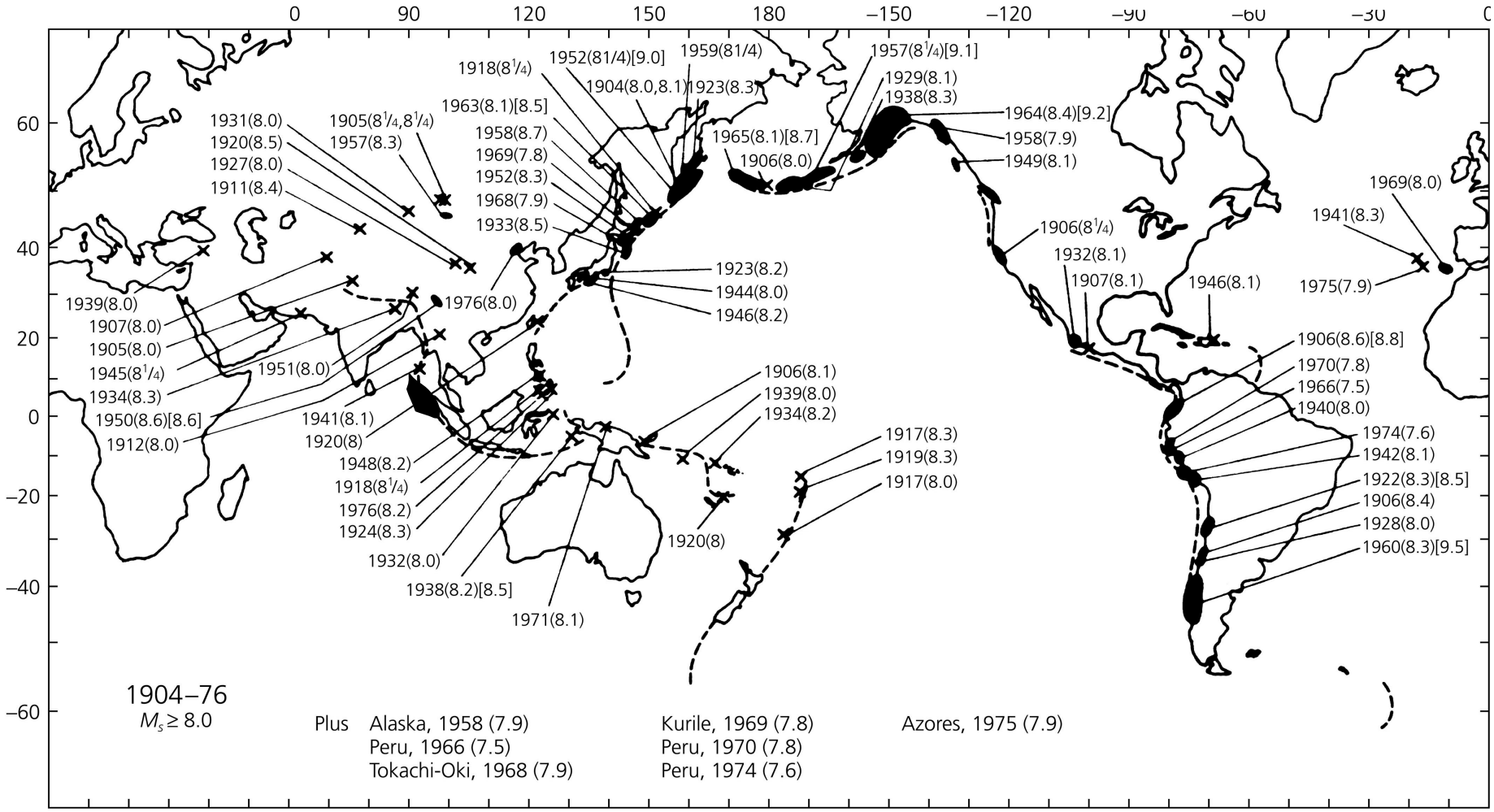


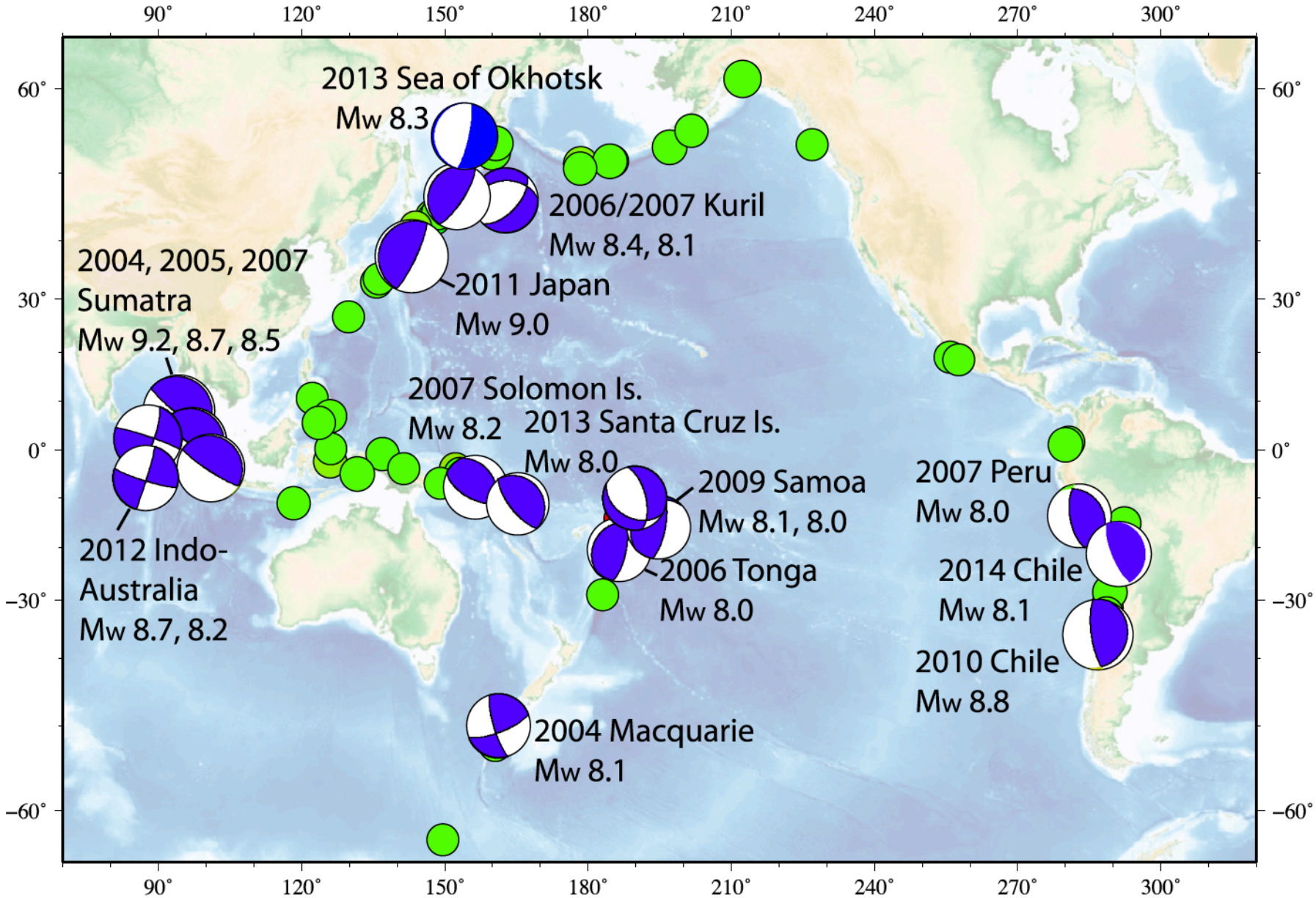
CIDER 2017
UC Berkeley
July 5, 2017

Locations of the largest earthquakes

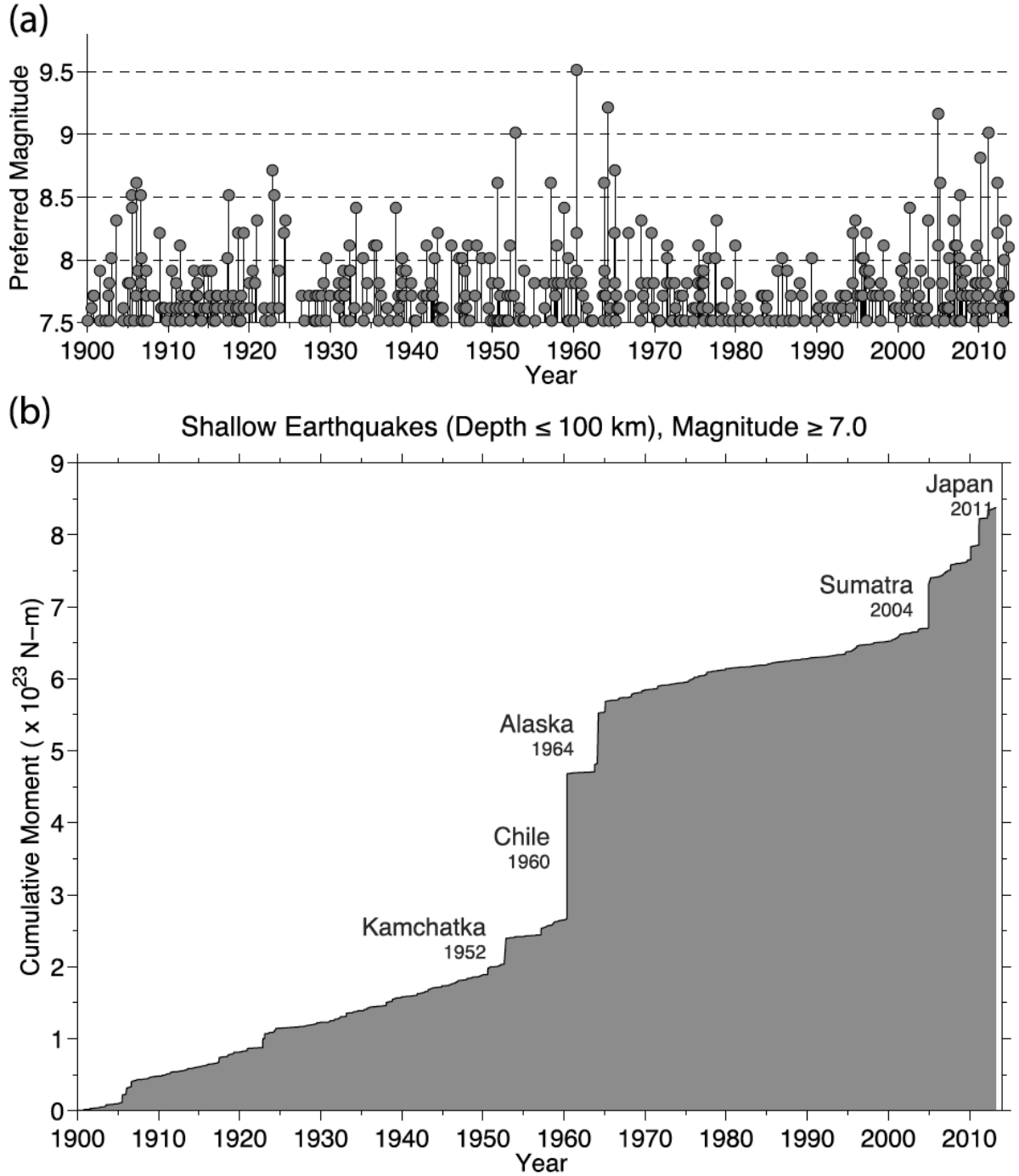


The largest megathrust events are not uniformally distributed at all subduction zones.

M>8 since 1900, blue events between 2004-2014



Lay, 2014


(a)
Preferred Magnitude
9.5
9
8.5
8
7.5
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
(b)
Shallow Earthquakes (Depth ≤ 100 km), Magnitude ≥ 7.0
Cumulative Moment (x 10^23 N–m)
Japan
2011
Sumatra
2004
Alaska
1964
Chile
1960
Kamchatka
1952
Year

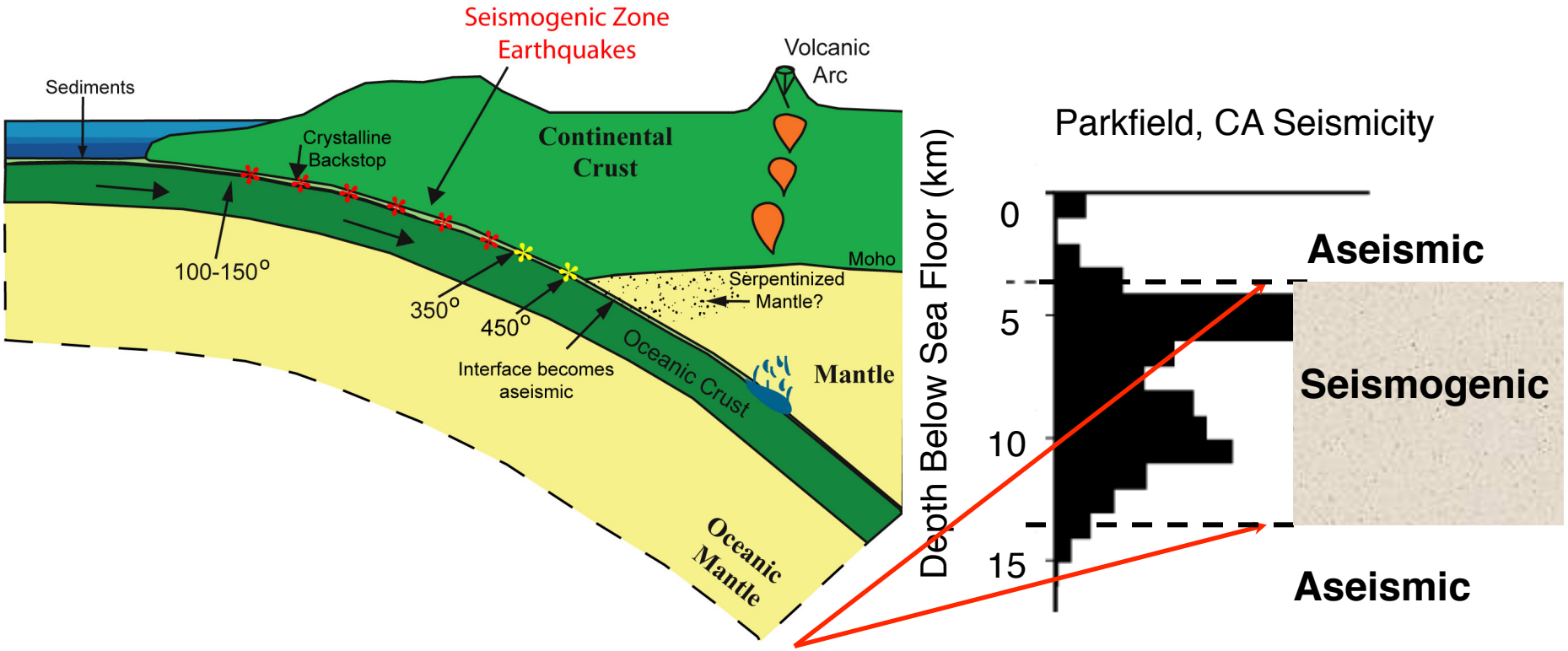
Lay, 2014

Goals of this talk

- Synthesize what has been learned from seismic studies of the numerous, well recorded recent megathrust earthquakes

- Discuss some outstanding questions and directions for future research

Earthquakes are Controlled by Friction



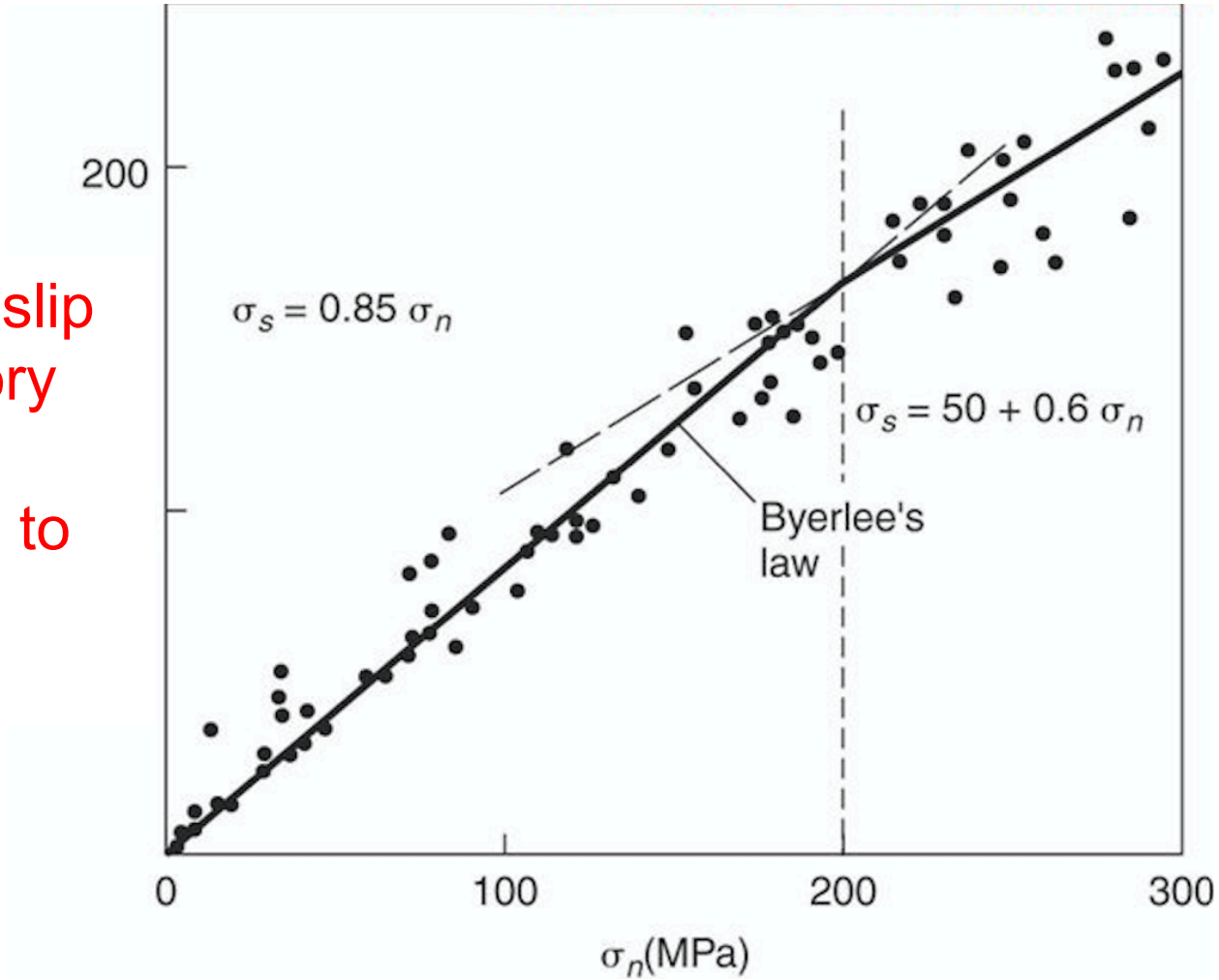
Marone & Scholz, 1988

The seismogenic zone is defined by the transitions from stable to unstable frictional deformation

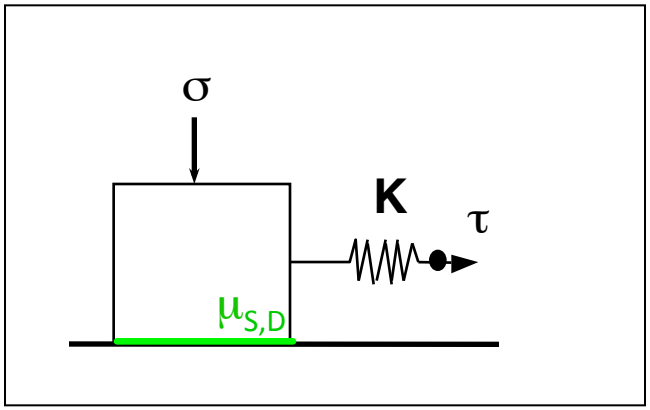
Friction

$$\tau = \mu \sigma_n$$

proposed that stick-slip behavior in laboratory friction experiments might be analogous to earthquake rupture

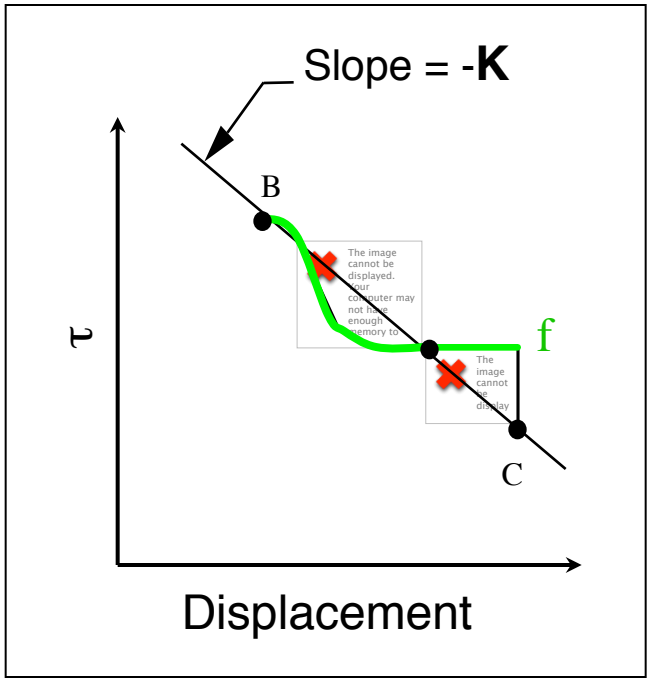


Stick Slip Behavior



$$\tau = \mu_s \sigma_n$$

Sliding initiates at static friction coefficient but frictional resistance falls once sliding starts resulting in a dynamic instability or slip



Condition for Instability:

$\delta\tau/\delta u > K$ (K- elastic properties of the medium)

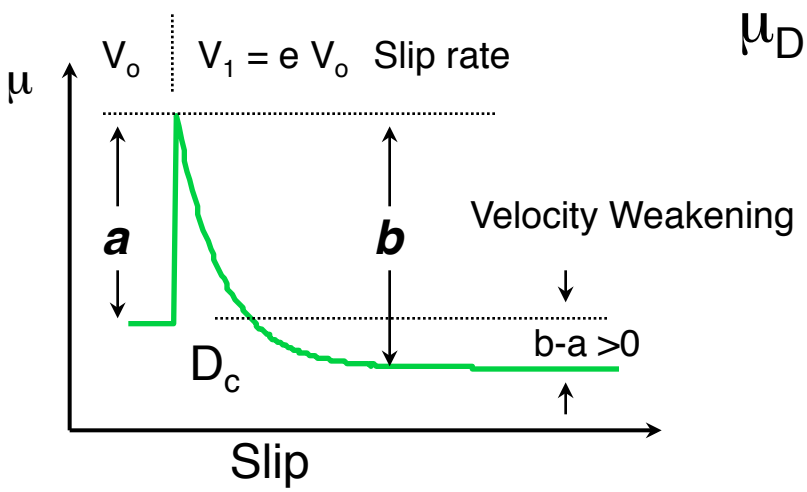
Frictional stability is determined by the combination of
1) fault zone frictional properties and
2) elastic properties of the surrounding material

Further work on physics of rock friction revealed:

1. Time dependence of friction

$$\mu_s = \mu_0 + A \ln (Bt+1) \quad \text{(Dietrich)}$$

2. Velocity dependence of friction

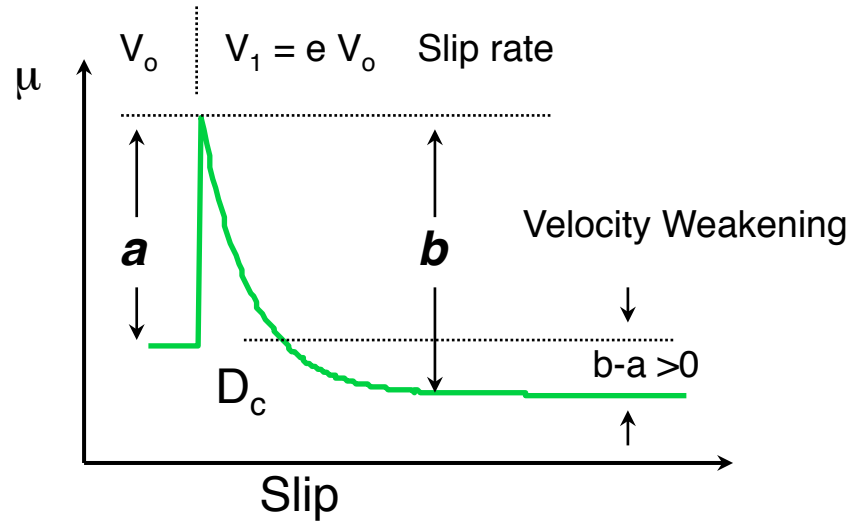


$$\mu_D = \mu_0 + a \ln (V/V_0) + b \ln(V_0\theta/D_c)$$

Instantaneous effect

Evolutionary effect

Rate and State Dependent Friction Law



a-b <0 velocity weakening- STICK-SLIP INSTABILITY

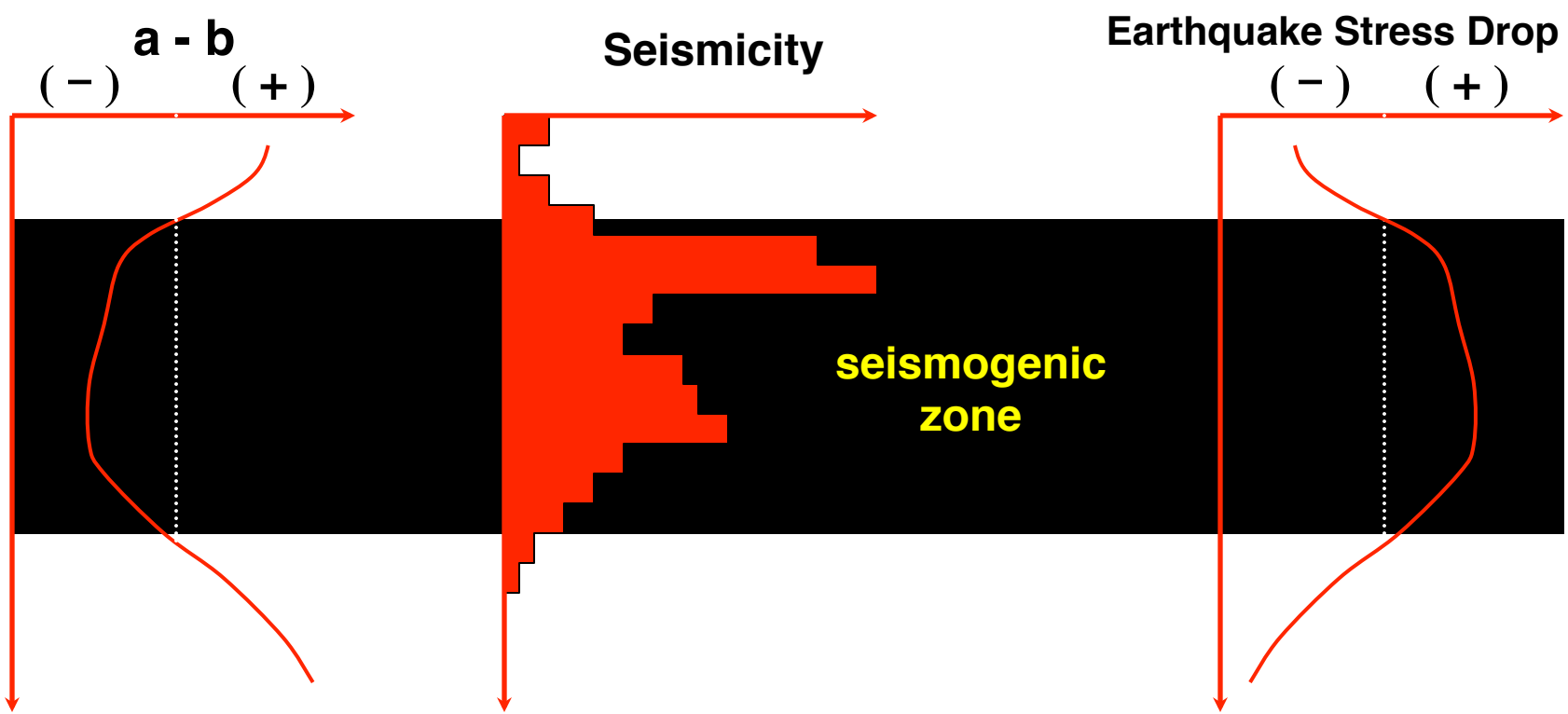
a-b $\geq$ 0 velocity strengthening and STABLE

Friction Laws and Their Application to Seismic Faulting

(a-b) > 0 Always Stable, No Earthquake Nucleation, Dynamic Rupture Arrested

(a-b) < 0 Unstable, Earthquakes May Nucleate, Dynamic Rupture Will Propagate

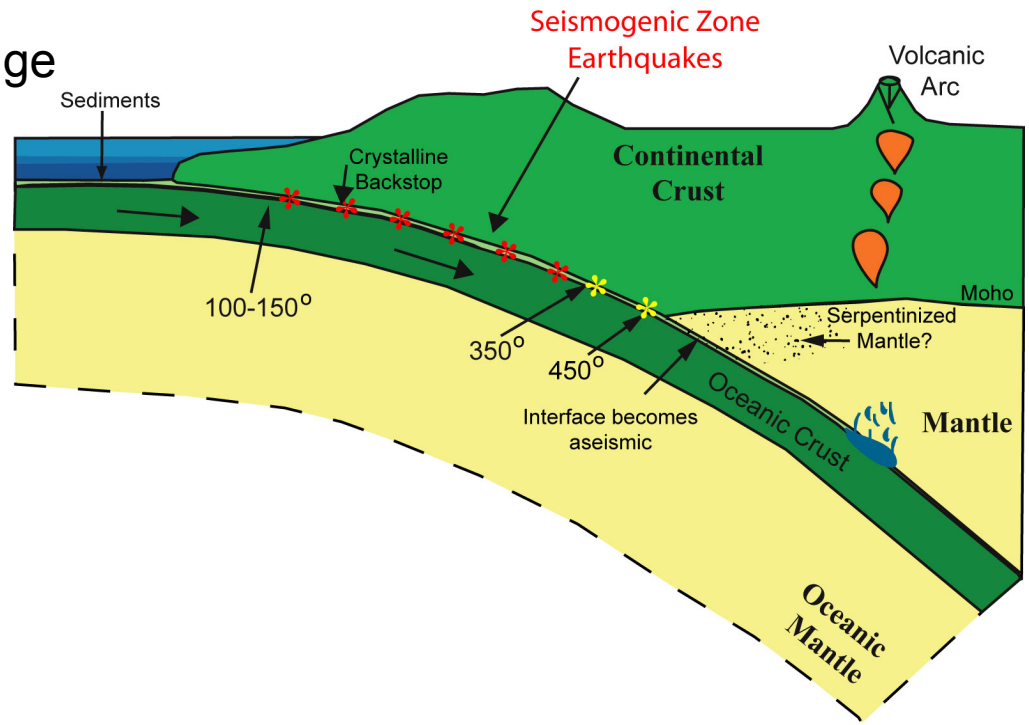
(a-b) ~ 0 Conditionally Stable, No Earthquakes Nucleate, Dynamic Rupture May Propagate



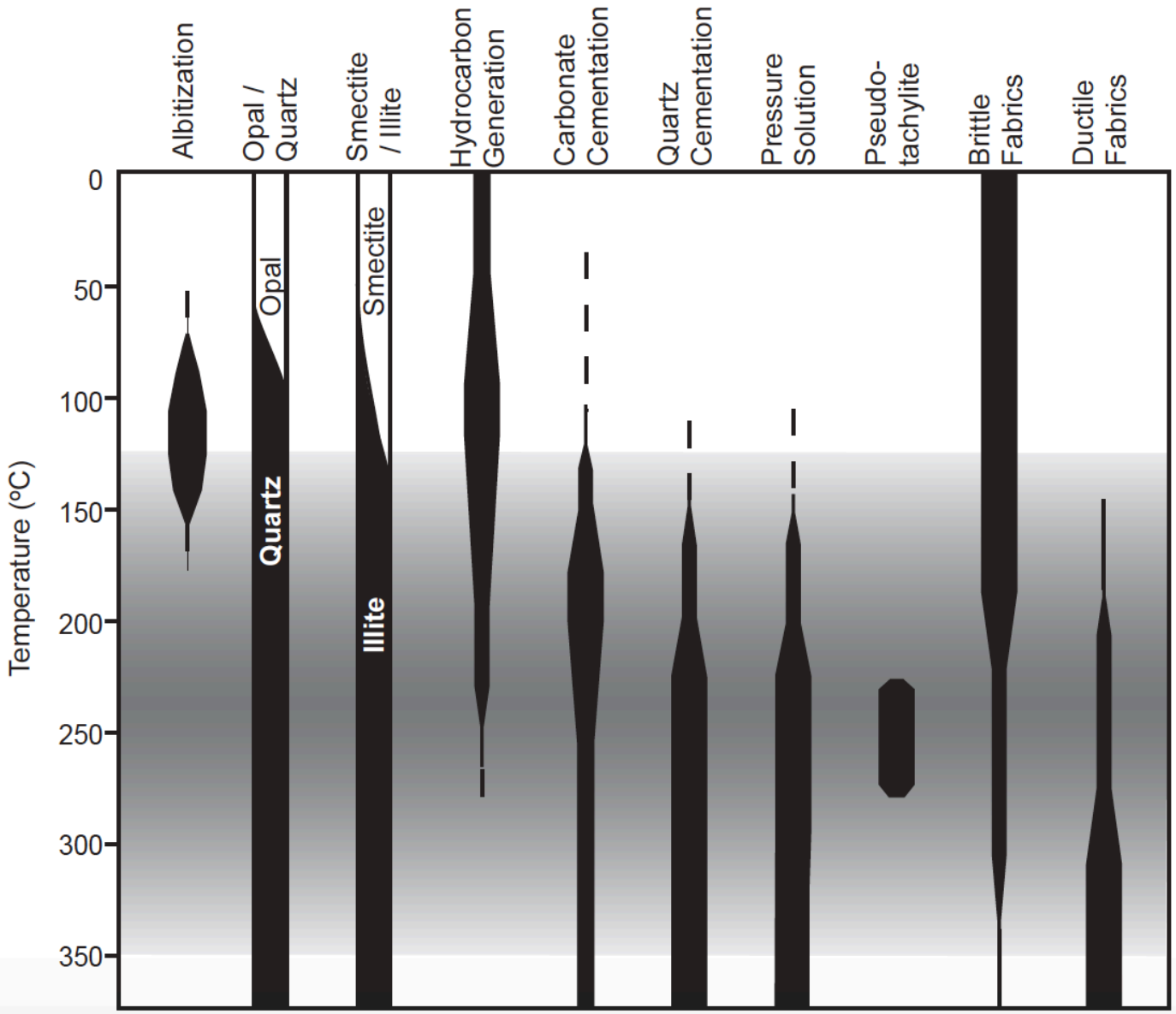
Seismogenic Zone

Up-Dip Stable/Unstable Frictional Transition

1) Clay mineral transformation
2) Consolidation/lithification state of fault gouge and accretionary prism materials
   - Poorly consolidated granular gouge exhibits velocity strengthening
   - Lithified materials and highly localized shear exhibit velocity weakening

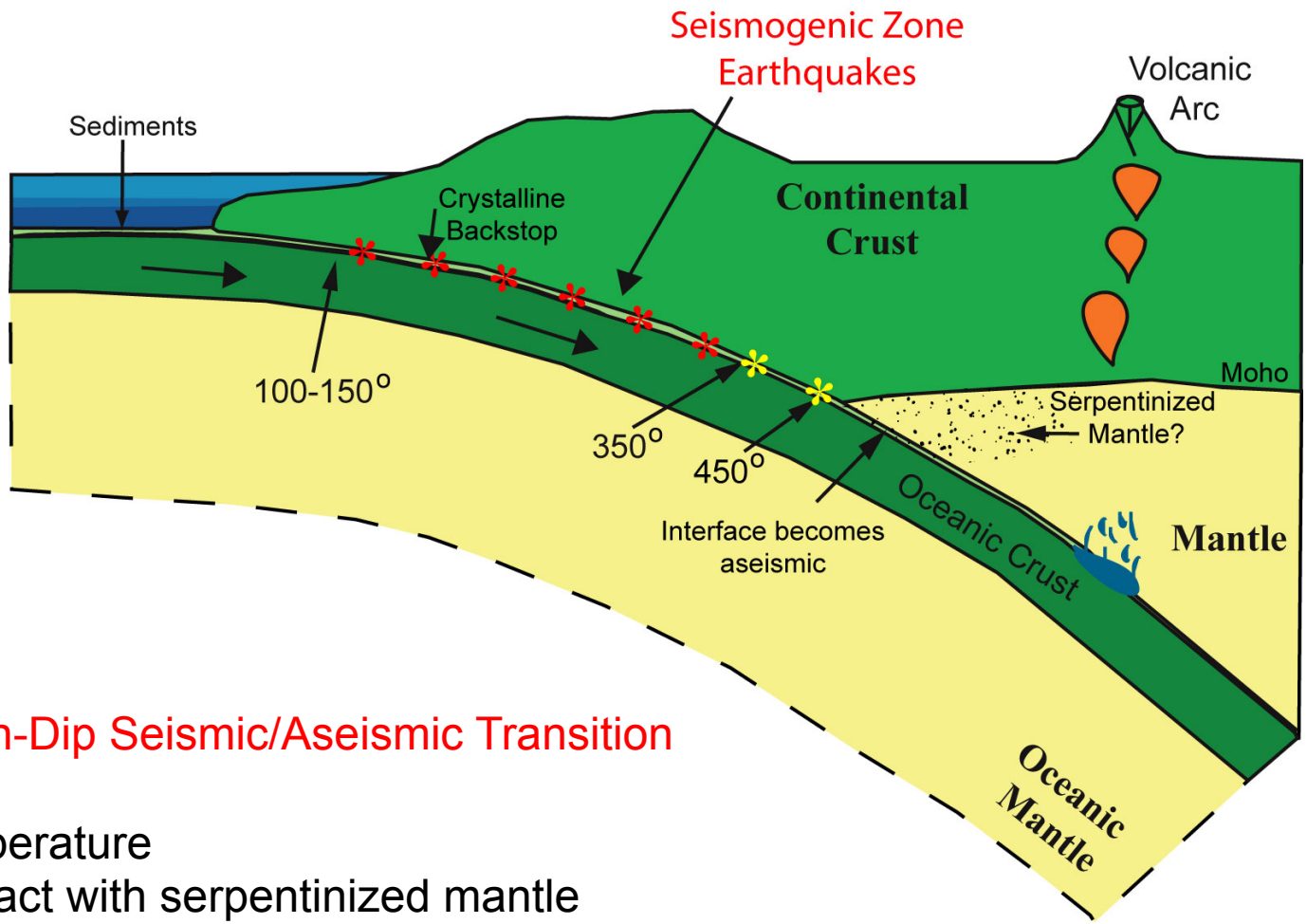


Seismogenic Zone



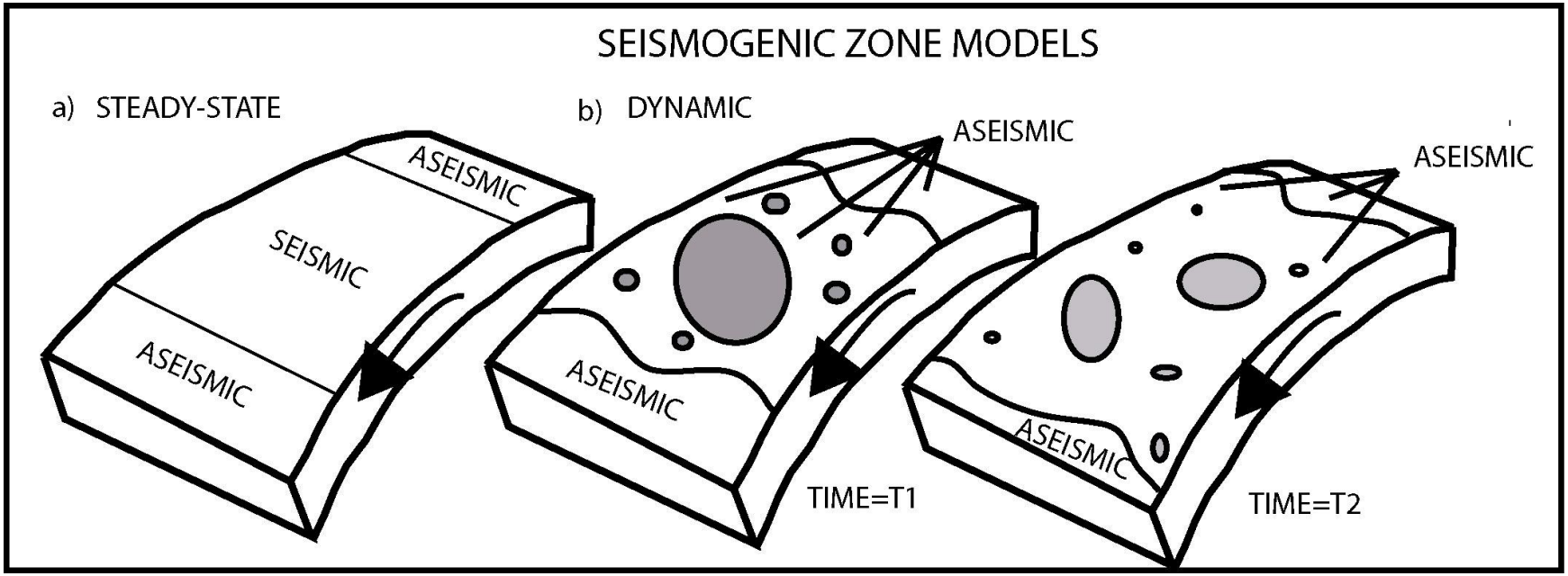
Moore et al., 2007

Seismogenic Zone



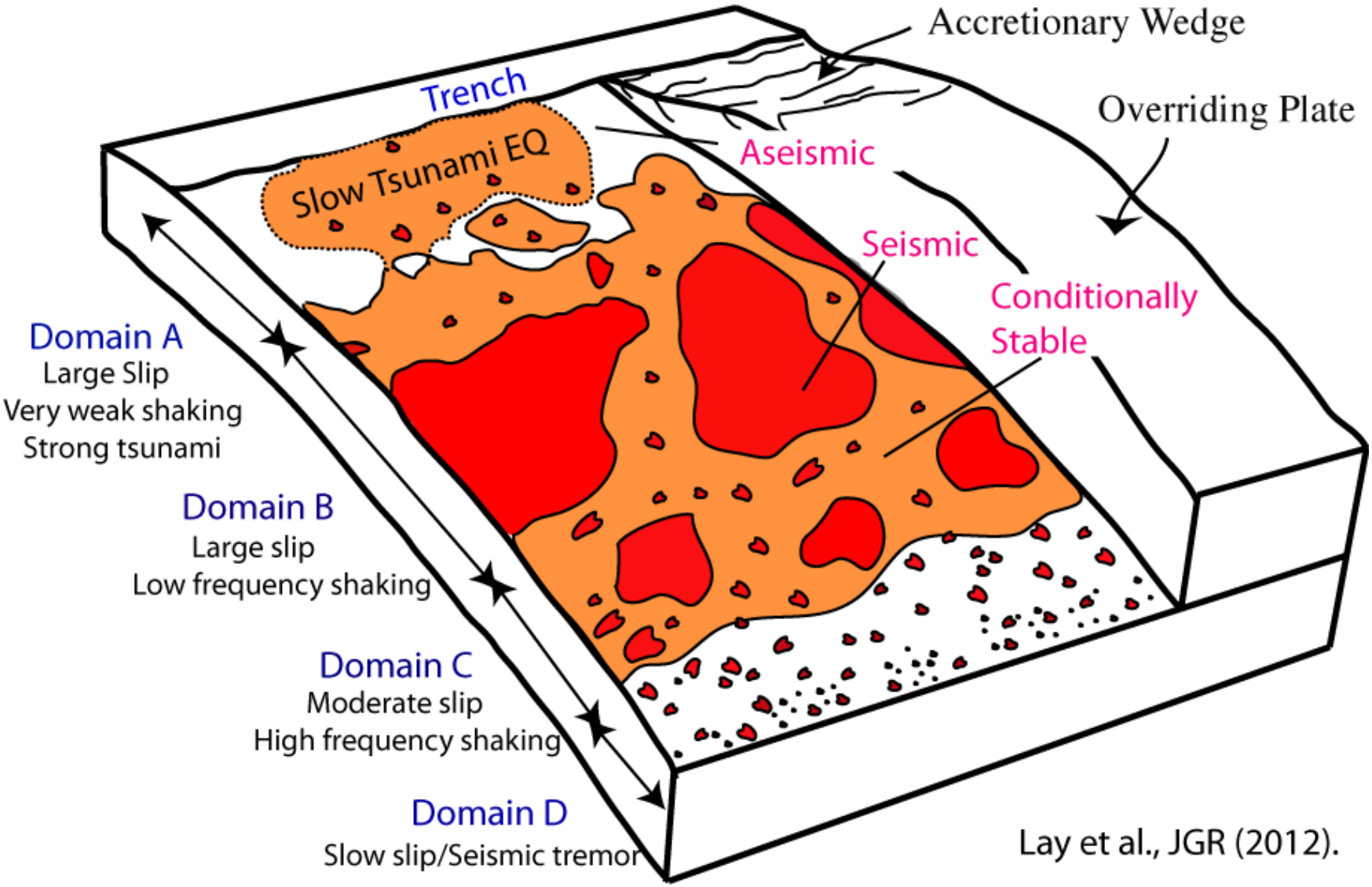
Down-Dip Seismic/Aseismic Transition

Temperature
Contact with serpentinized mantle



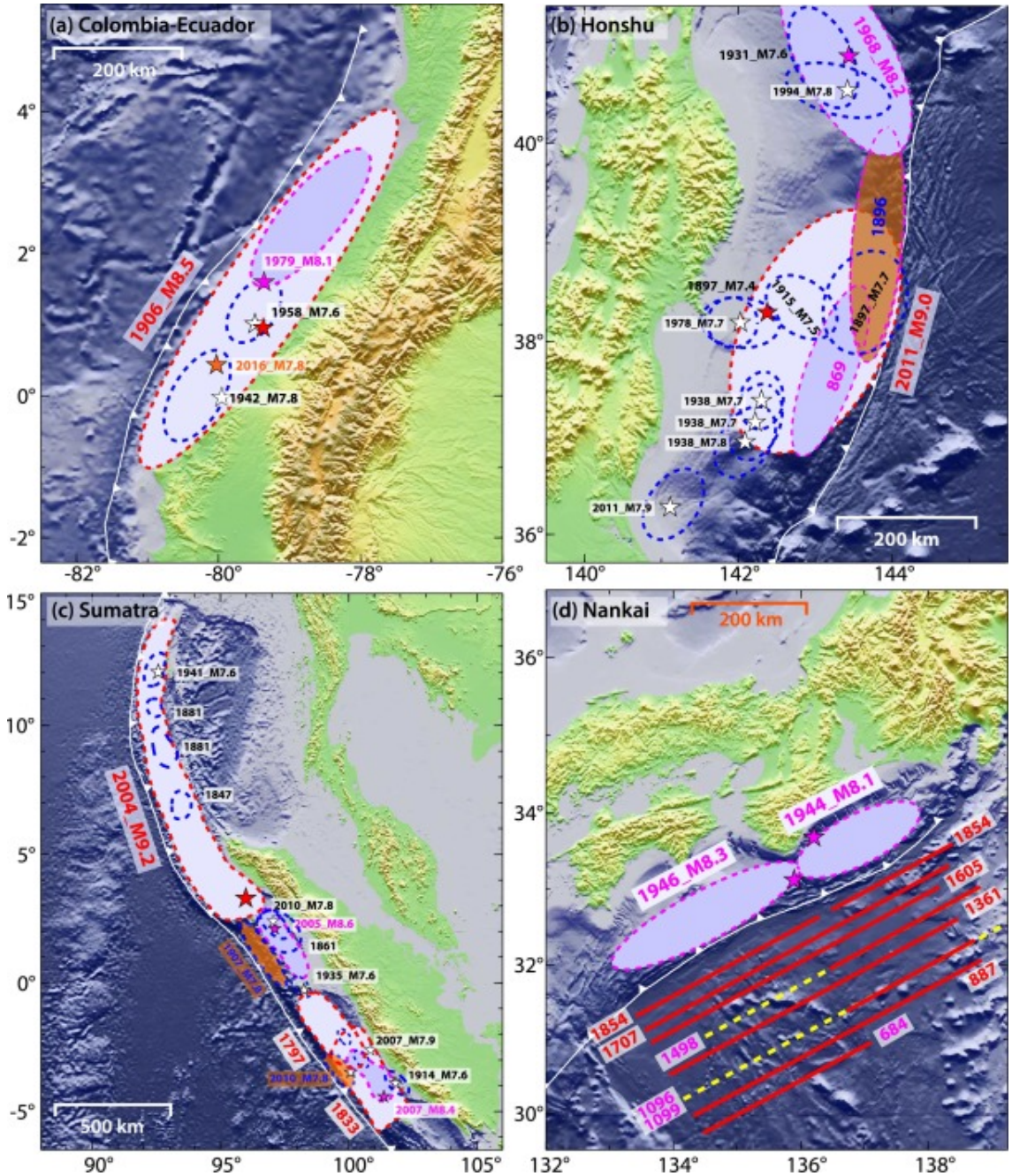
If a~b we have conditionally stable conditions where earthquakes do not nucleate but slip propagates.

At frictional transitions slow slip that occurs at velocities between steady creep and dynamic earthquake rupture can occur.



Lay et al., JGR (2012).

Main Asperity Regions

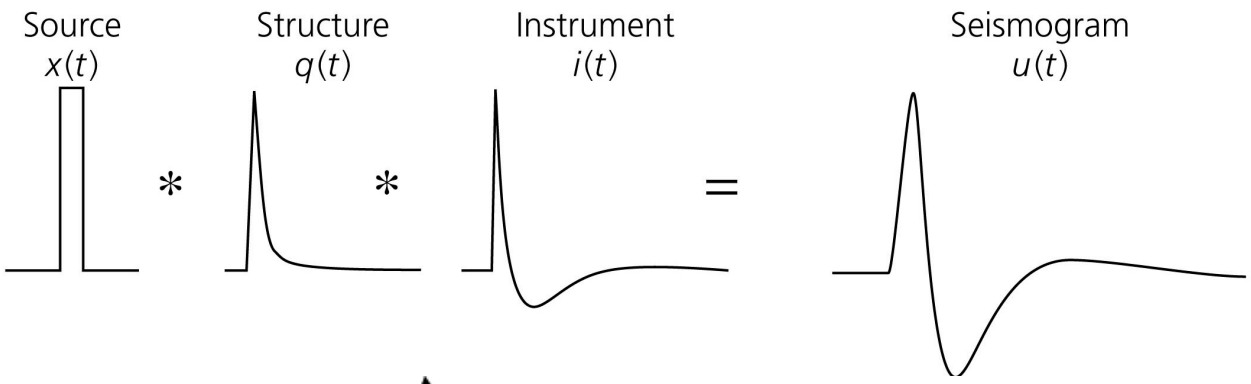


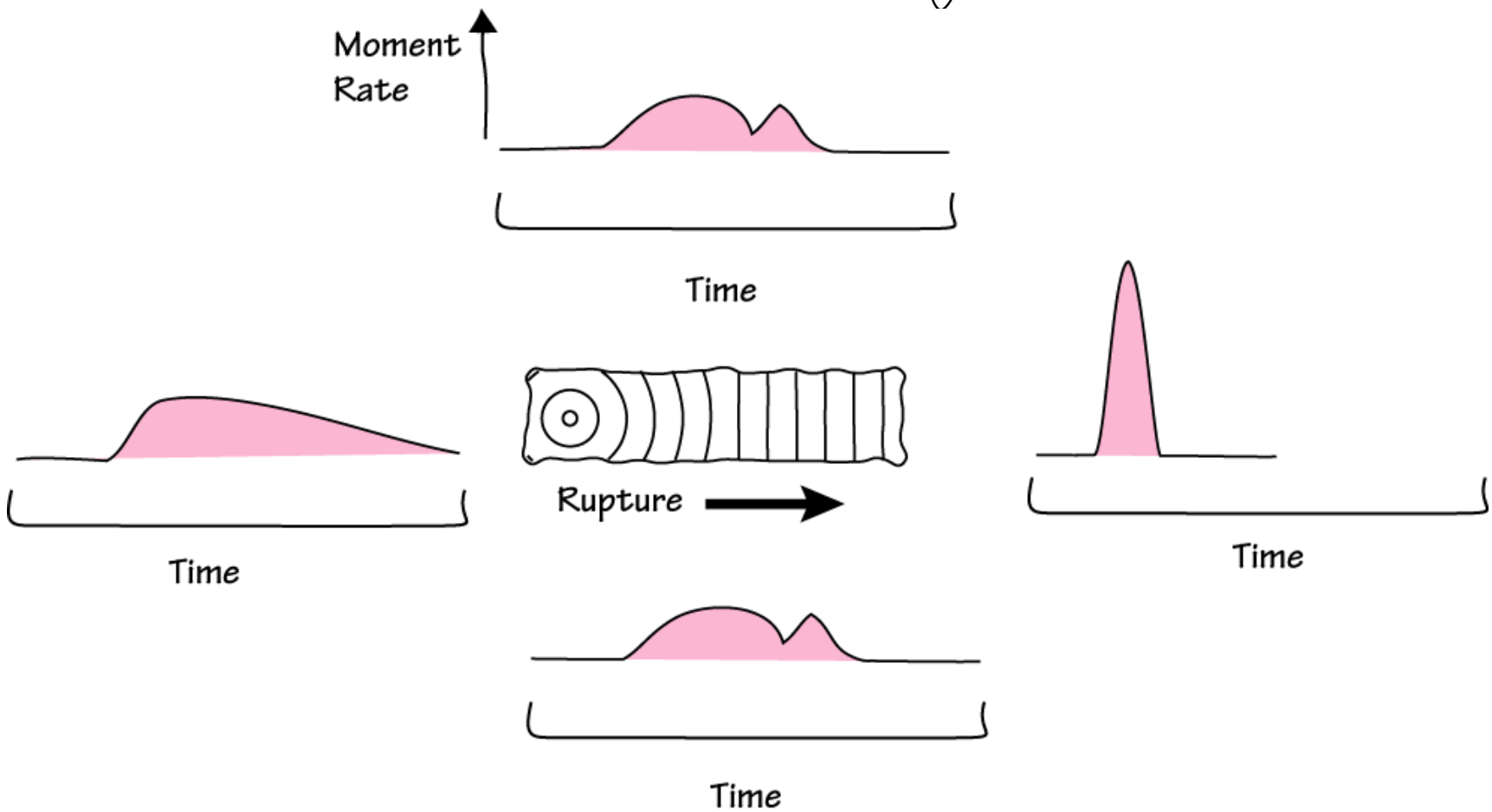
First Order Observations

1. Segmentation of the megathrust- rupture areas tend to abut one another
2. Megathrust events tend to have a characteristic recurrence interval

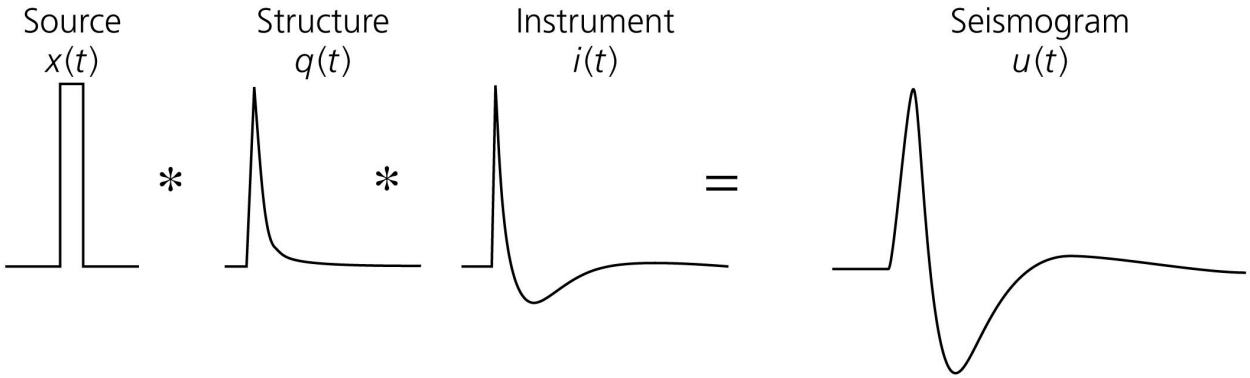
Ye et al., 2016

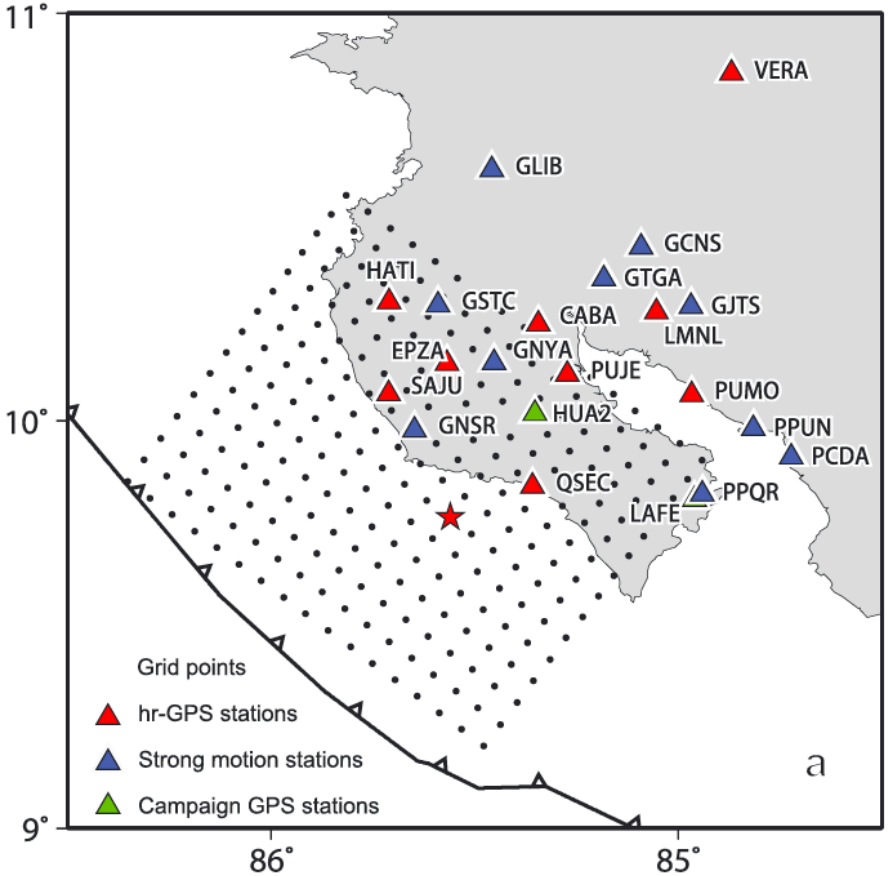
S(t) * G(t) * I(t) = U(t)

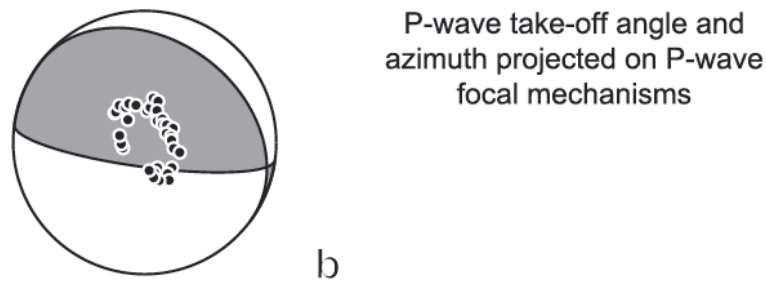

Source
x(t)
*
Structure
q(t)
*
Instrument
i(t)
=
Seismogram
u(t)

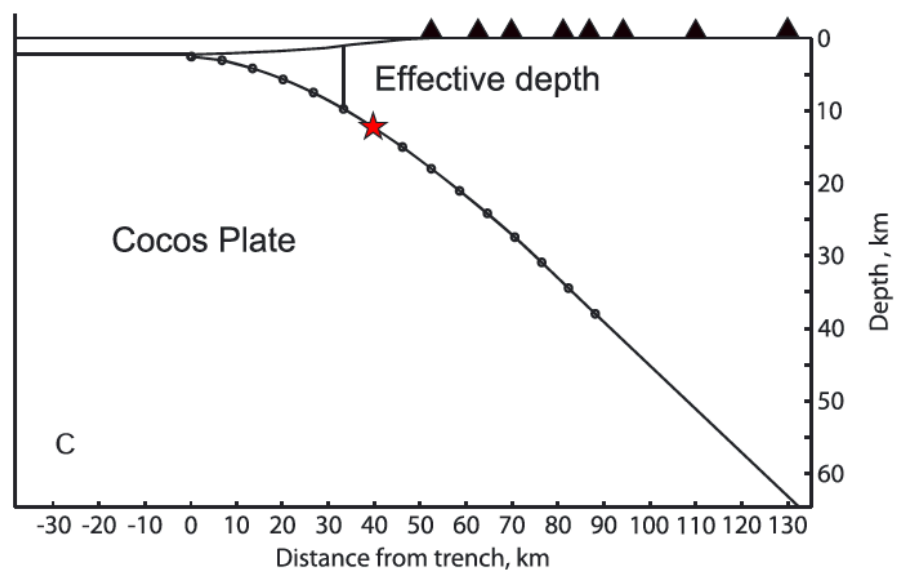

Moment
Rate
Time
Time
Rupture
Time
Time

S(t) * G(t) * I(t) = U(t)

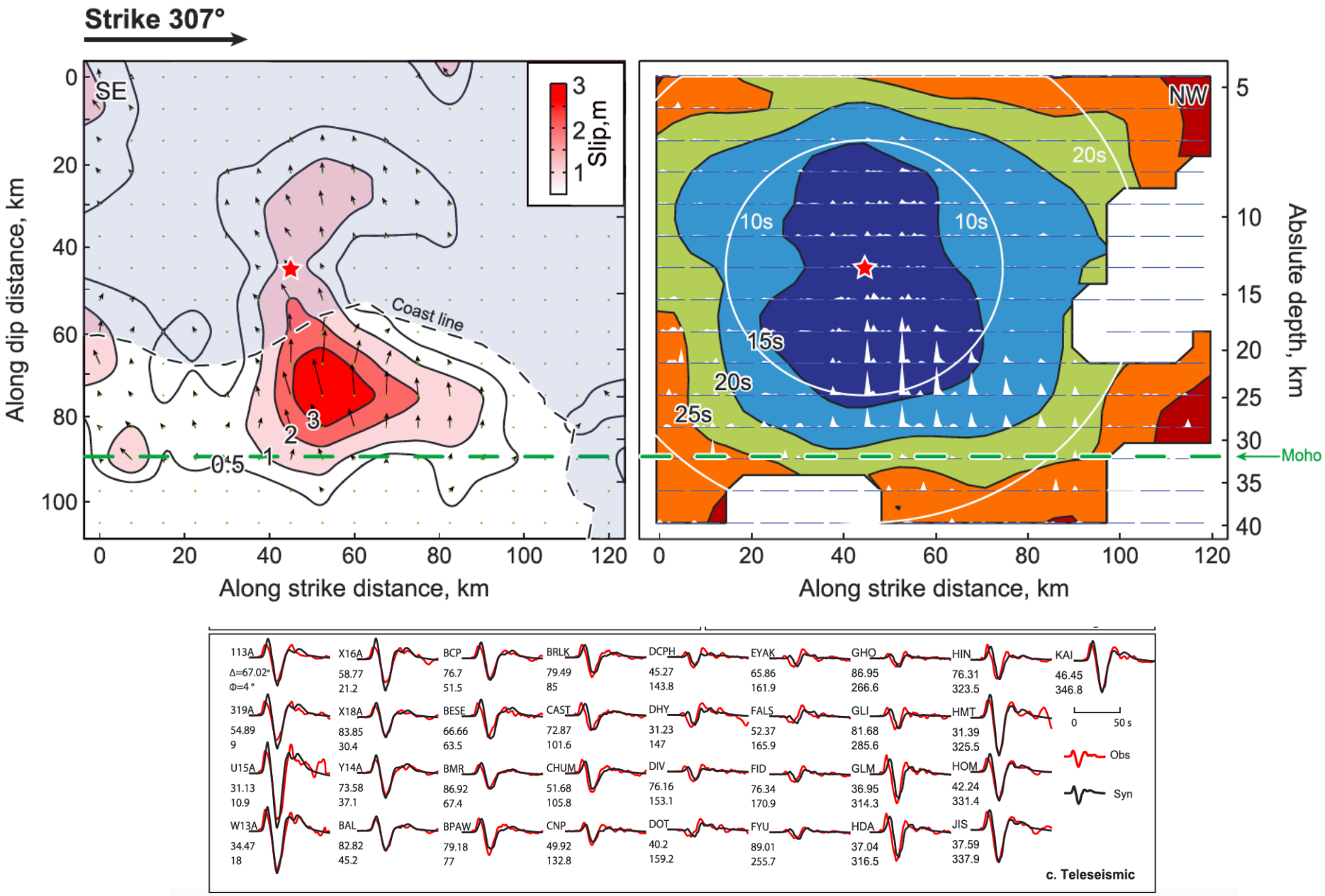






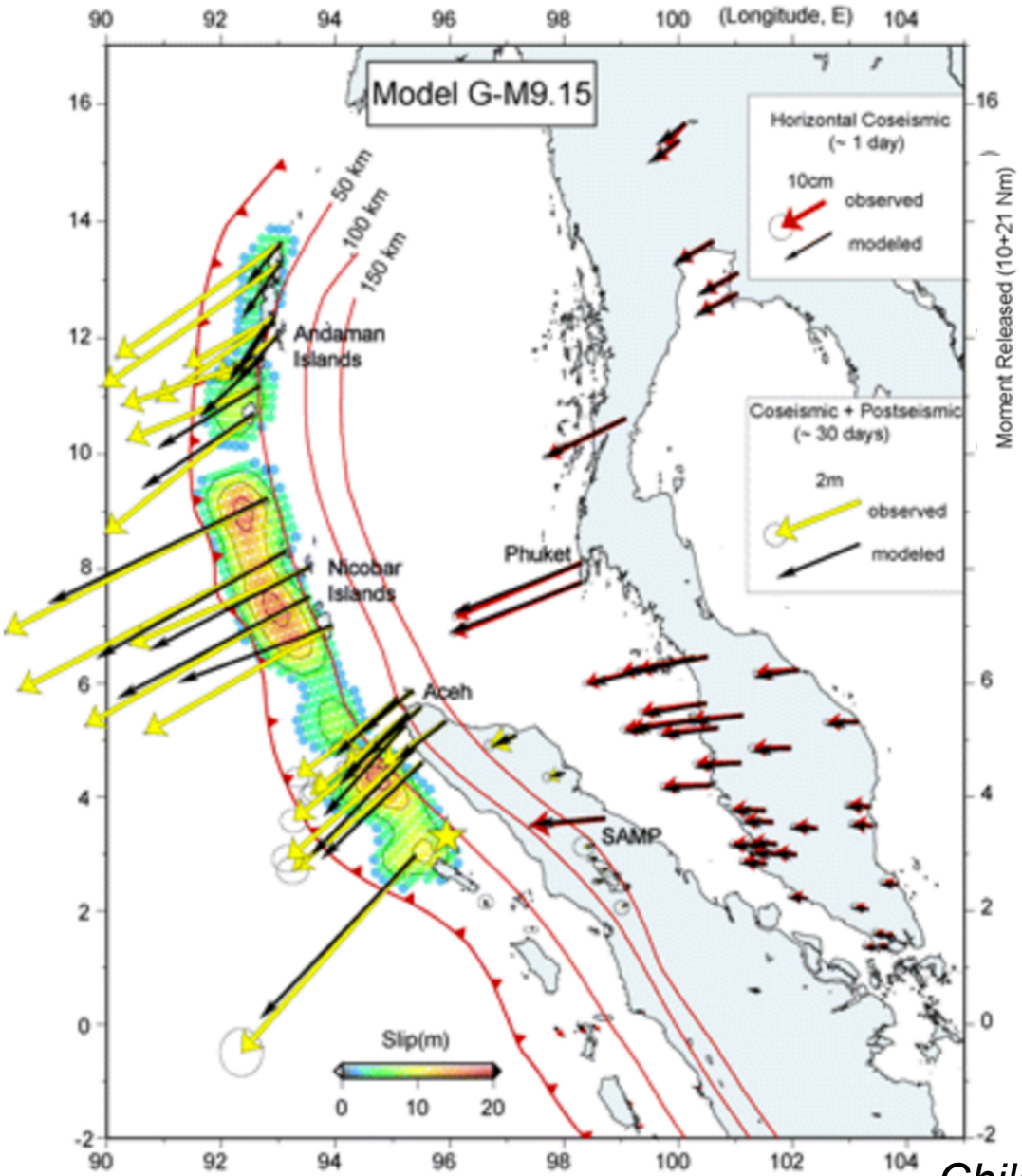


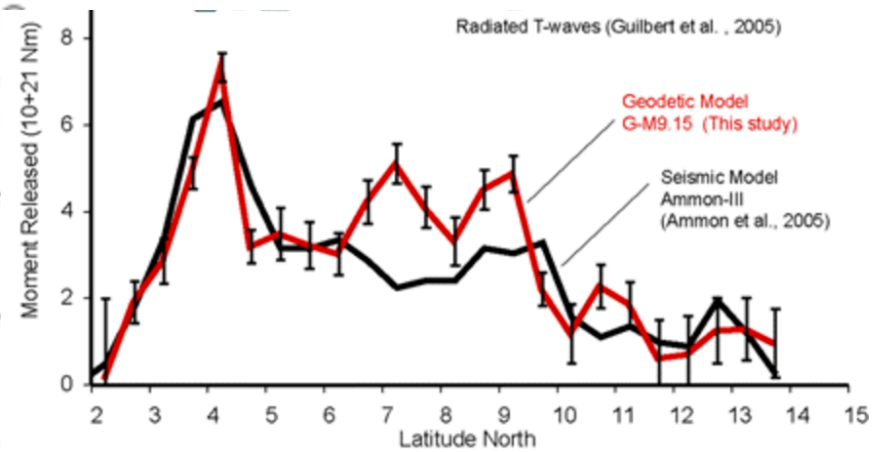
Yue et al., 2013



Yue et al., 2013

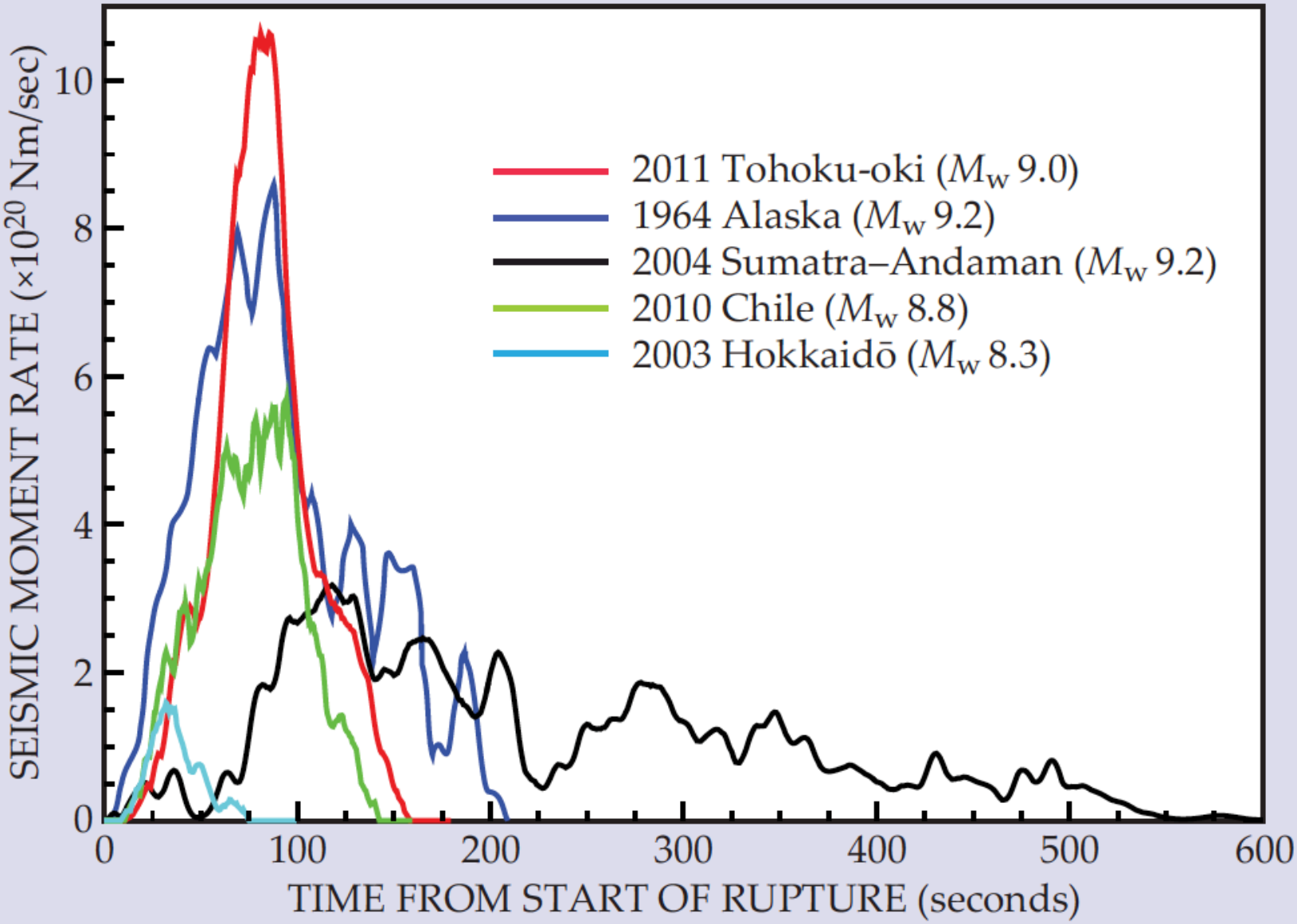
2004 M=9.2 Sumatra Earthquake GPS Inversion



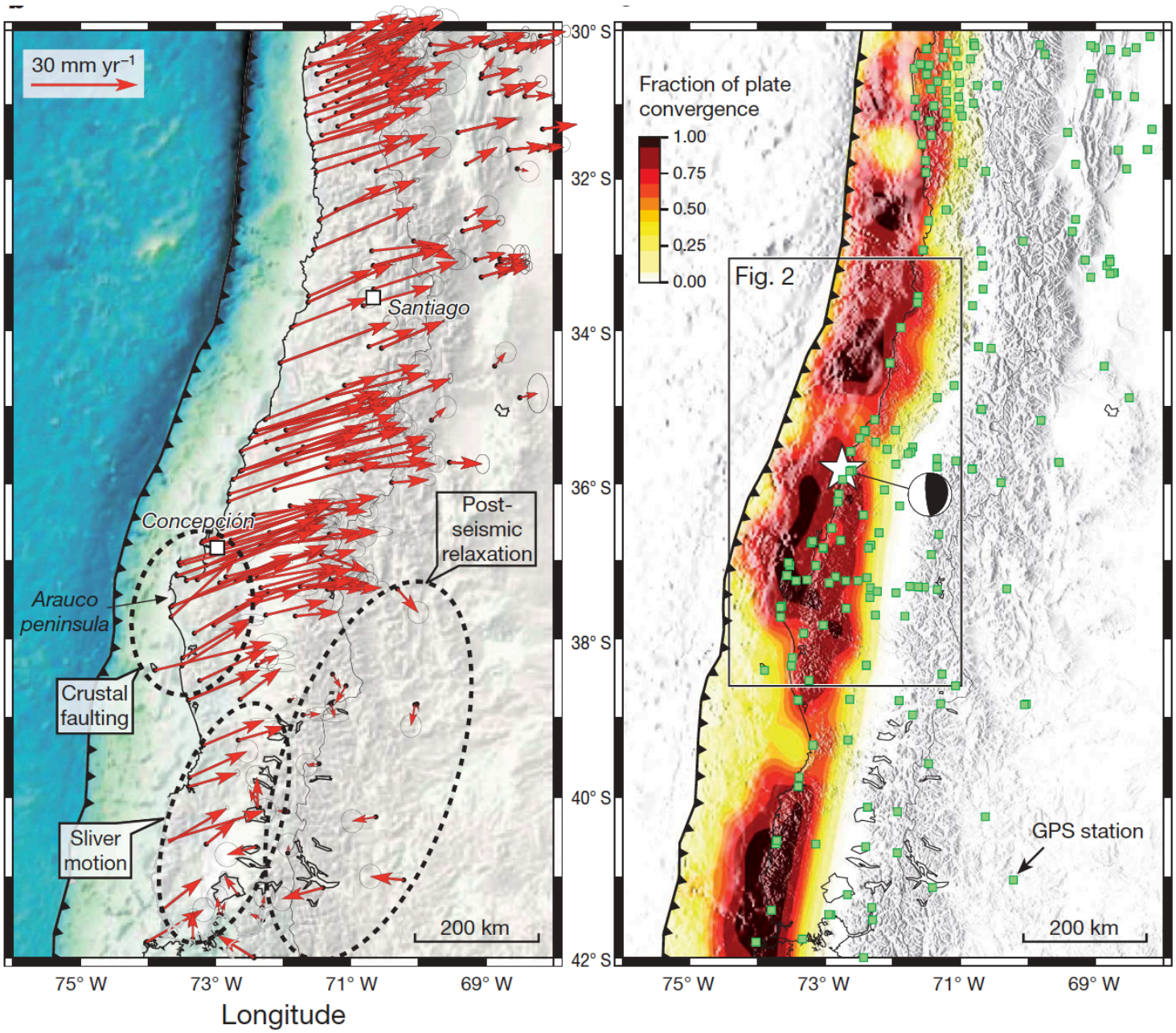


Chileh et al., 2007

Variation in Earthquake rupture- Due to various asperity distributions

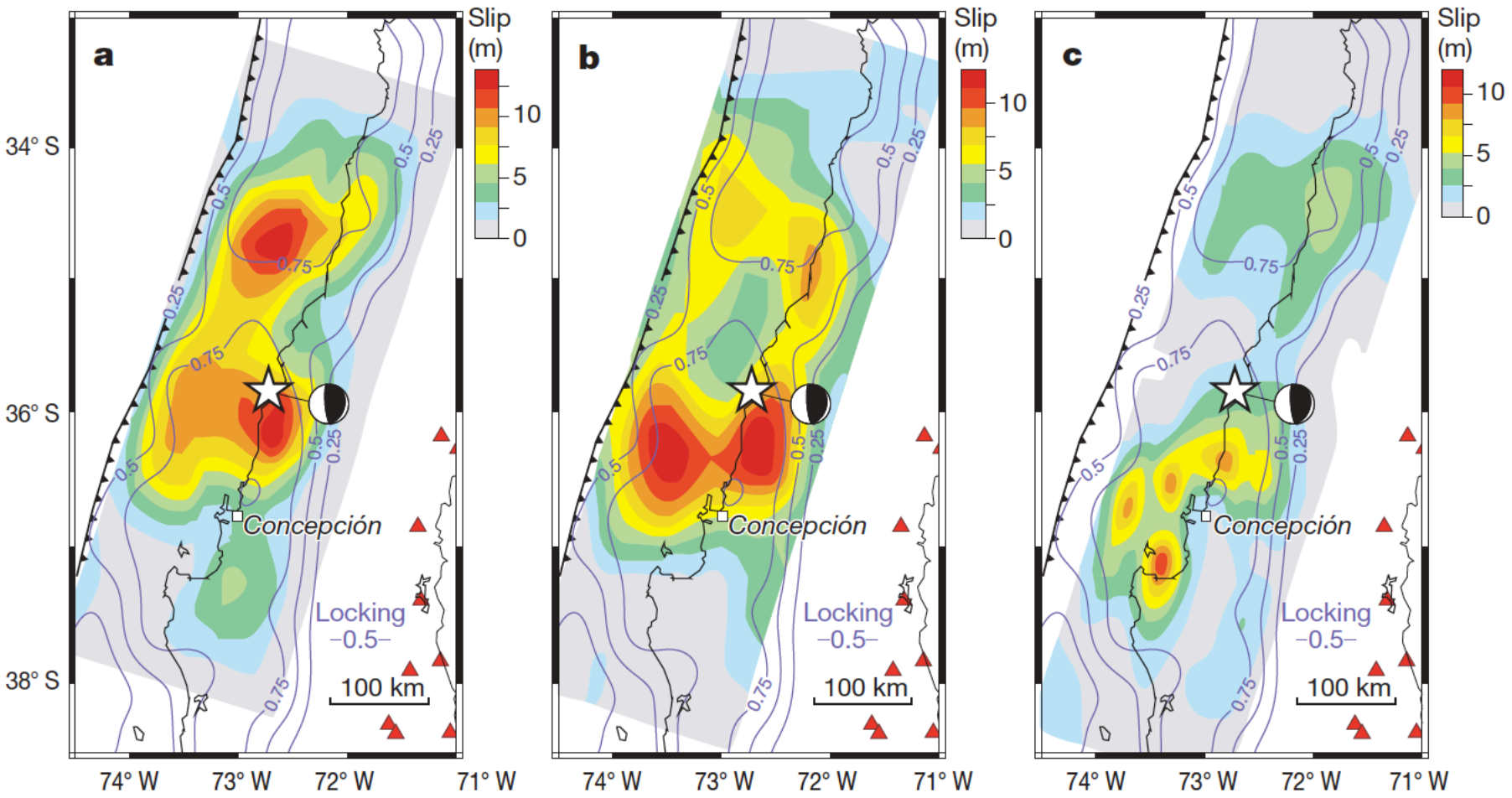


Inversion of GPS Velocity for Locking on the Plate Interface
2010 Maule Earthquake



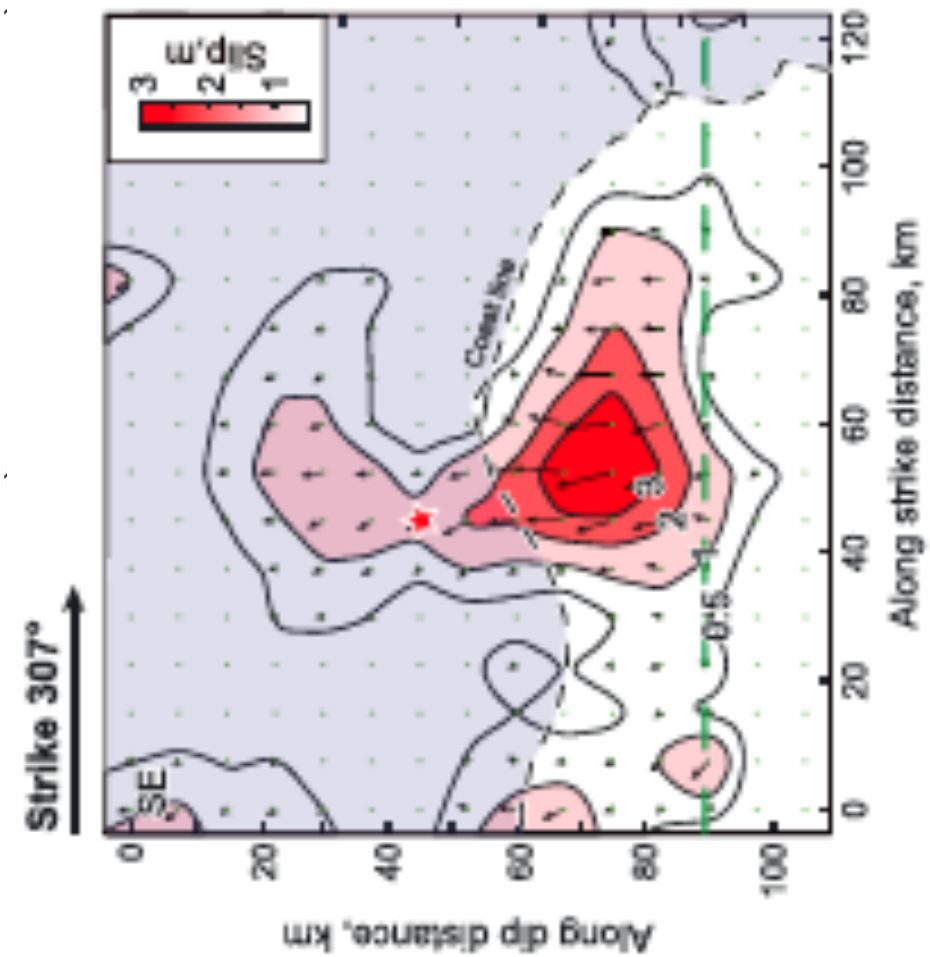
Moreno et al., 2010

Geodetic plate locking Vs. 3 Coseismic Rupture modes- 2010 Maule Earthquake

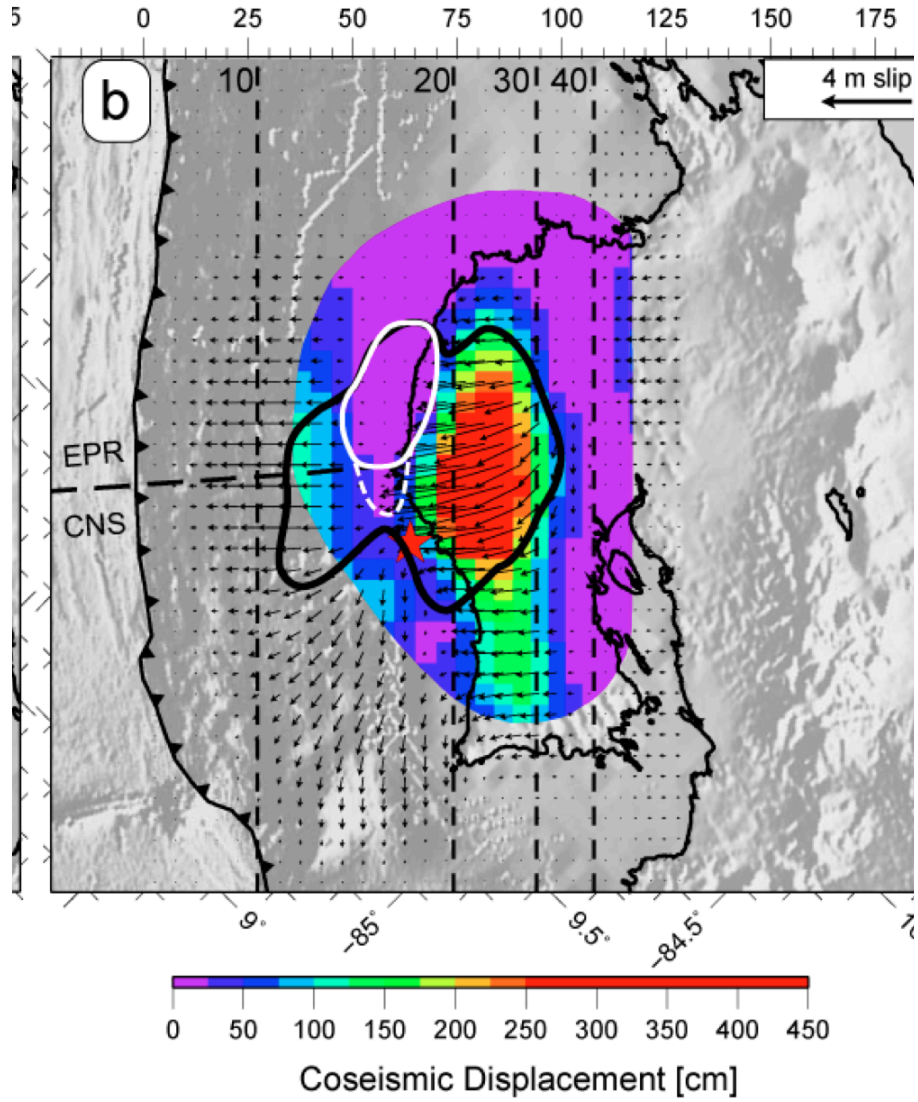


Moreno et al., 2010

Geodetic Locking Vs. Coseismic Slip for 2012 Nicoya Earthquake

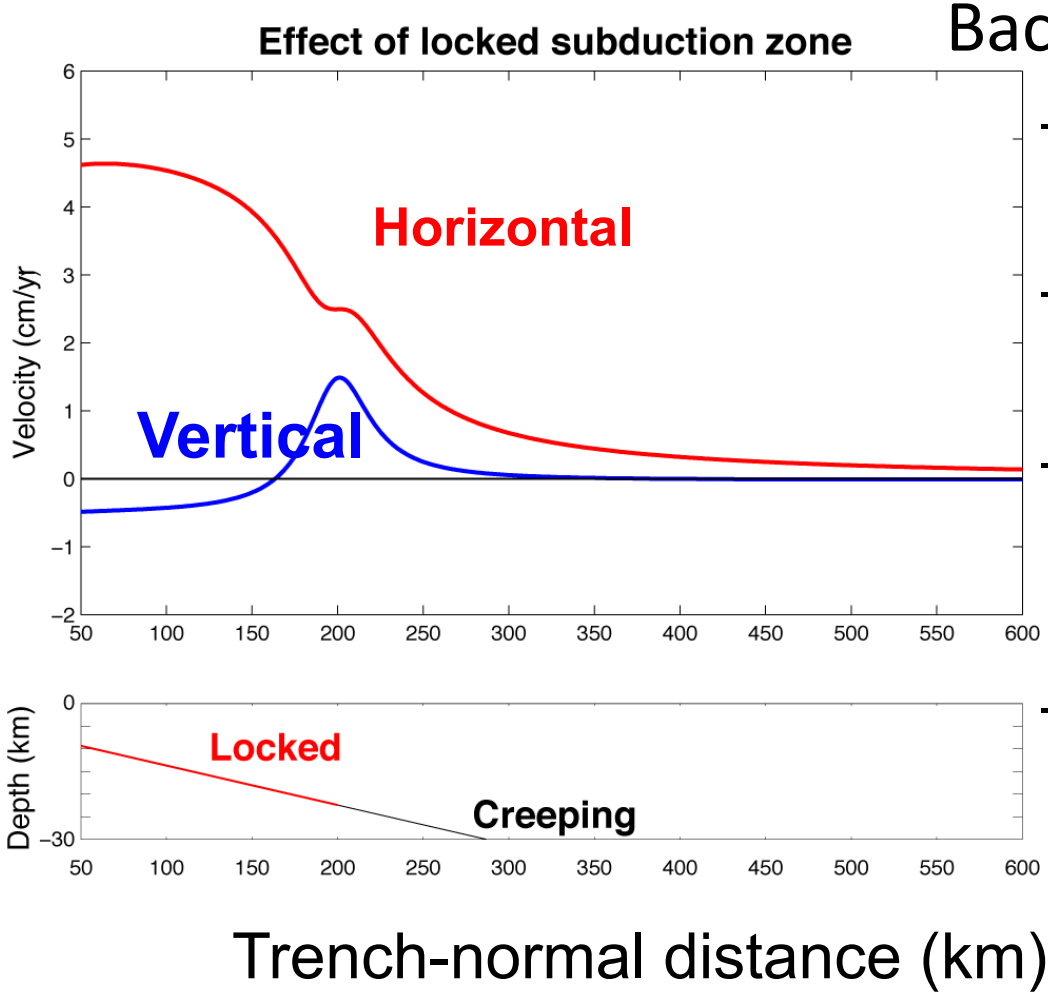


Yue et al. 2014



Protti et al. 2014

Deformation At Subduction Zone



Backslip model (Savage, 1983)

- Shallow part of fault slips only in earthquakes
- Deeper part slips steadily at long-term rate
- Superposition of steady slip on entire interface and backslip (***slip deficit***)
- Earth deforms as elastic or linear viscoelastic body
  - Viscoelasticity of mantle introduces time dependence!

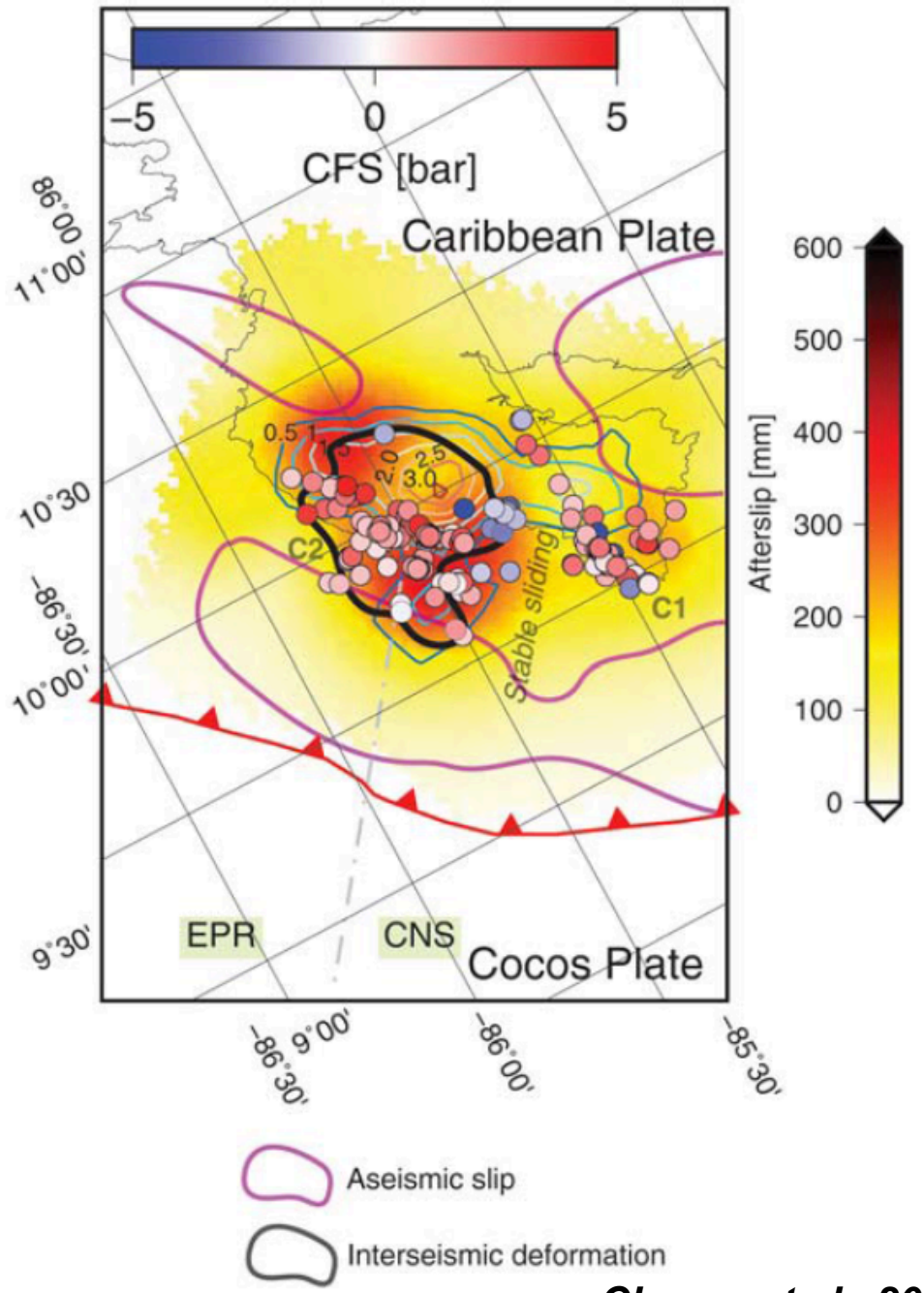
Nicoya, Costa Rica

April 2012

EARTHQUAKE-
September 2012

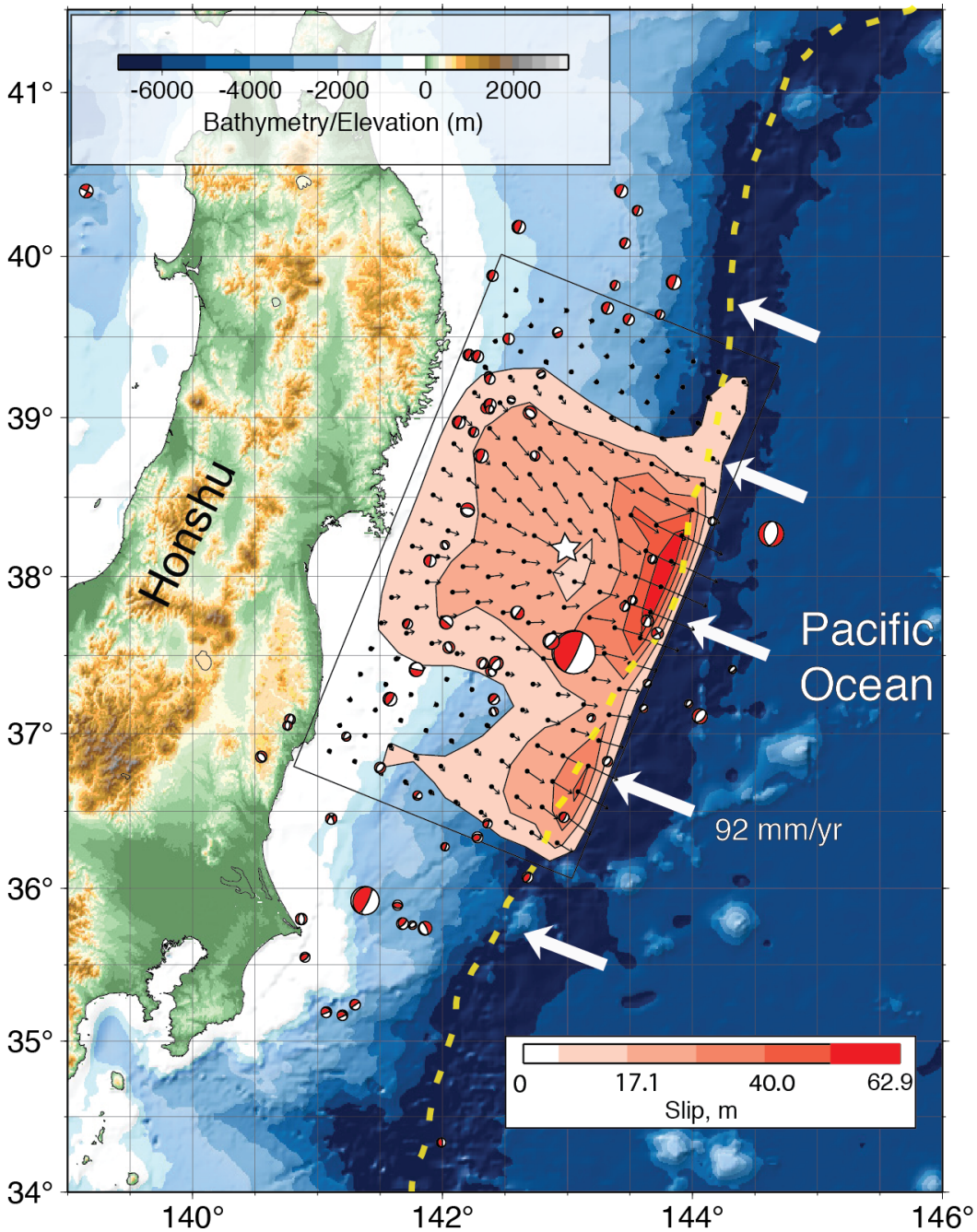
September 2014

Afterslip and plate boundary aftershocks tend to occur outside coseismic slip.



Chaves et al., 2017

Main Asperity Regions- From Coseismic Slip Distribution



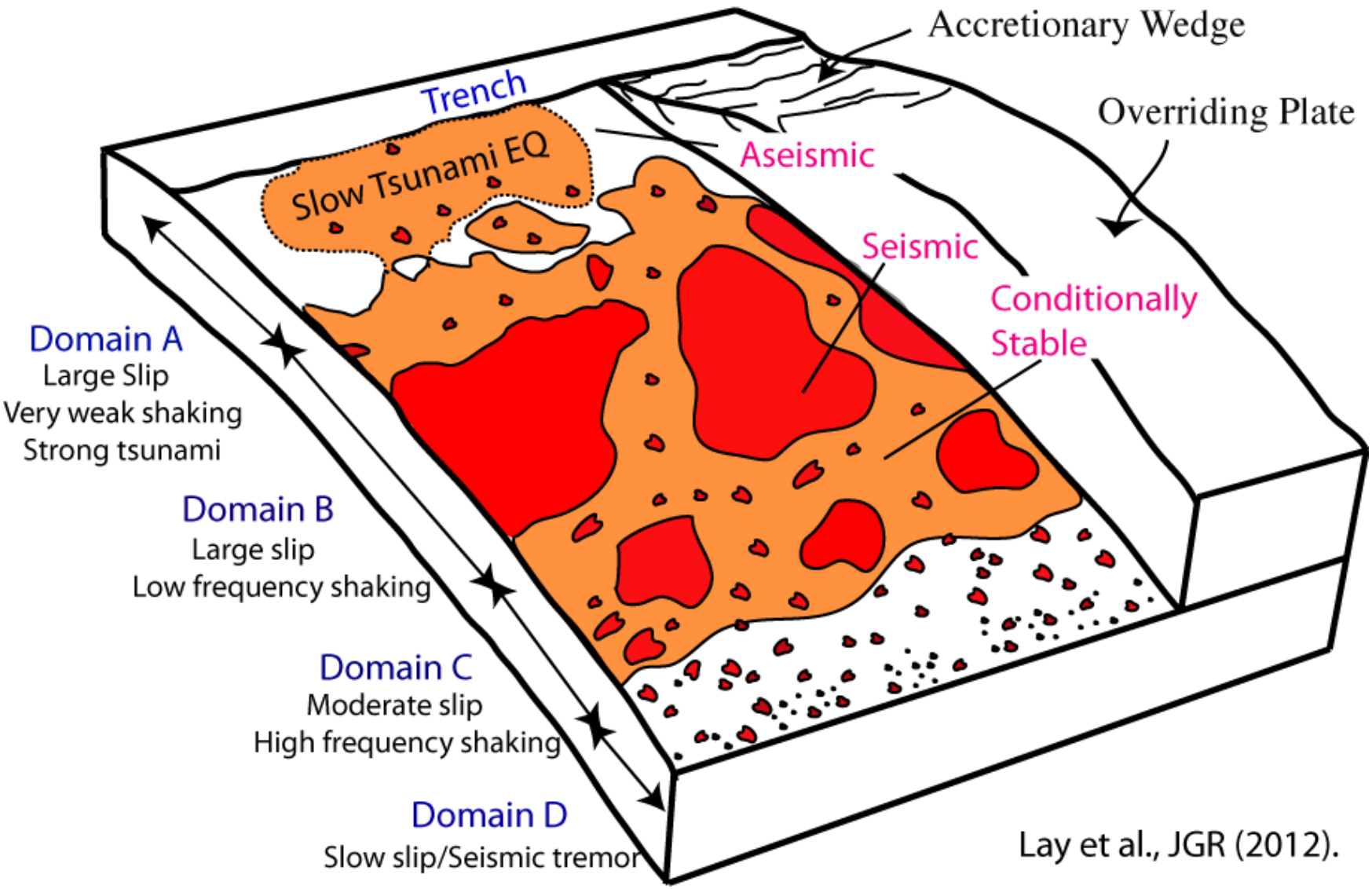
Slip distributions from megathrust earthquakes Also bring surprises.

Lay et al., 2011

Future Directions- Asperities

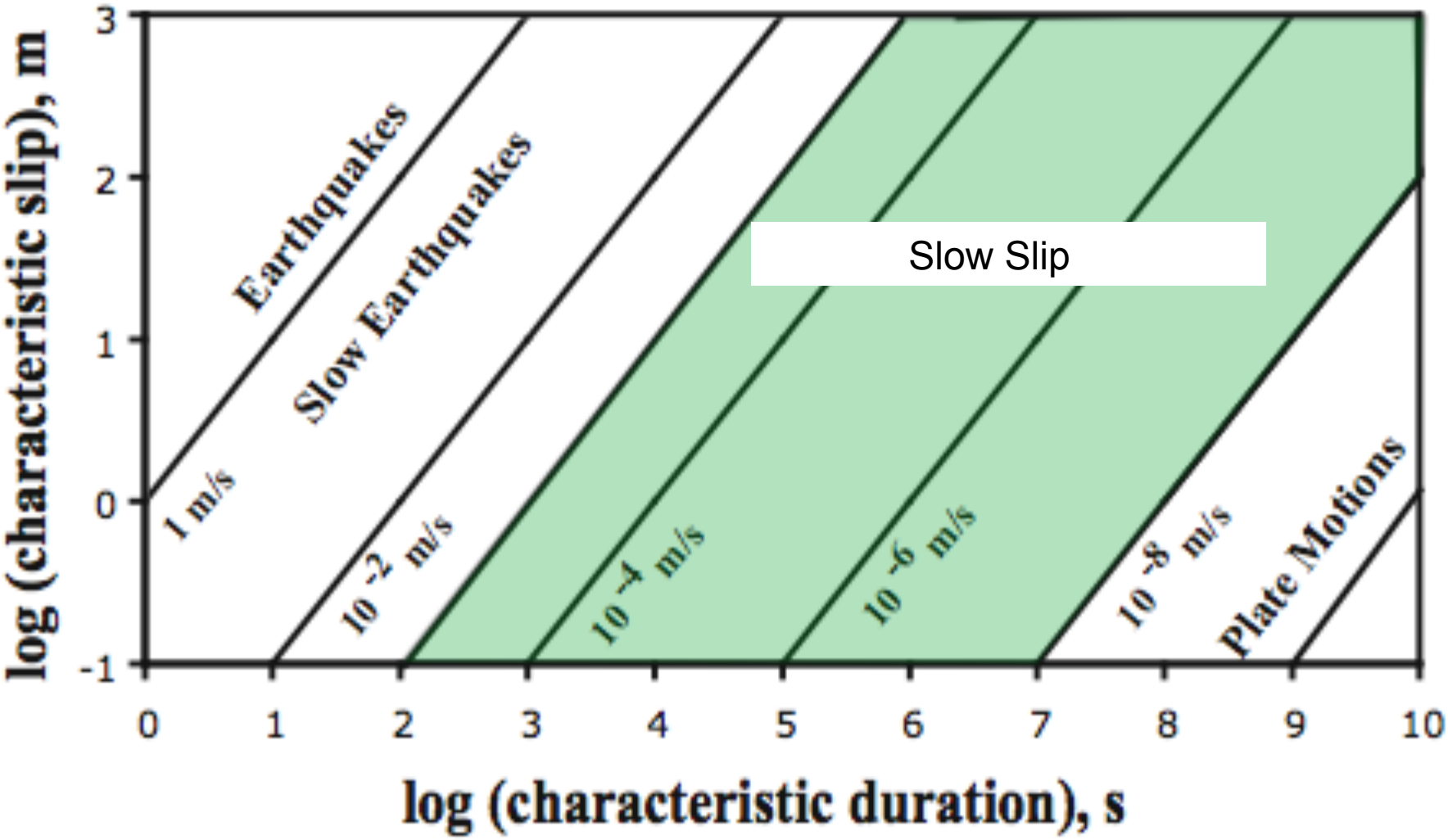
- Continued improvement of coseismic slip inversions integrating all available data sets- seismic, geodetic, tsunami earthquakes.
- What do slip patches (asperities) represent? Are they controlled by upper or lower plate, both, or neither?
- Do asperities persist through many earthquake cycles?

Down-dip Transition and Slow Slip

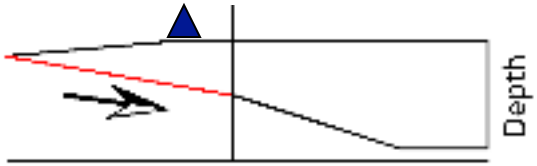


Lay et al., JGR (2012).

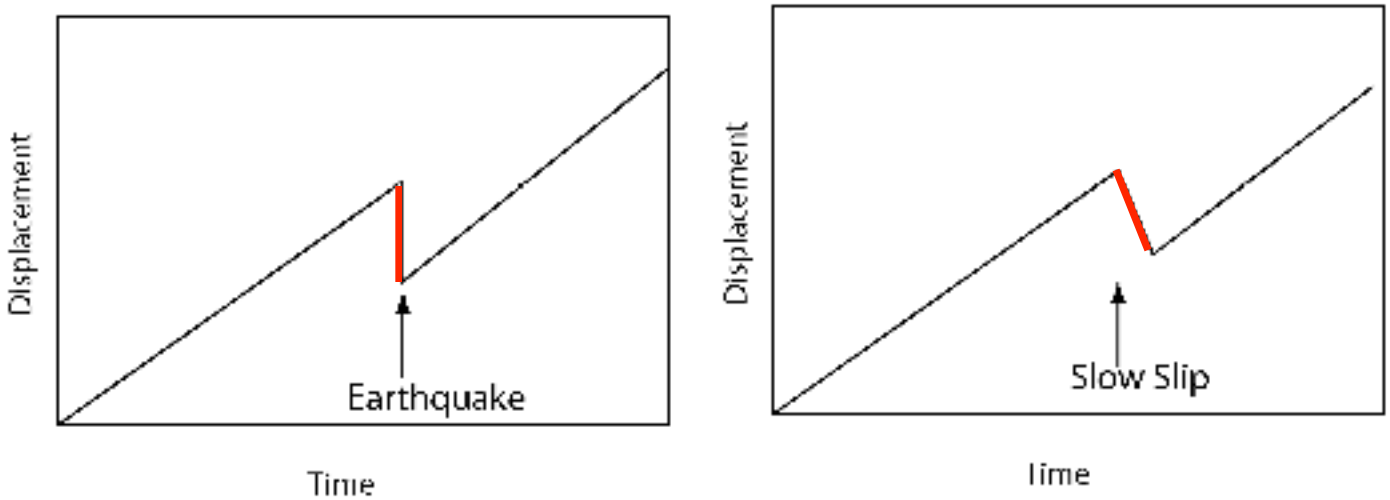
What is Slow Slip?



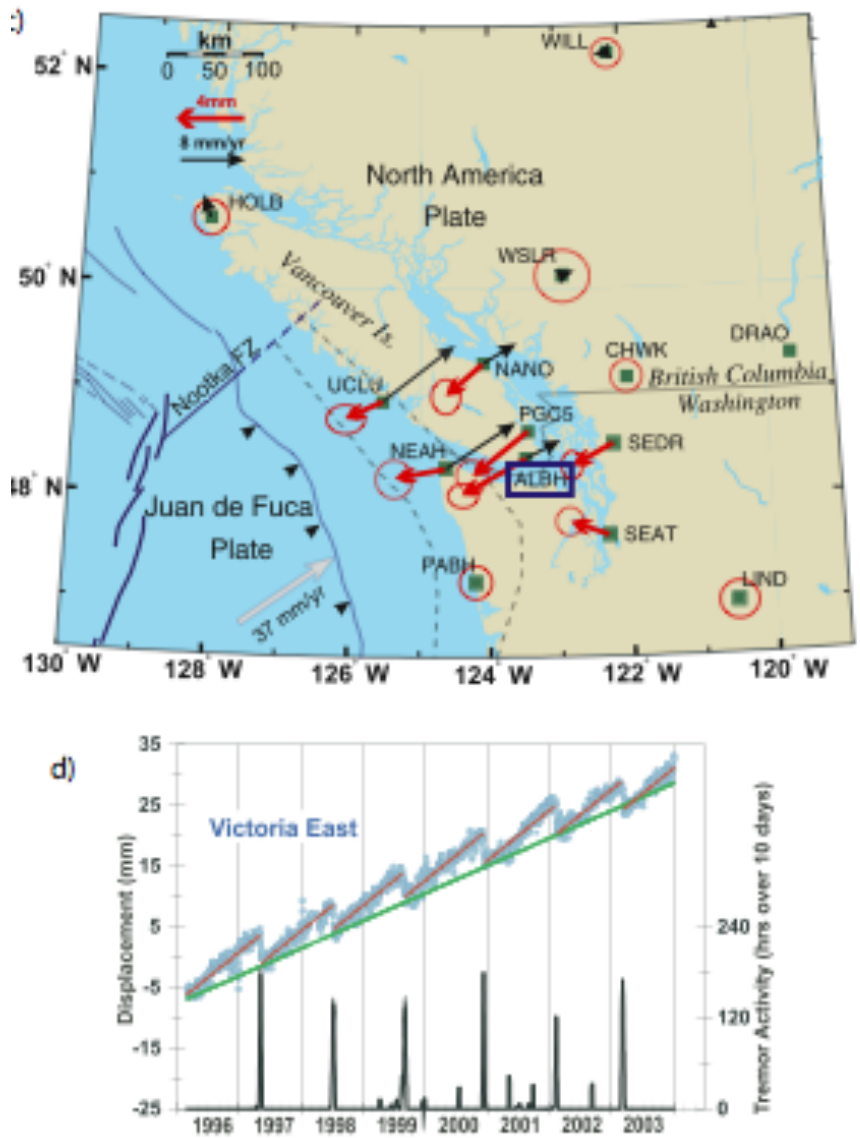
How do we Detect Slow Slip?



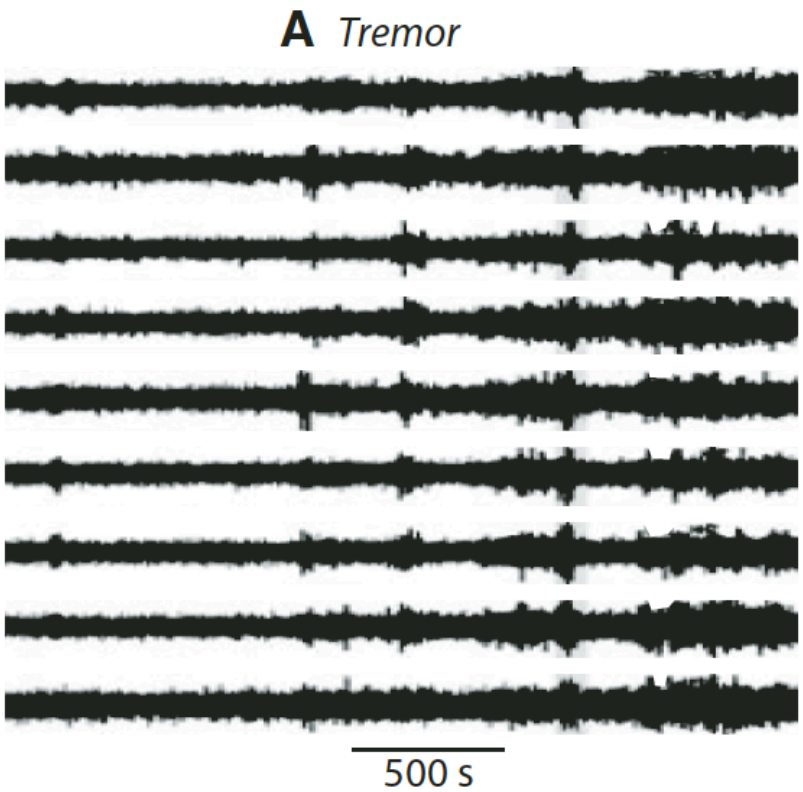
Trench Normal Distance

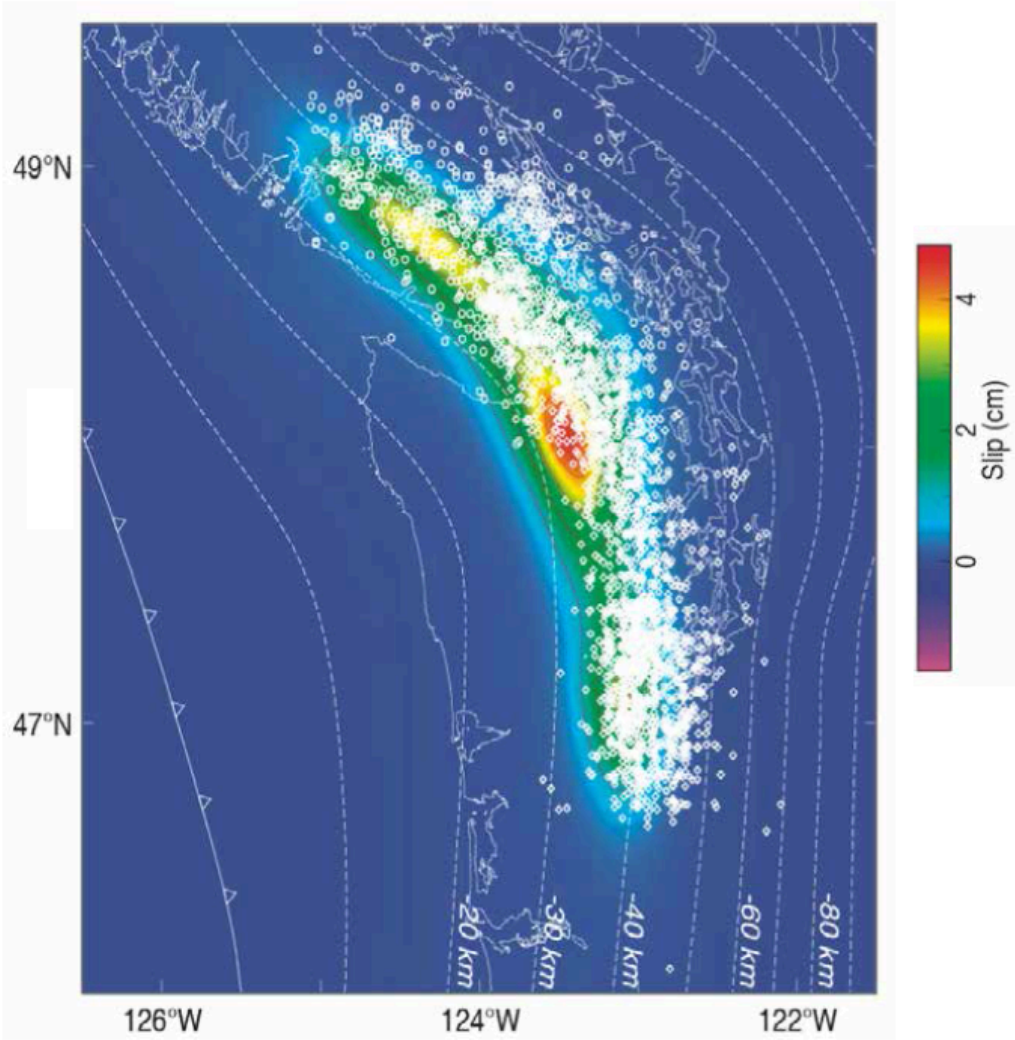


Cascadia Slow Slip Earthquakes- or Episodic Tremor and Slip (EPS)

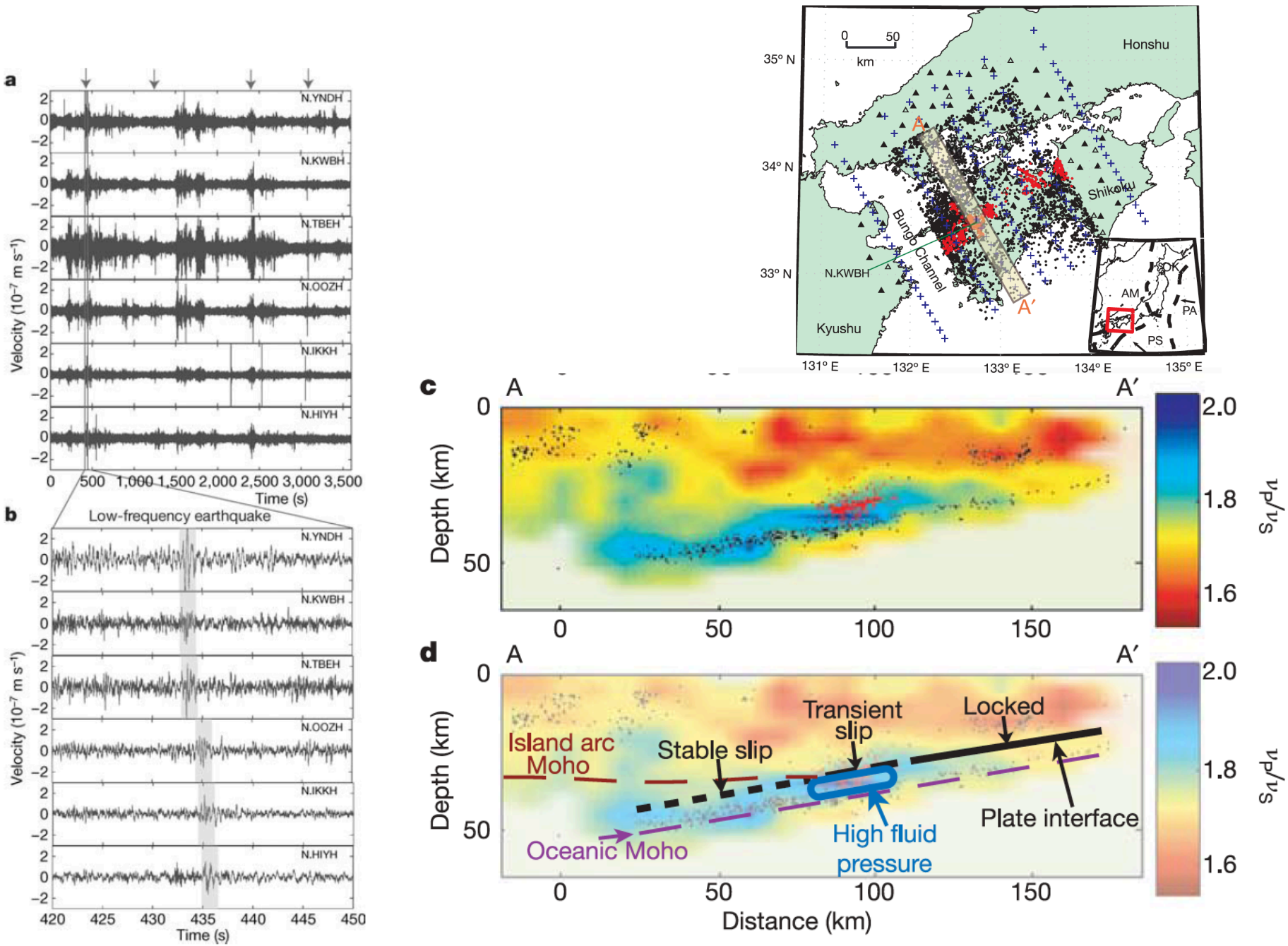


Modified from Dragert and Rogers [2004]

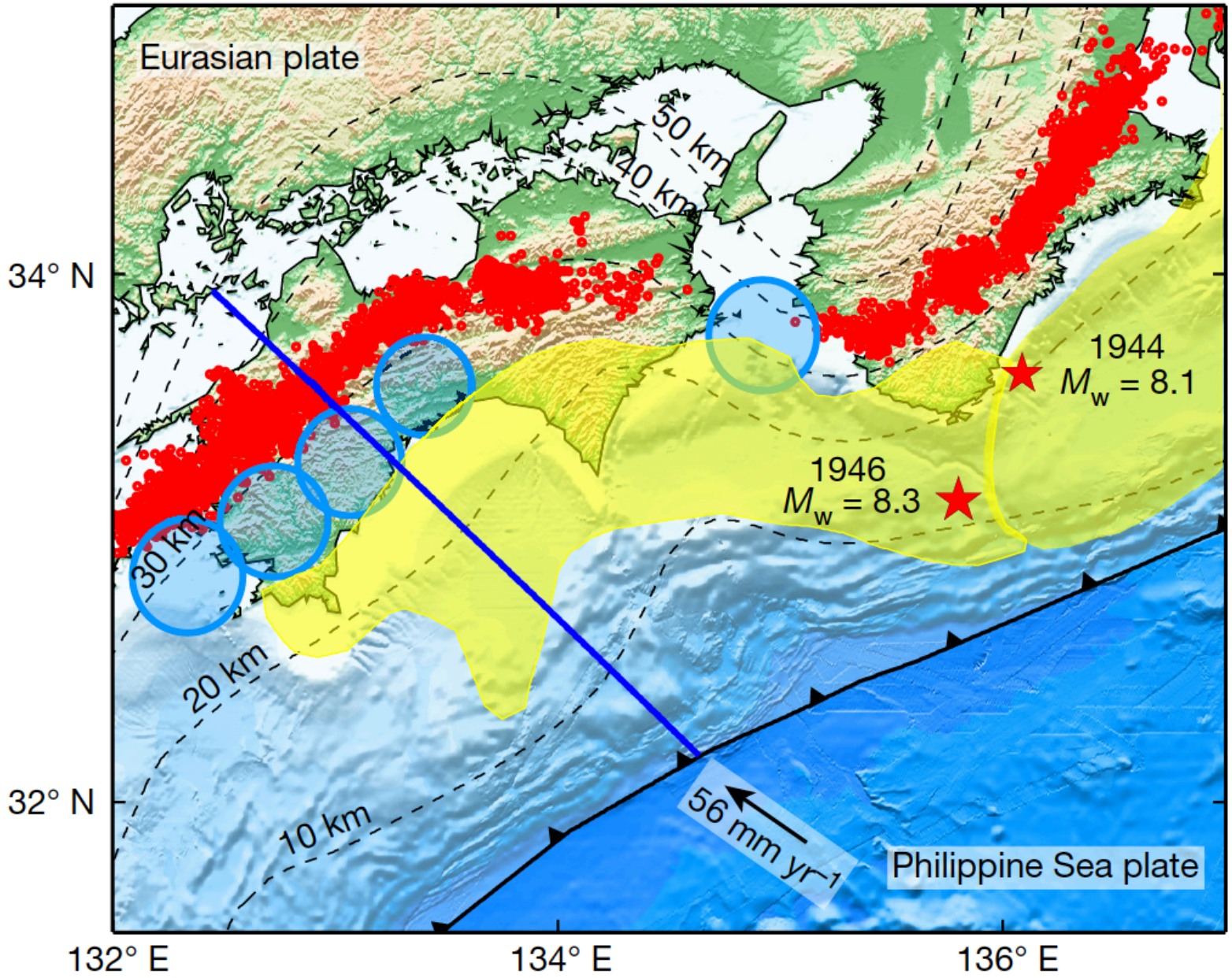




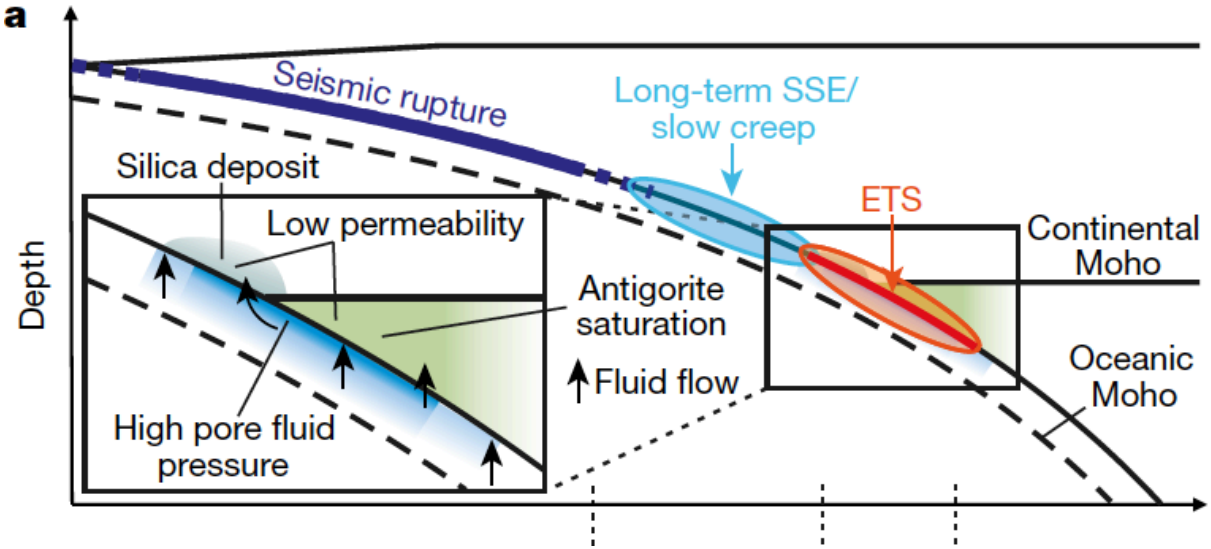
Gomberg et al., 2013

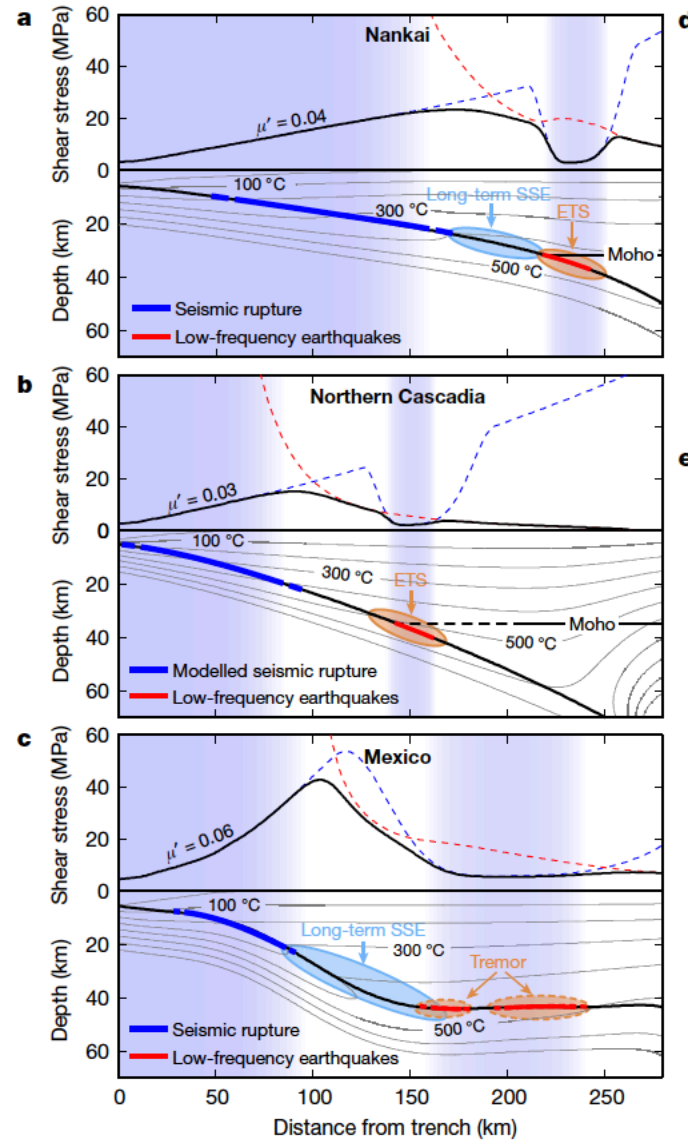


Shelly et al., 2006


Eurasian plate
50 km
40 km
30 km
20 km
10 km
1944
M_w = 8.1
1946
M_w = 8.3
56 mm yr^{-1}
Philippine Sea plate
34° N
32° N
132° E
134° E
136° E

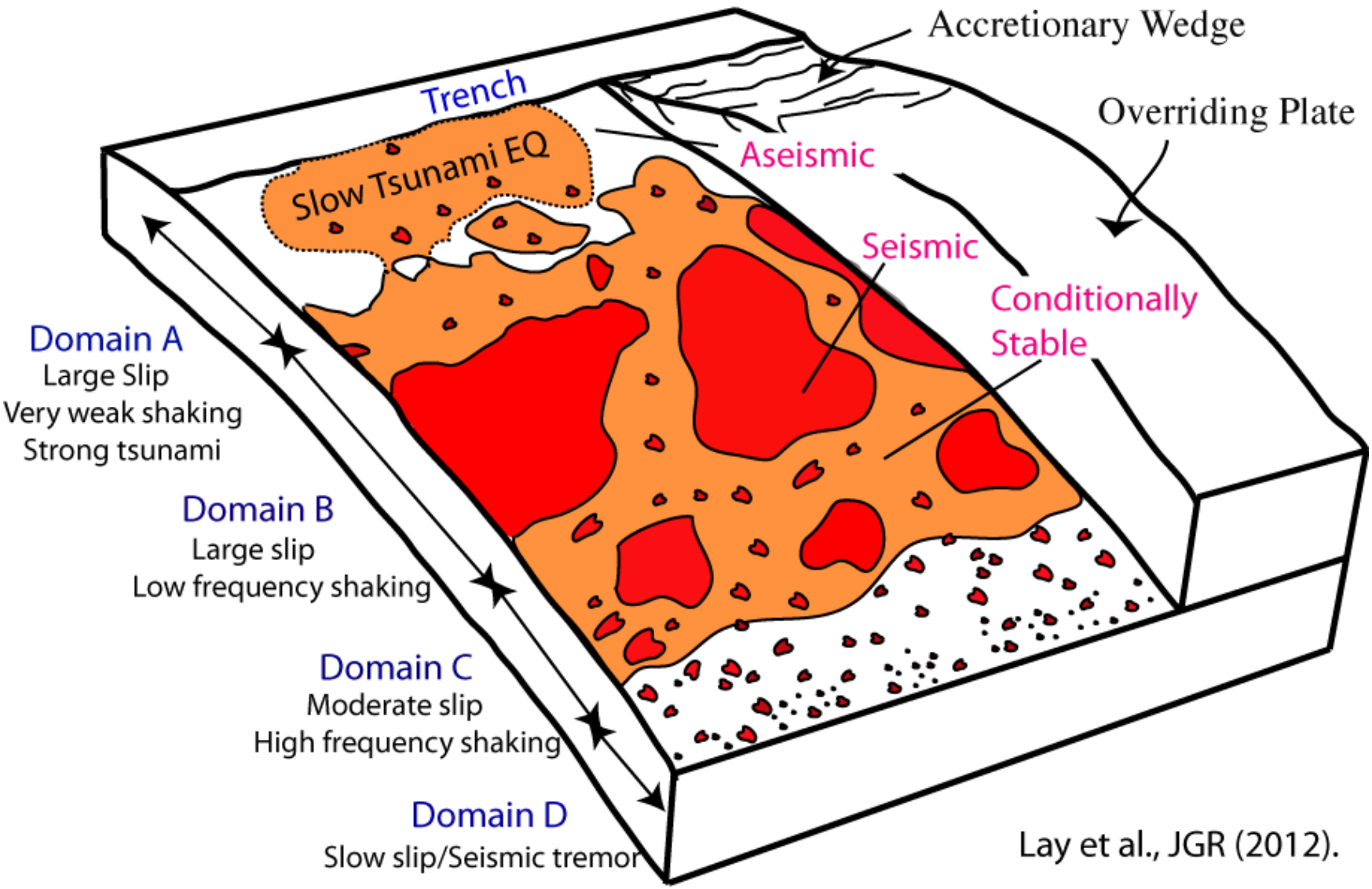
Obara, 2011





Gao & Wang, 2017

Up-dip Transition and Slow Slip

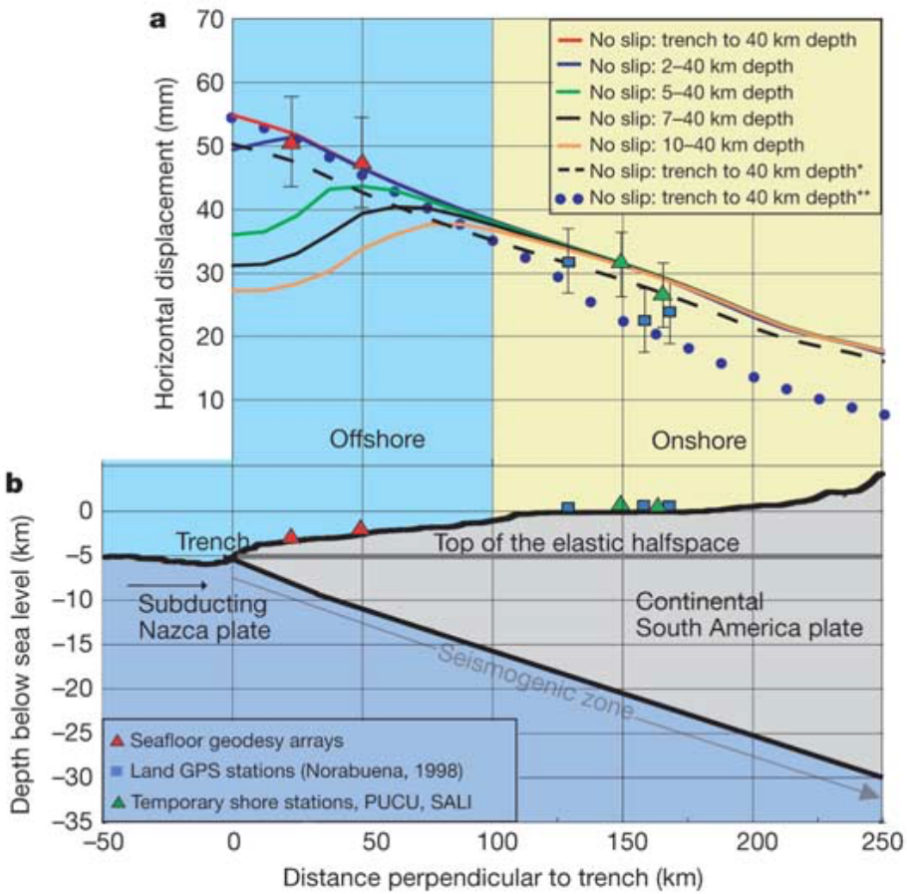


Lay et al., JGR (2012).

Is the Shallow Megathrust Locked?

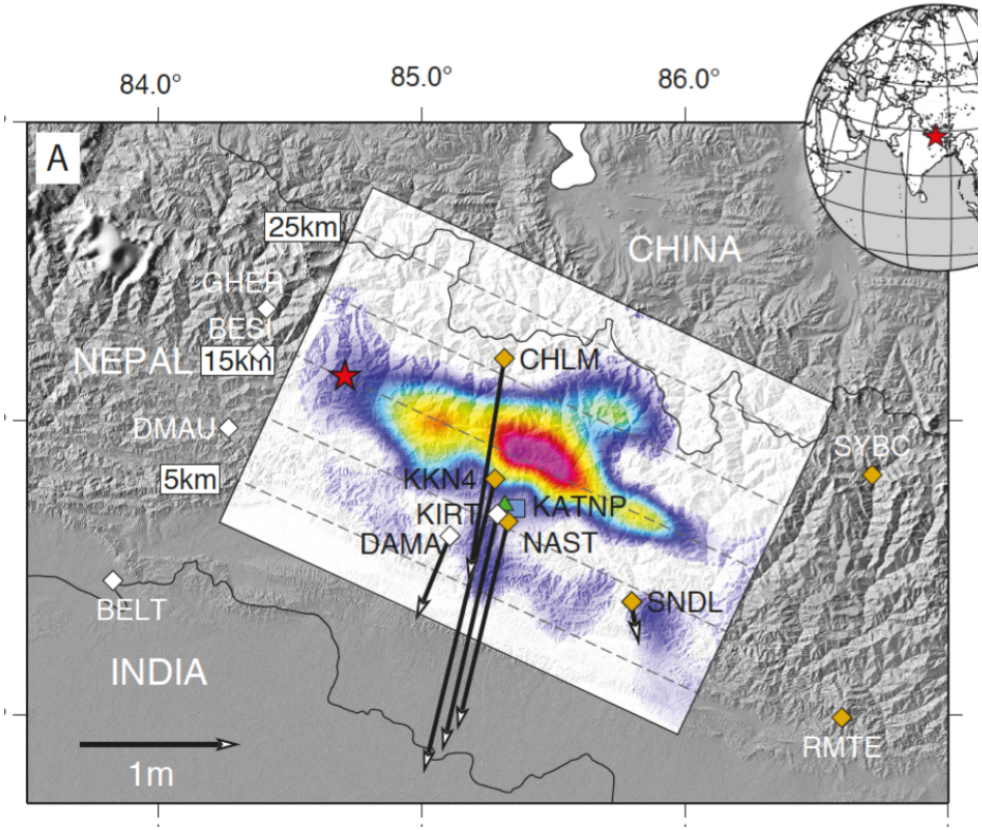
Peru Trench

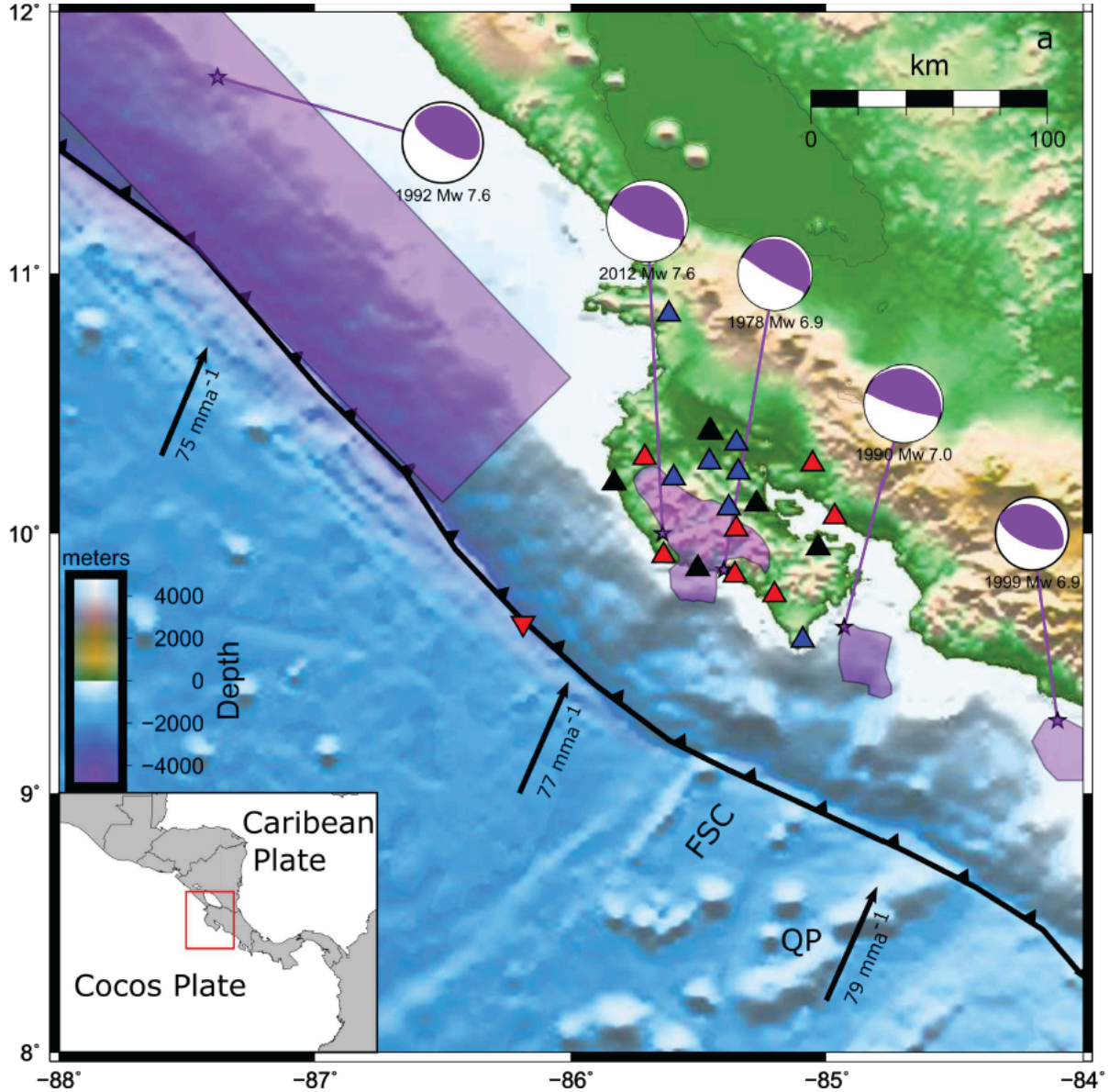
Gagnon et al. (2005)

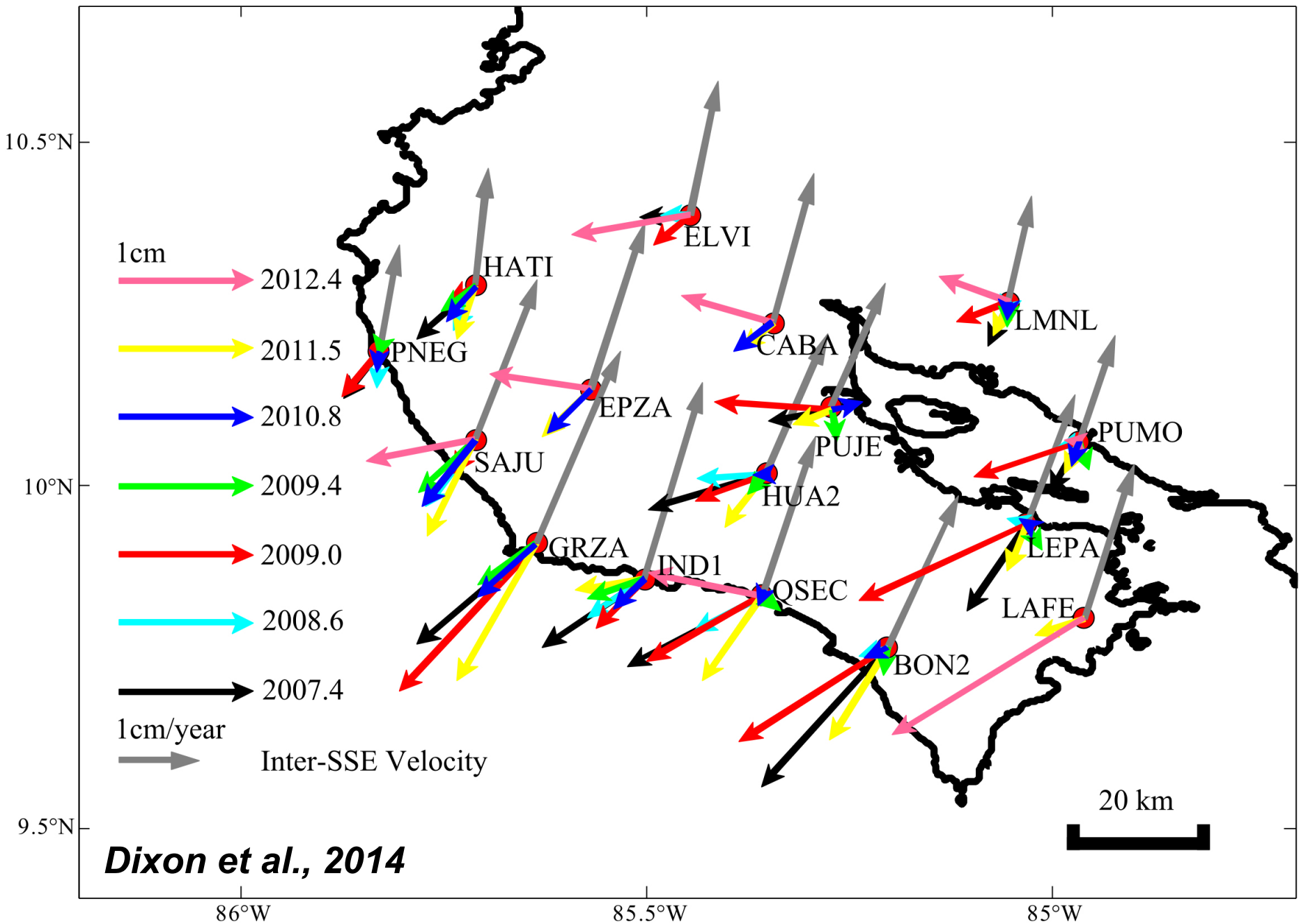


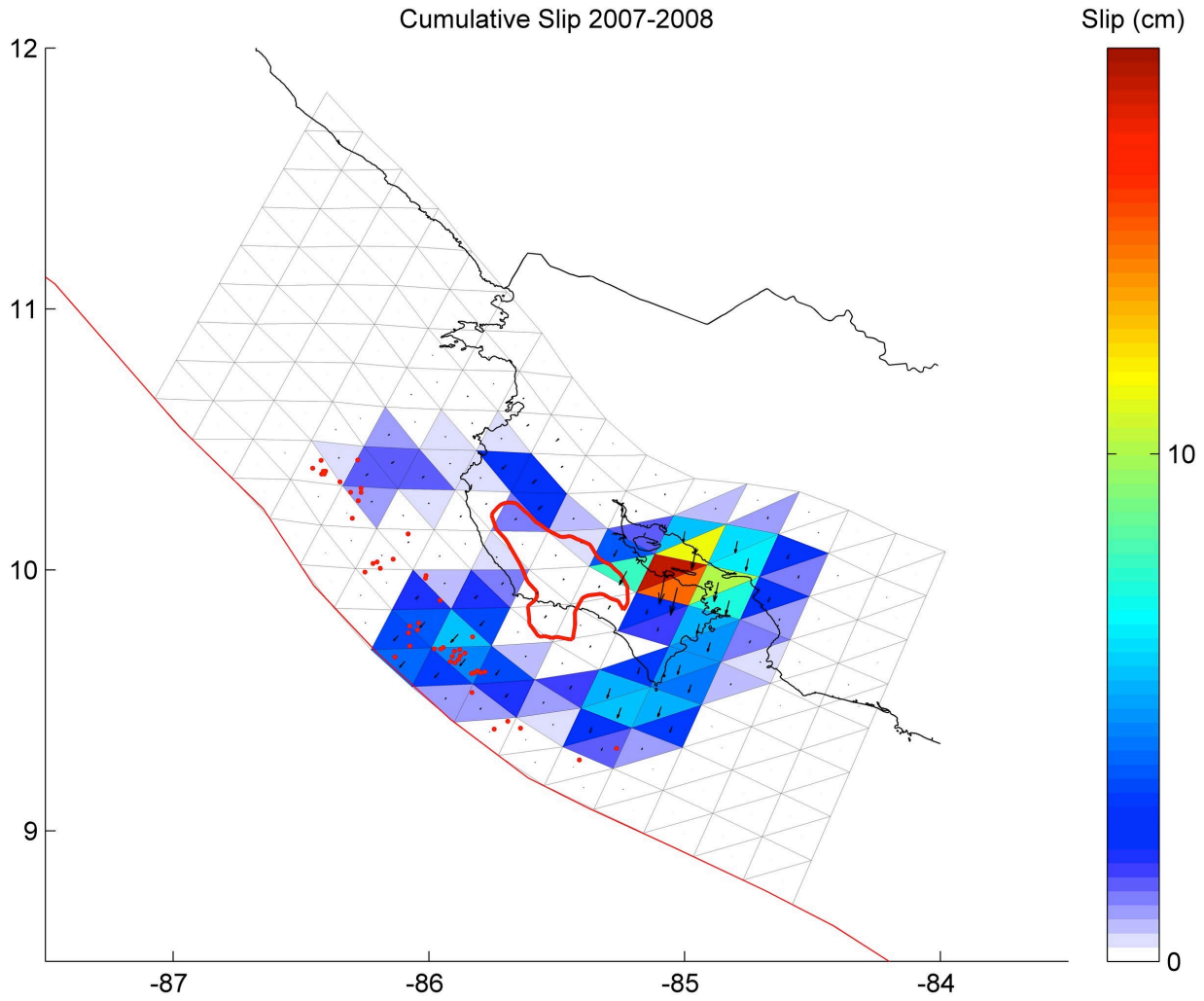
Continental Megathrust (Nepal)

Galetzka et al. (2015)




a
km
0
100
1992 Mw 7.6
2012 Mw 7.6
1978 Mw 6.9
1990 Mw 7.0
1999 Mw 6.9
75 mma-1
77 mma-1
79 mma-1
FSC
QP
meters
4000
2000
0
−2000
−4000
Depth
Caribean
Plate
Cocos Plate
12˚
11˚
10˚
9˚
8˚
−88˚
−87˚
−86˚
−85˚
−84˚

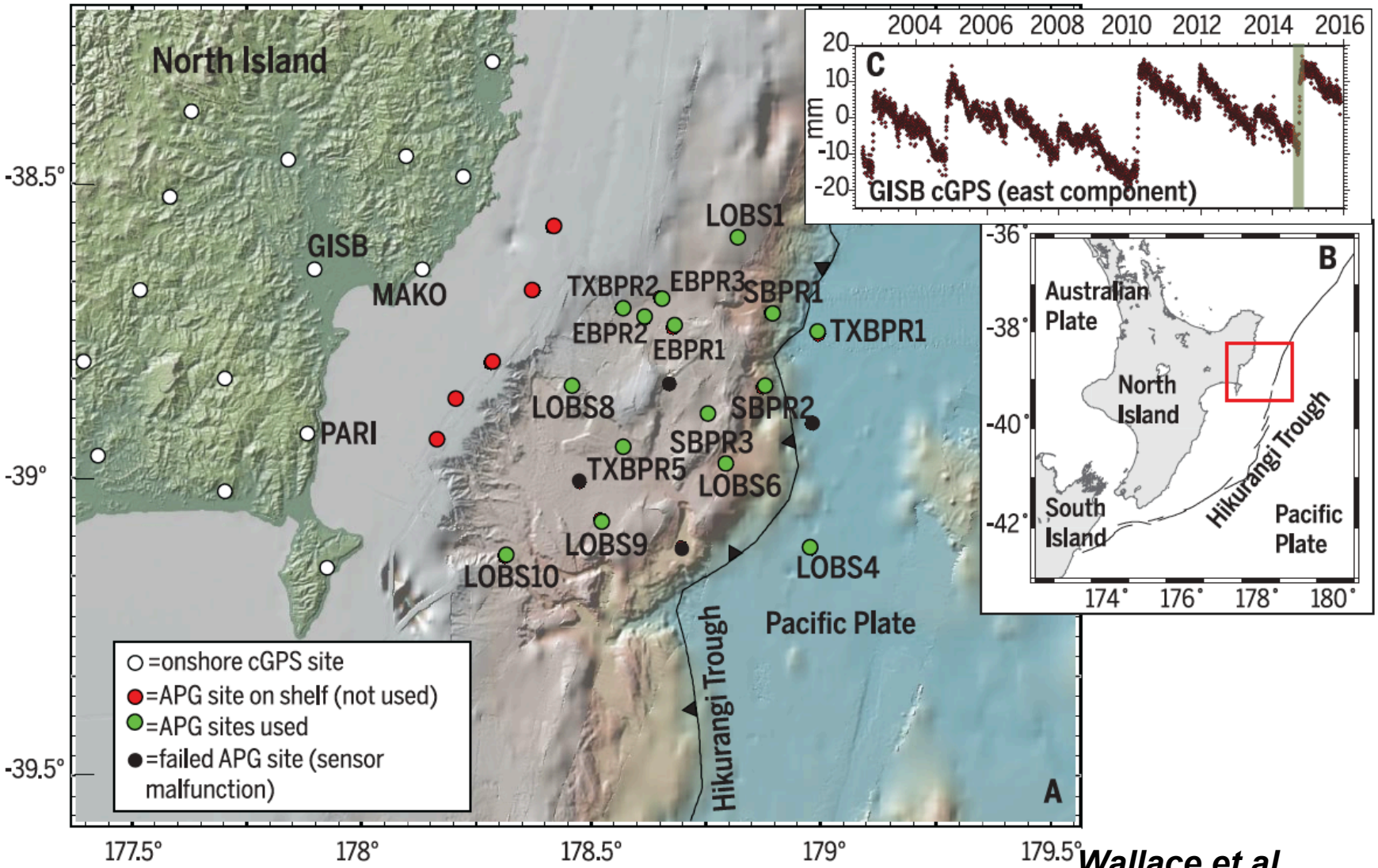

10.5°N
10°N
9.5°N
86°W
85.5°W
85°W
1cm
2012.4
2011.5
2010.8
2009.4
2009.0
2008.6
2007.4
1cm/year
Inter-SSE Velocity
ELVI
HATI
PNEG
CABA
LMNL
EPZA
PUJE
PUMO
SAJU
HUA2
GRZA
IND1
QSEC
LEPA
LAFE
BON2
20 km
Dixon et al., 2014



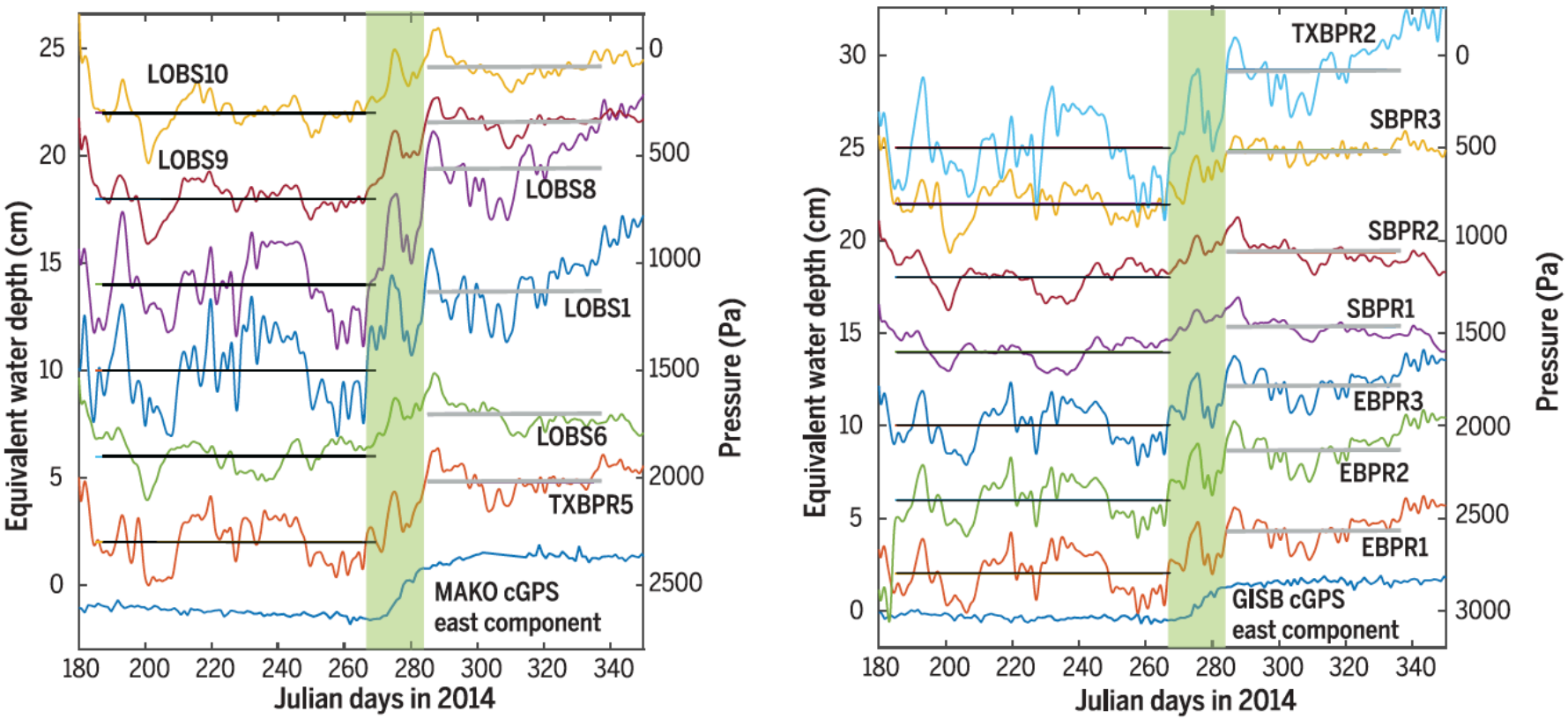
Jiang et al., 2017

Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip

HOBITSS

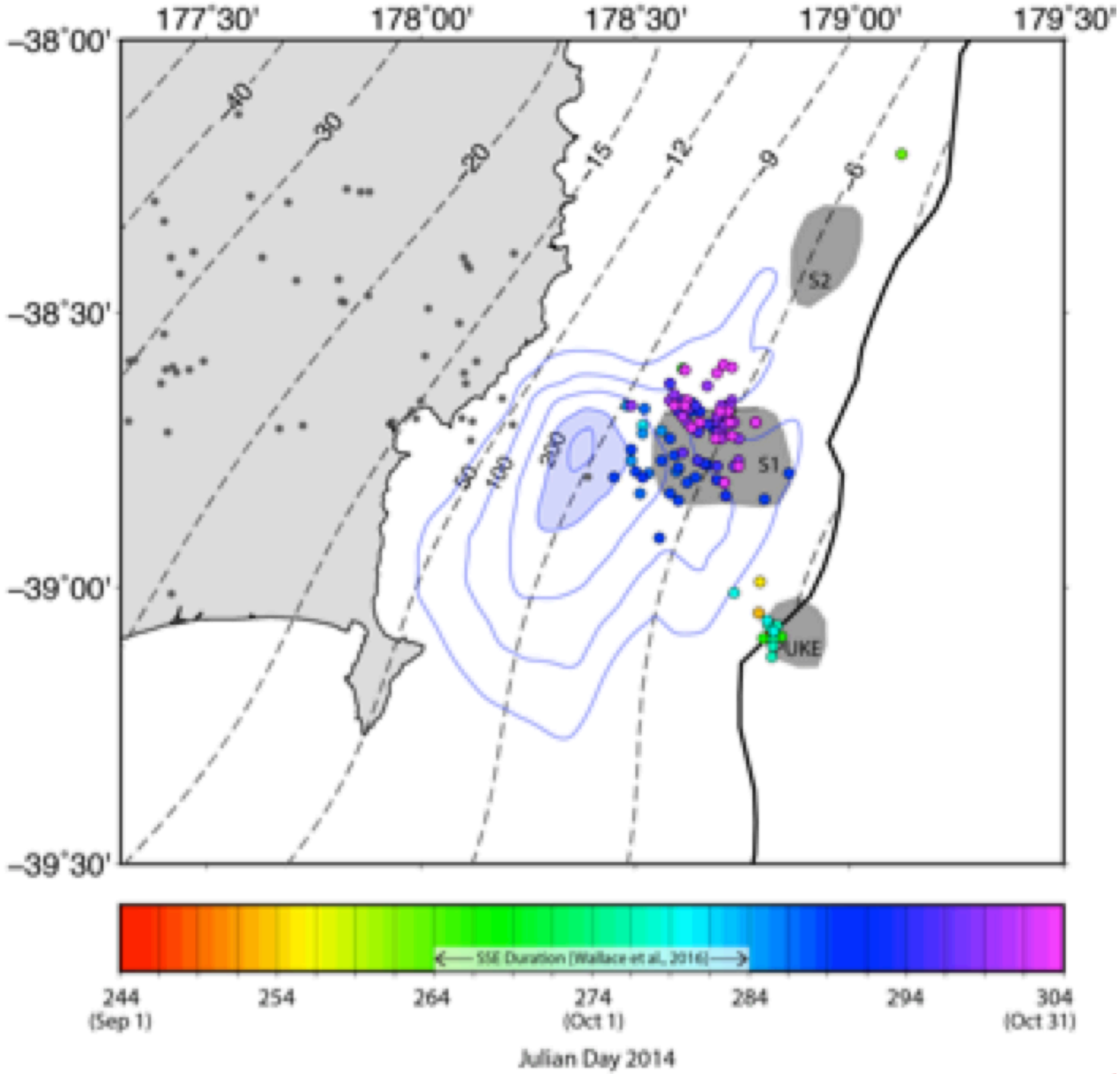


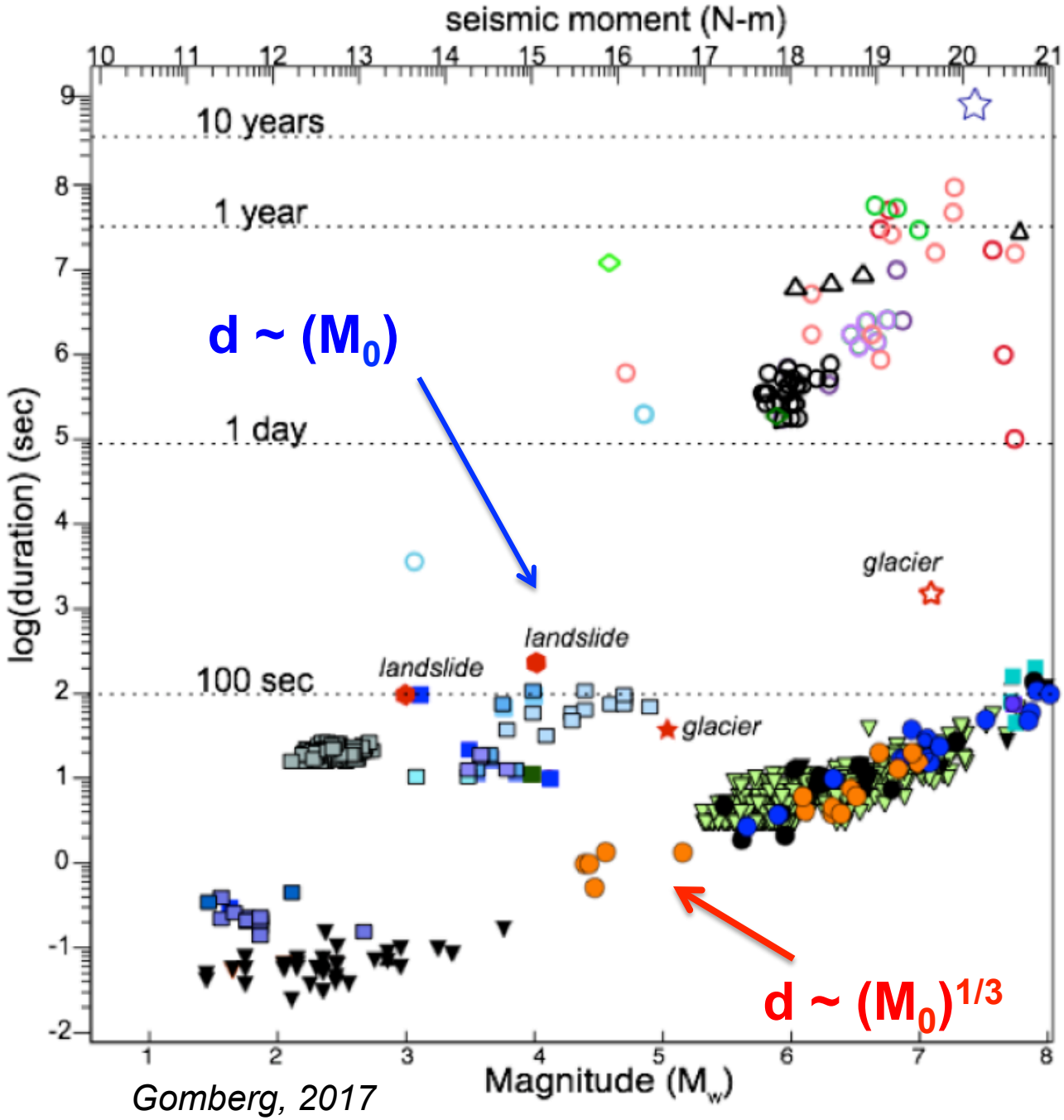
Wallace et al., 2016



Seafloor moves up ~2-5 cm

Wallace et al., 2016


177°30'
178°00'
178°30'
179°00'
179°30'
−38°00'
−38°30'
−39°00'
−39°30'
40
30
20
15
12
9
6
50
100
200
S2
S1
PUKE
SSE Duration (Wallace et al., 2016)
244
(Sep 1)
254
264
274
(Oct 1)
284
294
304
(Oct 31)
Julian Day 2014



Gomberg, 2017

$M_0 = \mu A x$

$M_0 \sim L^3$

$L = V_r d$

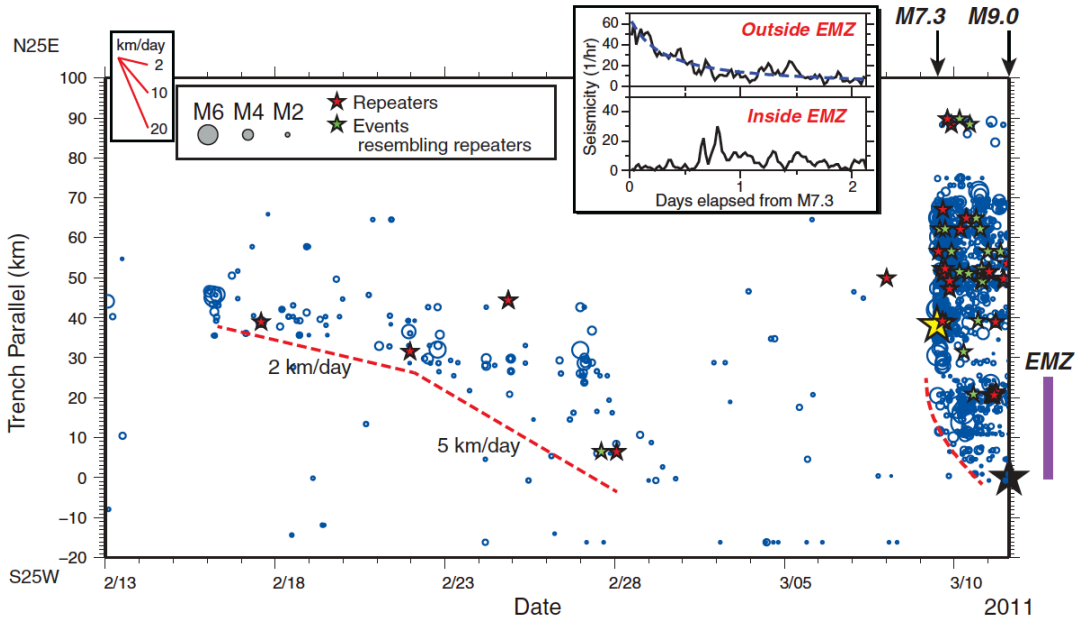
V_r is quasi-constant controlled by seismic velocity

$L \sim d$

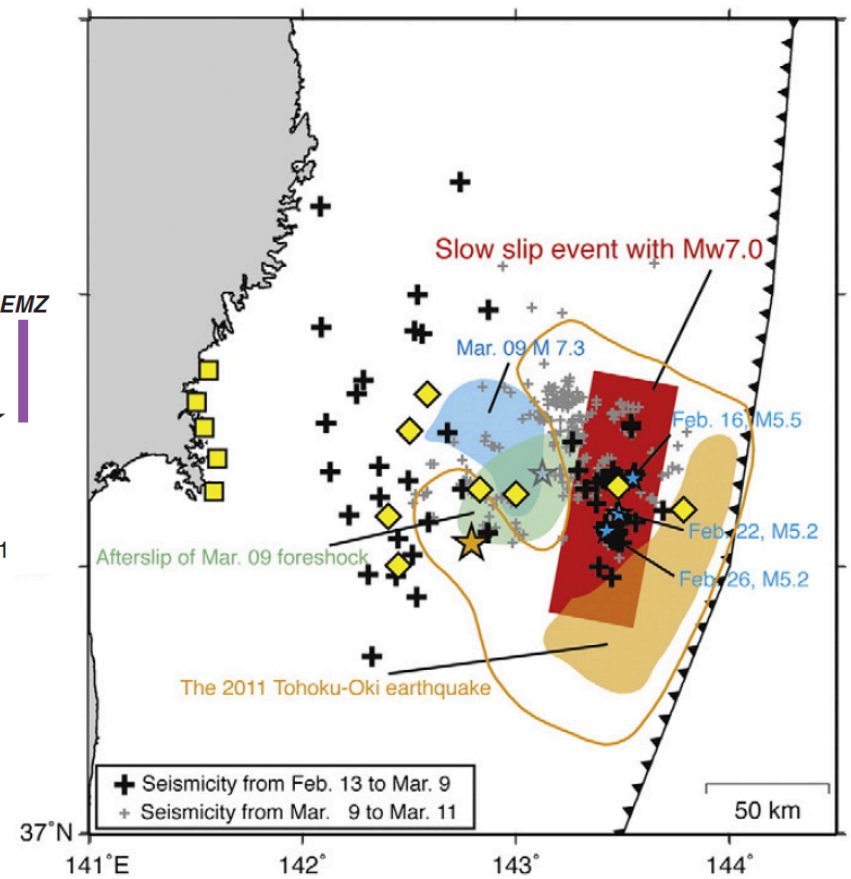
$M_0 \sim d^3$

$d \sim (M_0)^{1/3}$

Does Slow Slip Precede Megathrust Earthquakes?
2011 Tohoku Earthquake

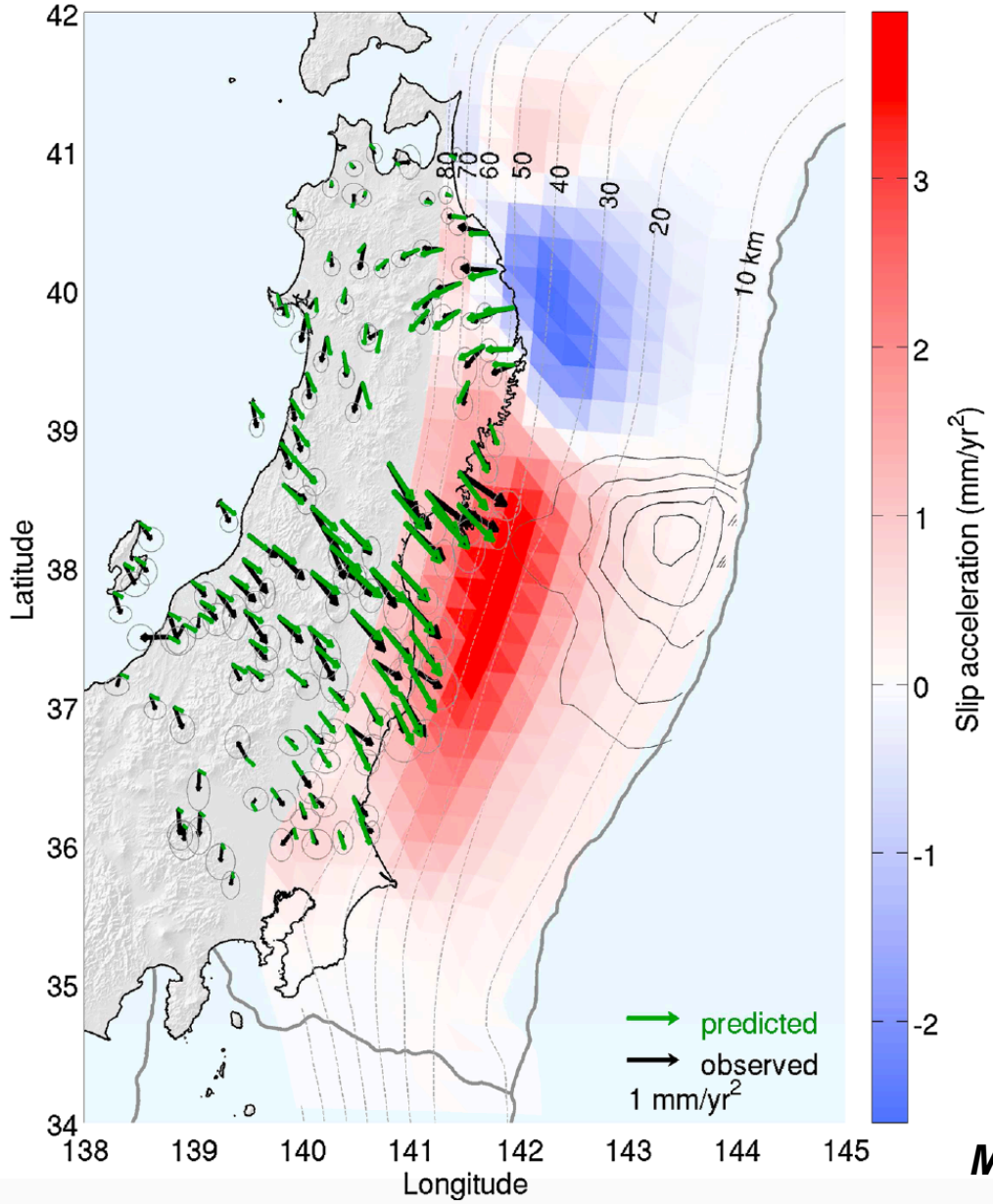


Kato et al, 2012



Ito et al., 2013

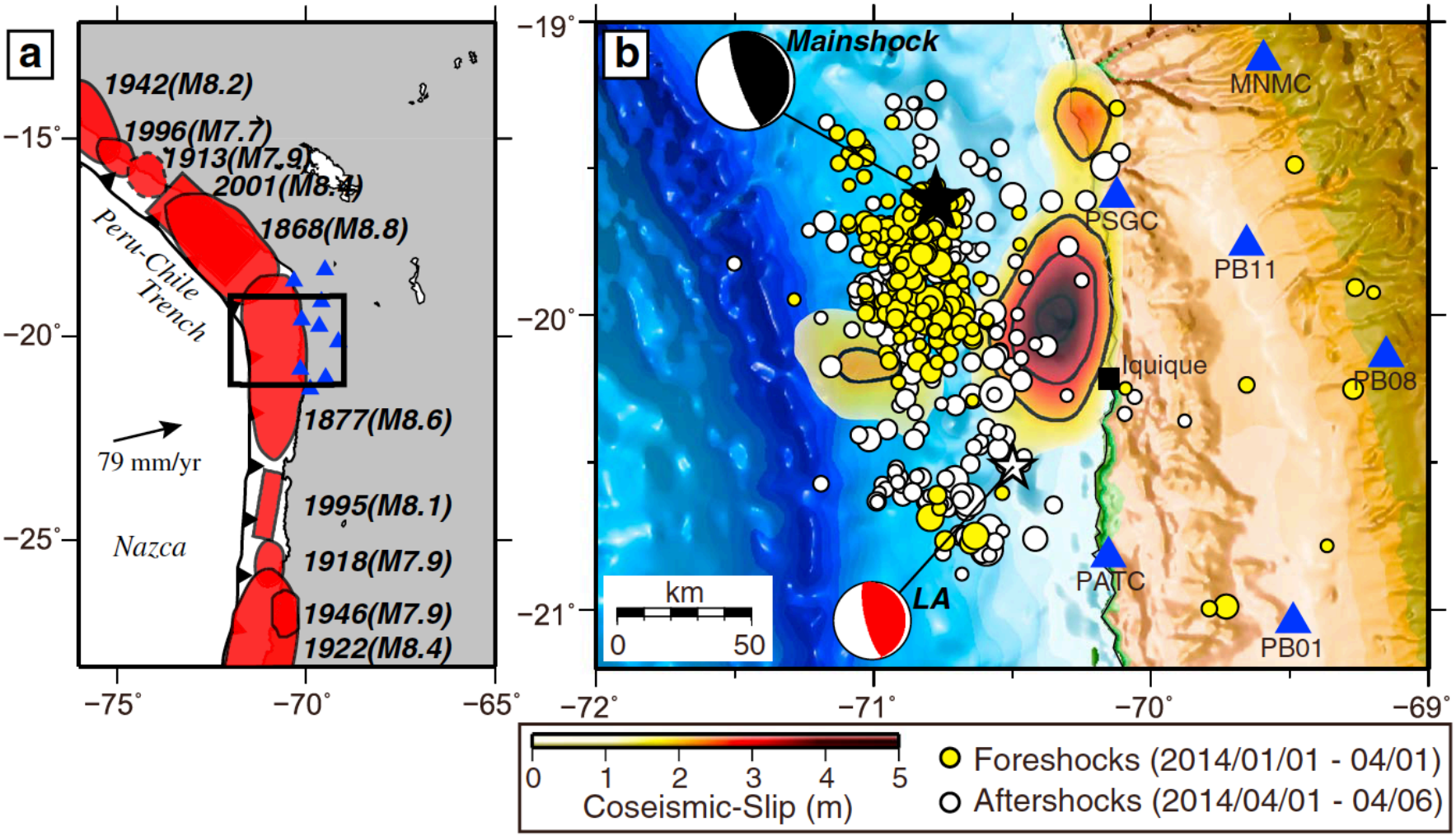
Does Slow Slip Precede Megathrust Earthquakes?
2011 Tohoku Earthquake



Acceleration from 1996-2011 interpreted as up-dip migration of slow slip

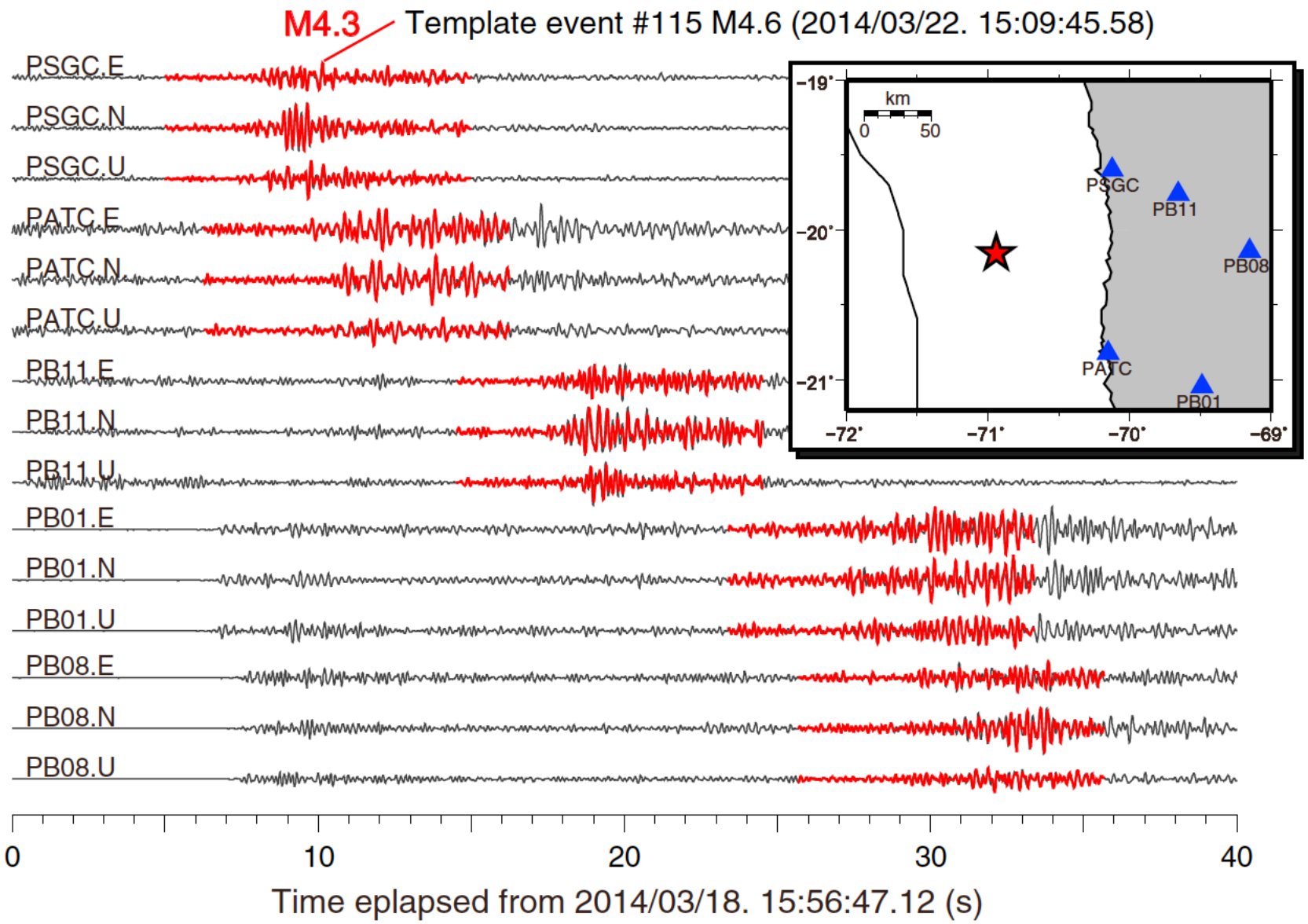
Mavrommatis et al., 2014

Does Slow Slip Precede Megathrust Earthquakes?
2014 Iquique, Chile Mw 8.1



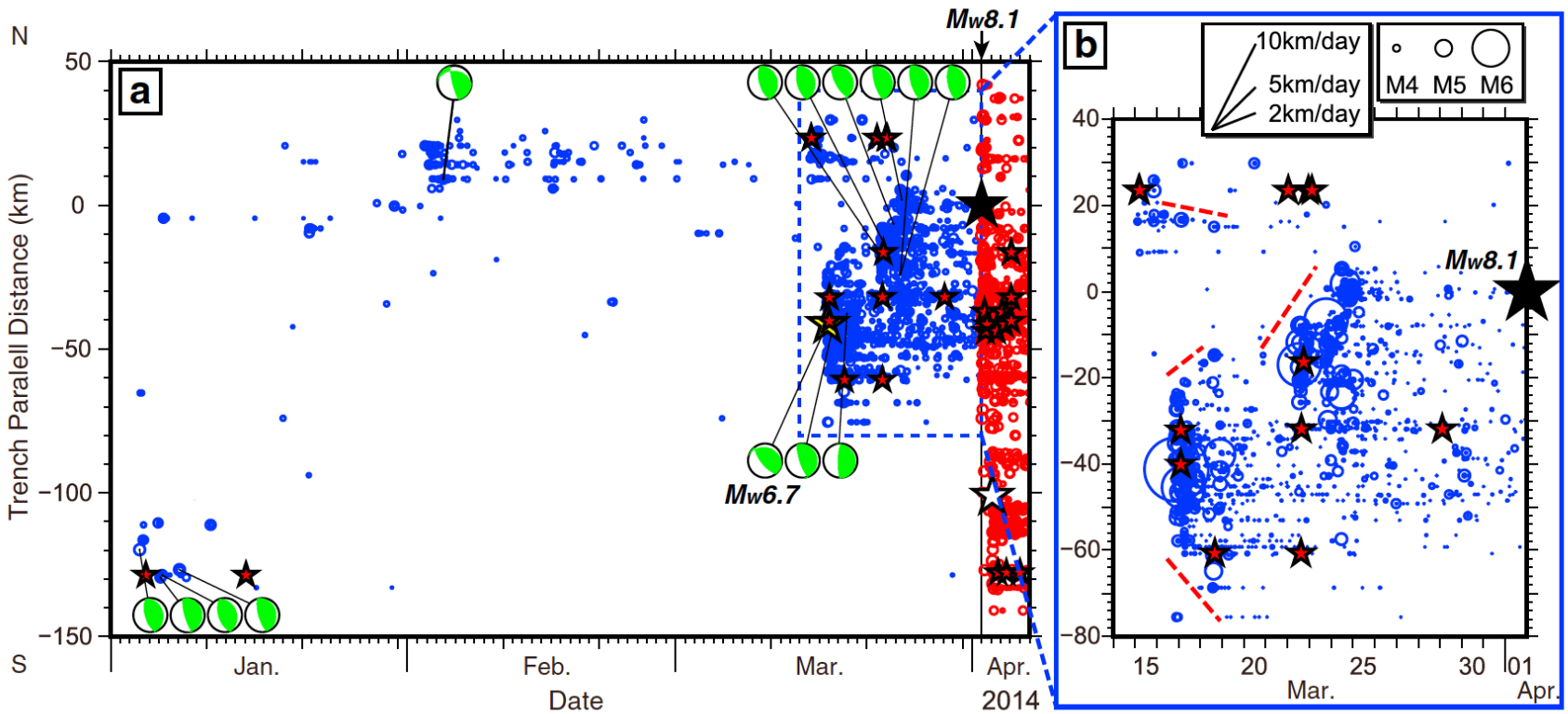
Kato & Nakagawa, 2014

2014 Iquique, Chile Mw 8.1



Kato & Nakagawa, 2014

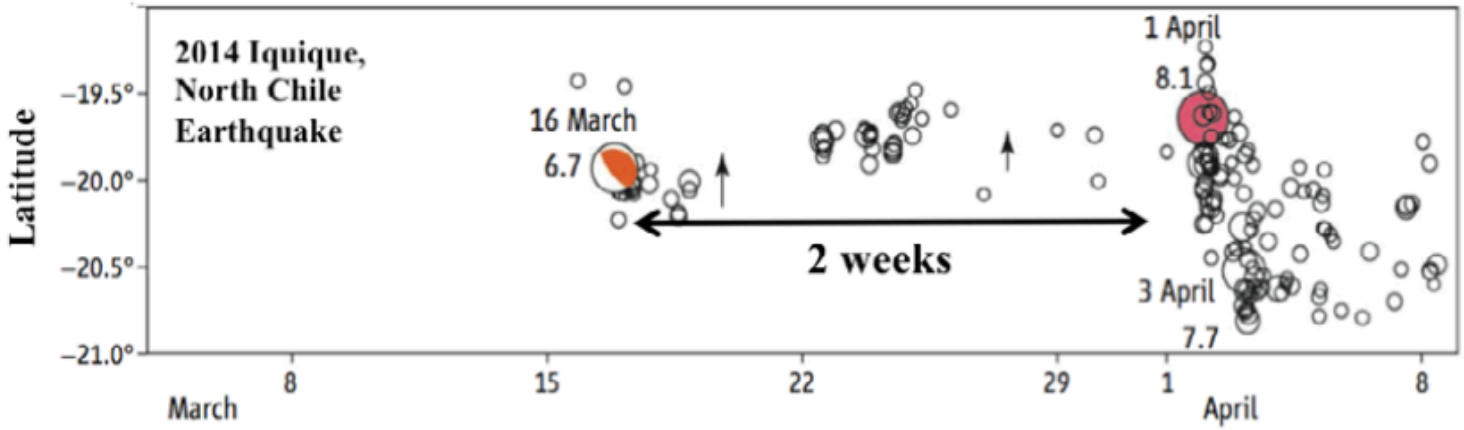
2014 Iquique, Chile Mw 8.1

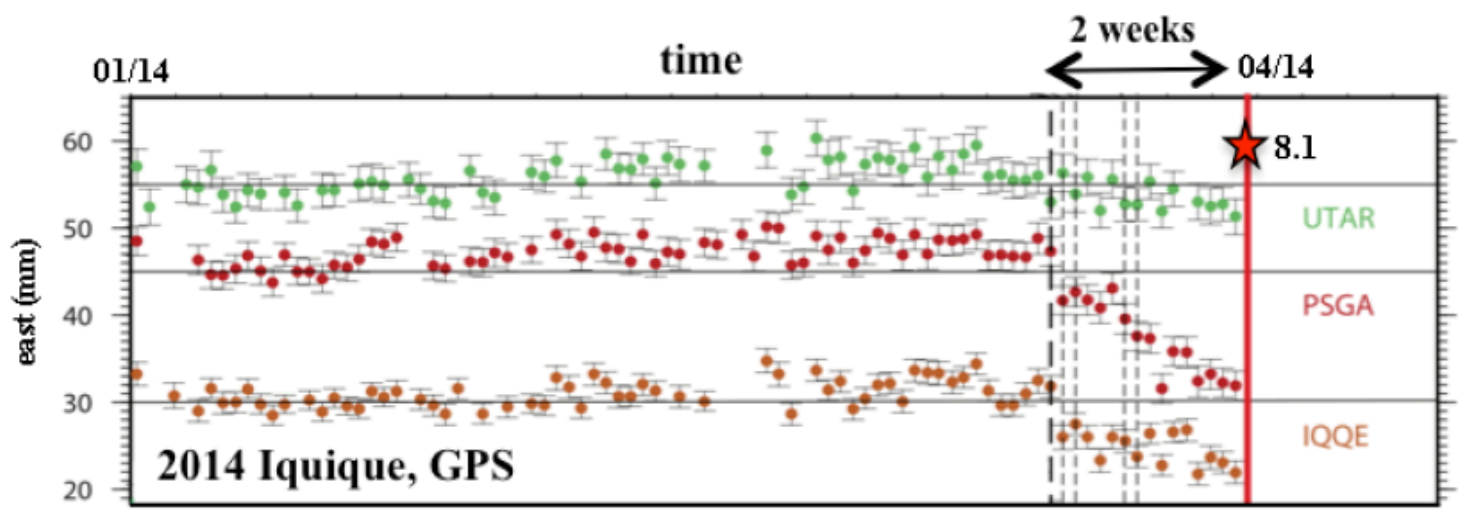


Kato & Nakagawa, 2014

2014 Iquique, Chile Mw 8.1

From Brodsky and Lay (2014)





From Ruiz et al. (2014)

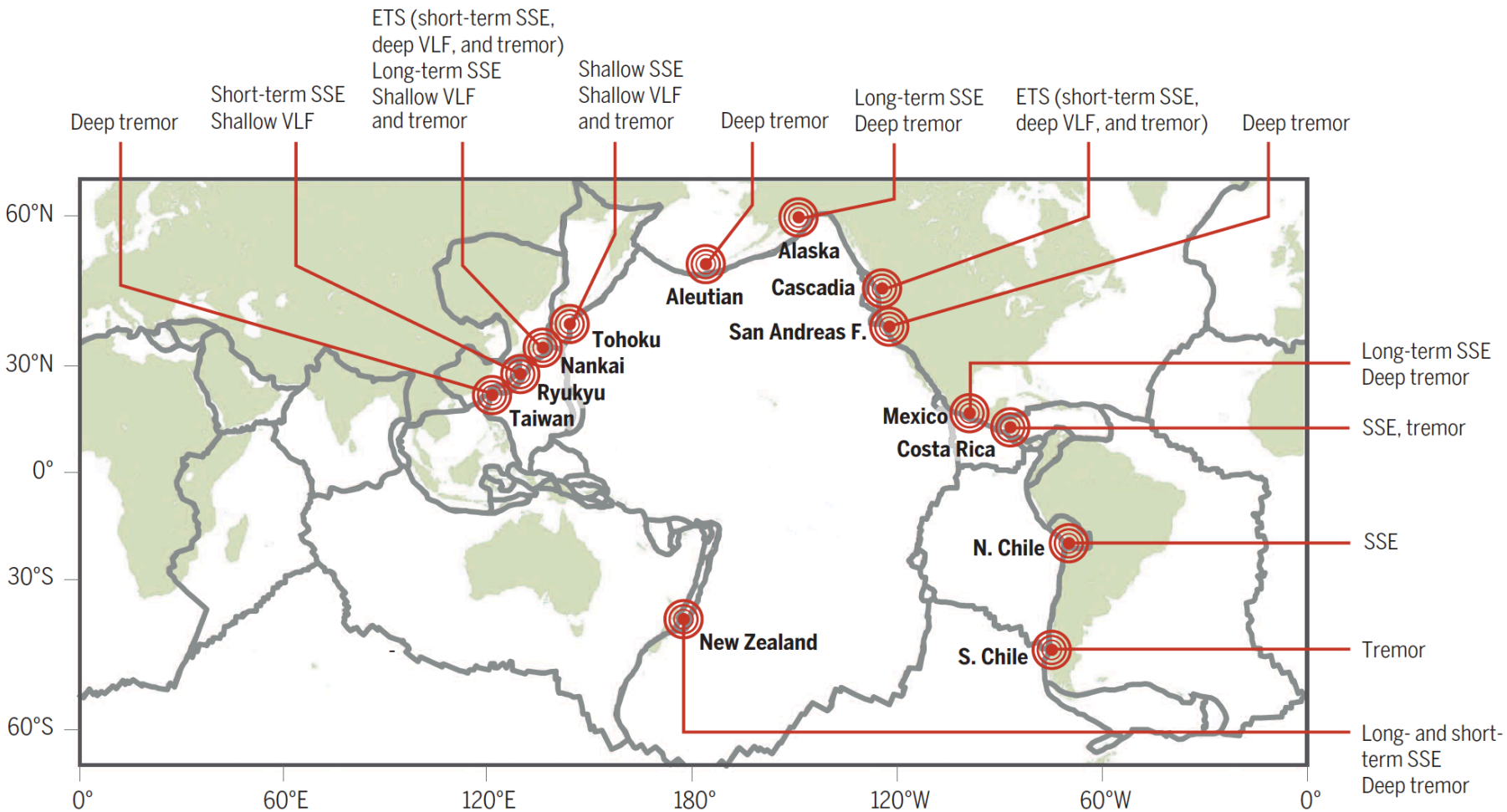
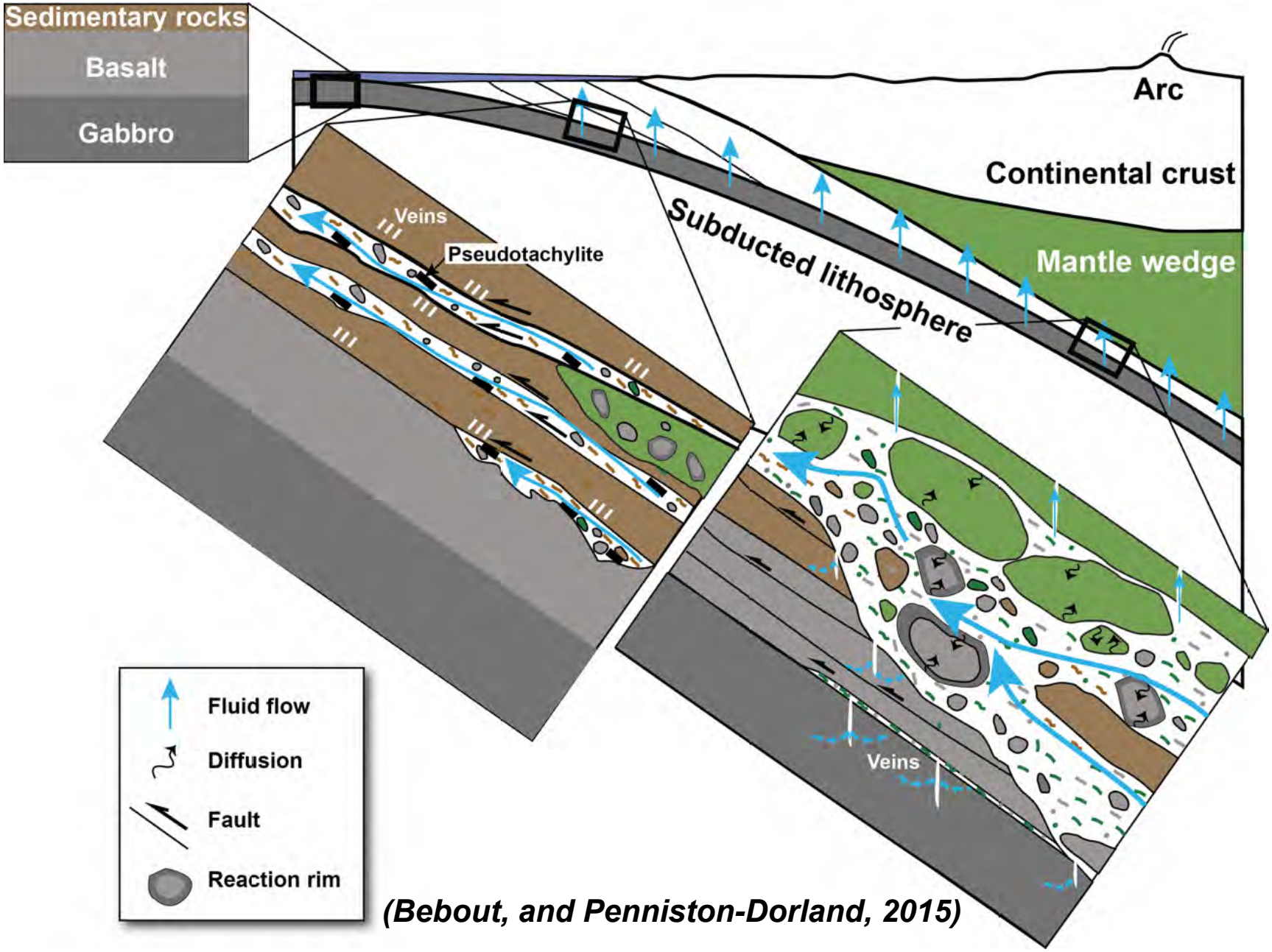


Fig. 3. Global distribution of slow earthquakes.

Obara & Kato, 2016

The subduction interface is more complex than we usually draw



(Bebout, and Penniston-Dorland, 2015)

Future Directions-Slow Slip

- Can seismic and aseismic processes occur at the same locations at different times?
- Are the mechanisms of slow slip different at different locations along the plate interface (up dip vs. down dip of the seismogenic zone)
- Does slow slip commonly precede megathrust earthquakes?
- What is the strain budget at the megathrust boundary?