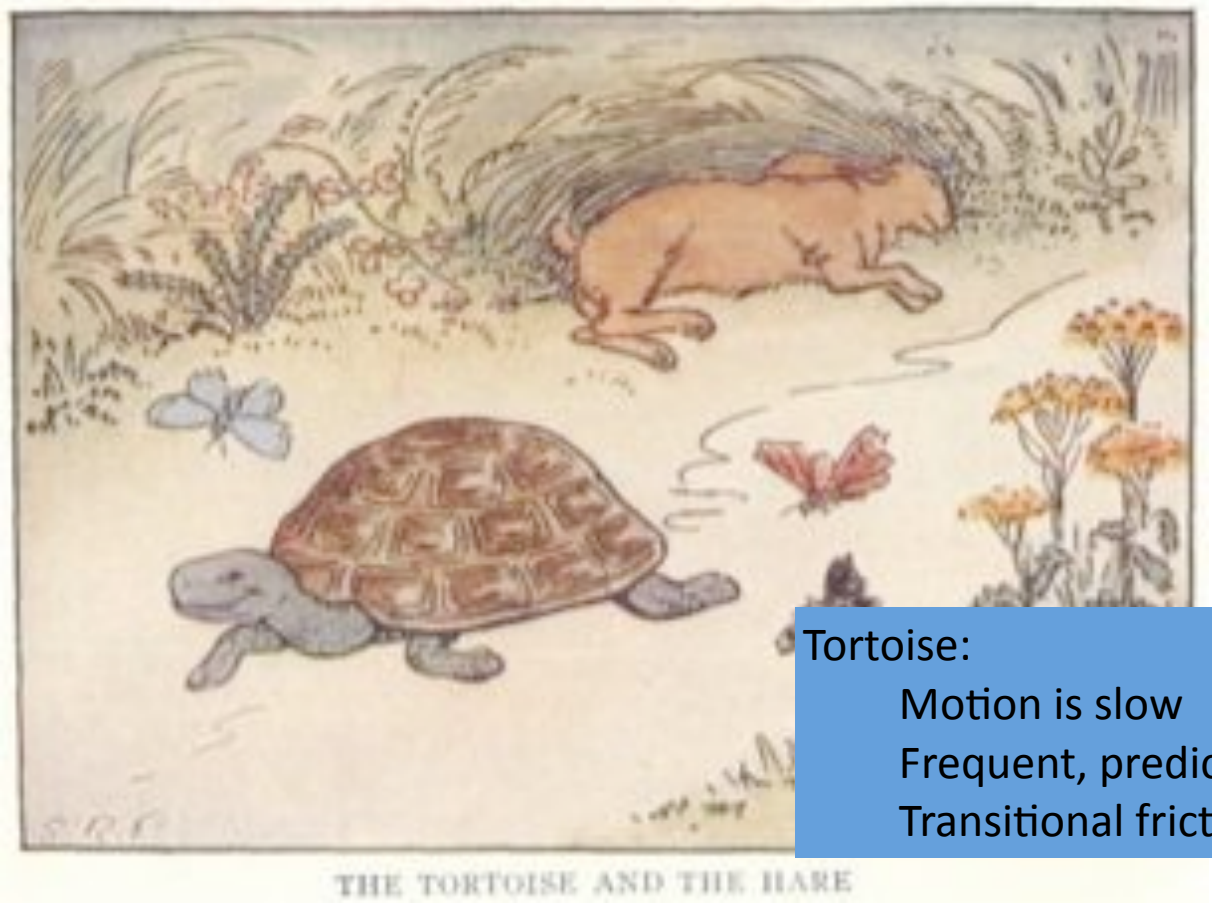
EARTHSCOPE INSTITUTE ON THE SPECTRUM OF FAULT SLIP

THE TORTOISE AND THE HARE

"The Slow and the Fast Ends of the Earthquake Spectrum"

Greg Beroza (Dept. of Geophysics, Stanford University)

EARTHSCOPE INSTITUTE ON THE SPECTRUM OF FAULT SLIP



Tortoise:

- Motion is slow
- Frequent, predictable activity
- Transitional frictional properties

"The Slow and the Fast Ends of the Earthquake Spectrum"

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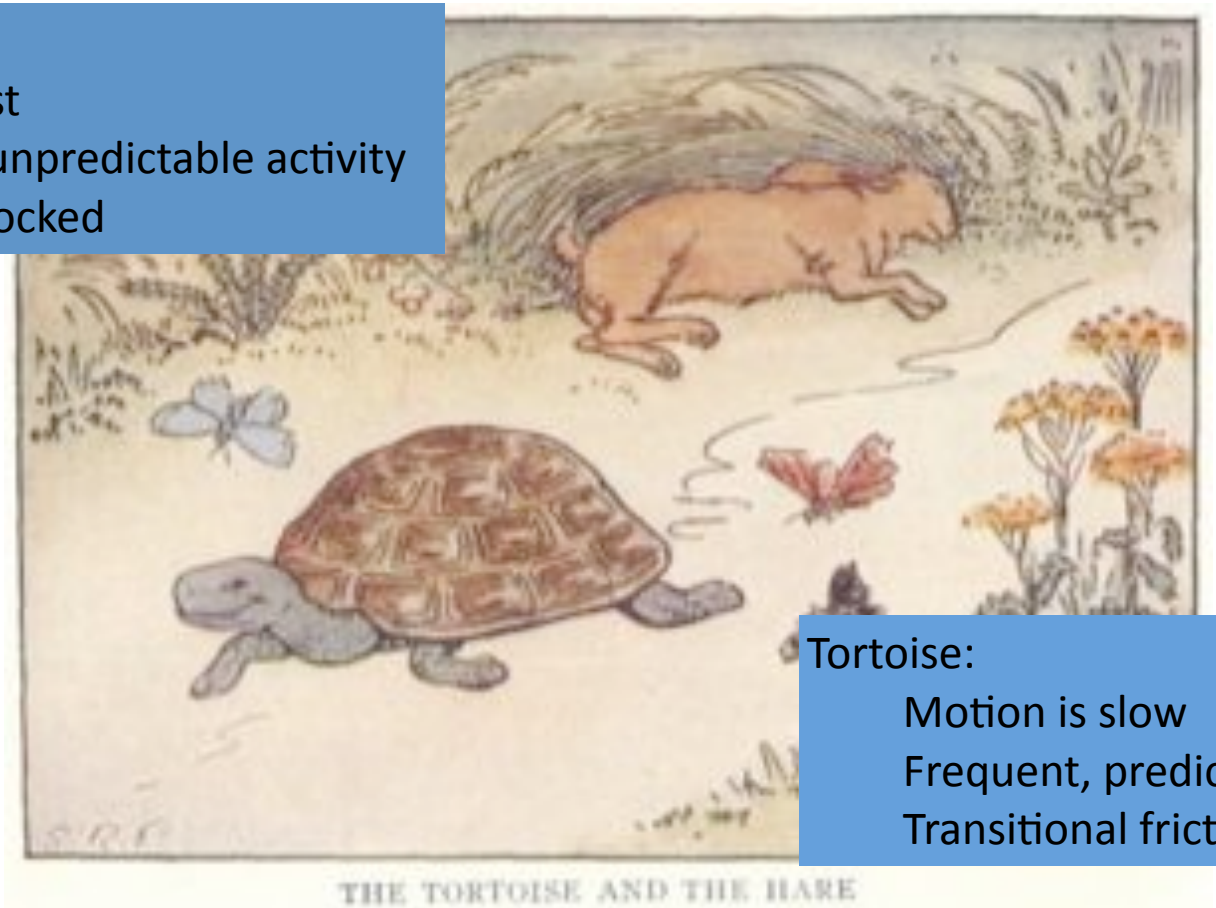
Hare:
- Motion is fast
- Infrequent, unpredictable activity
- Frictionally locked



Tortoise:
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"The Slow and the Fast Ends of the Earthquake Spectrum"

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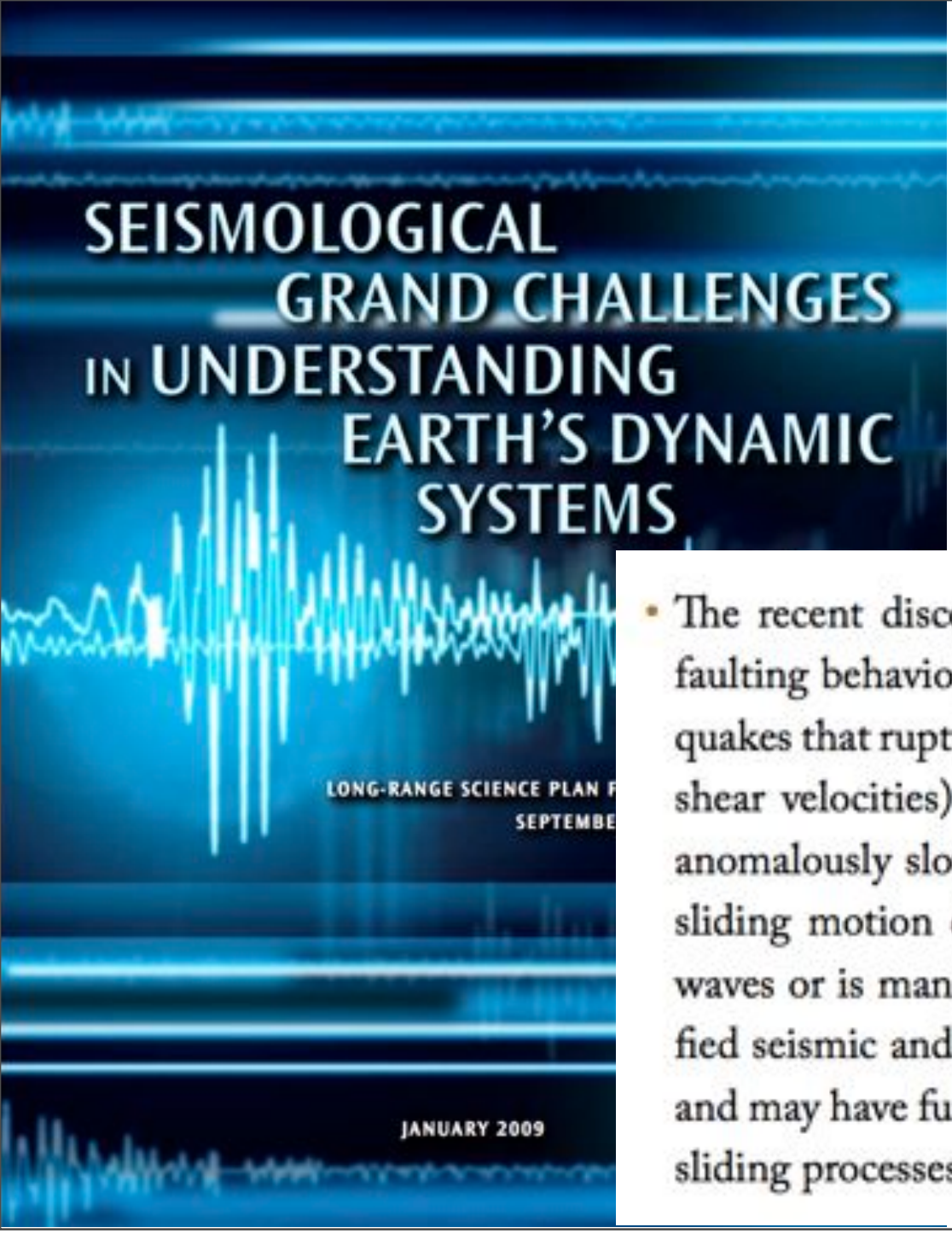
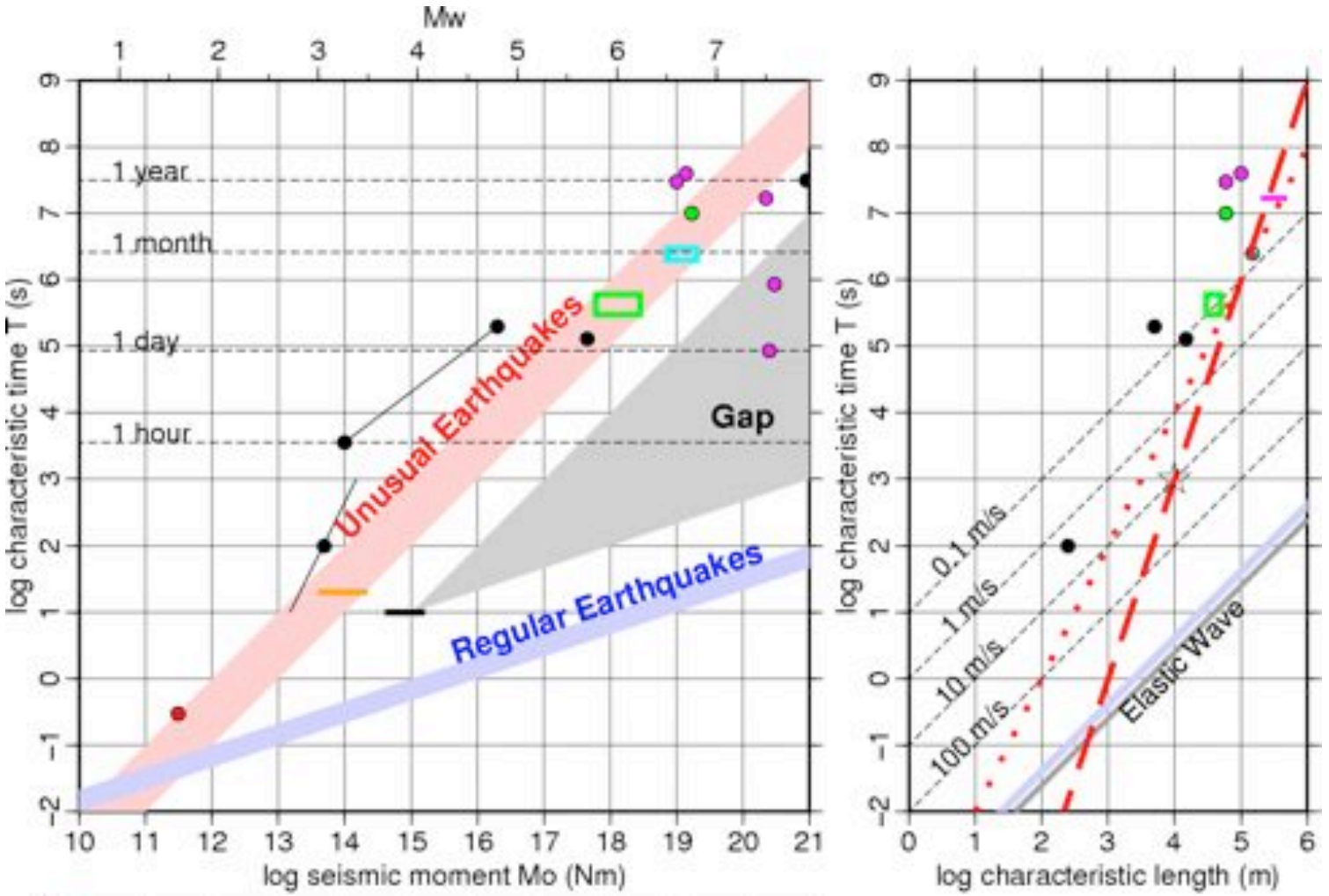


- The recent discovery of a continuous spectrum of faulting behavior, ranging from conventional earthquakes that rupture at great speeds (including supershear velocities) to "slow earthquakes" that involve anomalously slow ruptures—some so slow that the sliding motion does not radiate detectable seismic waves or is manifested in seismic tremor—has unified seismic and geodetic monitoring of fault zones and may have fundamental importance for frictional sliding processes and earthquake hazard.

Earthquake Scaling



Ide et al. [2007]

SOME CHARACTERISTICS OF "REGULAR" EARTHQUAKES

Rupture at ~70-90% of the *S*-wave velocity

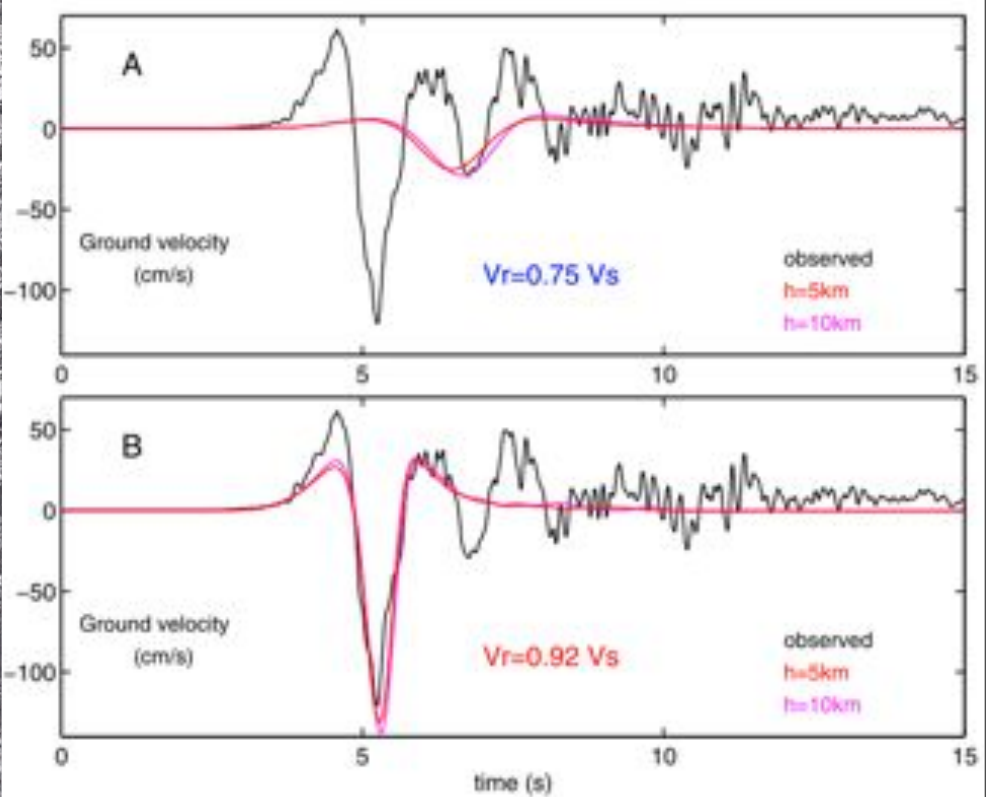
Constant stress drop of 3-5 MPa

Self-Similar Scaling $M_0 \sim L^3$

Scaled energy $(E_S/M_0) \sim 5 \times 10^{-5}$

SOME CHARACTERISTICS OF "REGULAR" EARTHQUAKES

12/26/2003 M 6.6 Bam, Iran, 30,000+ fatalities, ~80% of buildings destroyed



Sub-Shear Rupture at ~ Rayleigh wave velocity leads to strong directivity.

Bouchon et al. [2006]

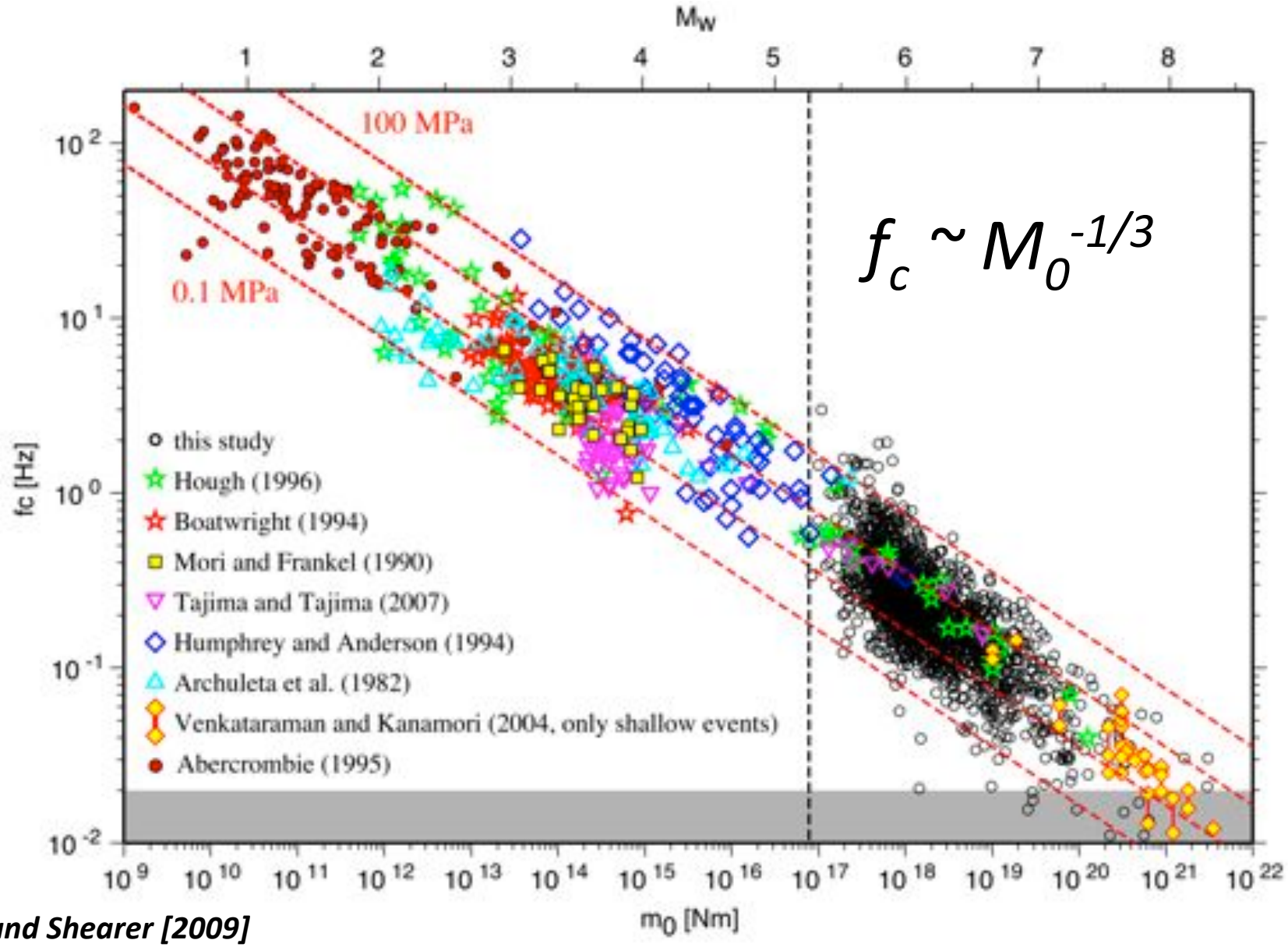
The Fast End of the Earthquake Spectrum

Two Kinds of "Fast":

High Slip Rate - High Stress Drop

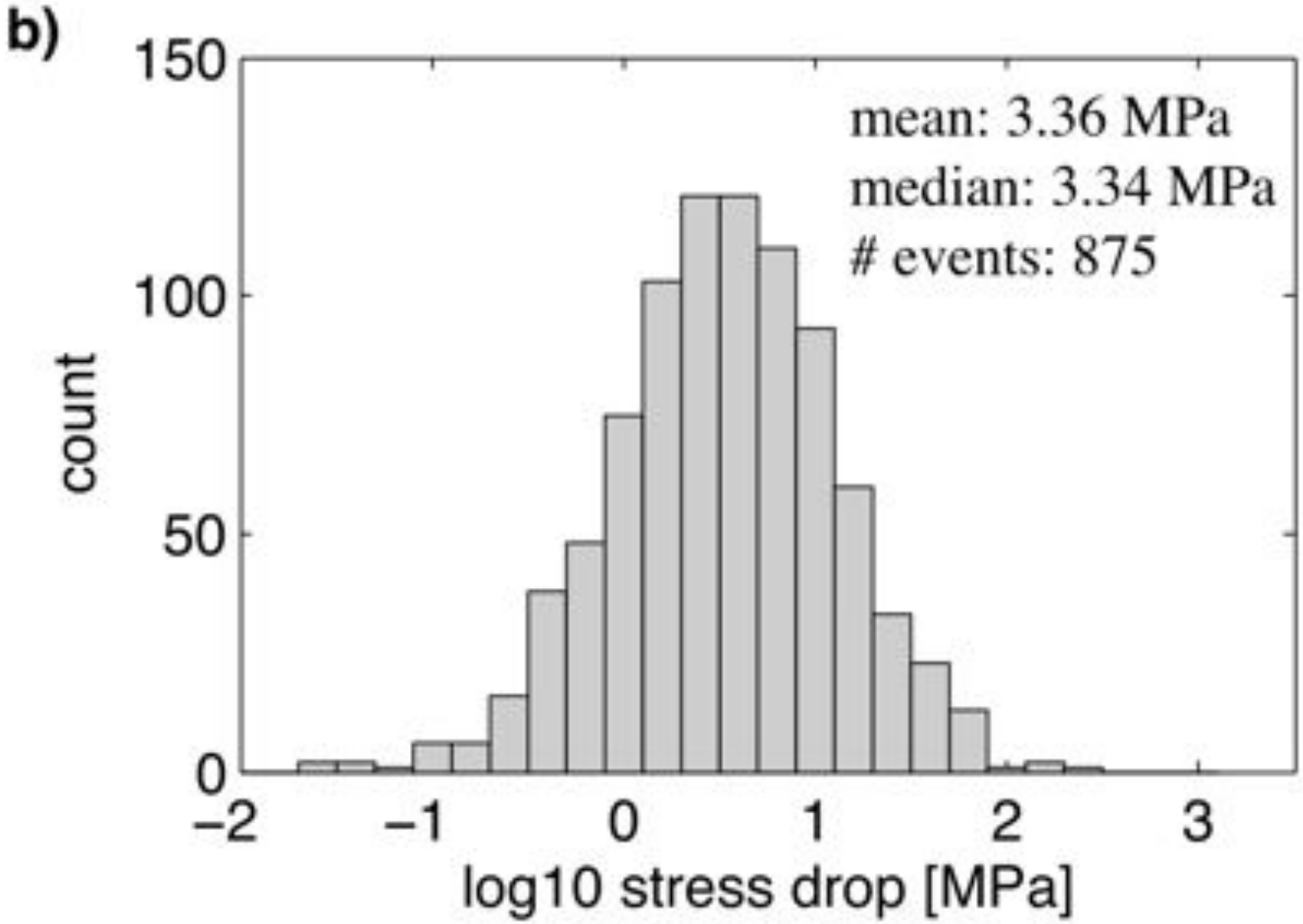
High Rupture Velocity - Supershear Rupture

Stress Drop



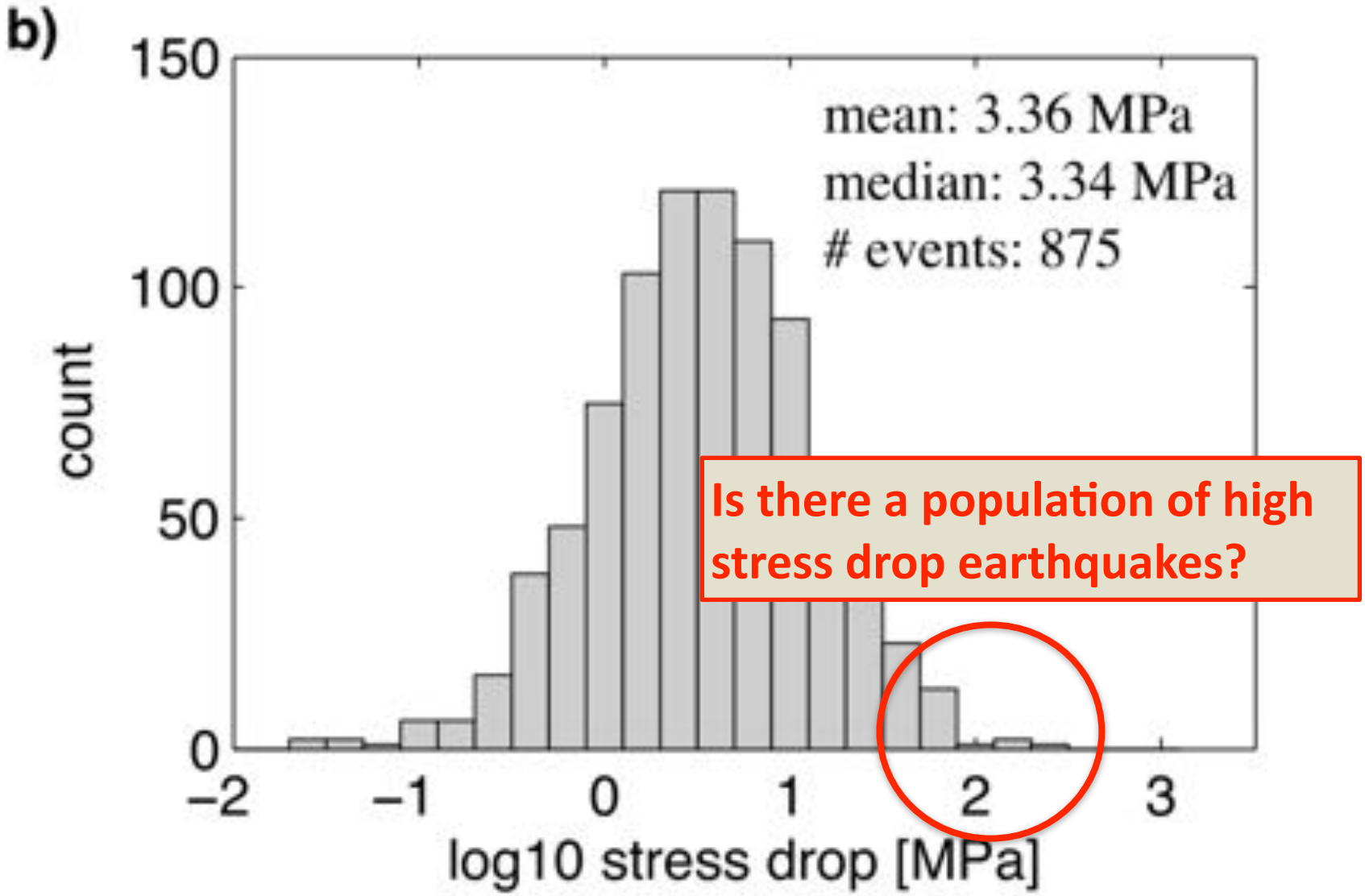
Allman and Shearer [2009]

Stress Drop



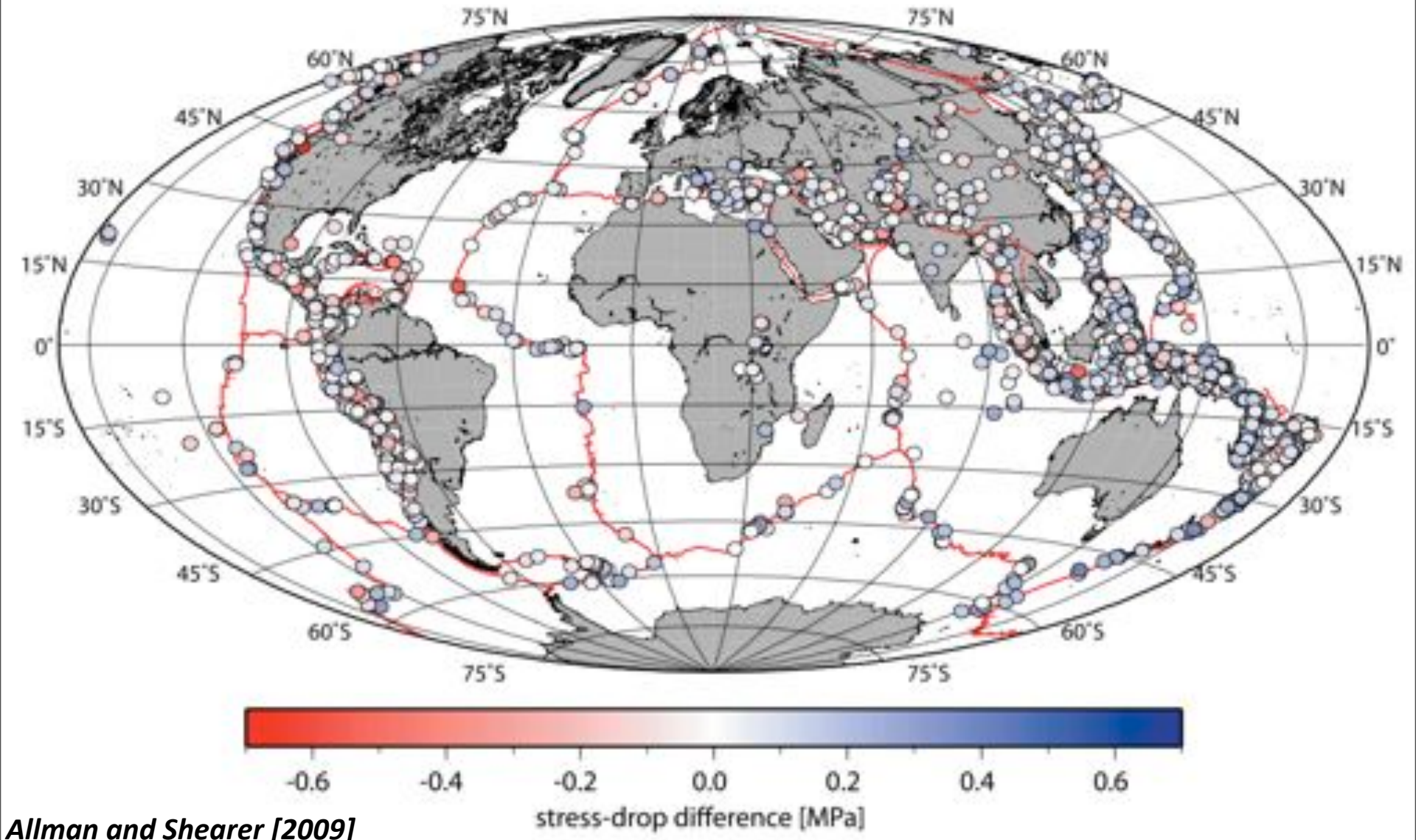
Allman and Shearer [2009]

Stress Drop



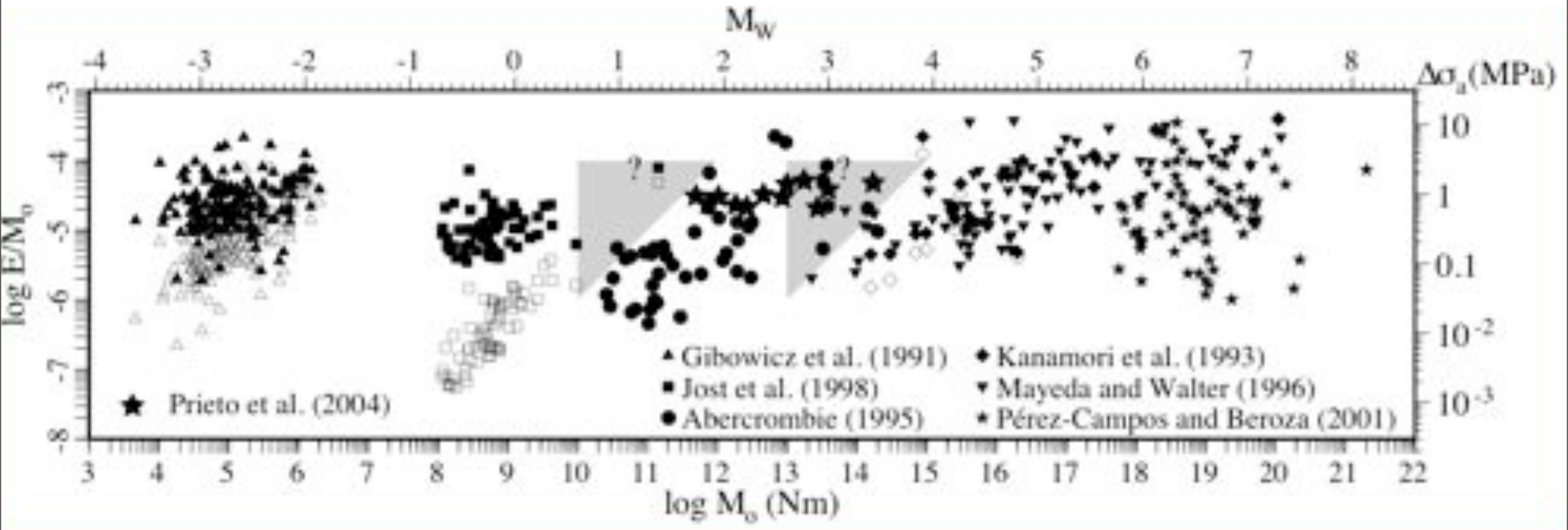
Allman and Shearer [2009]

Stress Drop



Allman and Shearer [2009]

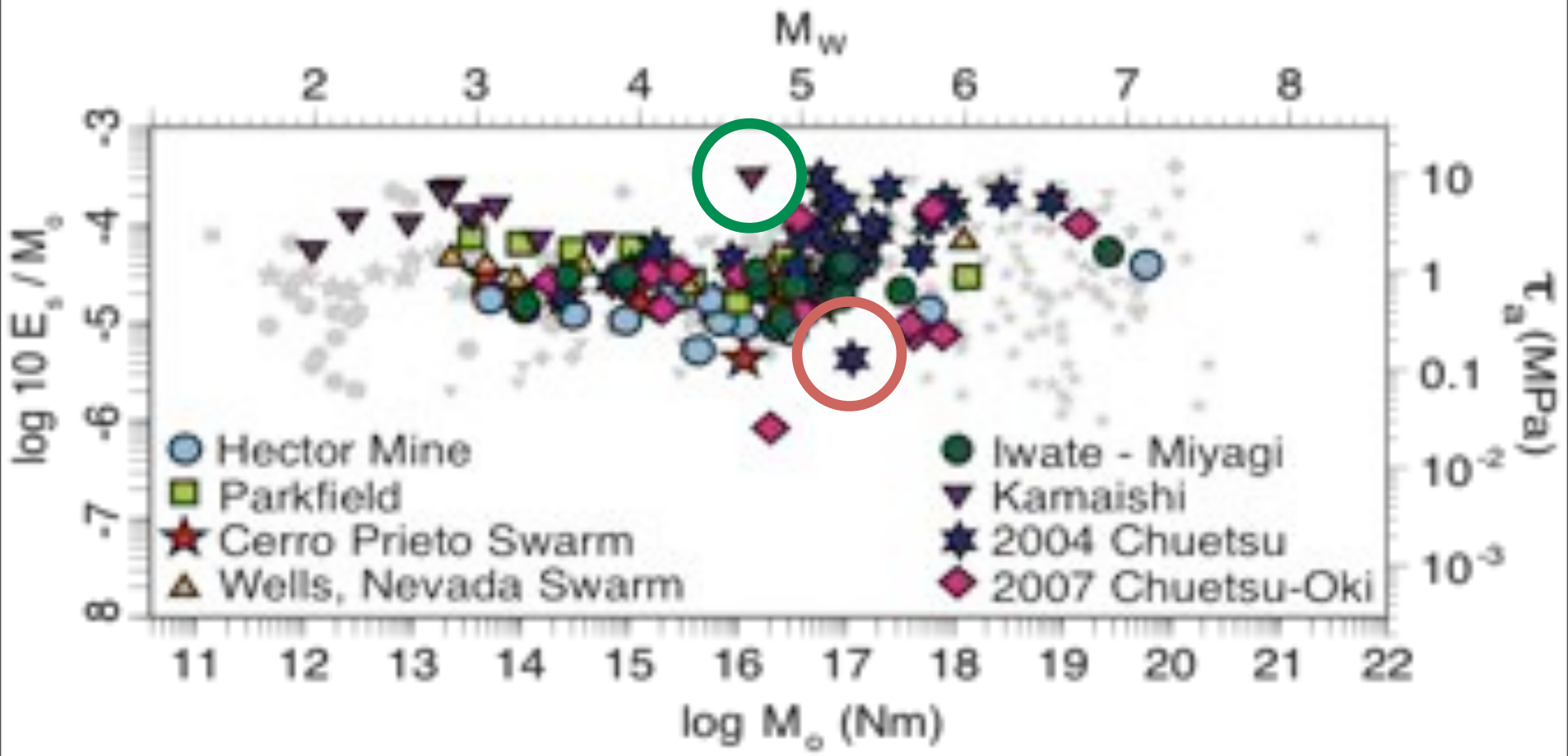
Scaled Seismic Energy (E_S/M_0)



No systematic variation of scaled energy with earthquake size.

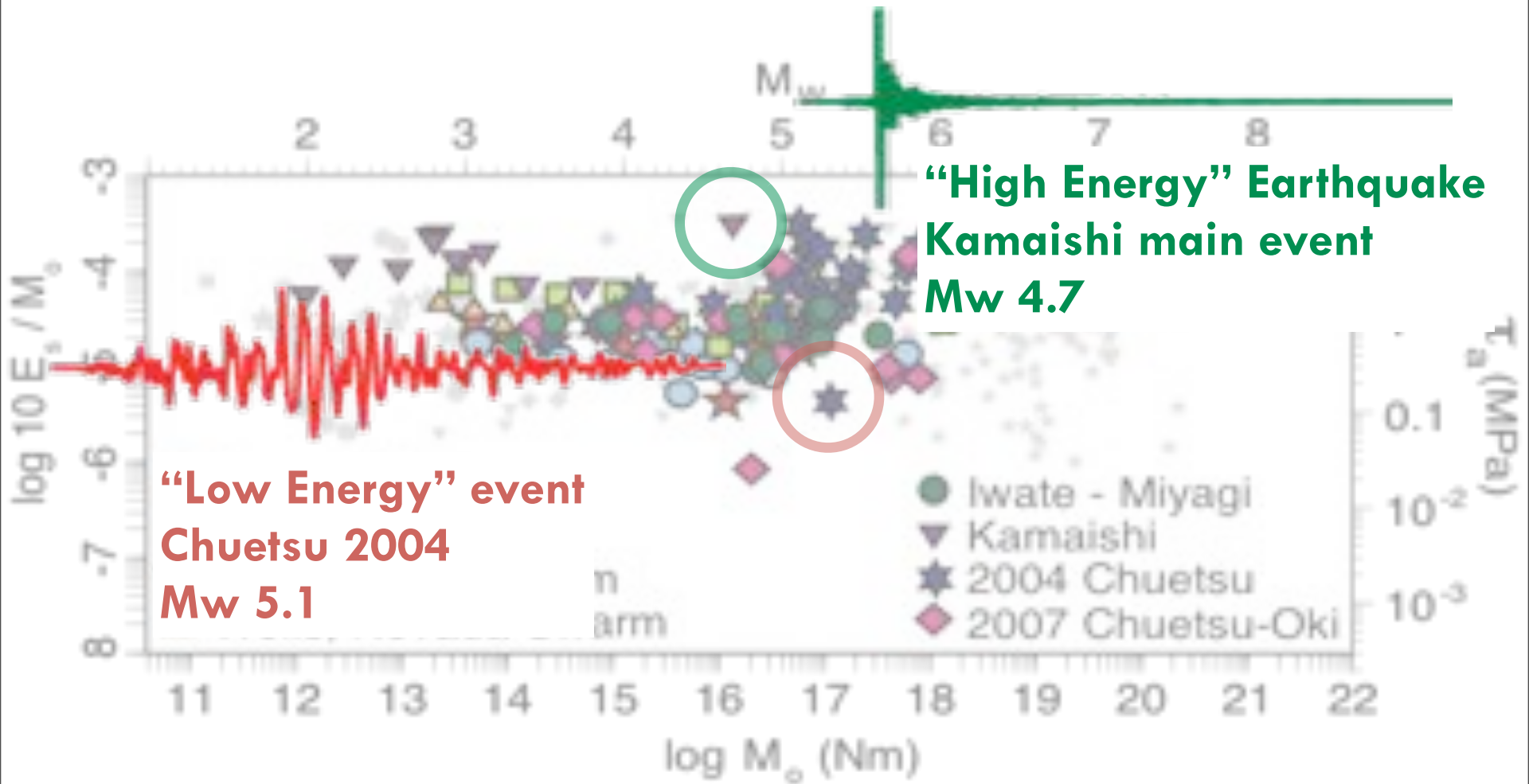
Ide and Beroza (2001)

Scatter in Scaled Energy



Baltay et al. [2010]

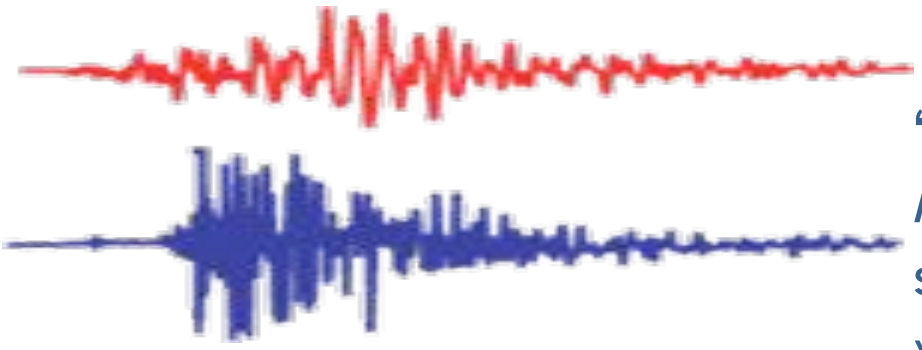
Scatter in Scaled Energy



Baltay et al. [2010]

Low Energy Earthquake

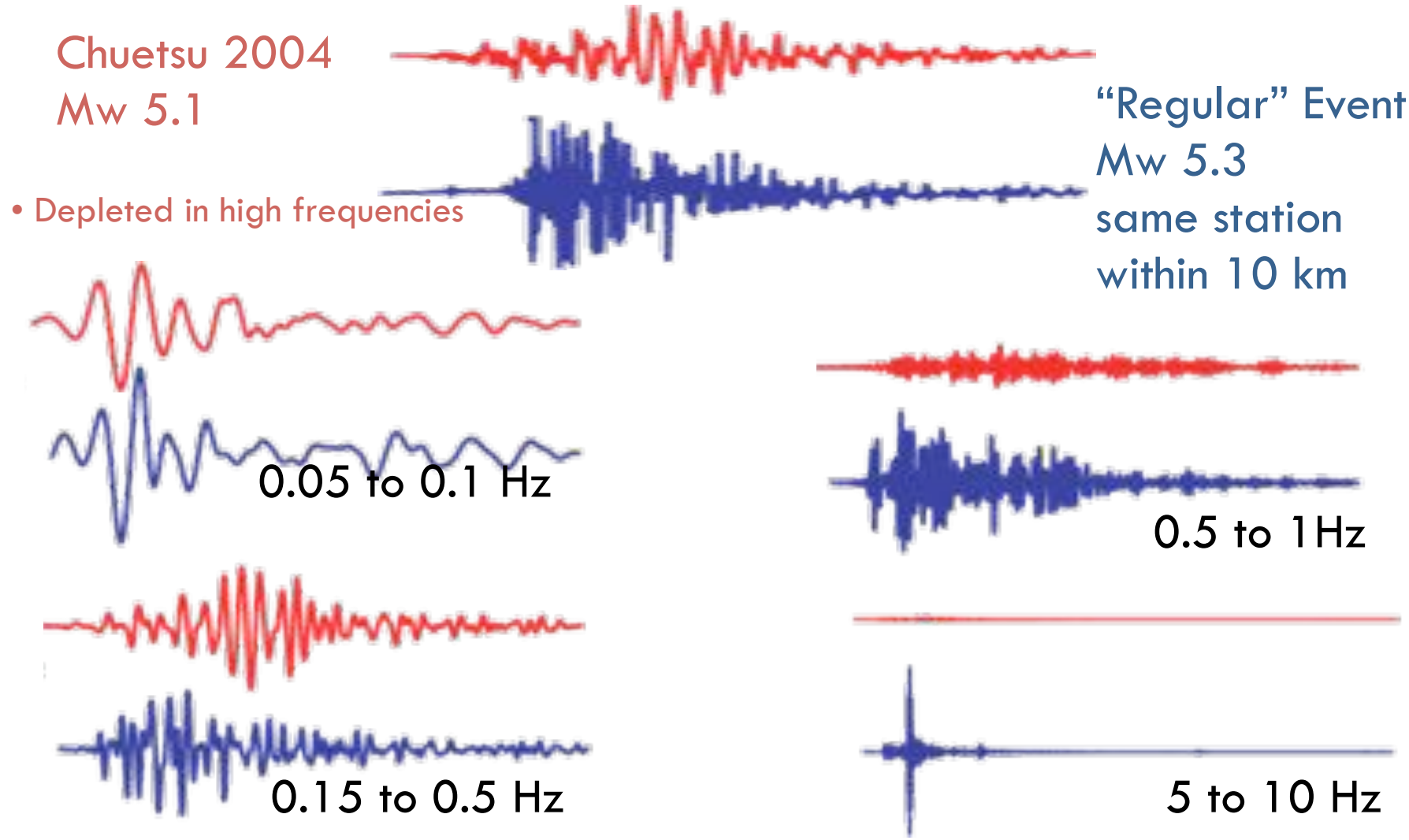
Chuetsu 2004
Mw 5.1



"Regular" Event
Mw 5.3
same station
within 10 km

Baltay et al. [2010]

Low Energy Earthquake

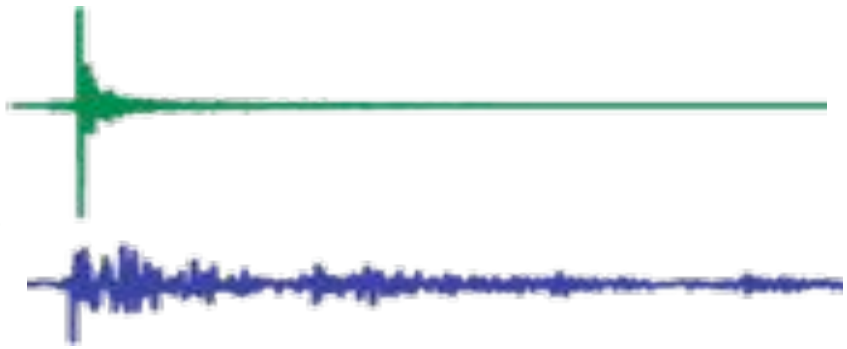


Baltay et al. [2010]

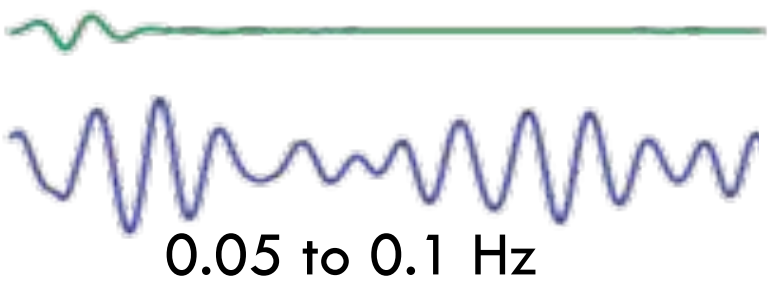
High Energy Earthquake

Kamaishi main event
Mw 4.7

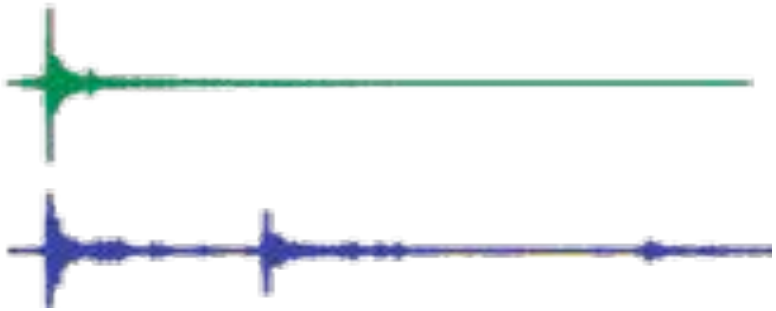
- Enriched in high frequencies



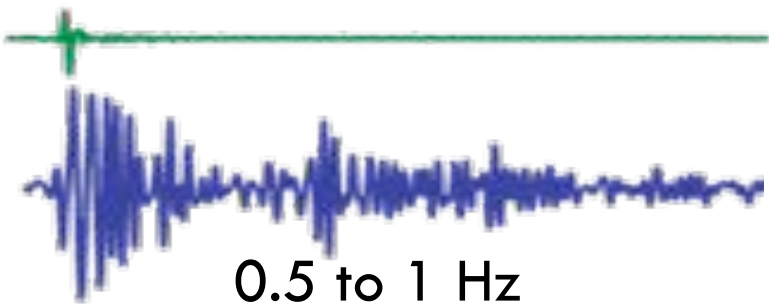
"Normal" Event
Mw 4.8
same distance



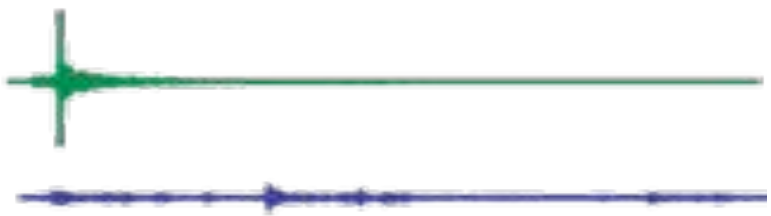
0.05 to 0.1 Hz



5 to 10 Hz



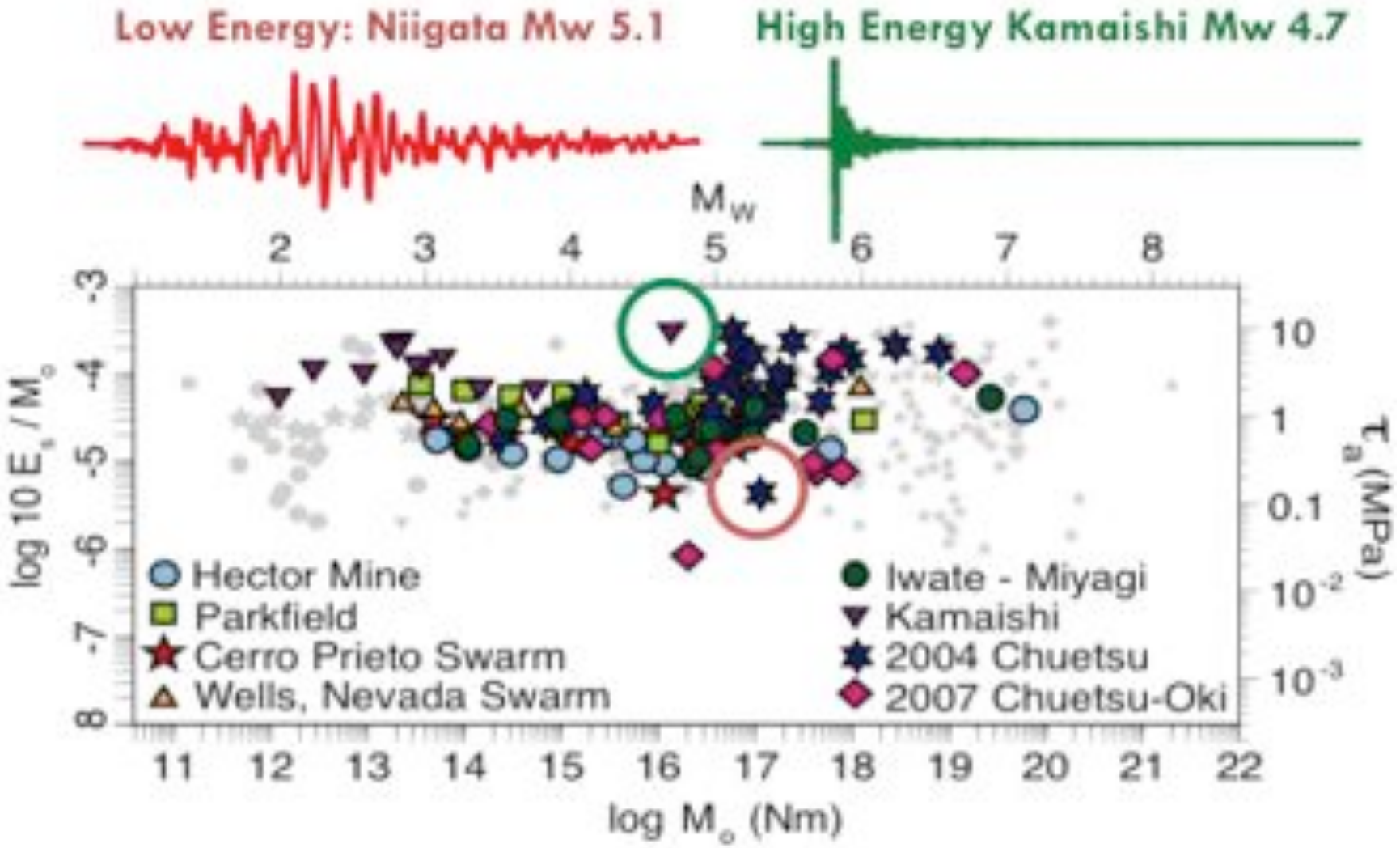
0.5 to 1 Hz



10 to 20 Hz

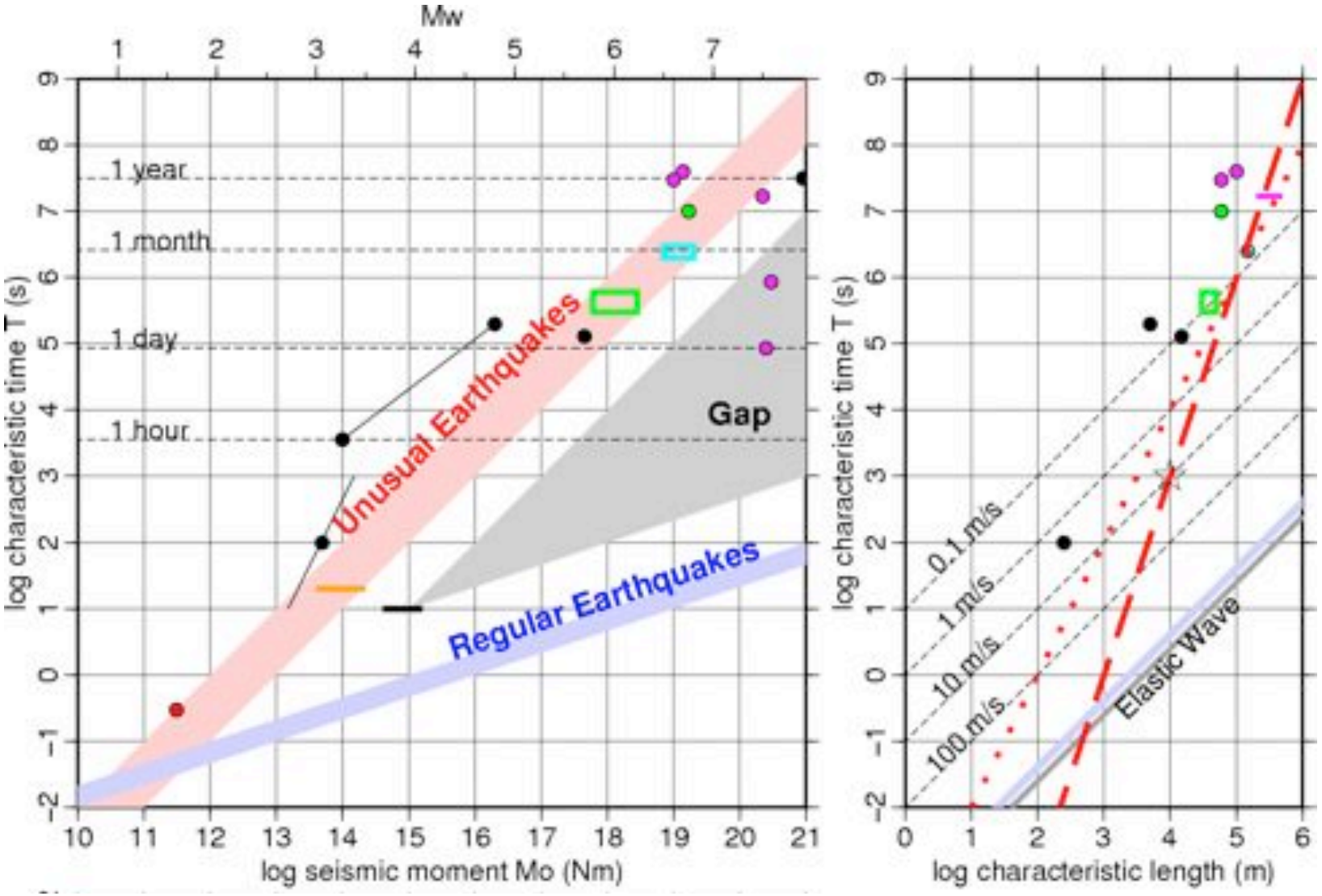
Baltay et al. [2010]

At Least some of Scatter in E_S/M_0 is real



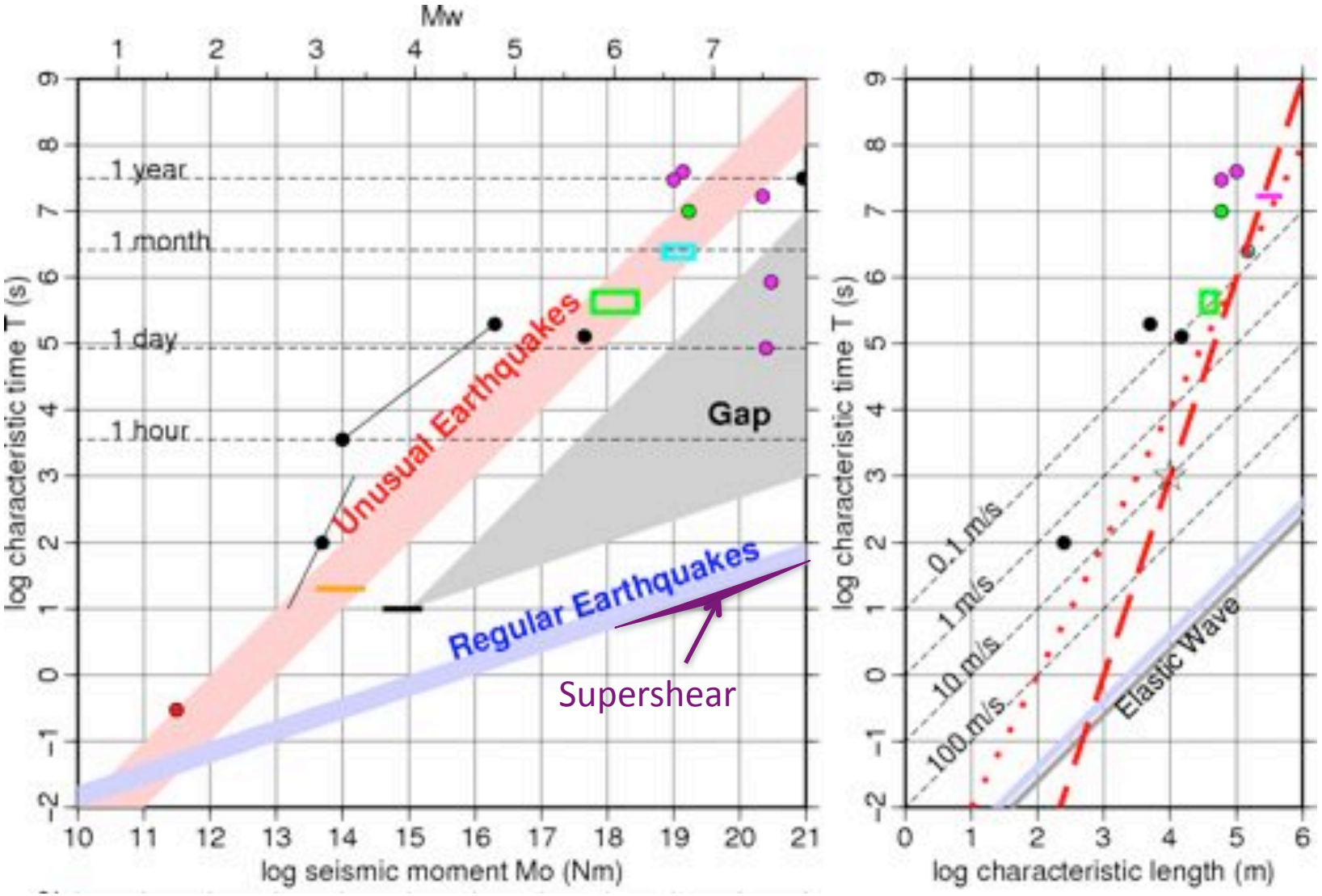
Baltay et al. [2010]

Earthquake Size-Duration Scaling



Ide et al. [2007]

Earthquake Size-Duration Scaling

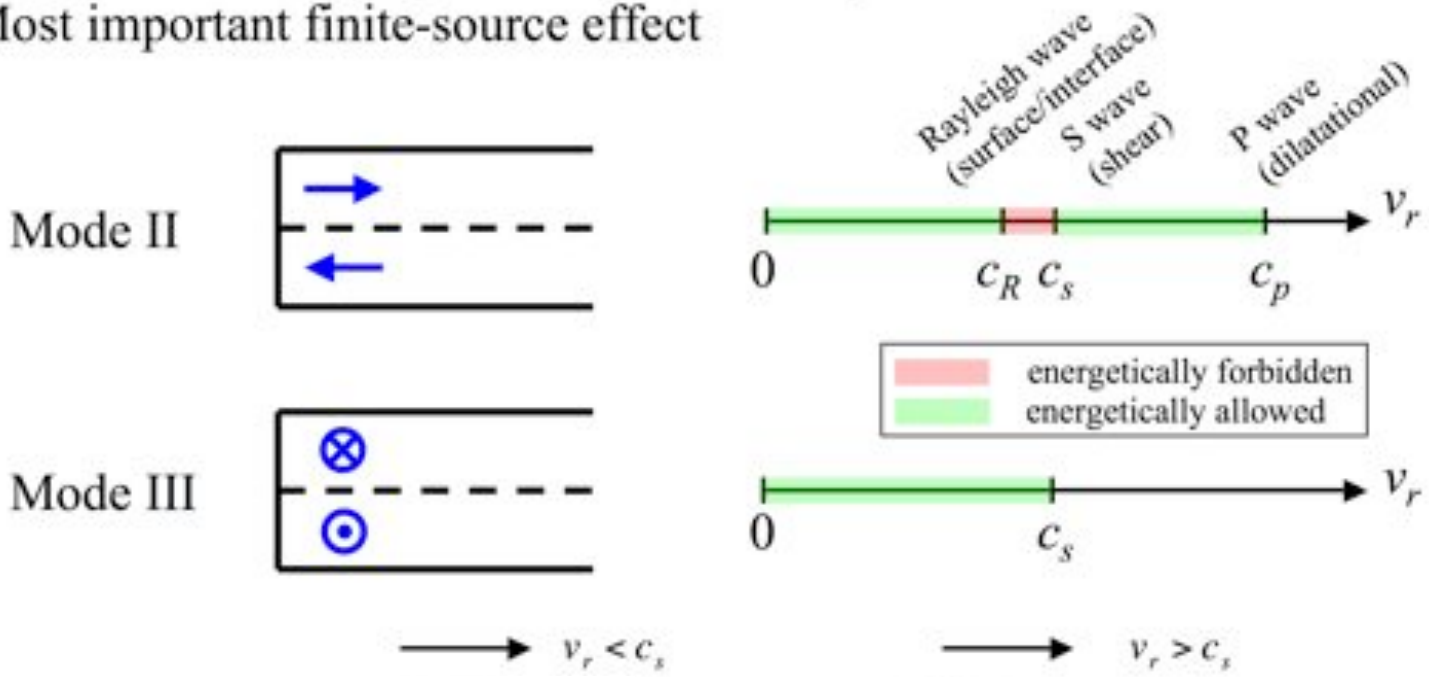


Ide et al. [2007]

SUPER-SHEAR RUPTURE

Rupture Velocity and Directivity:

Most important finite-source effect



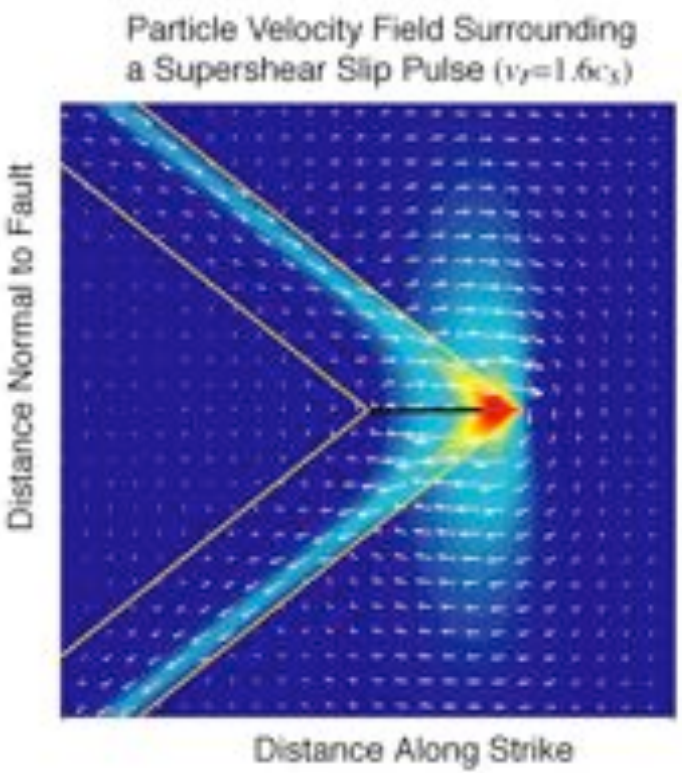
Dunham

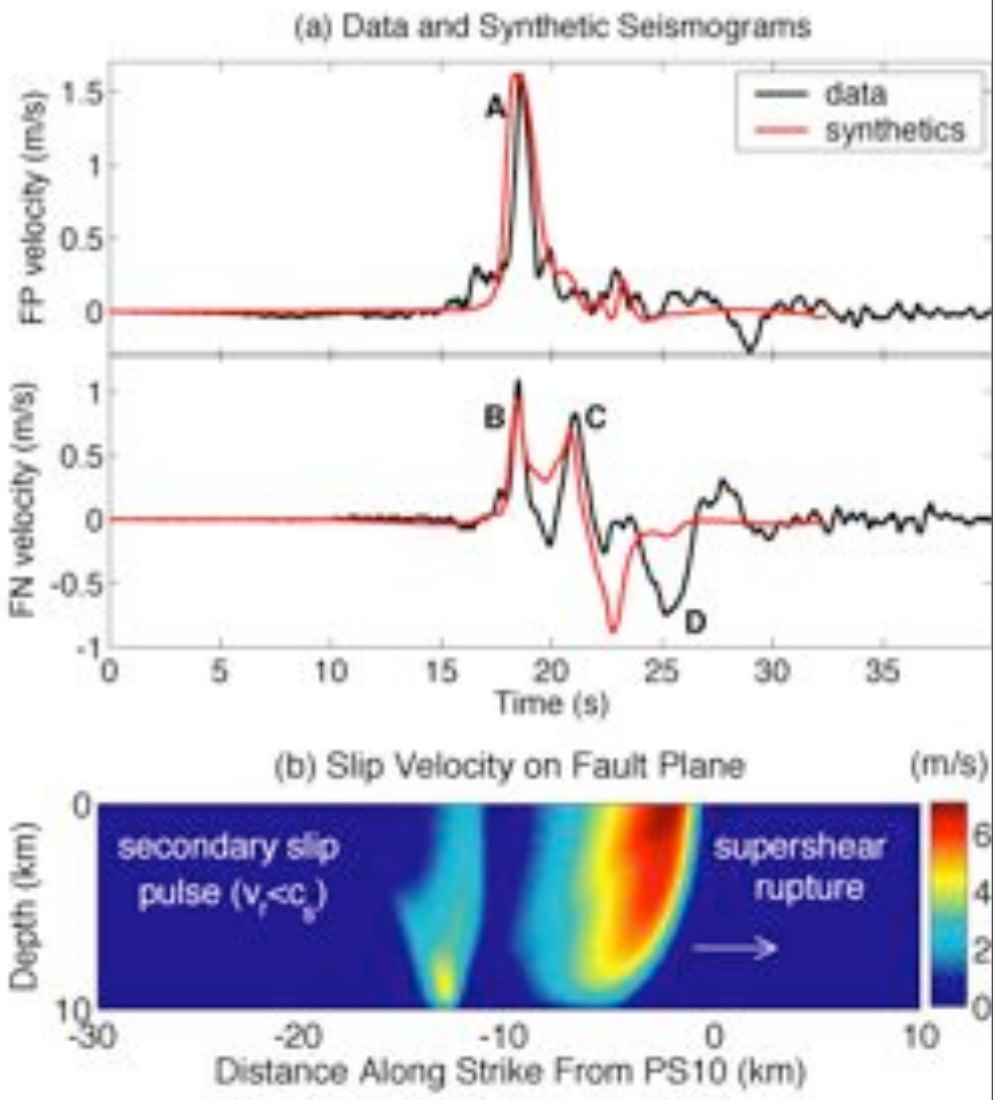
SUPER-SHEAR RUPTURE

1906 *M* 7.9 San Francisco	*Song et al. [2008]*
1979 *M* 6.5 Imperial Valley	*Archuleta [1994]*
	Spudich and Cranswick [1994]
1999 *M* 7.6 Izmit	*Ellsworth and Celebi [1999]*
	Bouchon et al. [2000]
1999 *M* 7.2 Duzce	*Bouchon et al. [2001]*
2001 *M* 7.8 Kunlun	*Bouchon and Vallee [2003]*
	Walker and Shearer, 2009]
2002 *M* 7.9 Denali	*Ellsworth et al. [2004]*
	Dunham and Archuleta [2004]
	Aagaard and Heaton [2004]

All are large strike-slip earthquakes.

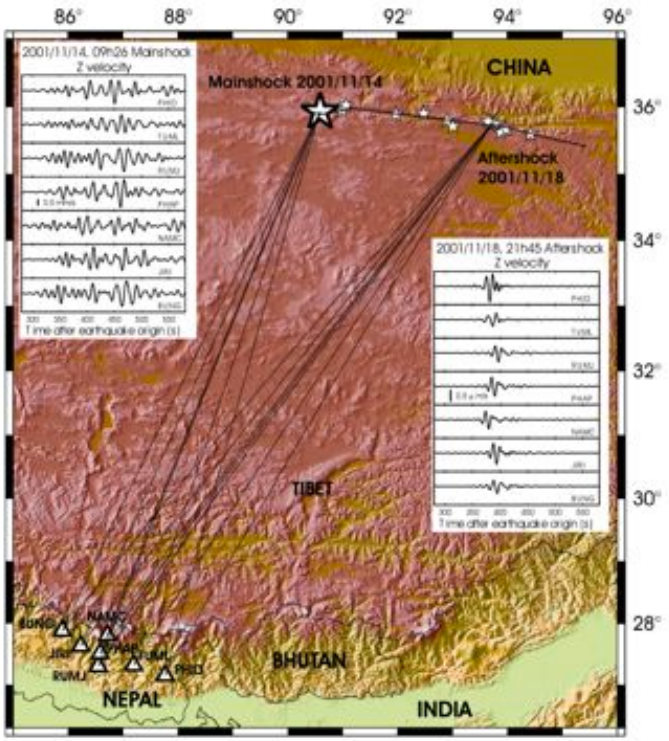
SUPER-SHEAR RUPTURE

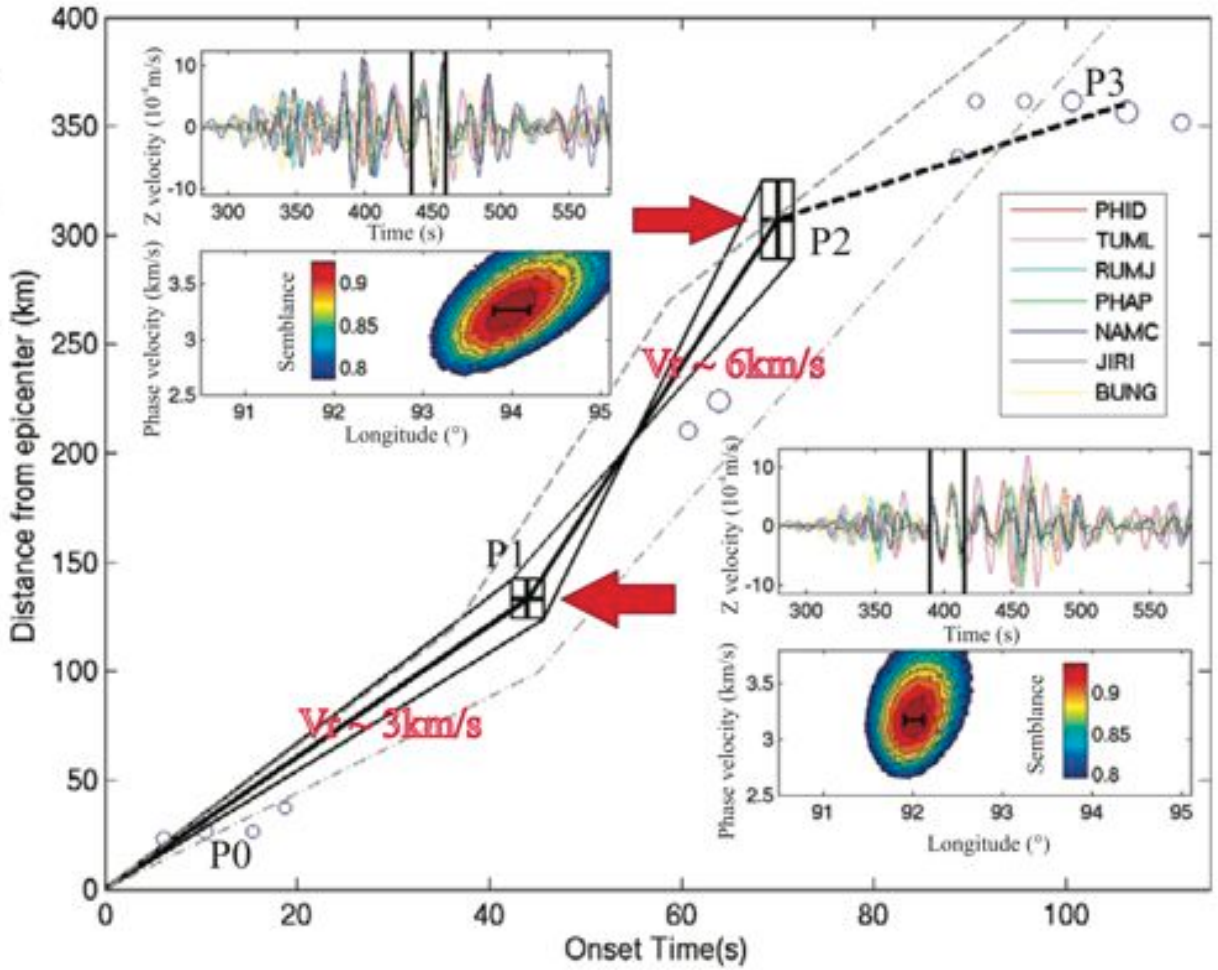




Dunham and Archuleta [2004]

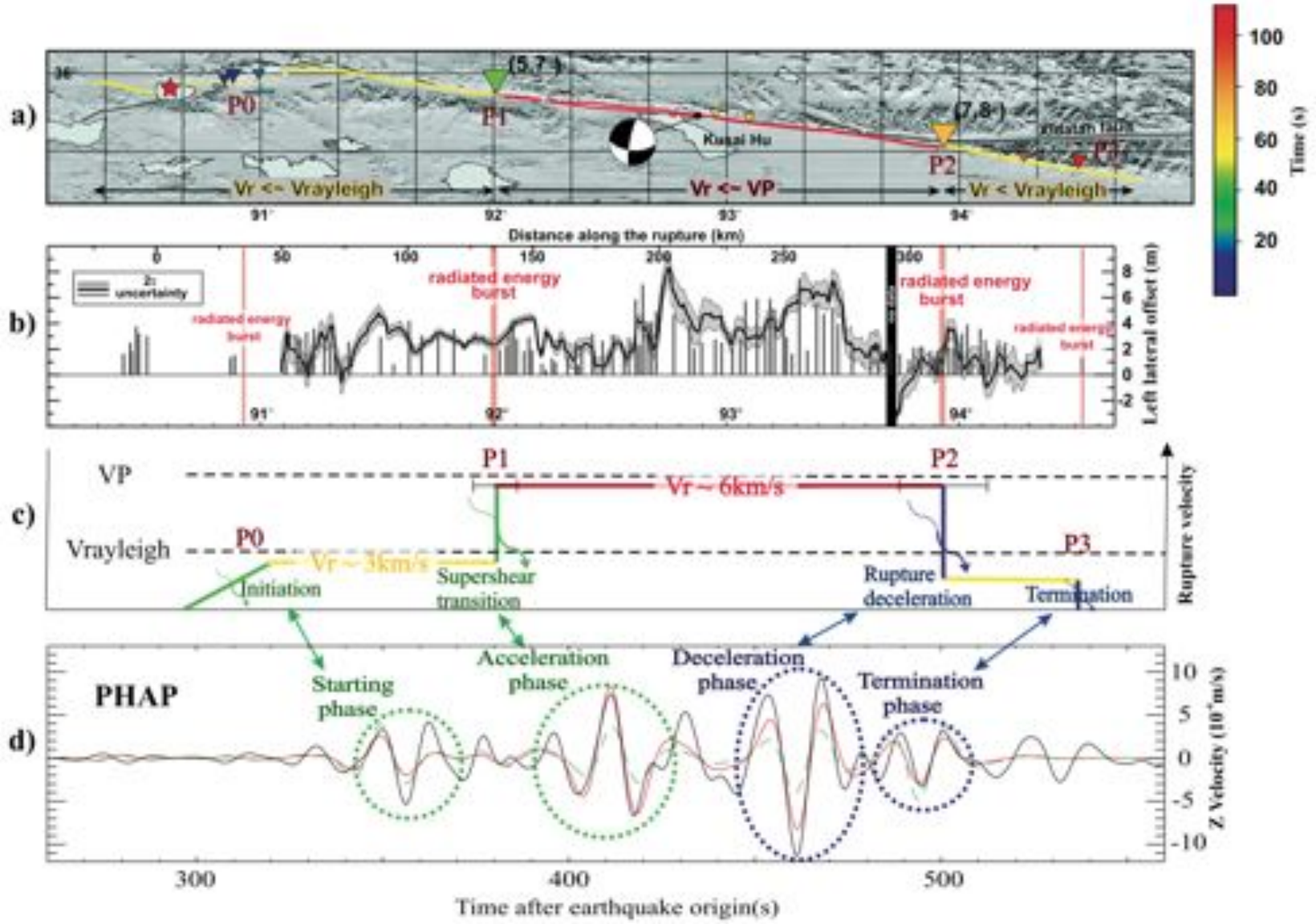
SUPER-SHEAR RUPTURE





Vallee et al. [2008]

SUPER-SHEAR RUPTURE



Consequences for strong ground motion

Vallee et al. [2008]

Some Fast Earthquake Questions

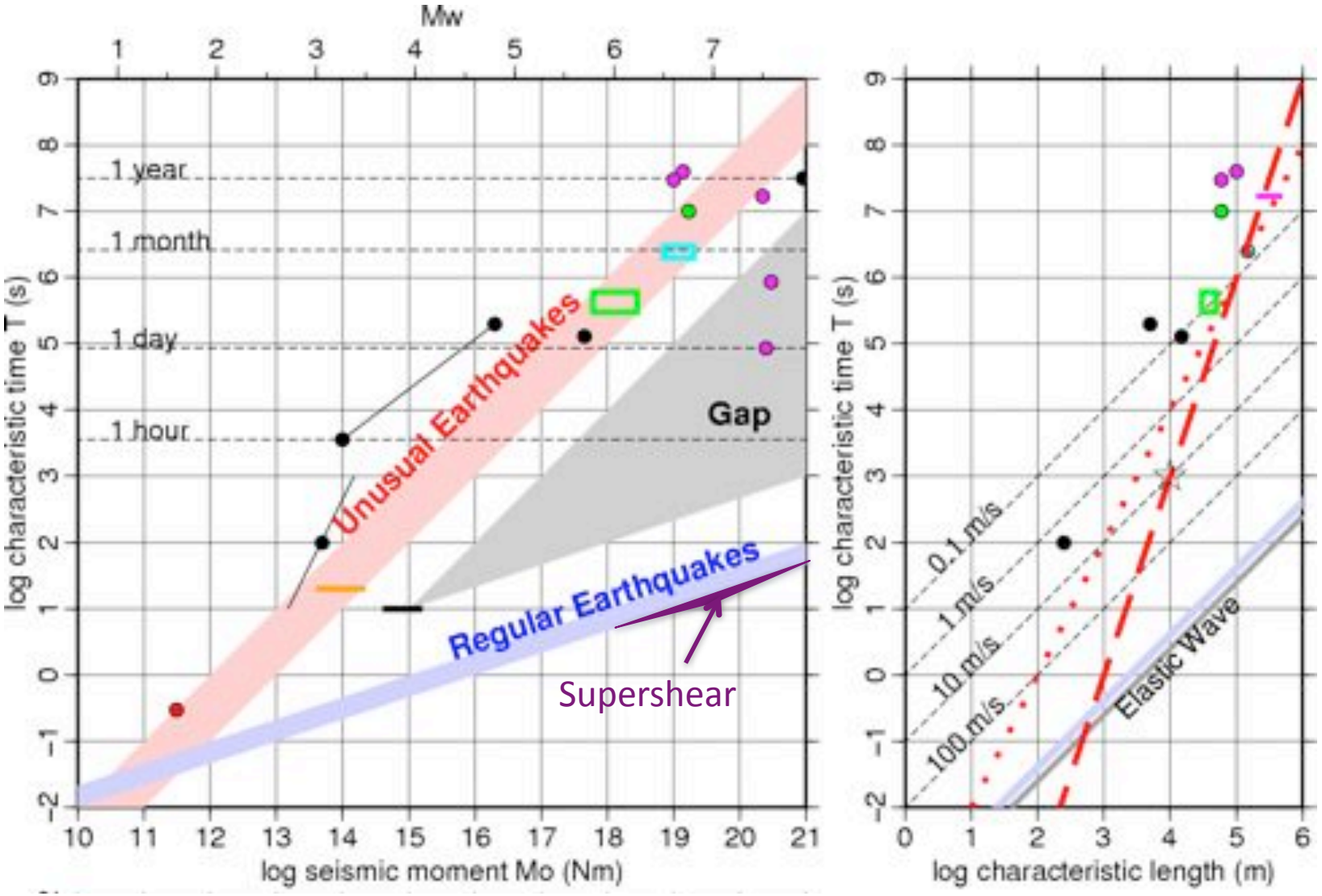
Are there large, very high stress drop earthquakes?

Is super-shear rupture exceptional, or typical, for large strike-slip earthquakes?

Does super-shear rupture occur for other earthquake types?

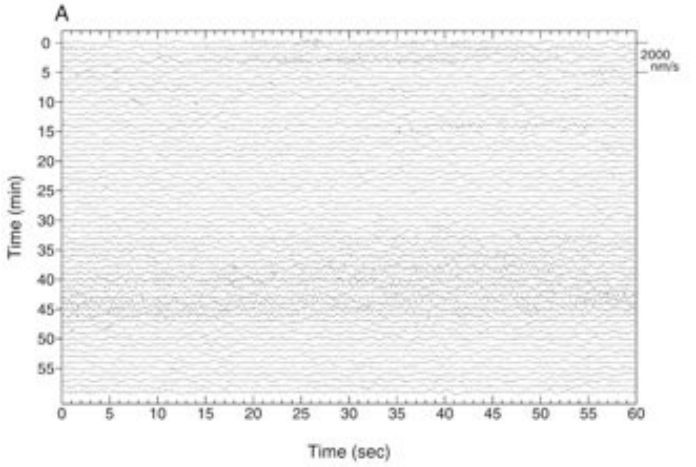
Why isn't super-shear rupture more obvious?
Why not stronger high-frequency ground motion?
Where are the Mach fronts?

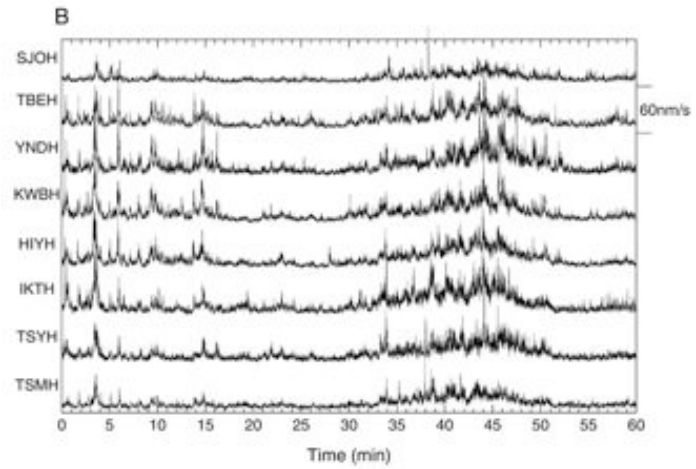
Earthquake Size-Duration Scaling

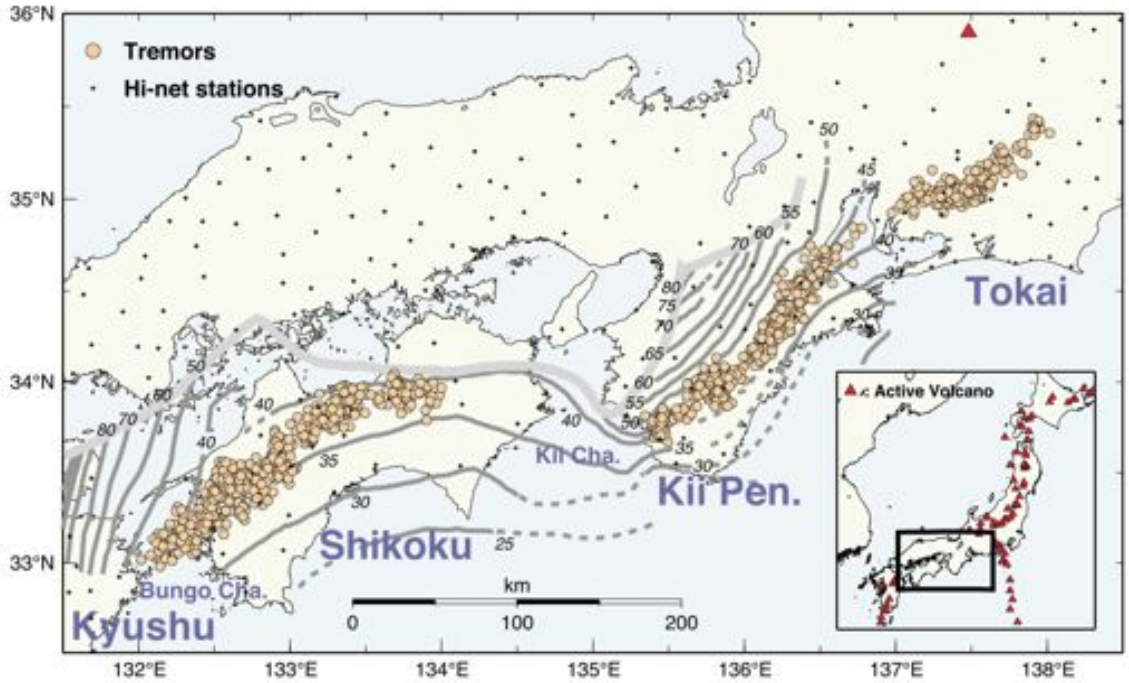


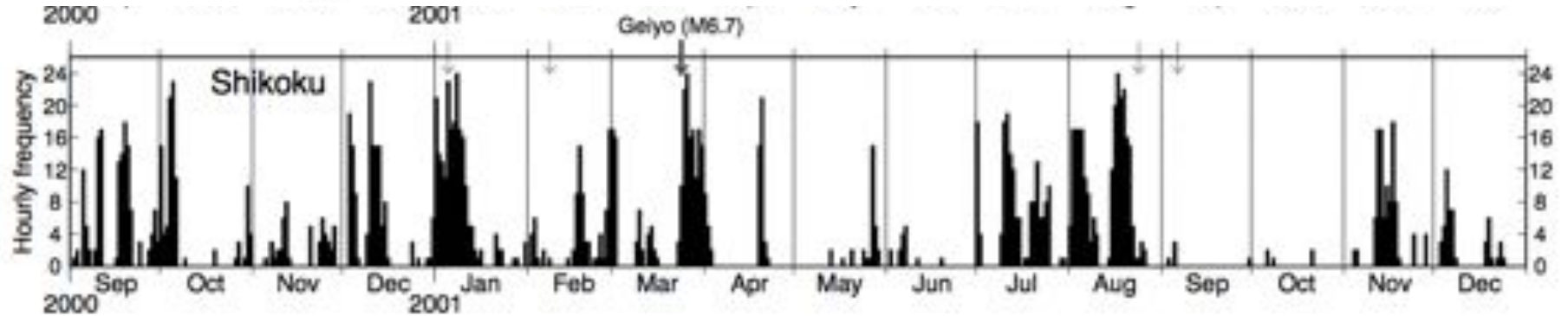
Ide et al. [2007]

Deep Non-Volcanic Tremor



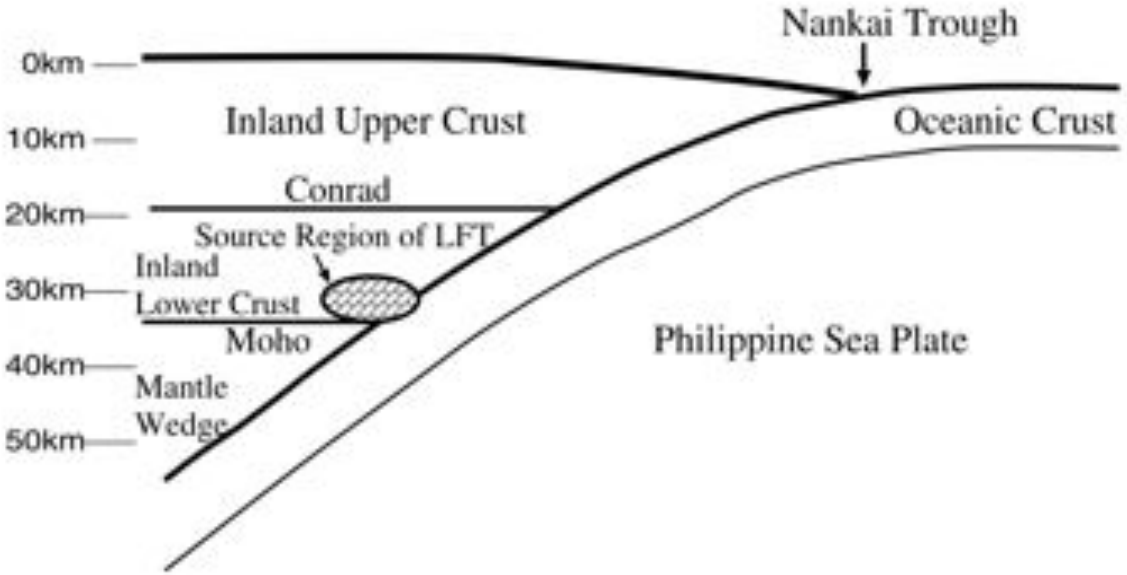


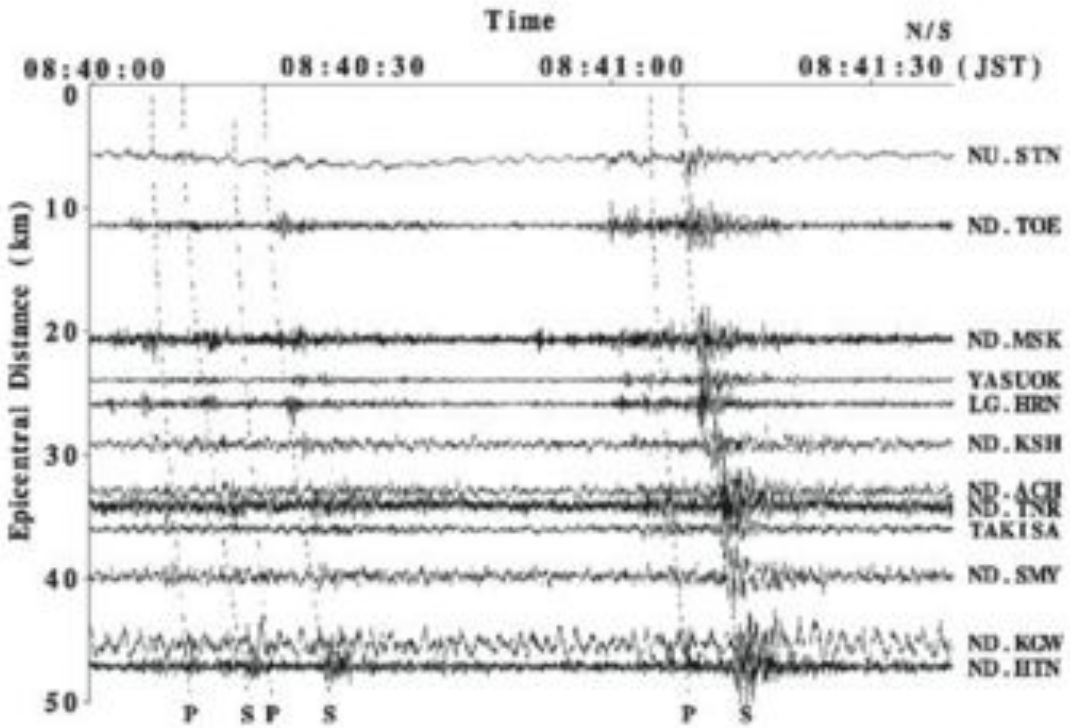


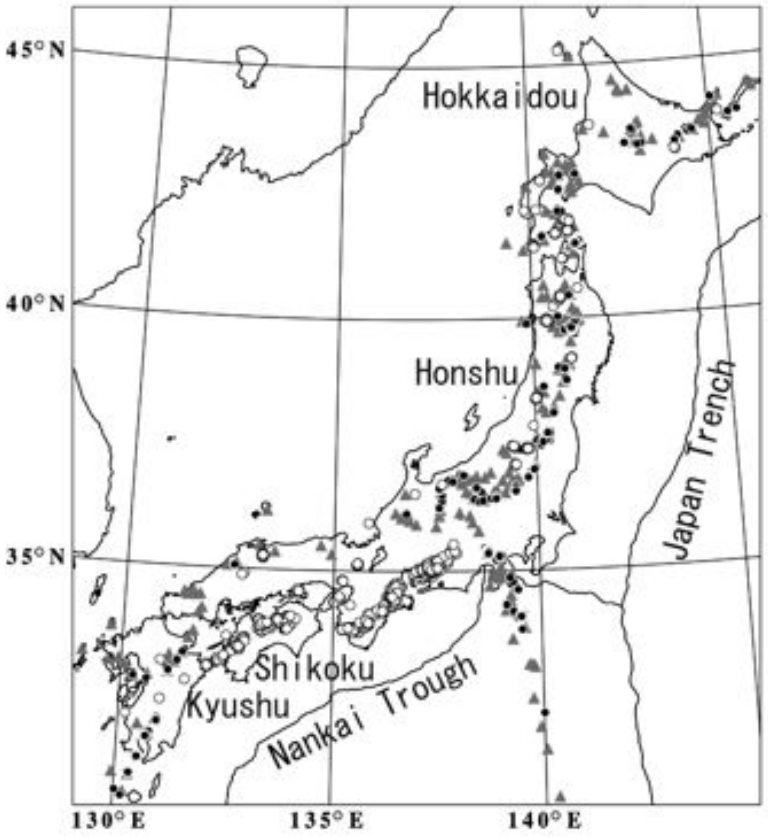


Obara [2002]

Low Frequency Earthquakes



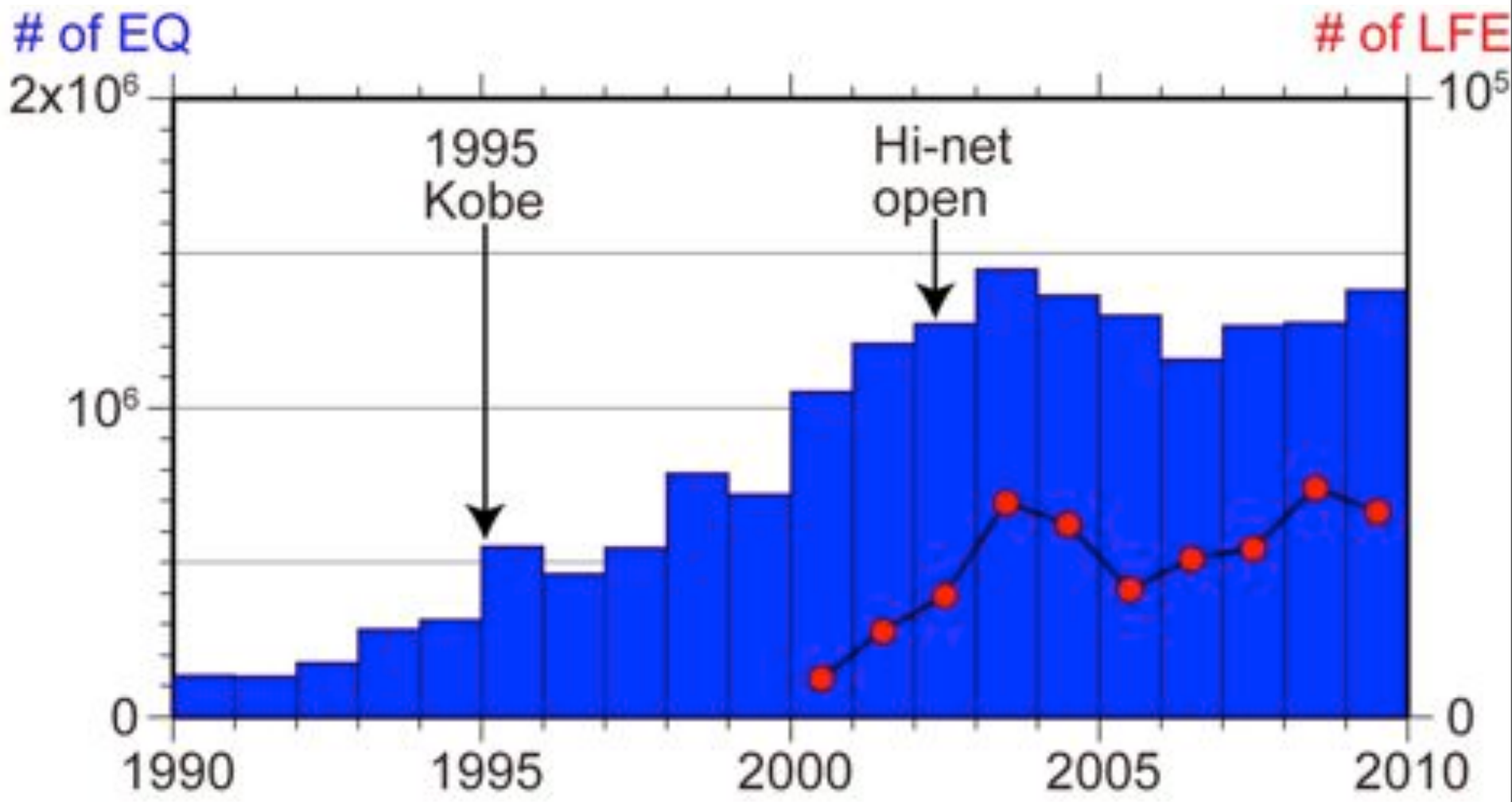




~1 s duration

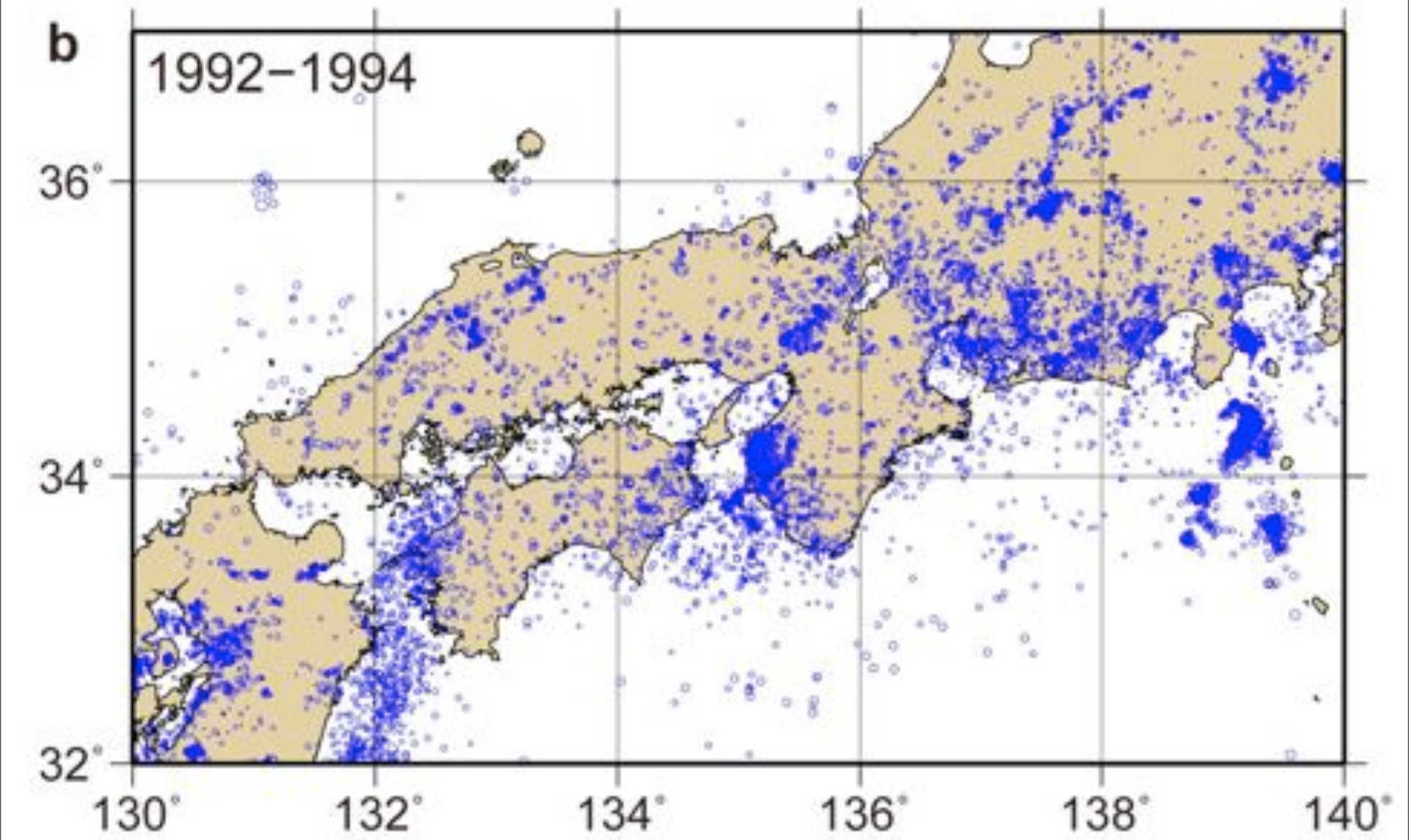
Katsumata and Kamaya [2003]

Importance of Improved Monitoring



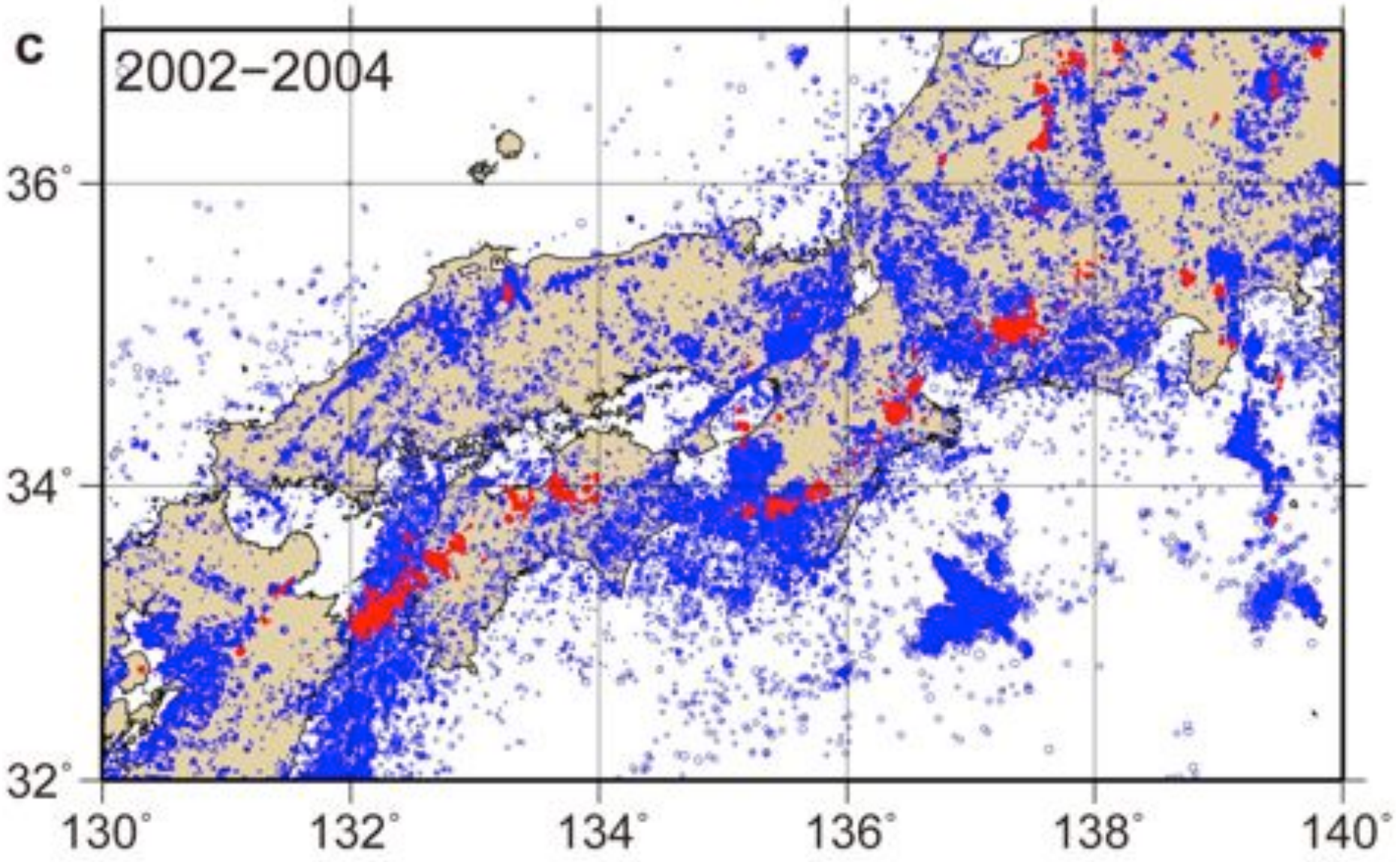
Beroza and Ide [2011]

Importance of Improved Monitoring



Beroza and Ide [2011]

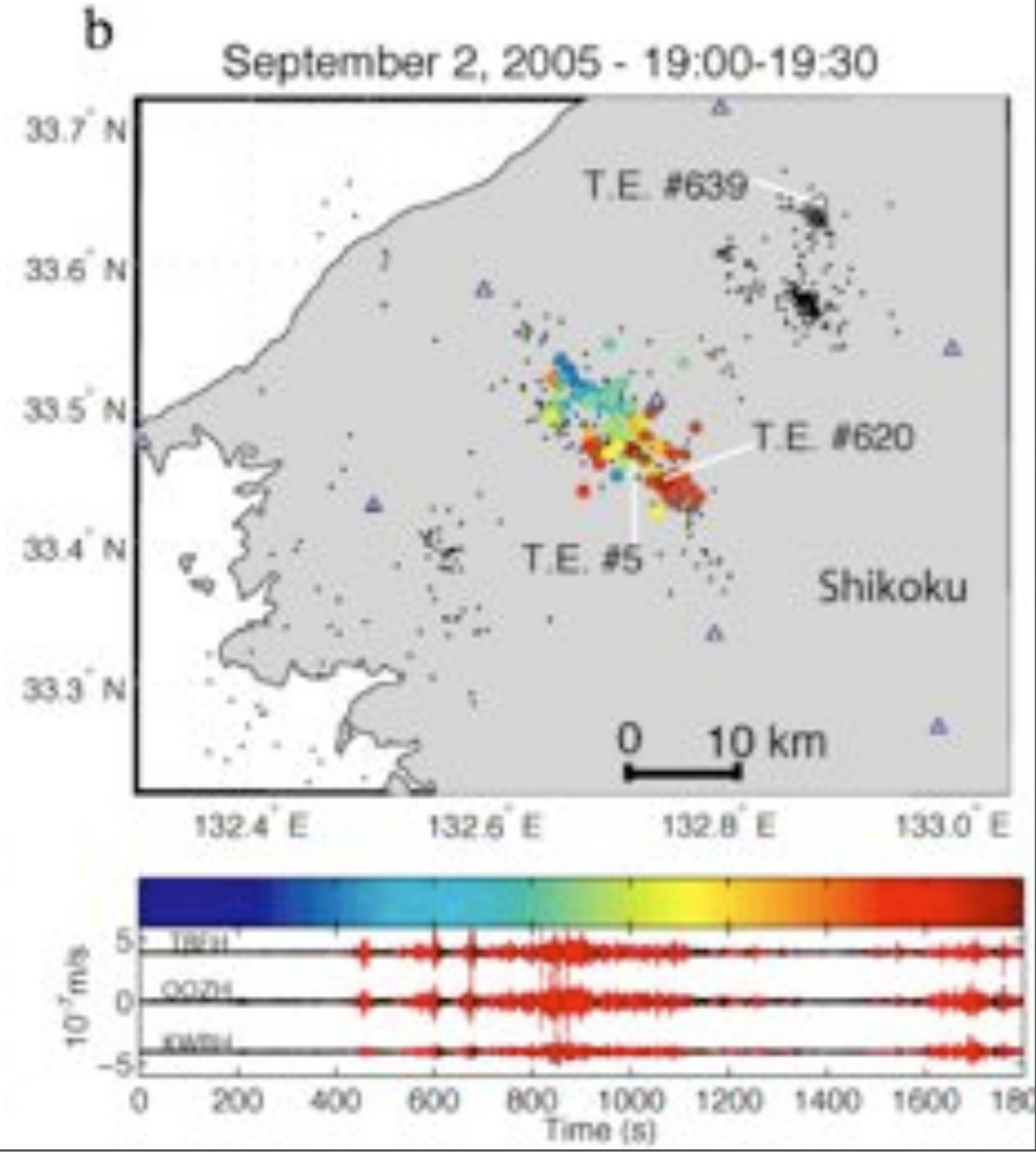
Importance of Improved Monitoring



Beroza and Ide [2011]

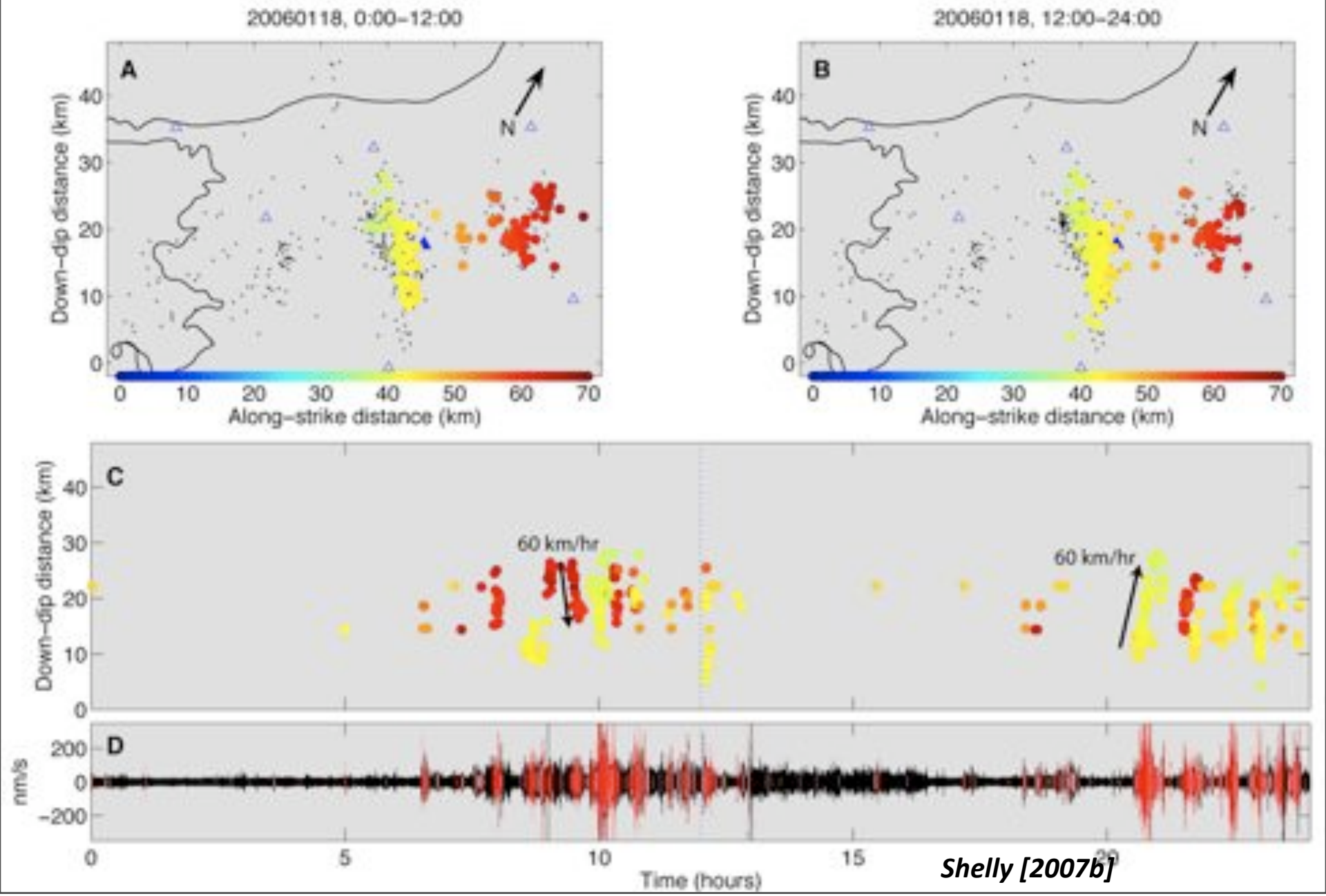
Tremor matches LFEs (red)

Can locate tremor precisely



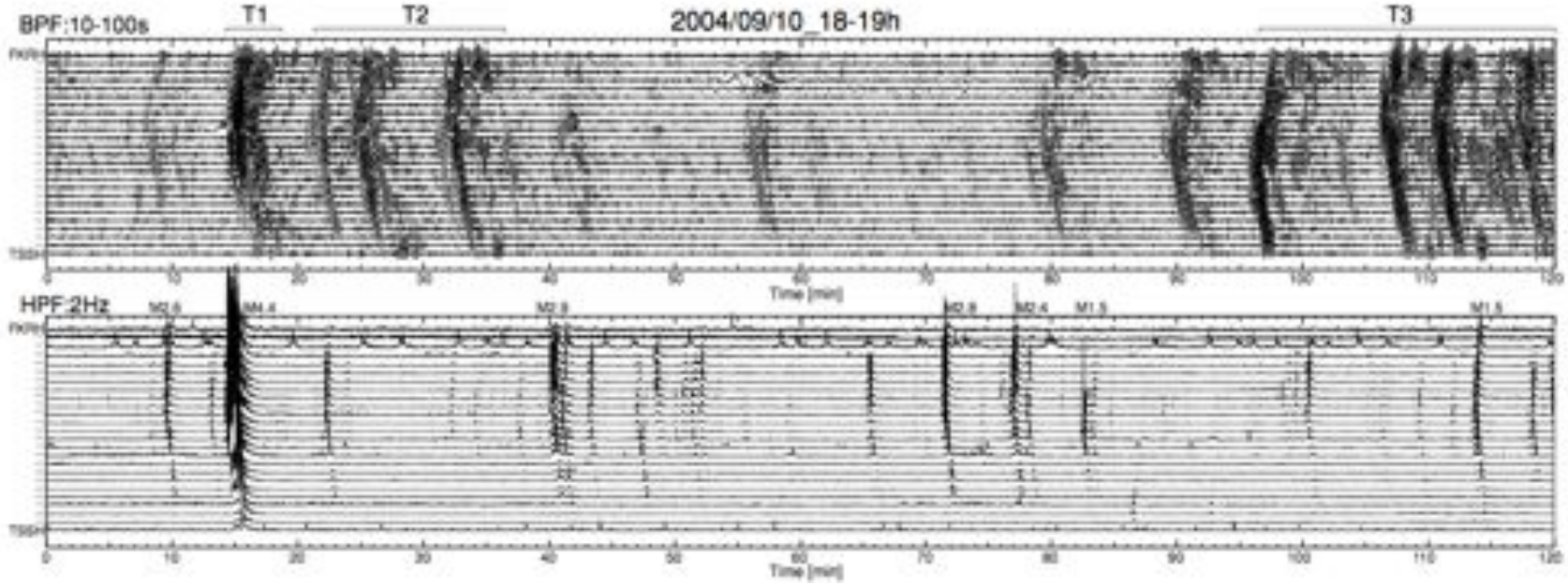
Shelly et al. [2007a]

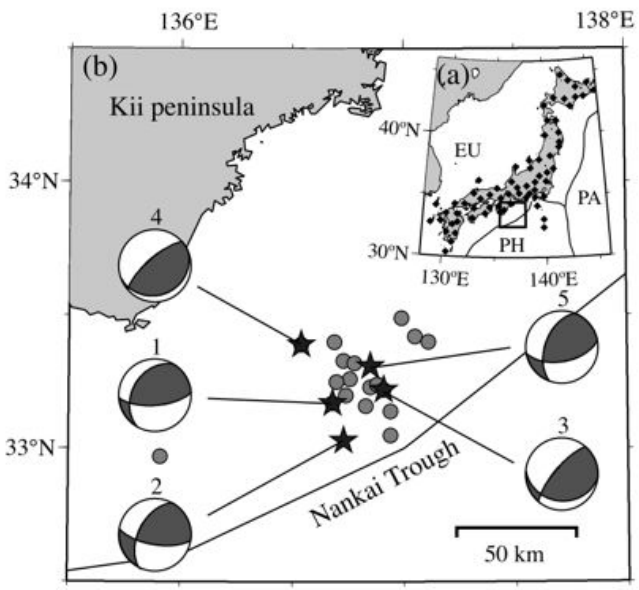
LFEs Allow us to Examine Tremor in Detail

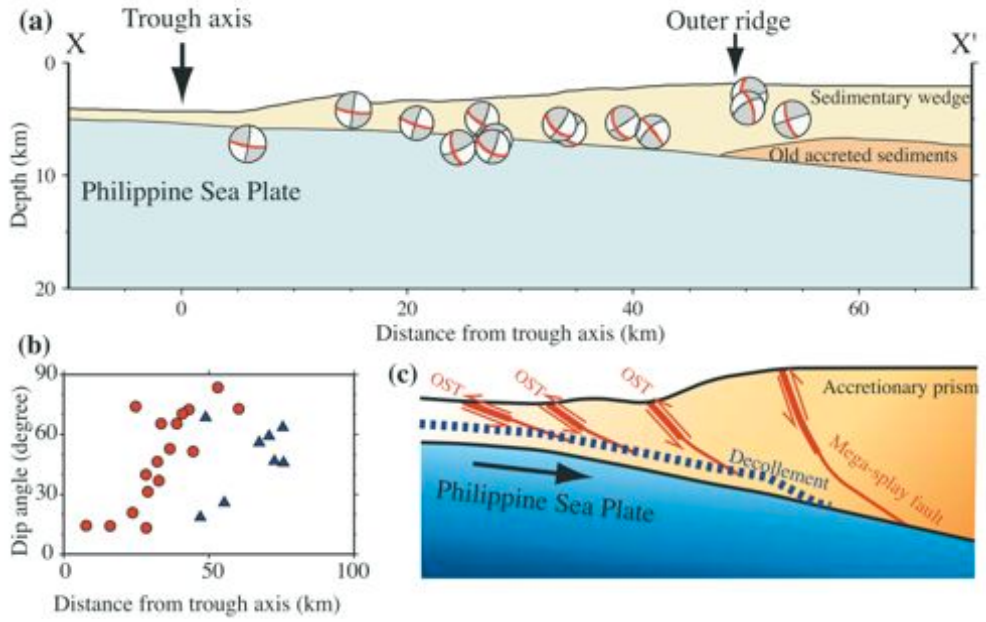


Shelly [2007b]

Very Low Frequency Earthquakes (Shallow)

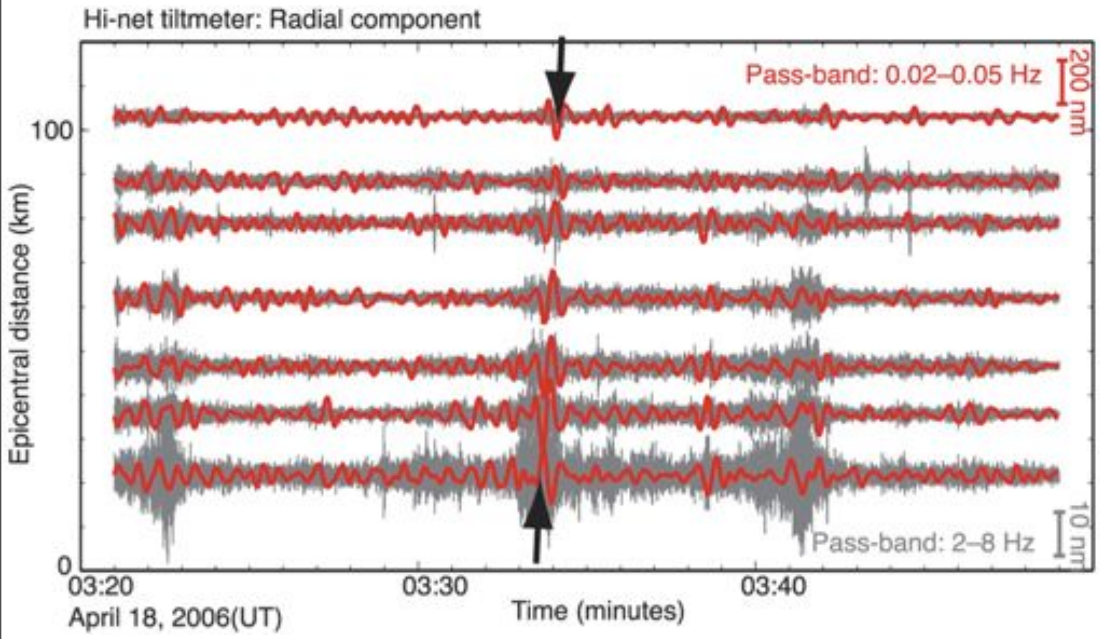


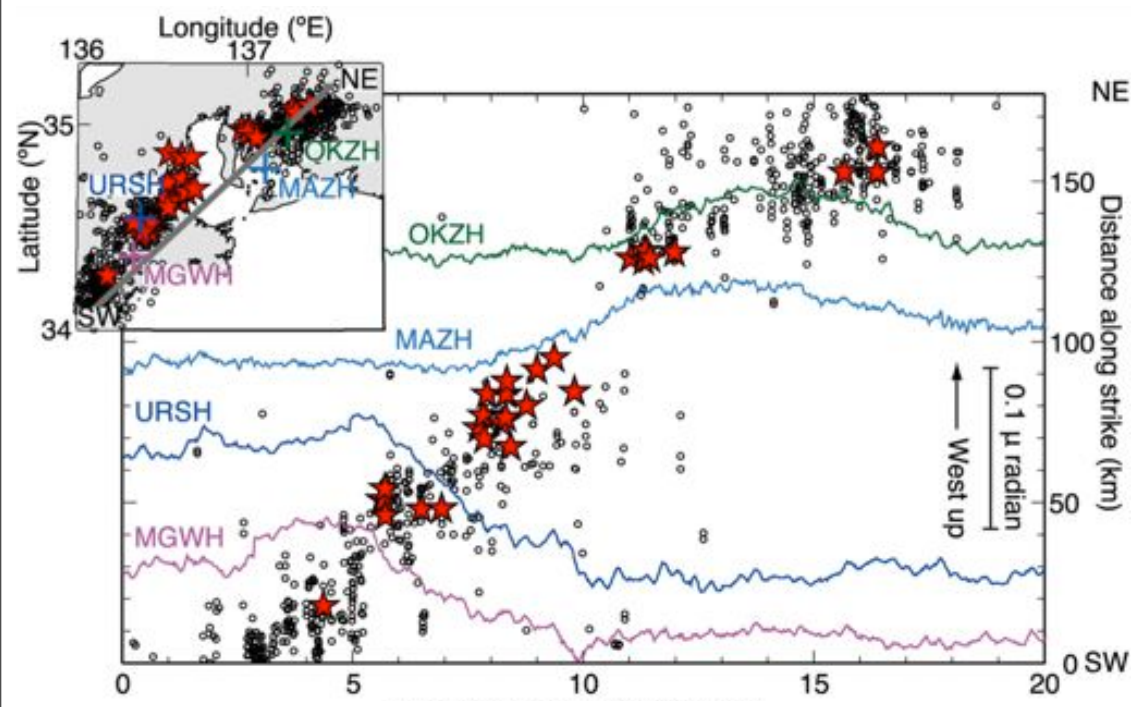


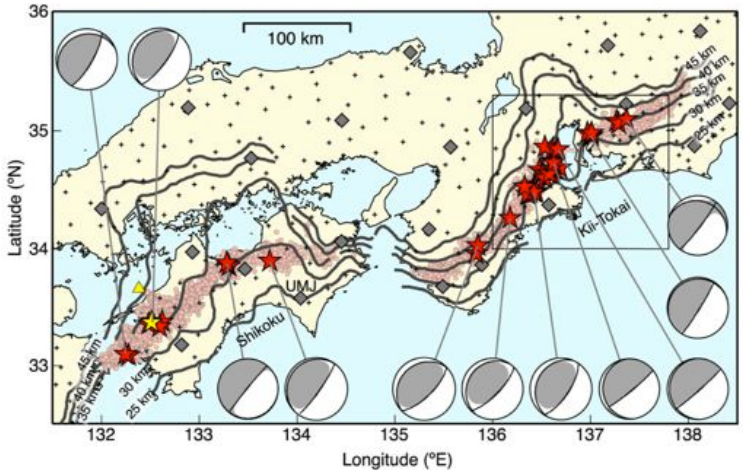


Obara and Ito [2005]; Ito and Obara [2006a,b]

Very Low Frequency Earthquakes (Deep)



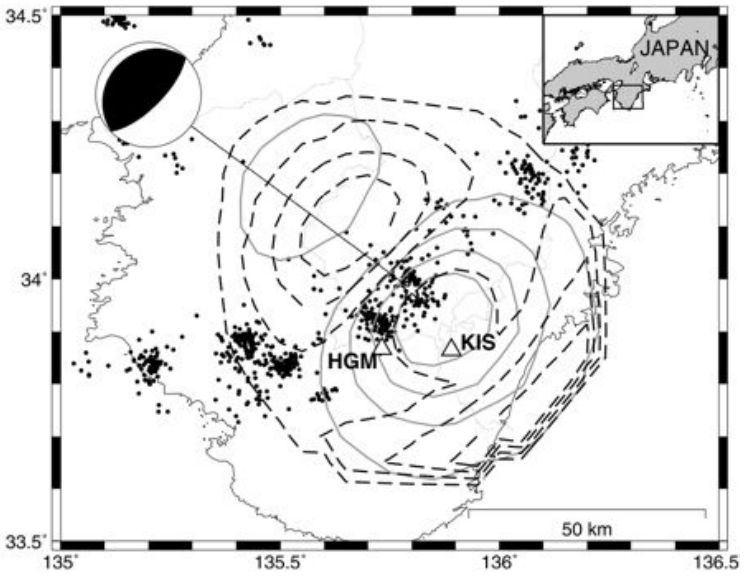


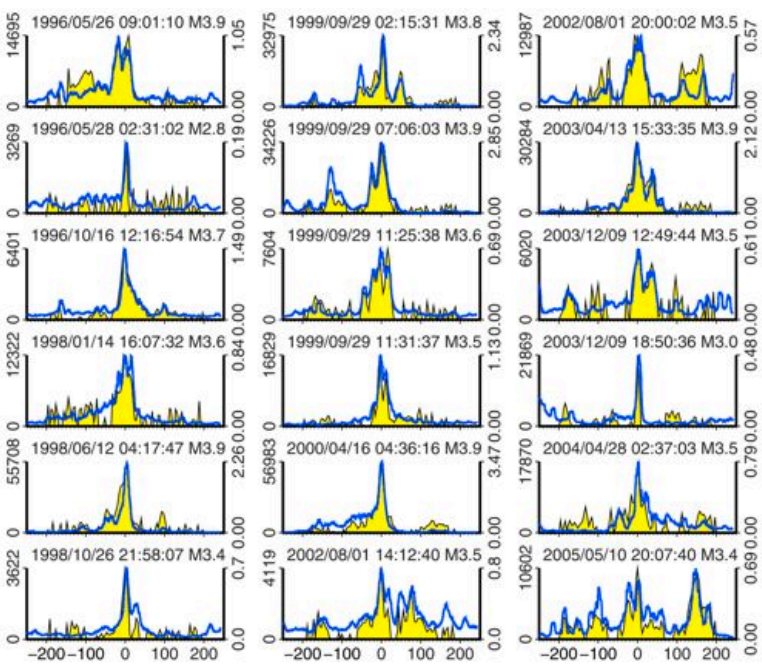


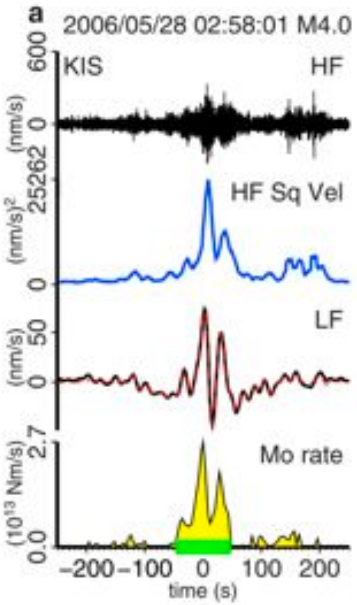
~10 s duration

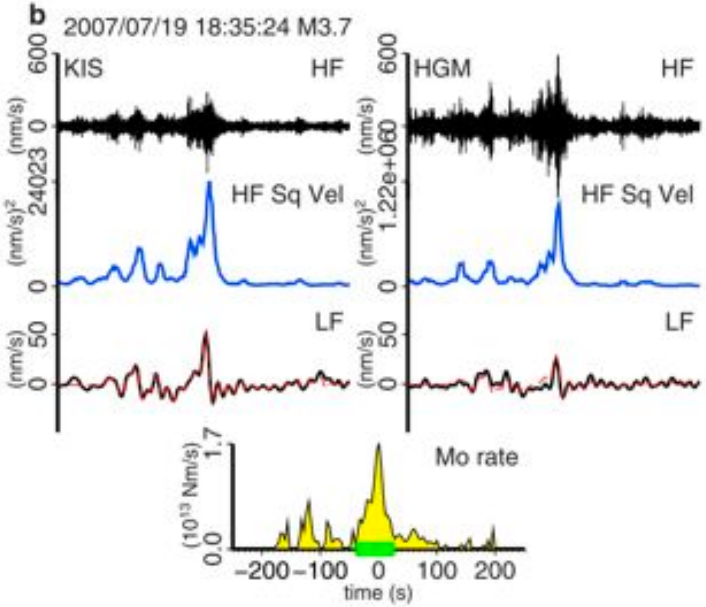
Ito et al. [2007]

Very, Very Low Frequency Earthquakes





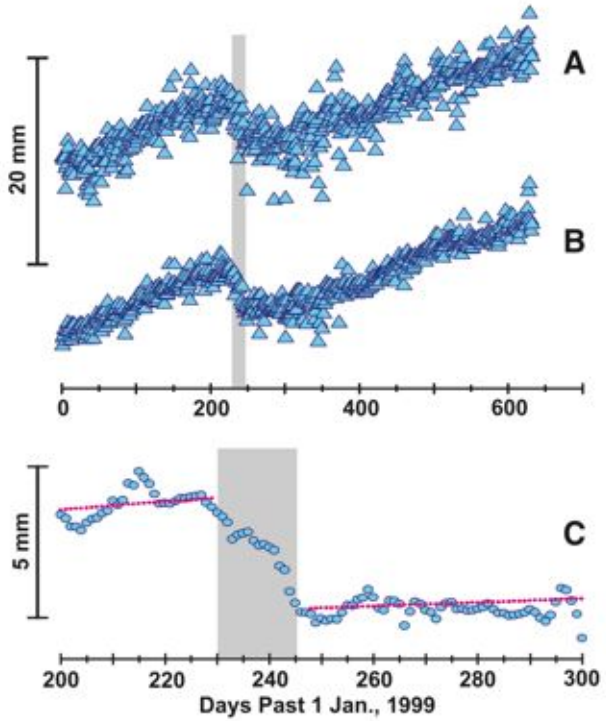


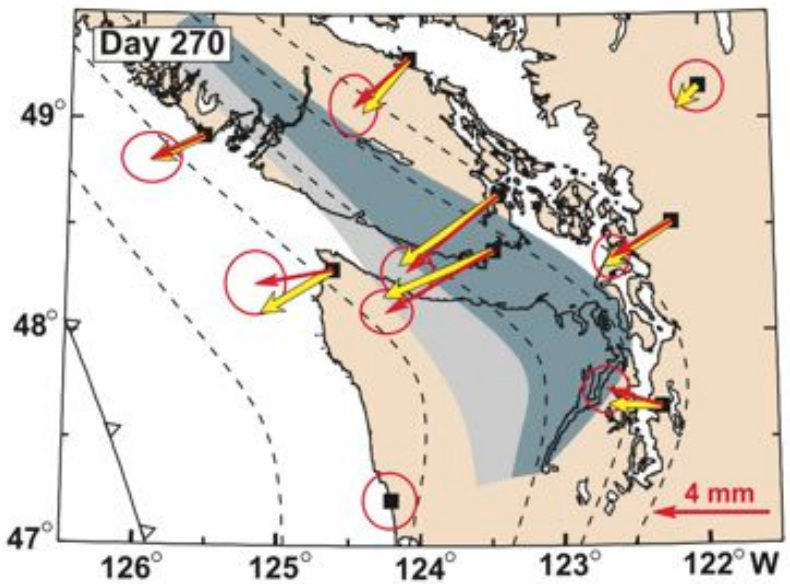


~100 s duration

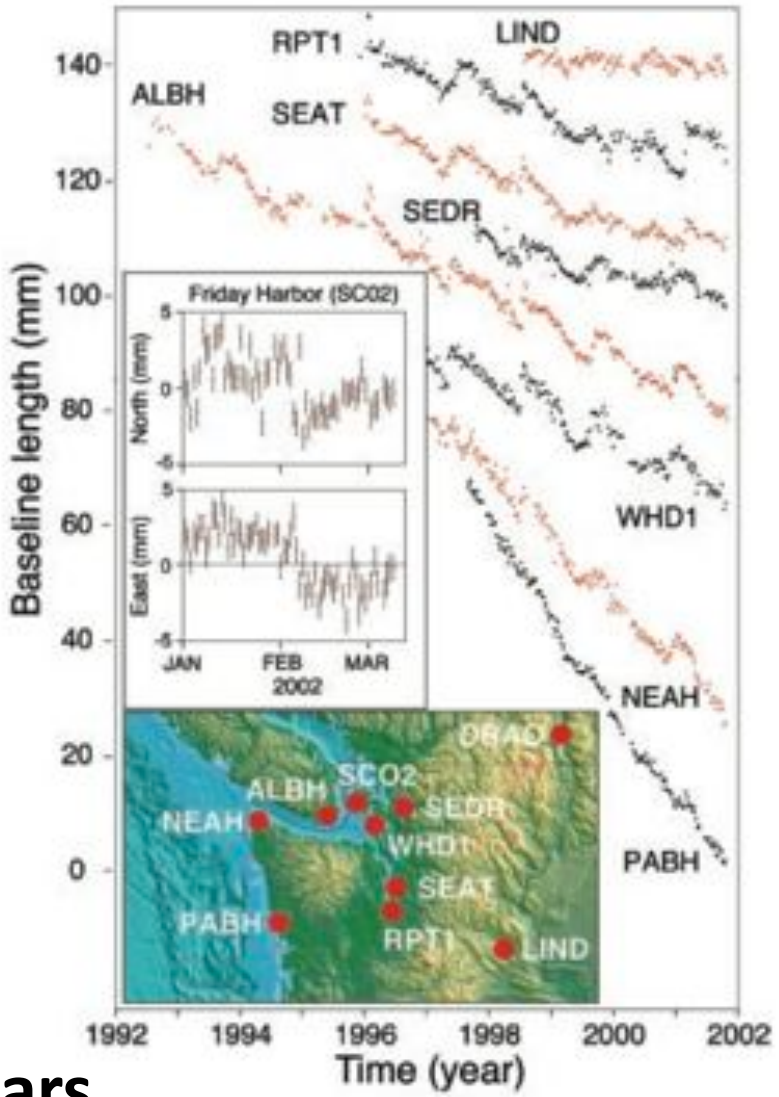
Ide et al. [2008]

Slow Slip Events





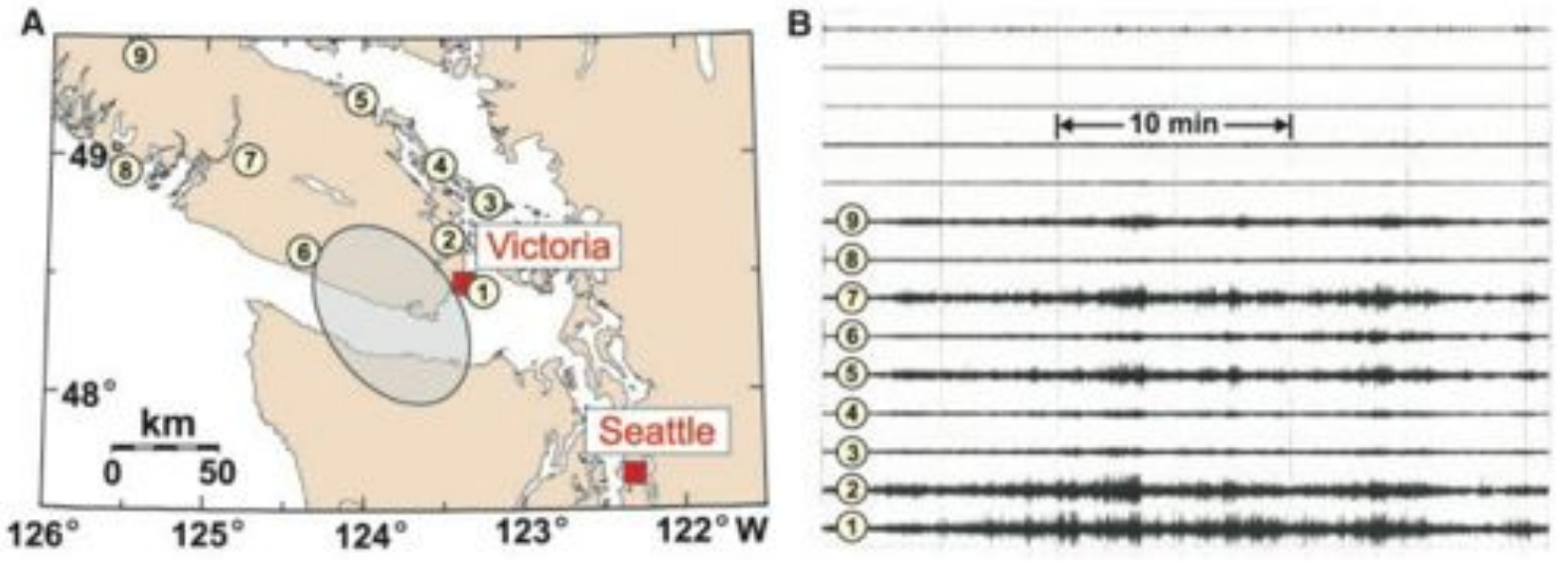
Dragert et al. [2001]



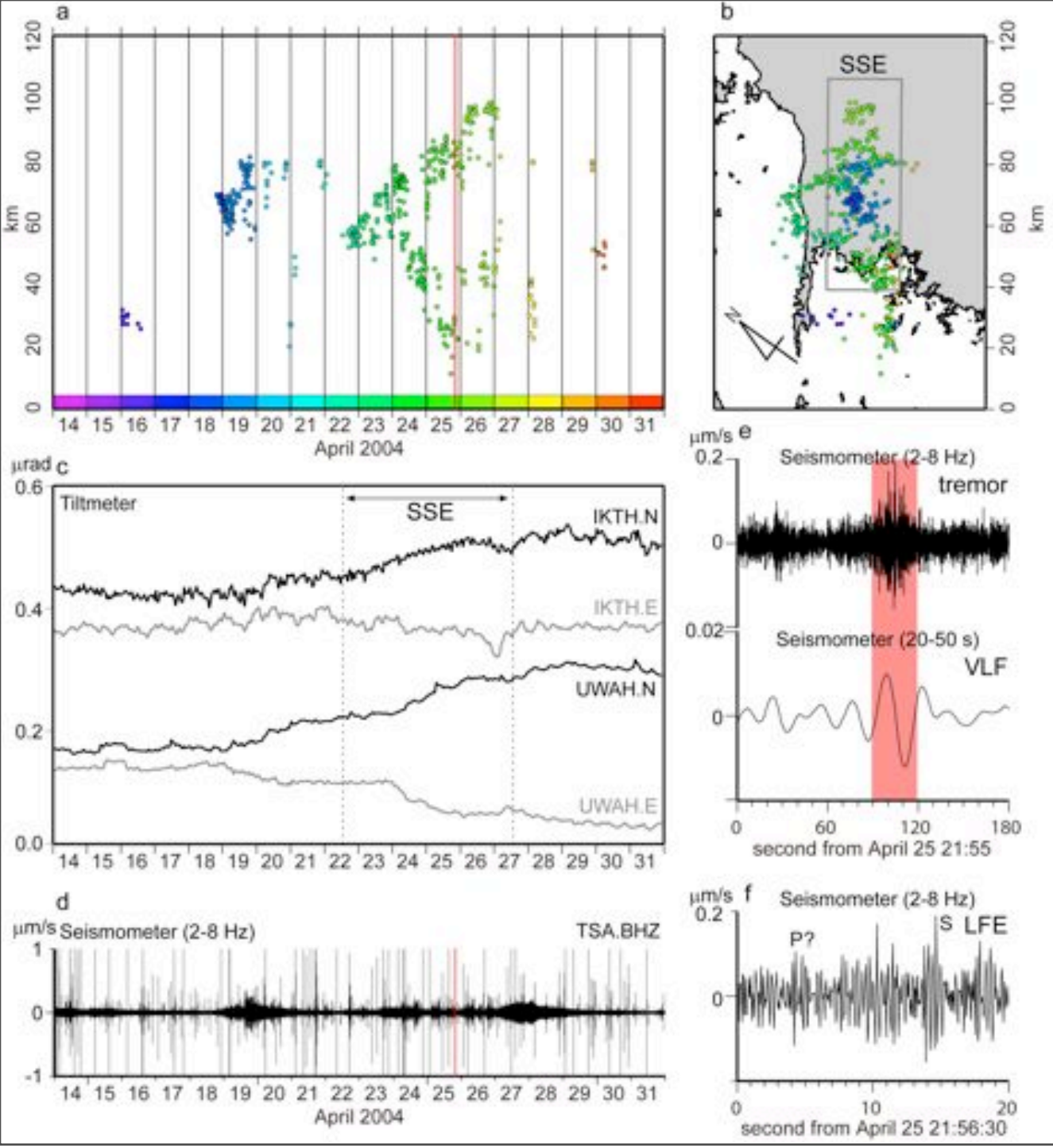
Miller et al. [2002]

days-years duration

Episodic Tremor and Slip



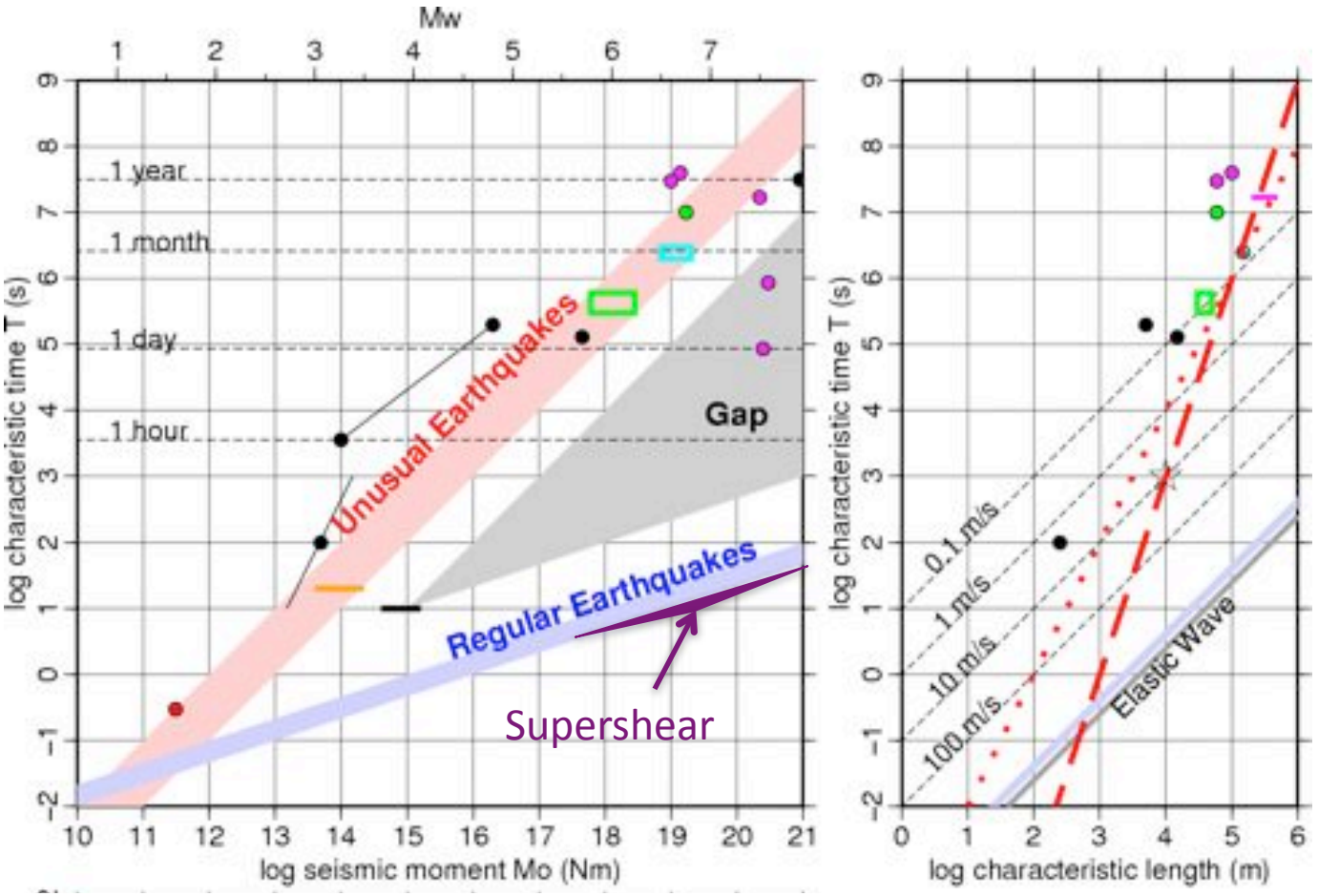
Rogers and Dragert [2003]



Various slow earthquakes: LFEs, VLFs, SSEs occur in synchrony.

Beroza and Ide [2011]

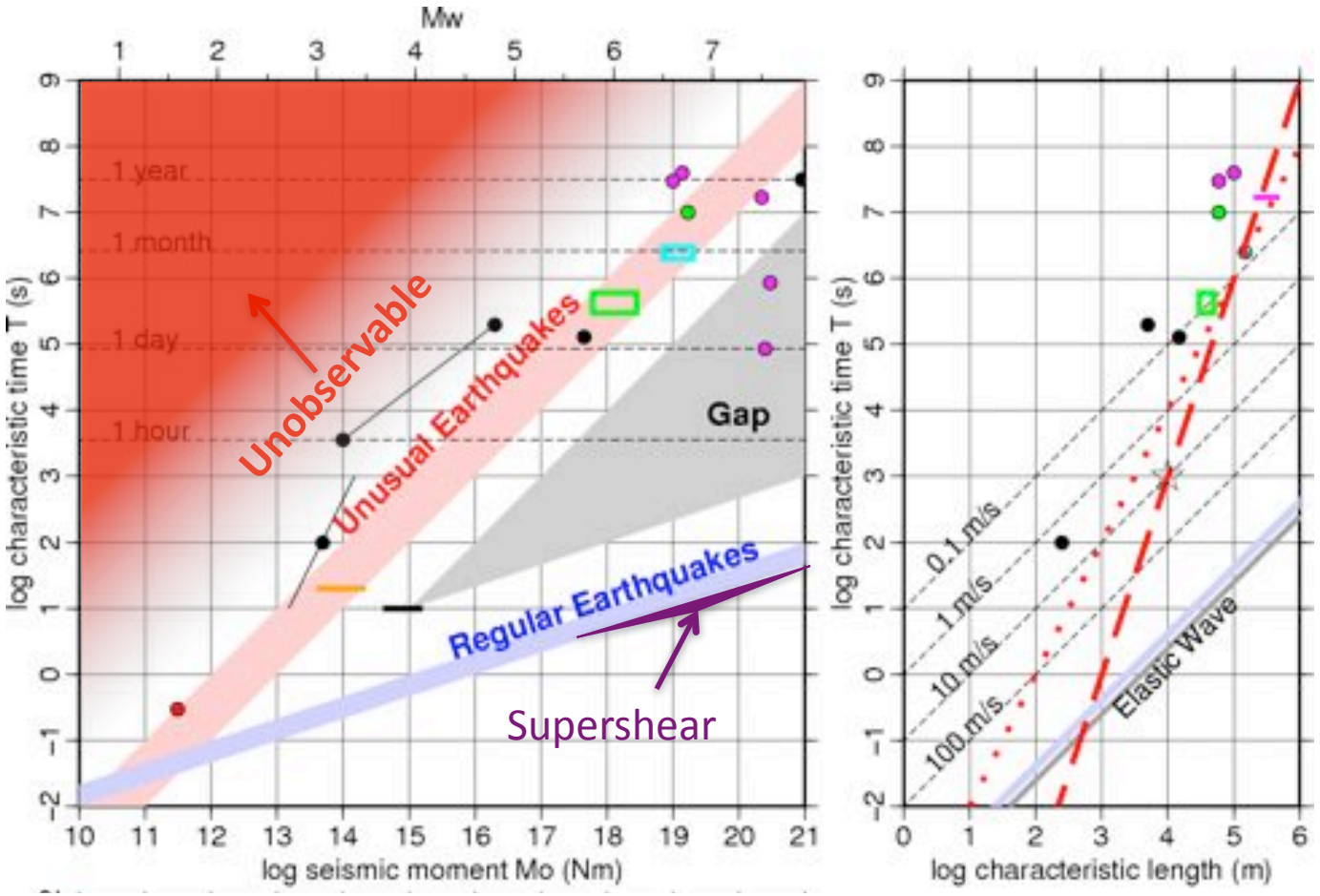
Earthquake Size-Duration Scaling



LFEs/Tremor	**1 s**	**M 1.0-2.0**
VLFs	**10-100 s**	**M 3.5-4.5**
SSEs	**10^5-10^8 s**	**M 6.0-7.5**

Ide et al. [2007]

Earthquake Size-Duration Scaling



LFEs/Tremor	**1 s**	**M 1.0-2.0**
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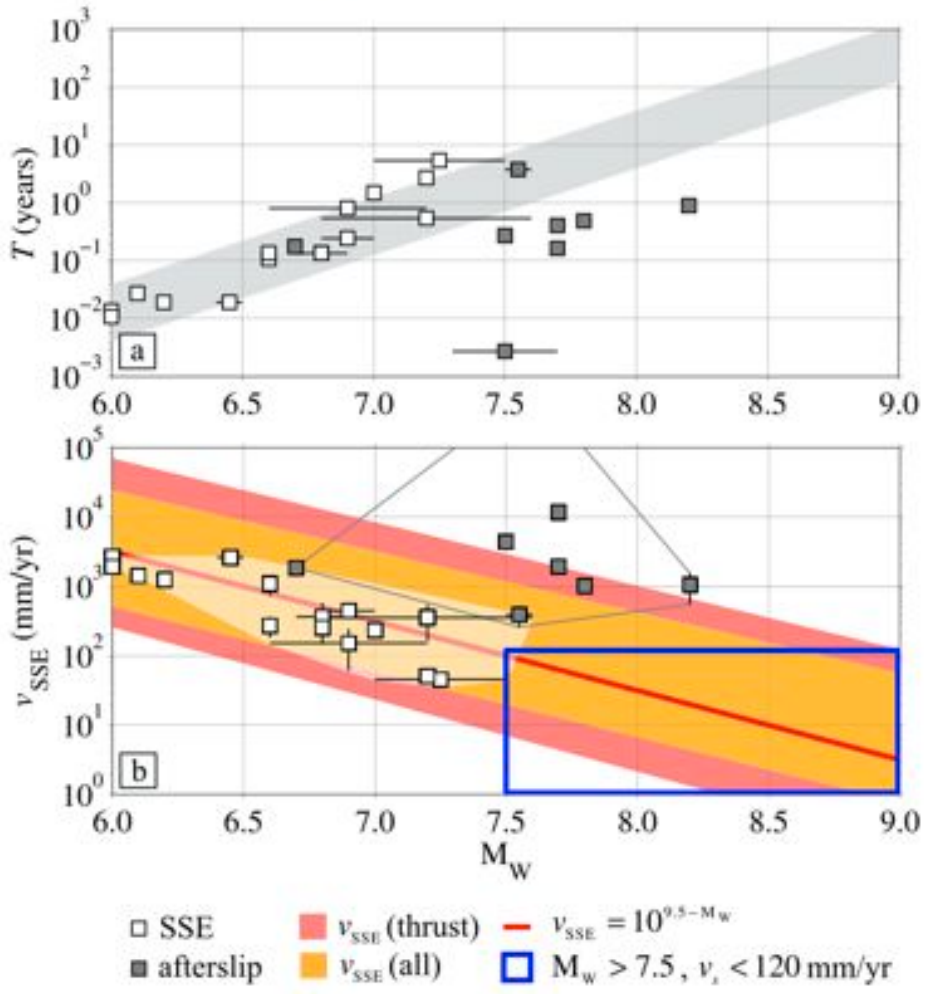
Ide et al. [2007]

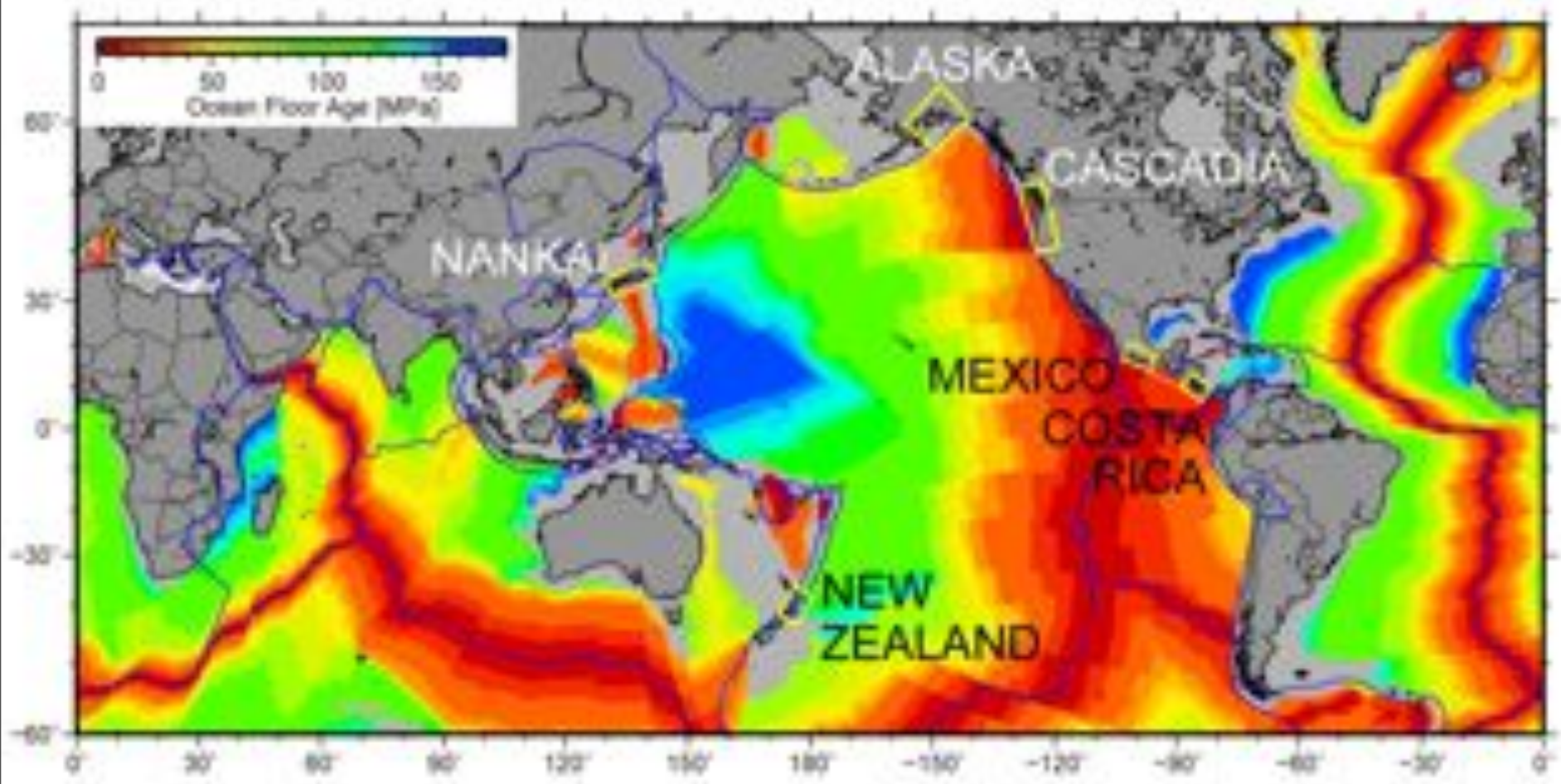
Very Slow Slip Events



If moment-duration scaling of slow earthquakes is extended to M > 8, then duration could be decades and slow earthquakes might be expressed as partial coupling, rather than an aseismic deformation transient.

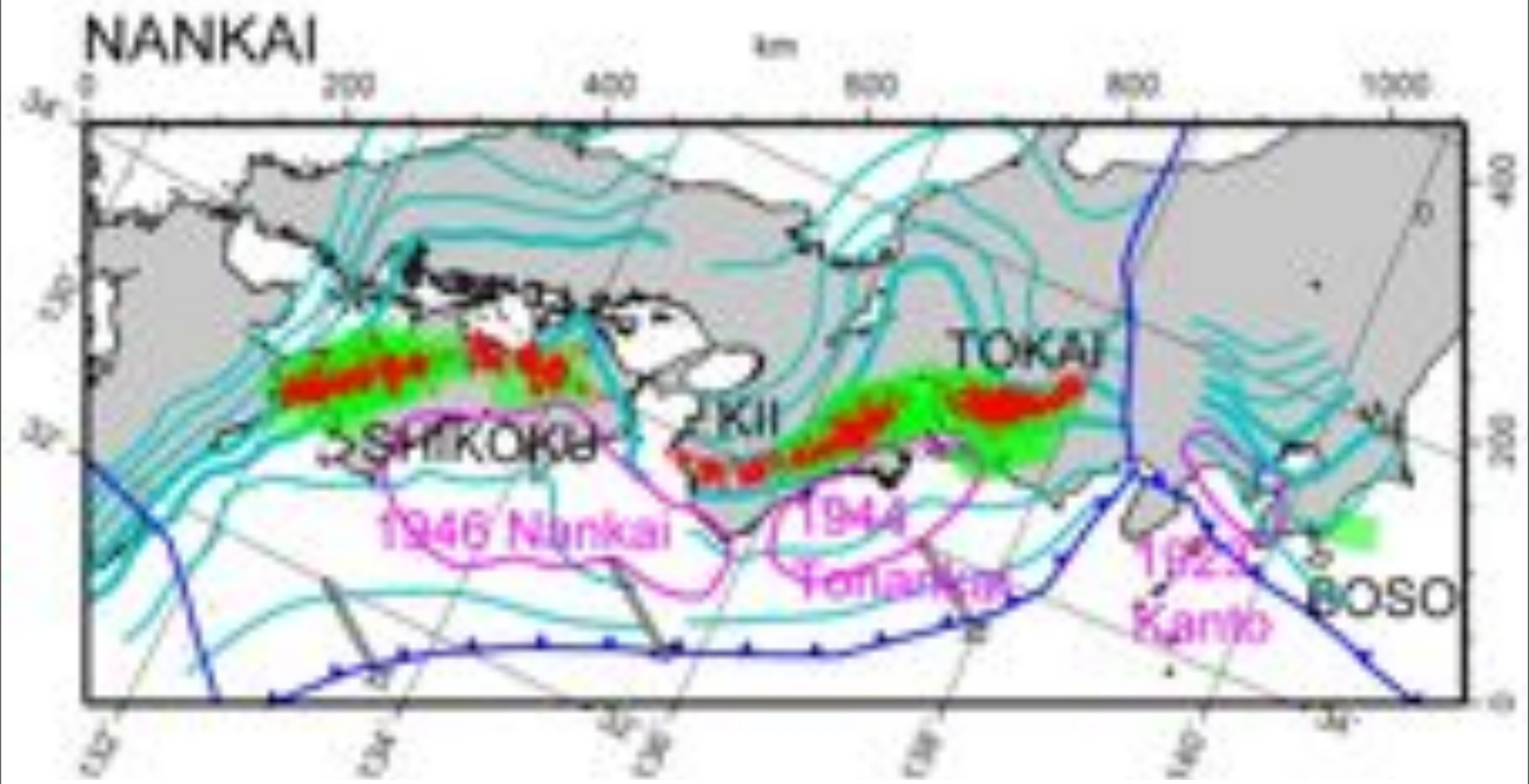
Meade and Loveless [2009]

Geography of Slow Earthquakes



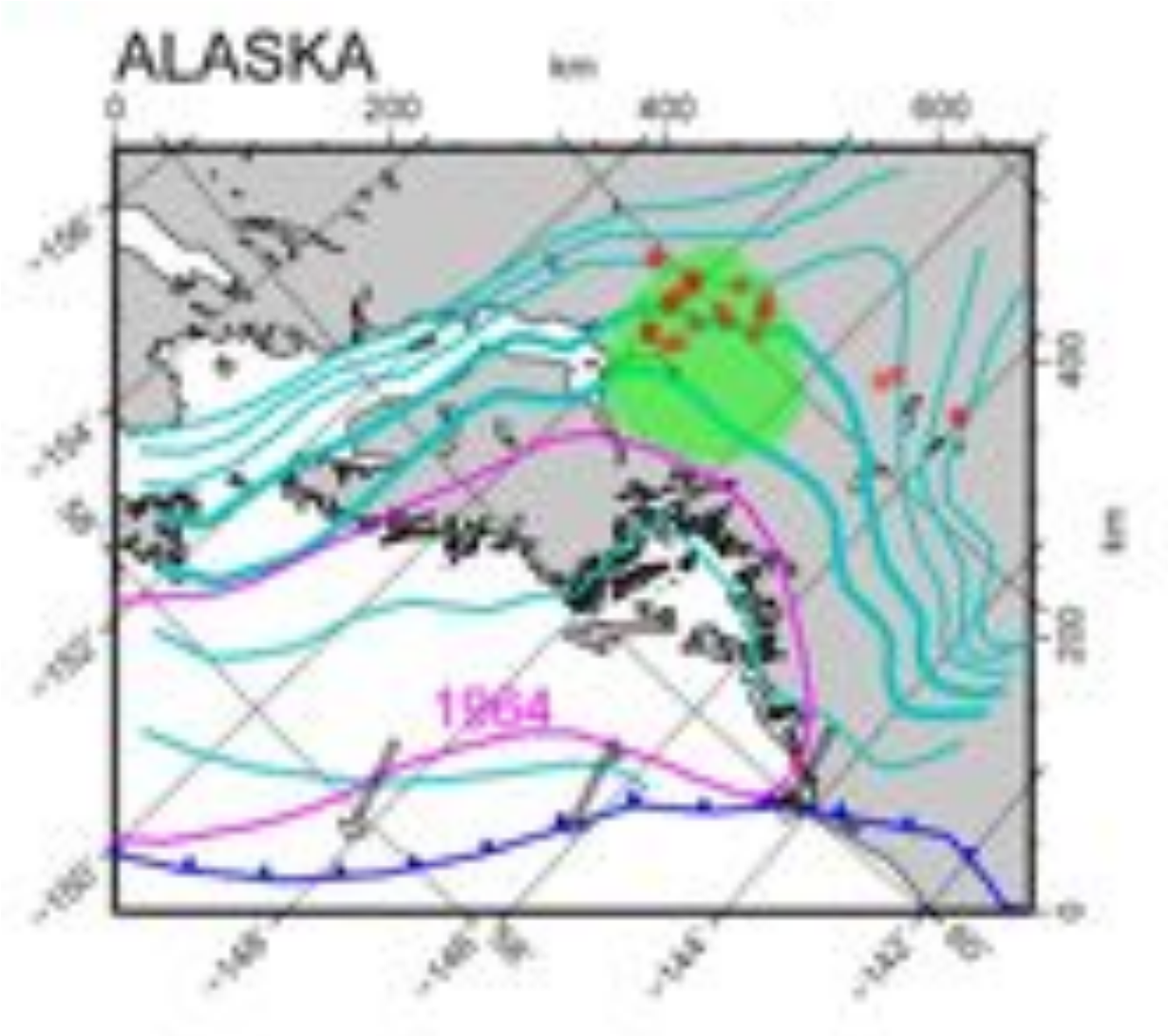
Beroza and Ide [2011]

Geography of Slow Earthquakes



Beroza and Ide [2011]

Geography of Slow Earthquakes

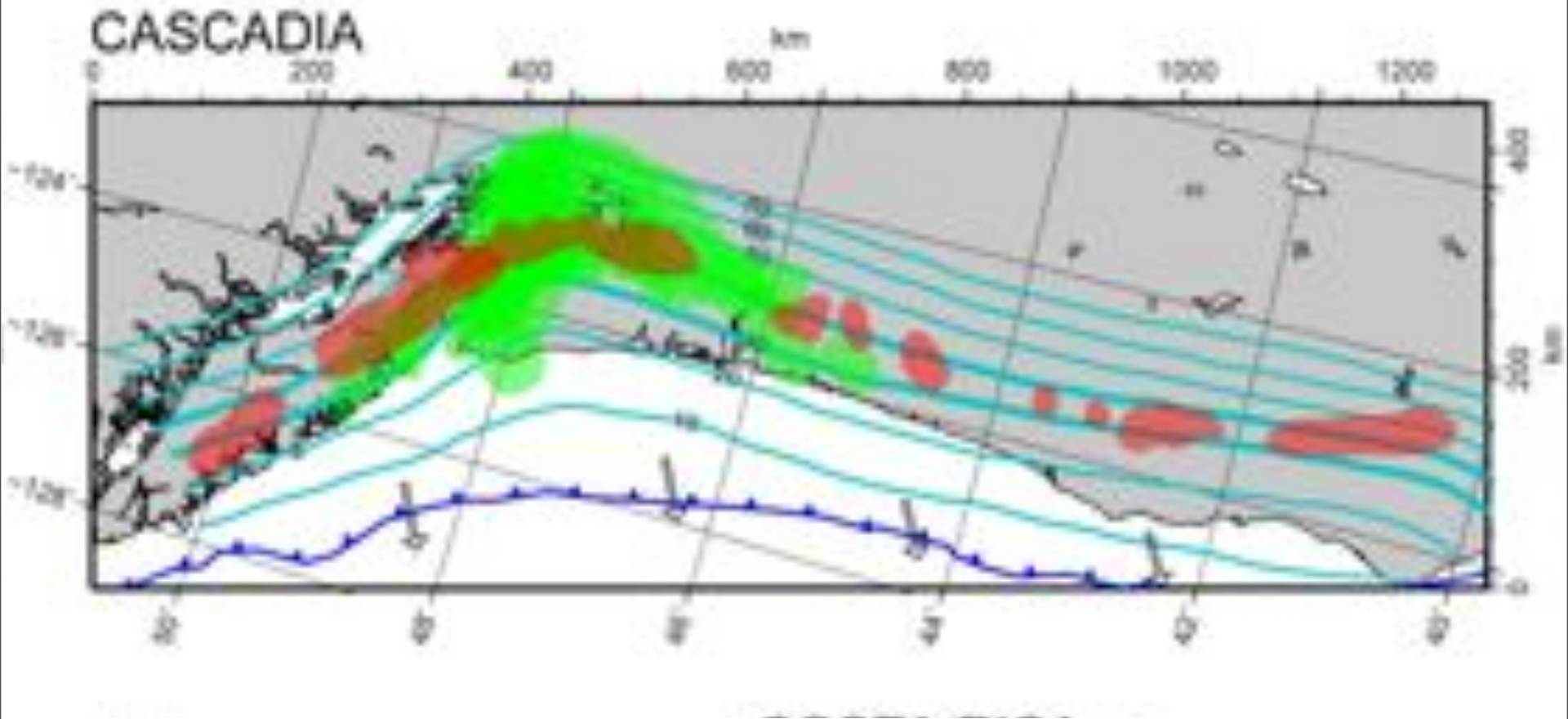


TREMOR SSE

MEGATHRUST

Beroza and Ide [2011]

Geography of Slow Earthquakes

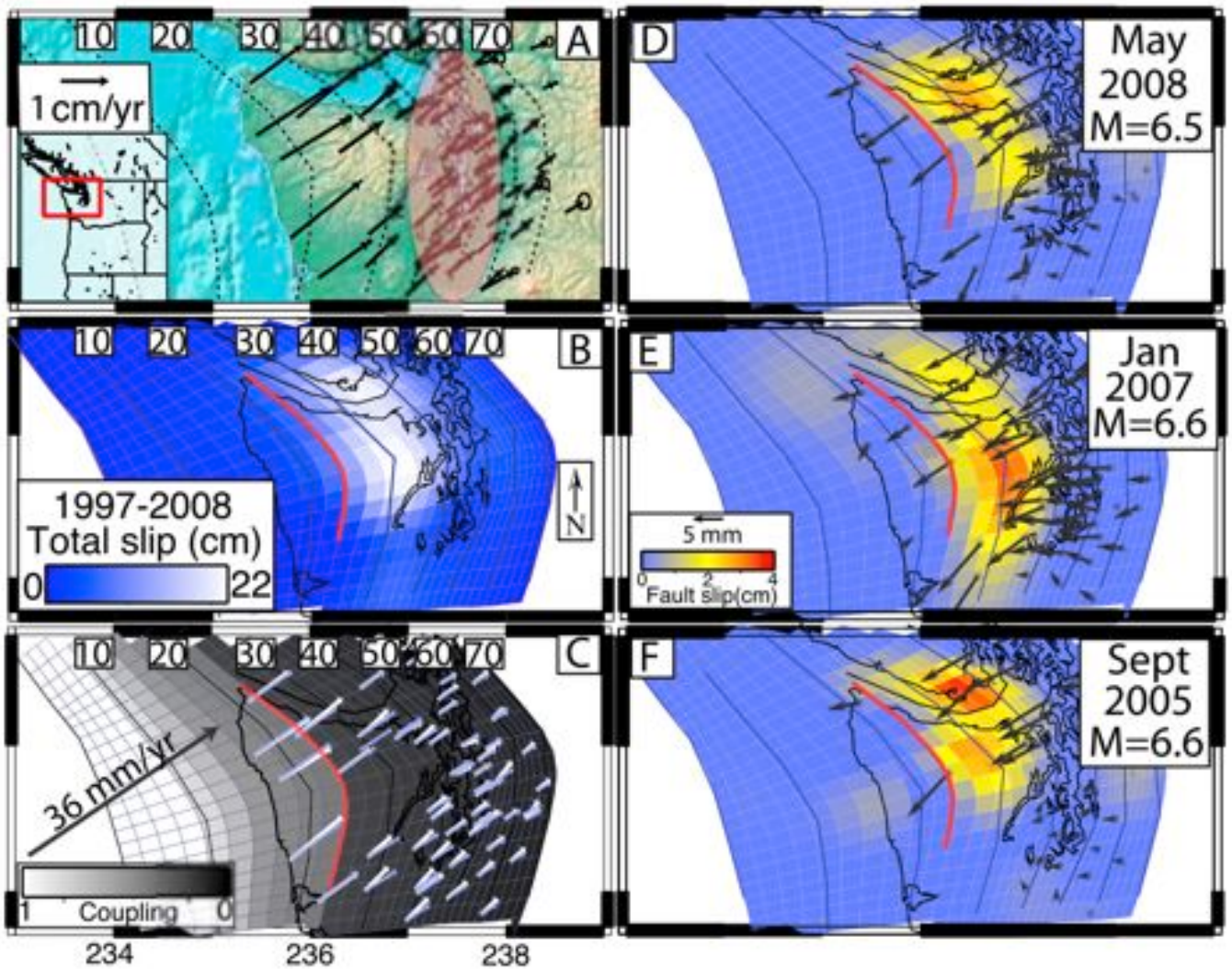


TREMOR SSE

MEGATHRUST

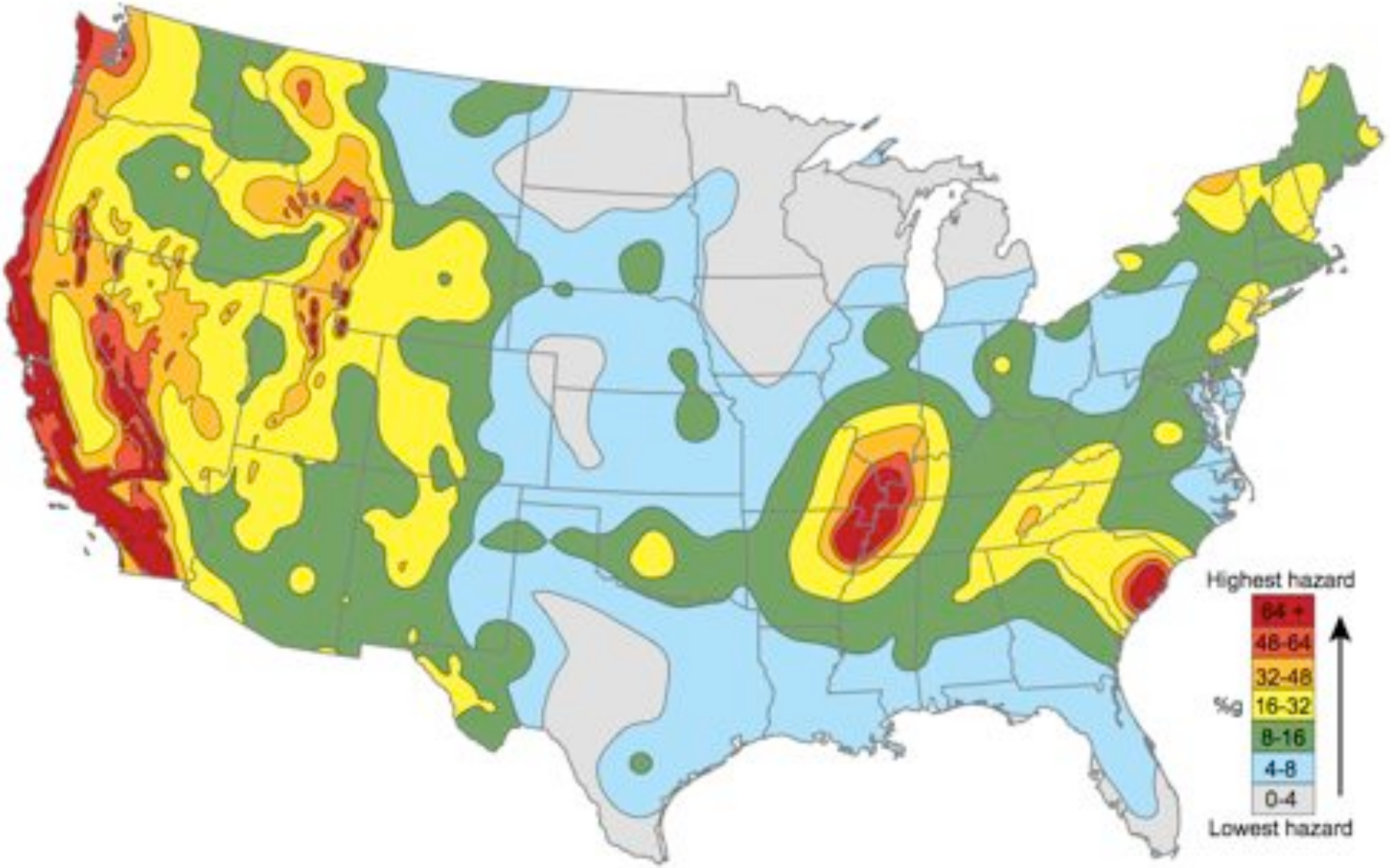
Beroza and Ide [2011]

If Tremor Limns the Edge of the Locked Zone in Cascadia, then Transition is Farther East than Thought

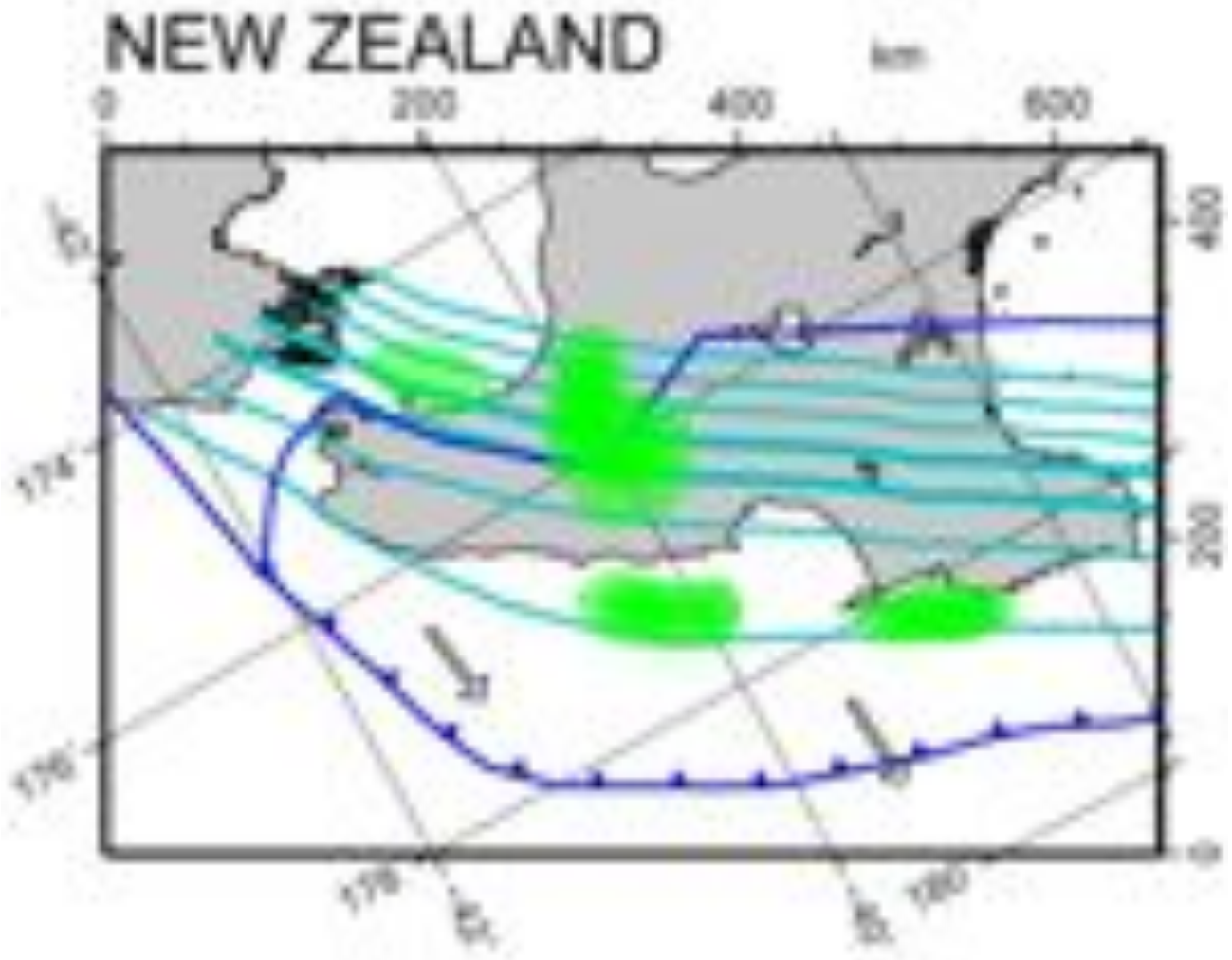


Chapman and Melbourne [2009]

Higher Hazard in Cascadia?



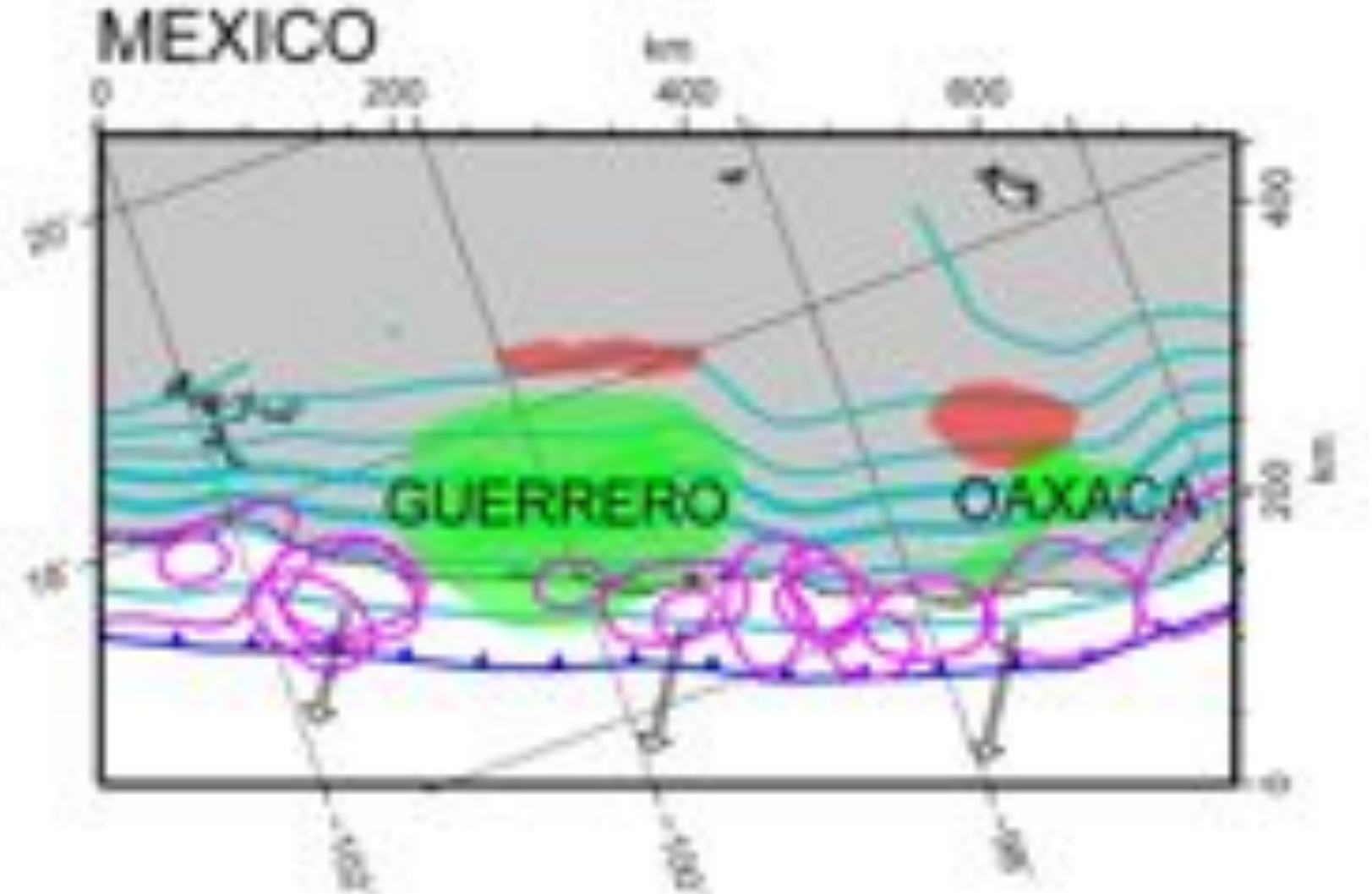
Geography of Slow Earthquakes



SSEs but no tremor

Beroza and Ide [2011]

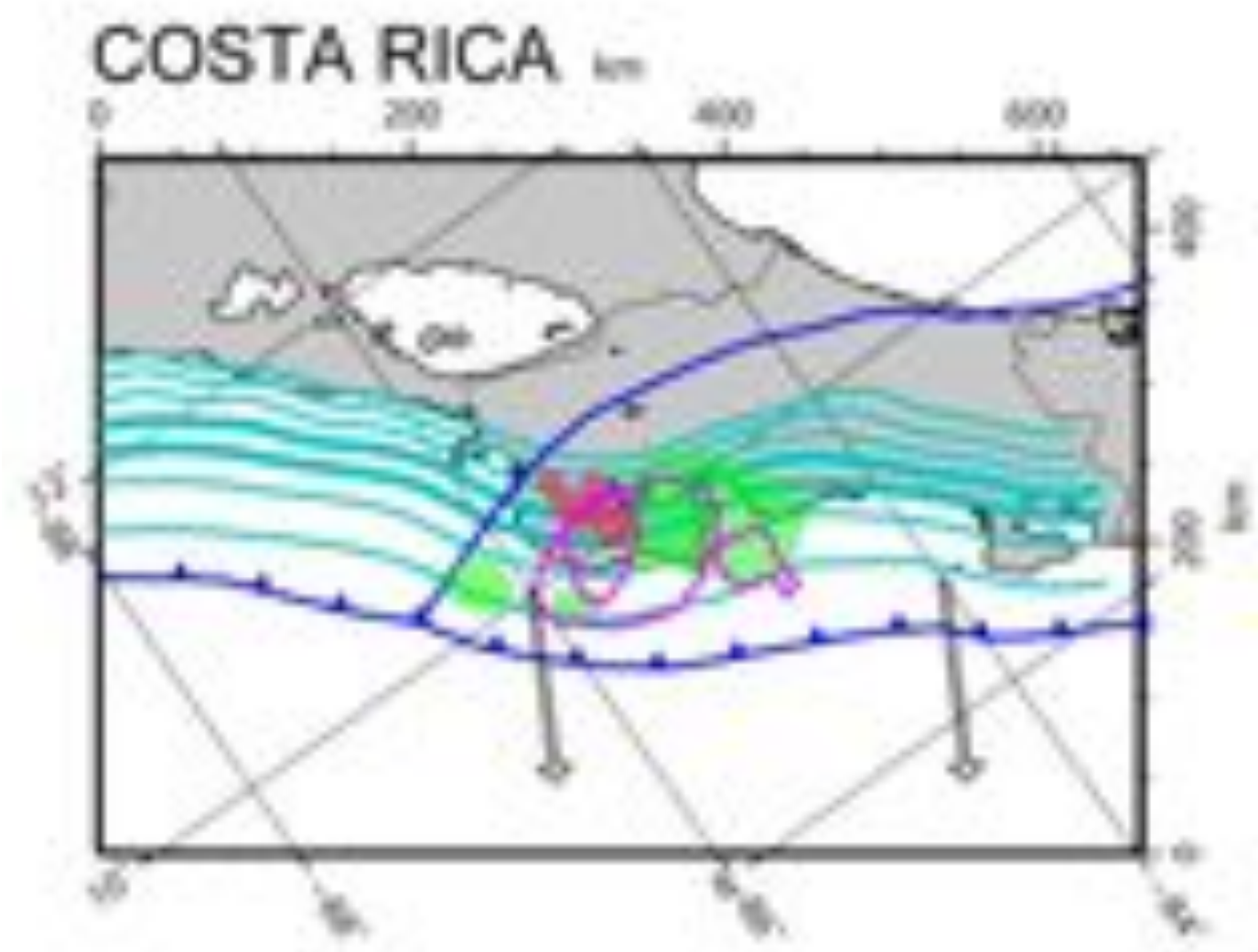
Geography of Slow Earthquakes



SSEs and tremor disjunct

Beroza and Ide [2011]

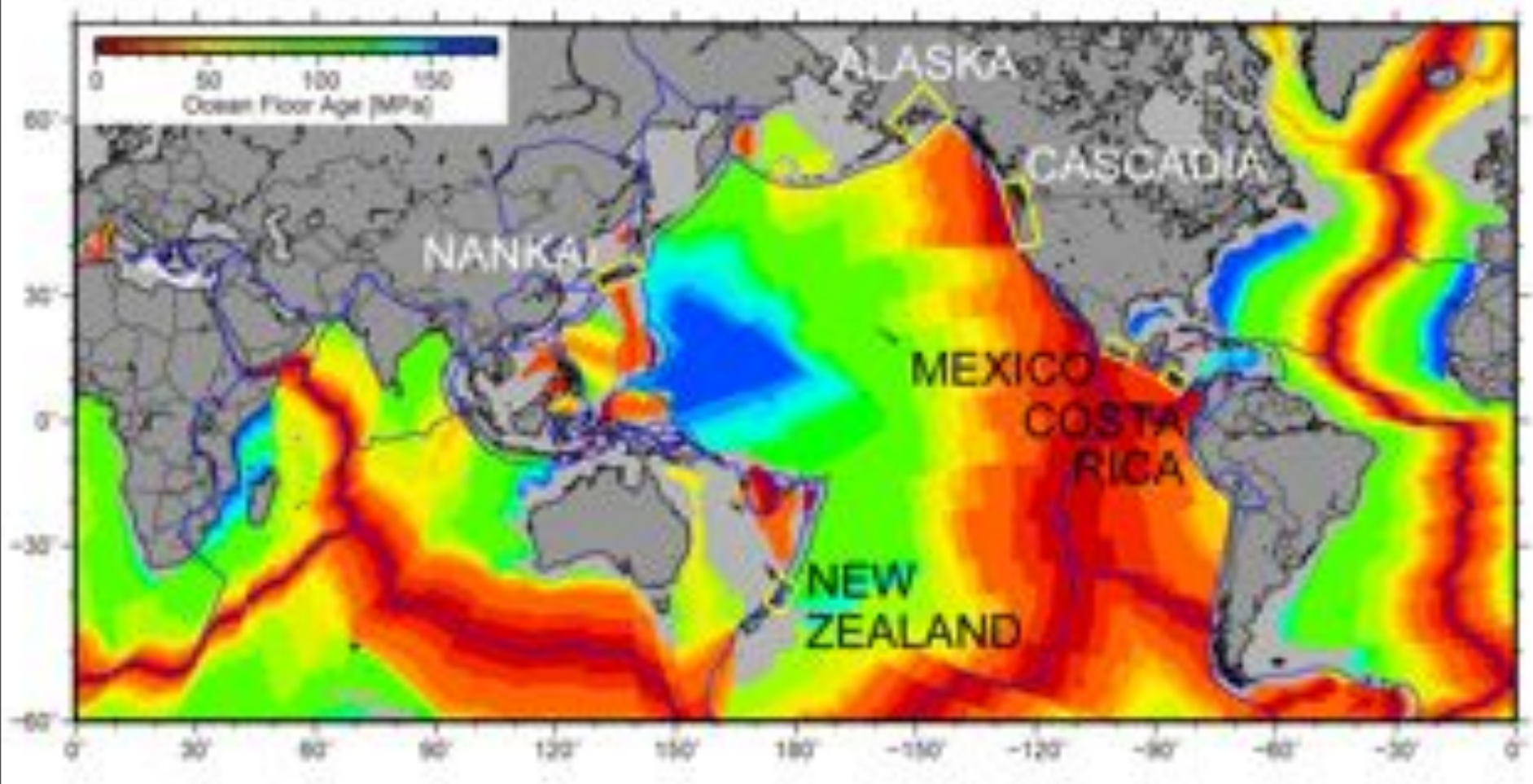
Geography of Slow Earthquakes



Tremor and large earthquake slip intermingled

Beroza and Ide [2011]

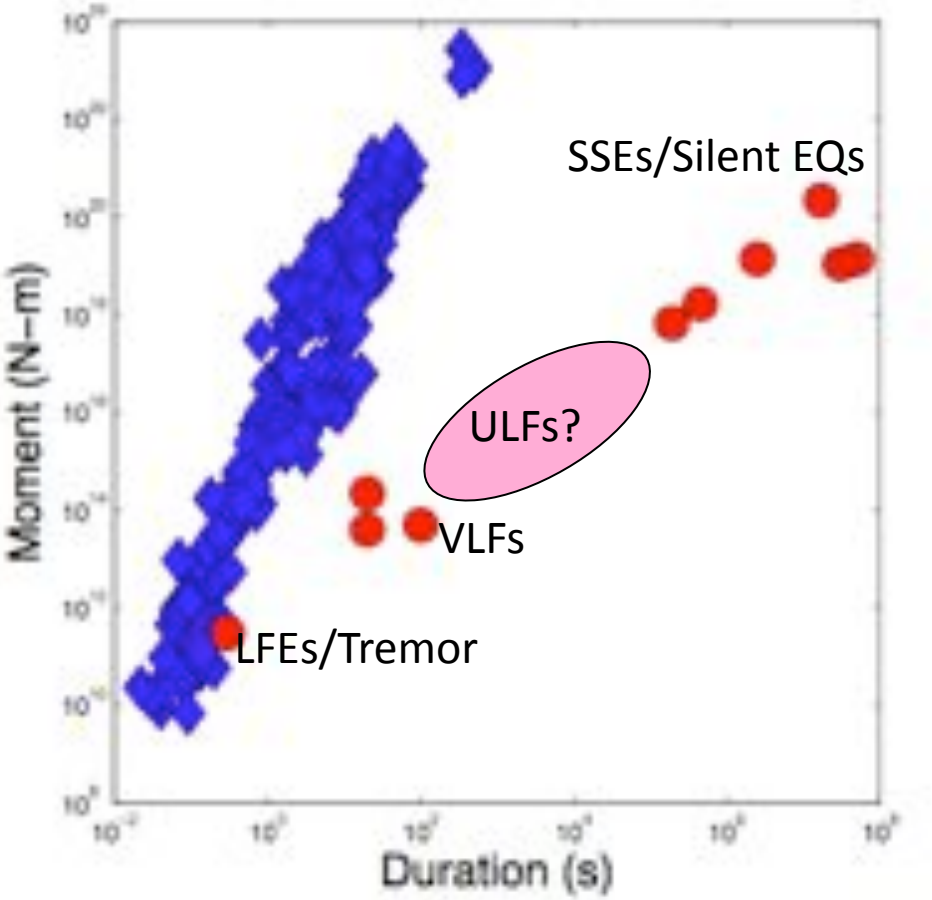
Observational Gap: Much of the World is Effectively Unmonitored



Where else do slow earthquakes occur?

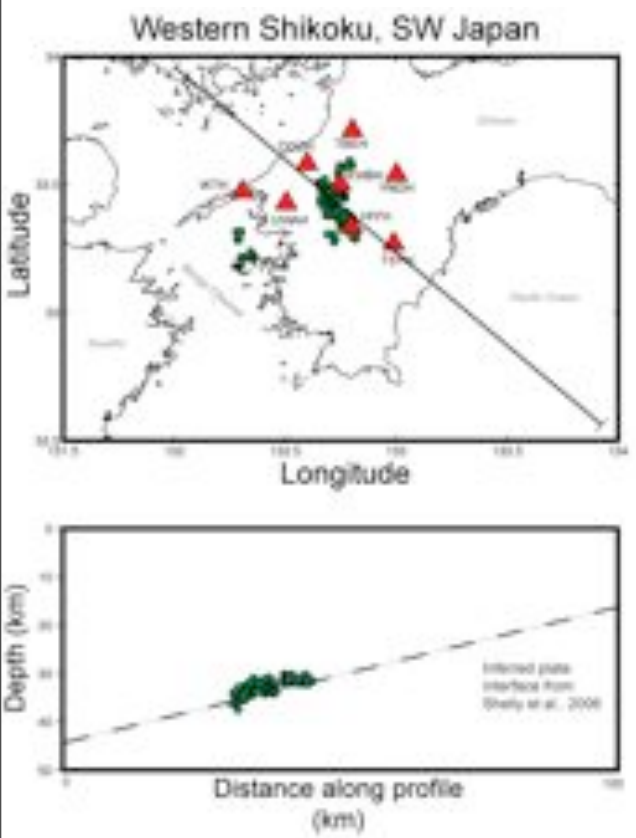
Beroza and Ide [2011]

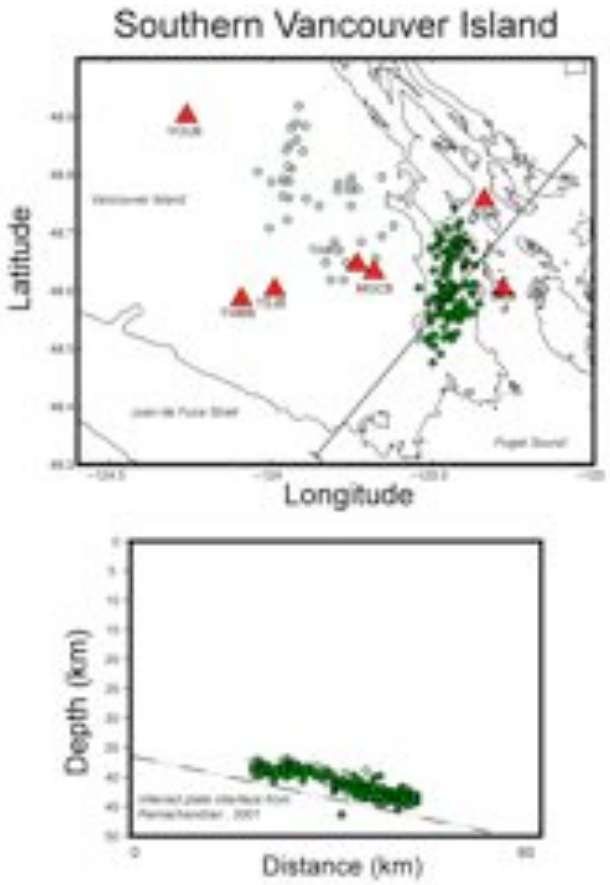
Observational Gap: Between Seismology and Geodesy

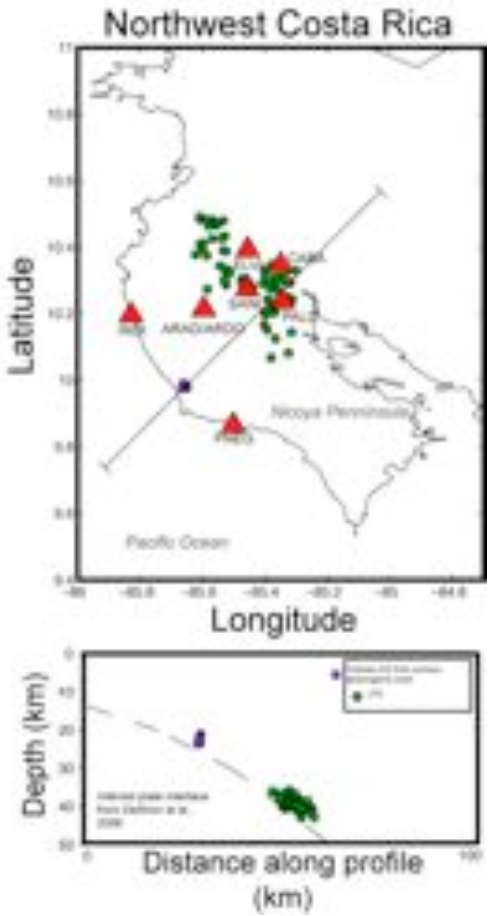


Also, if LFEs occur in isolation they will be difficult to detect

Tremor Occurs on the Deep Extension of Faults

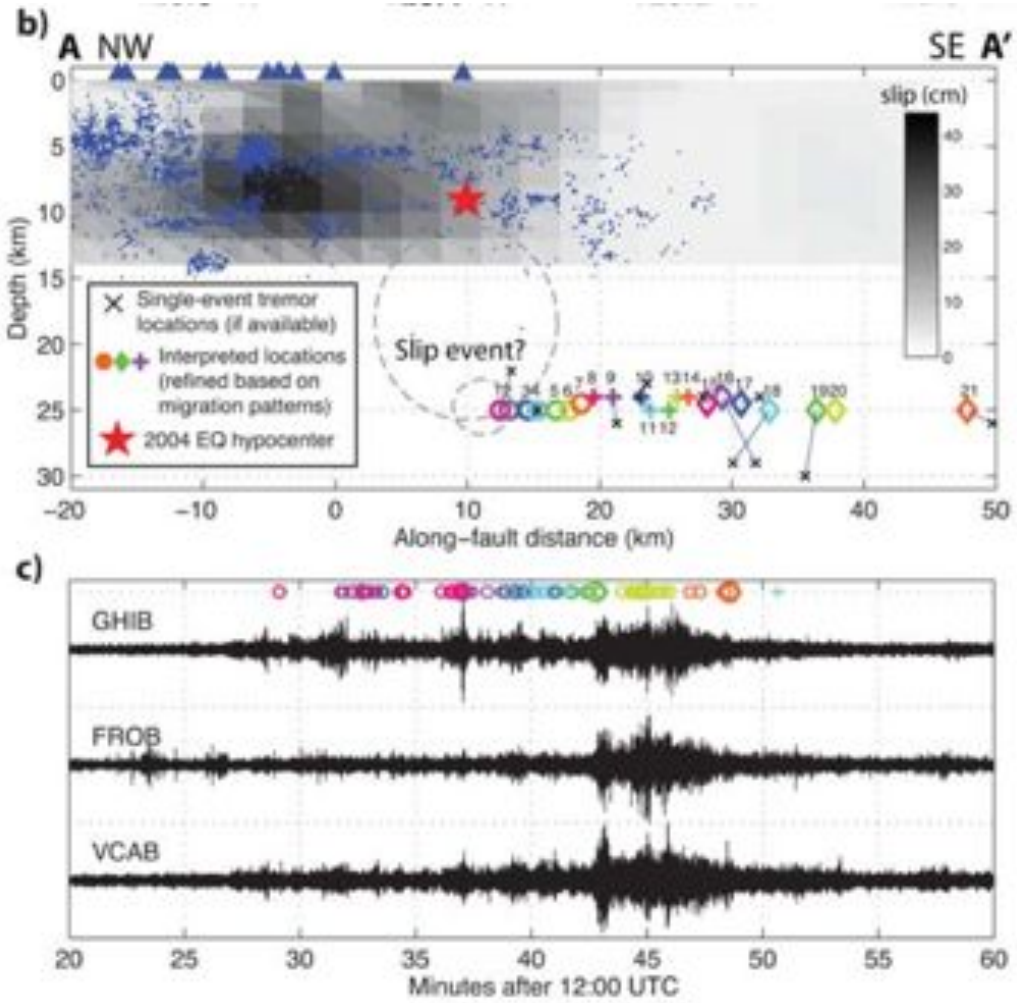






***Brown et al.* [2009]**

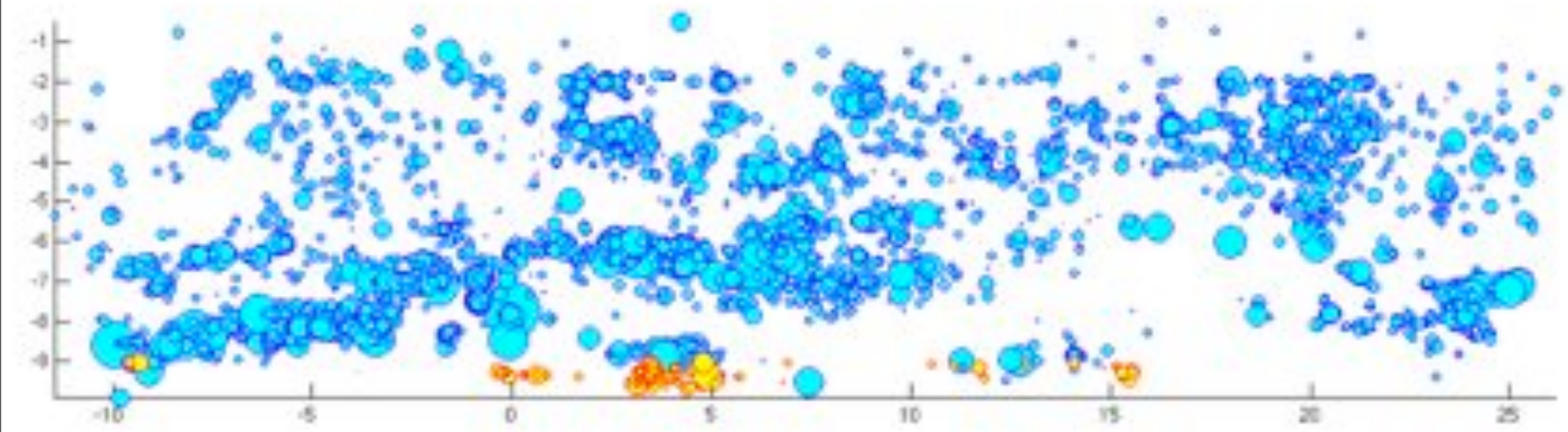
Tremor Occurs on the Deep Extension of Faults



Shelly [2009]

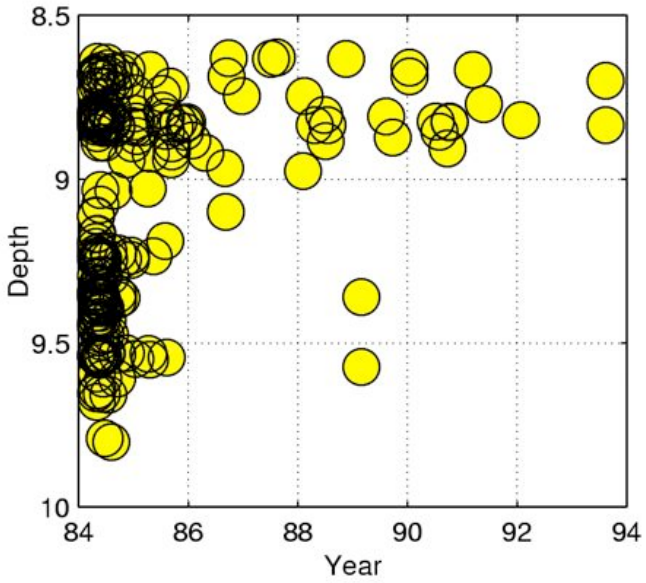
Shear failure to ~25 km? If so, fault likely to slip co-seismically in large events at this depth.

Time-Dependent Base of Seismogenic Zone



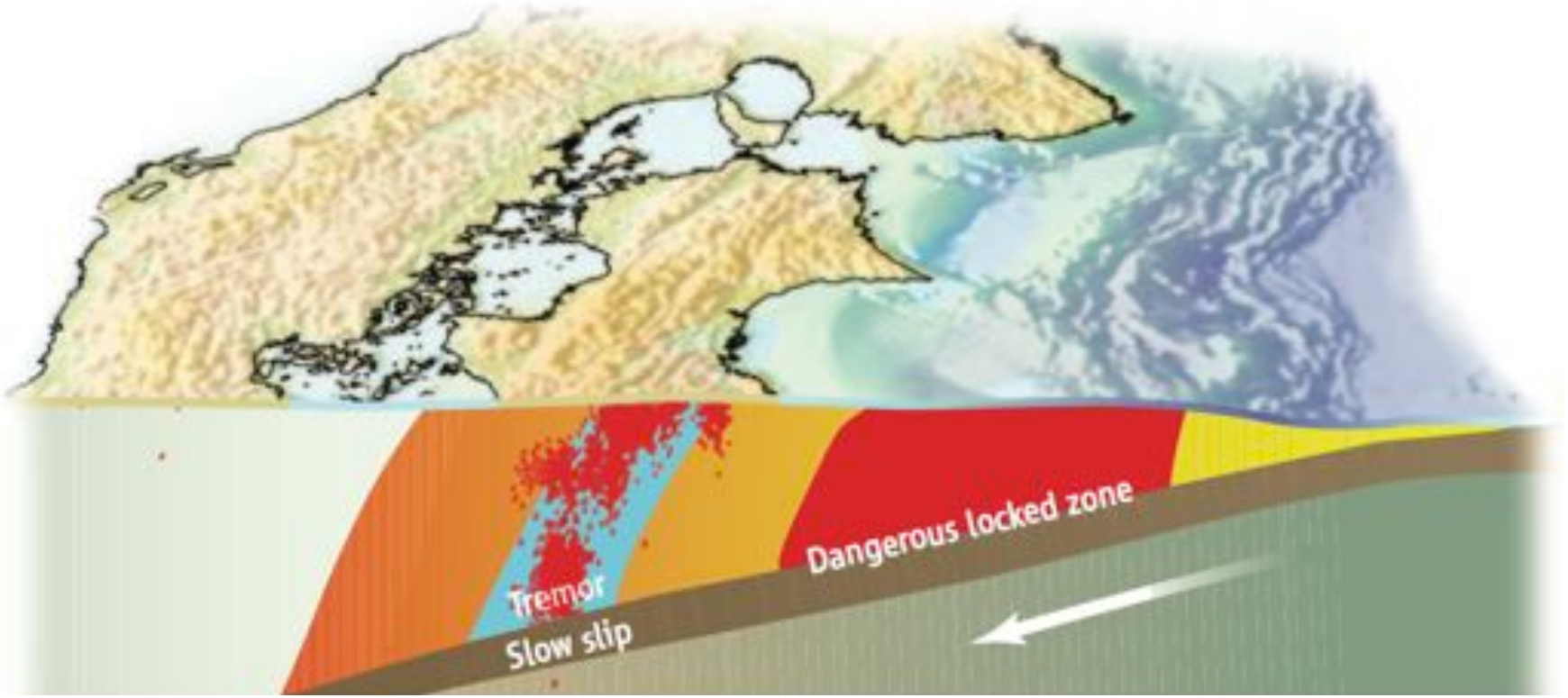
Almost all "deep" events (yellow) happen in 2 years after 1984 Morgan Hill earthquake.

Similar behavior after 1992 Landers earthquake



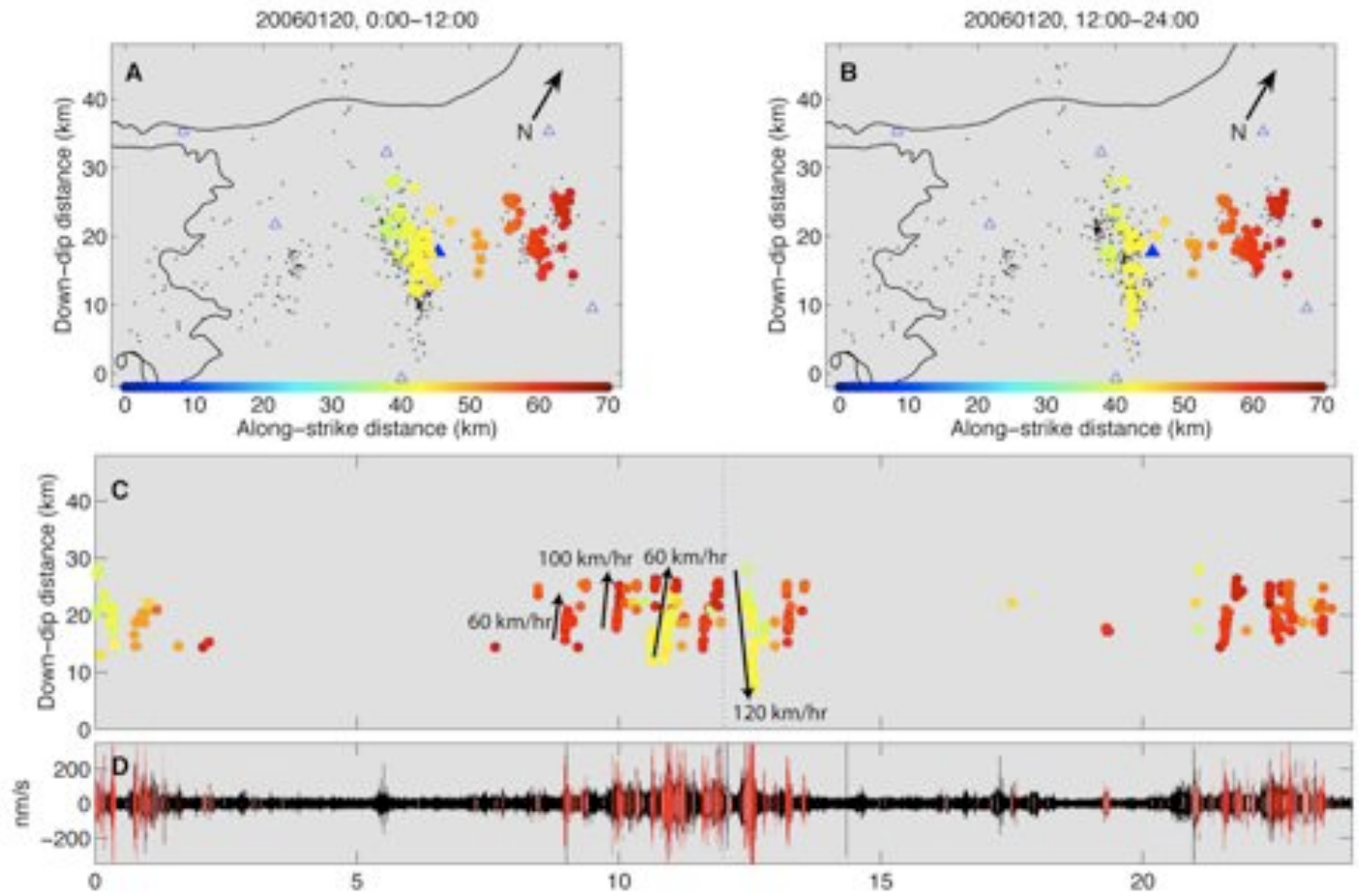
(*Schaff et al., 2002*)

Slow Earthquakes Occur in a “Strategic” Location



Tremor will accelerate loading of the locked zone. Is there a correlation of tremor with earthquakes?

Strong Tidal Response



Much more sensitive to stress than earthquakes:
Will behavior change before a large event?

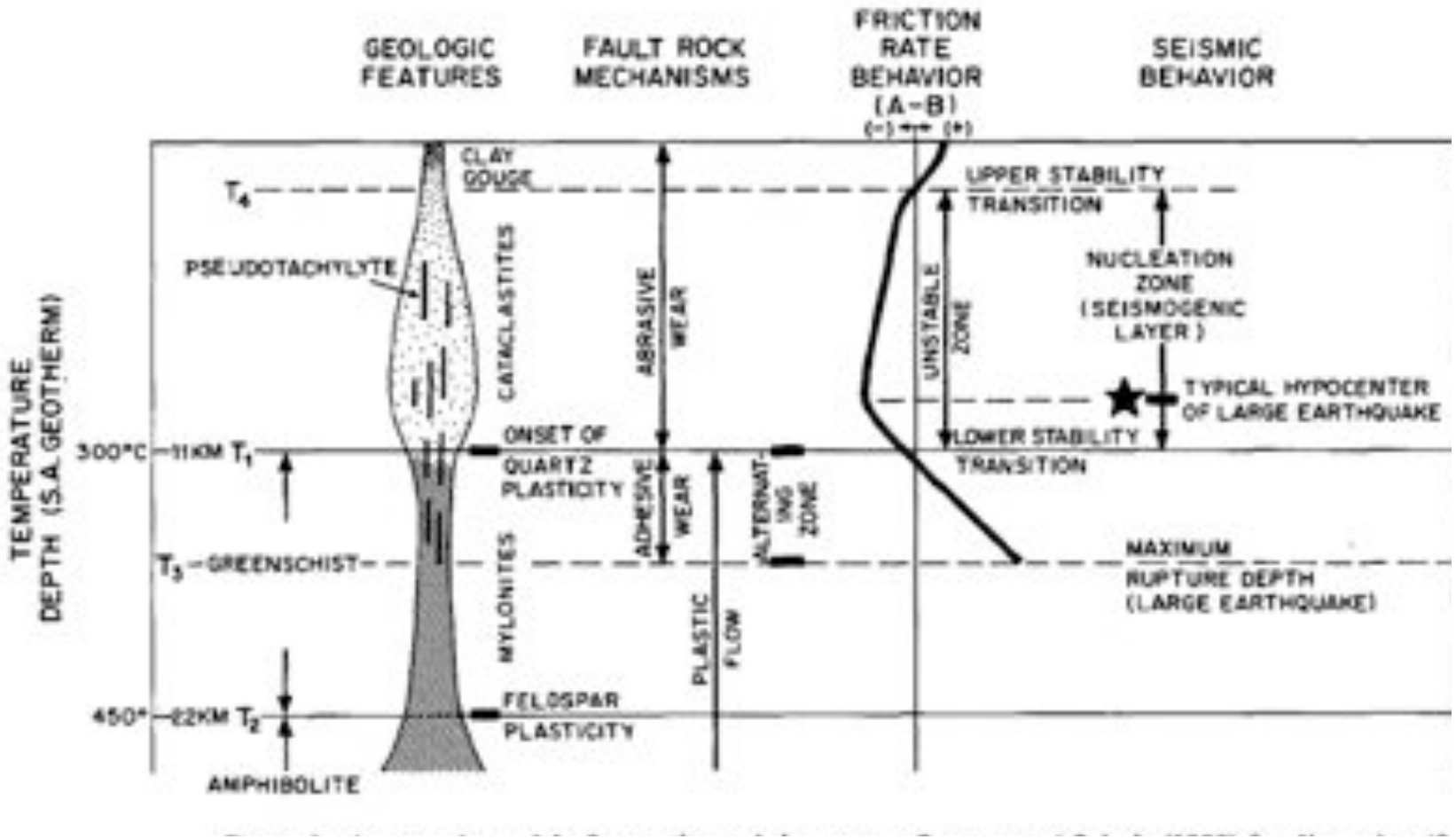
Some Slow Earthquake Questions

What makes earthquakes slow? How can we get swarms of 10s of thousands of LFEs without it growing into something larger?

What is relationship between slow earthquakes and fast earthquakes? What is the relationship of tremor zone to megathrust rupture?

What is temporal relationship between slow earthquakes and fast earthquakes? Do slow earthquakes trigger fast earthquakes?

SOME SLOW EARTHQUAKE QUESTIONS



What can we learn about the base of the seismogenic zone from slow earthquakes?

Some Slow Earthquake Questions

What are conditions under which slow earthquakes occur?

Association of slow earthquakes and creep? Are slow earthquakes of various kinds happening all over the place, but going unrecognized?

What controls occurrence of spontaneous vs. triggered tremor?