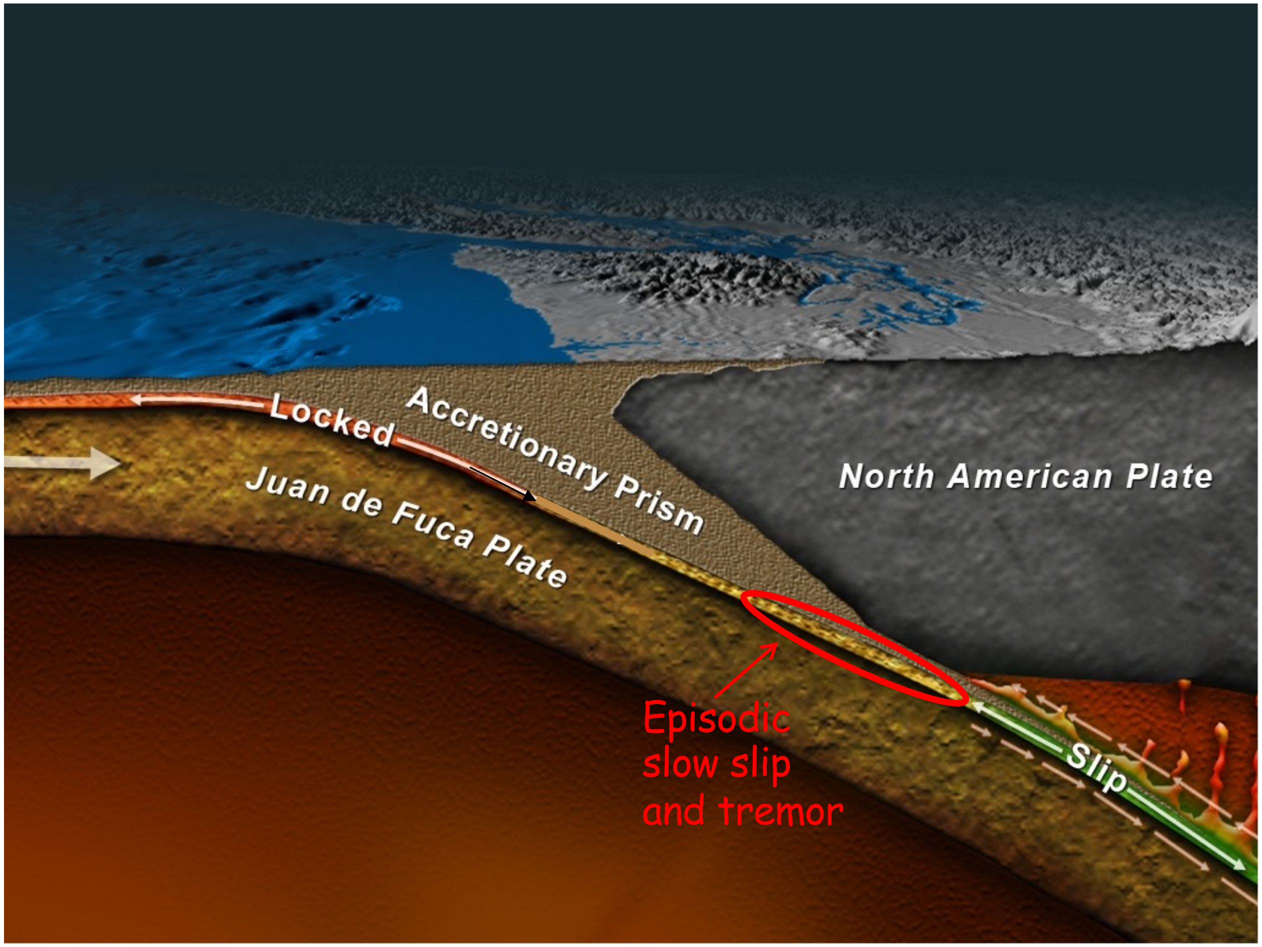
Workshop on Mechanics of the Earthquake Cycle

ICTP, Trieste, 16-27 October, 2023

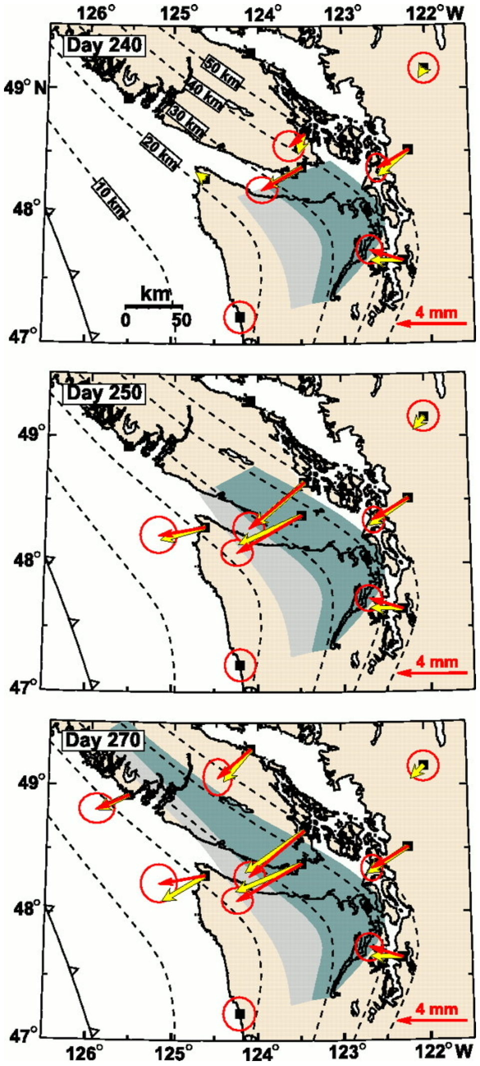
Wednesday October 18, Lecture 2:

Episodic slow slip and tremor in subduction zones: Some observations, some models

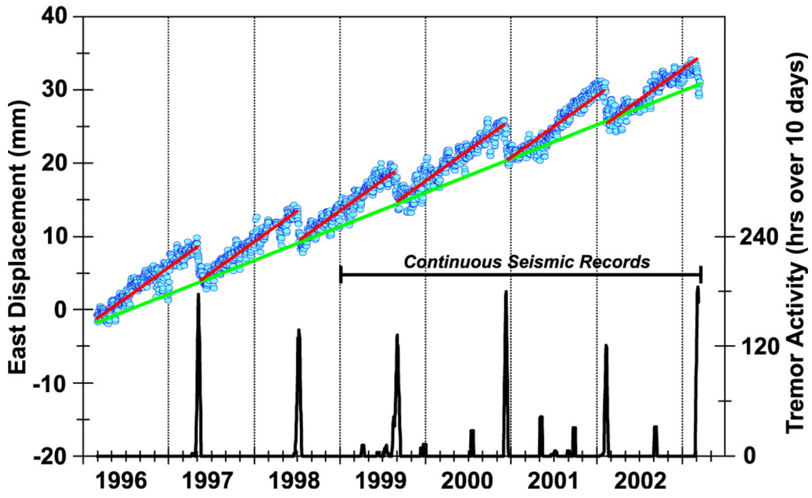
Allan Rubin, Princeton University



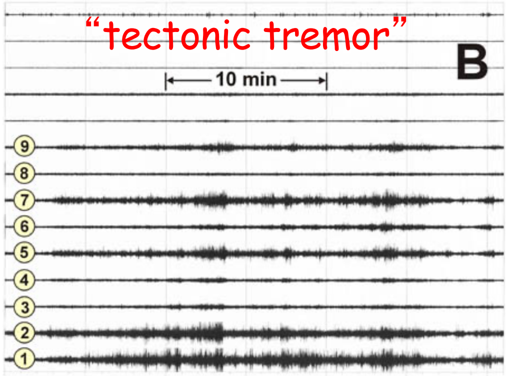
(from Steve Malone via the Central Wash. U. Geodesy website)



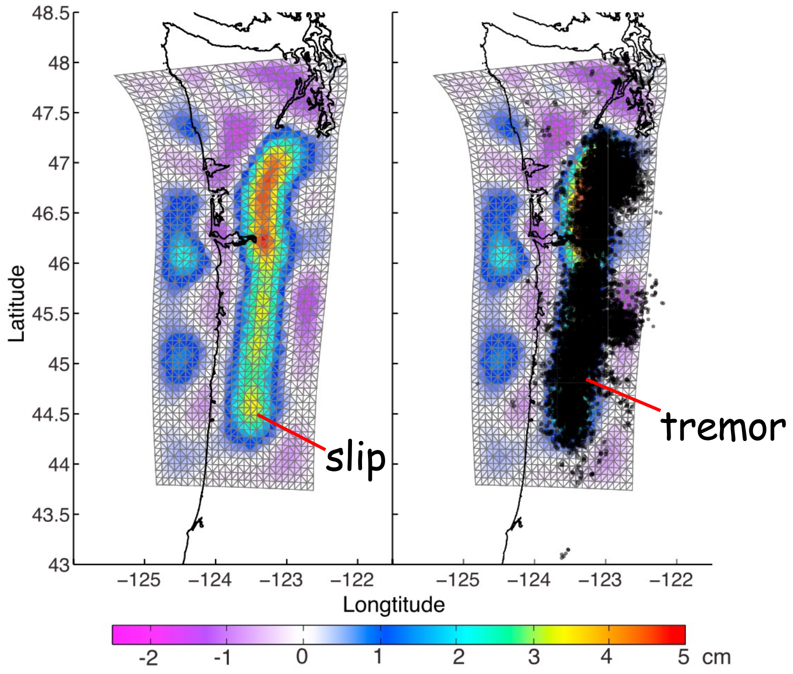
Dragert et al., 2001
(summer 1999 event)

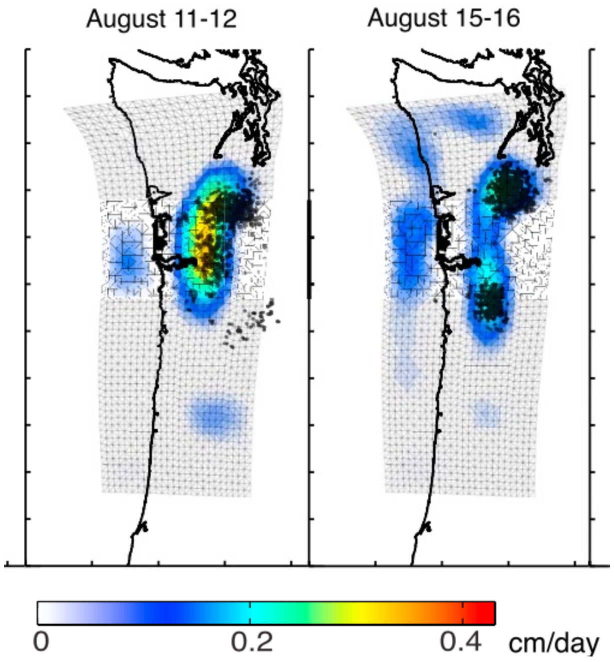


Rogers & Dragert, 2003

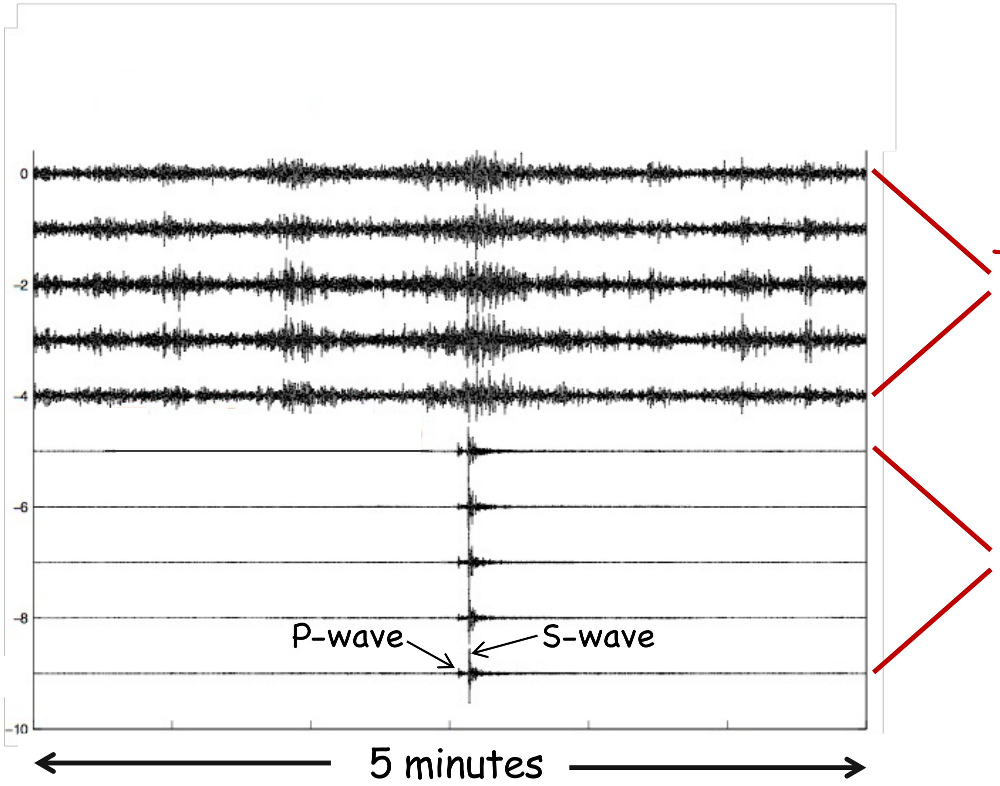

“tectonic tremor”

August 2009 slow slip event





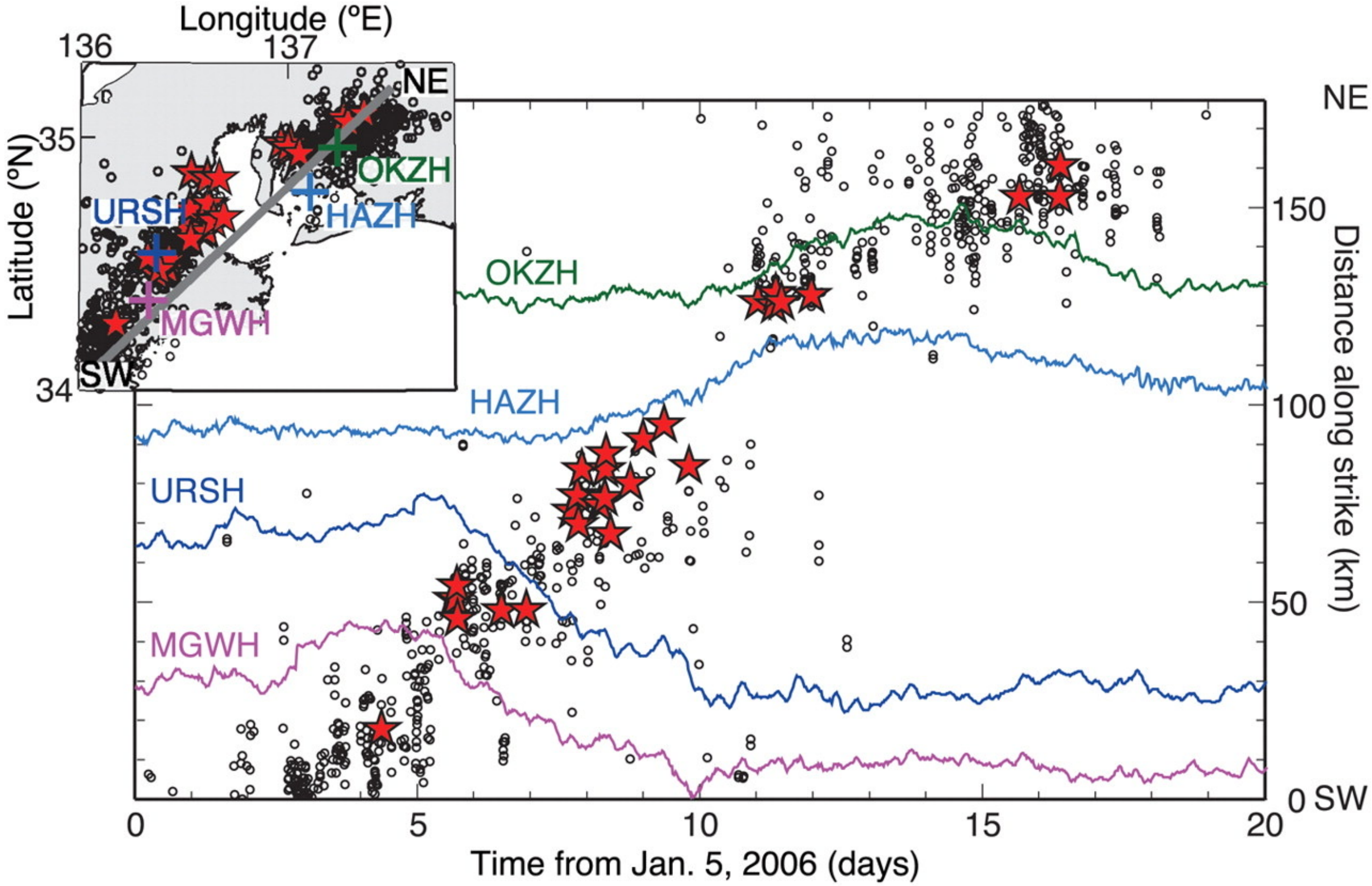
Bartlow et al., 2011
Tremor closely tracks slip in space and time



Tremor at 5 stations

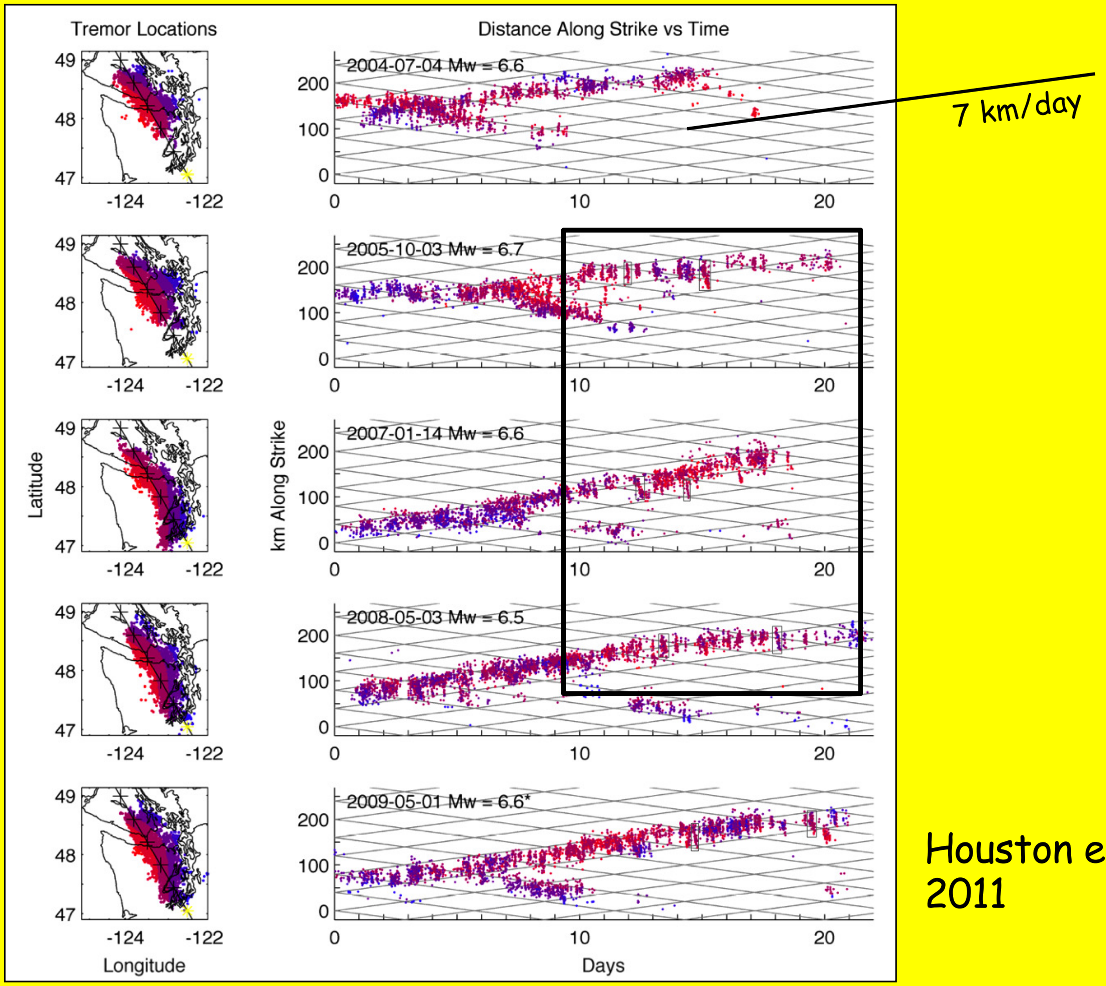
An earthquake at the same 5 stations

Courtesy of John Vidale



Kii Peninsula, Jan. 2006

Ito et al., 2007



Houston et al., 2011

Summary of (early) slow slip observations:

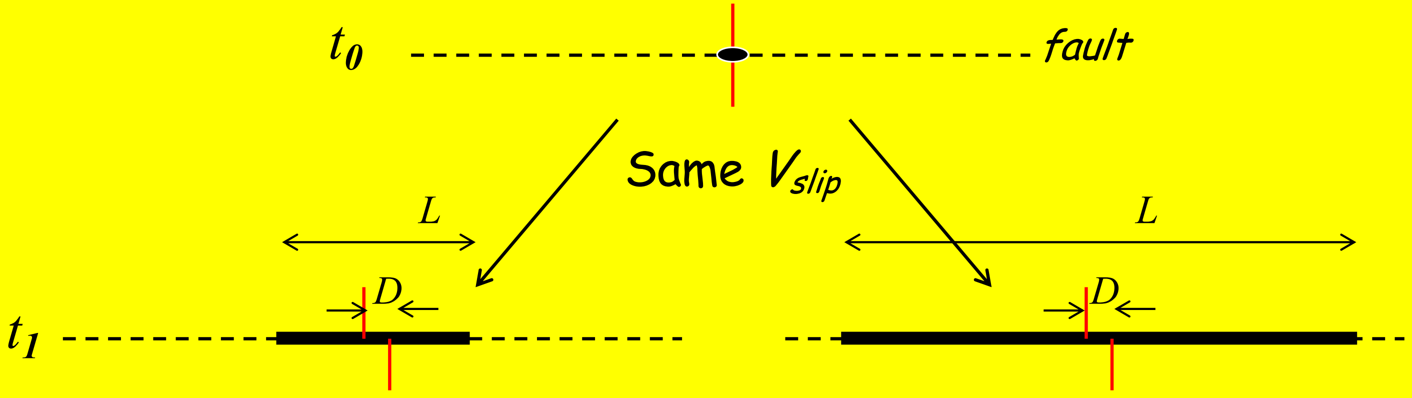
1. Stress drop is low (~10-30 kPa vs. 1-10 MPa: 2+ orders of magnitude lower than for “normal” earthquakes). From the small slip:length ratio (2 cm/50 km vs. 1 m/10 km)

2. Propagation speed is low (~10 km/day vs. ~3 km/s: 4.5 orders of magnitude low).

3. Slip speed is low (2 cm/2days = 0.1 μm/s vs. 1 m/s: 7 orders of magnitude low).

4. Triggerable by small stress perturbations (slow slip by typhoons & tides; tremor by tides & teleseismic surface waves). Seems qualitatively consistent with small stress drops and inferences of high pore fluid pressure in source region.
   [shear stress = (coeff. friction)(normal stress – pore pressure)]

SLOW SLIP PROPAGATION SPEEDS:



Slow V_{prop}

Large $\Delta\tau$

Fast V_{prop}

Small $\Delta\tau$

Elasticity:

$$\frac{D}{L} \approx \frac{\Delta\tau}{G}$$

Kinematically,

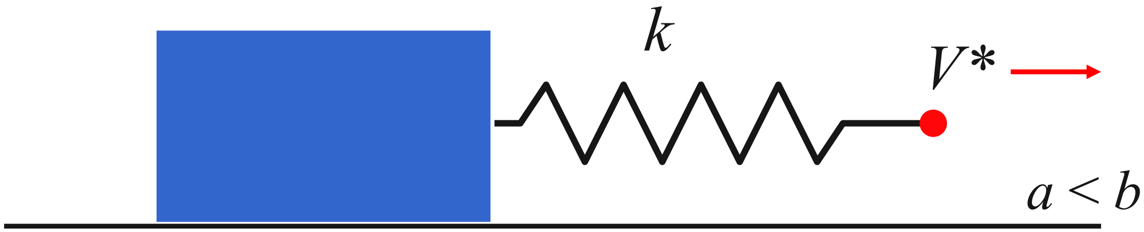
$$\boxed{\frac{V_{prop}}{V_{slip}} = \frac{L}{D} \approx \frac{G}{\Delta\tau}}$$

$$V_{prop} = V_{slip}\,\frac{G}{\Delta\tau}$$

$$V_{slip} = V_{prop}\,\frac{\Delta\tau}{G}$$

Instability:

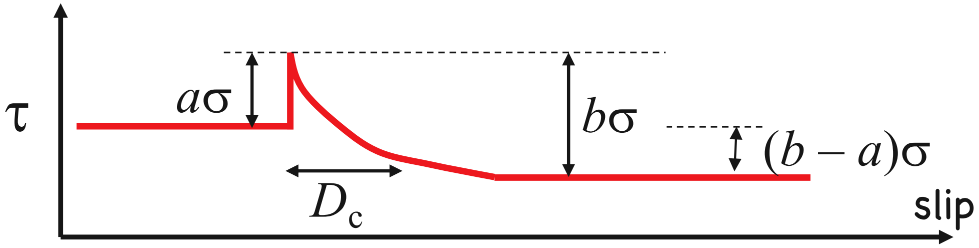
Surface must weaken faster than driving stress decreases



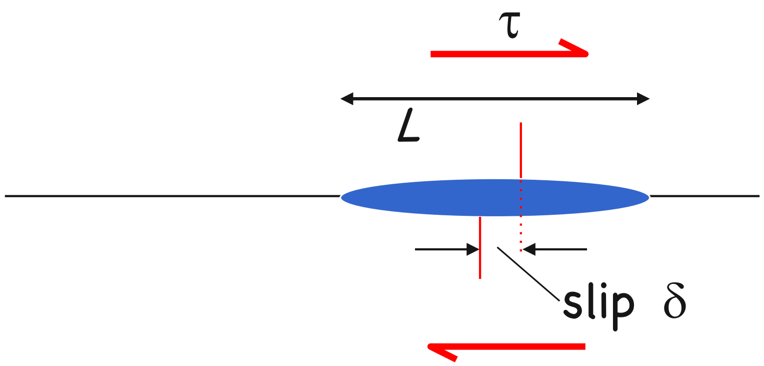
For a spring-block slider, instability requires (from a linear stability analysis in the vicinity of steady state)

$$\boxed{k < k_{crit} = \frac{(b-a)\sigma}{D_c}}$$

(Ruina, Rice, 1983)



What about a nucleating patch on a fault ?



Shear modulus μ!

At the center of a crack in an elastic solid,

$$\boxed{\frac{\delta}{L} \approx \frac{\Delta\tau}{\mu}}$$

$$\boxed{\left(\frac{\text{slip}}{\text{length}} = \frac{\text{stress drop}}{\text{shear modulus}}\right)}$$

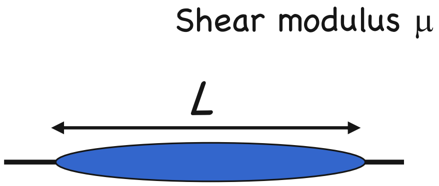
Patch stiffness (stress drop per unit slip)

$$\boxed{k_{patch} \equiv \frac{\Delta\tau}{\delta} \approx \frac{\mu}{L}}$$

(larger patches are less stiff; easier for them to accelerate because stress decays only slowly with slip.)

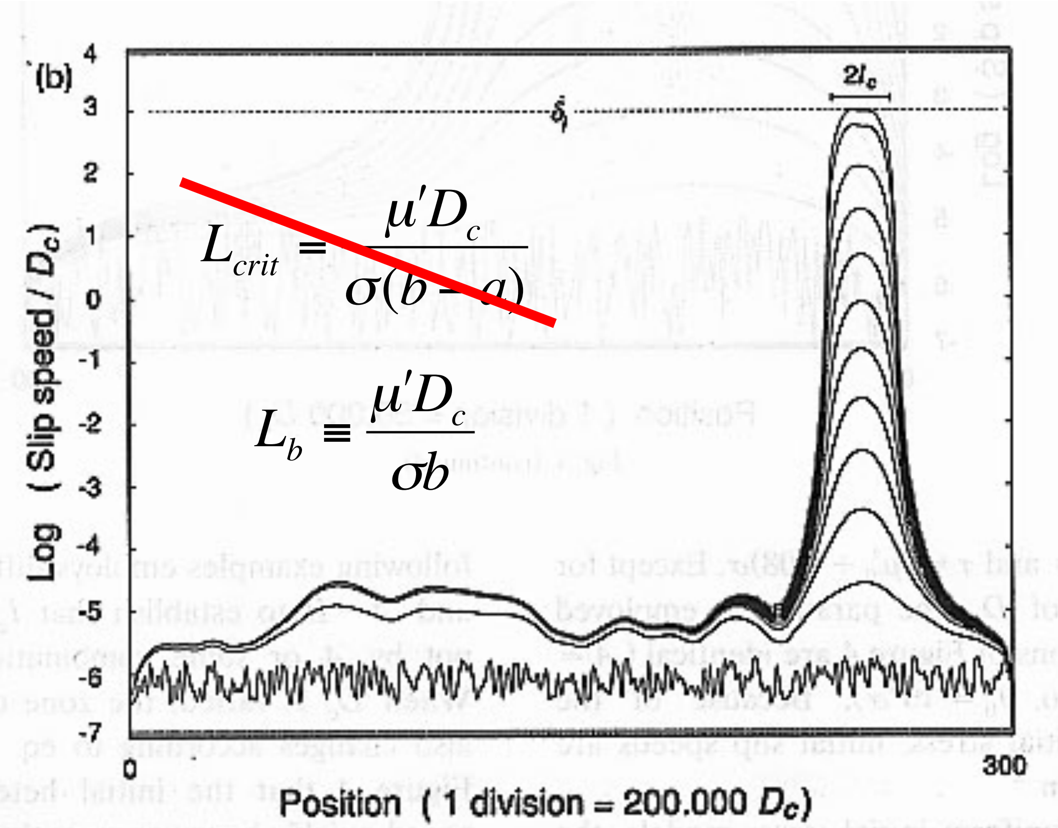
For instability,

$$\boxed{k_{crack} = \frac{\mu}{L} \; < \; k_{crit} = \frac{\sigma(b-a)}{D_c}}$$



$$\Rightarrow \quad \boxed{L > L_{crit} = \frac{\mu D_c}{\sigma(b-a)}}$$

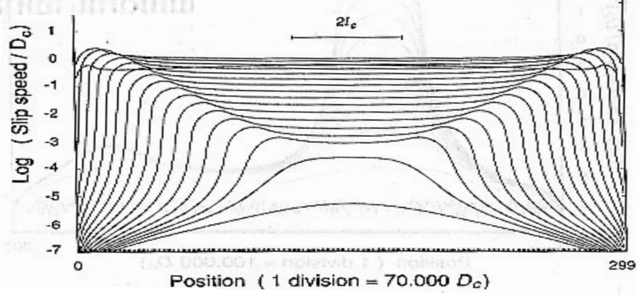
Or so it was thought...



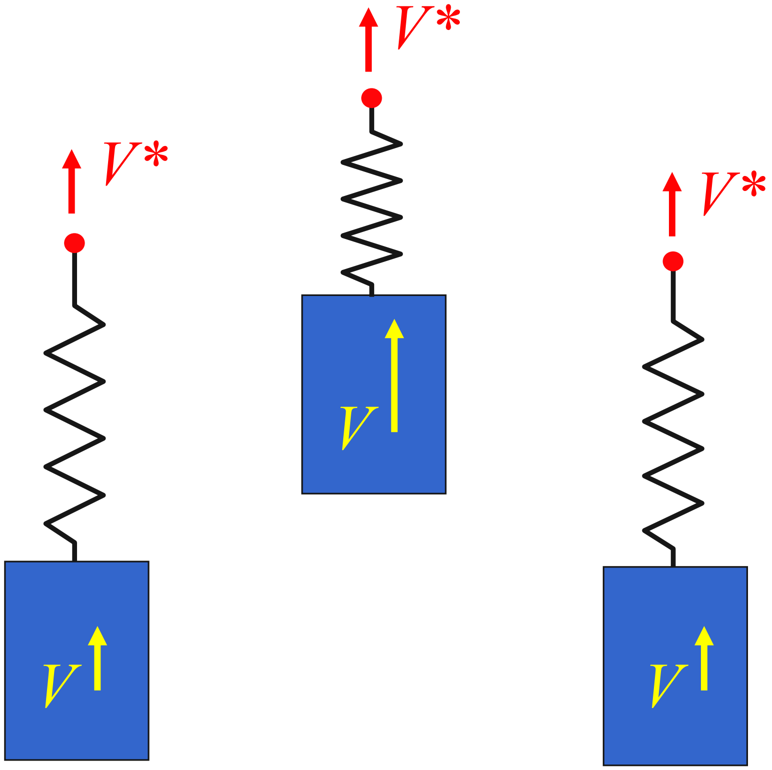
$$\cancel{L_{crit} = \frac{\mu' D_c}{\sigma(b-a)}}$$

$$L_b \equiv \frac{\mu' D_c}{\sigma b}$$

Dieterich, 1992



Instability: Surface must weaken faster than driving stress decreases



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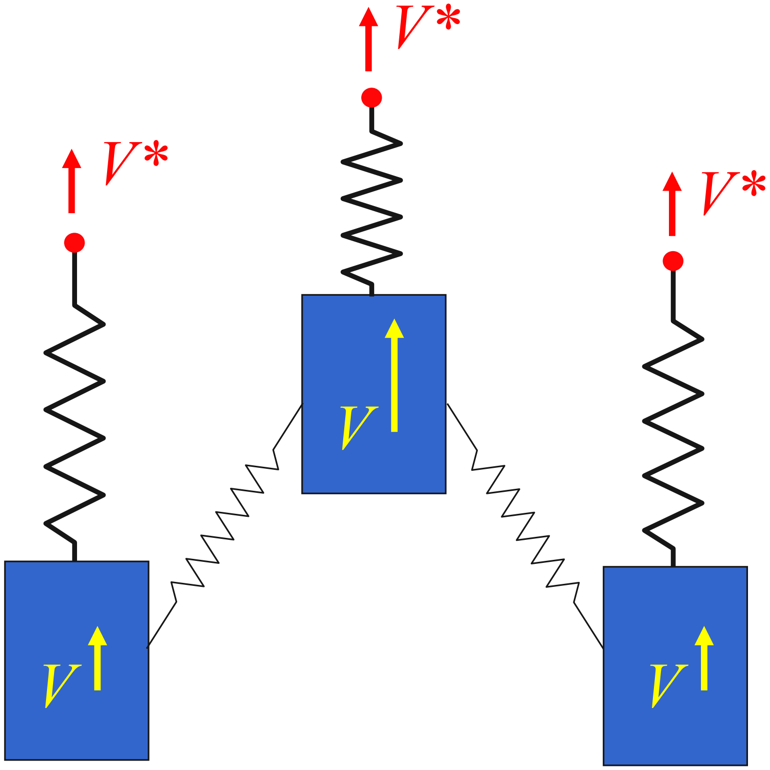


Three length scales:

$$L_b = \frac{\mu' D_c}{b\sigma}$$

(Dieterich 1992. Generic value of 1 m for σ = 100 MPa)
Appropriate well above steady state (Aging law)

$$L_{b-a} = \frac{\mu' D_c}{\sigma(b-a)} = \frac{b}{(b-a)} L_b$$

(Ruina 1983; Rice 1993)
In the vicinity of steady state

$$L_\infty = \frac{2}{\pi}\frac{b}{b-a} L_{crit} = \frac{2}{\pi}\left(\frac{b}{b-a}\right)^2 L_b$$

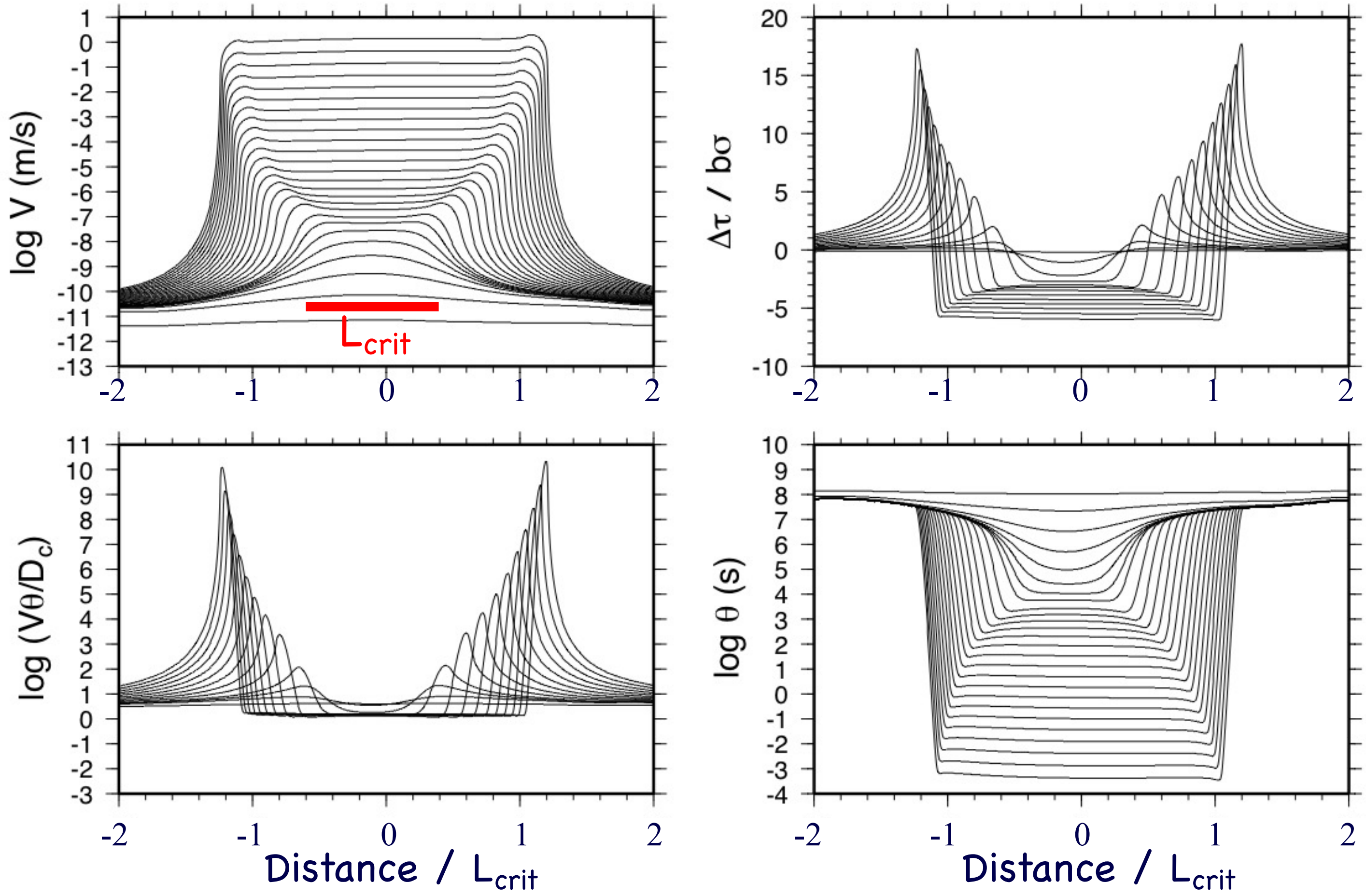
(Rubin & Ampuero 2005)
(full length)
(Aging law)

Why all these length scales, if a spring-slider has only a single critical stiffness?

An important difference between spring-sliders and faults:

Unlike a spring, a fault patch does not have a single stiffness. Its stiffness varies in space (it has a larger stress drop for a given slip distance near the patch ends than in the center), and its stiffness varies in time as the patch expands or shrinks. The portion of the fault accelerating to instability gets to choose its own stiffness.

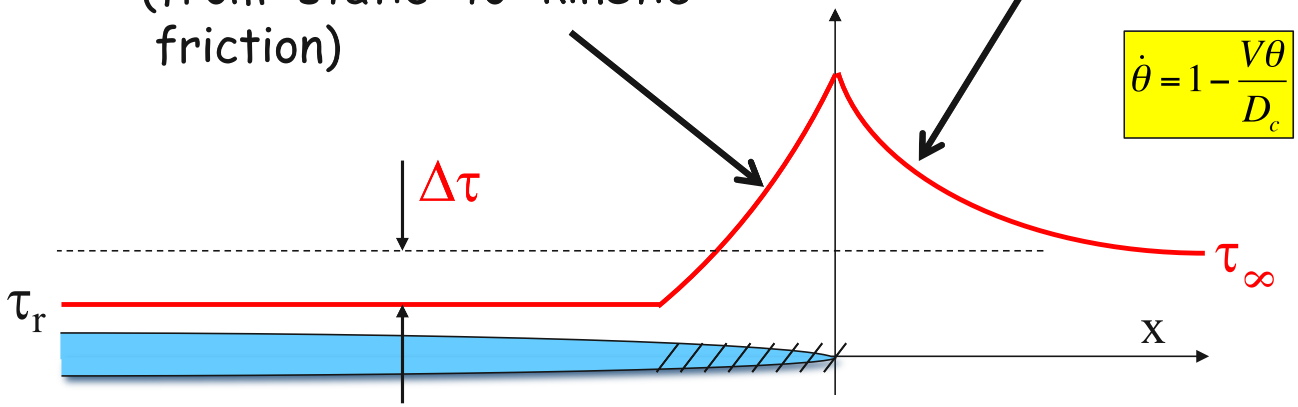
Aging law, *a/b*=0.8



Rate-State model:

(Log) slip speed ~ constant.
State and stress go way down
(from "static" to "kinetic"
friction)

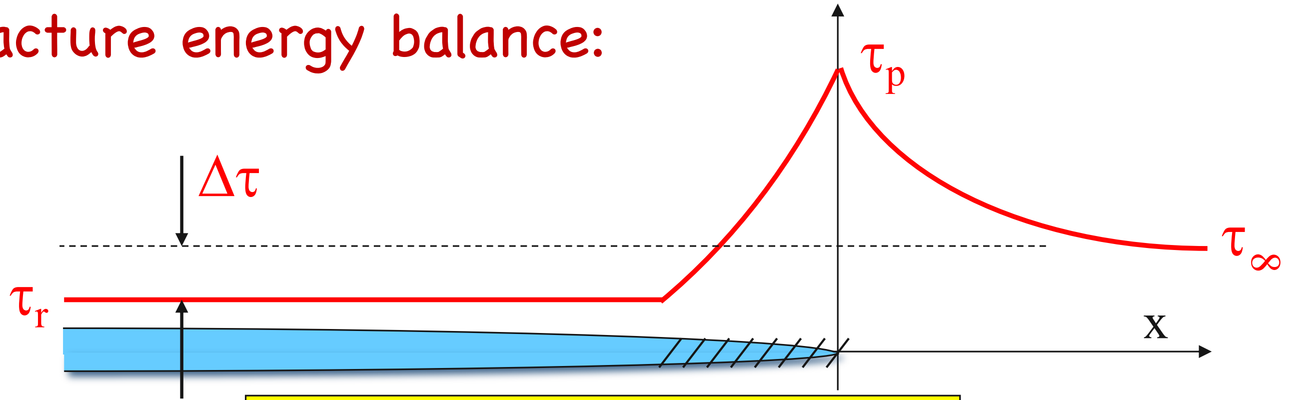
Slip speed very low.
(Log) state ~ constant.
Stress increase balances
(log) V increase



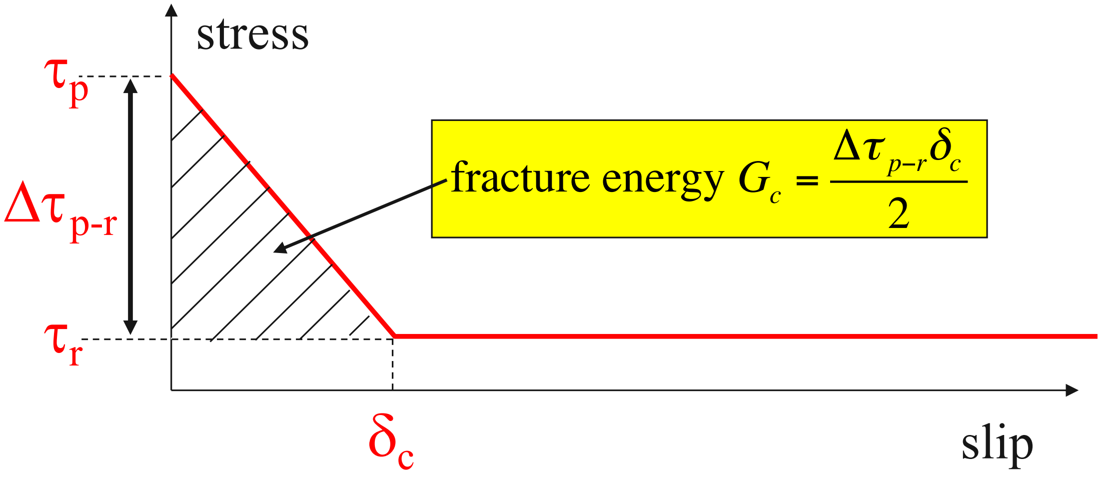
$$\dot{\theta} = 1 - \frac{V\theta}{D_c}$$

$$\tau = \tau^* + a\sigma \ln\frac{V}{V^*} + b\sigma \ln\frac{\theta}{\theta^*}$$

Fracture energy balance:



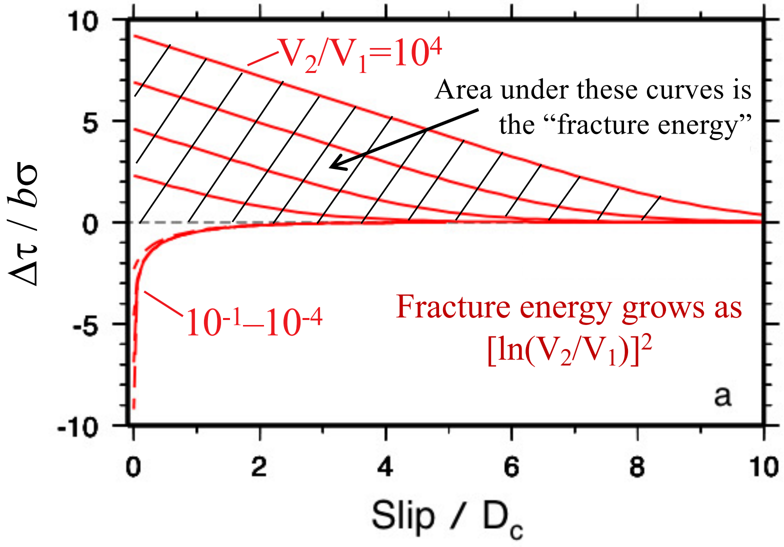
available strain energy: $G = \frac{\pi}{4}\frac{L}{\mu}\Delta\tau^2$



fracture energy $G_c = \frac{\Delta\tau_{p-r}\delta_c}{2}$

Aging law evolution

$$\dot{\theta} = 1 - \frac{V\theta}{D_c}$$

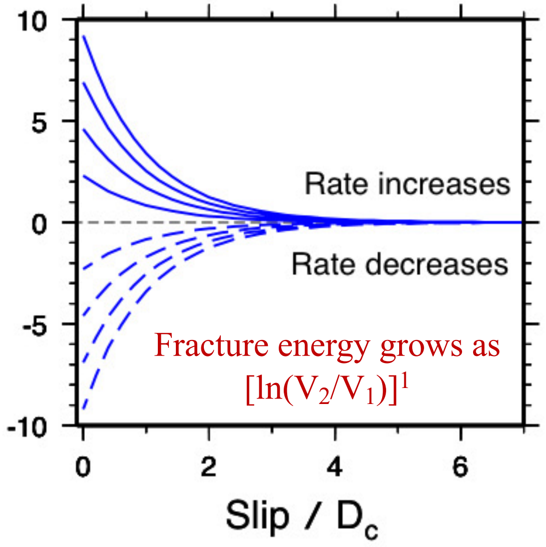


Area under these curves is the "fracture energy"

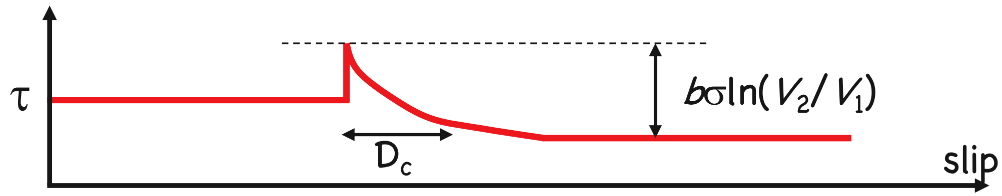
Fracture energy grows as $[\ln(V_2/V_1)]^2$

Slip law evolution

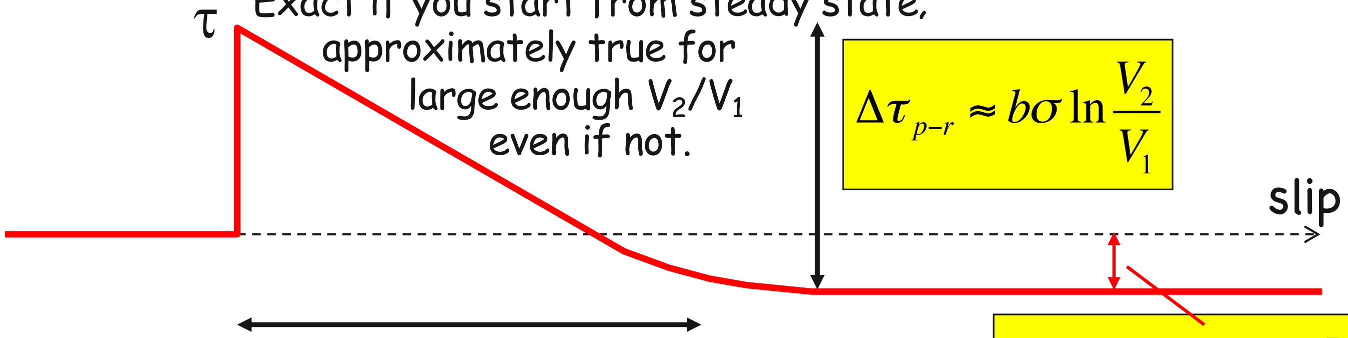
$$\dot{\theta} = -\frac{V\theta}{D_c}\ln\frac{V\theta}{D_c}$$



Fracture energy grows as $[\ln(V_2/V_1)]^1$



Aging law:



Exact if you start from steady state;
approximately true for
large enough V_2/V_1
even if not.

$$\Delta\tau_{p-r} \approx b\sigma \ln\frac{V_2}{V_1}$$

$$\delta_C \approx D_C \ln\frac{V_2}{V_1}$$

$$\Delta\tau \approx (b-a)\sigma \ln\frac{V_2}{V_1}$$

Fracture energy:

$$G_c \approx \frac{\Delta\tau_{p-r}\delta_c}{2} = \frac{D_C b\sigma}{2}\ln^2\frac{V_2}{V_1}$$

Strain energy release rate:

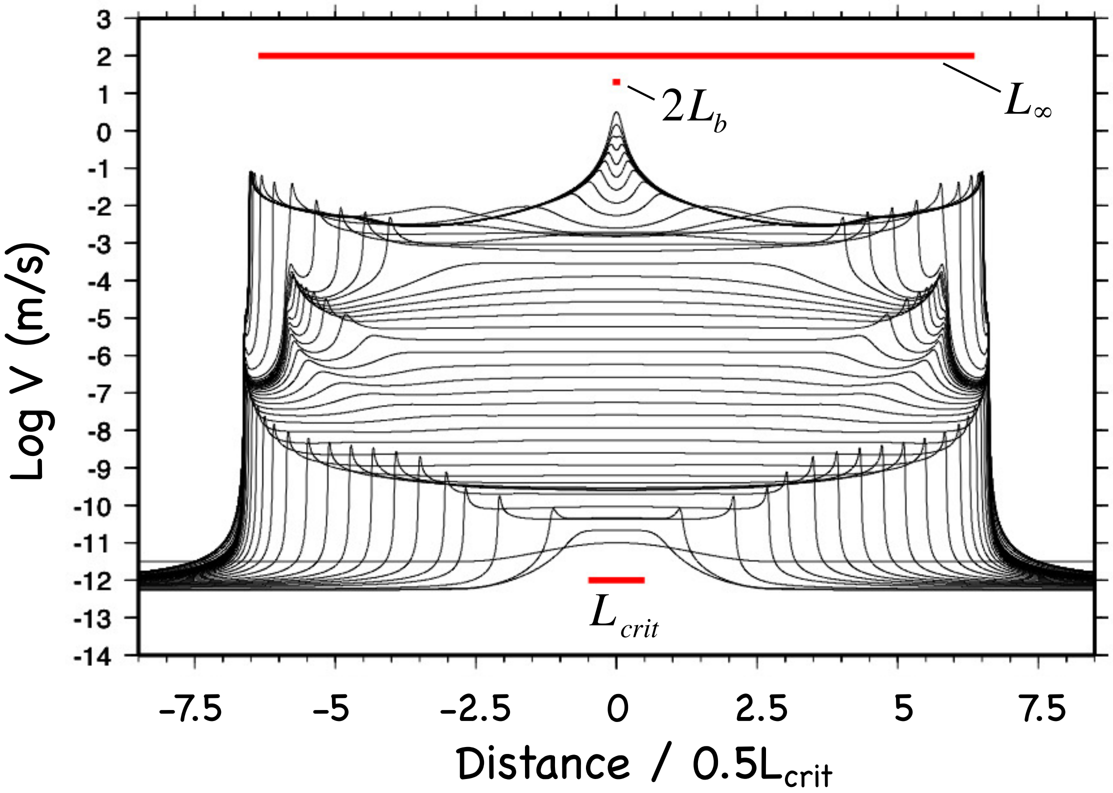
$$G \approx \frac{\pi}{4}\frac{L}{\mu}\Delta\tau^2 = \frac{\pi}{4}\frac{L}{\mu}(b-a)^2\sigma^2\ln^2\frac{V_2}{V_1}$$

$\Big\}$ G = G_c :

$$L_\infty = \frac{2}{\pi}\left(\frac{b}{b-a}\right)L_{crit}$$

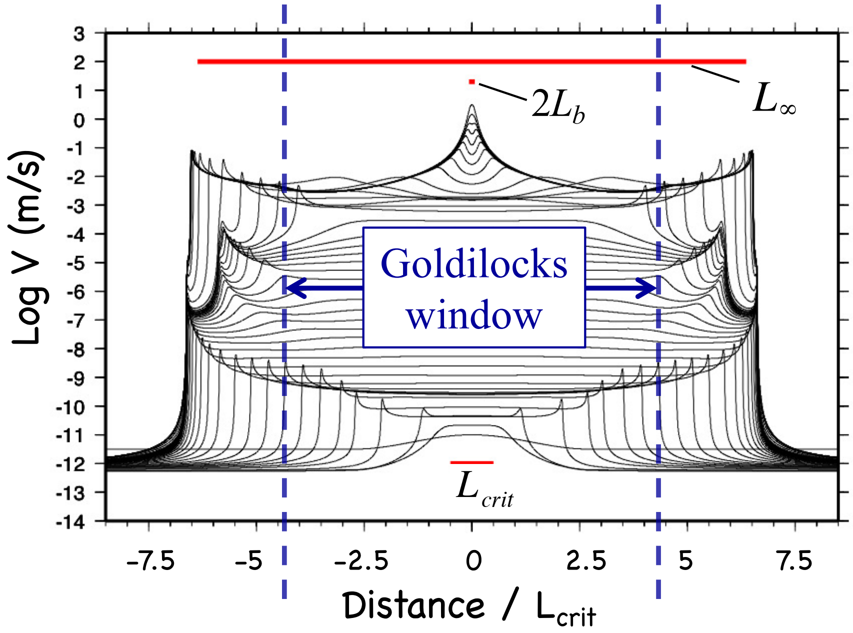
(in the limit of large slip speeds)

Aging law, *a*/*b*=0.95



Slow Slip Explanation #1: The "Goldilocks hypothesis"

(a fault that is neither too large nor too small but just right…)
[Yoshida and Kato, 2003; Kuroki et al. 2004;
Liu and Rice, 2005, 2007, 2009; Rubin, 2008]



Liu and Rice, 2007

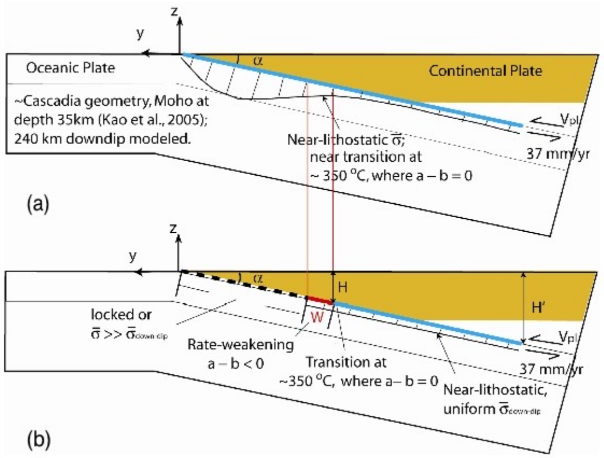
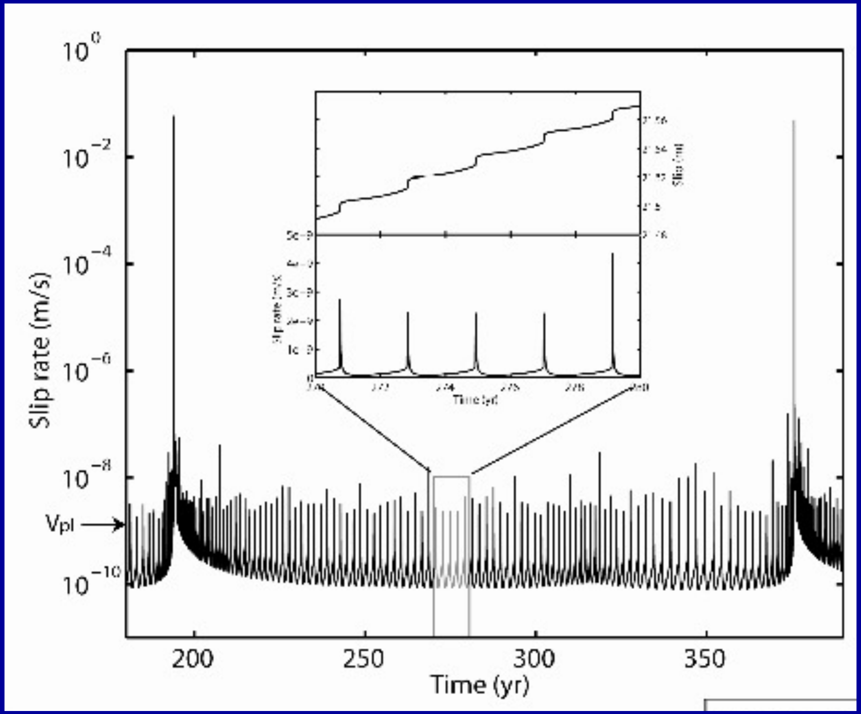


Figure 5.



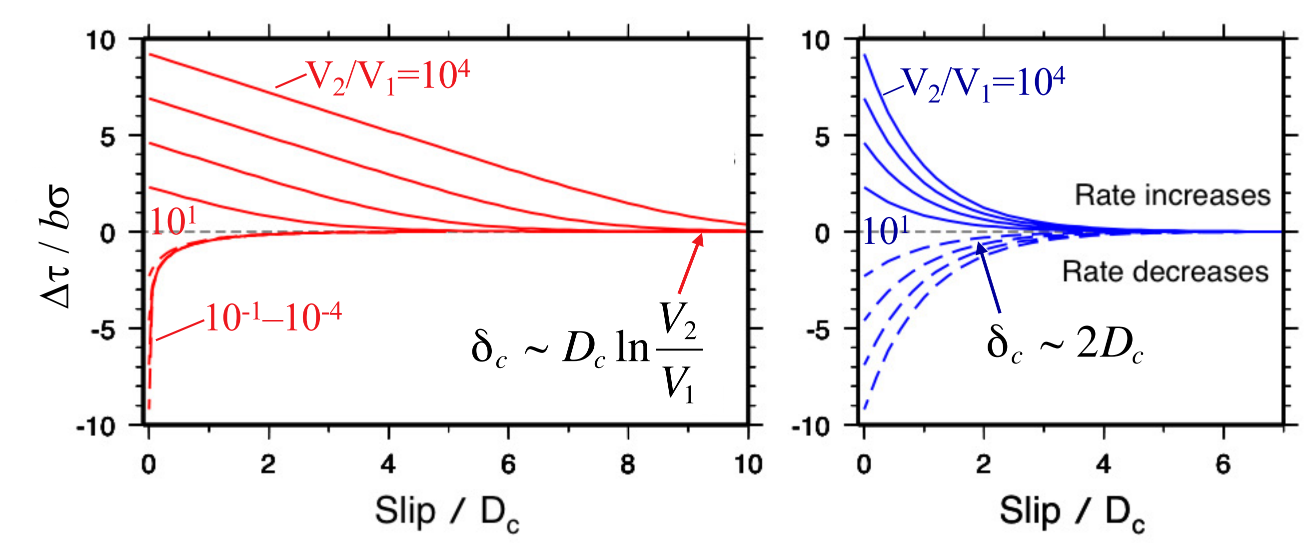
$$L_b = \frac{\mu' D_c}{b\sigma}$$

(30 GPa, 10 μm, 0.01, 30 MPa => 1 m)
(30 GPa, 100 μm, 0.01, 3 MPa => 100 m => $2L_{\text{inf}}$ = 25 km, a/b=0.95)

What about the slip law?

Aging law

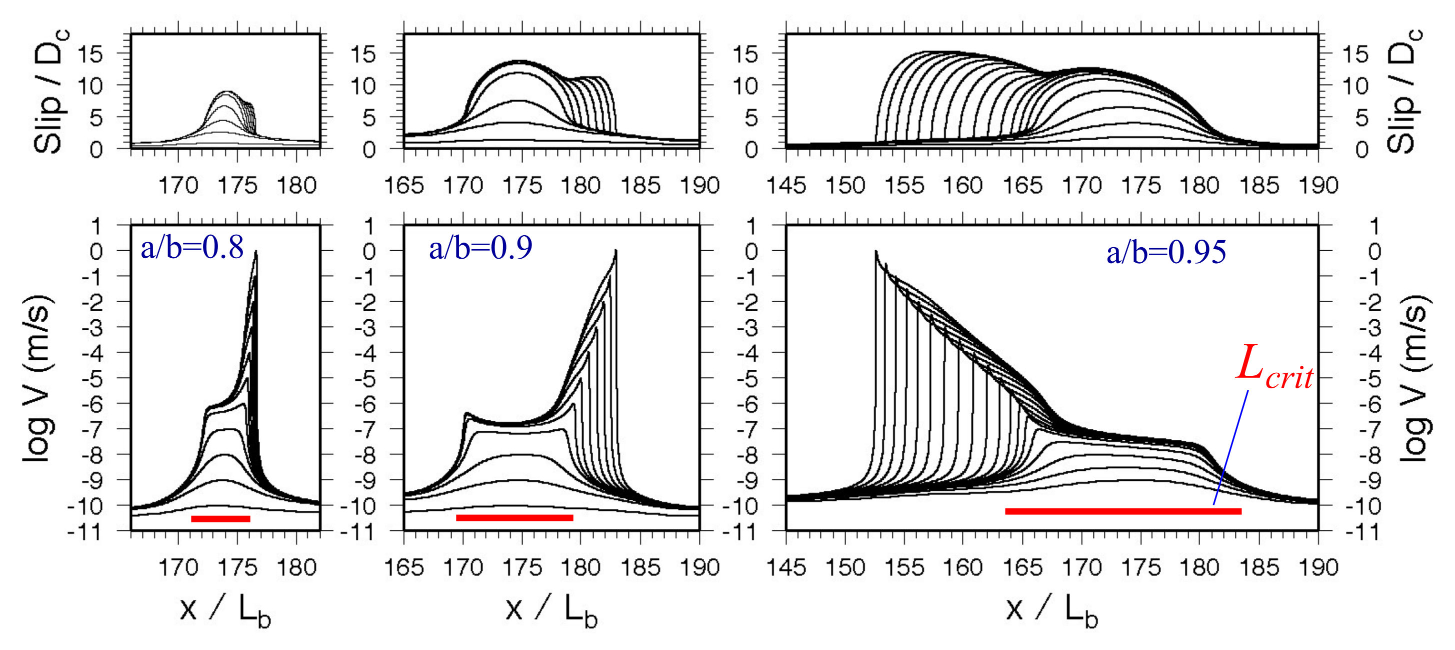
Slip law



Fracture energy: $G_c \sim \left(\ln \frac{V_2}{V_1}\right)^2$

$G_c \sim \left(\ln \frac{V_2}{V_1}\right)^1$

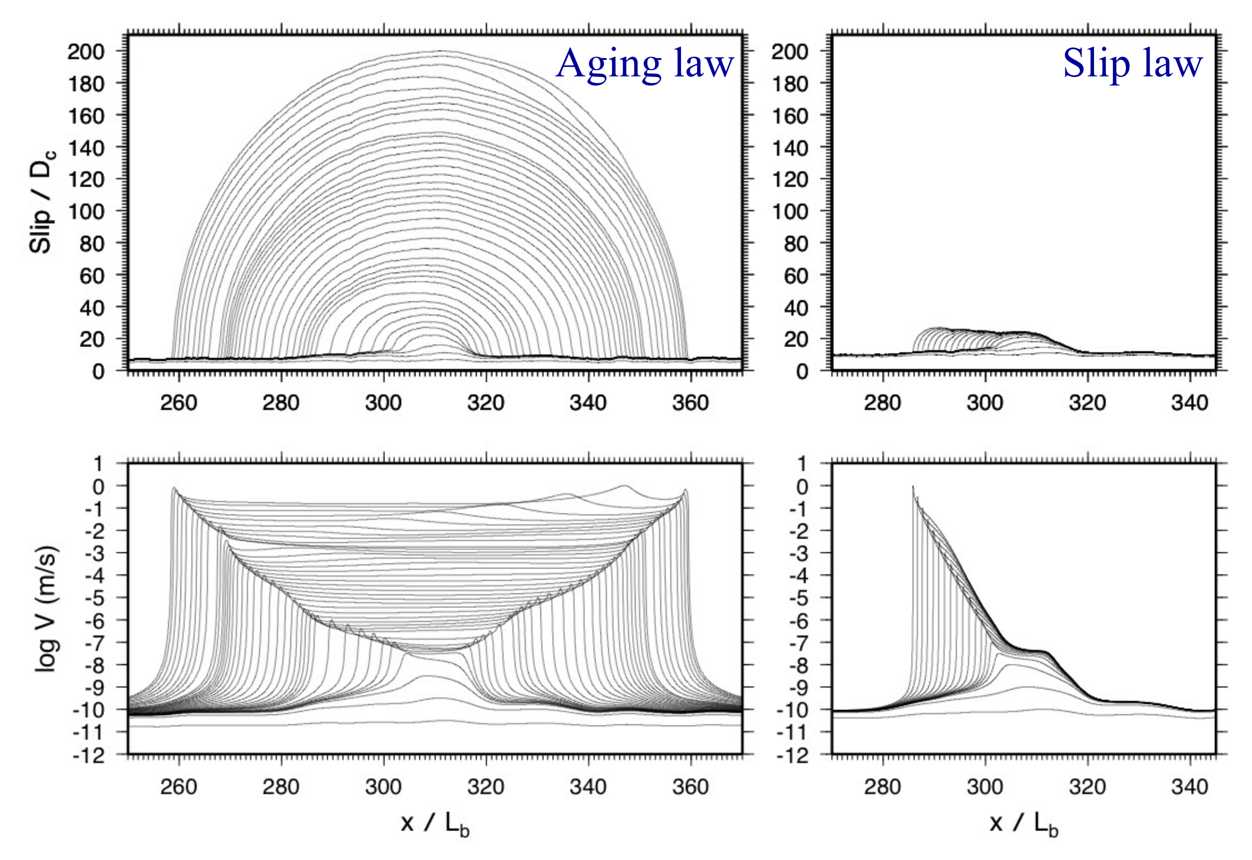
Slip law, $V\theta/D_c \sim 1$

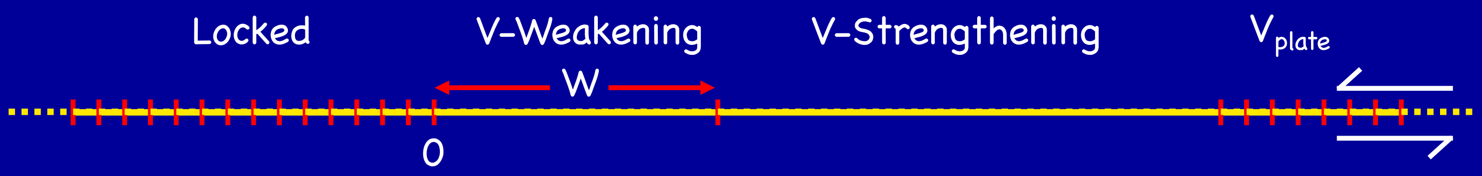


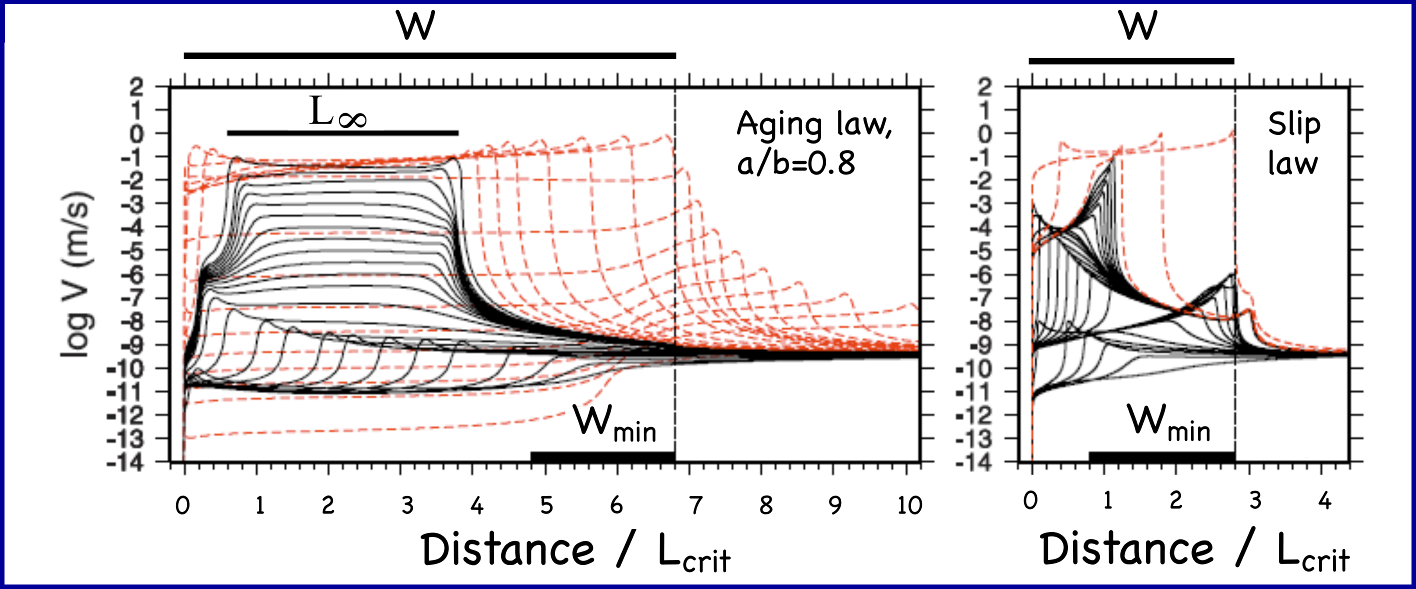
$$G^{crack} \propto L\left(\ln\frac{V_2}{V_1}\right)^2$$, but $$G_c^{SLIP} \propto \left(\ln\frac{V_2}{V_1}\right)^1$$

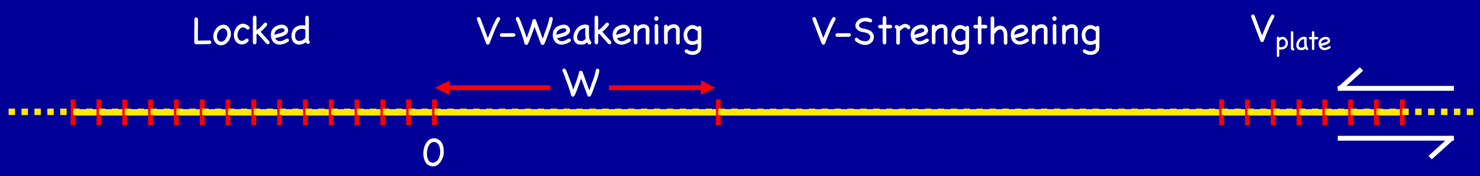
Crack-like growth not possible!

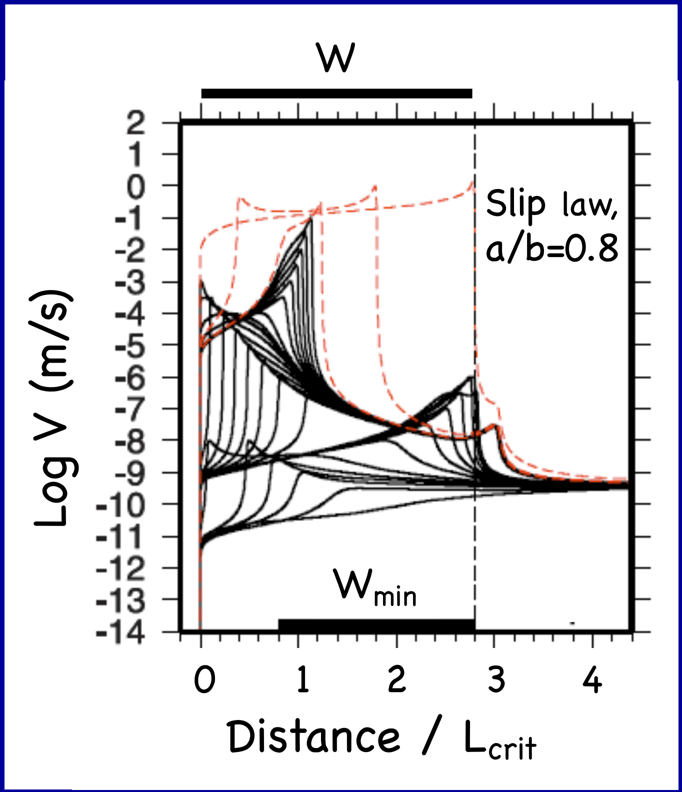
$a / b = 0.95$


Aging law
Slip law
Slip / D_c
log V (m/s)
x / L_b
x / L_b
0
20
40
60
80
100
120
140
160
180
200
260
280
300
320
340
360
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12


Locked
V-Weakening
V-Strengthening
V_{plate}
W
0

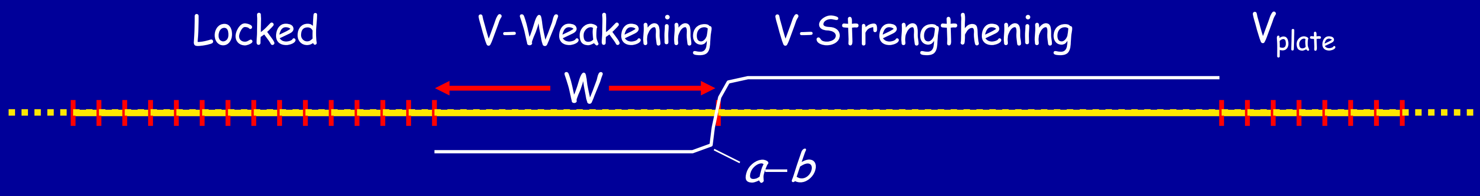

W
L_∞
Aging law, a/b=0.8
W_{min}
log V (m/s)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
0
1
2
3
4
5
6
7
8
9
10
Distance / L_{crit}
W
Slip law
W_{min}
0
1
2
3
4
Distance / L_{crit}

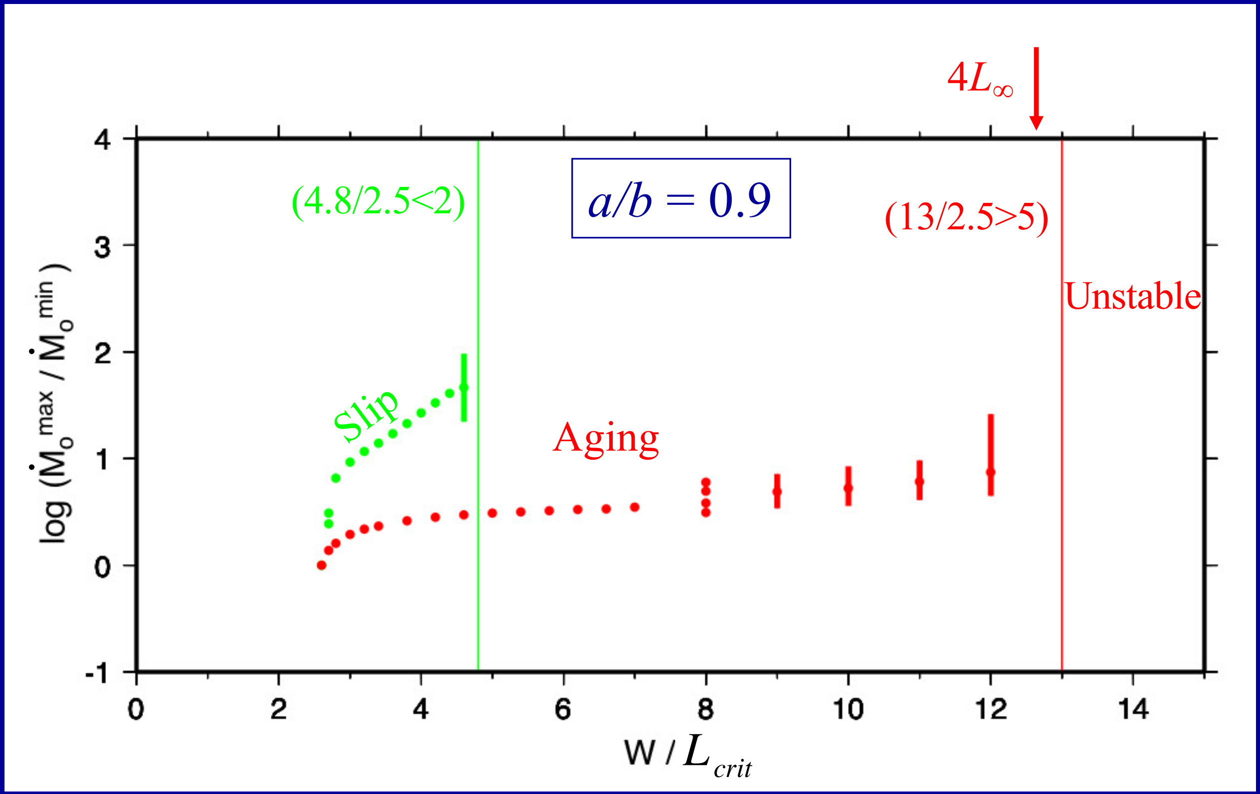




For the Slip law, fracture energy increases much less rapidly with slip speed.

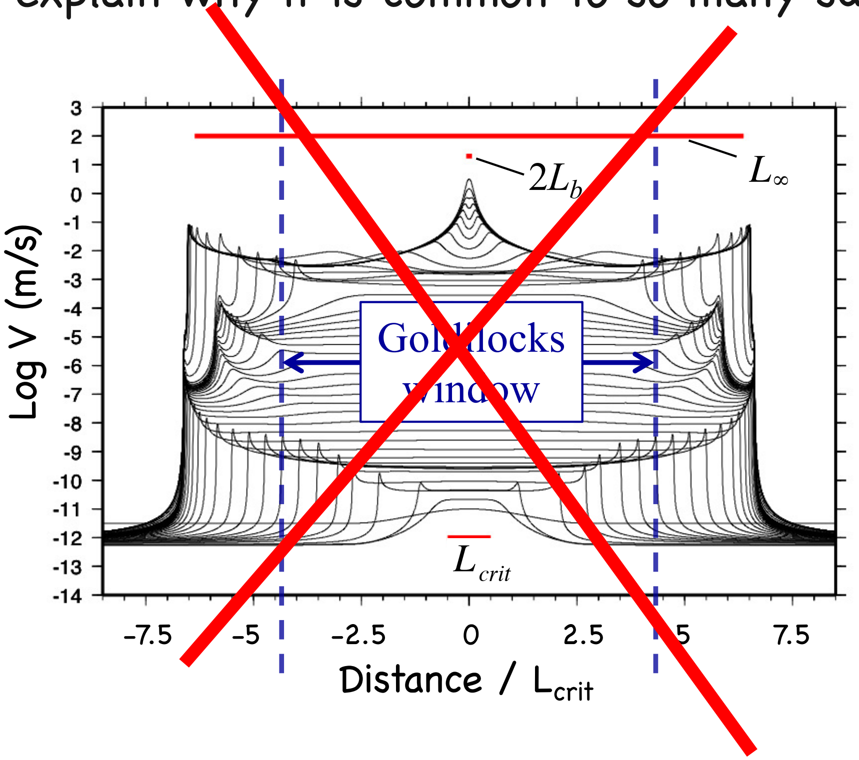
Much less expansion is required to reach elastodynamic speeds

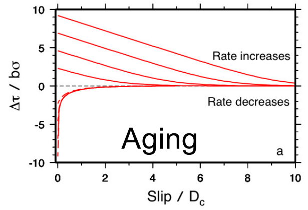

Locked
V-Weakening
V-Strengthening
V_{plate}
W
$a-b$

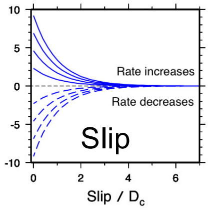

$4L_\infty$
(4.8/2.5<2)
$a/b = 0.9$
(13/2.5>5)
Unstable
Slip
Aging
$\log(\dot{M}_o^{max} / \dot{M}_o^{min})$
-1
0
1
2
3
4
0
2
4
6
8
10
12
14
W / L_{crit}

Slow Slip Explanation #1: The "Goldilocks hypothesis"

If you use the (Slip) state evolution law that properly captures the laboratory response to rapid velocity increases, the range of fault lengths hosting episodic slow slip is too narrow to credibly explain why it is common to so many subduction zones.

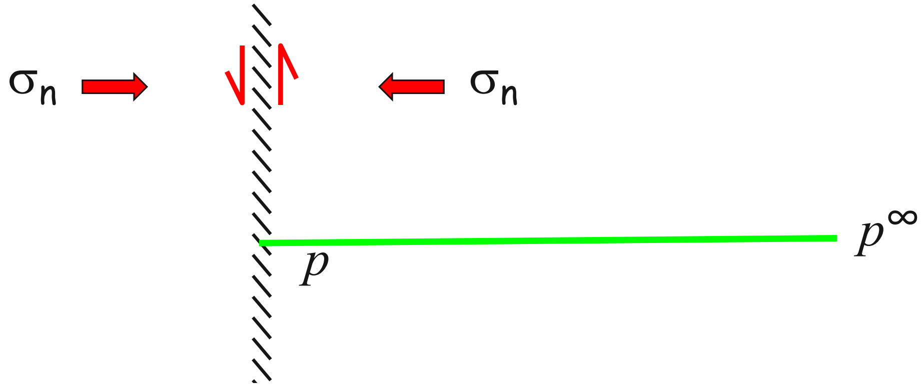






Slow Slip Explanation #2:

Stabilization due to pore dilatancy/pore pressure reduction during accelerating slip. Expected to dominate over standard rate-and-state strength changes at low effective normal stress [Suzuki and Yamashita (2009); Liu and Rubin (2010); Segall et al., 2010; Yamashita, 2013].



Shear strength = friction * (σ_n- p)

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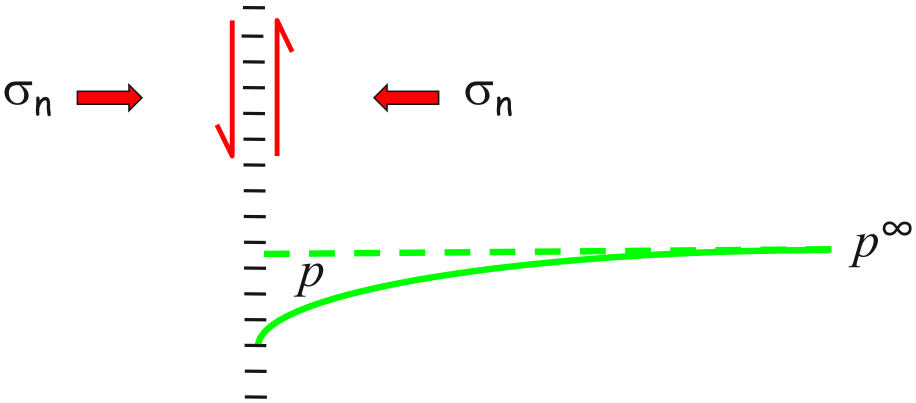
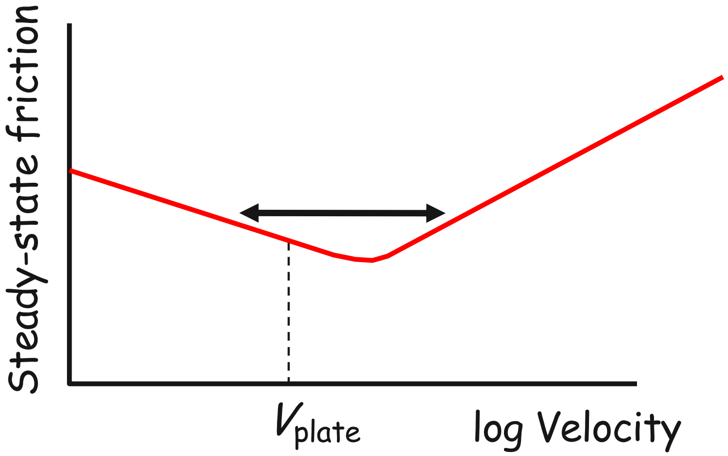


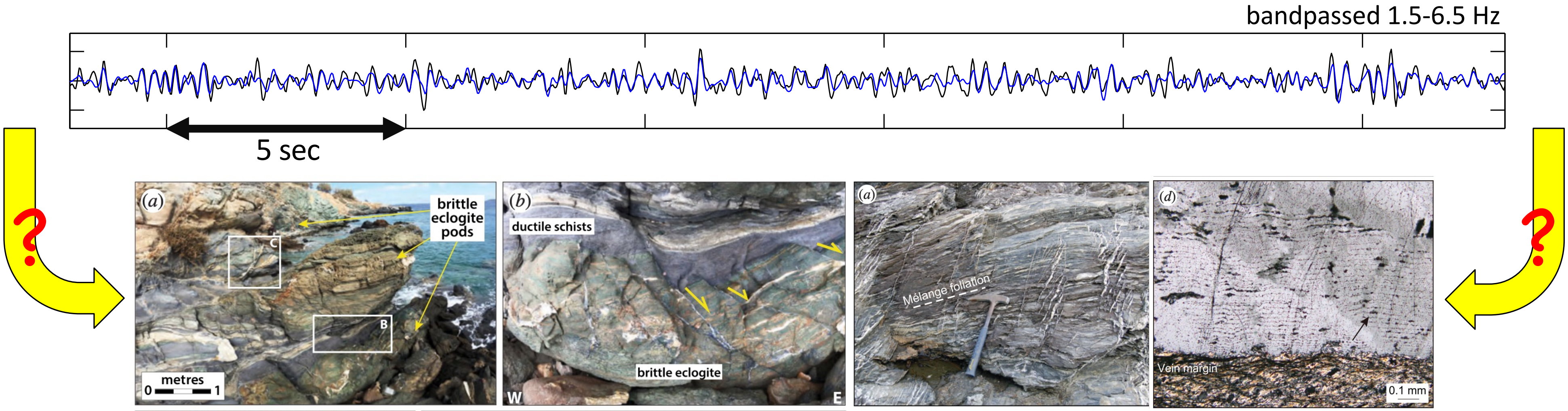
Shear strength = friction * (σ_n- p)

Slow Slip Explanation #3:

A transition from steady-state velocity-weakening to velocity-strengthening behavior in the appropriate range of slip speeds [e.g. Kato, 2003; Shibazaki and Iio, 2003; Shibazaki and Shimamoto, 2007; Hawthorne and Rubin, 2013].



Toward a physical interpretation of Low Frequency Earthquakes (LFEs)



Behr & Burgmann, 2020

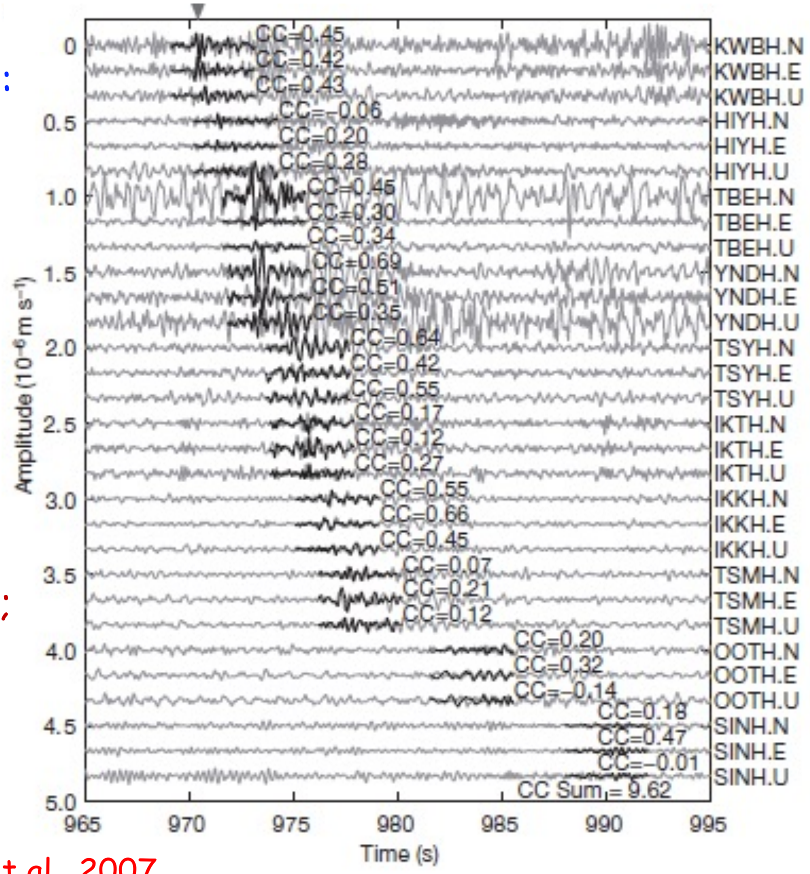
Syros Island, Greece

Shimanto accretionary complex, Japan

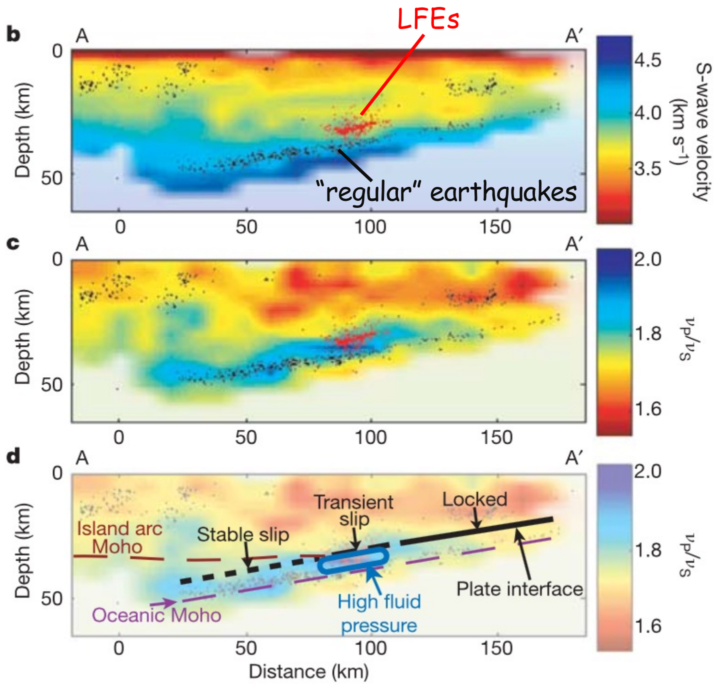
One Low Frequency Earthquake (LFE) cross-correlated with continuous tremor seismograms in Japan: Tremor is comprised of myriad LFEs.

Gives you "families" of LFEs: Anything with waveforms and moveouts similar enough to your template event.

(10 stations; 3 channels)



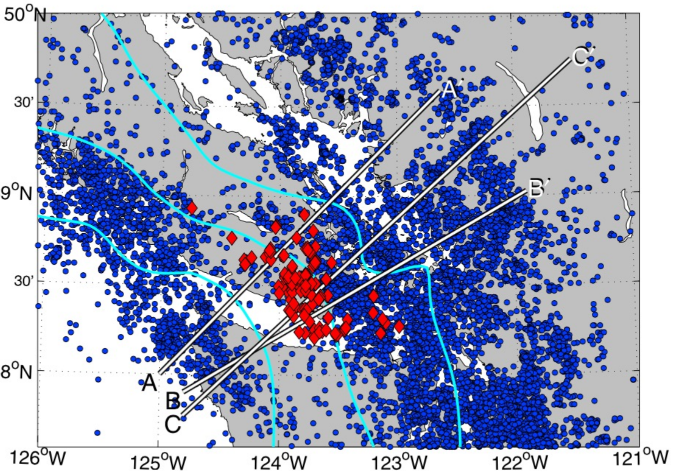
Shelly et al., 2007

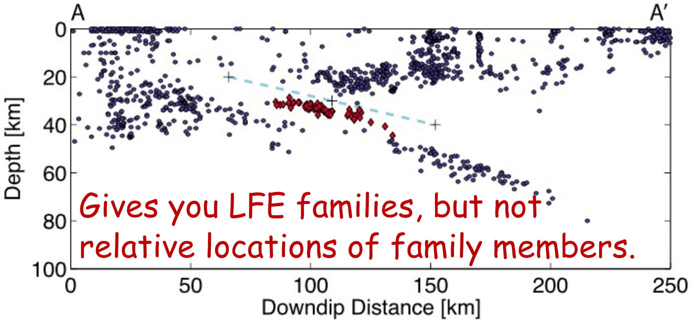


Shelly et al., 2006

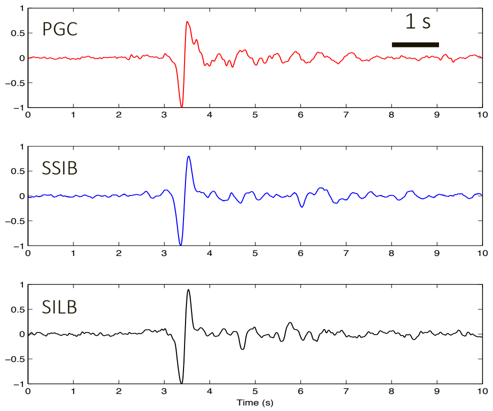
Bostock et al. 2012: LFE families in Cascadia from cross-correlating each time window with all other time windows (following Brown and Beroza).

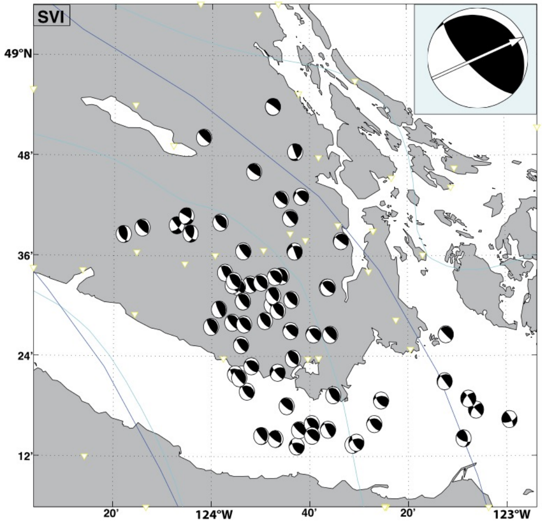
“CROSS-TIME” DETECTIONS





Gives you LFE families, but not relative locations of family members.

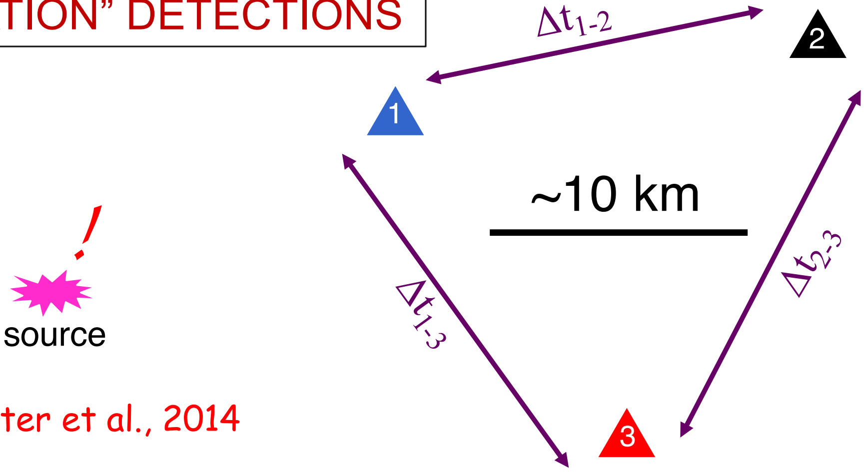




Stacking of LFEs w/in families gives good focal mechanisms - Royer & Bostock 2014 (also Ide et al. 2007 for Japan):

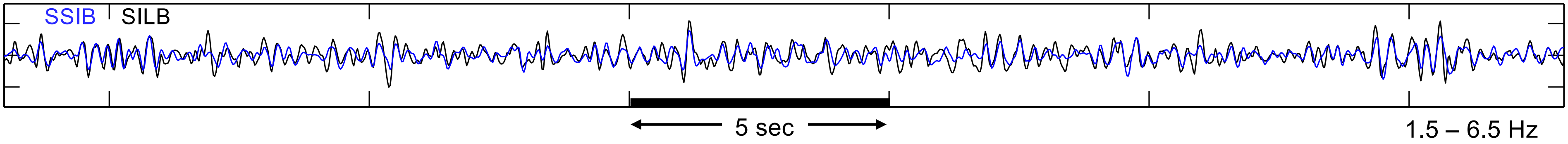
LFEs represent slip on the plate interface, in the direction of relative plate motion.

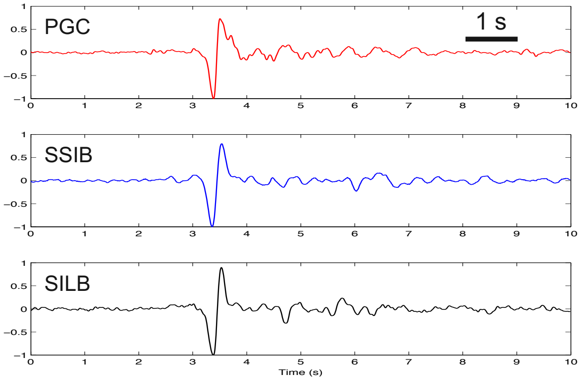
“CROSS-STATION” DETECTIONS



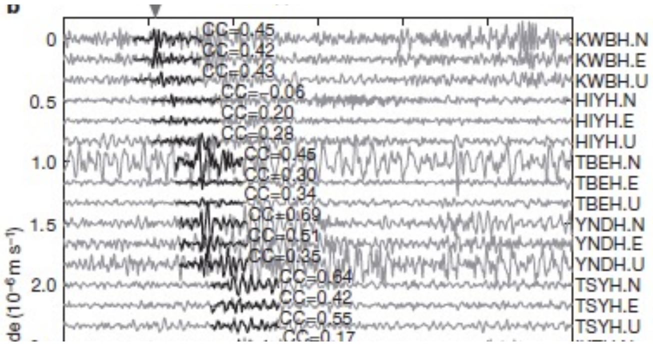
Armbruster et al., 2014

1. Rotate the horizontal components at 3 stations into the particle motion direction.
2. Cross-correlate the 3 station-station pairs.
3. Average CC value > threshold and “loop of time offsets” < threshold gives a detection.
4. Two independent time offsets give a map location, assuming the source to lie on the plate interface.



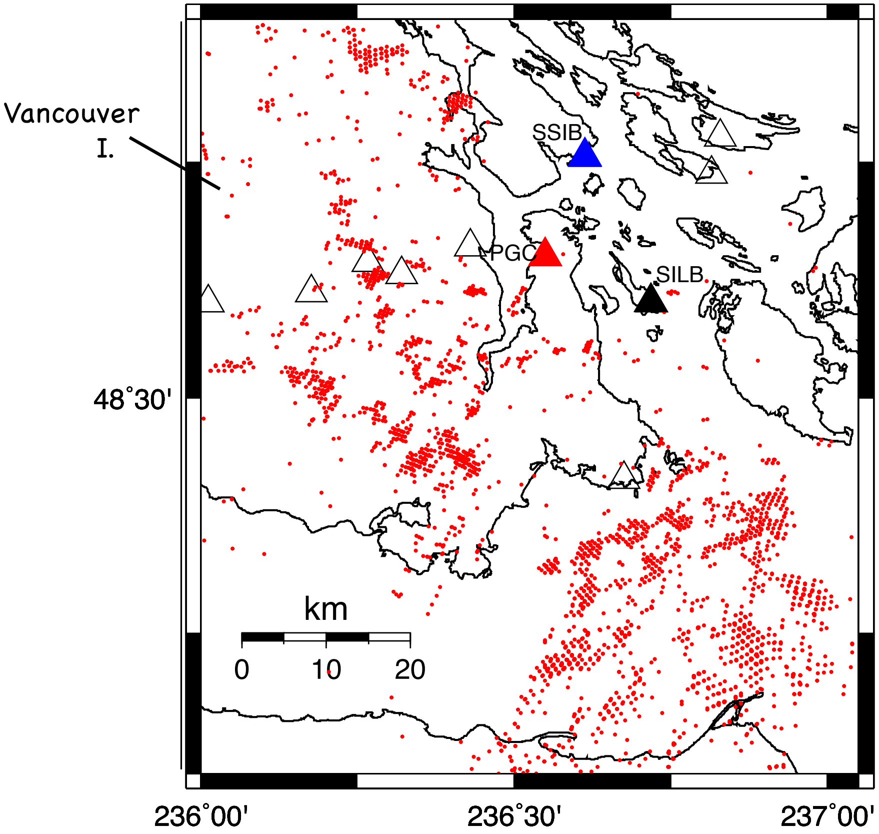


stacks of ~2000 LFEs
in Bostock’s Family #002



Slow slip episodes:

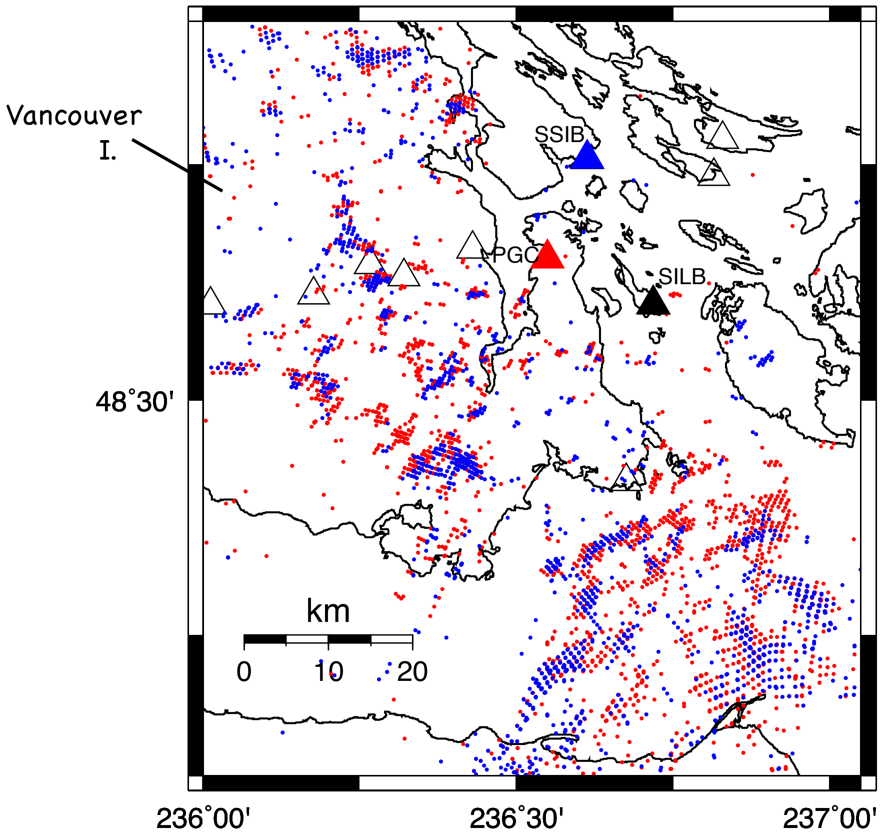
Sept 2005



Armbruster et al., 2014 (150 s windows)

Slow slip episodes:

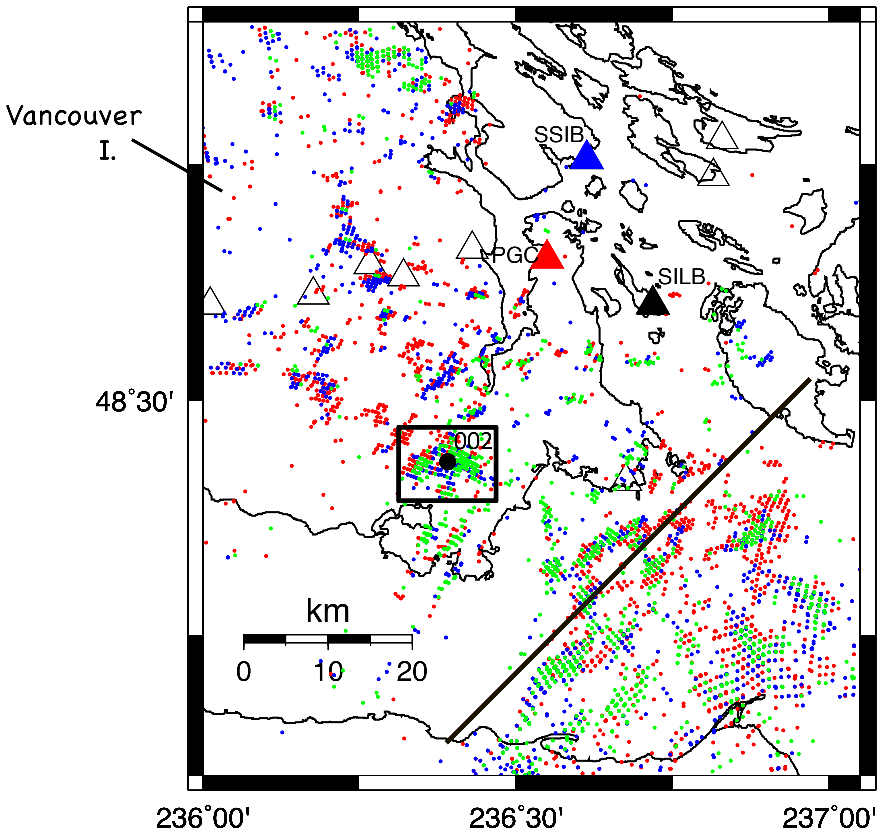
Sept 2005 + July 2004



Armbruster et al., 2014 (150 s windows)

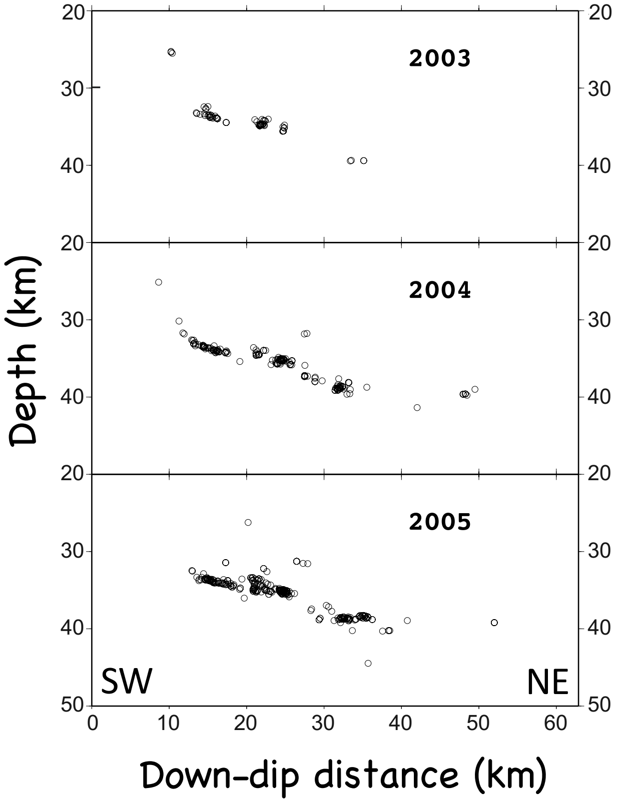
Slow slip episodes:

Sept 2005 + July 2004 + March 2003



"Four S plus one P" catalog

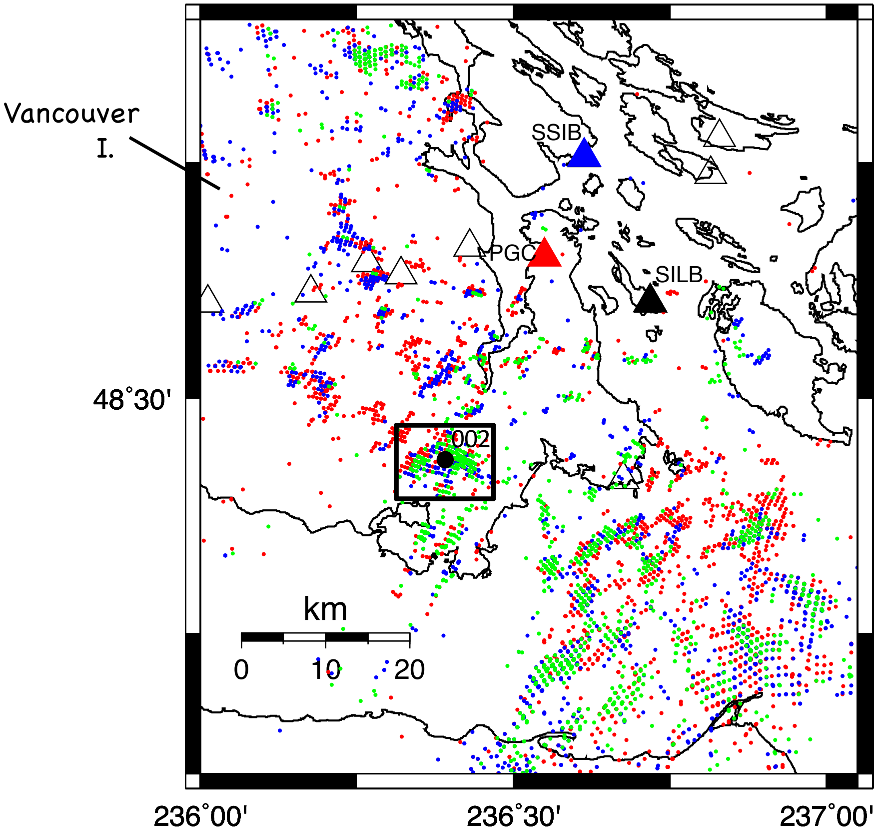
(753 detections vs 22,000)



Armbruster et al., 2014 (150 s windows)

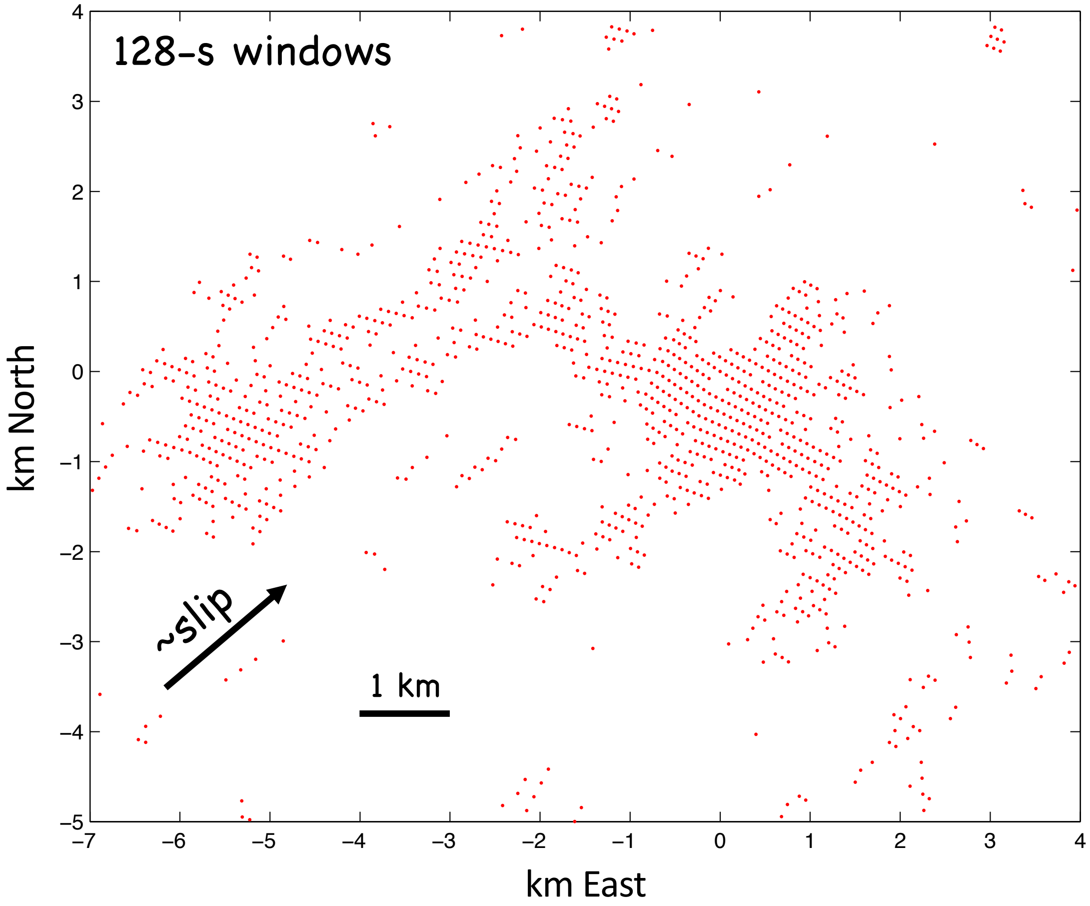
Slow slip episodes:

Sept 2005 + July 2004 + March 2003

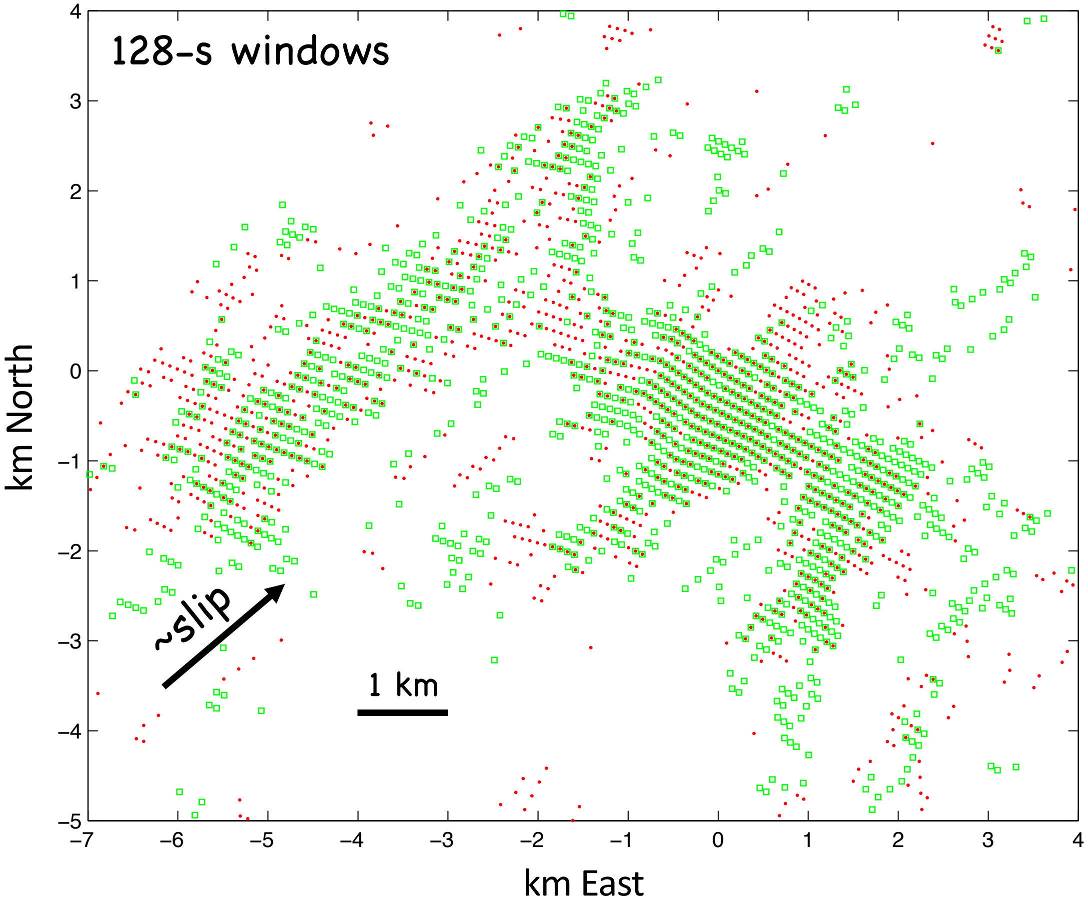


Armbruster et al., 2014 (150 s windows)

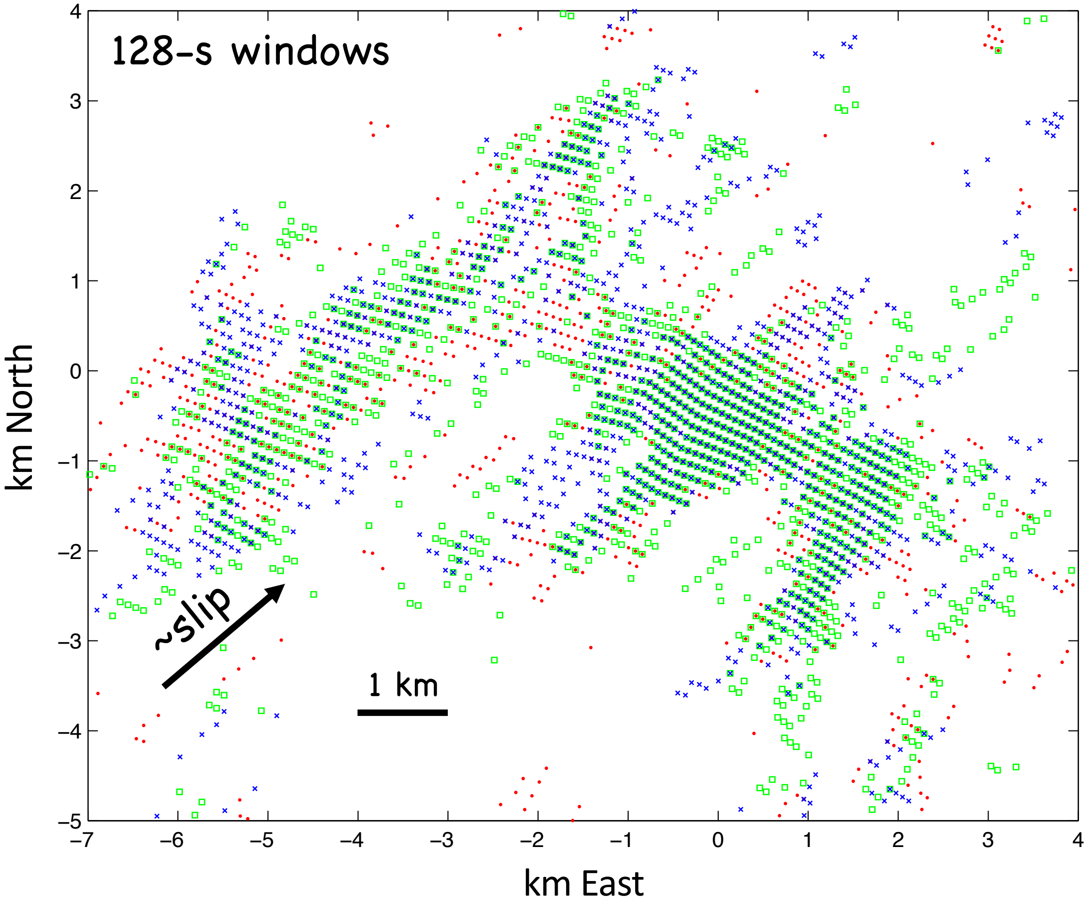
September 2005

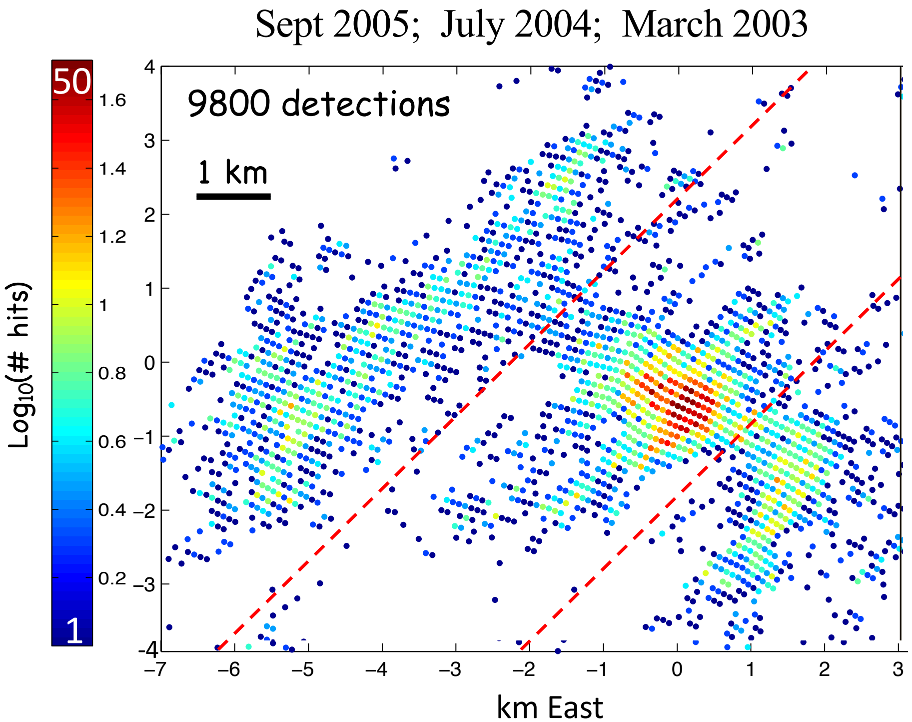


Sept 2005; July 2004

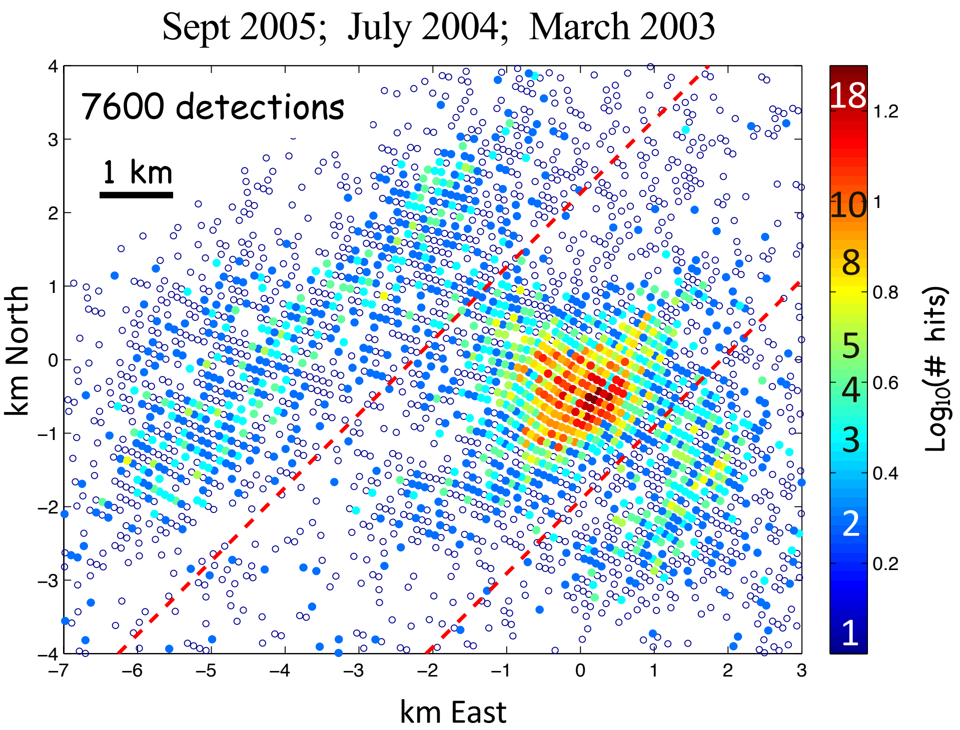


Sept 2005; July 2004; March 2003

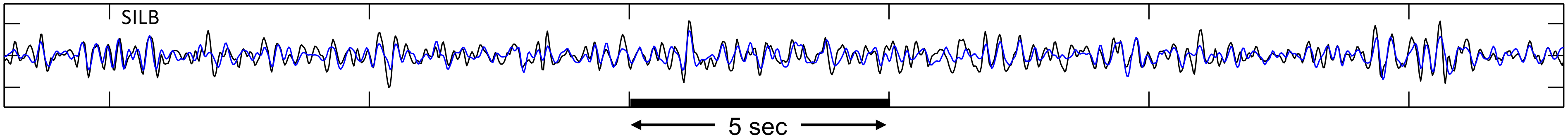


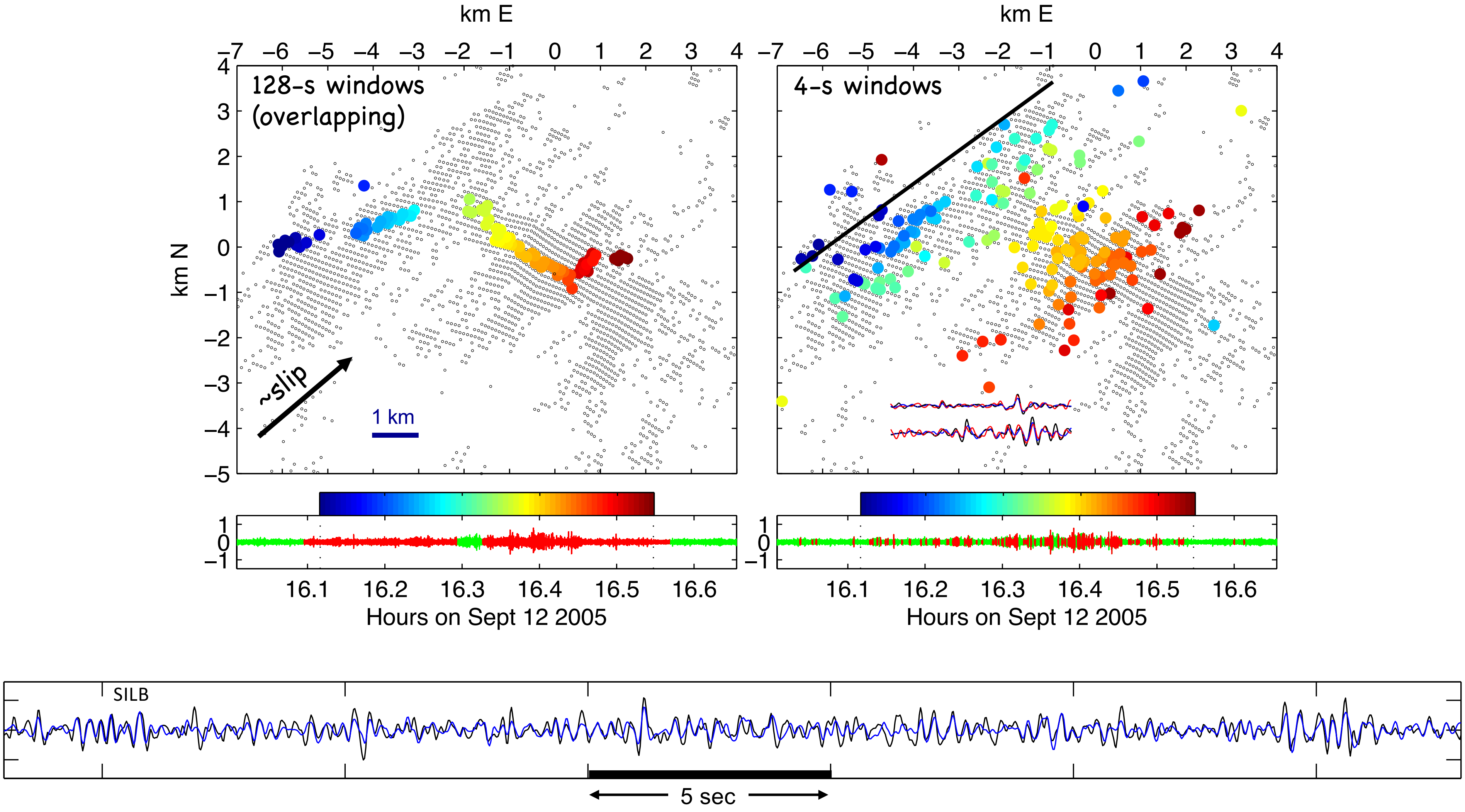

Sept 2005; July 2004; March 2003

128-s windows

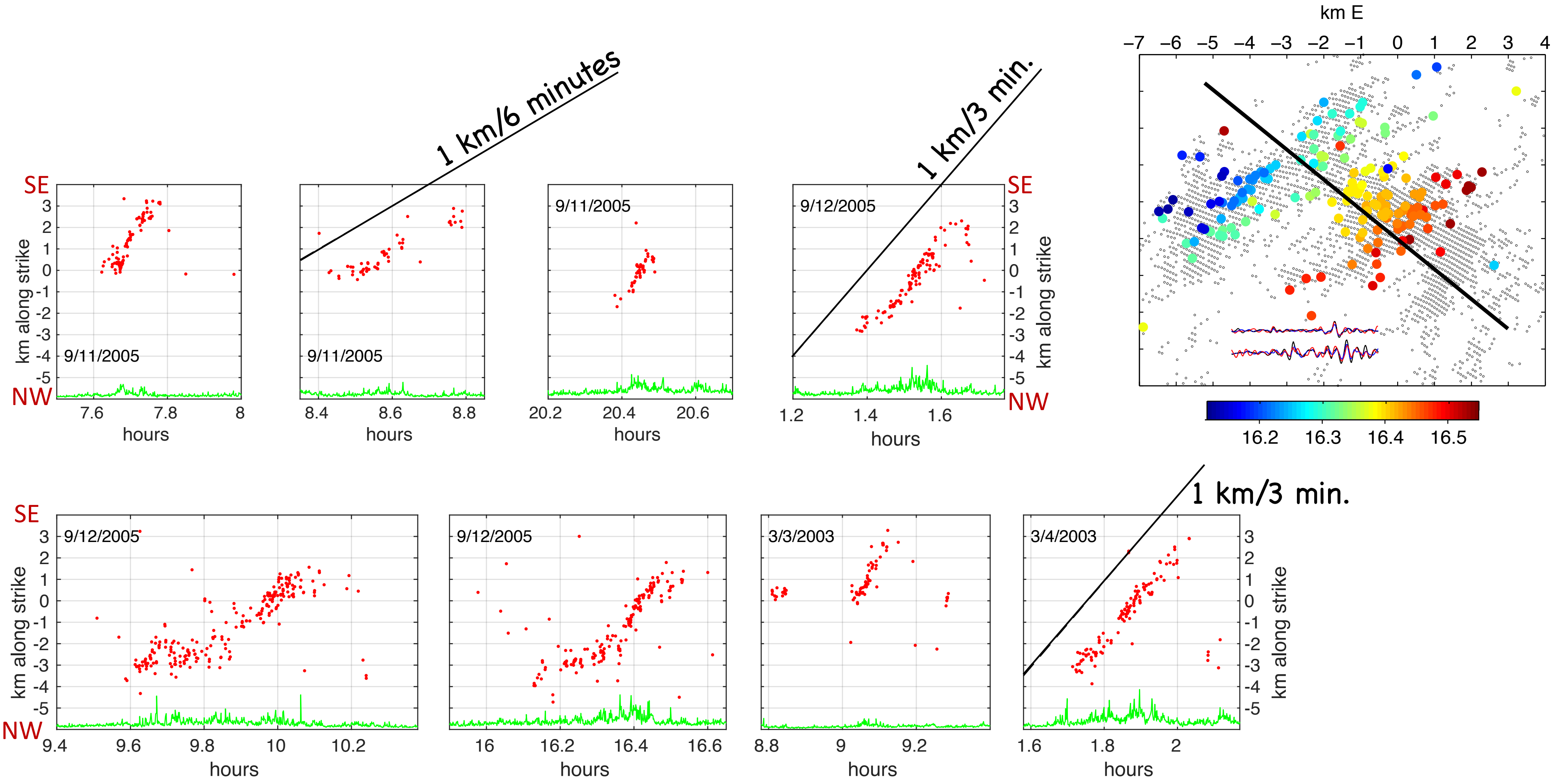

Sept 2005; July 2004; March 2003

4-s windows

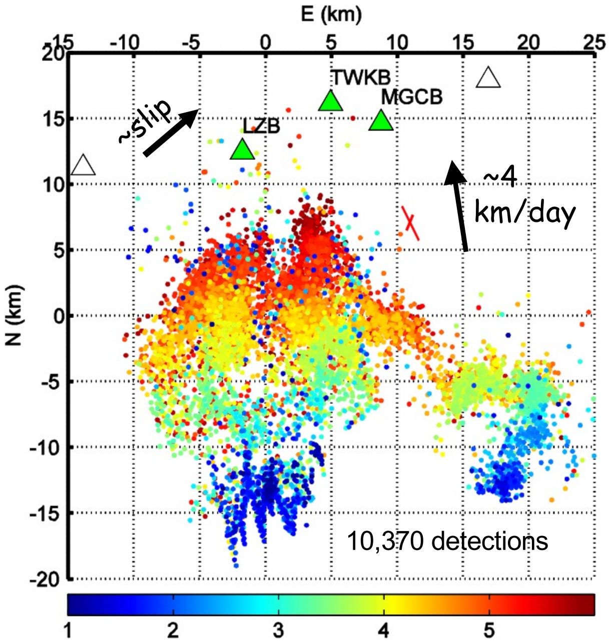




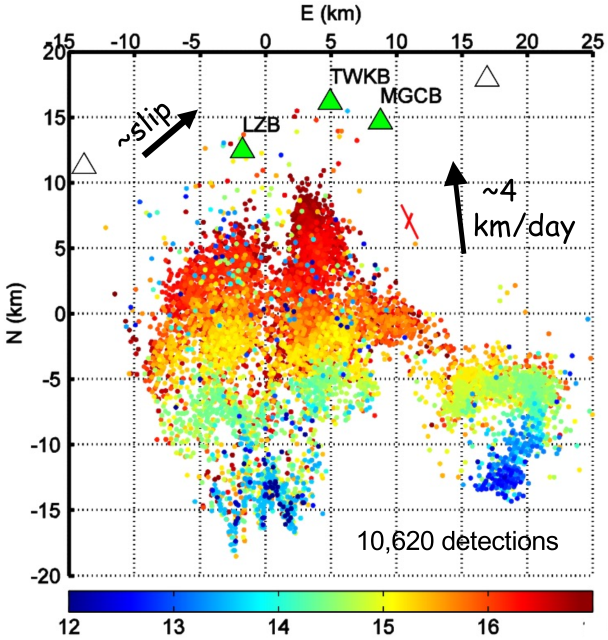
km E
km E
128-s windows
(overlapping)
4-s windows
km N
~slip
1 km
−7 −6 −5 −4 −3 −2 −1 0 1 2 3 4
4 3 2 1 0 −1 −2 −3 −4 −5
1 0 −1
16.1 16.2 16.3 16.4 16.5 16.6
Hours on Sept 12 2005
Hours on Sept 12 2005
SILB
5 sec



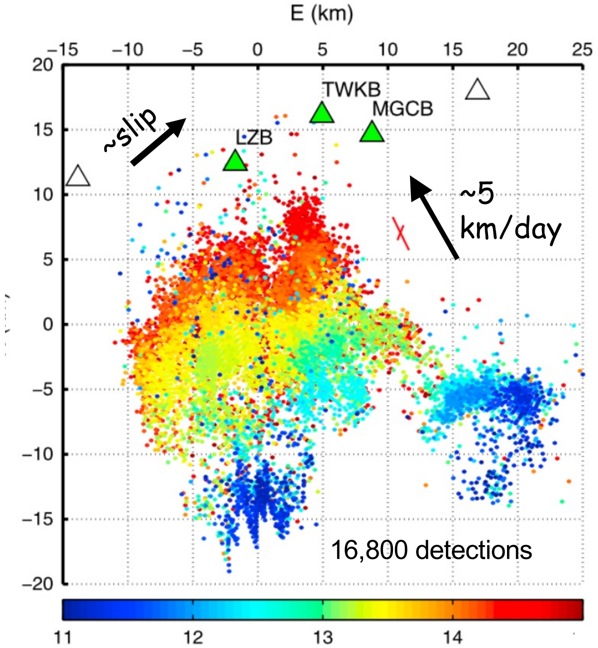
The "apparent" width of the slipping front tends to be 1 – 1.5 km. Each accumulates about 1-2 mm of slip. In roughly 200 s (1 km/[1 km/200 s]). Average slip speed 5–10 μm/s.



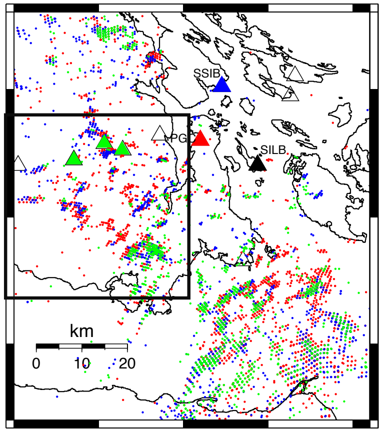
March 2003

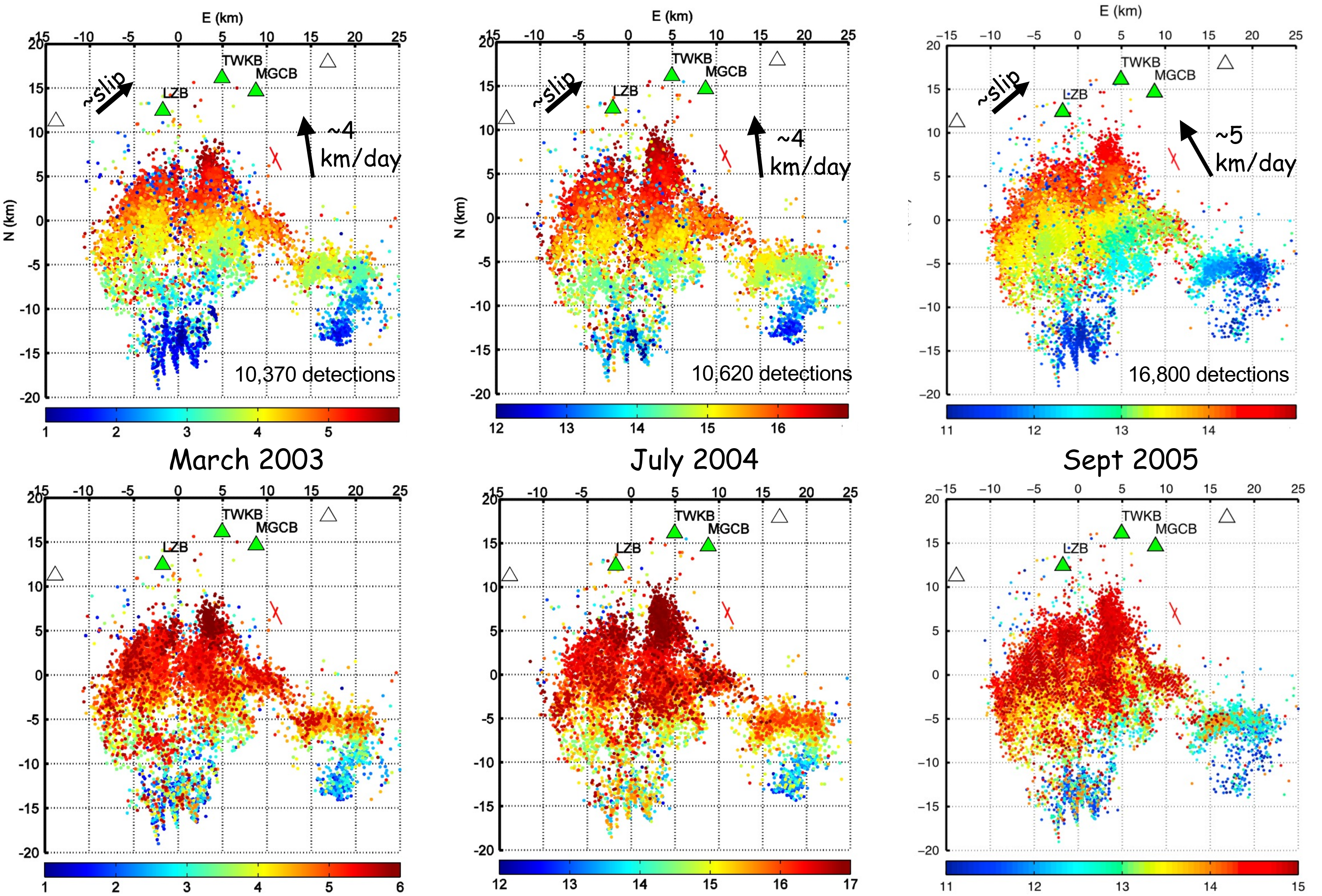


July 2004



Sept 2005





~slip

~4 km/day

~5 km/day

10,370 detections

10,620 detections

16,800 detections

March 2003

July 2004

Sept 2005

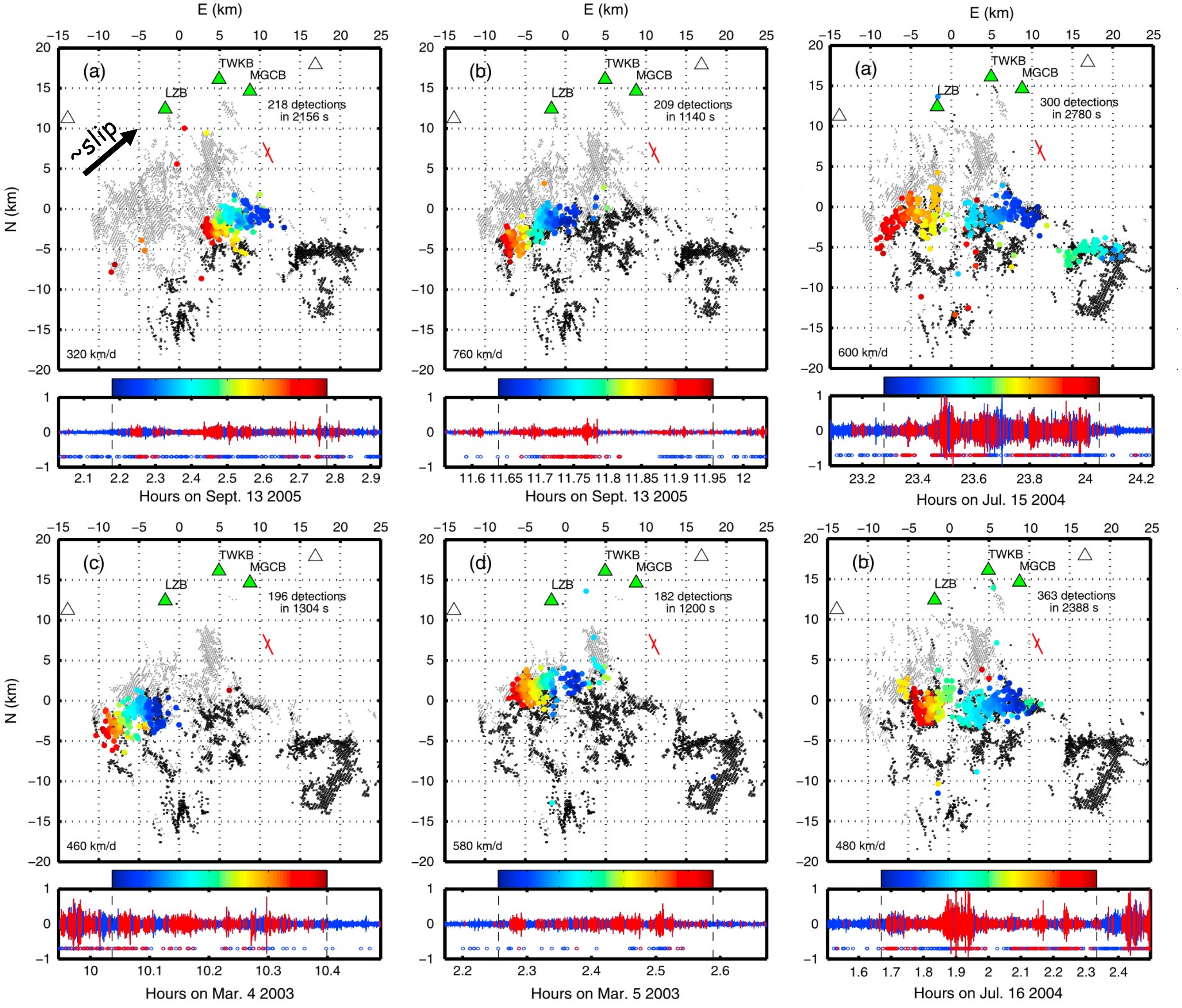
Earliest (blue)
on top

Latest (red)
on top

Gray dots: All detections

Black dots: Detections thus far in this SSE

Migrations are along the main front, 50 – 150 times faster than the main front propagation rate (hundreds of km/day).

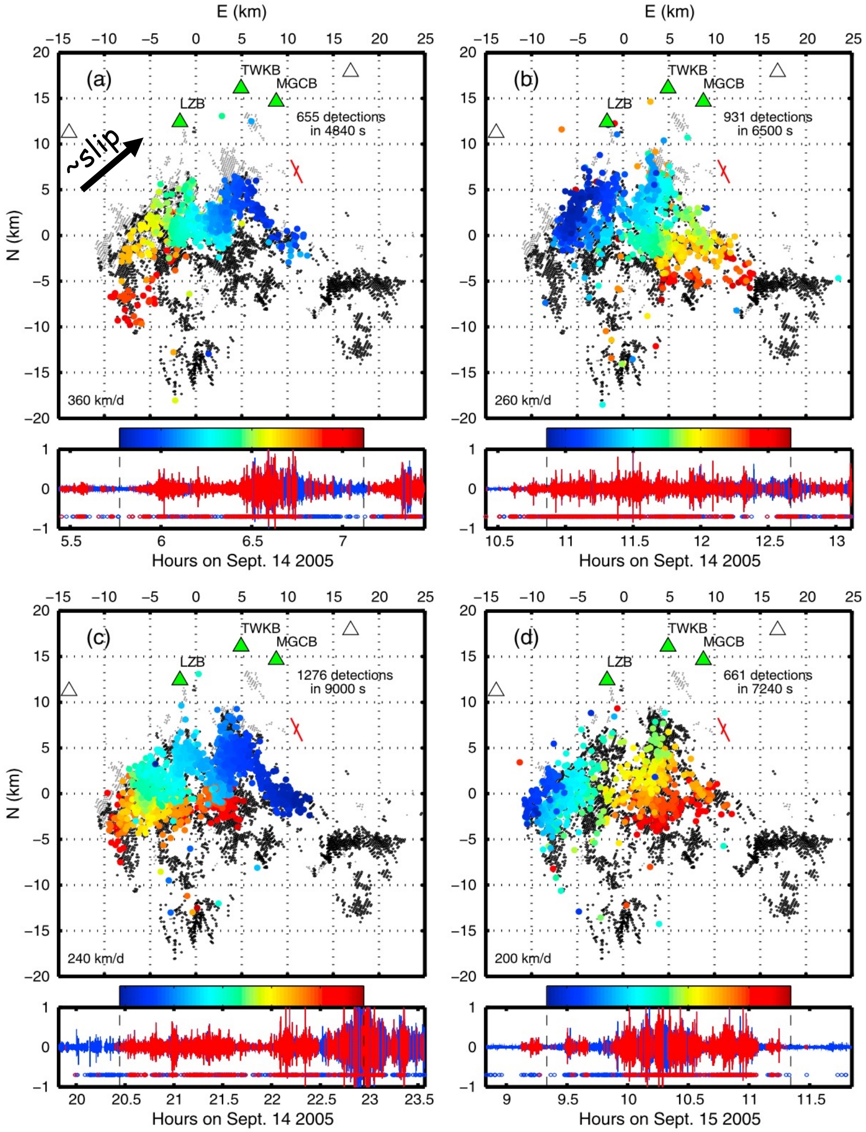


Gray dots: All detections

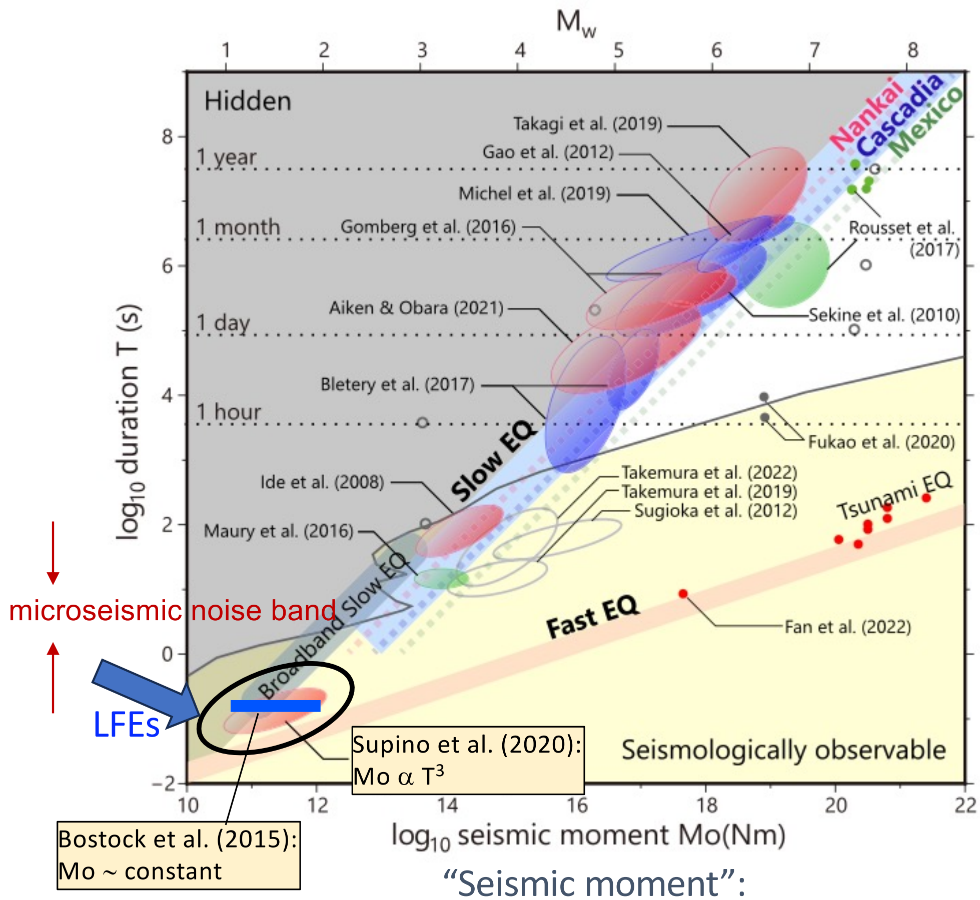
Black dots: Detections
thus far in this SSE

4 migrations in 30 hours.
Propagation speeds
1 km/4-6 minutes.

>3500 detections in 460
minutes (4-s windows).
On average, one 4-s
detection every 7-8 s.



So what are Low Frequency Earthquakes?



microseismic noise band

LFEs

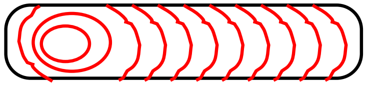
Supino et al. (2020):
Mo α T^3

Bostock et al. (2015):
Mo ~ constant

"Seismic moment":
(slip area) x (slip distance) x (shear modulus)

Ide & Beroza, 2023

$M_o \propto T \quad (T = \text{duration})$



$M_o \propto T^3$:

Area $\propto R^2$ (geometry)

Slip $\propto R$ (elasticity & uniform stress drop)

⇨ $M_o \propto R^3$

$T \propto R$ (uniform rupture velocity)

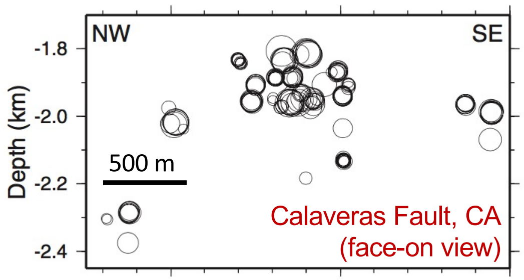
⇨ $M_o \propto T^3$

What are Low-Frequency Earthquakes?

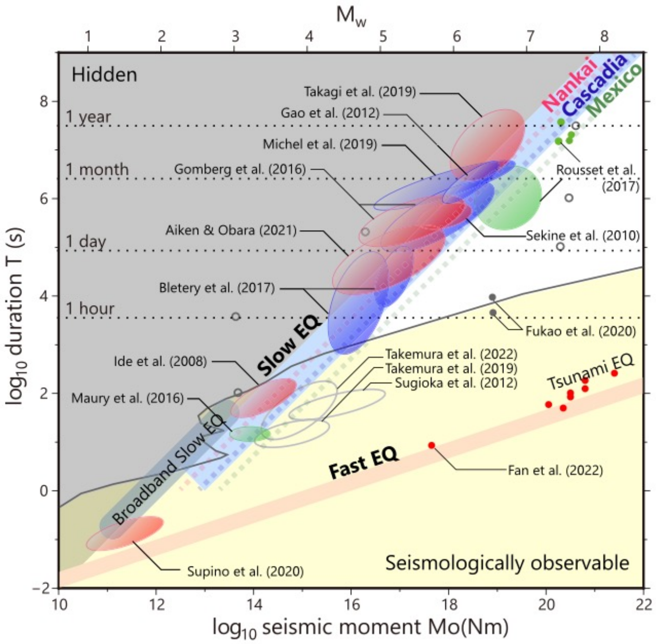
Two (somewhat) different views:

1. The "Slow earthquake trend" just links two familiar end-members: LFEs are stick-slipping brittle asperities embedded in an otherwise creeping fault zone; that creep gives rise to slow slip. 50-second "VLFEs" are just a bunch of LFEs concentrated in space and time (Ando et al, 2010; Gomberg et al., 2016).

2. "LFEs" occupy the high-frequency limit of a continuous spectrum extending from periods <1 sec to several weeks or more ("slow slip events"). "LFEs" are just what we see of this continuum when we look in the frequency band 1-8 Hz (Ide). (Think stochastic fluctuations of fault slipping area and/or sliding speed.)



Each LFE is an acceleration followed by a deceleration. Each LFE source is mechanically distinct from its surroundings.



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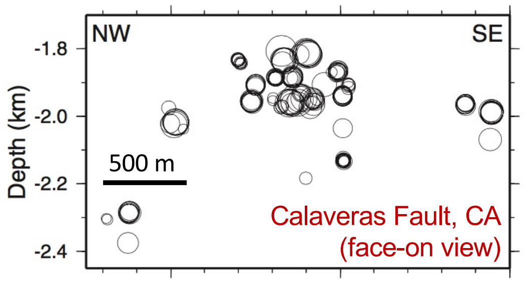

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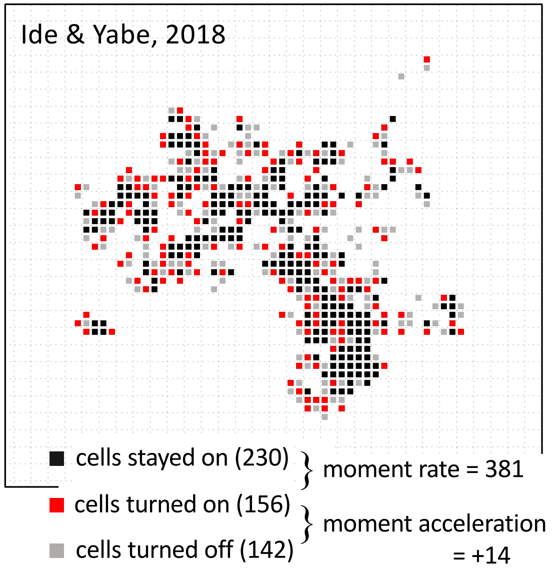
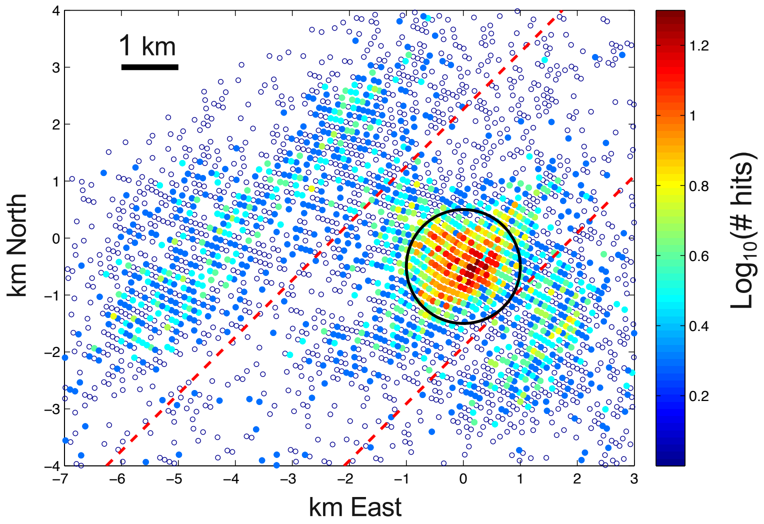


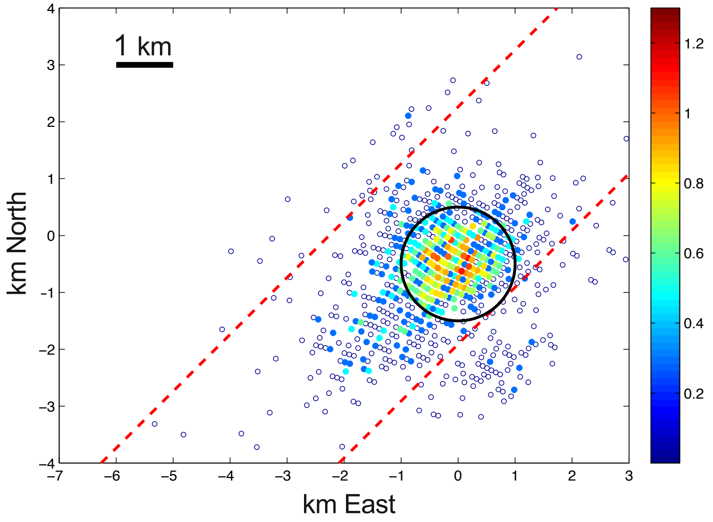
Accelerations and decelerations need not come from the same spot. "An LFE" is inherently a composite of many events, not necessarily mechanically distinct from their surroundings.

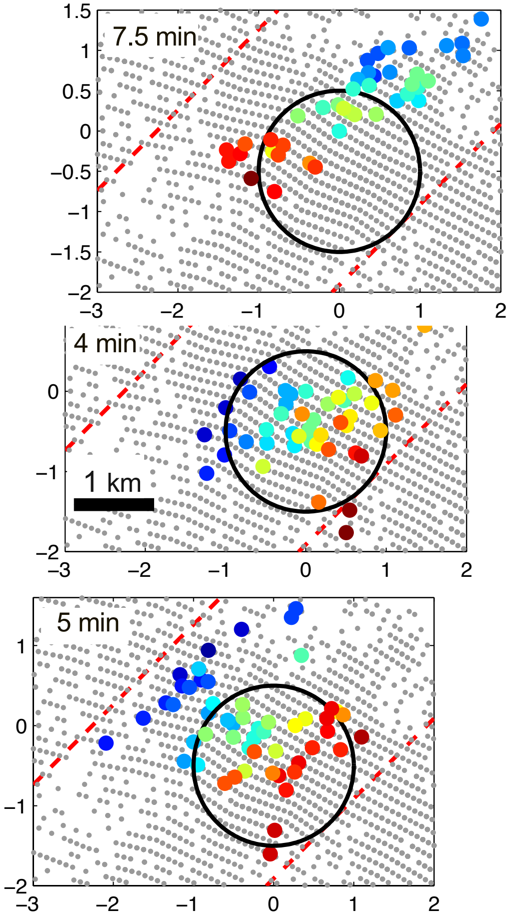
Our 4-second-window locations (7800)

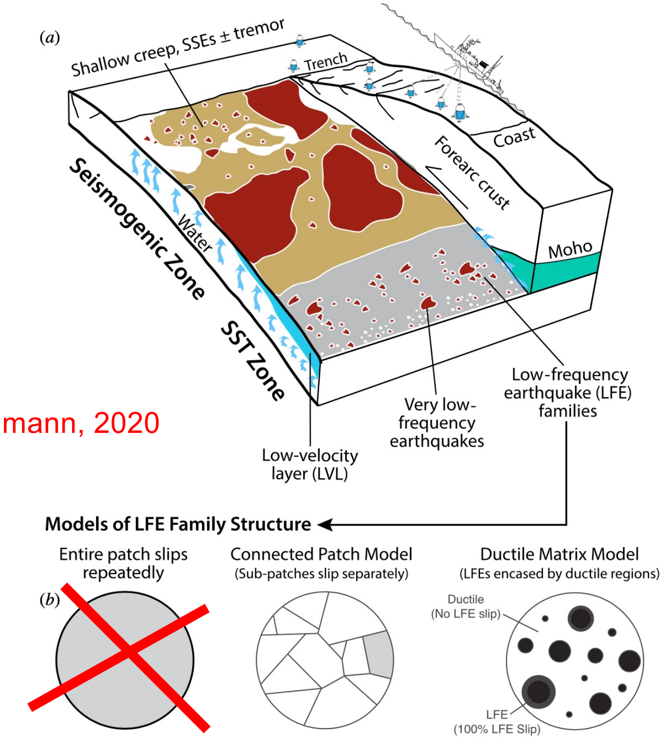


SO – What can we learn from good tremor locations?

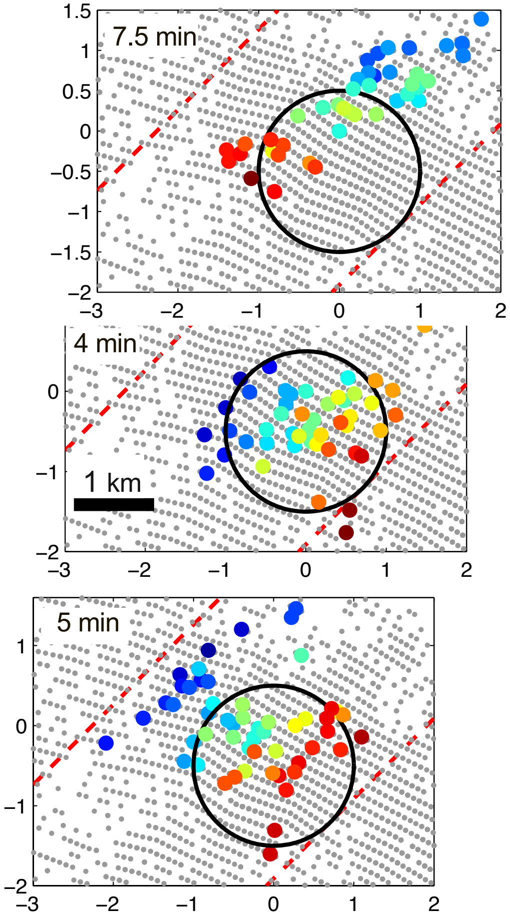
Our 4-second locations of Bostock LFE family #002 (~2/3 of them; 1472/2287)



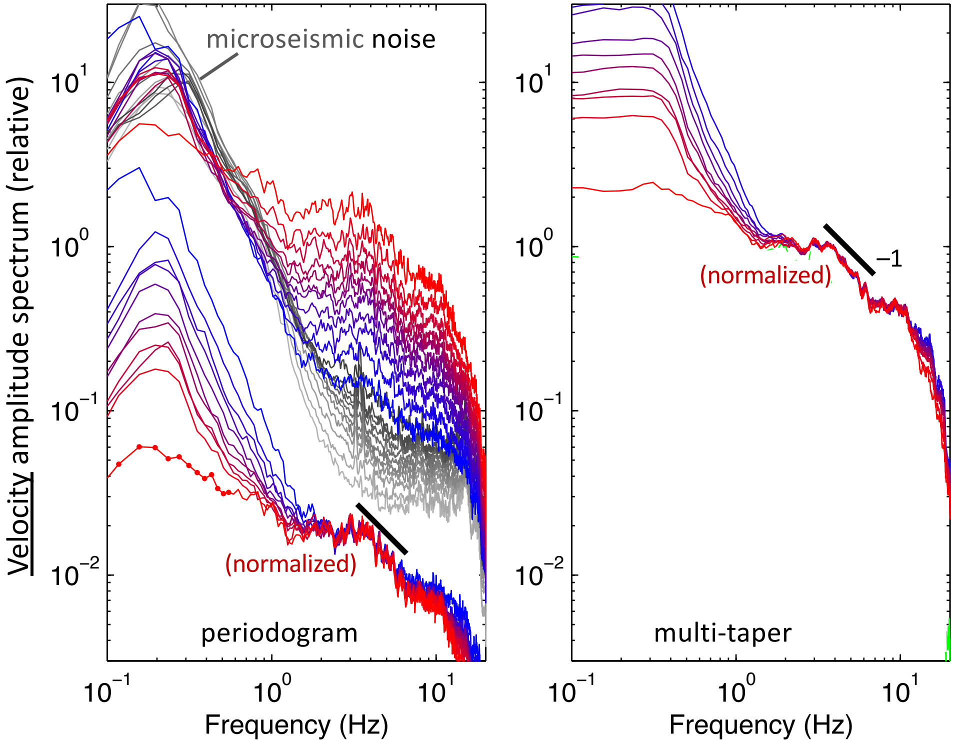




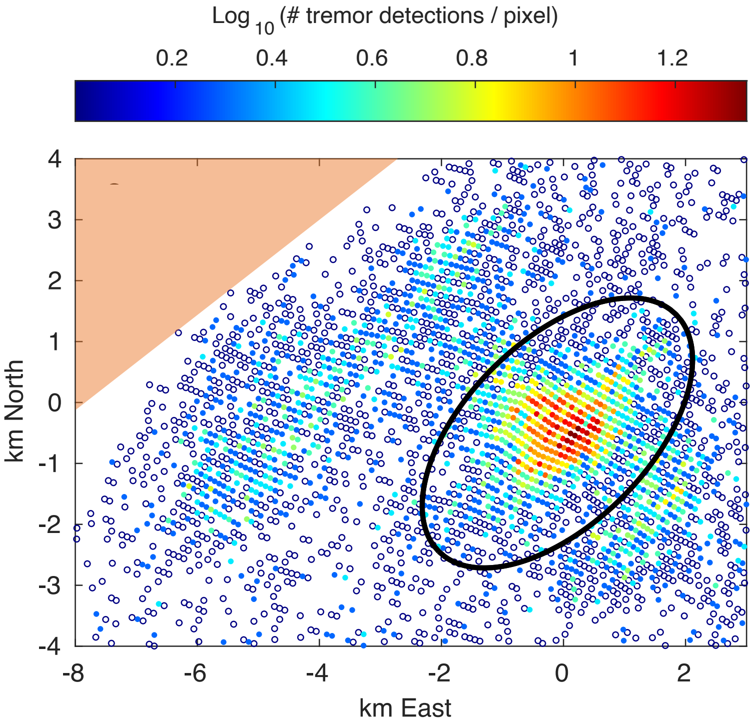
Behr & Burgmann, 2020



LFE "families" are an observational convenience;
they don't reflect the distribution of seismic sources on the fault.



Tremor spectra are independent of tremor amplitude!



154 time windows with:
- a minimum of five 4-s detections
- a maximum gap of 30 s

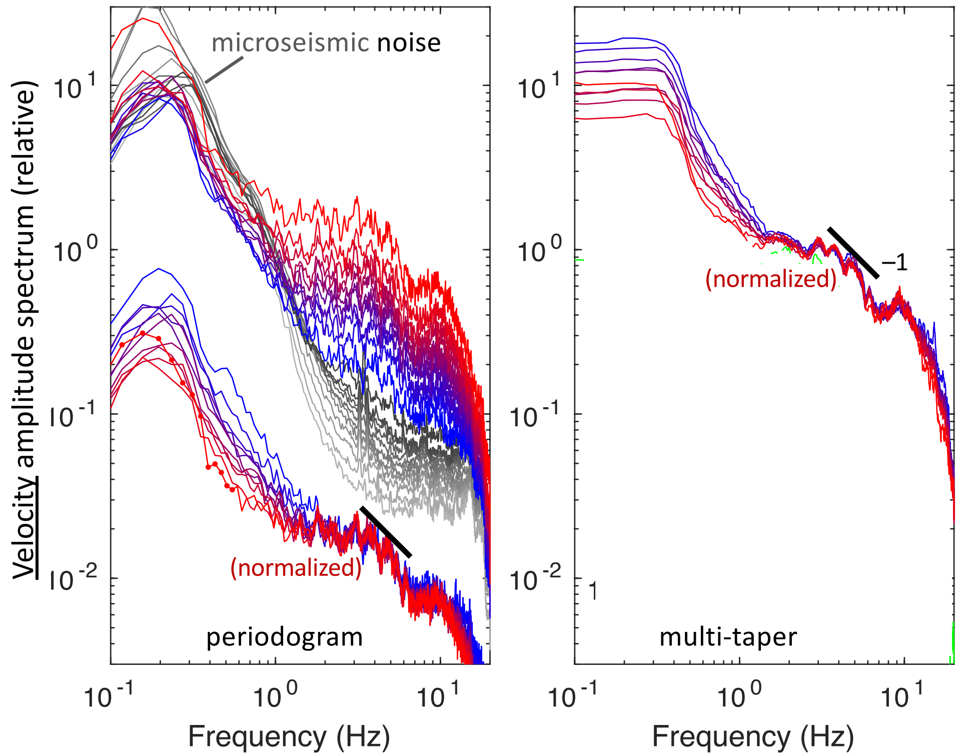
14,300 s (4 hours) of data

1288 half-overlapping 18-s windows

3-station median

binned by amplitude 2.4-4 Hz

Tremor spectra are independent of tremor amplitude!



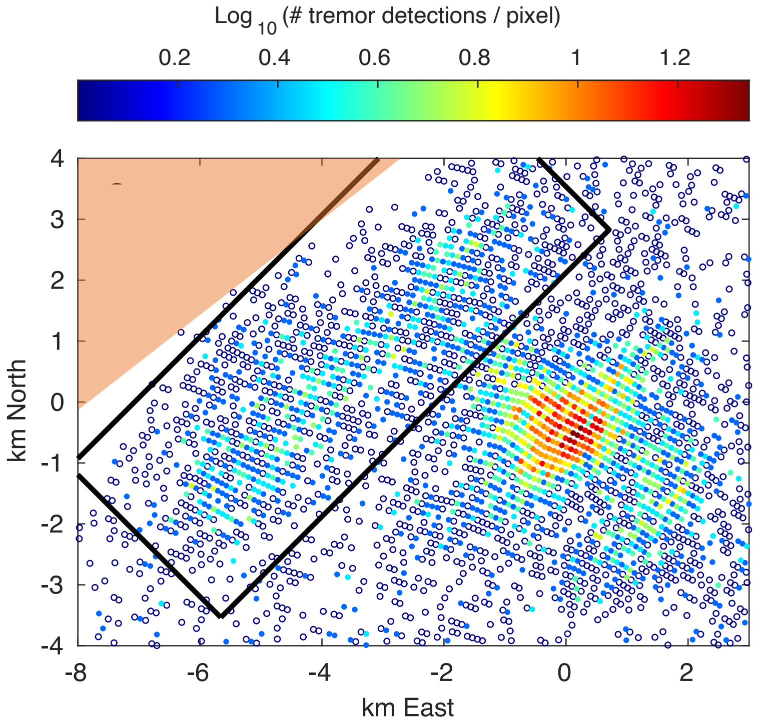
101 time windows with:
  - a minimum of five 4-s detections
  - a maximum gap of 30 s

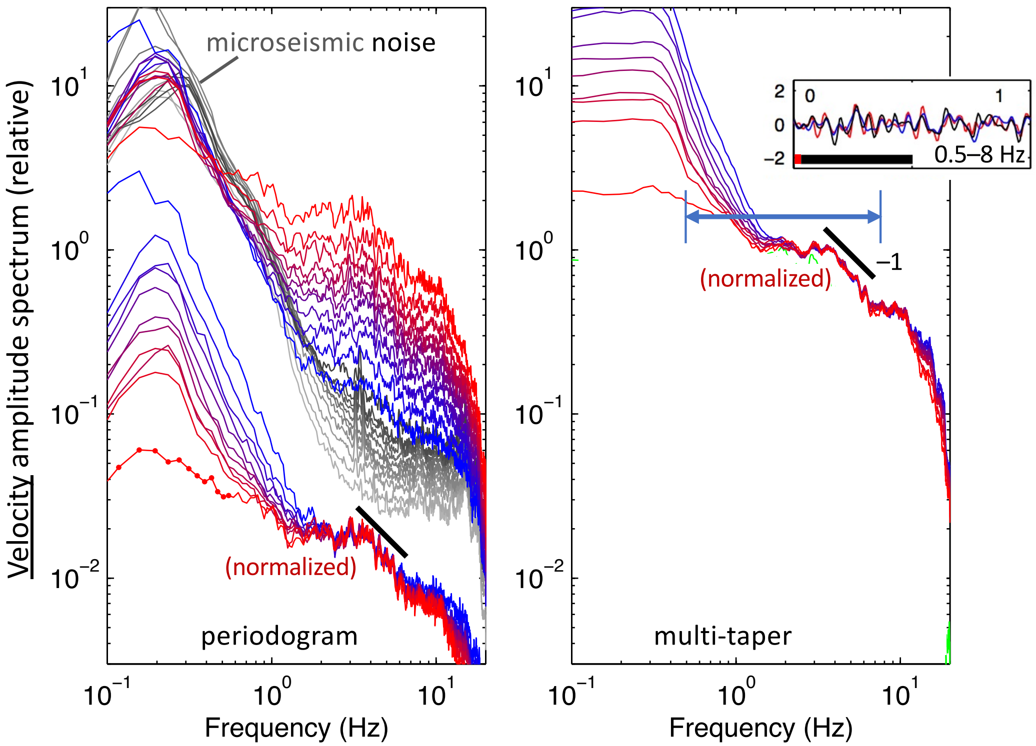
9270 s (2.6 hours) of data

833 half-overlapping 18-s windows

3-station median

binned by amplitude 2.4-4 Hz





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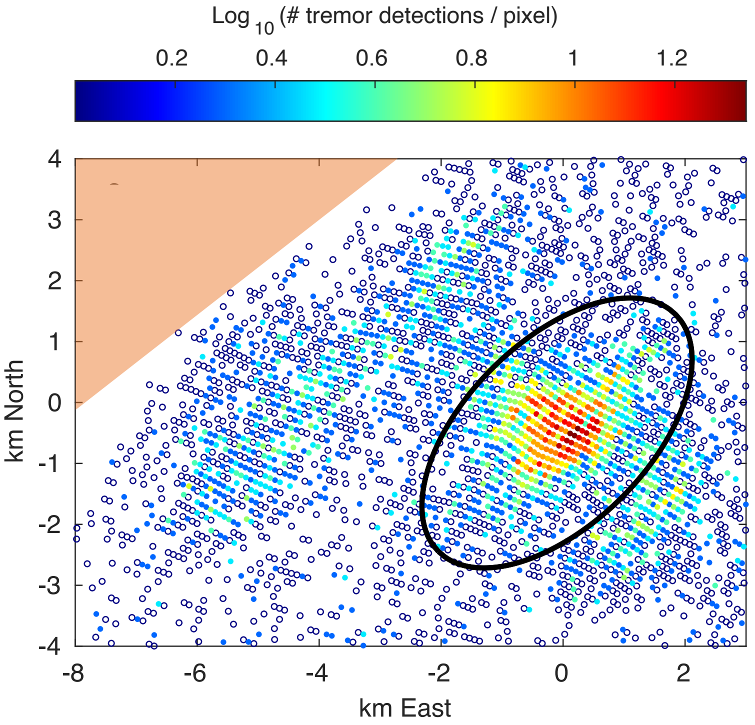

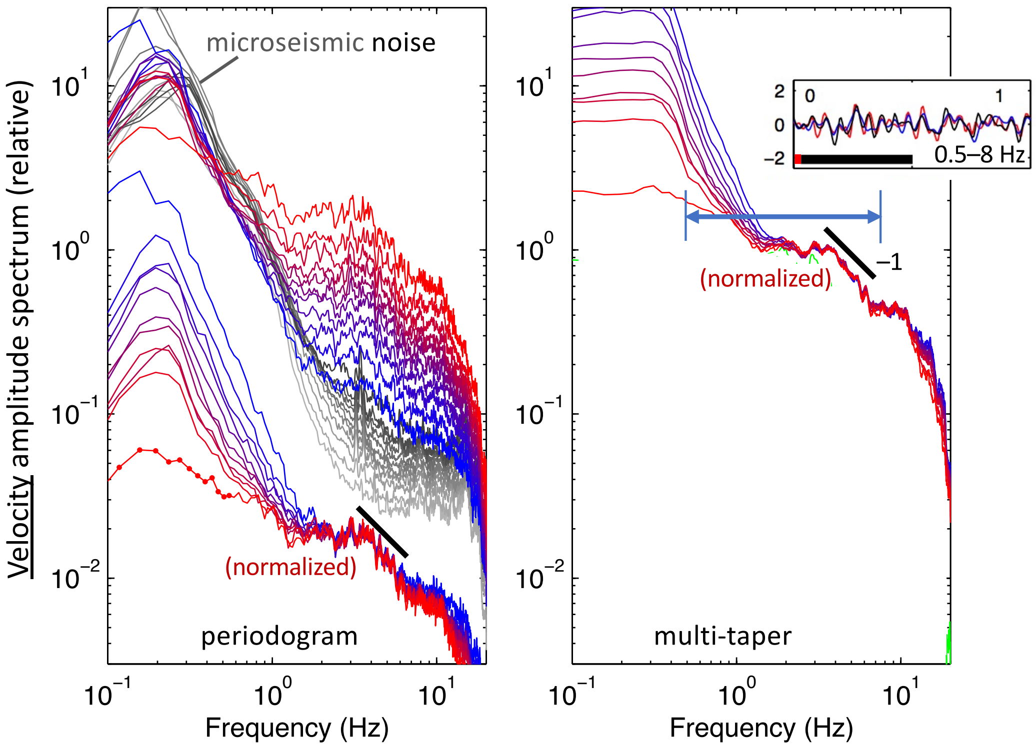

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  - a maximum gap of 30 s
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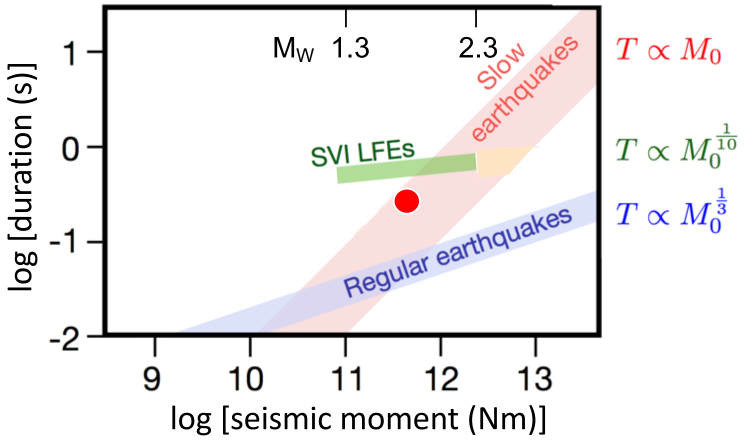
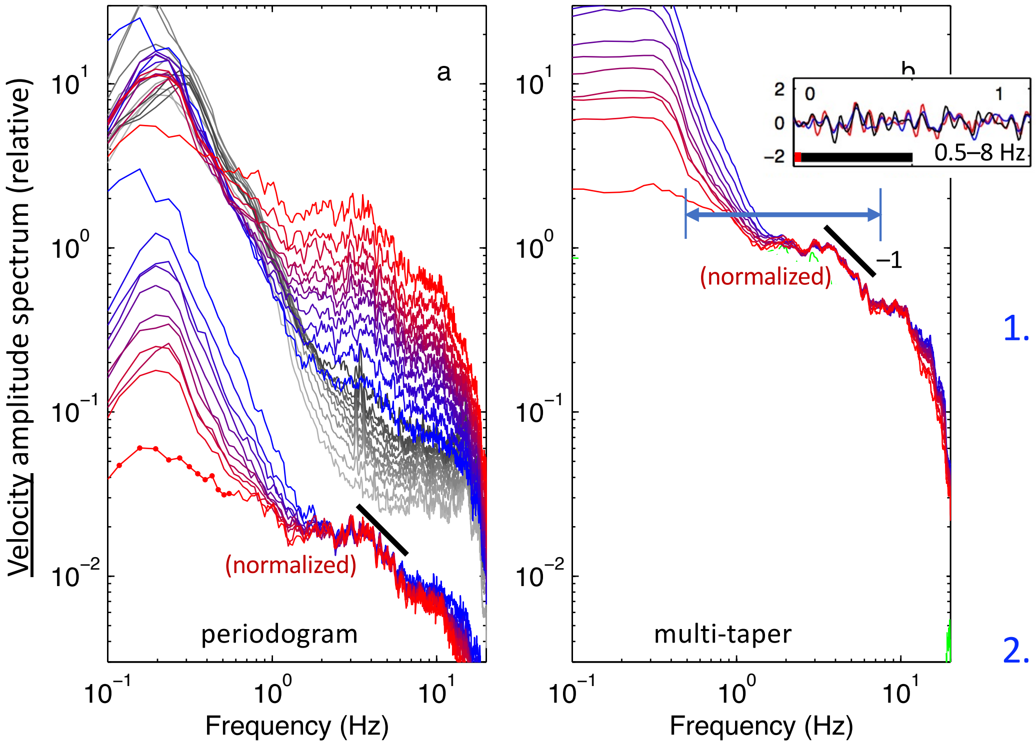


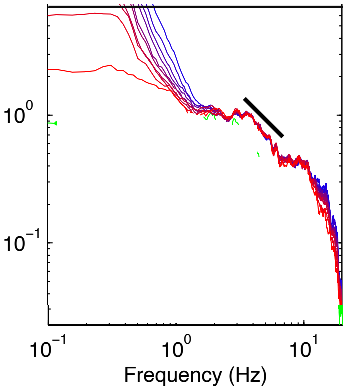
(courtesy M. Bostock)

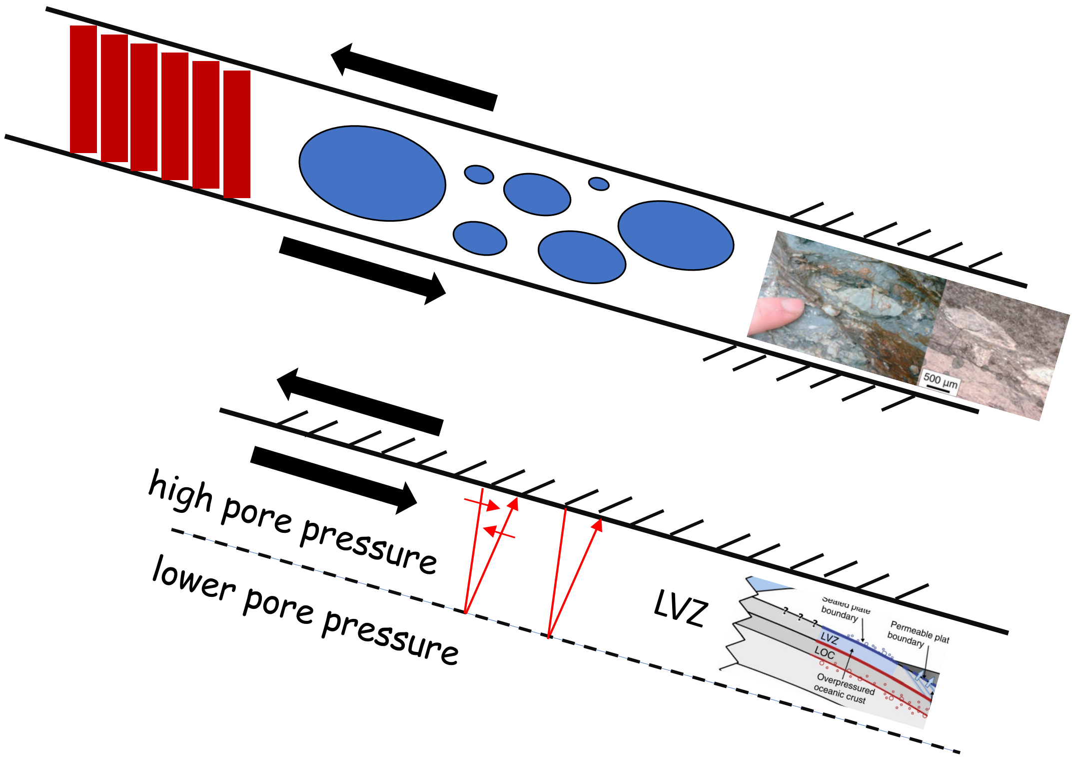


1. LFEs are more than just what one sees of tremor in the ~2-8 Hz passband of good signal-to-noise ratio. (If not due to attenuation) the 4-Hz “corner” represents a fundamental time scale of the tremor source region. Whatever process sets that time scale defines the basic building block of tremor.

2. The characteristic duration of ~1/4 s is independent of tremor amplitude, and is most plausibly a characteristic length scale divided by a characteristic velocity, for example a fault-zone thickness or largest clast size divided by a shear wave speed.

Mechanisms for generating a characteristic time scale:



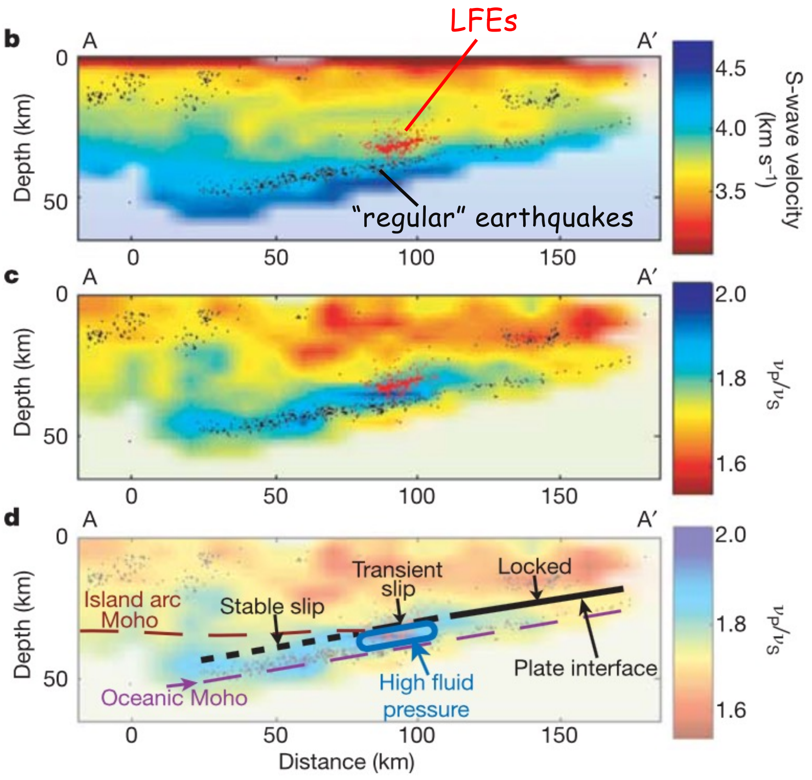


Busted-up eclogite blocks;
bookshelf faulting; etc.

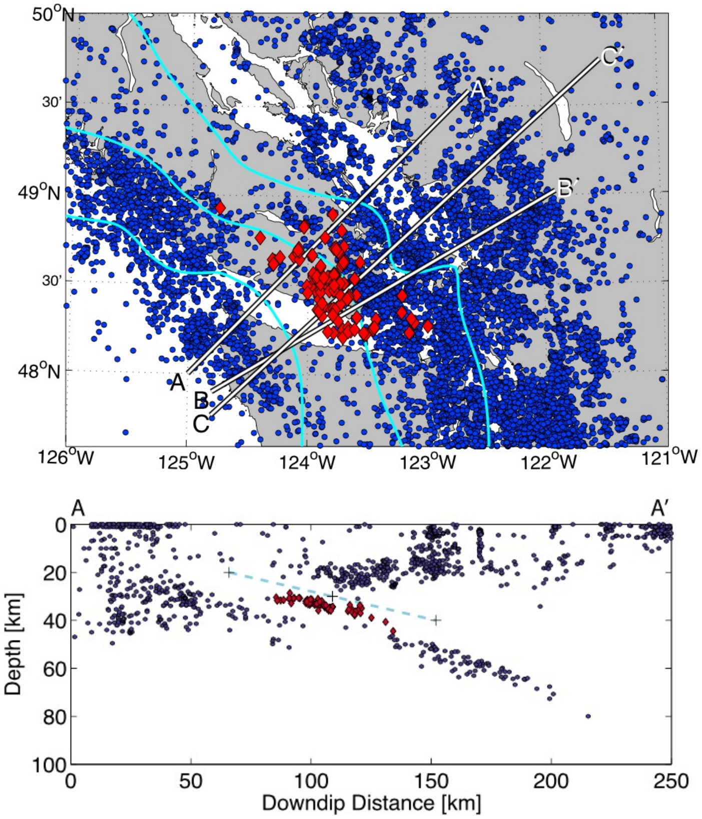
Reflected waves in a
compliant fault zone

(all of these rely on the fault zone thickness plus a wave speed)
(or maybe a fault zone thickness plus a reduced propagation speed)

Some consensus that the corner is not due to attenuation…

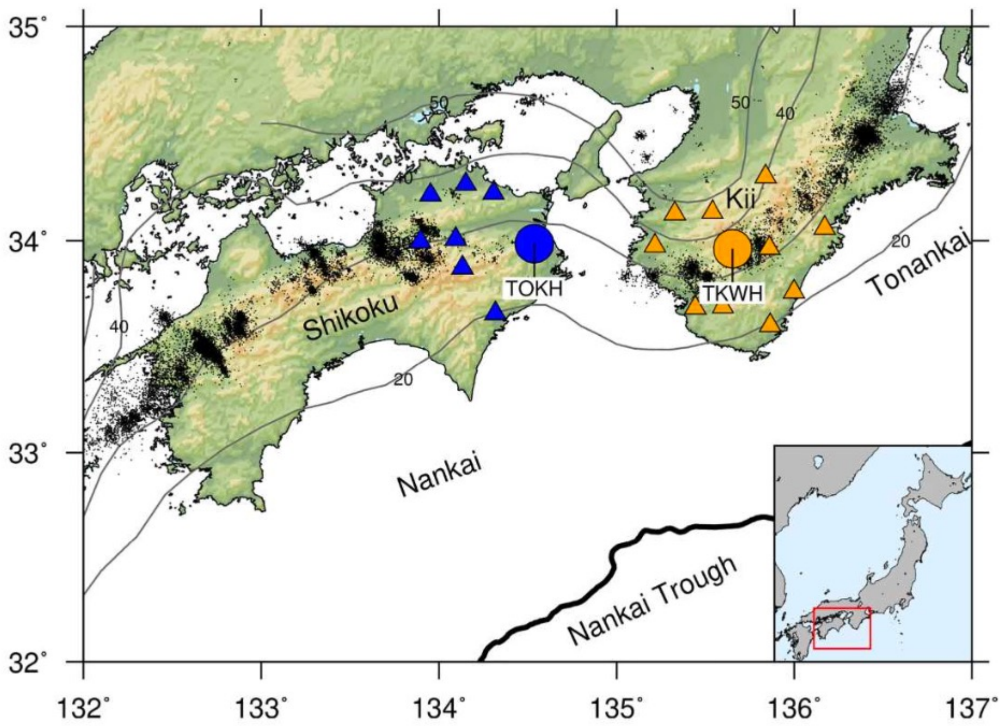


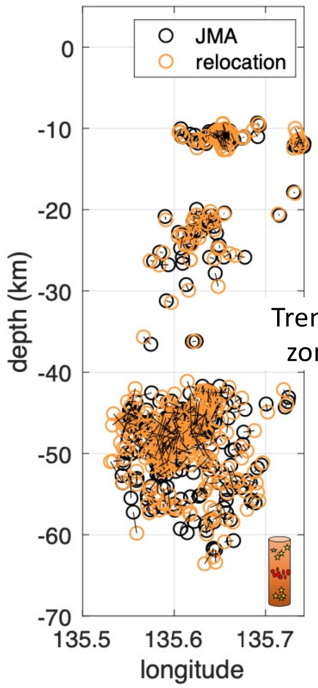
Shelly et al., 2006



Bostock et al., 2012

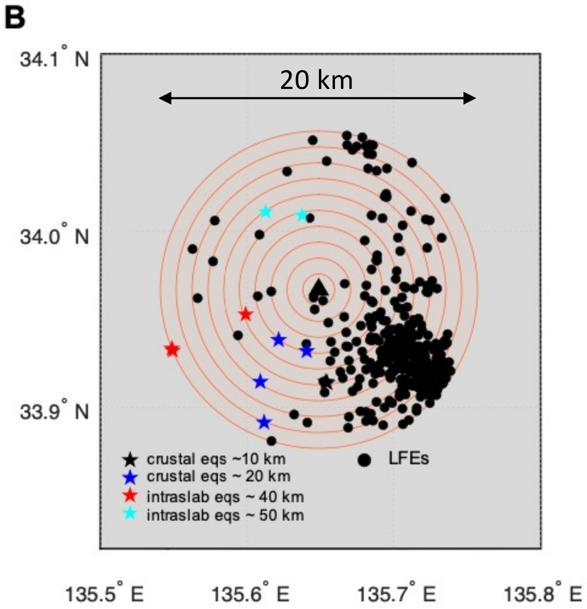
This was also the conclusion of Wang et al. (2023):



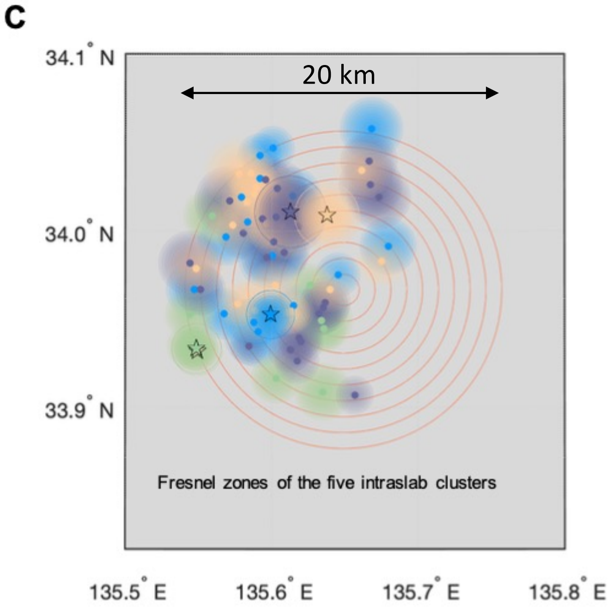


↓
Tremor
zone
↑

This was also the conclusion of Wang et al. (2023):

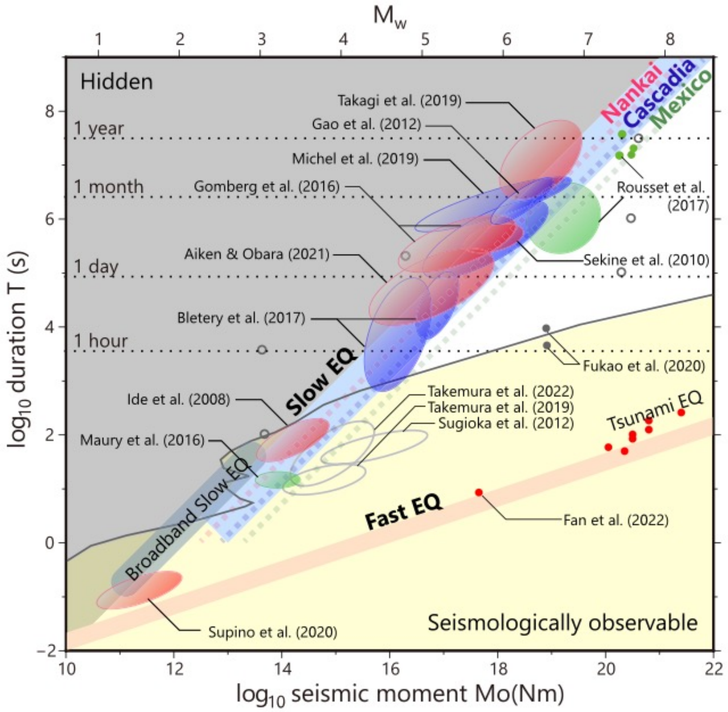


Map view of tremor locations

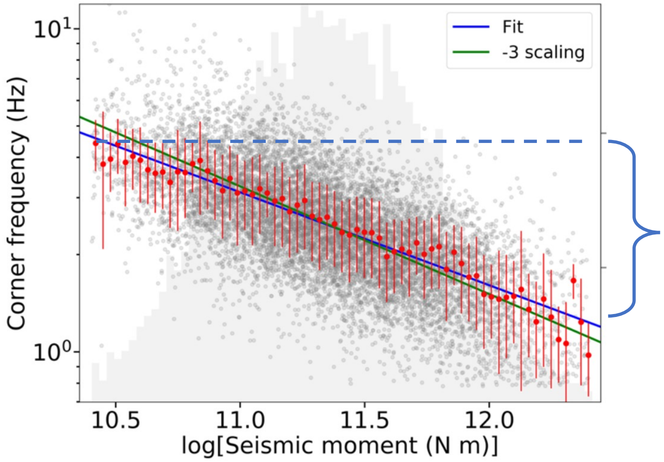


Map view of the “Fresnel zones” of deeper earthquakes as they pass through the tremor zone

Is it good enough?



Ide and Beroza, 2023



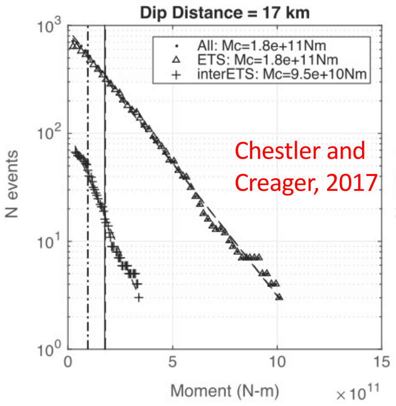
factor of
3.5x in
duration

Supino et al., 2022

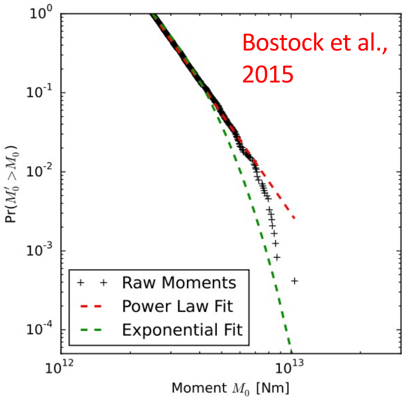
So how to interpret the Supino et al. result that LFE moment in Shikoku is proportional to duration^3, in light of the Bostock/Farge result that LFE duration is ~independent of moment, and the result that tremor corner frequency is independent of amplitude?

An observation related(?) to the "characteristic duration" observation:

Bostock's SVI catalog has 160,000 LFE's with M>1.6, and 0 with M>2.6:
LFEs have a well-defined average, or "characteristic", moment
(e.g., exponential distribution; power-law with *b*-values in the range 6–8; etc.)
Due to a characteristic (well-defined average) length scale in the source region?



Chestler and Creager, 2017



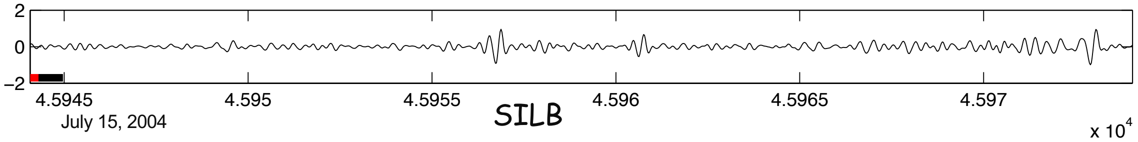
Bostock et al., 2015

A characteristic moment implies that if tremor is the superposition of myriad LFEs, the seismogram is dominated by the sum of the little ones, not the occasional big ones (unlike regular earthquakes).

Saturated (in time) seismogram:

A seismogram for which, on average, the time lag between the direct wave arrivals of different events is shorter than the typical event duration.

(Most? All?) SVI tremor seismograms are “saturated” in time:



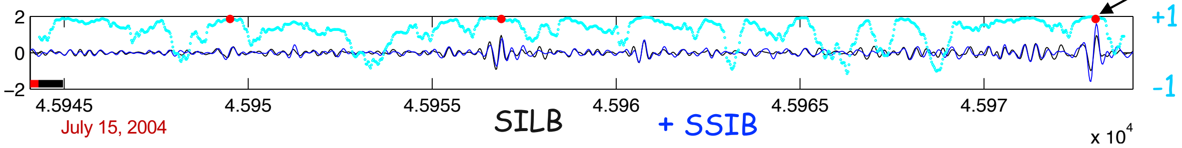
SILB

1.5-4.5 Hz

30 seconds

(Most? All?) SVI tremor seismograms are "saturated" in time:

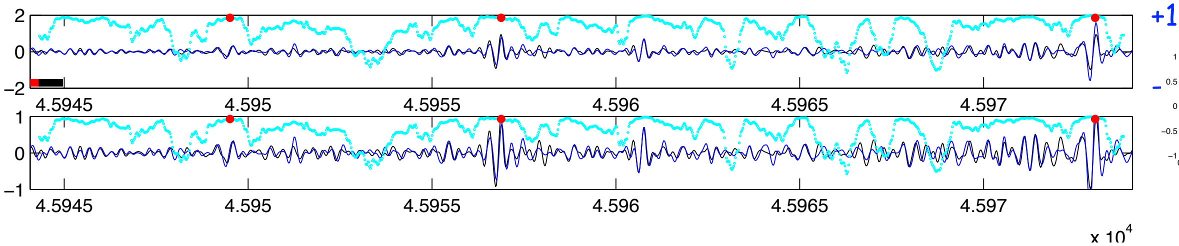
Red dots are Bostock LFE detections



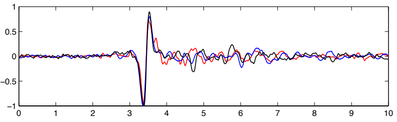
(running CC) (cyan)

30 seconds

(Most? All?) SVI tremor seismograms are "saturated" in time:



(running CC)



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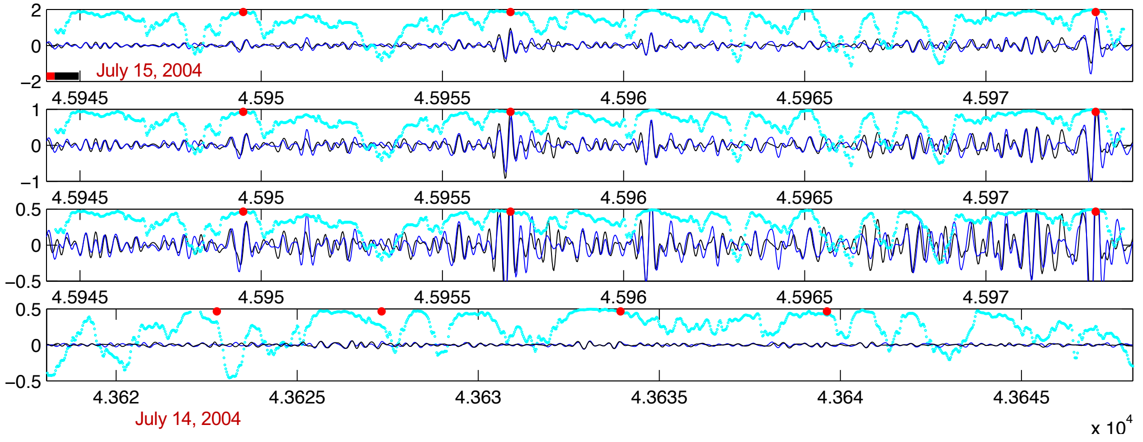
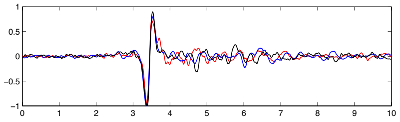


+1

(running CC)

-1



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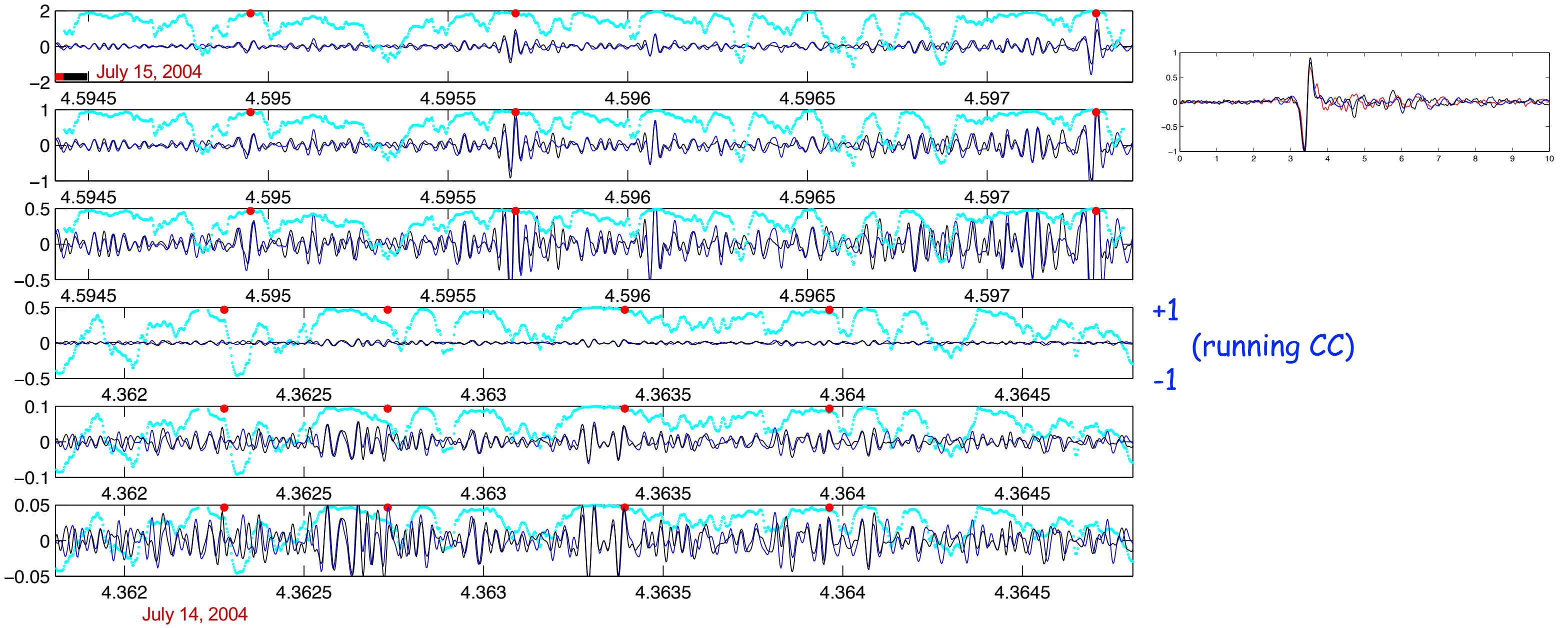
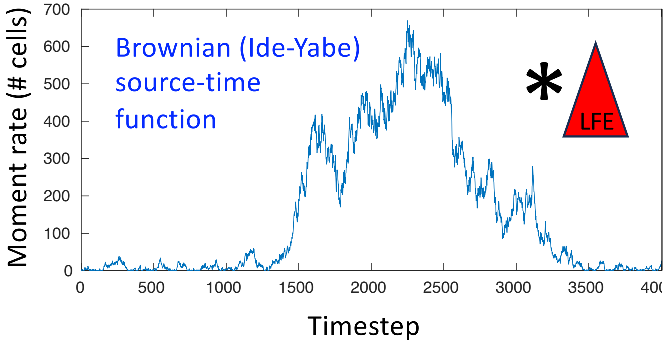


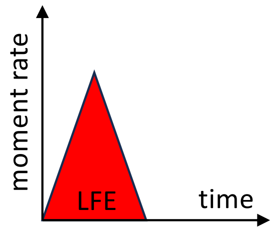
If the LFEs that make up tremor are drawn from a time-independent magnitude-frequency distribution, the tremor amplitude increases only as the square-root of the event rate.

e.g., if 5 consecutive peaks at the lowest amplitude represent at least 5 LFEs, then at the largest amplitude 5 consecutive peaks represent at least 500 LFEs. We can’t count them. This is built into the Ide-Yabe (2018) model.

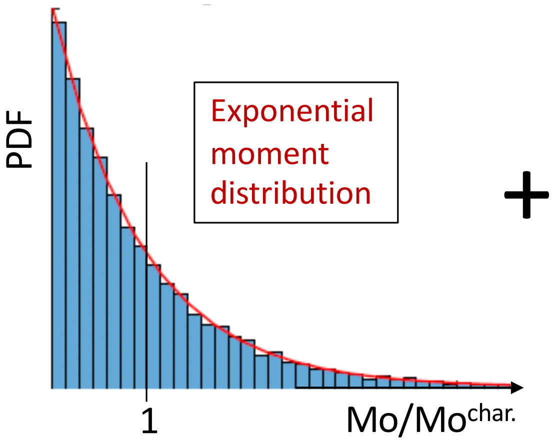
Alternatively, 10x louder tremor could be comprised of 10x larger (in Moment) LFEs (e.g., same source duration; seismogram amplitude proportional to driving slip rate).

What does this mean for estimates of the moment-duration and magnitude-frequency distributions?



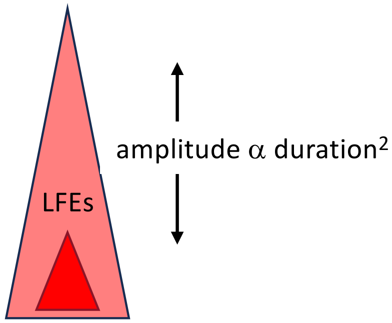


Uniform moment and duration

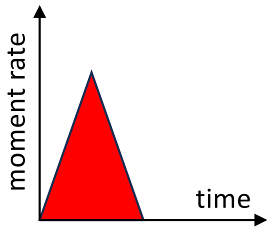


Exponential moment distribution

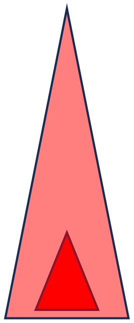
+



Moment α duration^3

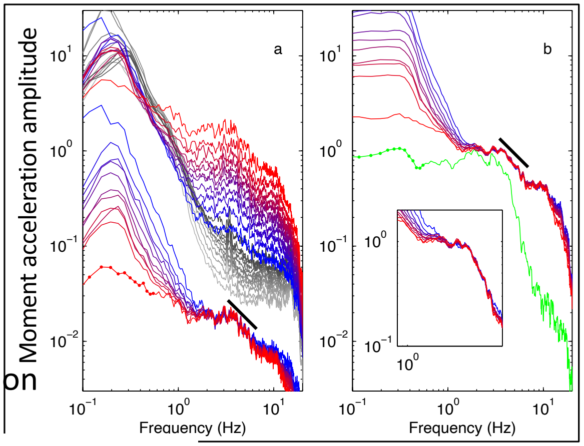


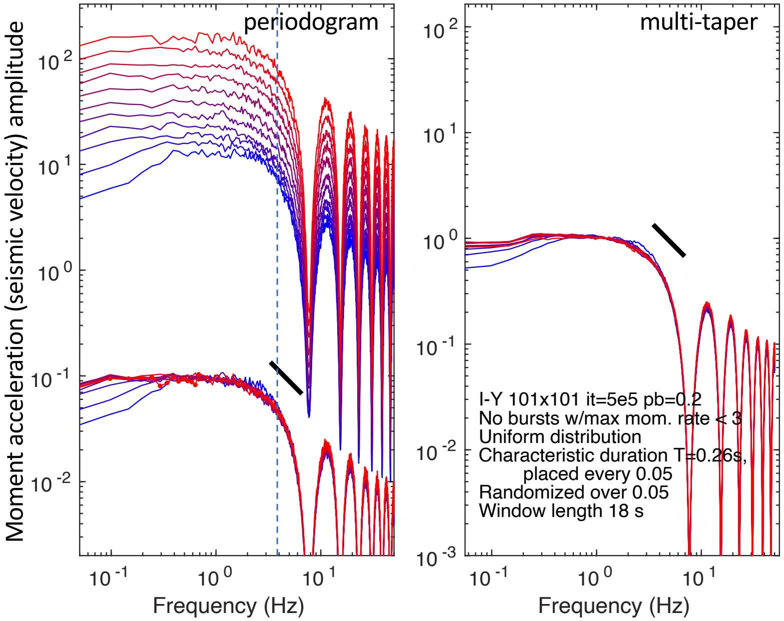
Uniform moment and duration



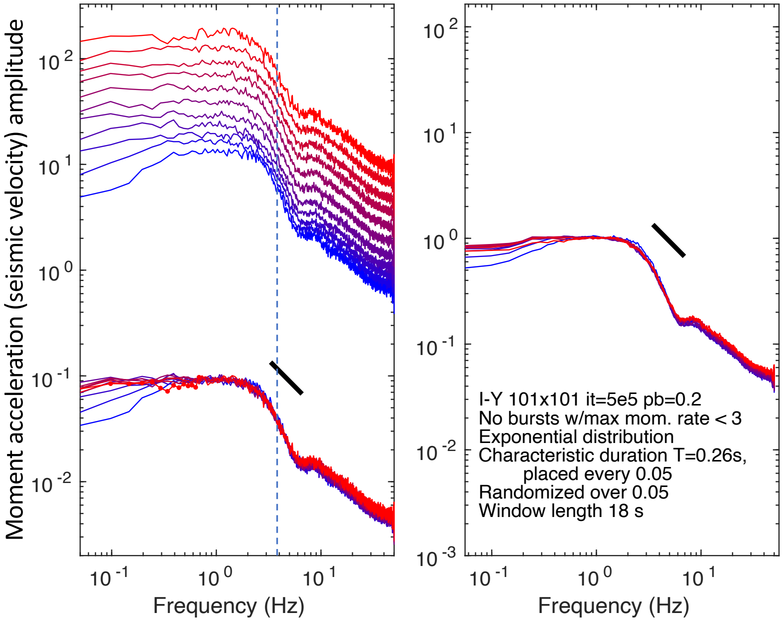
Exponential moment distribution

Moment α duration^3





I-Y 101x101 it=5e5 pb=0.2
No bursts w/max mom. rate < 3
Uniform distribution
Characteristic duration T=0.26s,
placed every 0.05
Randomized over 0.05
Window length 18 s



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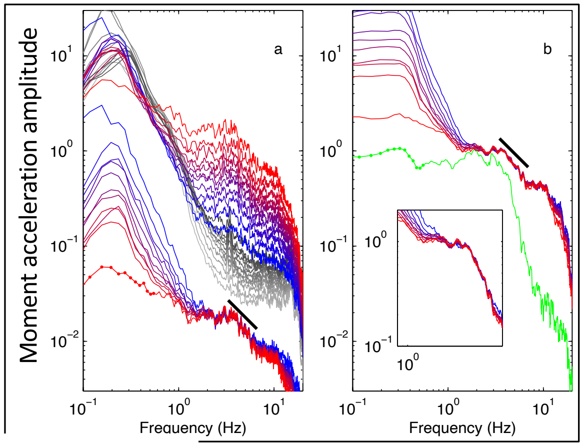
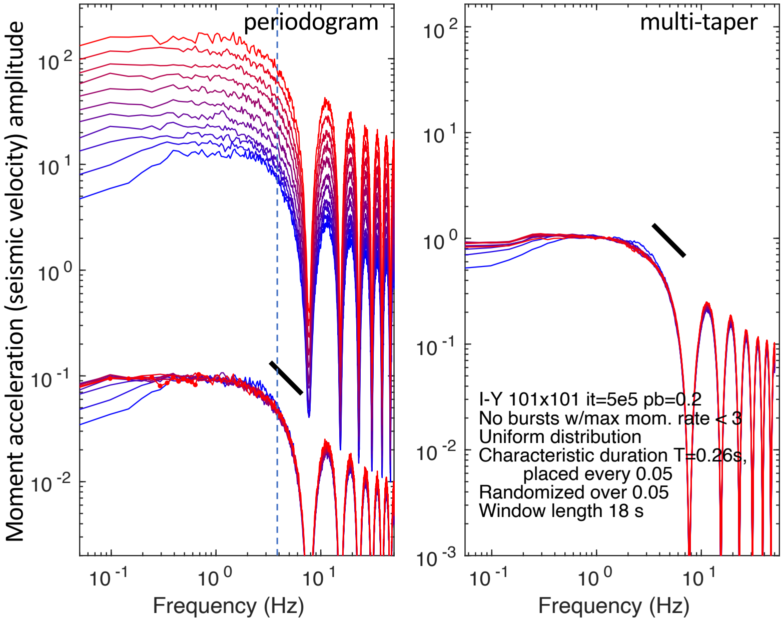
Window length 18 s

If you are drawing LFEs from a size distribution that has a well-defined average*, and if your tremor seismogram is saturated in time, then larger tremor amplitudes do not result from larger LFEs (with possibly longer durations), they result from more frequent LFEs of the same average duration. Unlike regular earthquakes.

(*and if, in addition, that average is not varying with time)





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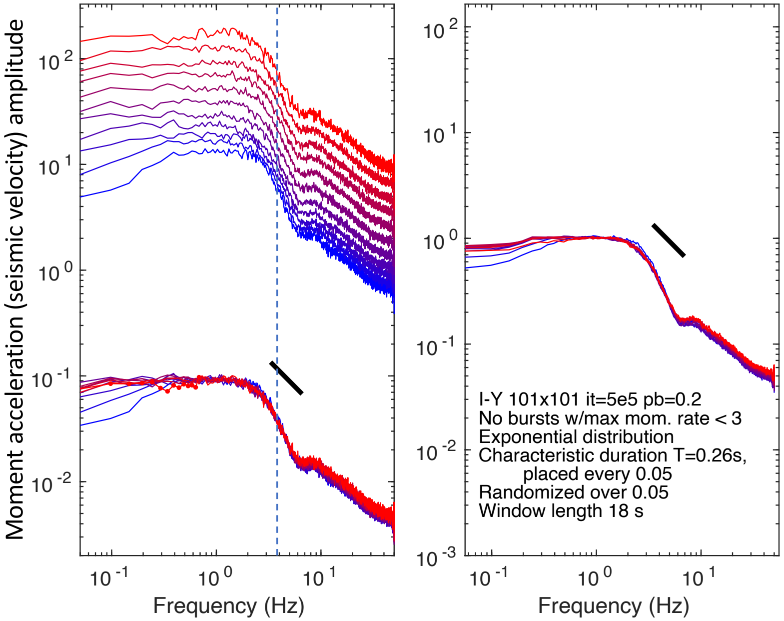

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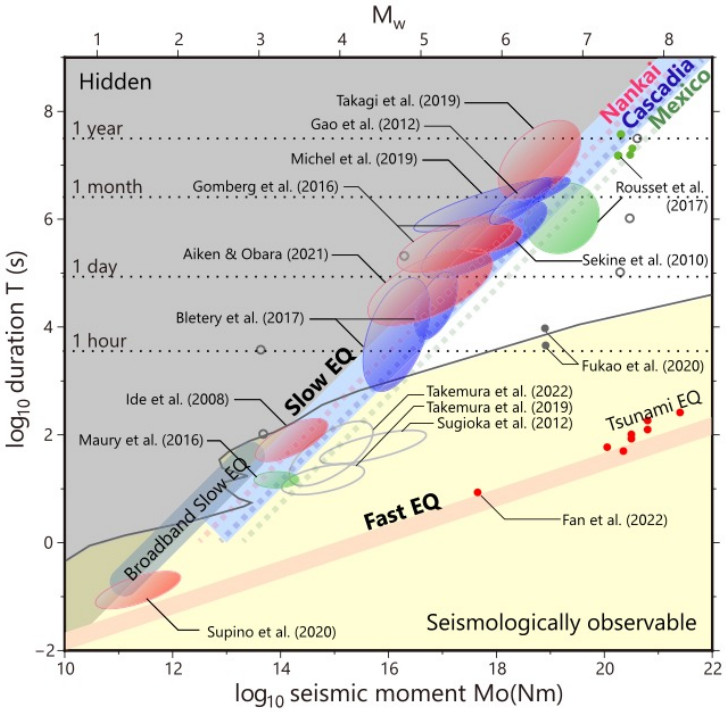
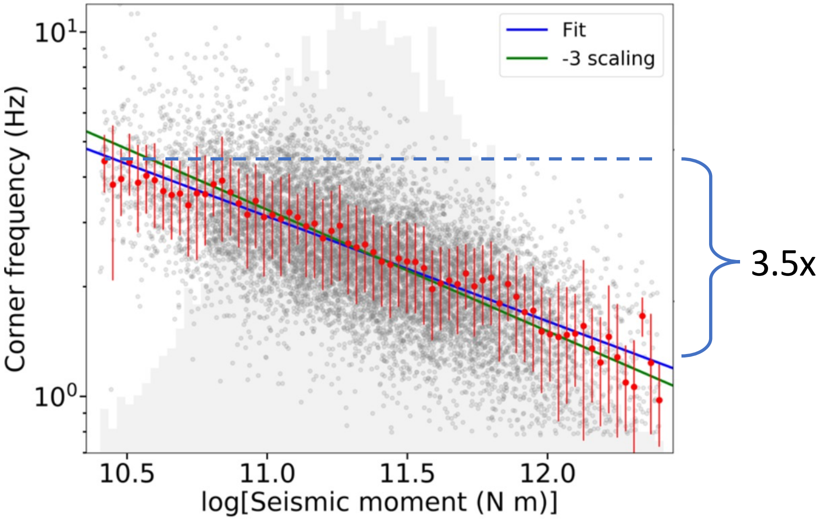


Ide, 2023

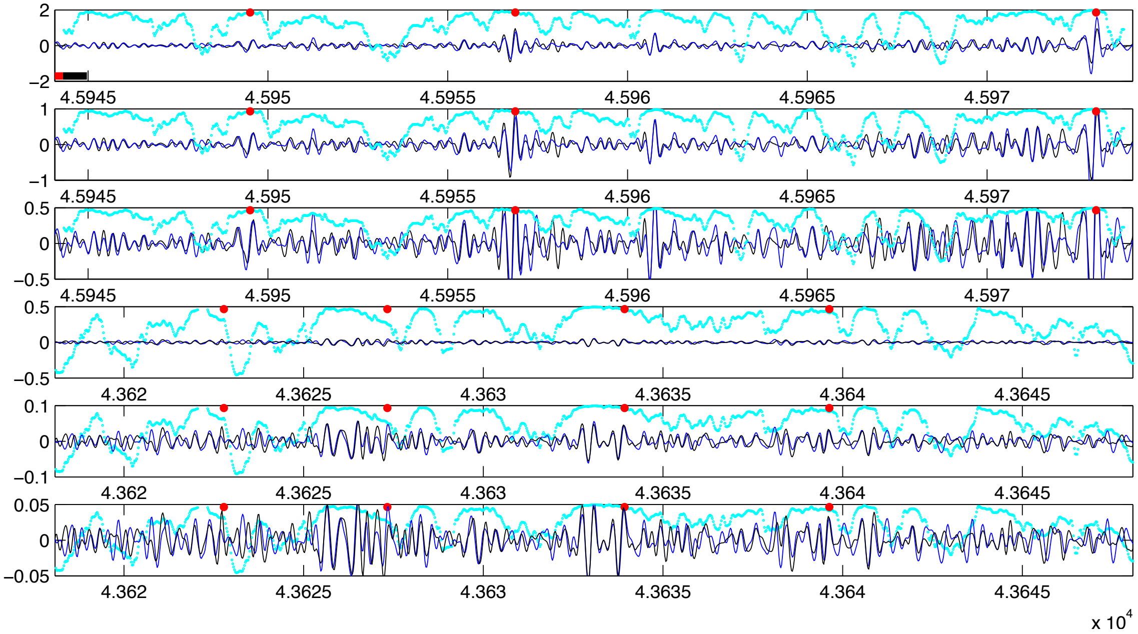


Supino et al., 2022

Either: Supino et al. managed to find LFEs in seismograms that were not saturated in time (but with a narrow, log-normal moment-frequency distribution, over a moment range very similar to that in Cascadia),

Or: Their catalog mixes saturated seismograms from regions with characteristic durations that differ by a factor of 3 to 4.

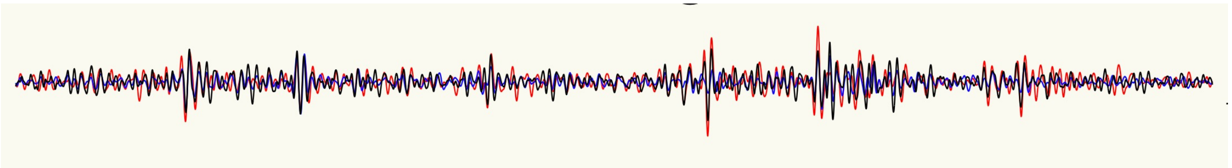
Many (many) SVI tremor seismograms are saturated. Are all SVI tremor seismograms saturated?

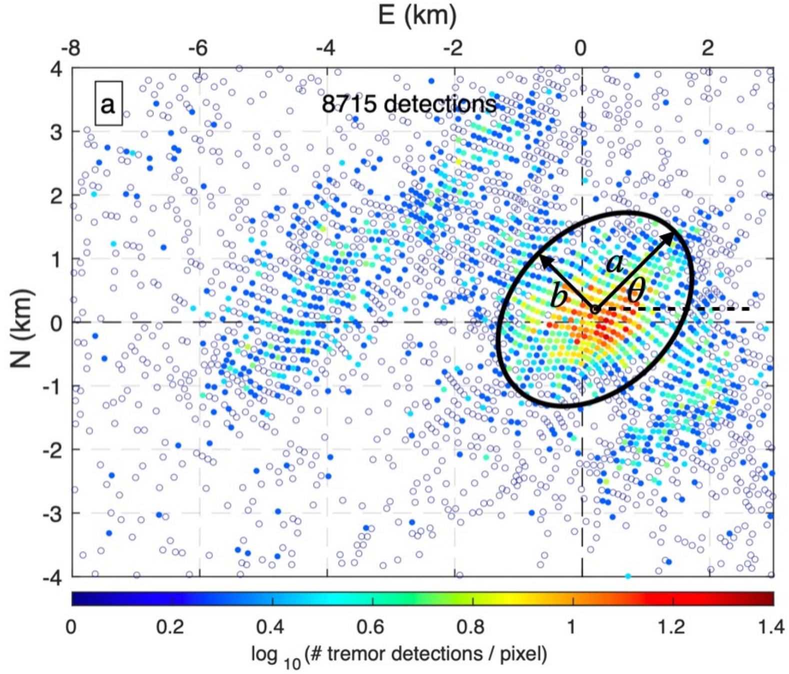


This is not a trivial question to answer, given the presence of noise (mostly tremor from elsewhere)

Time-domain deconvolution (trying to locate every coherent wiggle in tremor)

1. Identify tremor bursts in Bostock's 002 region using our 4-s catalog.
2. Cross-correlate the seismogram at each station with the template for that station.
3. Rank the resulting CC peaks at each station by their amplitude, weighted by the running CC between the stations.
4. Run the time-domain deconvolution.
5. Starting from the highest-ranked impulse at one station, find at the other two stations the nearest impulse in time to form a triplet.
6. Reject the impulse if the triplet spans too long a time.
7. Identify and remove "secondary sources".



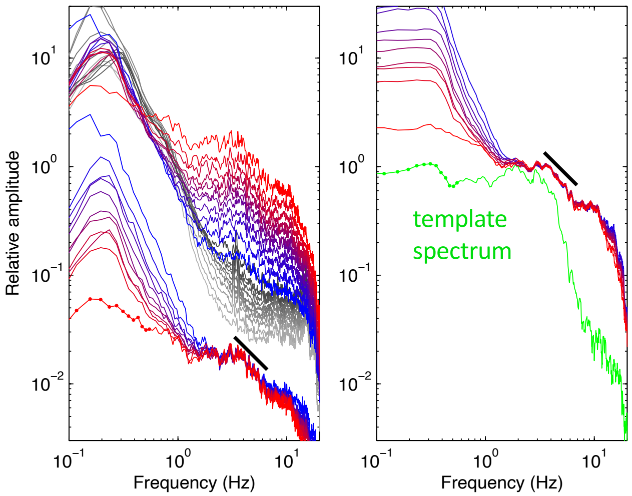


3.5 x 2.5 km

Conclusions

LFEs are the “quantum event” of tremor (i.e., they are more than just what we see of tremor in the narrow passband of 2-8 Hz).

Tremor has a well-defined “corner frequency” that is independent of tremor amplitude. This reflects a characteristic time scale in the source region. The simplest interpretation would be a characteristic length scale (e.g., the fault zone thickness; largest clast size; etc.) divided by a significant fraction of the shear wave speed.



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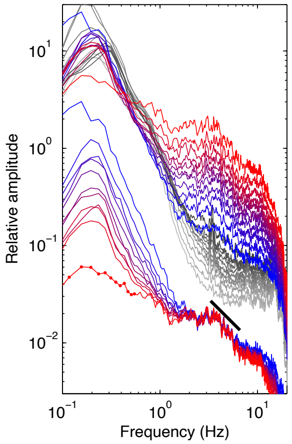
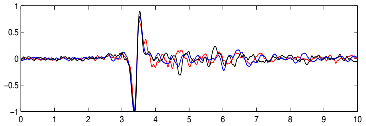
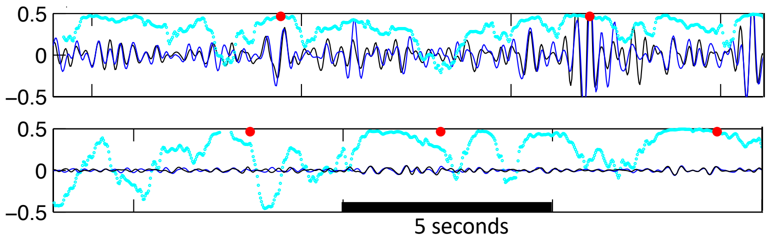
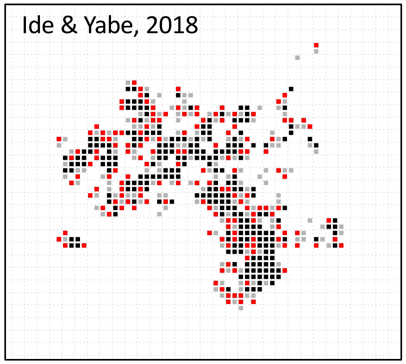
From the loudest to the quietist, the tremor seismograms we have examined are "saturated in time", in that the typical interval between LFE arrivals is smaller than the characteristic LFE duration. This is consistent with Ide's stochastic model of tremor generation.









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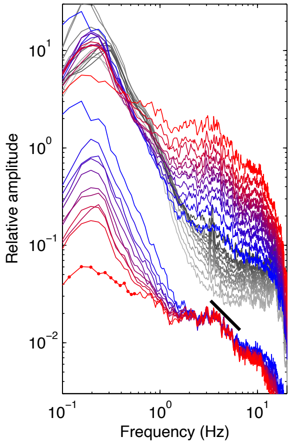
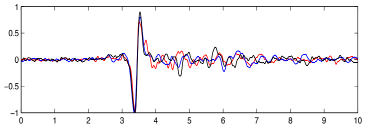
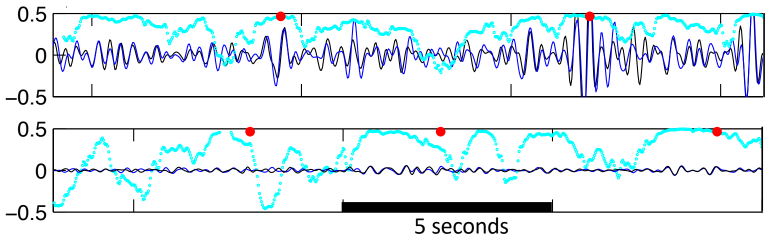
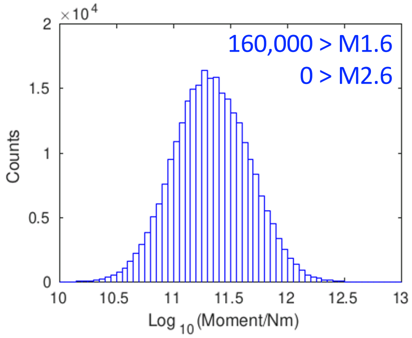
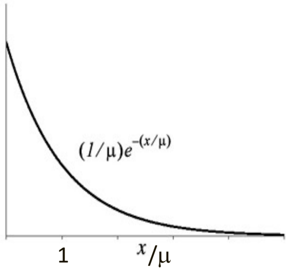
LFEs have a characteristic moment as well as a characteristic duration (exponential; log-normal; power-law with an extremely large b-value, etc.). This mean that saturated seismograms are dominated by the sum of all the little ones, not the occasional big ones.











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LFEs have a characteristic moment as well as a characteristic duration (exponential; log-normal; power-law with an extremely large b-value, etc.). This mean that saturated seismograms are dominated by the sum of all the little ones, not the occasional big ones.

Given a characteristic LFE size, seismograms that are saturated in time hide BOTH the underlying moment-duration distribution AND the underlying magnitude-frequency distribution of the LFEs that make up tremor. Assuming that LFE moment varies as duration^3 provides a possible mechanism for reconciling the observations of Supino and Bostock/Farge.