Learning about modes and scaling of fault slip from *in situ*, fault-scale observations.

J. Gomberg & Evelyn Roeloffs, Kathleen Hodgkinson, David Schmidt, Paul Bodin, Jeff McGuire, Brendon Crowell, Sarah Minson, & many others….

Talk Topics

Scaling of slip event duration versus moment – why care?

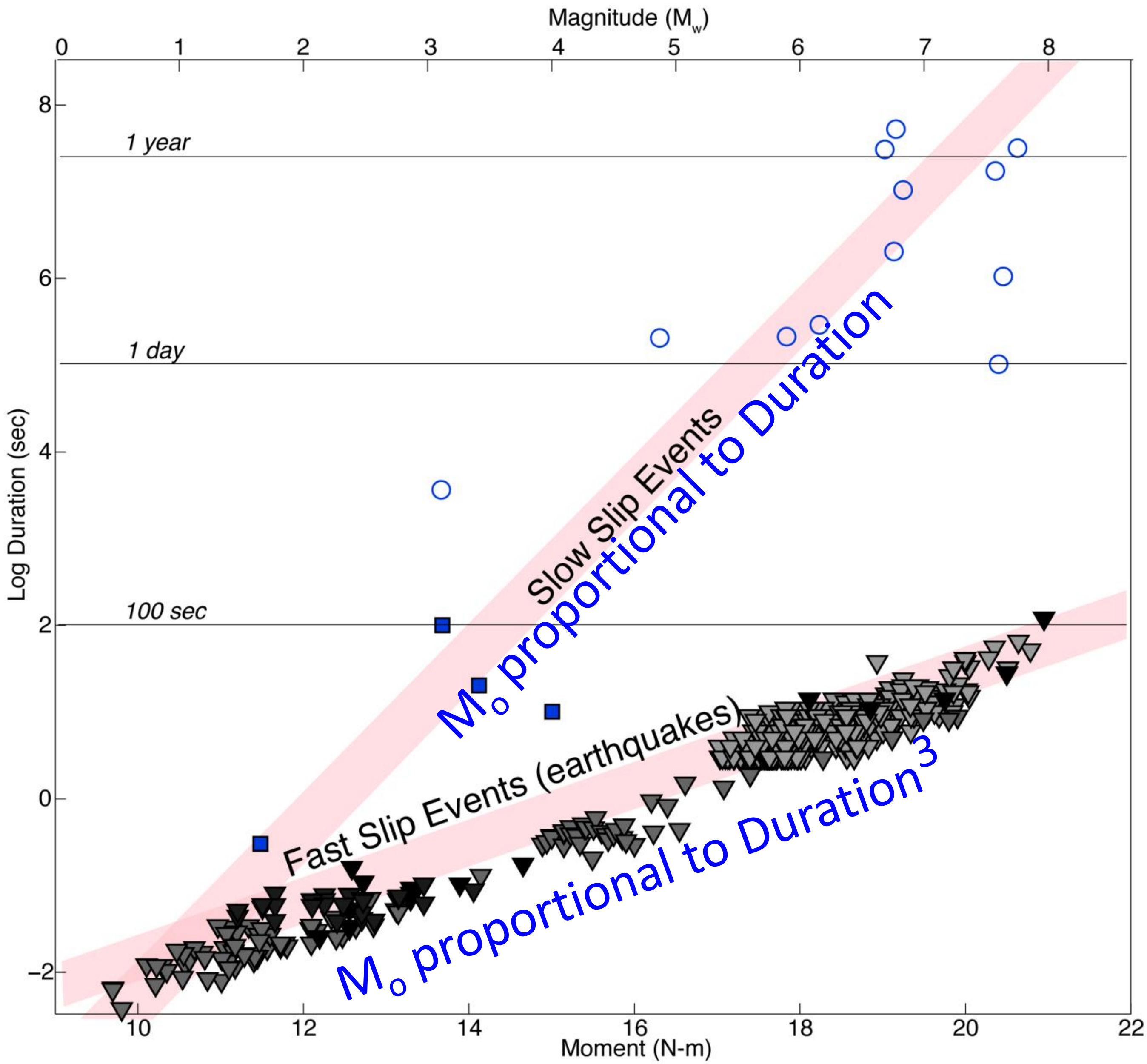
Assessing what can really observe & its imprint on our understanding.

Gap-filling possibilities (high-rate strainmeter data).

Spectral scaling – assessing not only what we measure, but what it means.

USGS
science for a changing world

Moment/duration scaling – key constraint on rupture physics



Ide et al., 2007

Moment/duration scaling – key constraint on rupture physics

Moment M_o= *rigidity* x *Slip* x Length^2

Stress drop $\Delta\sigma$ ~ *rigidity* x *Slip* /Length

Length = Rupture Velocity V_r x *Duration*

$M_o=\Delta\sigma \times L^3 = \Delta\sigma \times V_r^3 \times \text{Duration}^3$

Earthquake data show

$M_o=C \times \text{Duration}^3$

implying

$C=\Delta\sigma \times V_r^3$

V_r & $\Delta\sigma$ independent of rupture dimension, L

Moment/duration scaling – key constraint on rupture physics

Moment M_o= *rigidity* x *Slip* x Length^2

Stress drop $\Delta\sigma$ ~ *rigidity* x *Slip* /Length

Length = Rupture Velocity V_r x Duration

$M_o = \Delta\sigma \times L^3 = \Delta\sigma \times V_r^3 \times \text{Duration}^3$

If M_o is ~proportional to Duration, or

M_o= C x Duration

implying

$C = \Delta\sigma V_r L^2$

V_r & $\Delta\sigma$ decrease as rupture dimension, L, grows

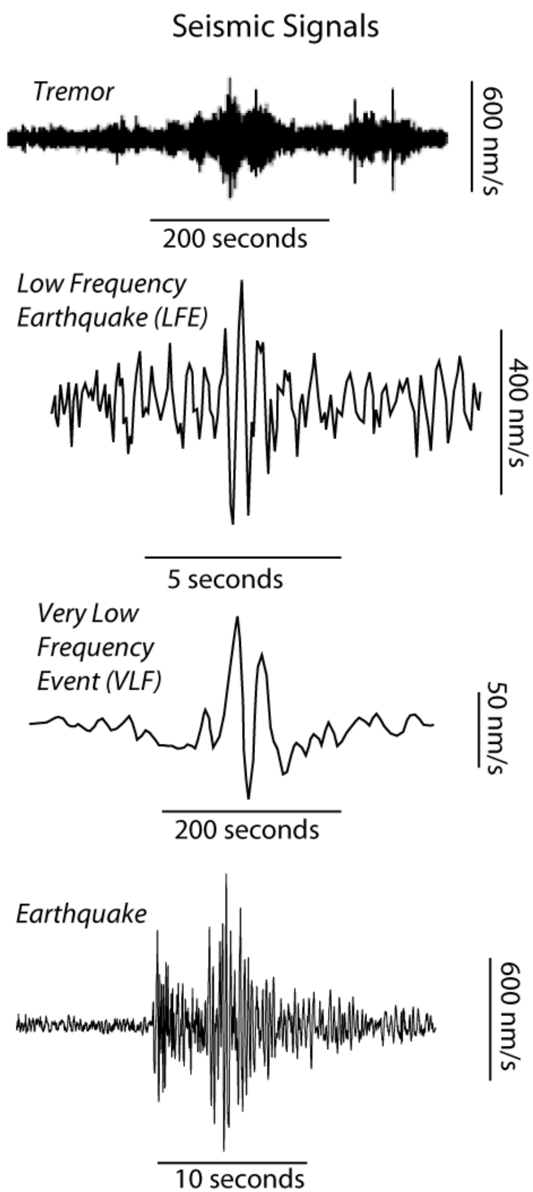
Measurables

Sec to hours,
M≤1.5

Few sec,
M≤1.5

Tens of sec,
M≤4

Few sec to mins,
M≤9.5

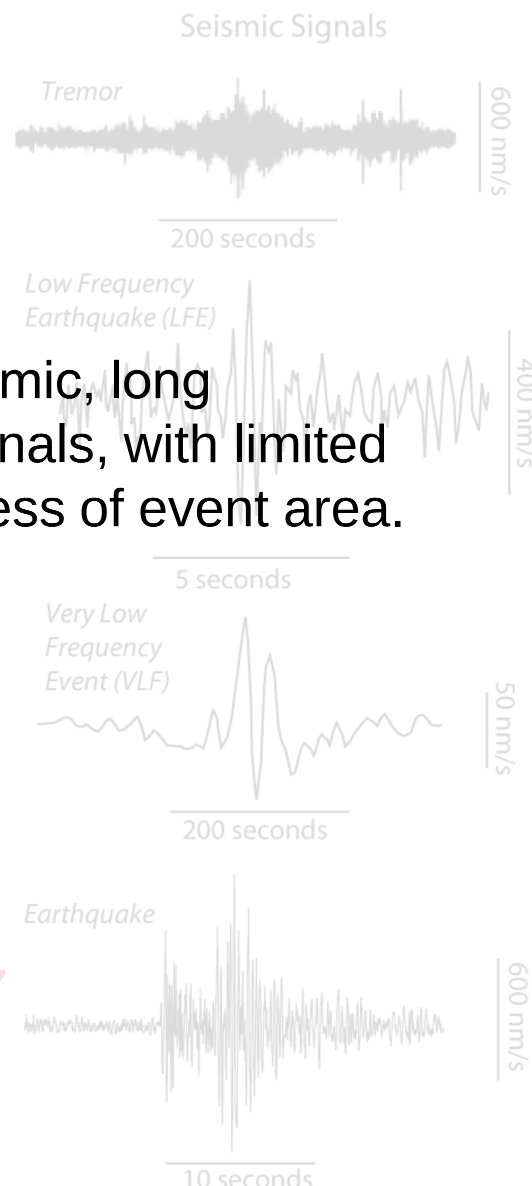


‘Slow’ (low frequency?) seismic signals, with quenched amplitudes regardless of event size.

‘Fast’ (higher frequency) seismic signals, with amplitudes that grow with event size; earthquakes!

Measurables

Sec to hours,
M≤1.5

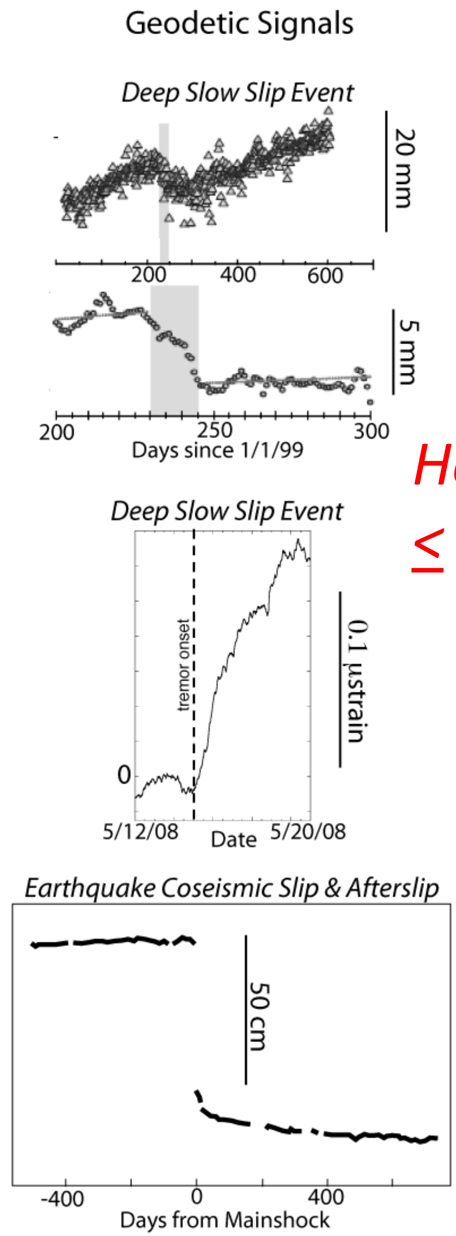


Few
M≤1.5

‘Slow’ aseismic, long duration signals, with limited slip regardless of event area.

Tens of sec,
M≤4

Few sec to mins,
M≤9.5

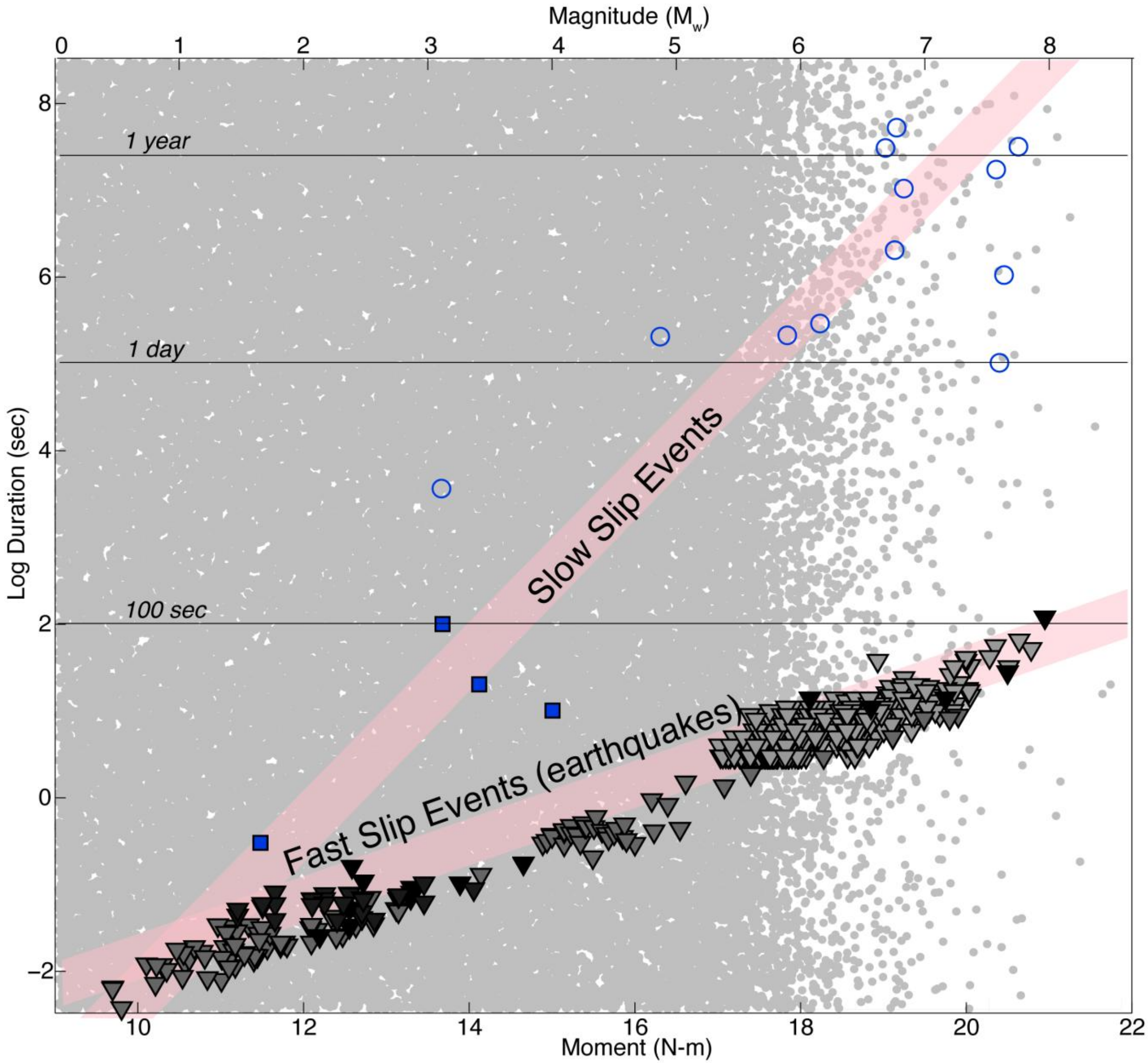


Hours to days,
≤ few cm

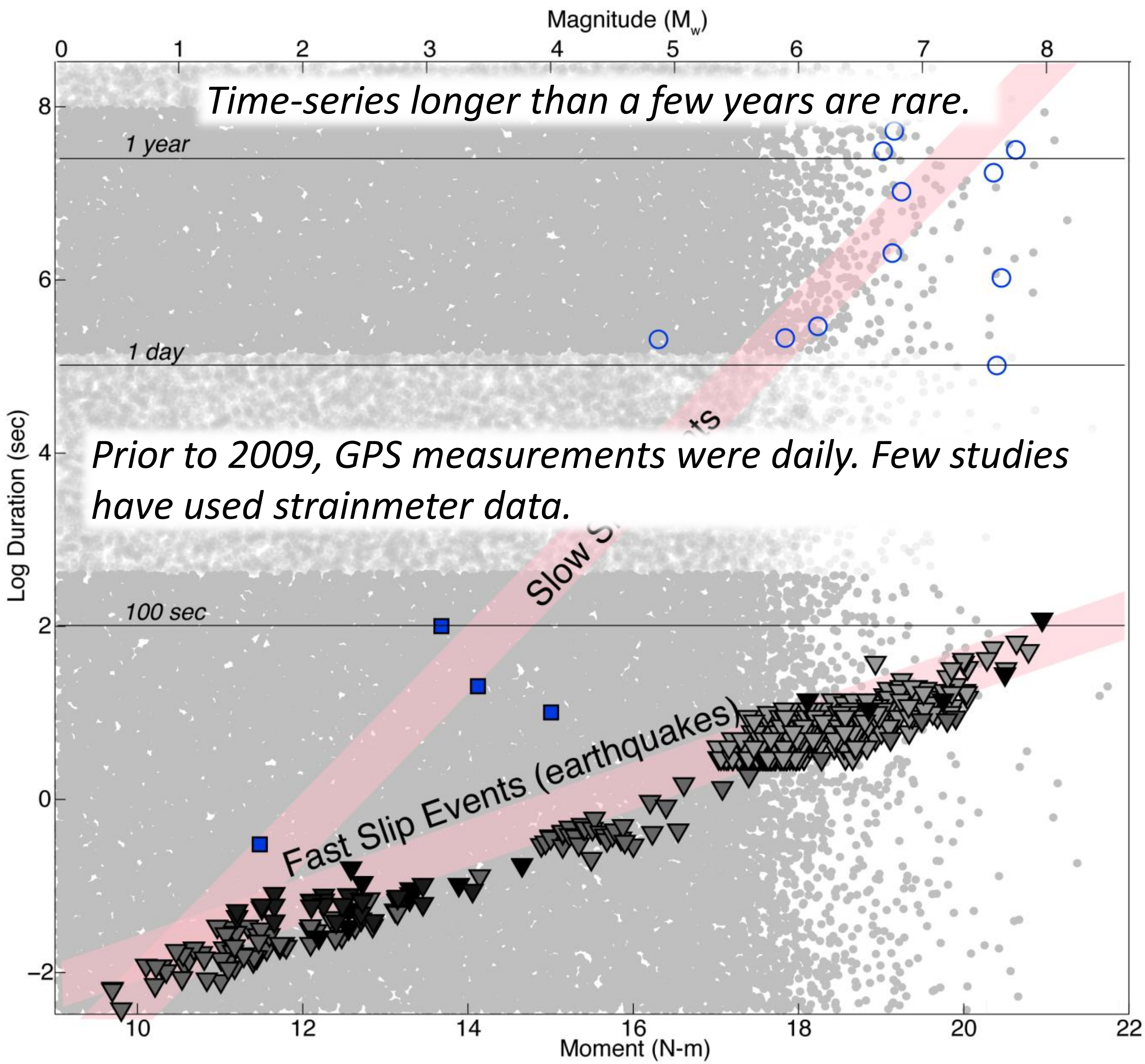
Few to 100s
of sec,
≤10s of m

Assessing what we can observe: Natural recurrence rates affect apparent scaling

(smaller events are more frequent).



Sampling rate & longevity of measurements affect apparent scaling.



Consider measurement detection thresholds

Agnew (UNAVCO Course, 2014)

Displacement, $u(t)$, at a distance, r, from a moment-tensor source, $M_0(t)$

$$u(t) = u_N + u_F = \underbrace{\frac{G_N(\theta,\phi)}{4\pi\rho c^2}\frac{1}{r^2}M_0(t-r/c)}_{\text{near-field term, } r^{-2} \text{ decay}} + \underbrace{\frac{G_F(\theta,\phi)}{4\pi\rho c^3}\frac{1}{r}\frac{dM_0(t-r/c)}{dt}}_{\text{far-field term, } r^{-1} \text{ decay}}$$

If $u(t)$ has time constant t_s,

$$u(t) \sim \frac{G(\theta,\phi)}{4\pi\rho c^2}\frac{1}{r^2}\left[M_0 + \frac{r}{c}\frac{M_0}{ts}\right]$$

distance dependence

$u(t)$ has Fourier amplitude spectrum $U(f)$ & noise power spectrum $N(f)$.

The signal-to-noise ratio is

$$\mathrm{SNR} = \left[\int^{\infty} \frac{|U(f)|^2}{N(f)}\,df\right]^{\frac{1}{2}} \sim \frac{u_{RMS}}{B(t_S)}$$

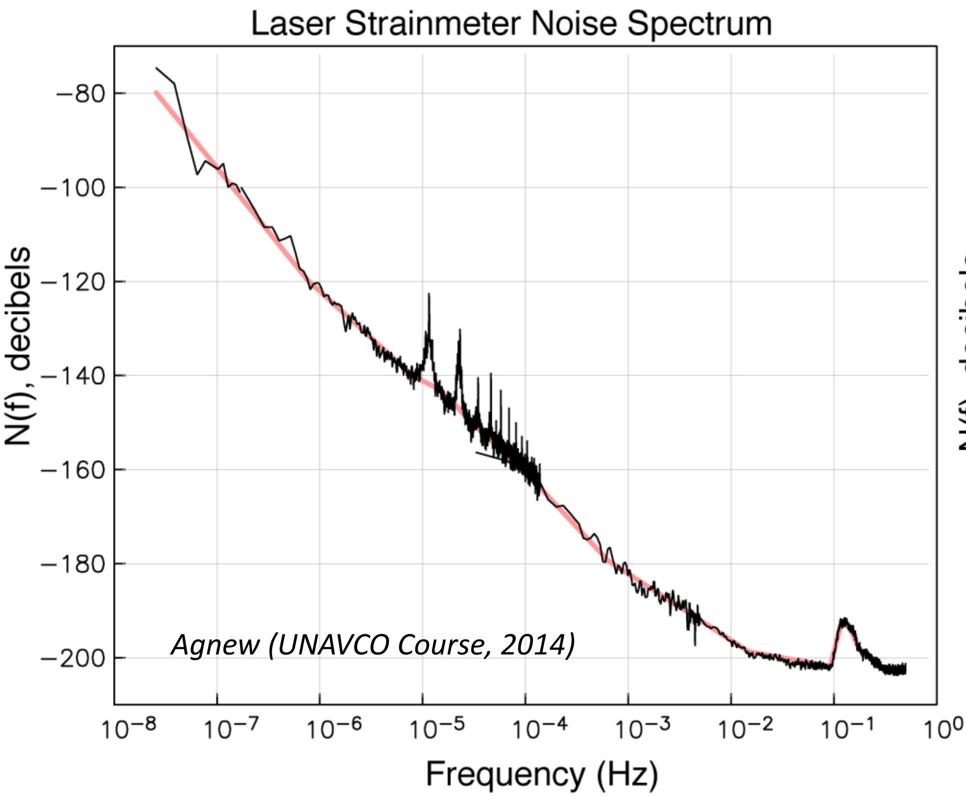
$B(t_S)$ is the RMS noise over a one-octave band,

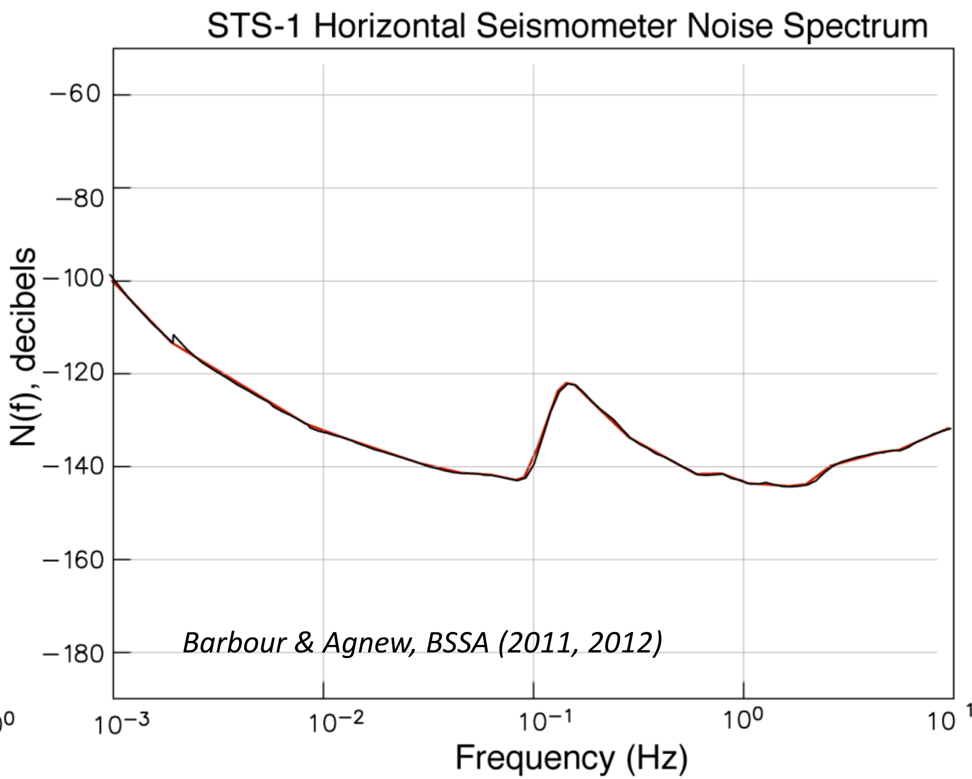
$$B(t_S) = \left[\int_{\frac{1}{\sqrt{2}t_S}}^{\frac{\sqrt{2}}{t_S}} N(f)\,df\right]^{\frac{1}{2}}$$

Detection requires SNR > 1 or $U_{RMS} > B(t_s)$. Detection threshold, M_0, for a value of t_s is

$$B(t_s) \sim \frac{G}{4\pi\rho c^2}\frac{1}{r^2}\left[1 + \frac{r}{ct_s}\right]M_0$$

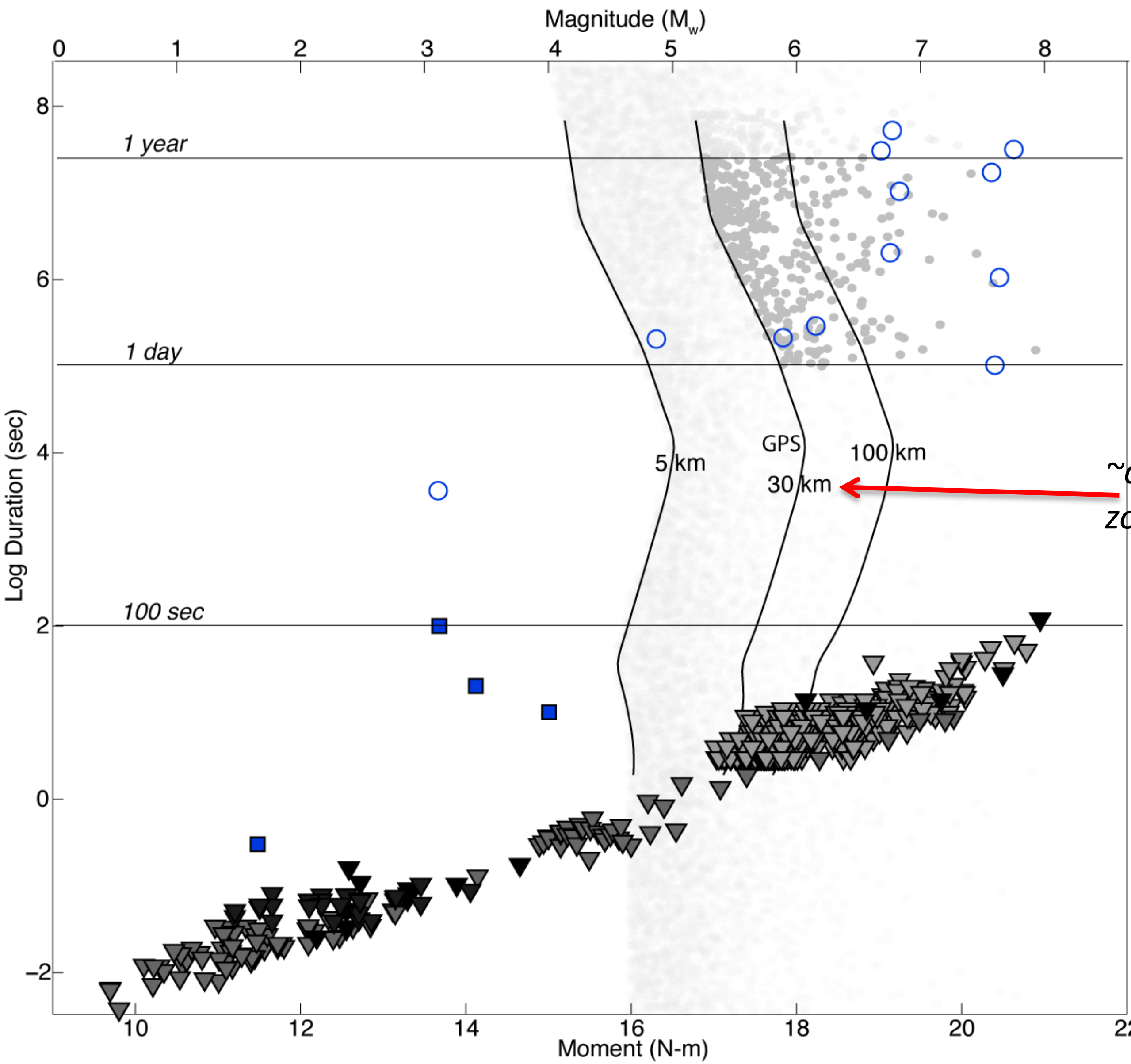
Measurement detection thresholds.





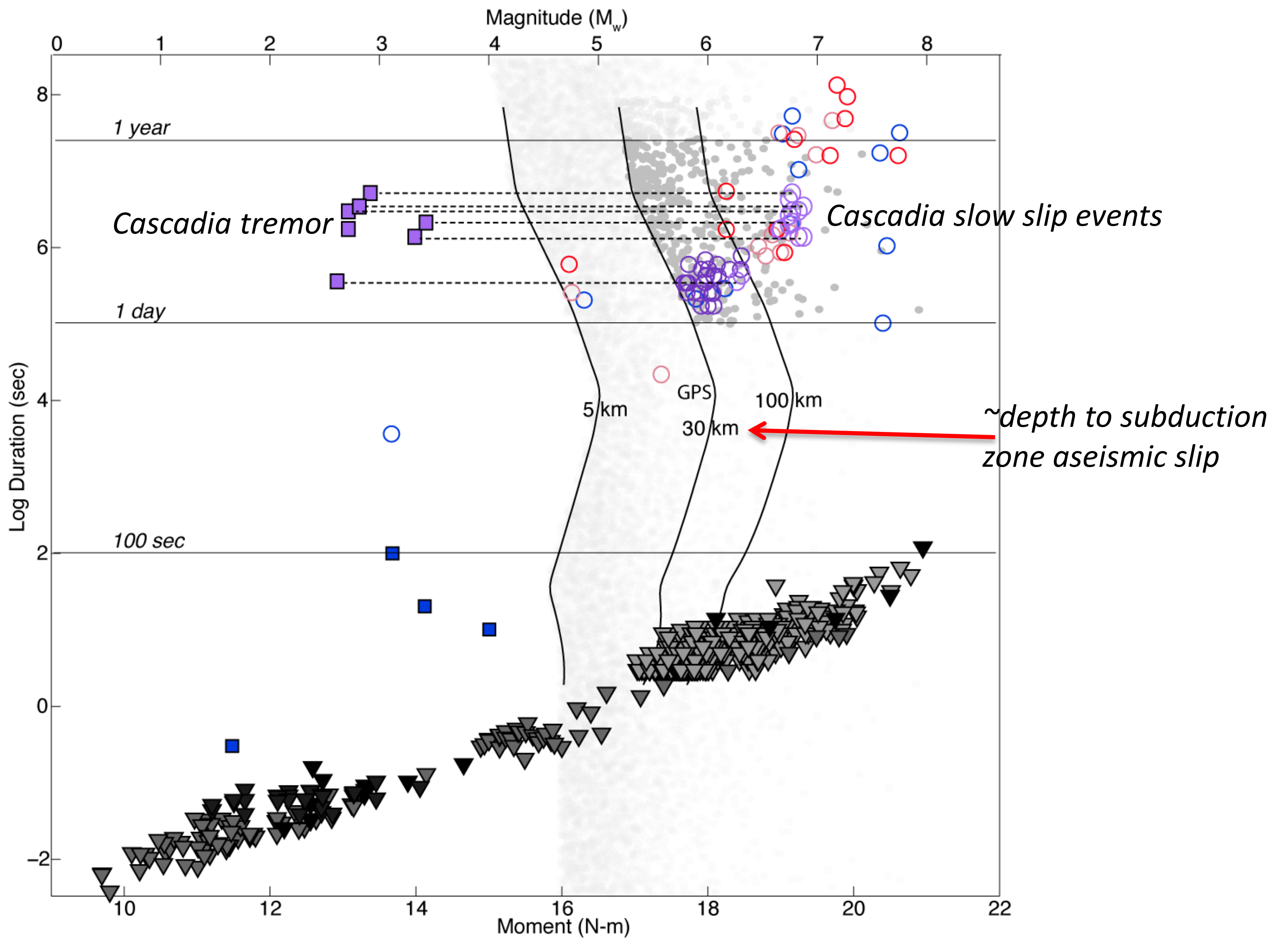
Compute $B(t_S) = \left[\int_{\frac{1}{\sqrt{2} t_S}}^{\frac{\sqrt{2}}{t_S}} N(f)\, df \right]^{\frac{1}{2}}$

GPS detection thresholds



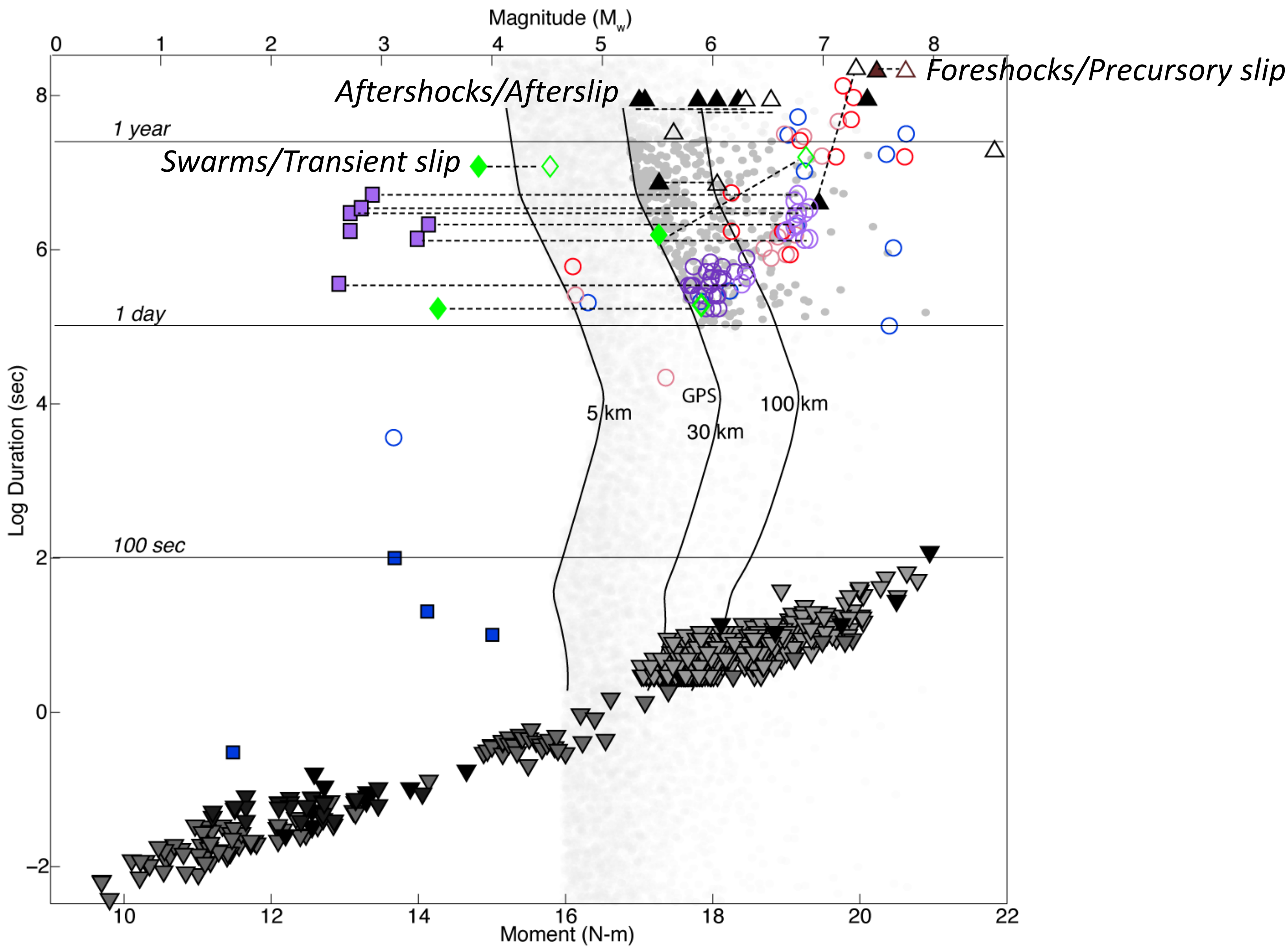
~depth to subduction zone aseismic slip

More GPS measurements of spontaneous slip events. The Earth also imposes sampling limitations.

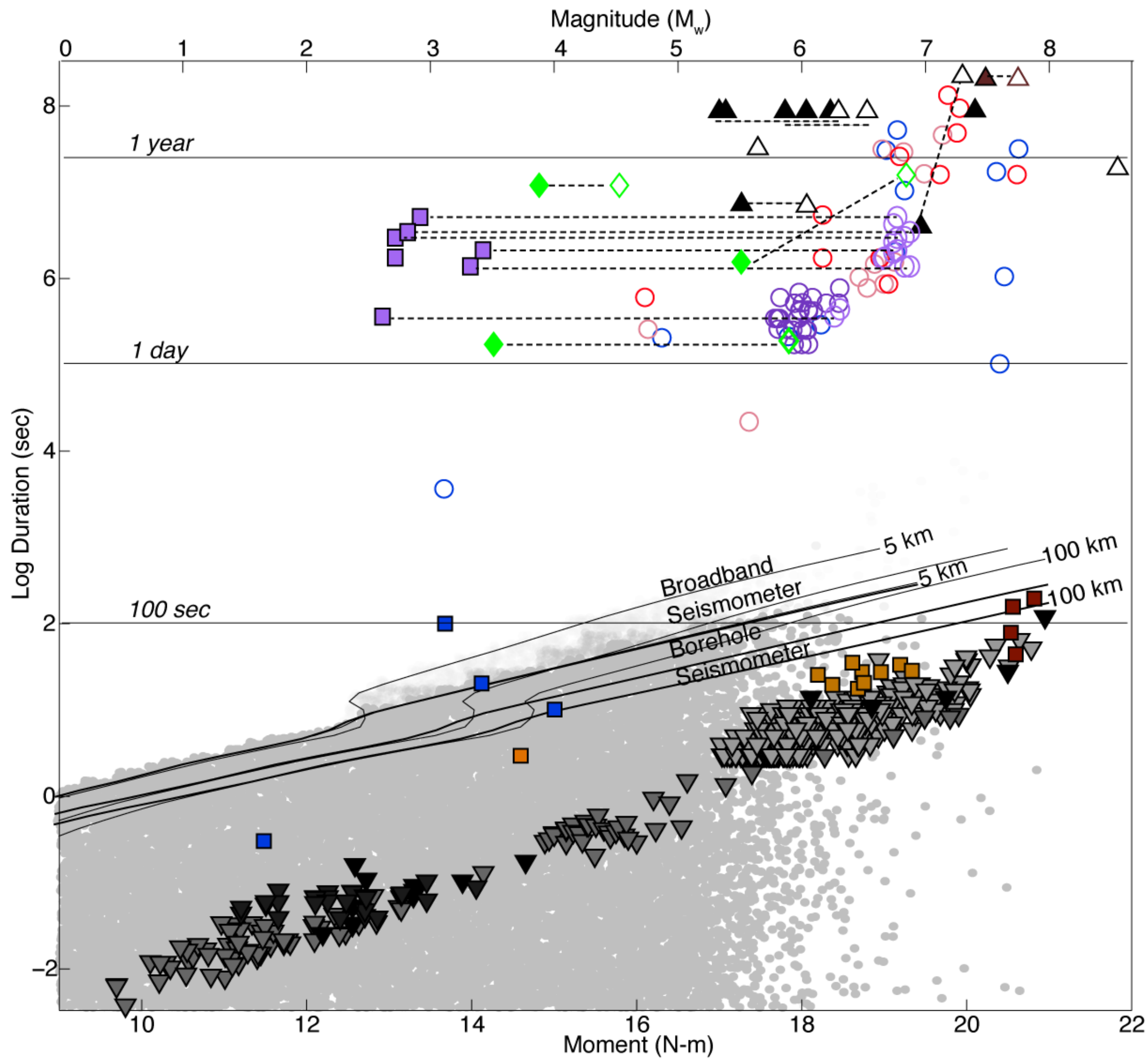


Coupled seismic & aseismic slip event measurements.

We begin to fill the GPS detectable region. Aseismic moment > seismic moment always!

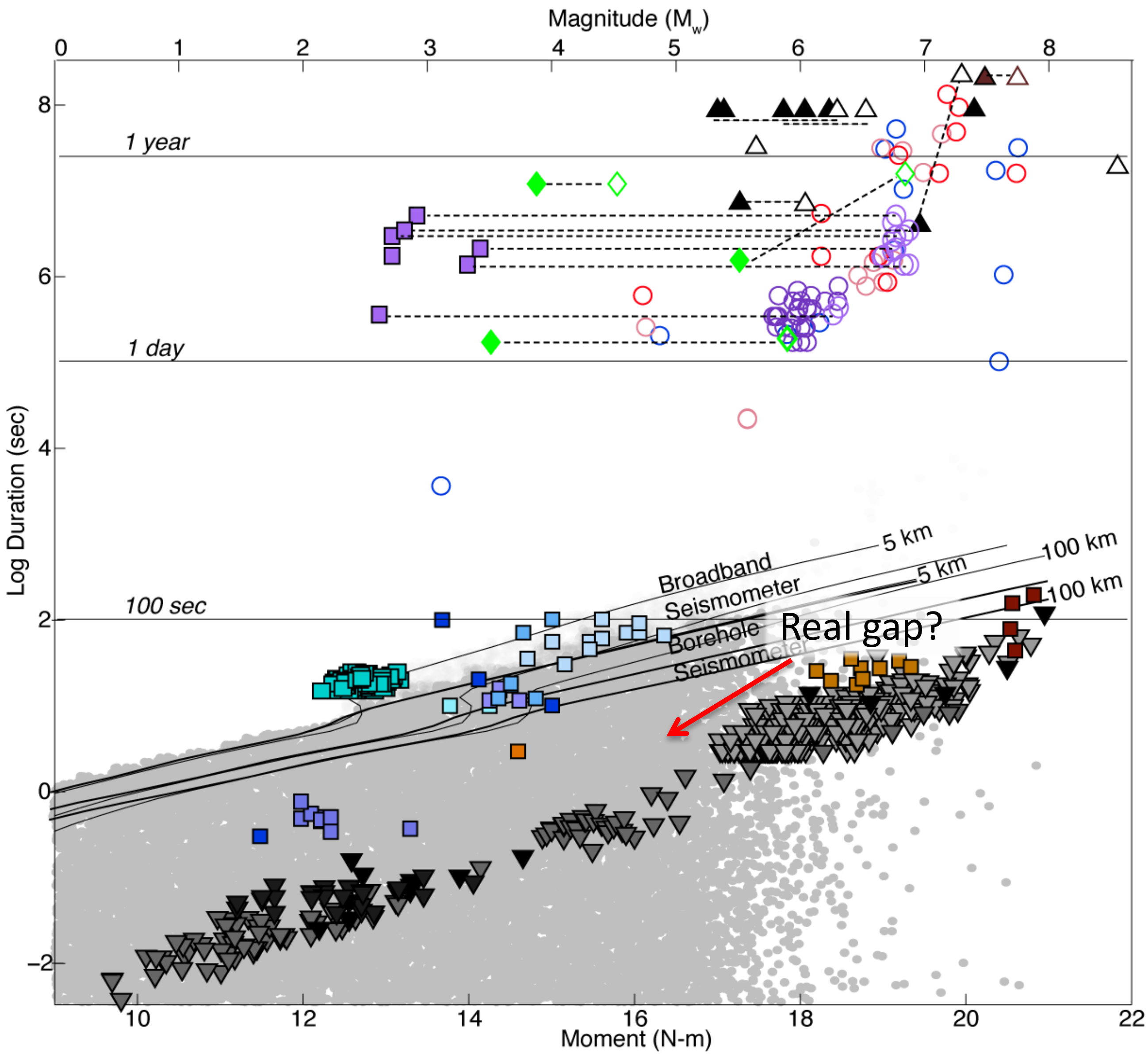


Seismic detection thresholds.

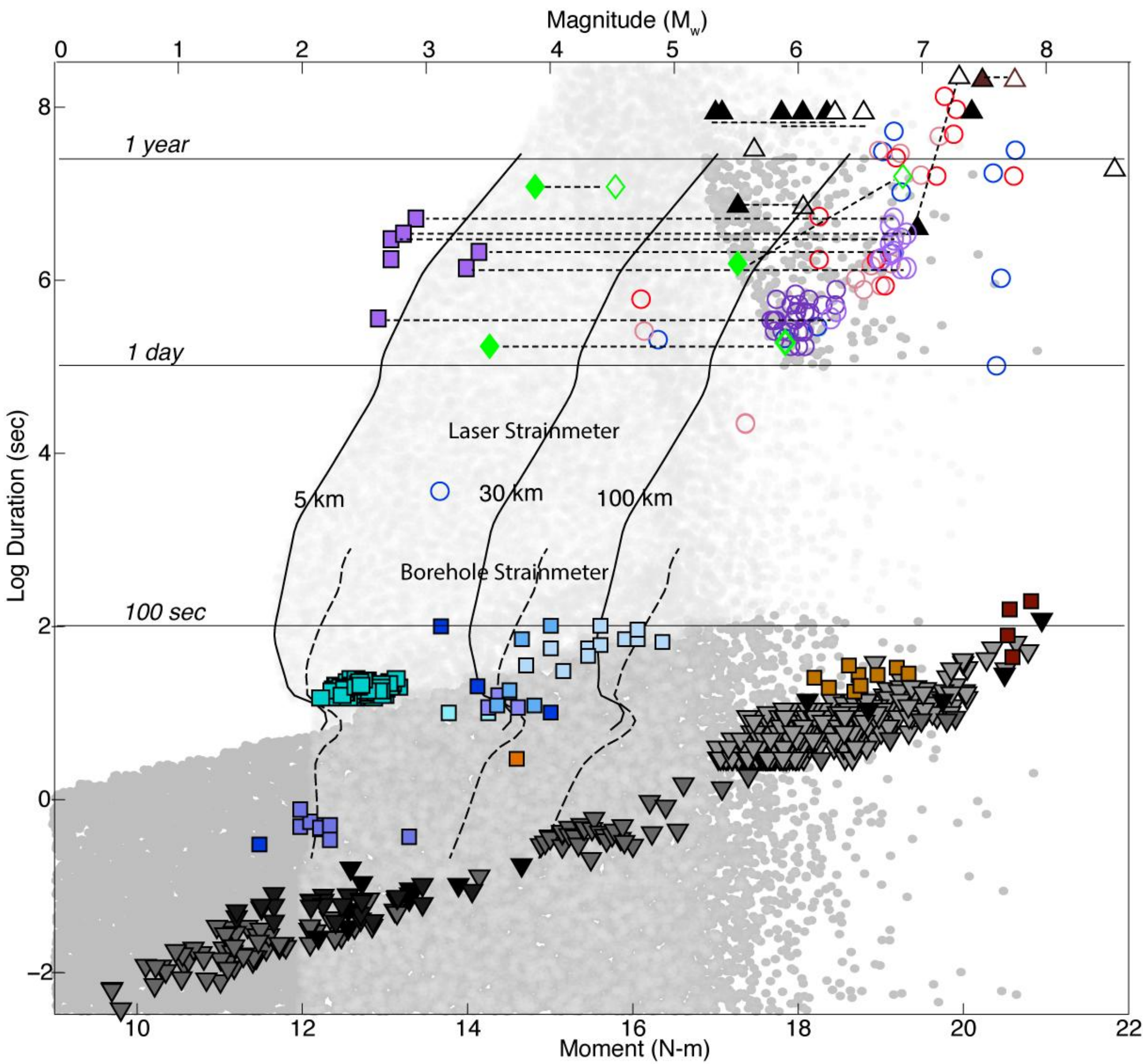


Seismic detection thresholds.

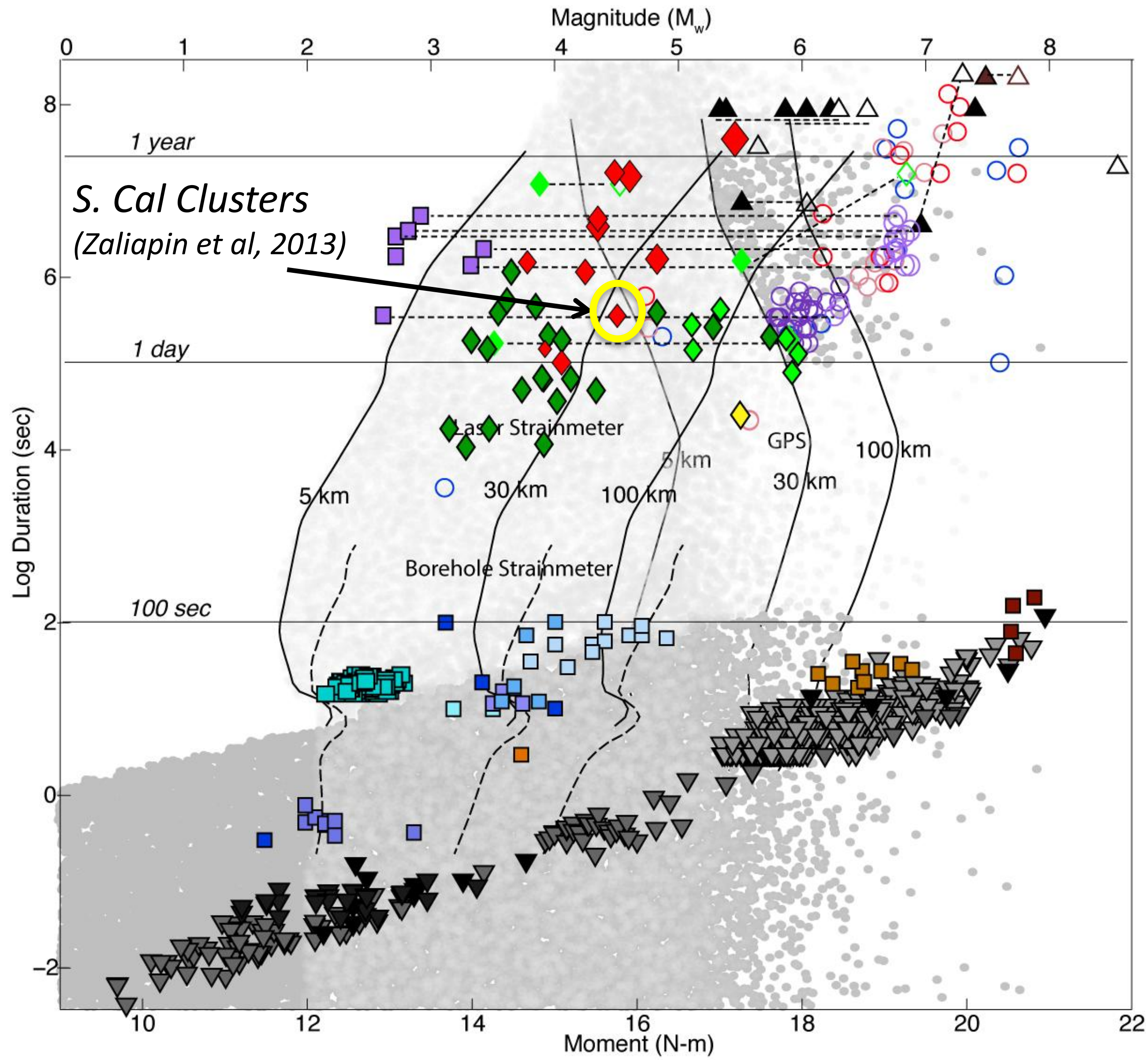
A real gap exists?



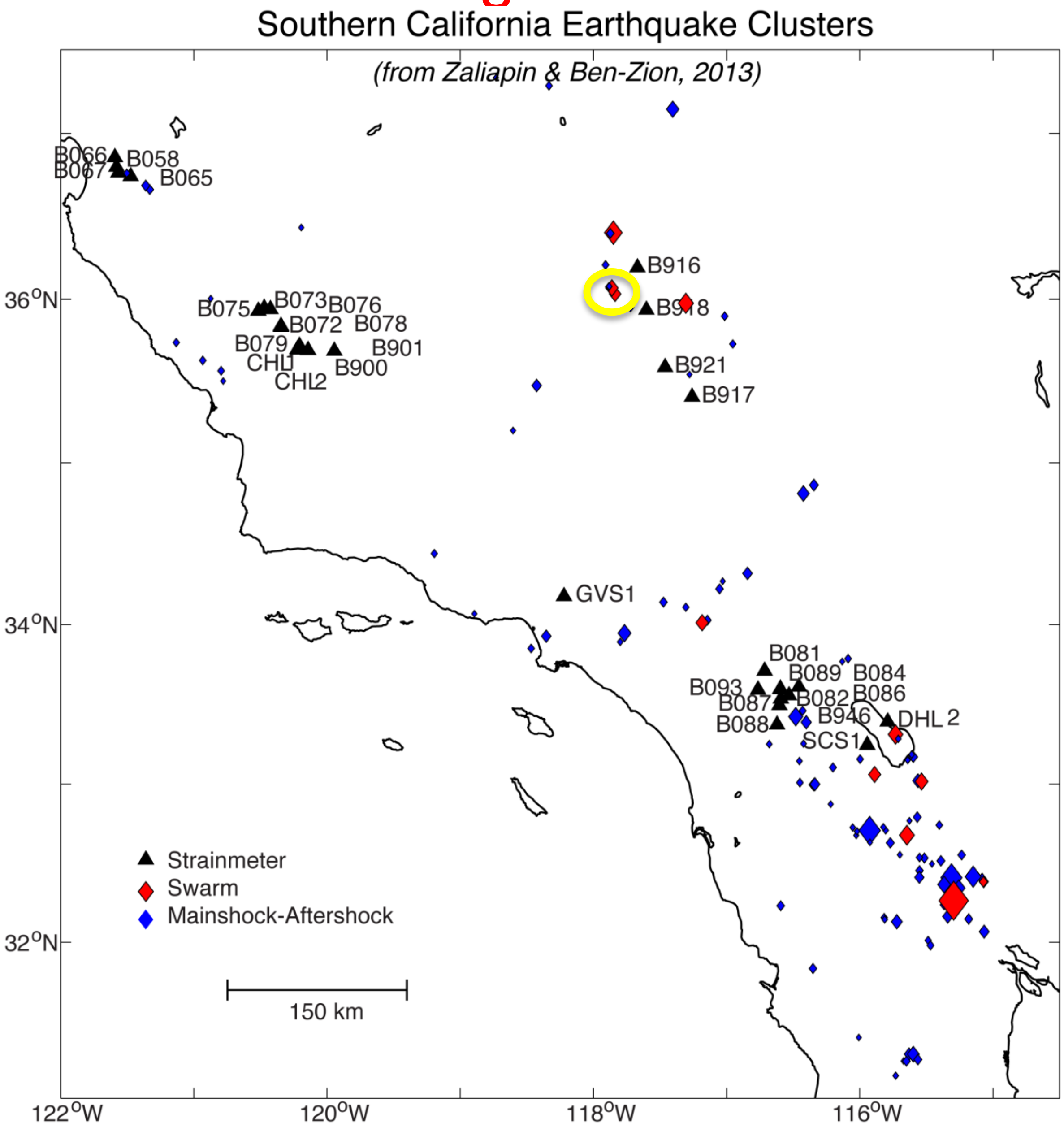
Strainmeter detection thresholds – promising!



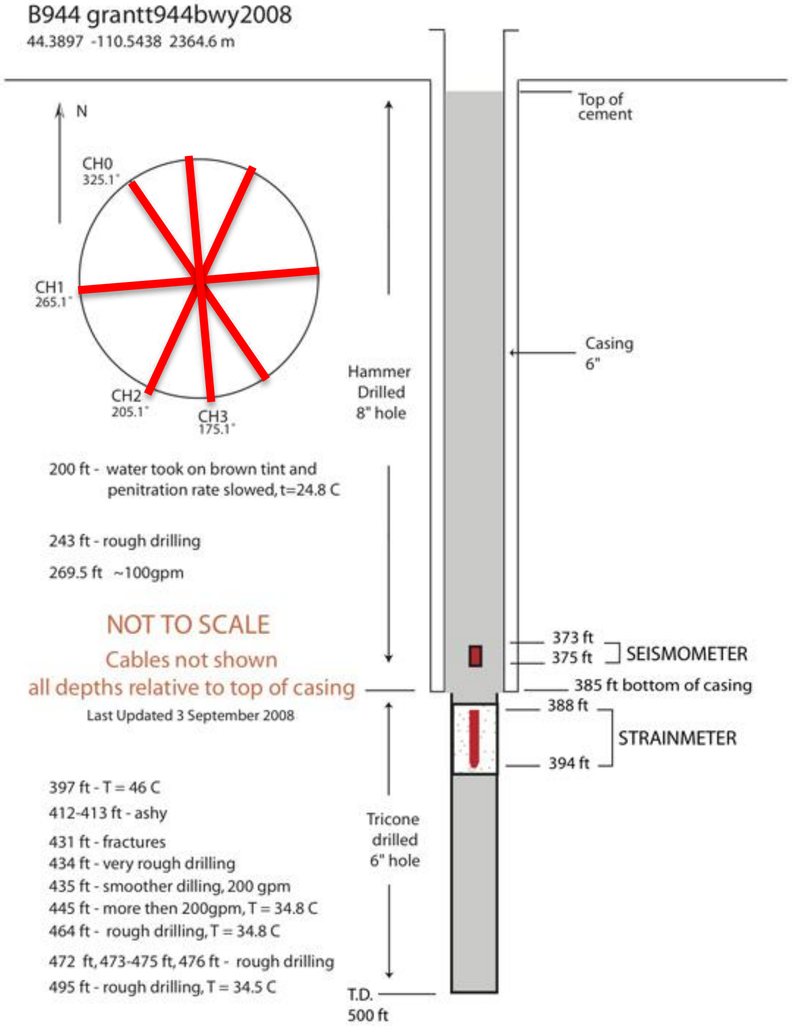
Shallow swarms (proxies for shallow slow slip) & strainmeters hold most promise to fill in gaps.



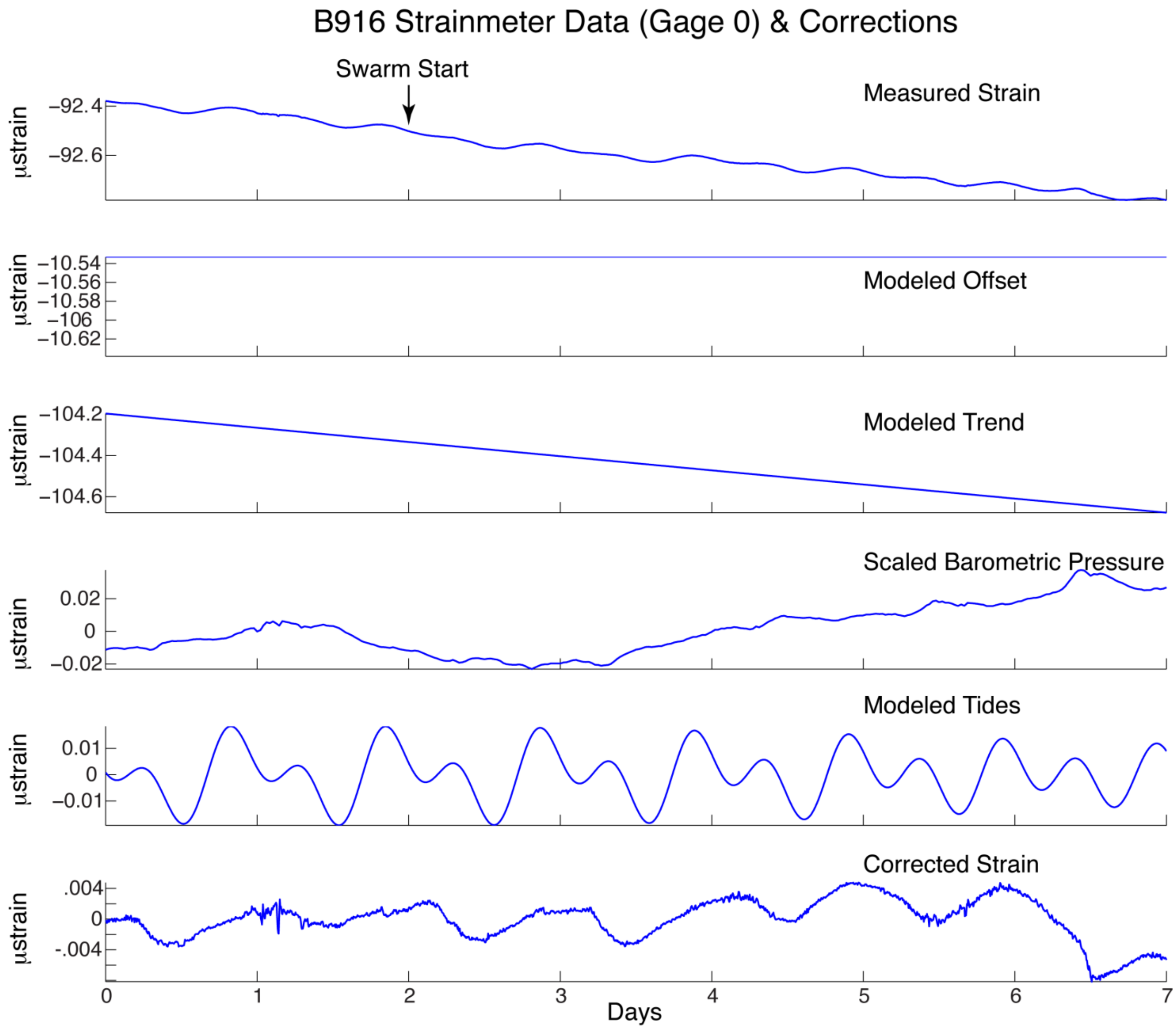
Clustered strainmeters help discriminate Earthly signals?



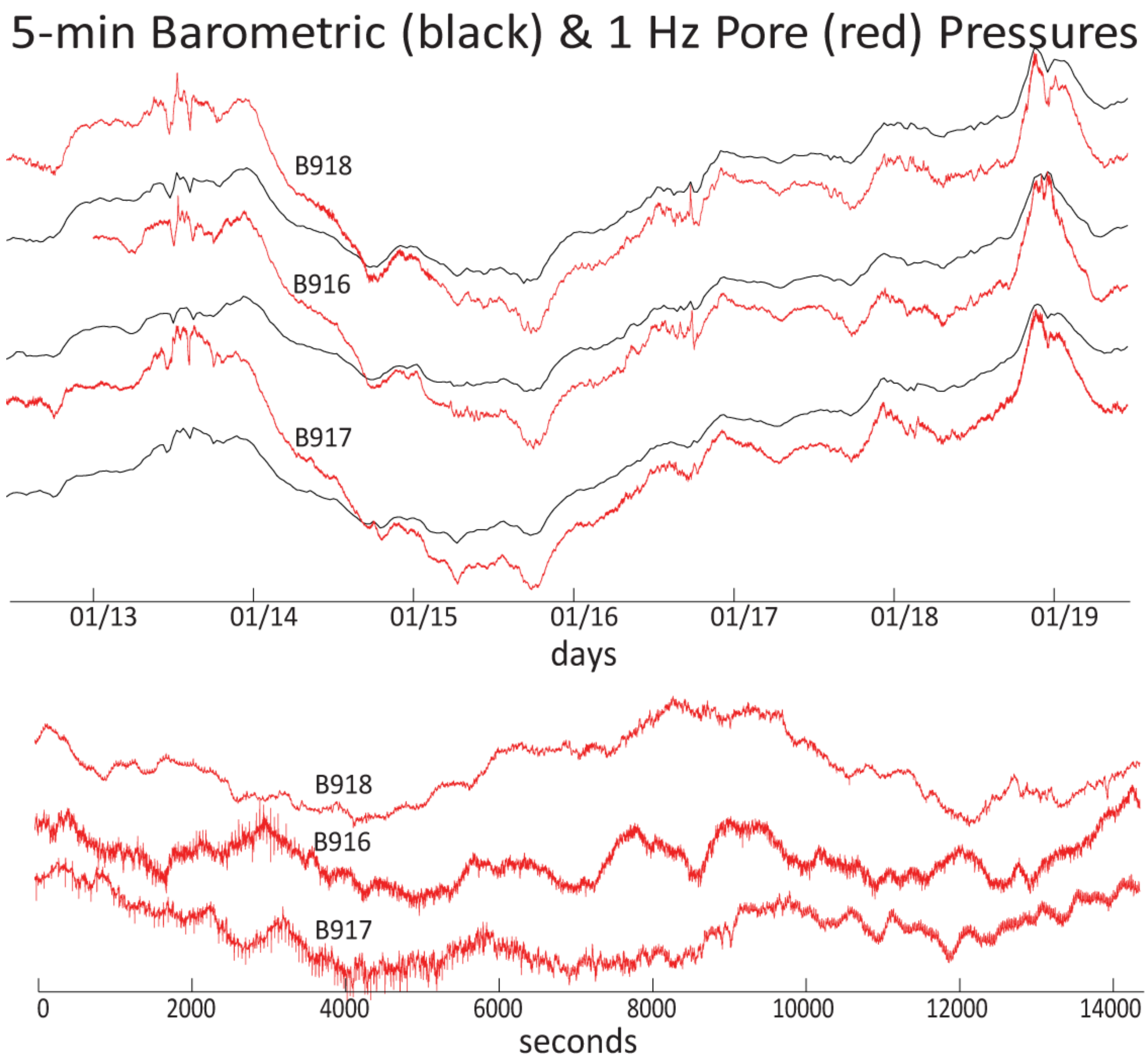
Know thy data: 1) 4 measurements combined



Know thy data: 2) Low detection threshold = high deterministic noise levels (5 min data)

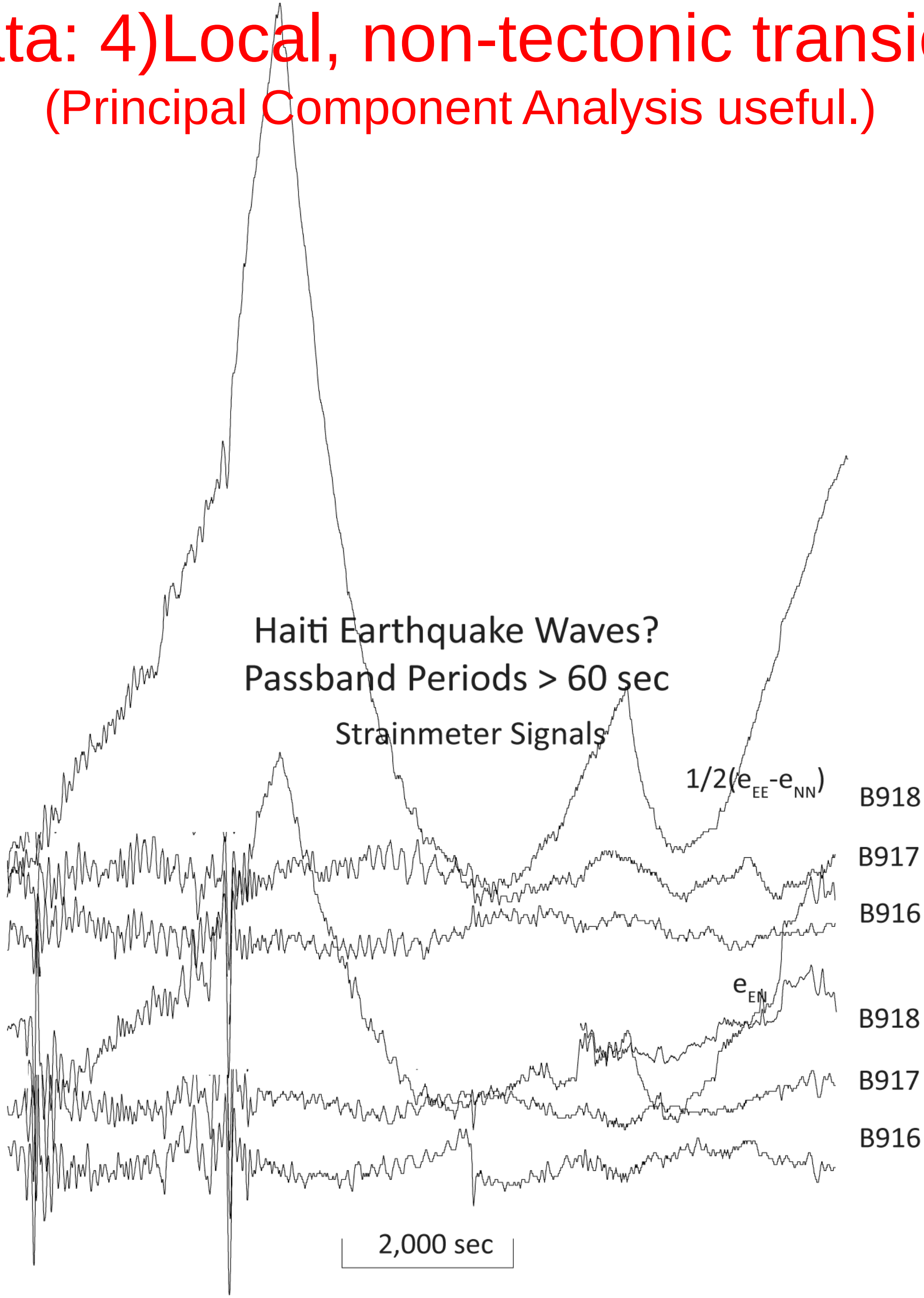


Know thy data: 3) Coherent noise (pressures).

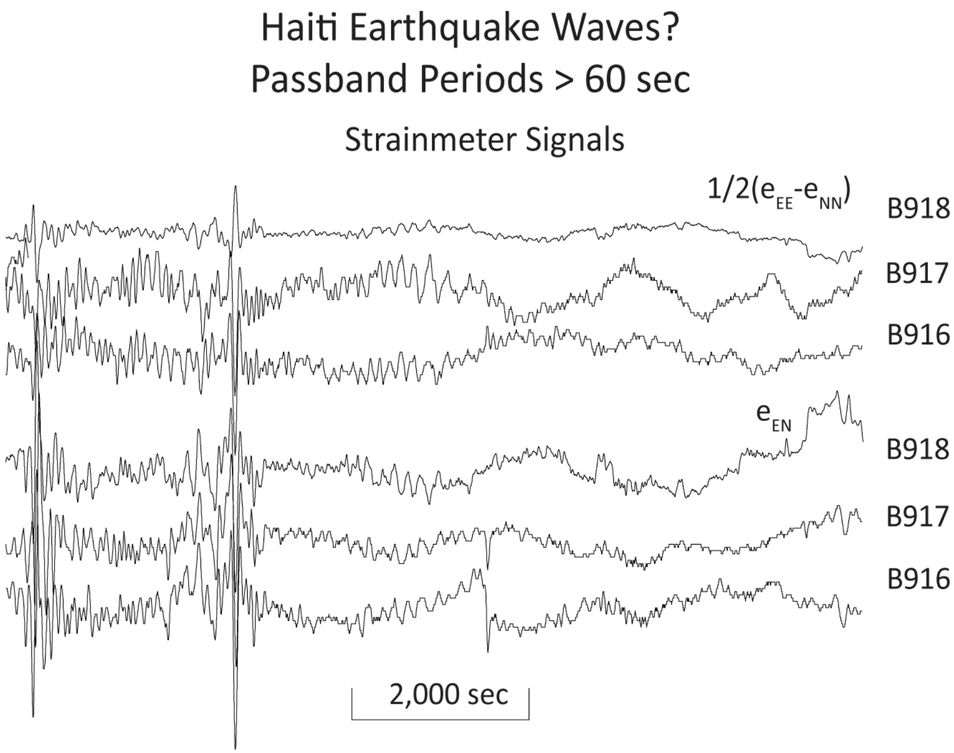


Know thy data: 4)Local, non-tectonic transient sources.

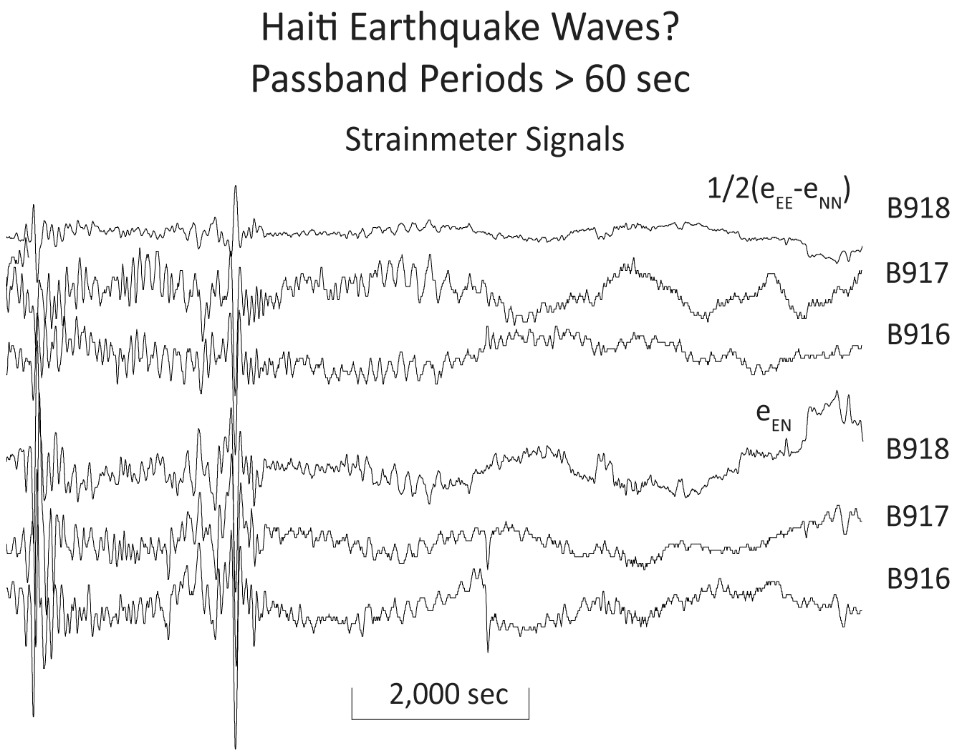
(Principal Component Analysis useful.)



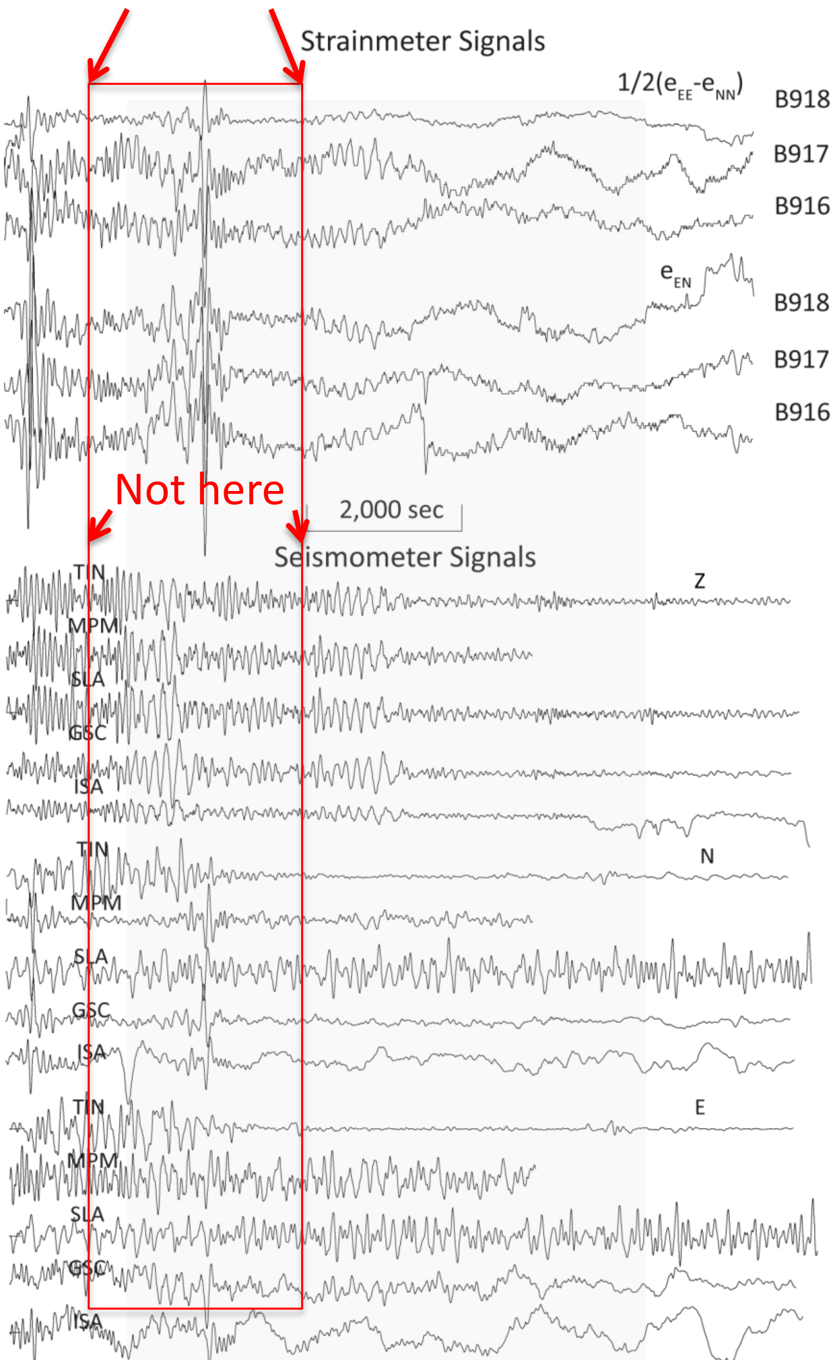
Know thy data: 1st Principal Component Removed



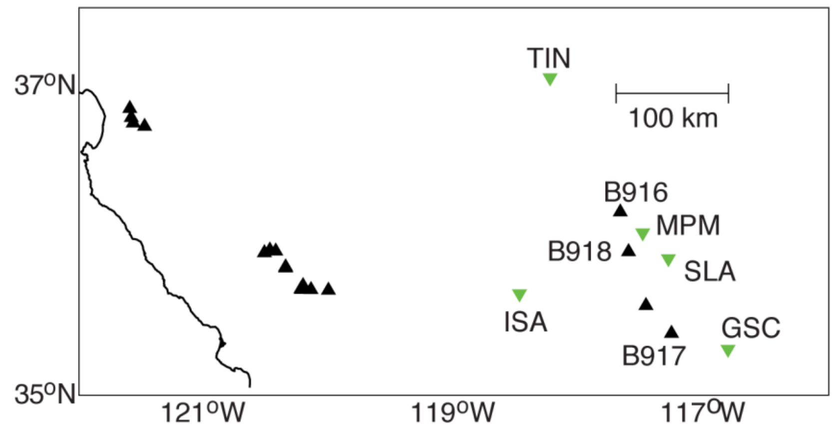
Only Earthly coherent signals during 2 swarm intervals from distant earthquake waves.



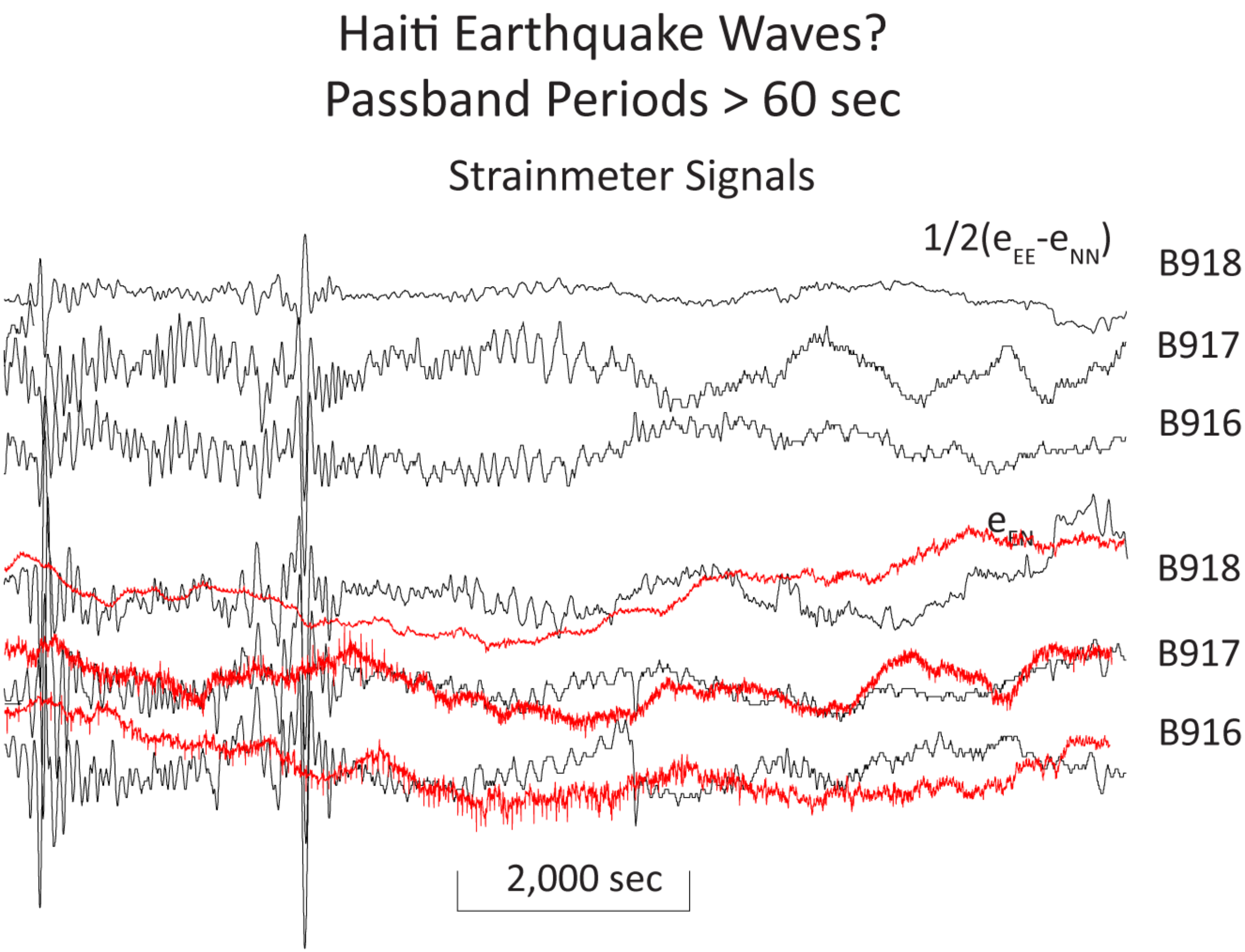
Coherent long period energy here



Strainmeter signals <u>may</u> fill duration gap not possible with seismic data, but…

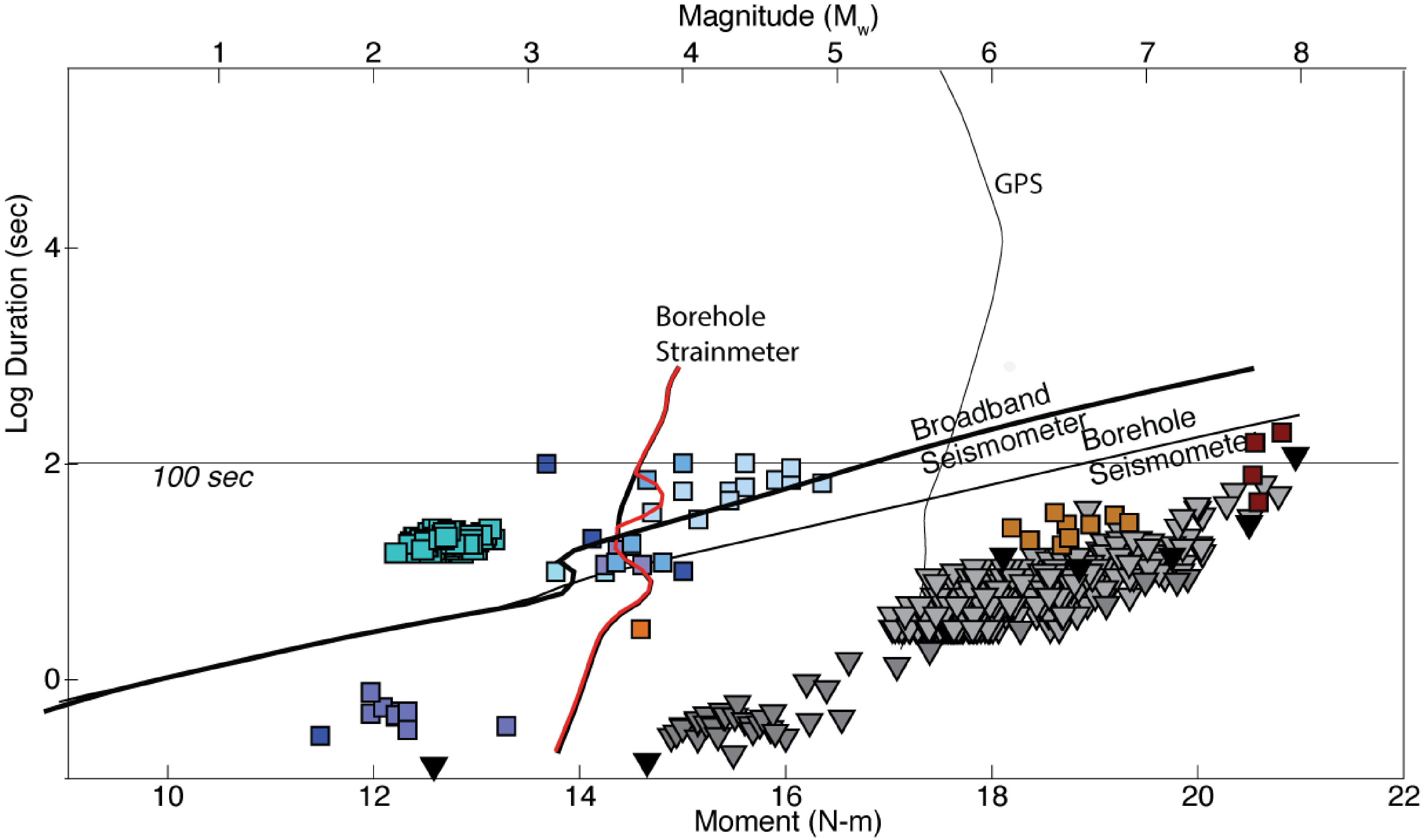


…beware the coherent noise (pressures)?



Another possibility - ‘Very Low Frequency’ (VLF) Events

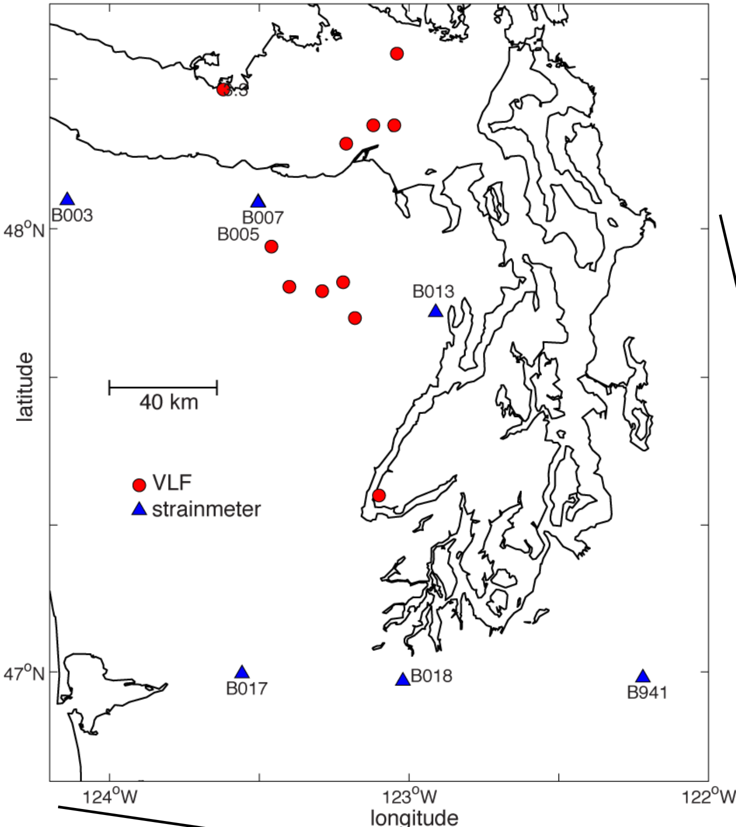
Observable on strainmeters?

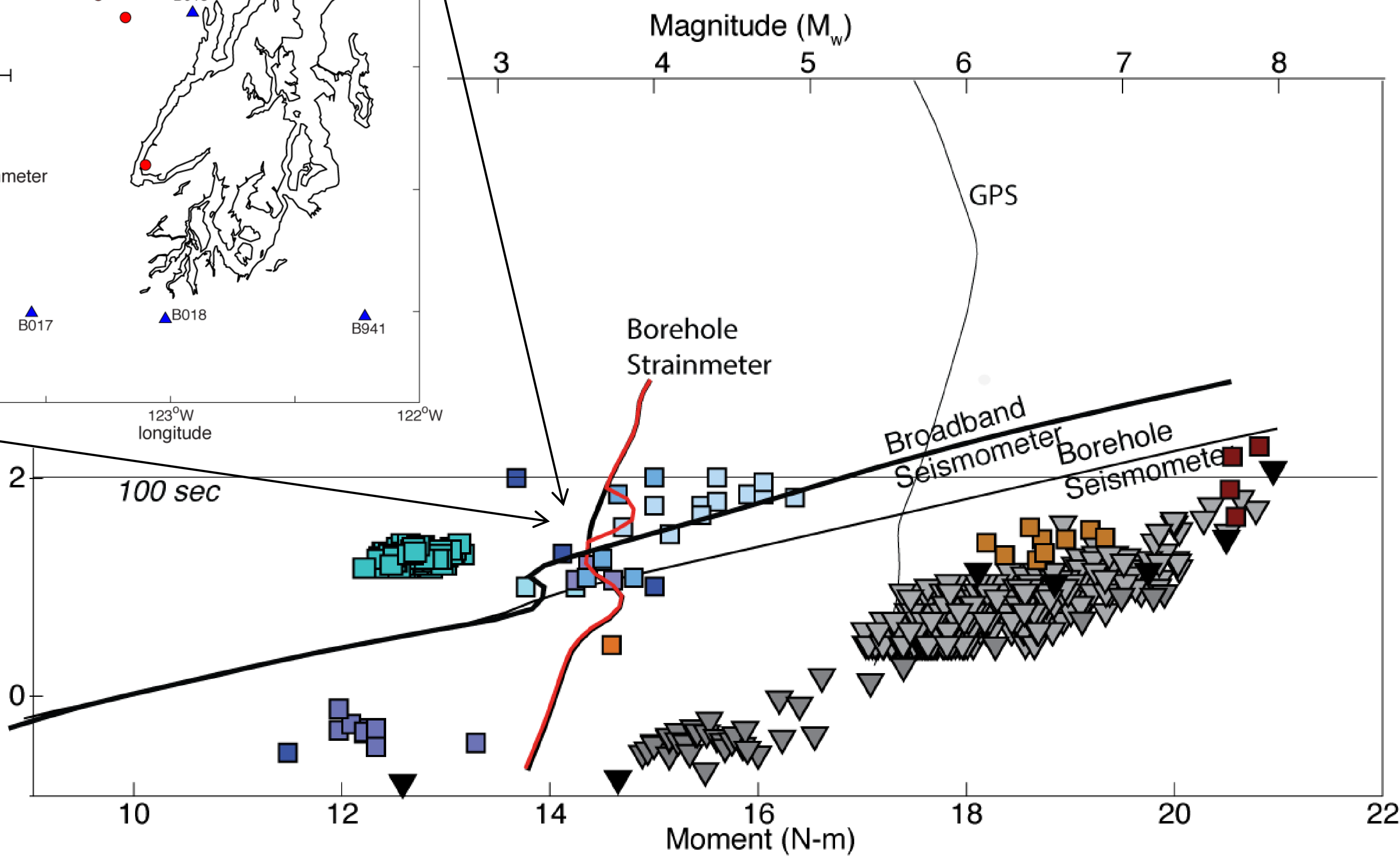


Another possibility - VLF Events

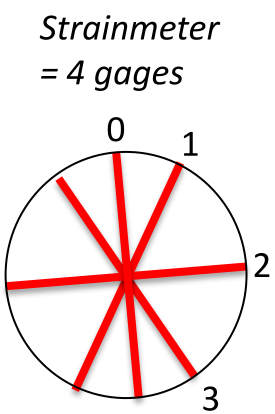
'Observed' in stacked seismic data.

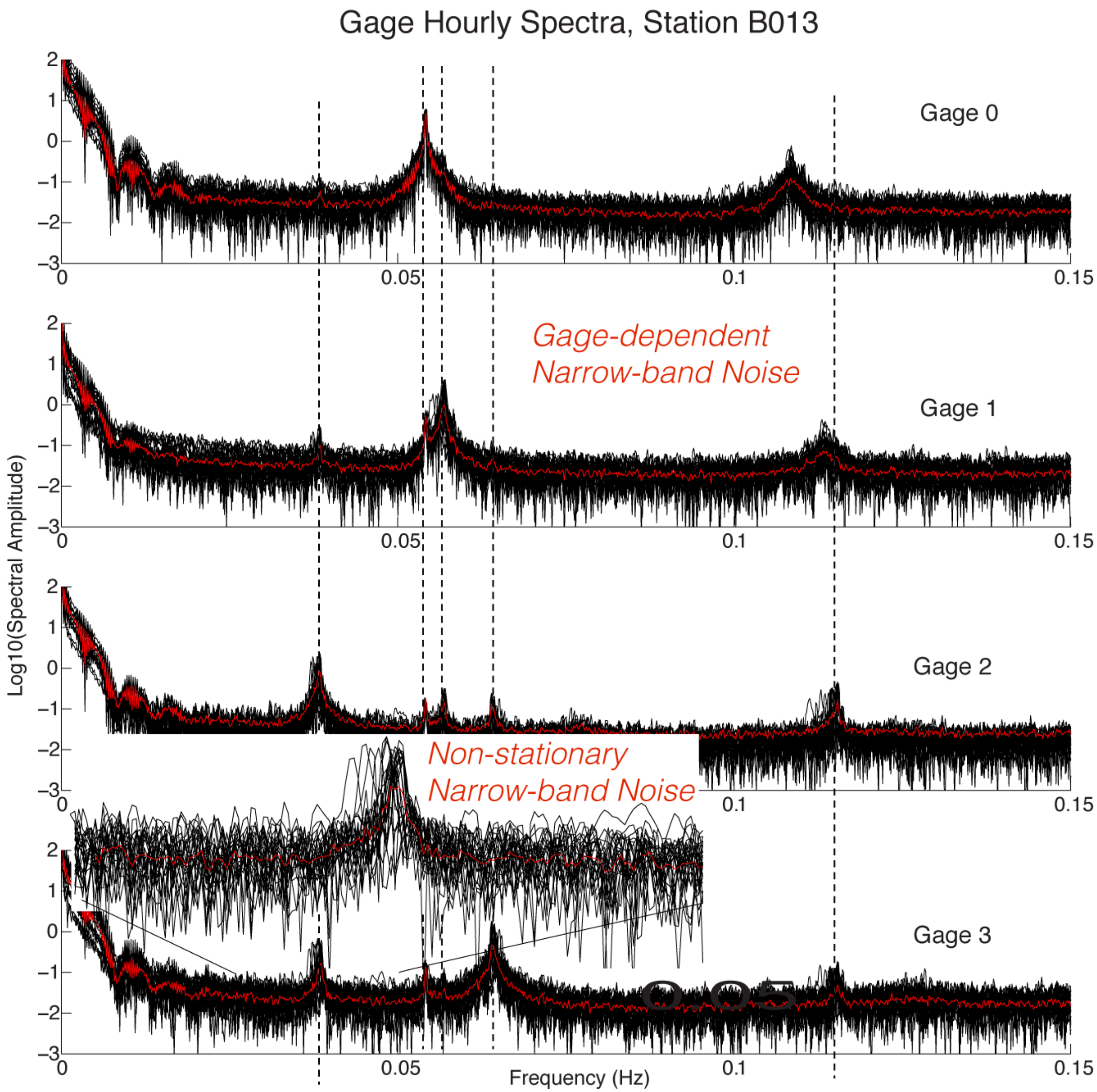
from Akiko Takeo





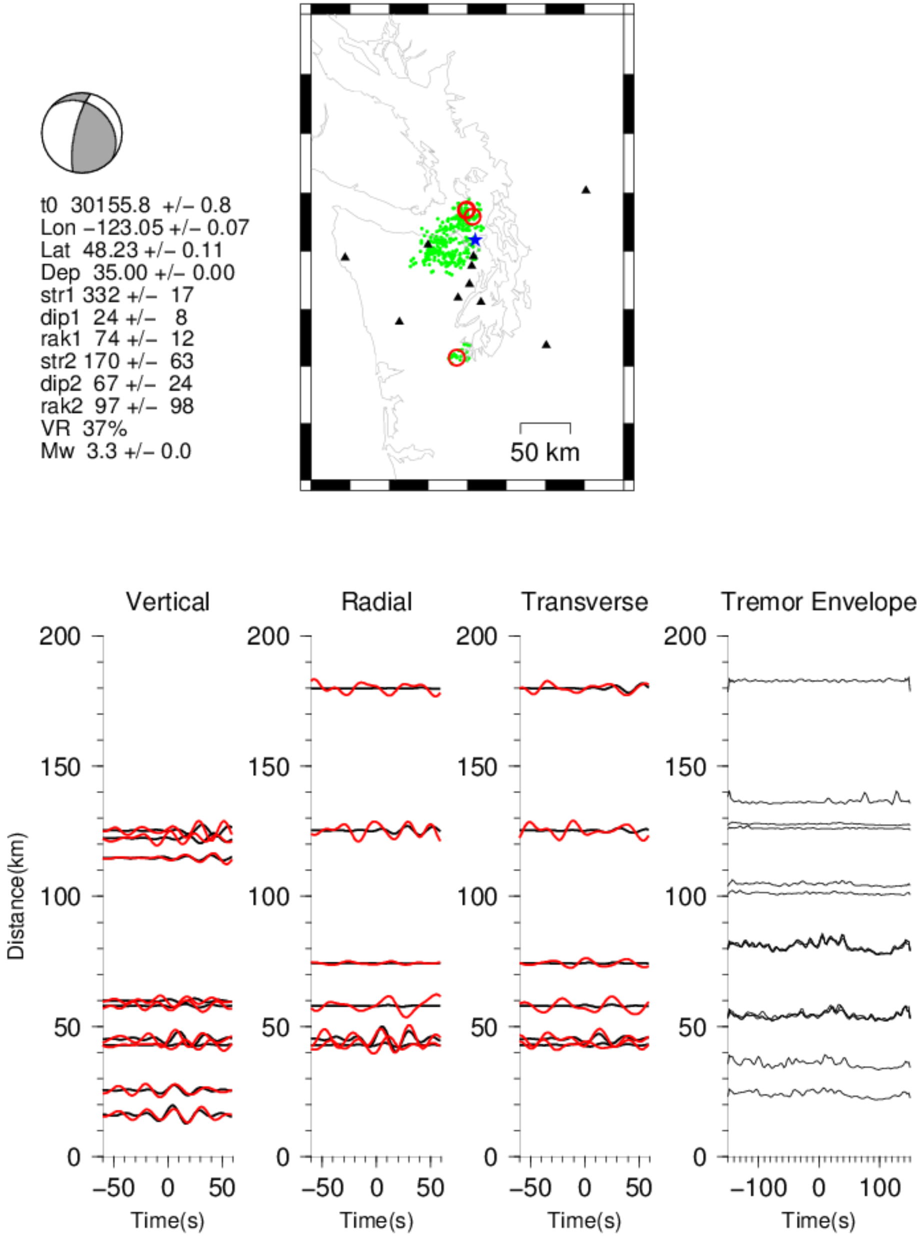
Know thy data: 5) Non-stationary, narrow band electronic noise.



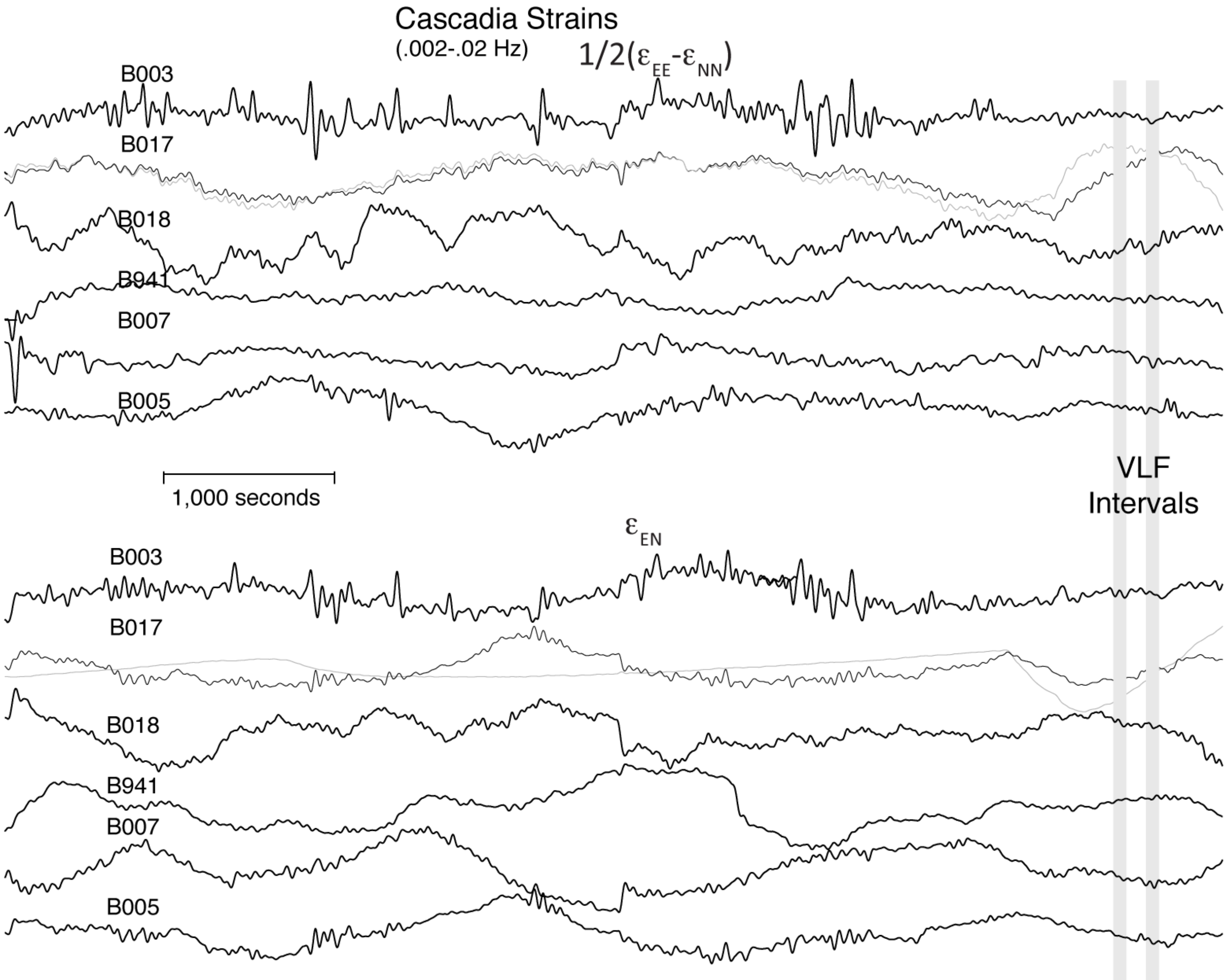


Seismically Observed VLF Event

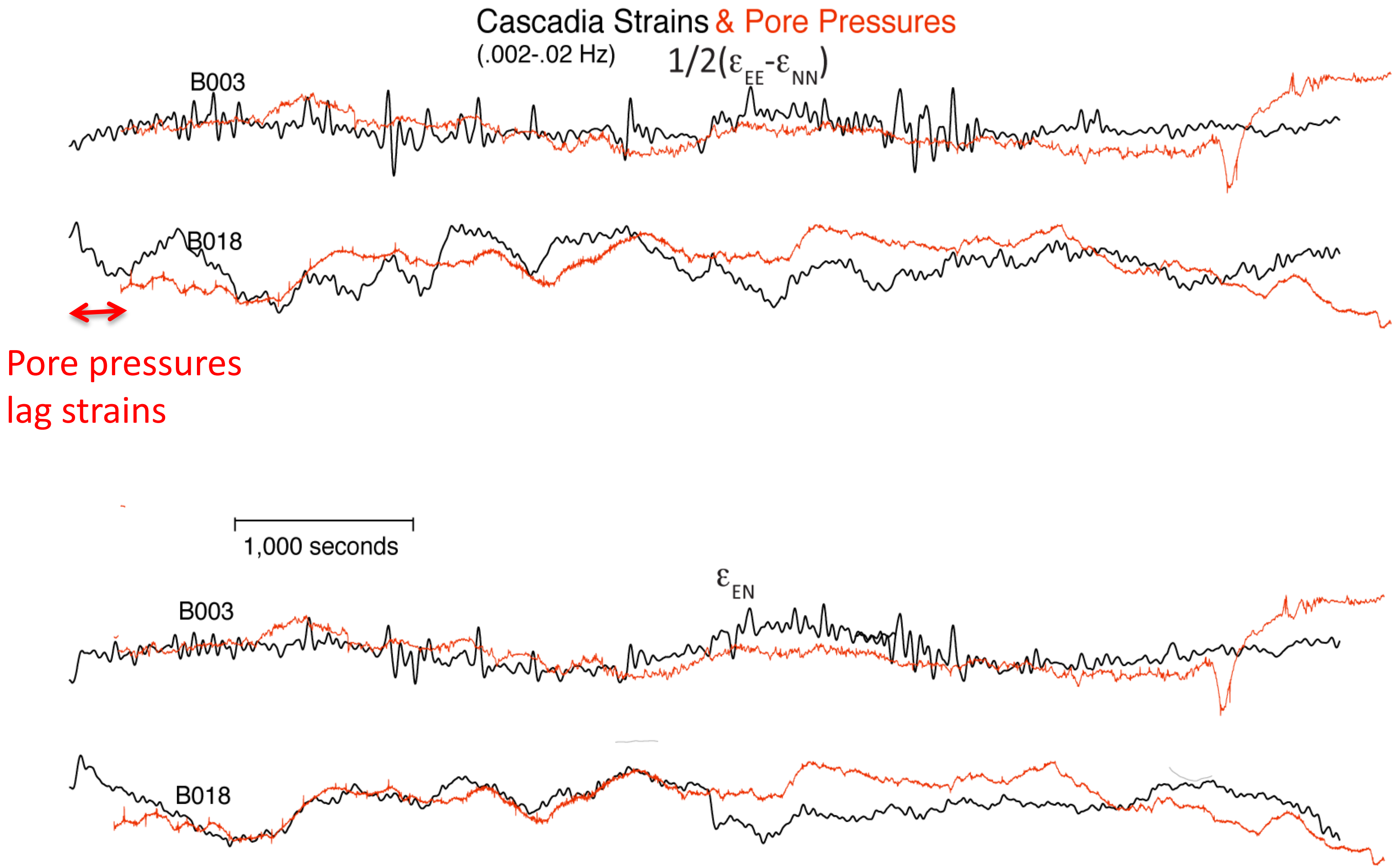
from Akiko Takeo



Preliminary Strainmeter VLF Search – Nothing Found (as anticipated)

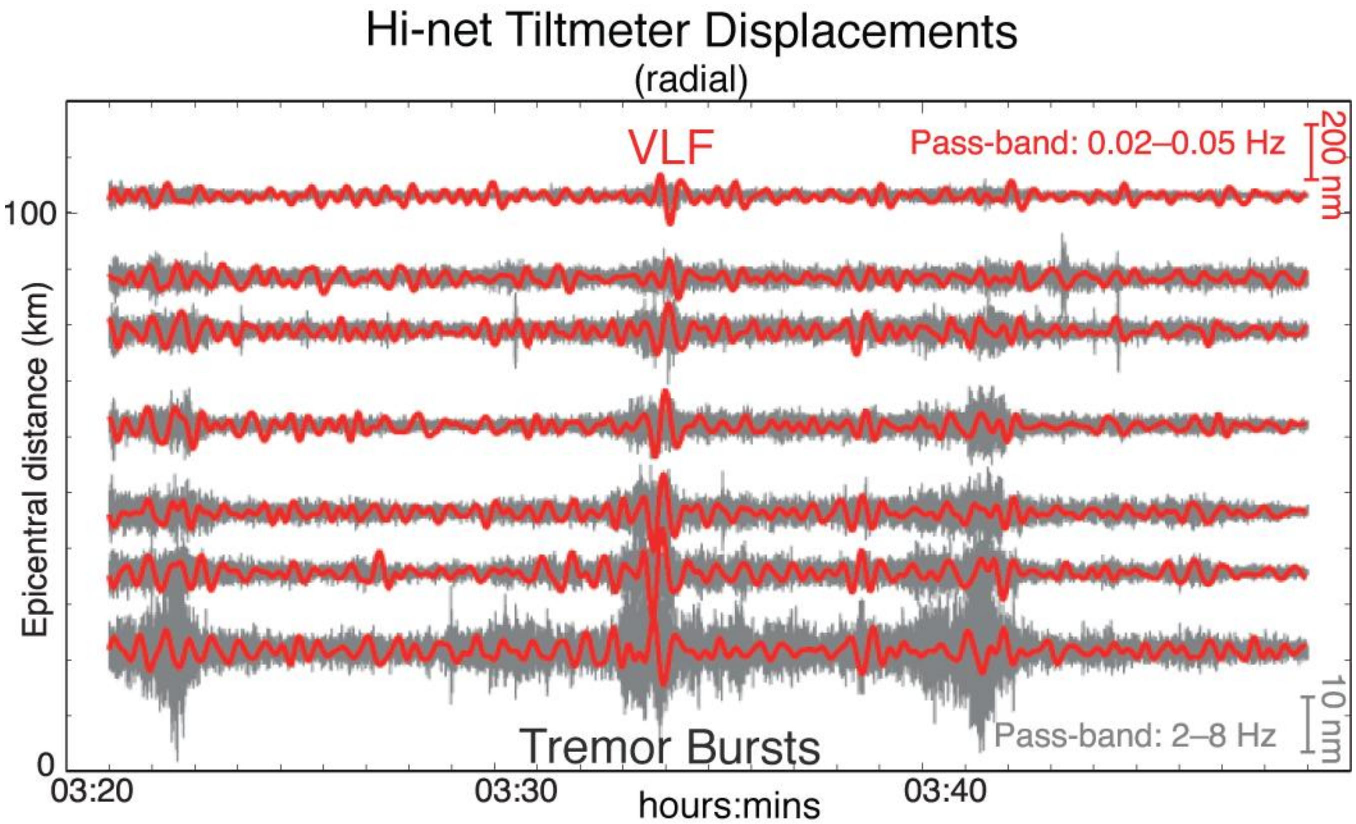


Preliminary Strainmeter VLF Search – Strains drive pore pressure changes?



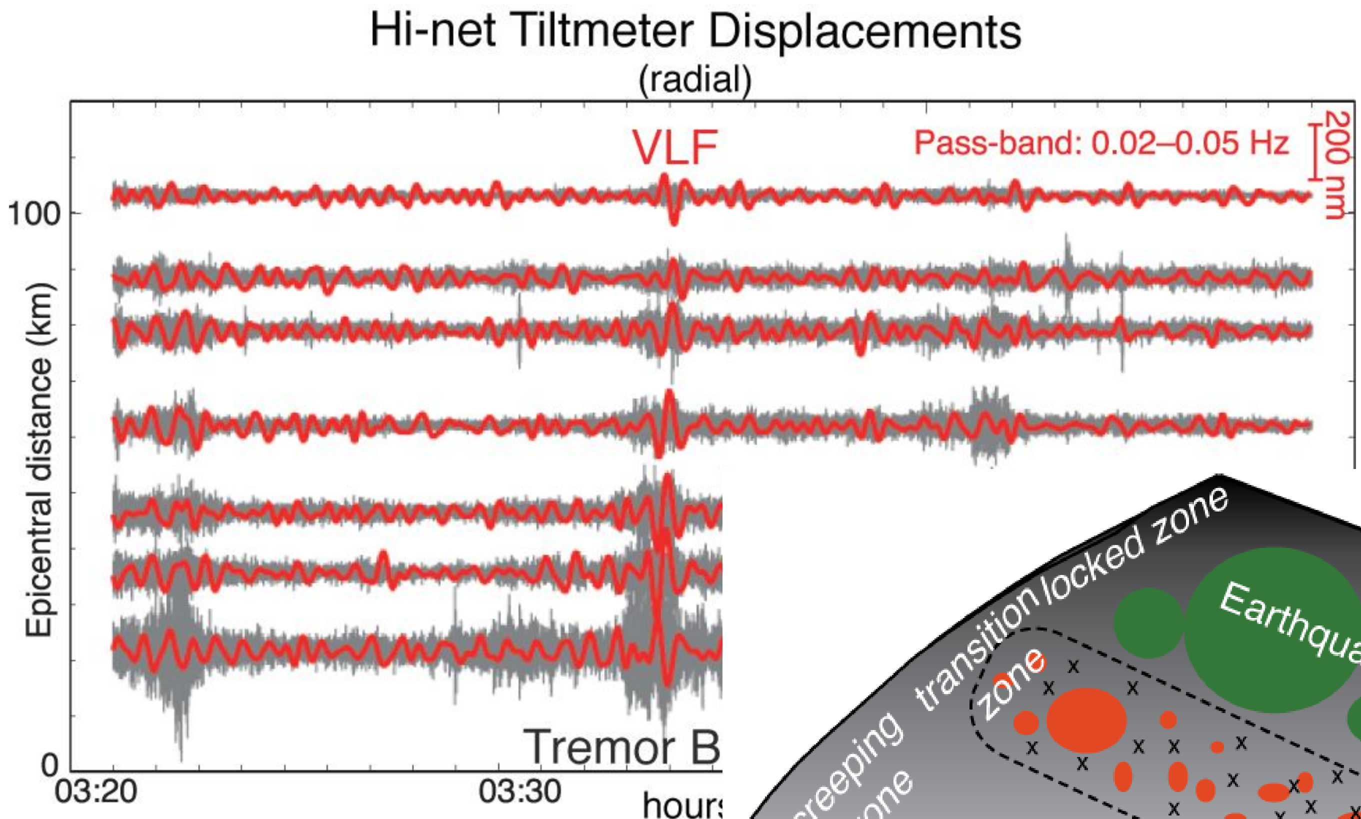
What are these Very Low Frequency events?

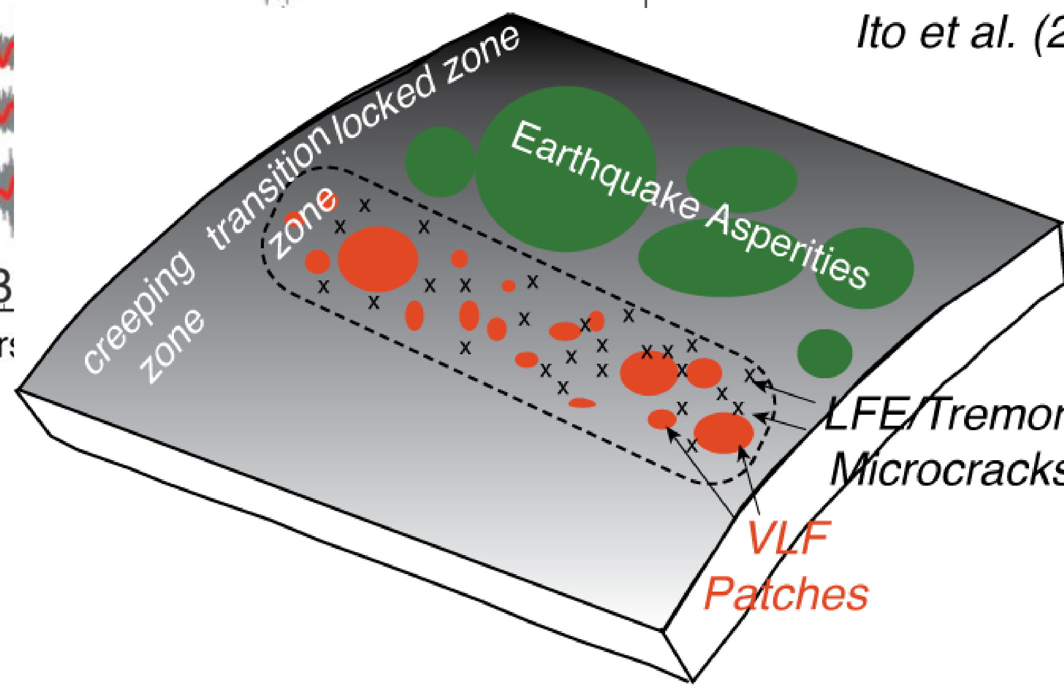
Always observed with tremor bursts.



Ito et al. (2007)

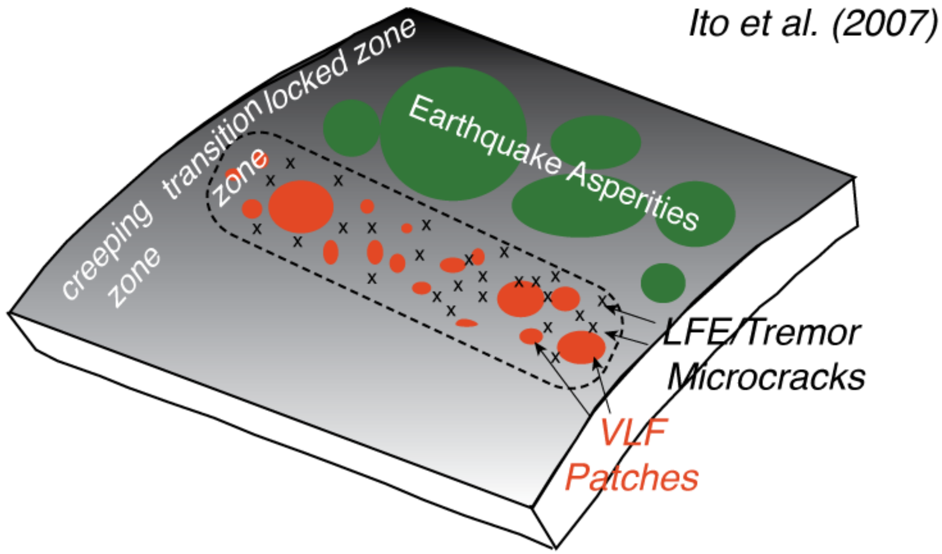
Inferred 'slow', M3-4, seismic sources.



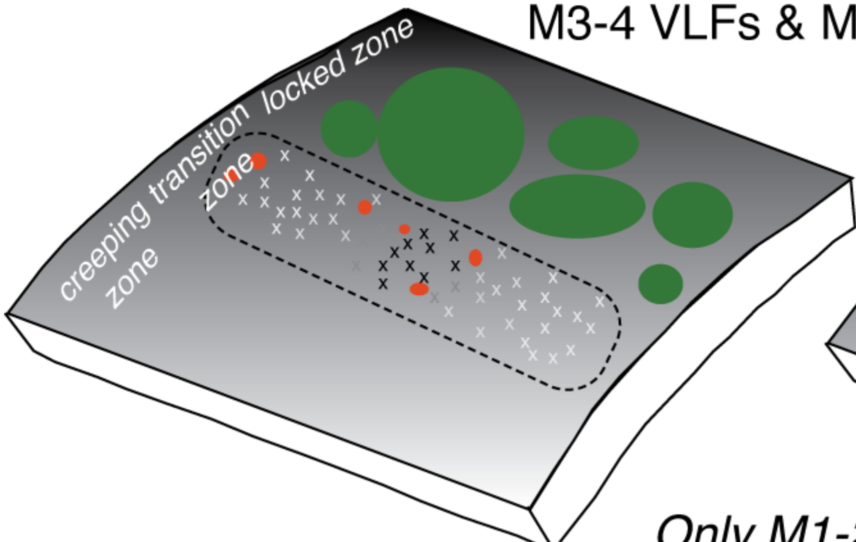


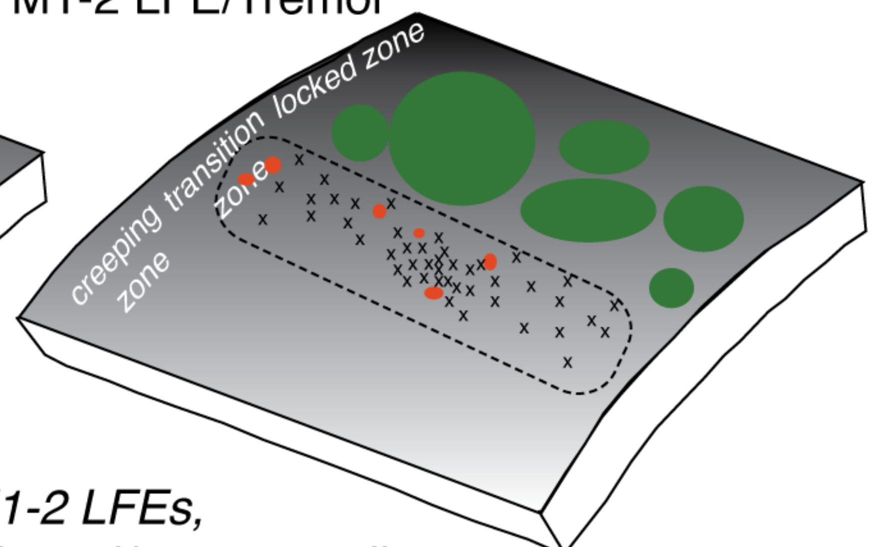
Ito et al. (2007)

Are VLFs really distinct M3-4 sources?
Consider what is being measured & alternative interpretations -



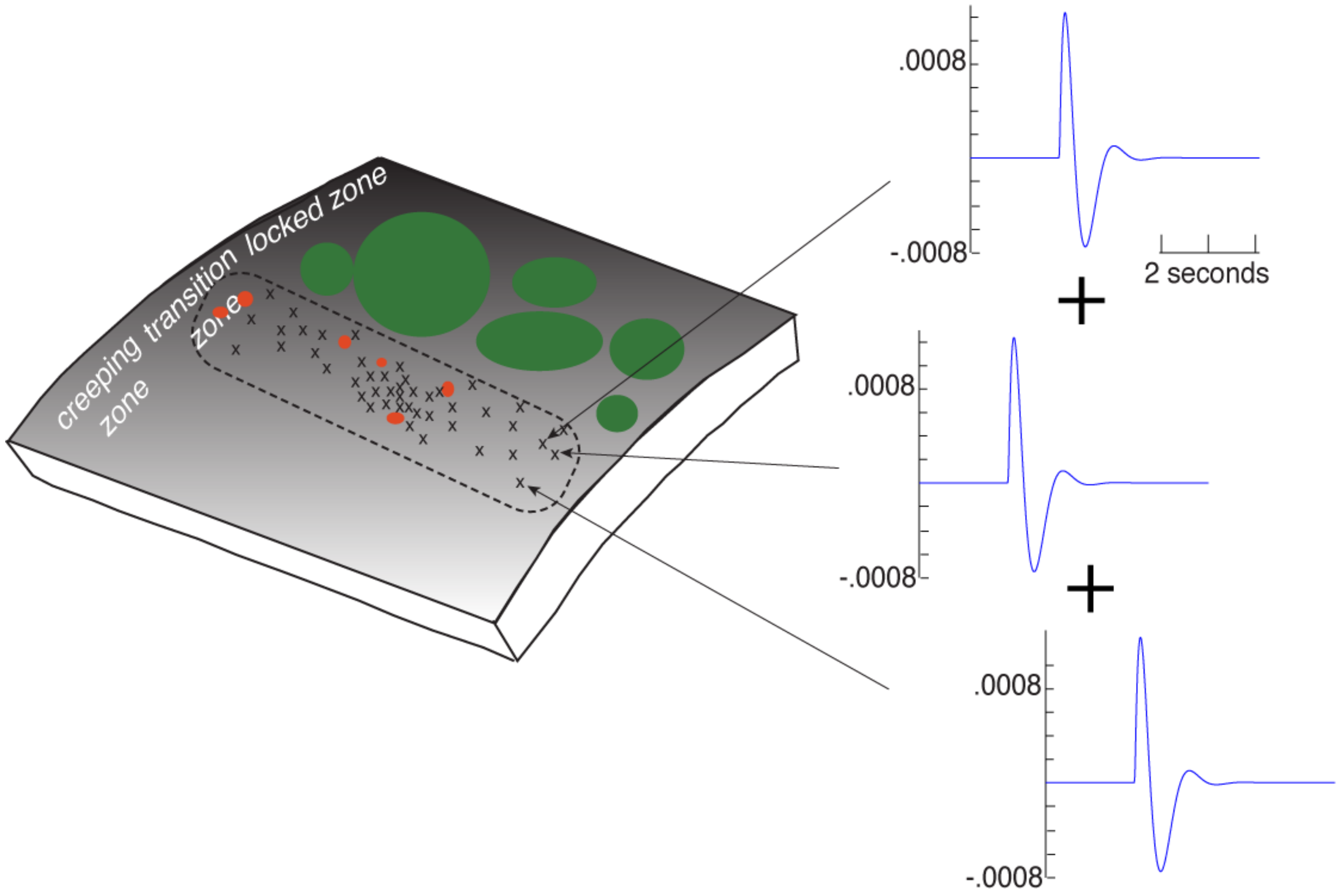
M3-4 VLFs & M1-2 LFE/Tremor



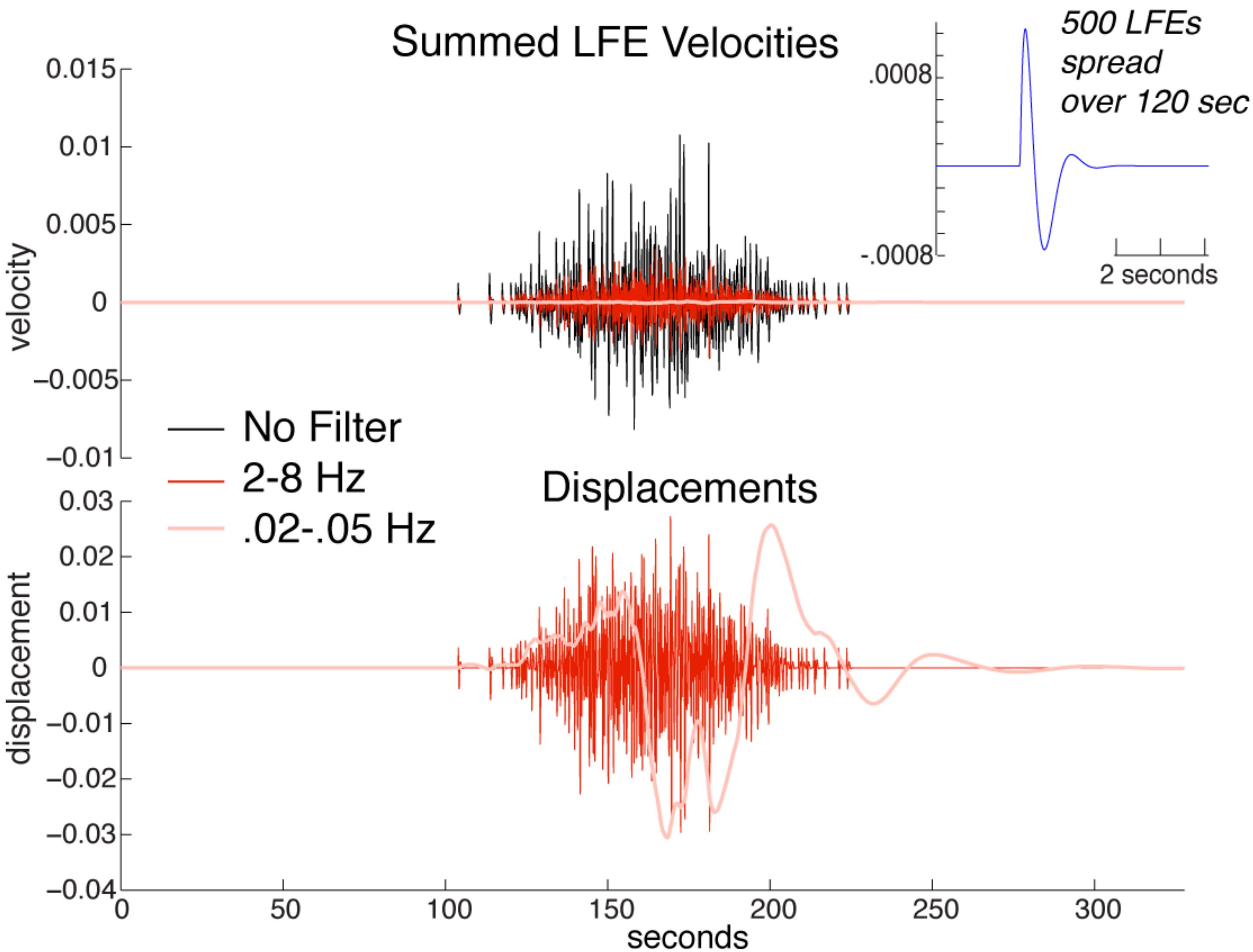


Only M1-2 LFEs,
clustered spatially and/or temporally

Alternative VLF interpretation –summed LFEs? Synthetic example.



Alternative VLF interpretation –summed LFEs? Synthetic example.

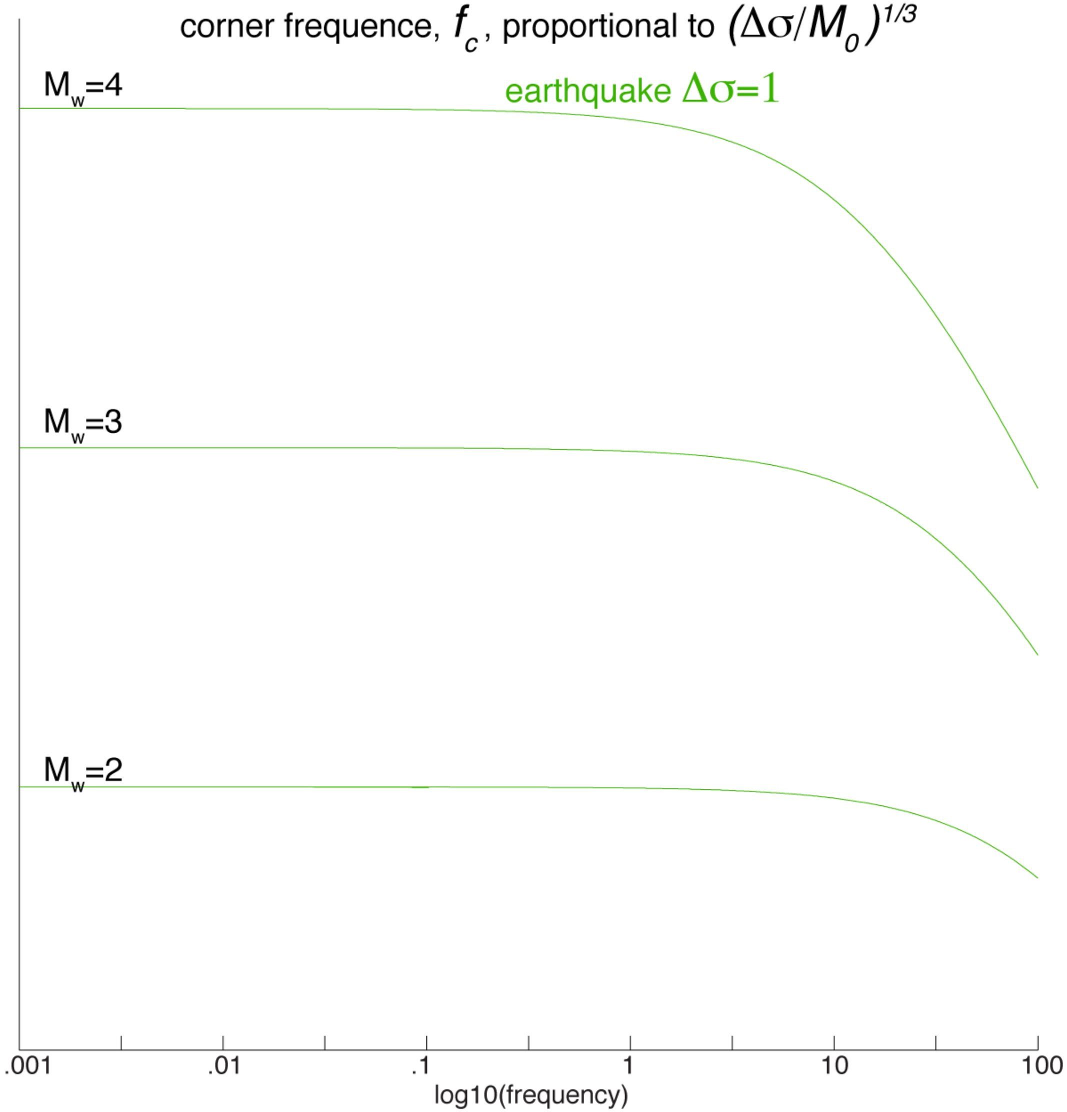


Quick Primer on Source Spectral Scaling

Spectral Scaling

spectral amplitude = $\frac{M_0}{(1+f/f_c)^2}$

corner frequence, f_c, proportional to $(\Delta\sigma/M_0)^{1/3}$

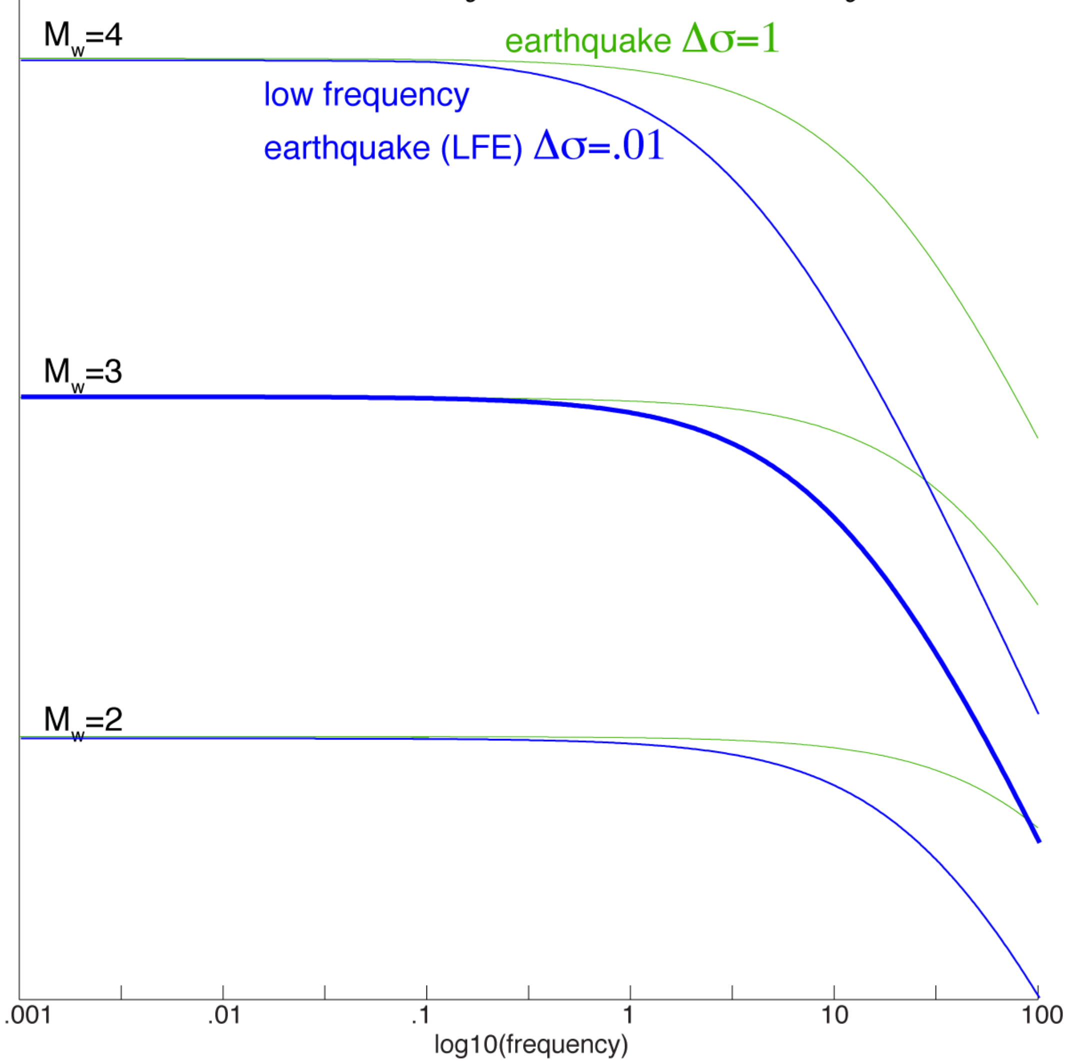


Low frequency events may have low stress drops.

Spectral Scaling

$$\text{spectral amplitude} = \frac{M_0}{(1+f/f_c)^2}$$

corner frequence, f_c, proportional to $(\Delta\sigma/M_0)^{1/3}$

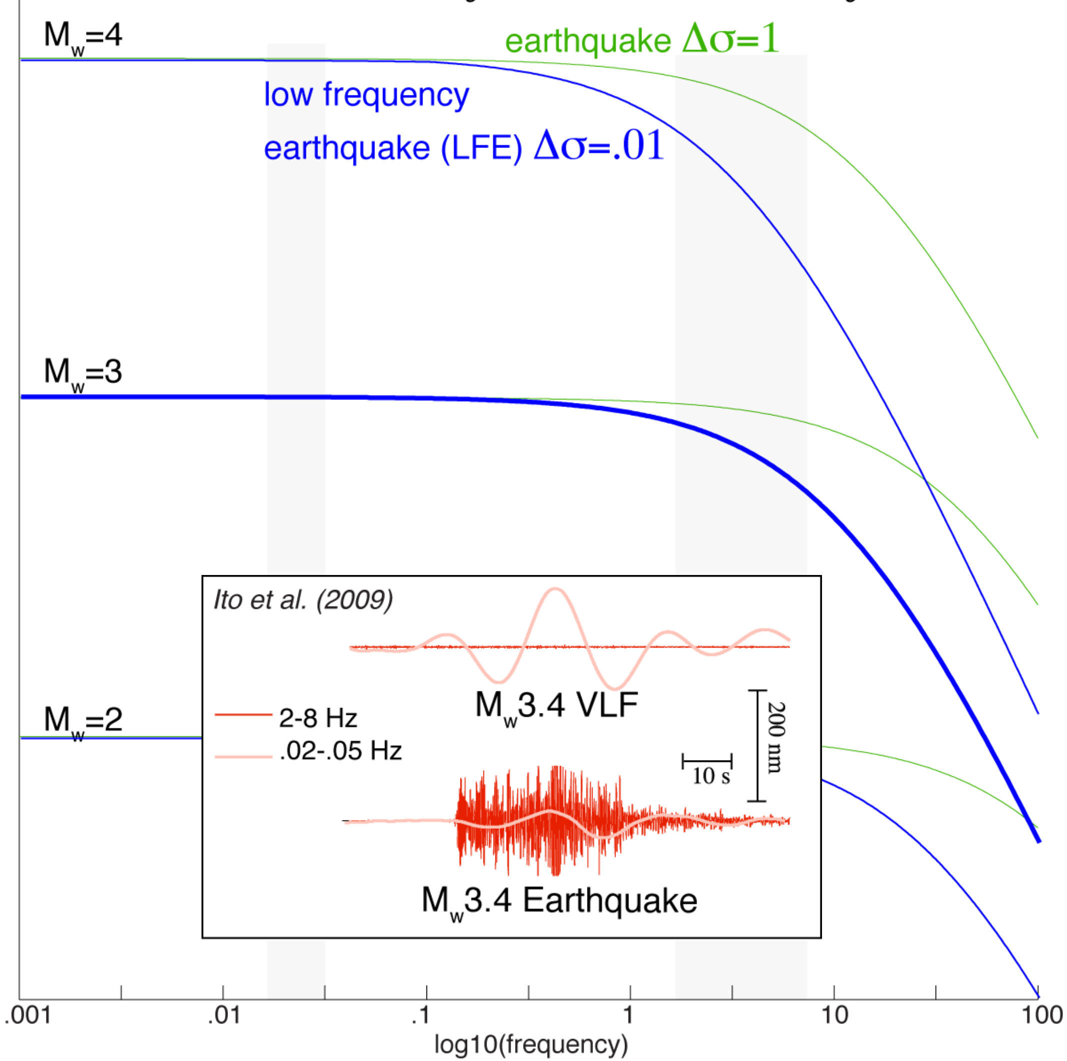


Explains comparisons of VLFs & LFEs with earthquakes.

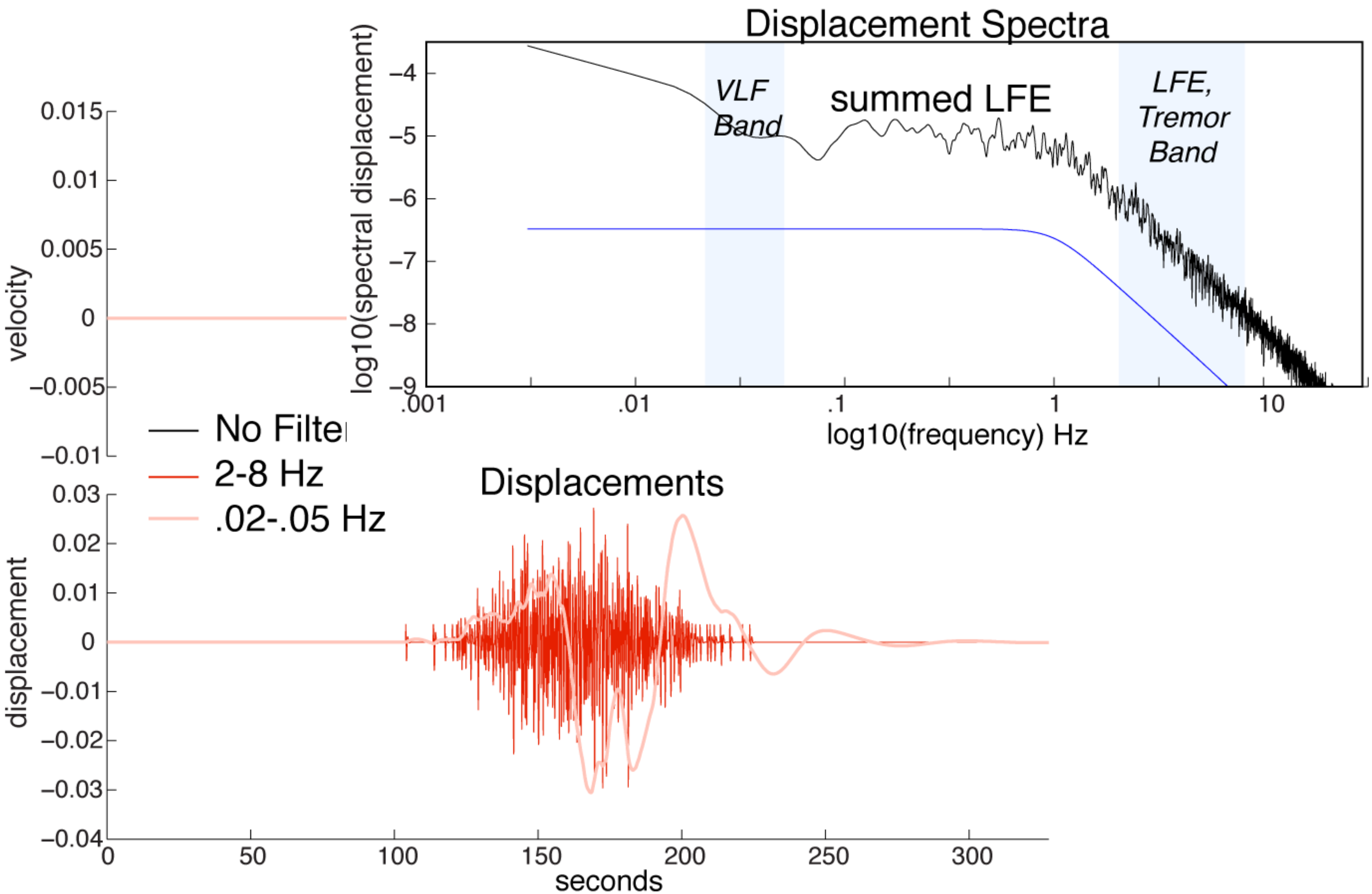
Spectral Scaling

$$\text{spectral amplitude} = \frac{M_0}{(1+f/f_c)^2}$$

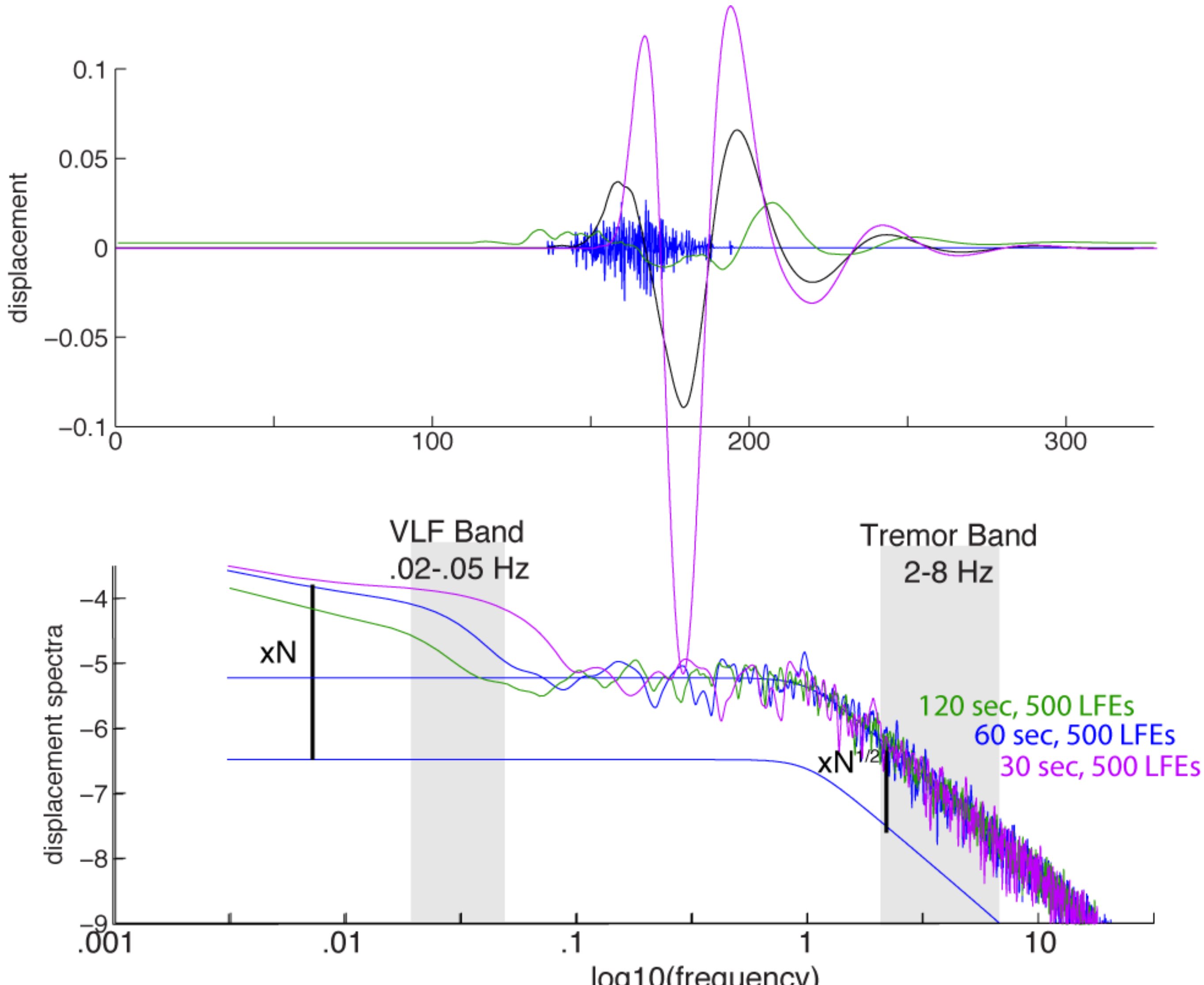
corner frequence, f_c, proportional to $(\Delta\sigma/M_0)^{1/3}$



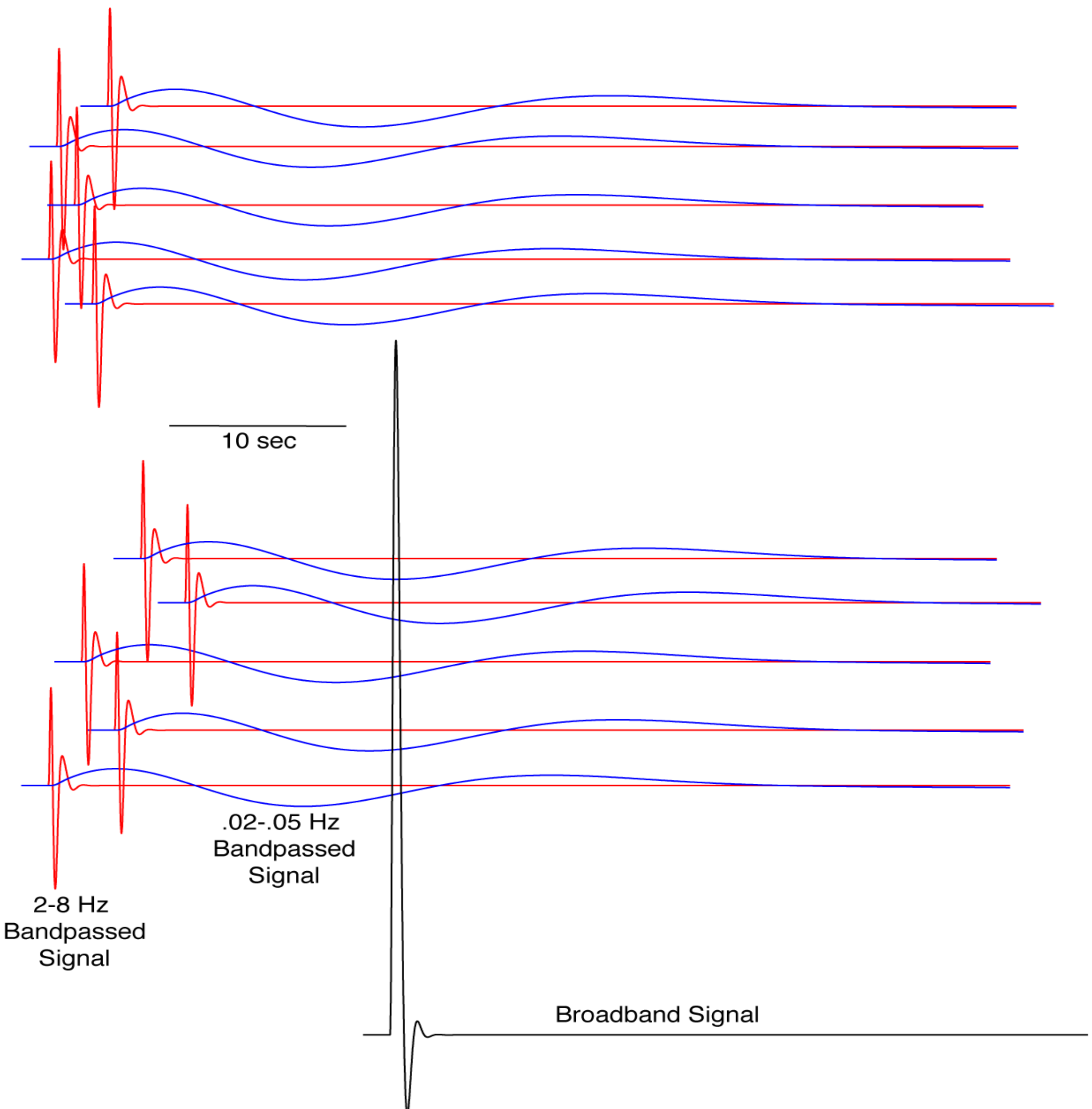
Summed LFEs = larger VLF, almost…



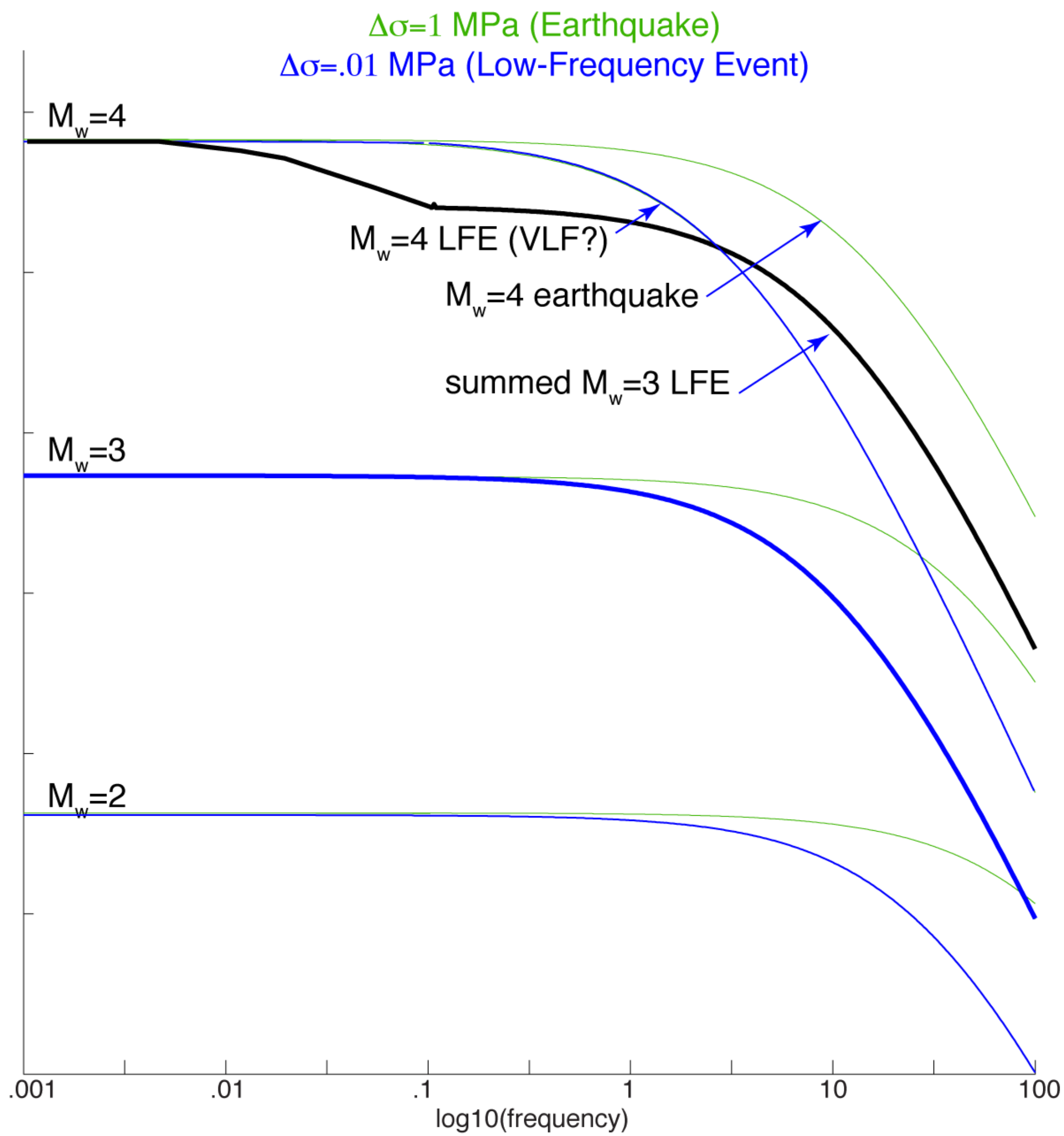
The more clustered LFEs are, the more coherently low frequencies add (sum ~linearly). High frequencies always add incoherently(sum as sqrt(N)).



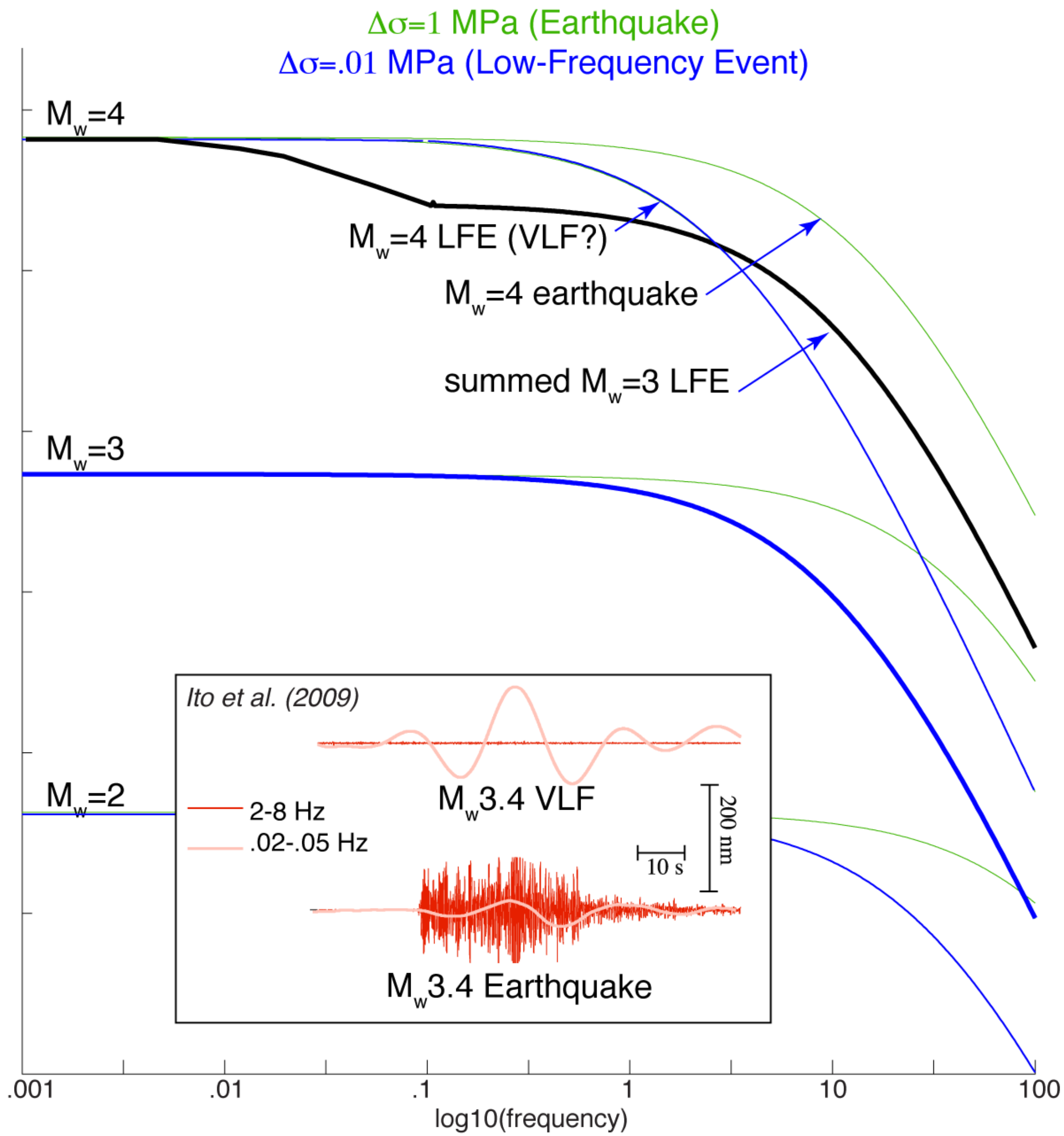
The more clustered LFEs are, the more coherently low frequencies add (sum ~linearly). High frequencies always add incoherently(sum as sqrt(N)).



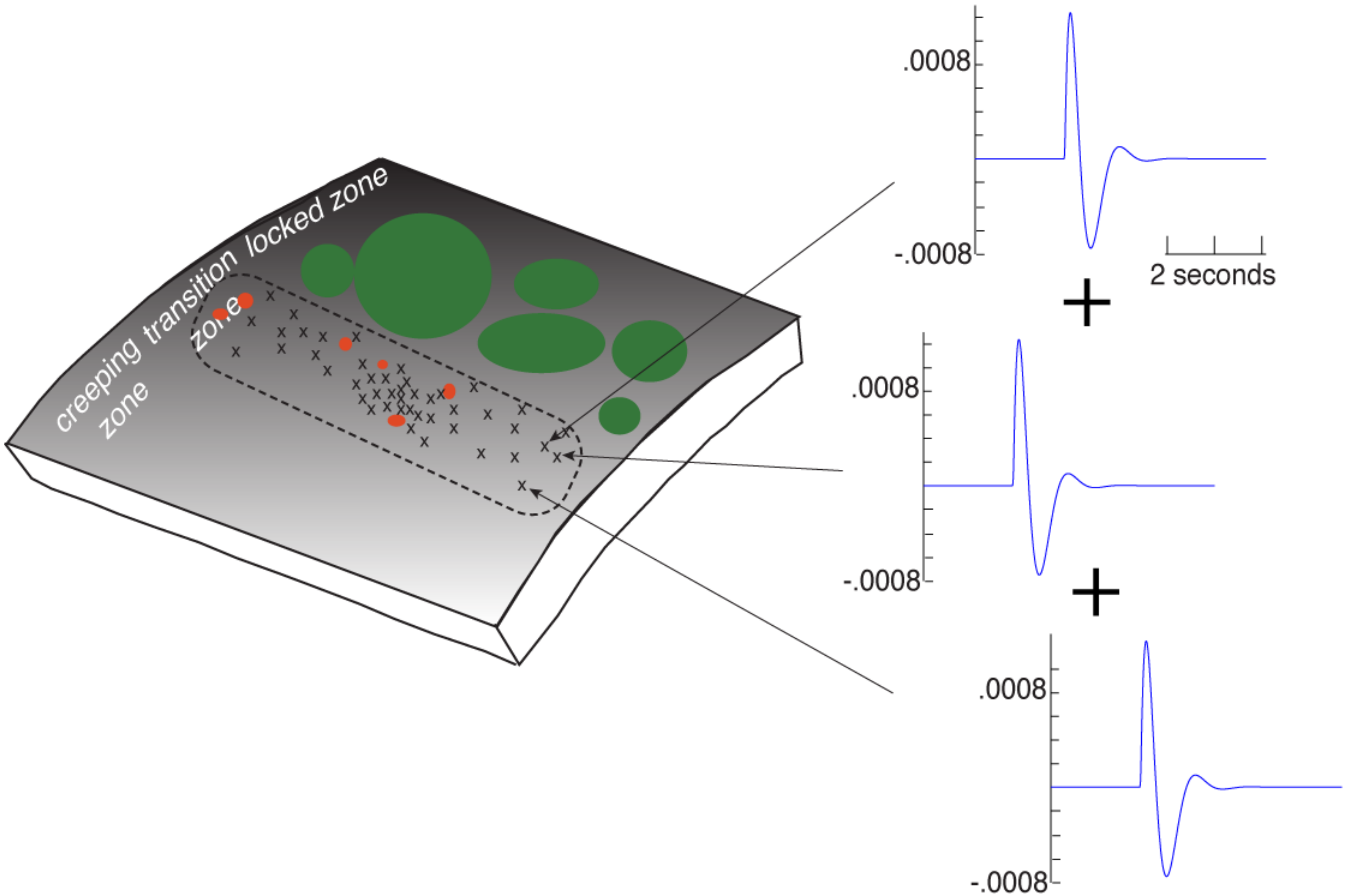
Summed LFEs = larger VLF, almost… *has excess high frequencies*



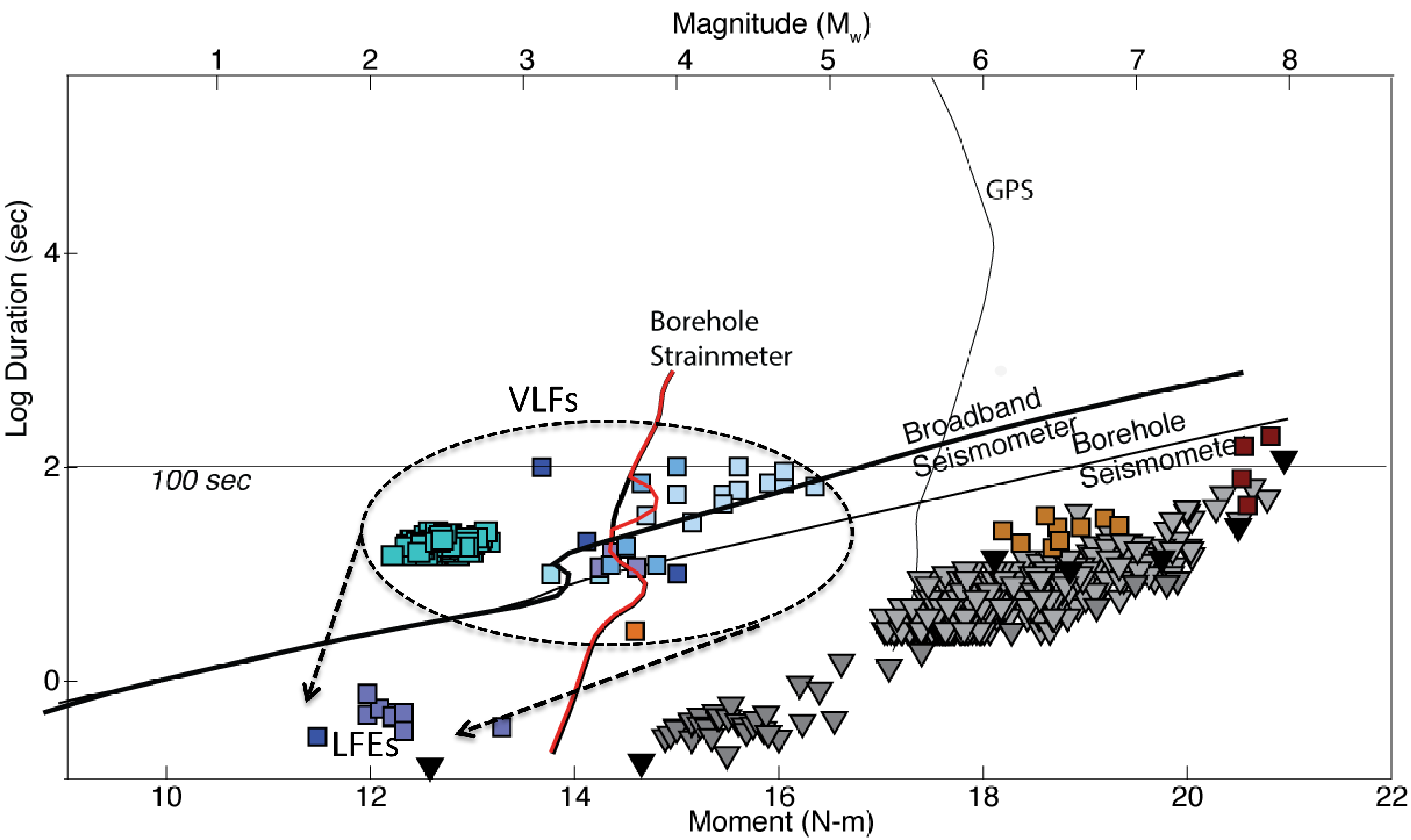
Summed LFEs = larger VLF, almost… has excess high frequencies *but still less than an earthquake*.



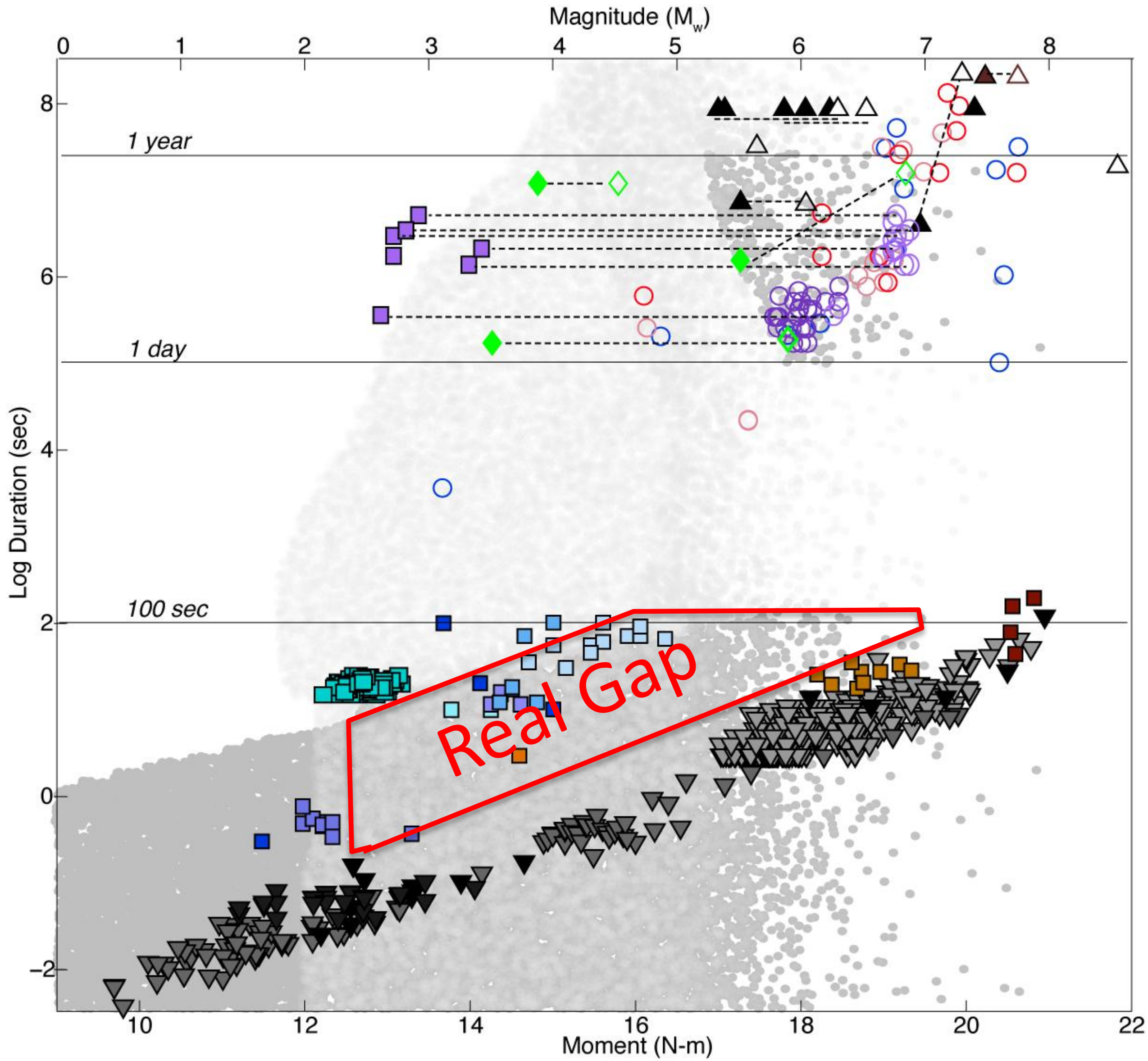
VLFs may just be tremor 'bursts', comprised of clusters of randomly summed LFEs



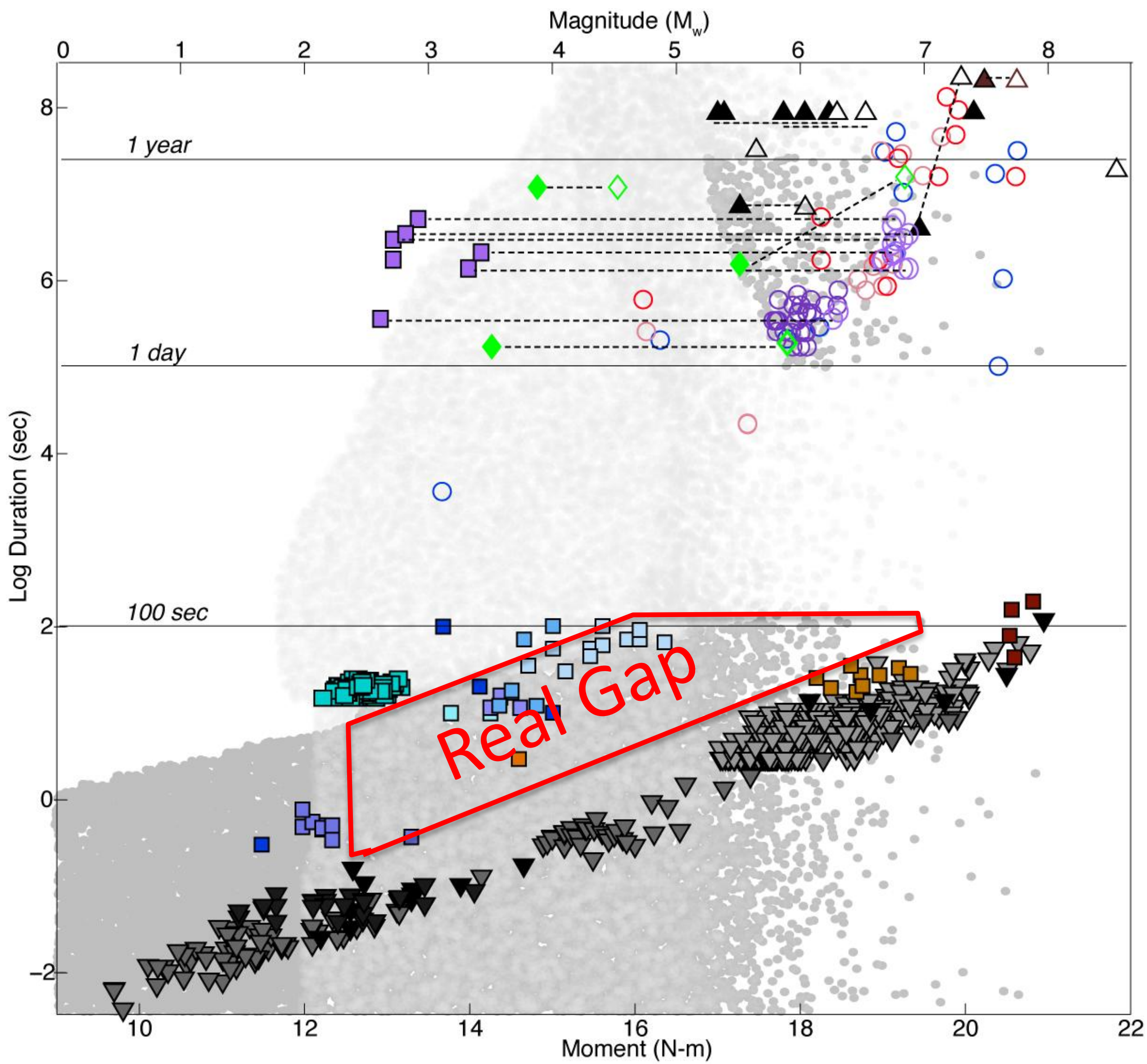
Consider how you interpret what you're measuring!



What we 'see' may just reflect our observational windows. We need bigger windows before making scaling inferences.



New measurement types may open new windows. We also need to uniquely determine what's being measured!



Thank you!