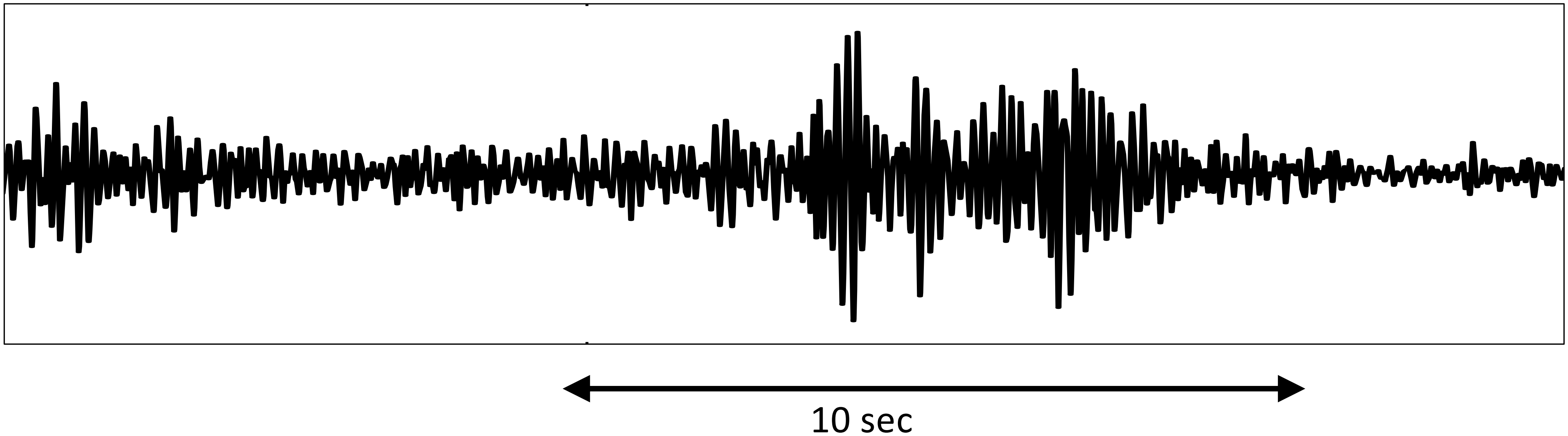
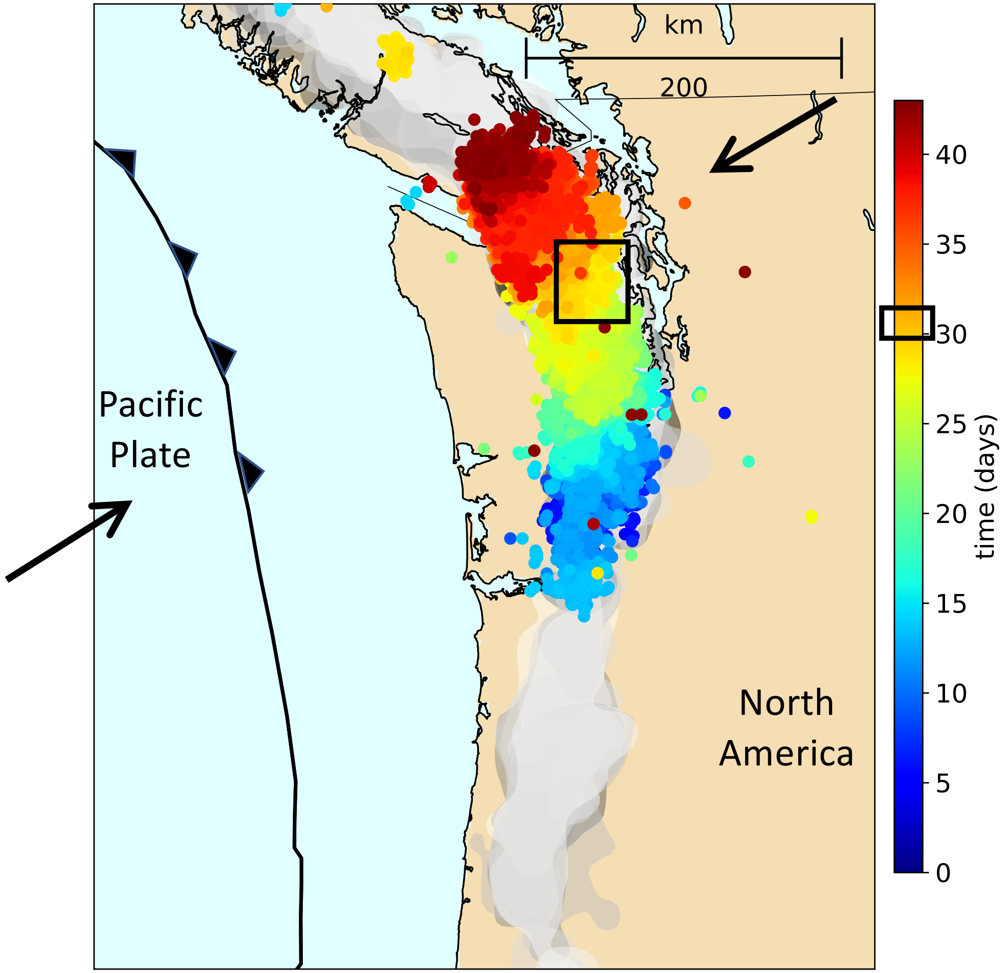
Probing the properties of seismic tremor

Jessica Hawthorne (Oxford)



Tremor: tracked in real time



Houston et al, 2011;
Obara et al, 2010

Wech et al, 2009

Millions of tiny earthquakes: LFEs

Ideally, want to

- Use them to learn about subduction
- Use them to learn about hazard

But first, need to

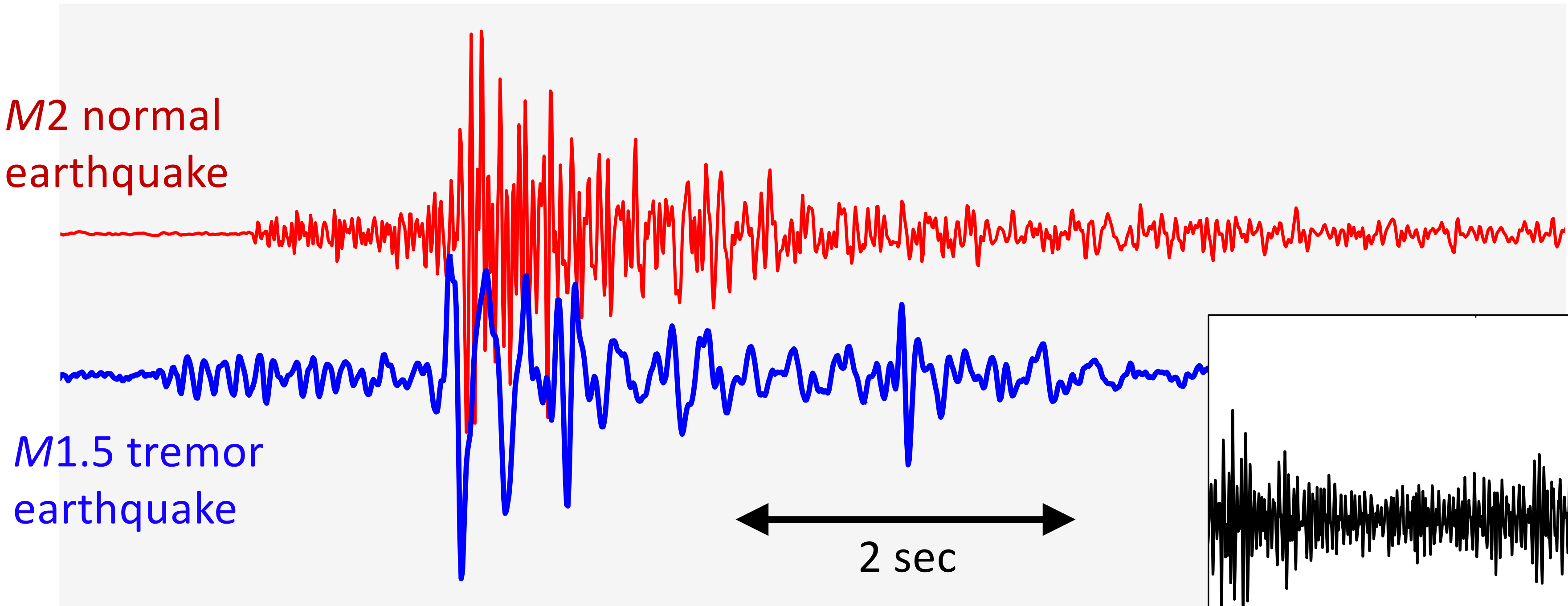
- Understand what LFEs are: why they're slow

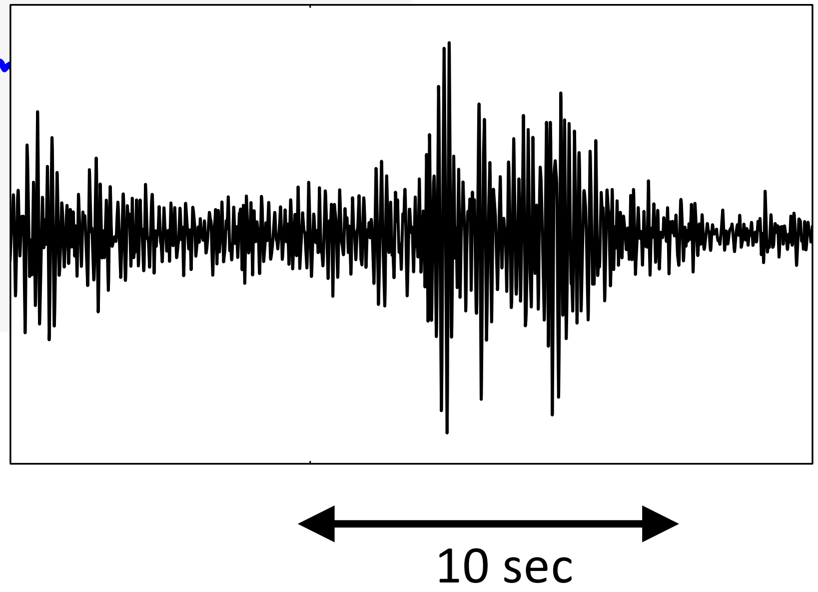
Tremor was first observed >20 years ago

Obara, 2002

- *Why don't we know what it is yet?*

Tremor: composed of numerous overlapping low frequency earthquakes





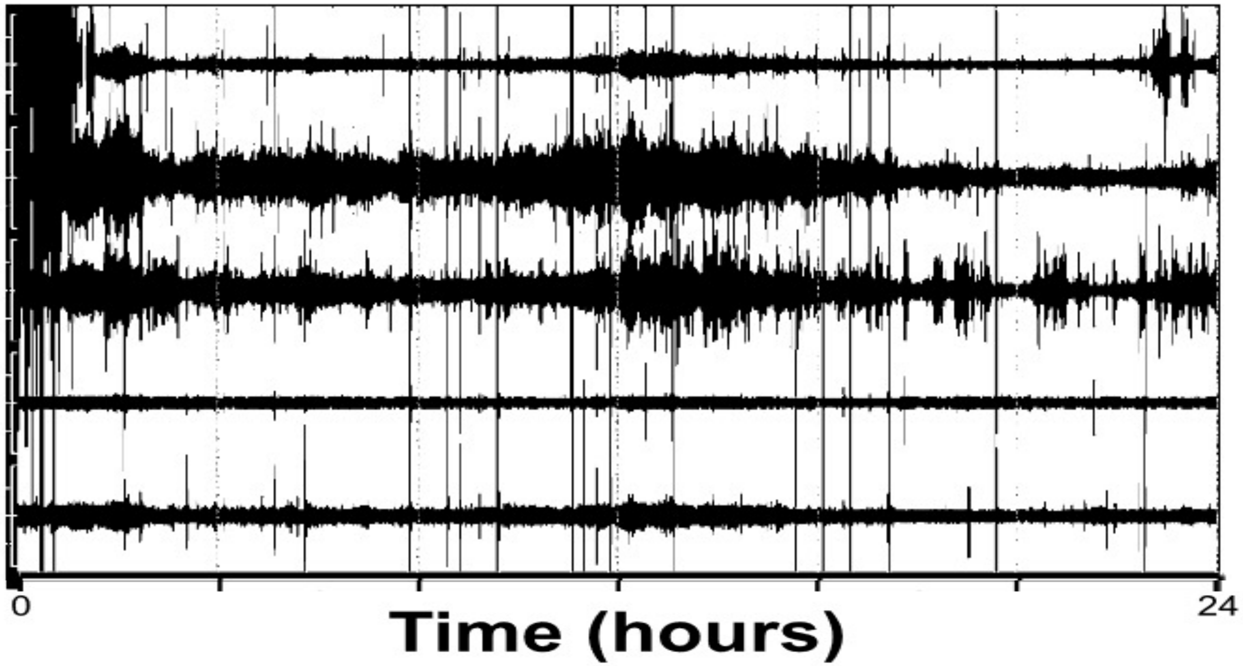
Tremor earthquakes, or low frequency earthquakes

- Often occur in clusters to form a tremor-like seismogram
- All small: M 1 – 2.5
- May be part of a spectrum of slow earthquakes

Outline

- Detecting and locating tremor
  - Envelopes
  - LFEs
  - Inter-station
  - Coherence
- Tremor energy
- LFE moment and duration
- LFE rupture extent
- More moment-duration scaling
- Focal mechanisms

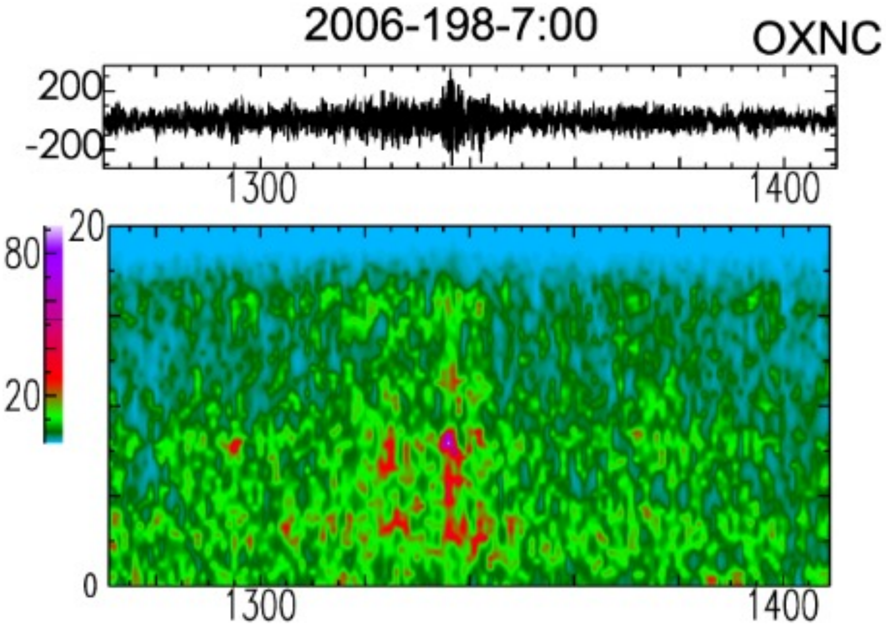
Tremor in Oaxaca, Mexico

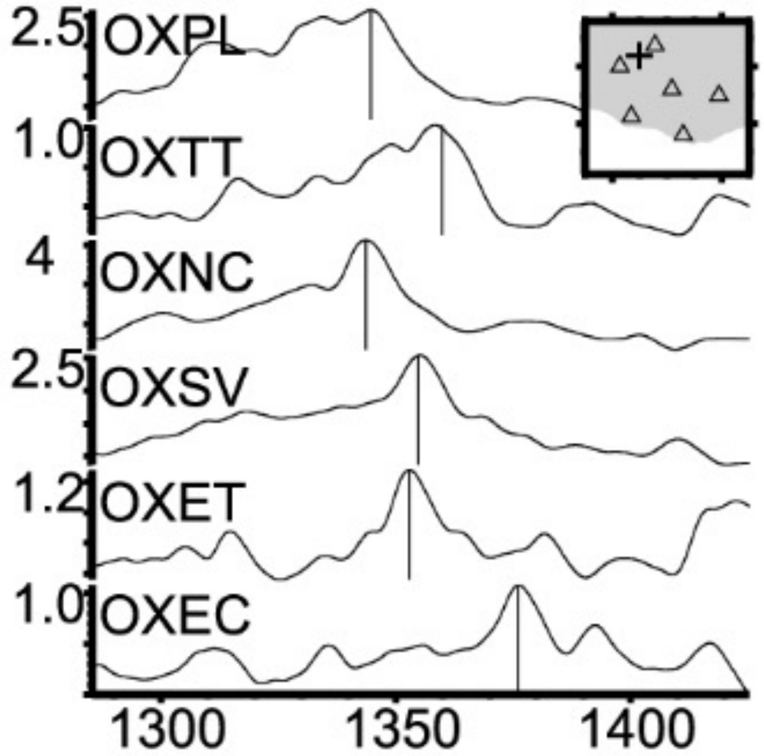


Brudzinski et al, 2010

Motivation: Must understand the nuances of the observations in order to develop (1) testable models and (2) new tests of the models.

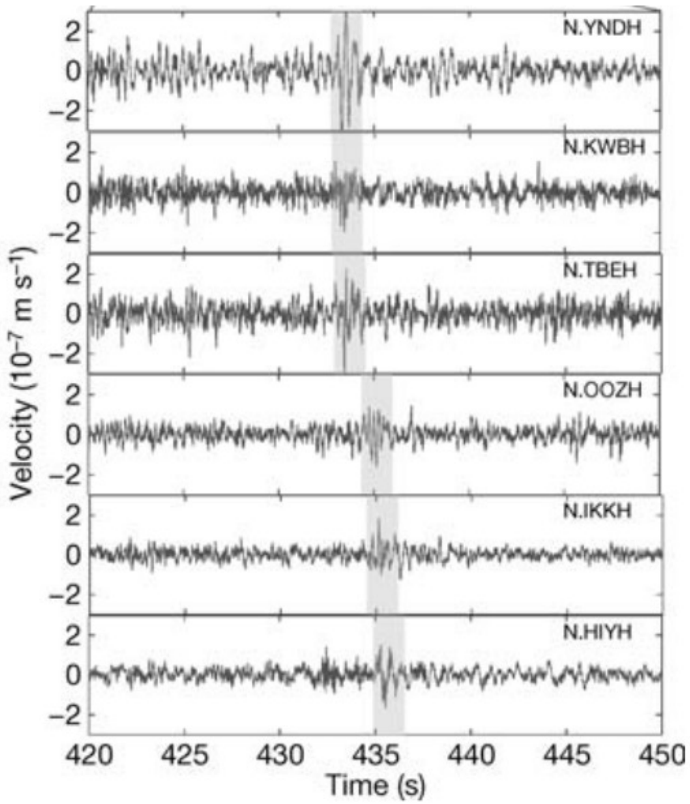
Envelope correlation



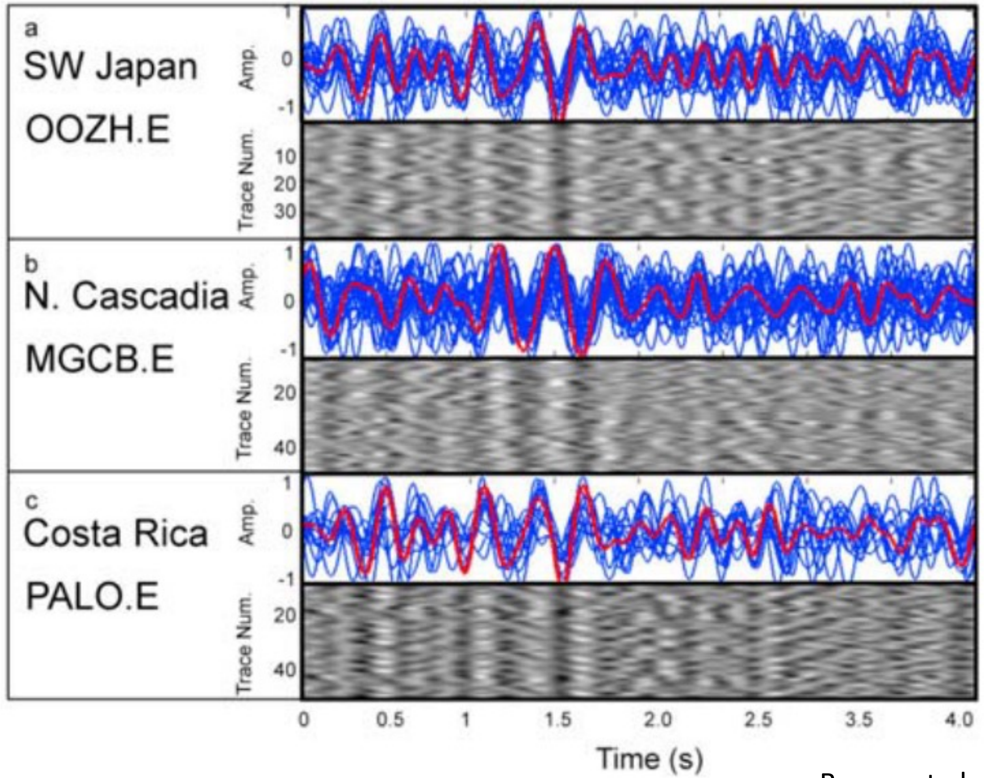


Compute envelope of bandpassed filtered seismograms (here 2-5 Hz).
Find location required to align envelopes at all stations.

Low frequency earthquake (LFE) matching



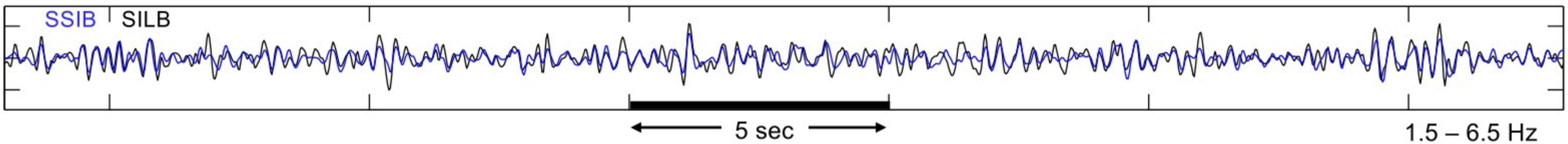
Shelly et al, 2006



Brown et al, 2009

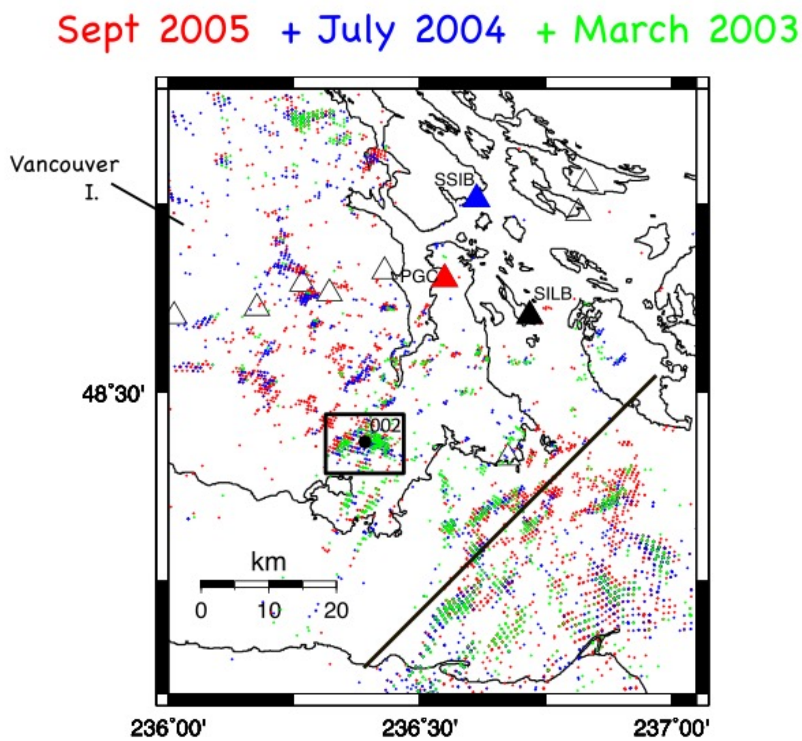
Identify individual LFEs within seismograms and search for more.
Stack, then search again.

Cross-station comparison



- Identify intervals with similar signals at several stations
- Determine time shifts and location for each interval

Some highly tremorgenic patches



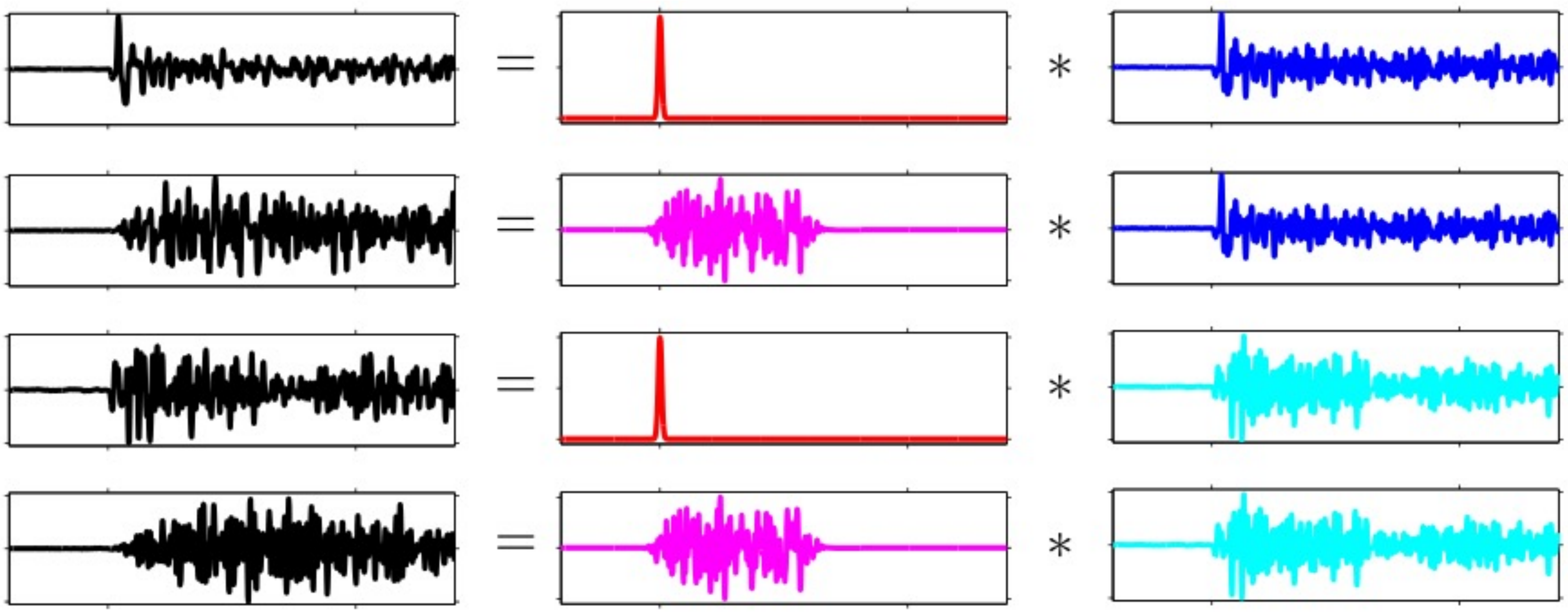
Armbruster et al, 2014

Inter-station coherence

- Compare with a template Green's function, as in LFE matching
- But also compare between stations, to compare tremor source time functions

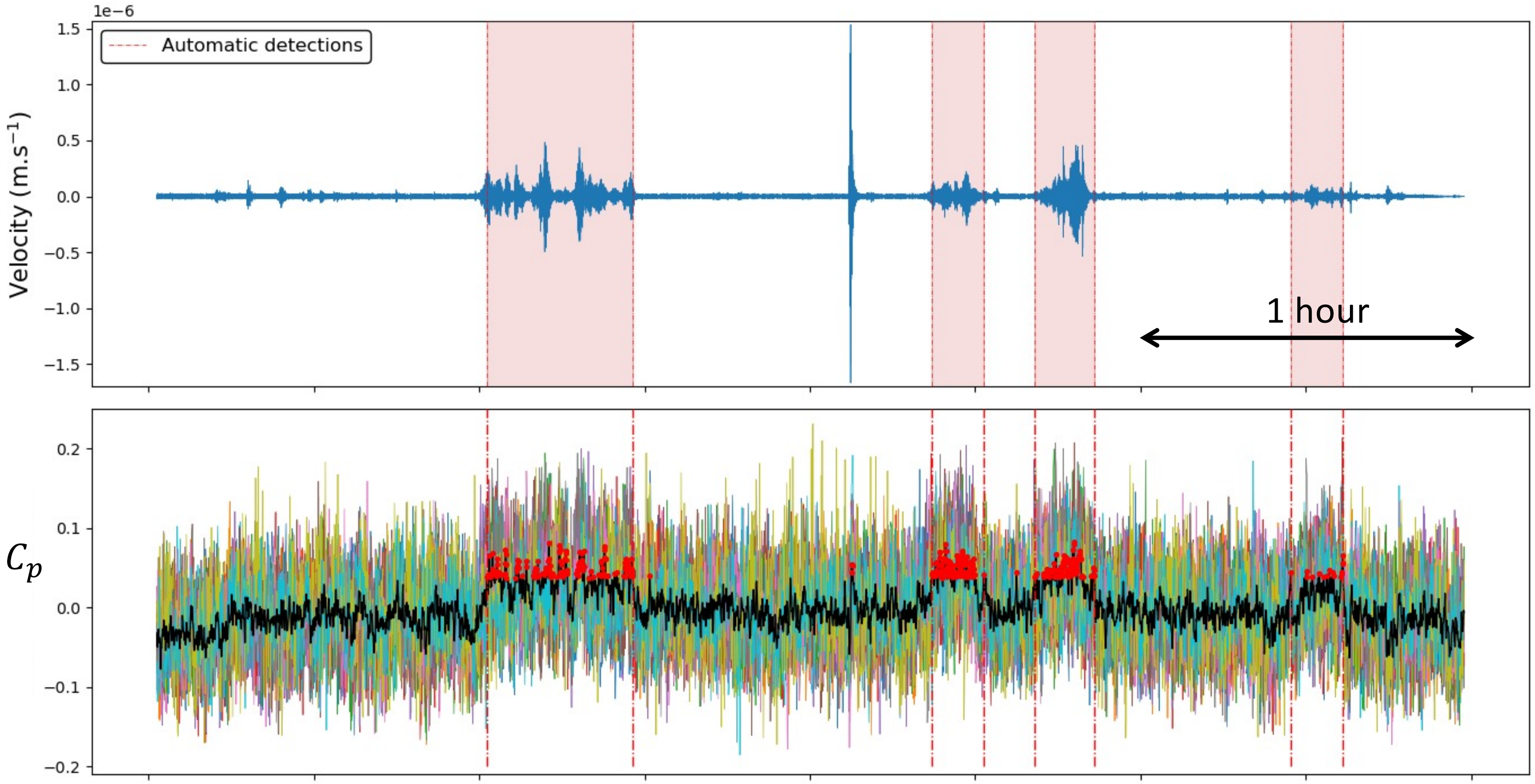
template and
tremor at station 1

template and
tremor at station 2

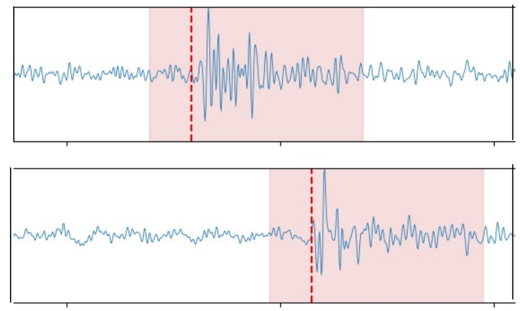


4 observations, 4 unknowns → can identify signals from the same source

Few-minute tremor bursts offshore Costa Rica



Identify the tremor times using local earthquakes as templates.



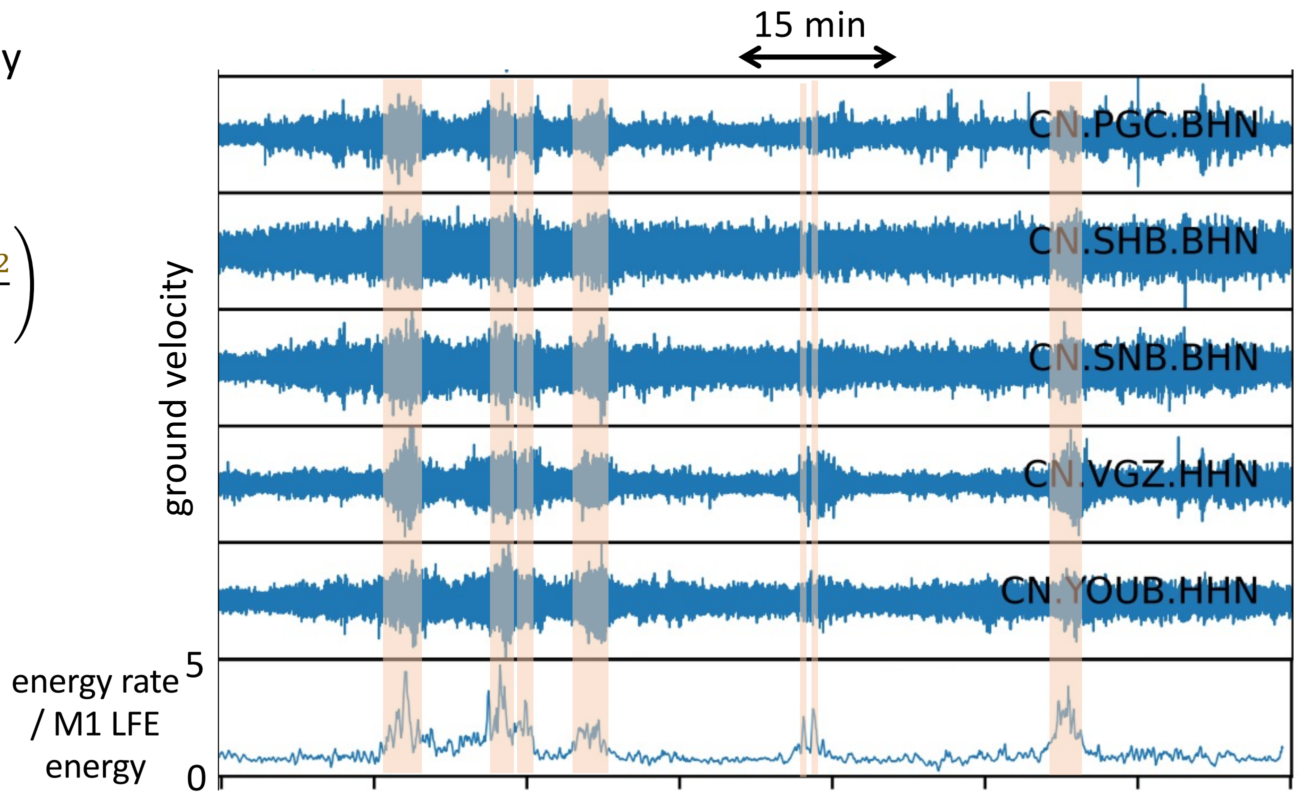
$$C_p = Re\left(\frac{\hat{d}_{template,\ component\ 1}\hat{d}^*_{tremor,\ component\ 1}\hat{d}_{template,\ component\ 2}\hat{d}^*_{tremor,\ component\ 2}}{\left|\hat{d}_{template,\ component\ 1}\hat{d}^*_{tremor,\ component1}\hat{d}_{template,\ component\ 2}\hat{d}^*_{tremor,\ component\ 2}\right|}\right)$$

by Julien Renou

Tremor energy

Similar approach to coherence, but only normalize by the template

$$E_c = Re\left(\frac{\hat{d}_{temp,1}\hat{d}^*{}_{trem,1}\hat{d}_{temp,2}\hat{d}^*{}_{trem,2}}{\left|\hat{d}_{temp,\,1}\hat{d}_{temp,\,2}\right|^2}\right)$$
$$= Re\left(\frac{\left|\hat{s}^*{}_{trem,1}\hat{s}^*{}_{trem,2}\right|}{\left|\hat{s}_{temp,\,1}\hat{s}_{temp,\,2}\right|}\right)$$
$$= Re\left(\frac{\left|\hat{s}^*{}_{trem,}\right|^2}{\left|\hat{s}_{temp,}\right|^2}\right)$$



Bottom panel: Seismic energy per second, coming from within 10-20 km of a template,
Divided by energy in a M1 LFE

Work by Hui Huang

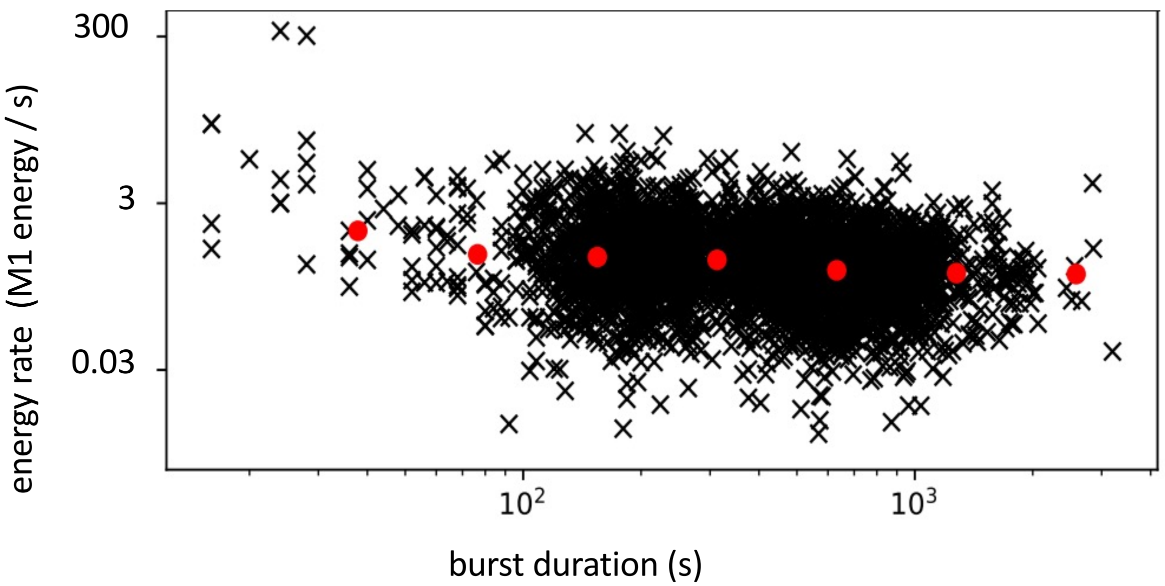
Tremor energy

Similar approach to coherence, but only normalize by the template

$$E_c = Re\left(\frac{\hat{d}_{temp,1}\hat{d}^*{}_{trem,1}\hat{d}_{temp,2}\hat{d}^*{}_{trem,2}}{\left|\hat{d}_{temp,\,1}\hat{d}_{temp,\,2}\right|^2}\right)$$

$$= Re\left(\frac{\left|\hat{s}^*{}_{trem,1}\hat{s}^*{}_{trem,2}\right|}{\left|\hat{s}_{temp,\,1}\hat{s}_{temp,\,2}\right|}\right)$$

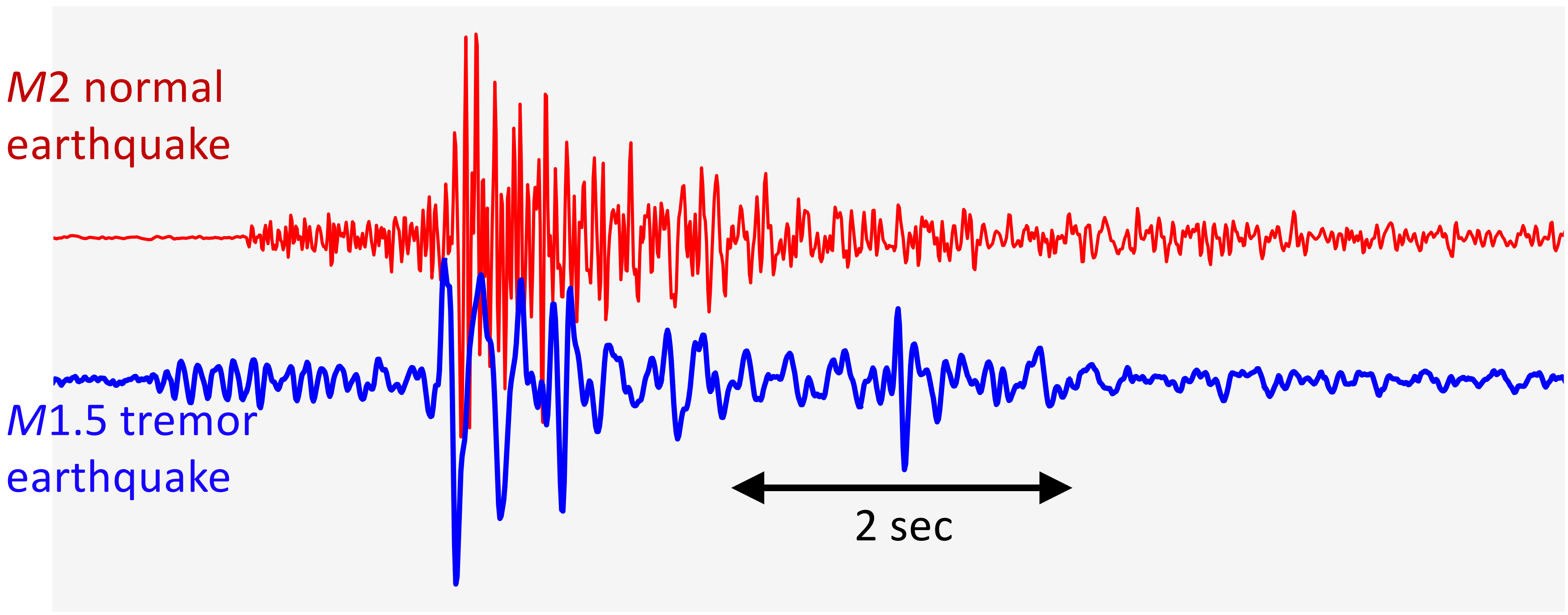
$$= Re\left(\frac{\left|\hat{s}^*{}_{trem,}\right|^2}{\left|\hat{s}_{temp,}\right|^2}\right)$$



- Estimate coherent energy in thousands of few-minute tremor bursts
- If we assume that tremor is composed mostly of M1 LFEs, appear to be about 0.5 LFEs per second
- *Only a few percent of the moment in few-minute slow earthquakes is seismic*

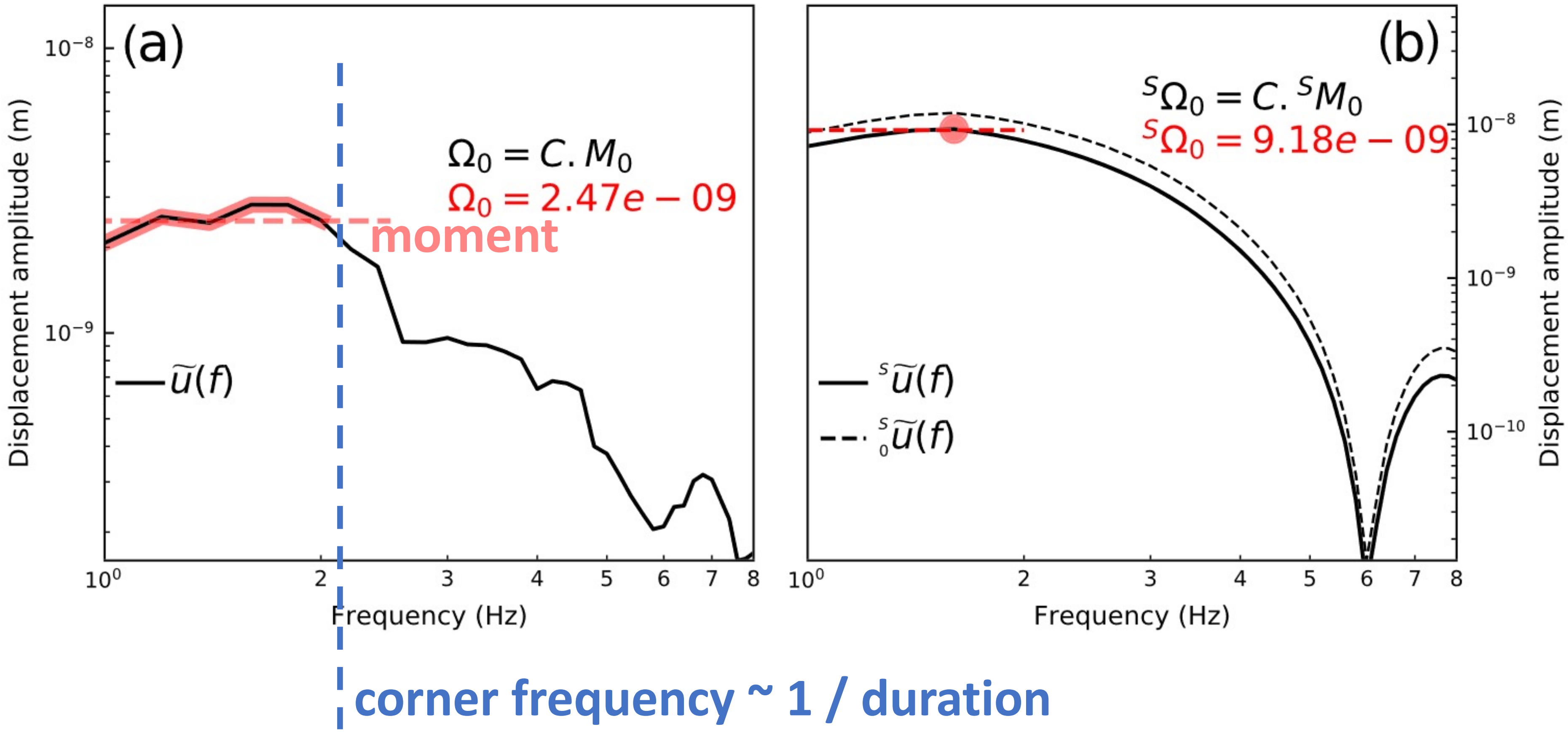
Work by Hui Huang

LFE durations and moments



Which event lasts longer?

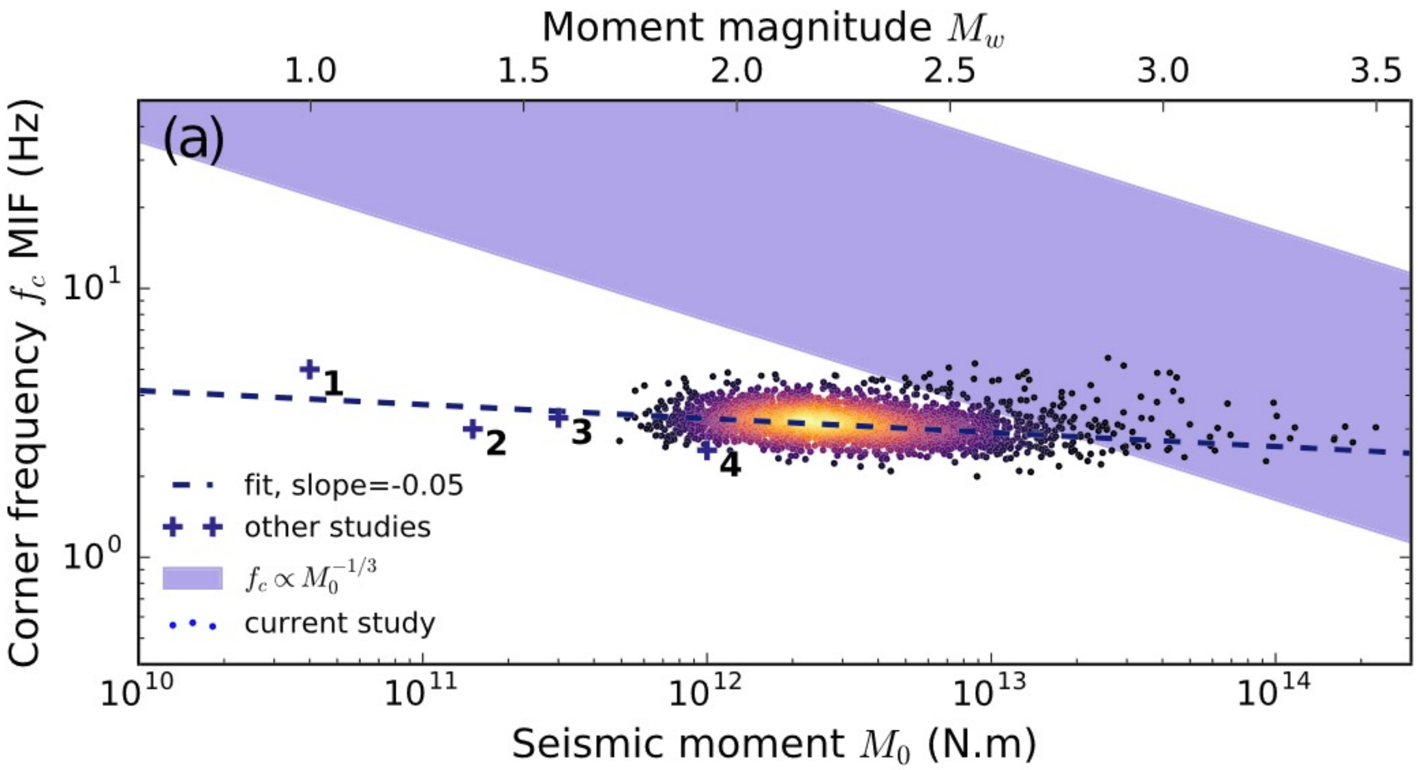
Moments and durations from spectra



corner frequency ~ 1 / duration

Farge et al, 2020

Moments and durations from spectra

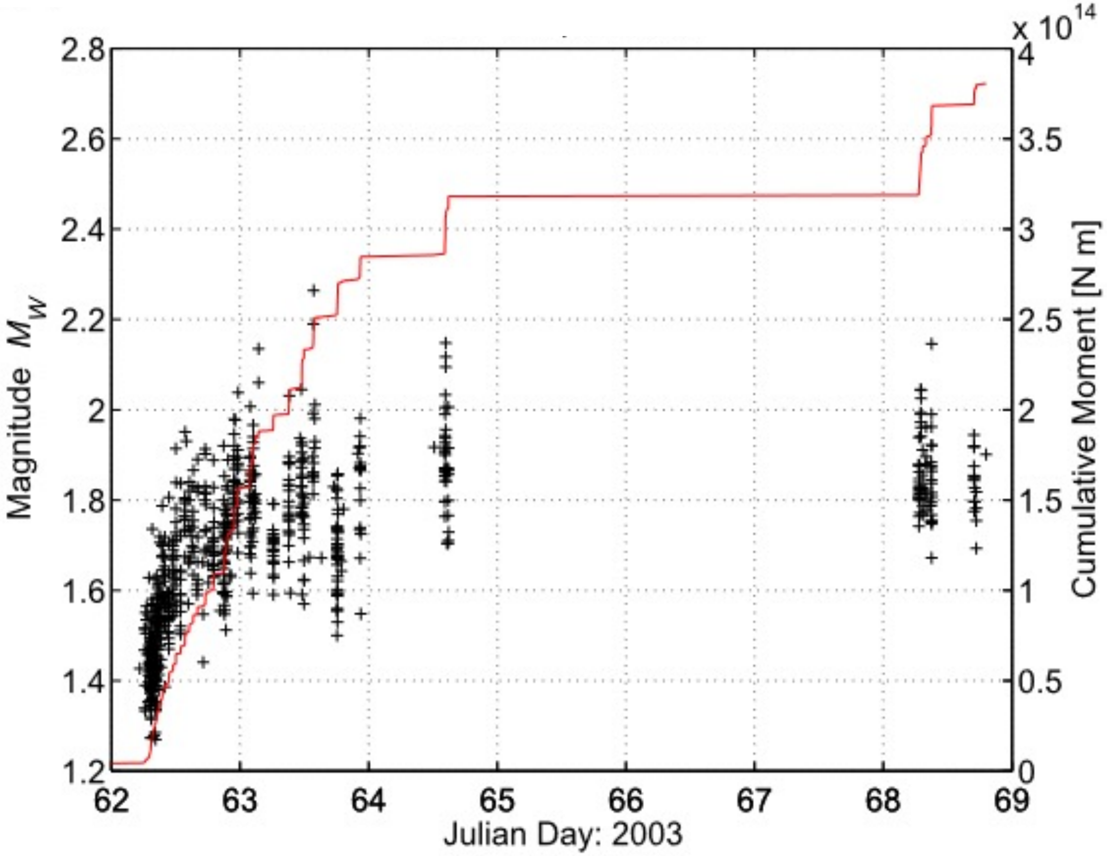


Moment is independent of duration?

→ Tremor has a characteristic duration

Farge et al, 2020

LFE moments through time



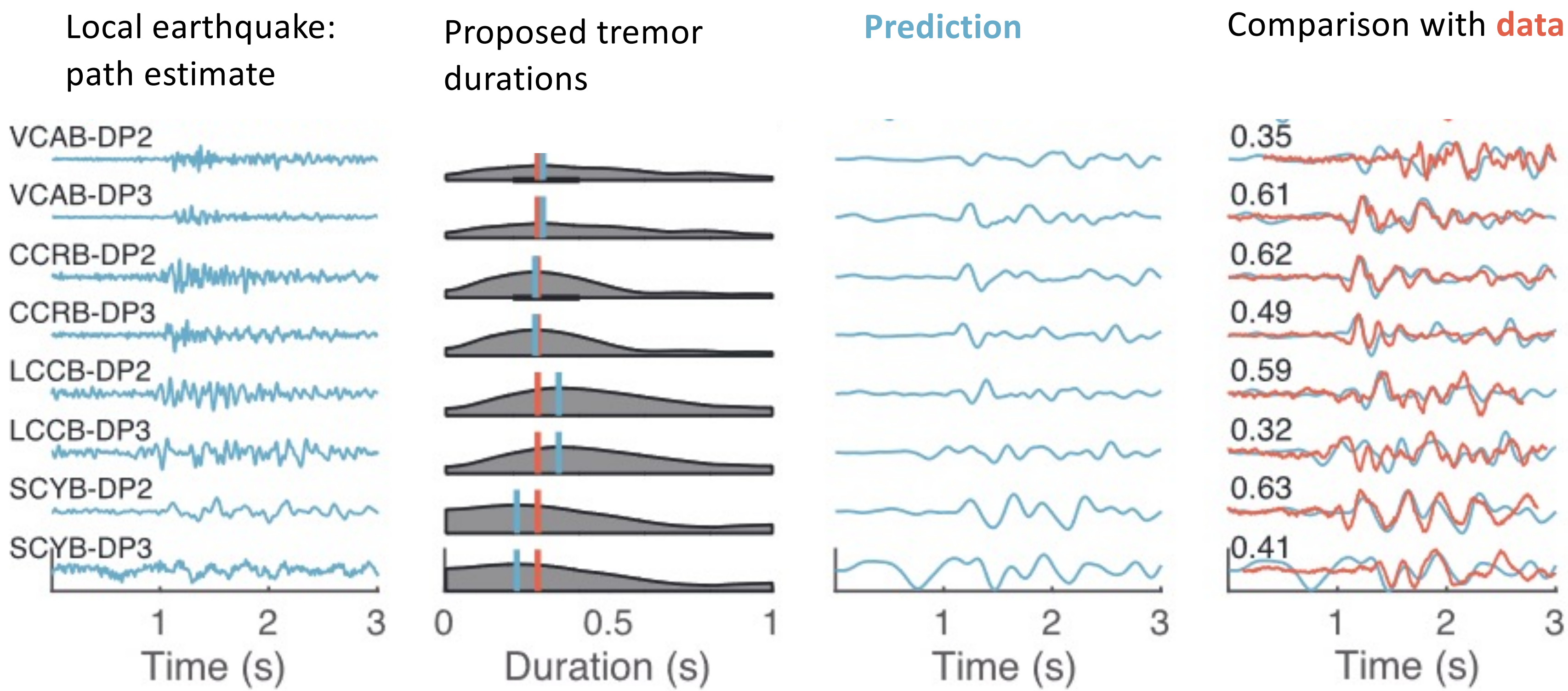
Bostock et al, 2015

Moments at one location through time

- Start small
- But increase as the main front moves farther ahead

→ A change in smoothness or permeability through time?

Durations from grid search with path effect corrections

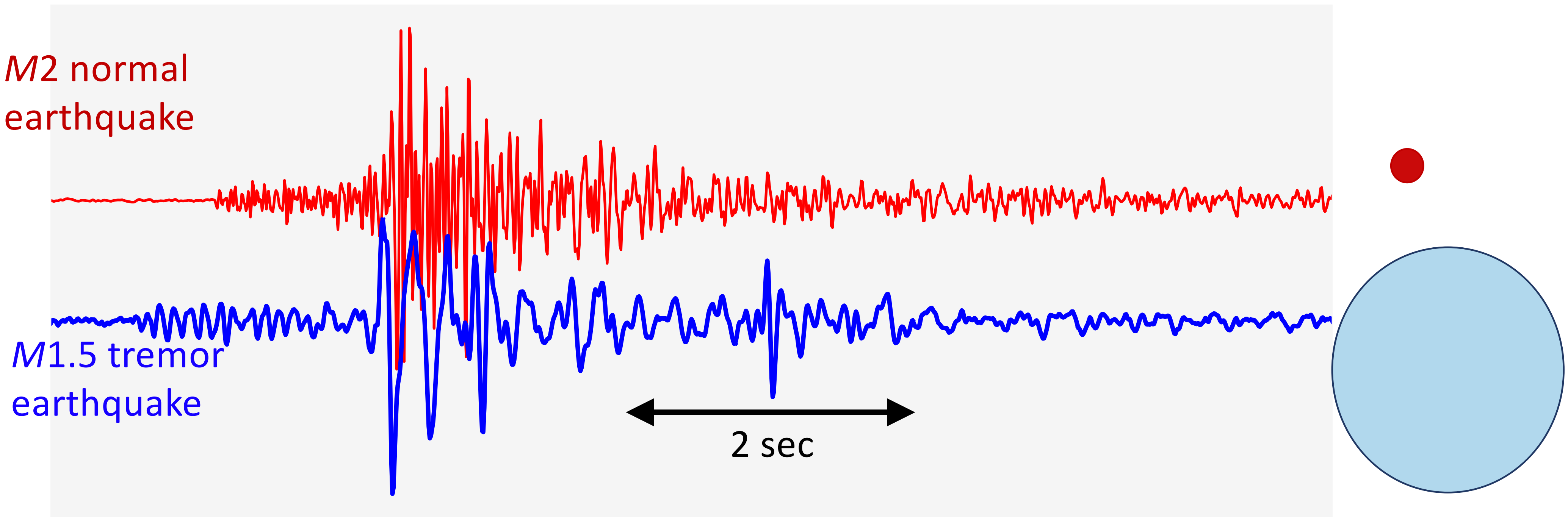


- Use a local earthquake as an estimate of the path effect
- Convolve with proposed source time functions
- Determine which one matches the data

Best-fitting duration here and elsewhere: 0.2 – 0.5 s

Thomas et al, 2016

LFE spatial extents and rupture speeds

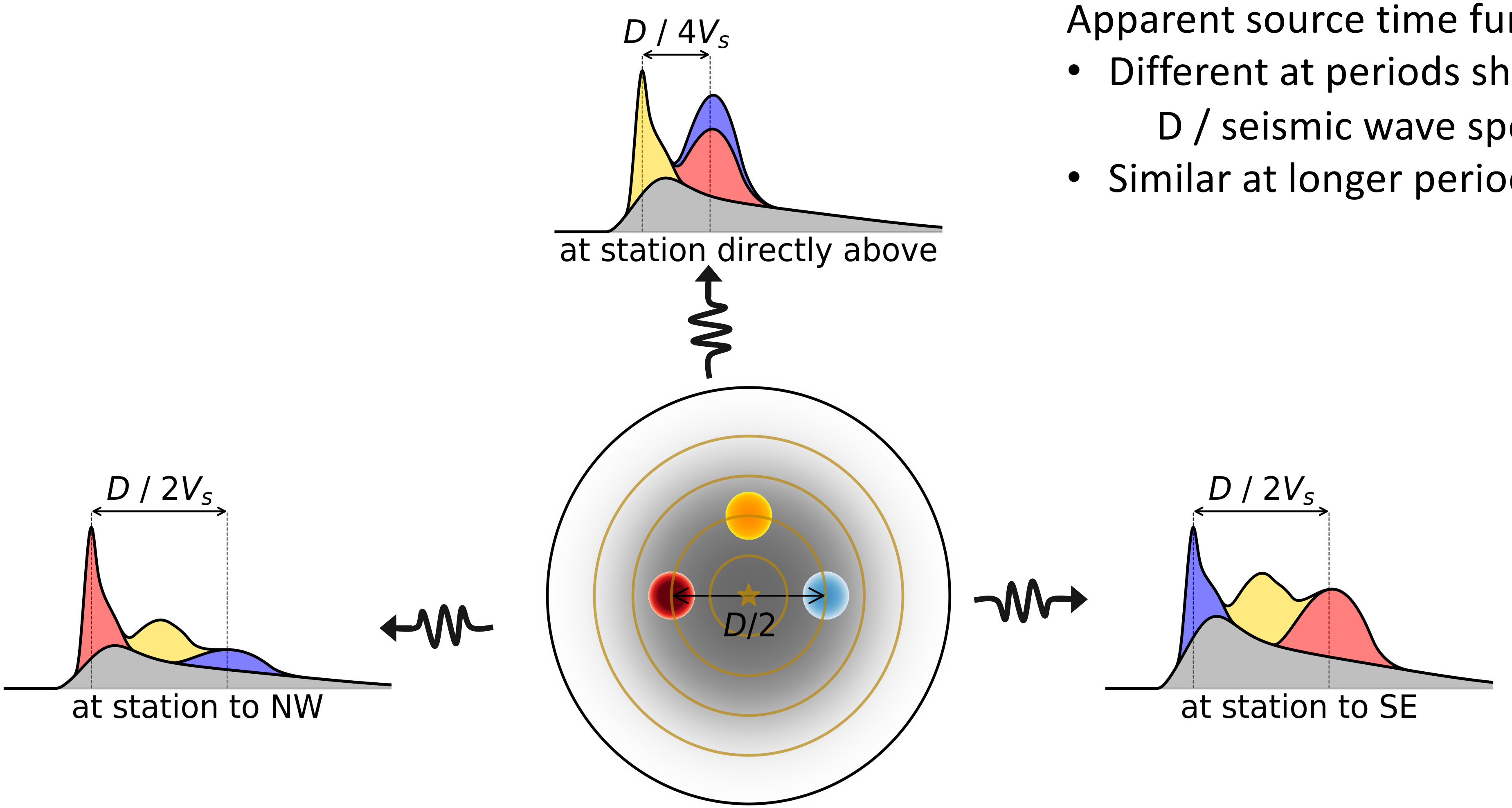


Tremor's earthquakes are long, and create low frequency signals

But are we sure they're slow? Maybe the slip is just spread out.

- Ruptures limited by seismic wave radiation propagate at near shear wave speeds.
- Rupture duration = Width / Propagation speed

To measure the width, look for inter-station differences

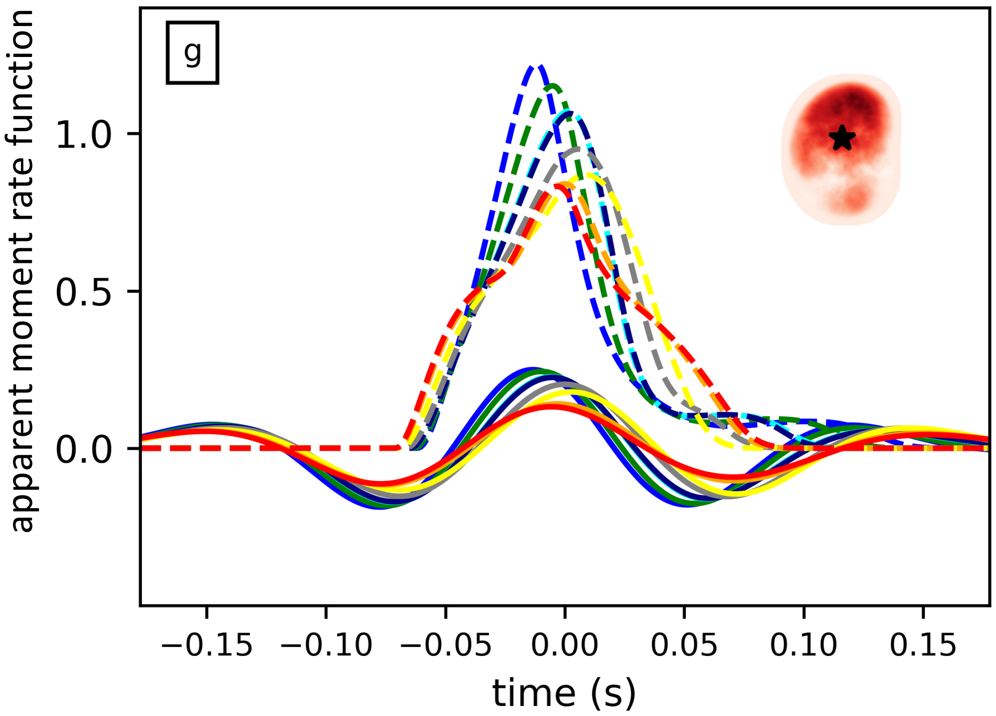


Apparent source time functions s_k

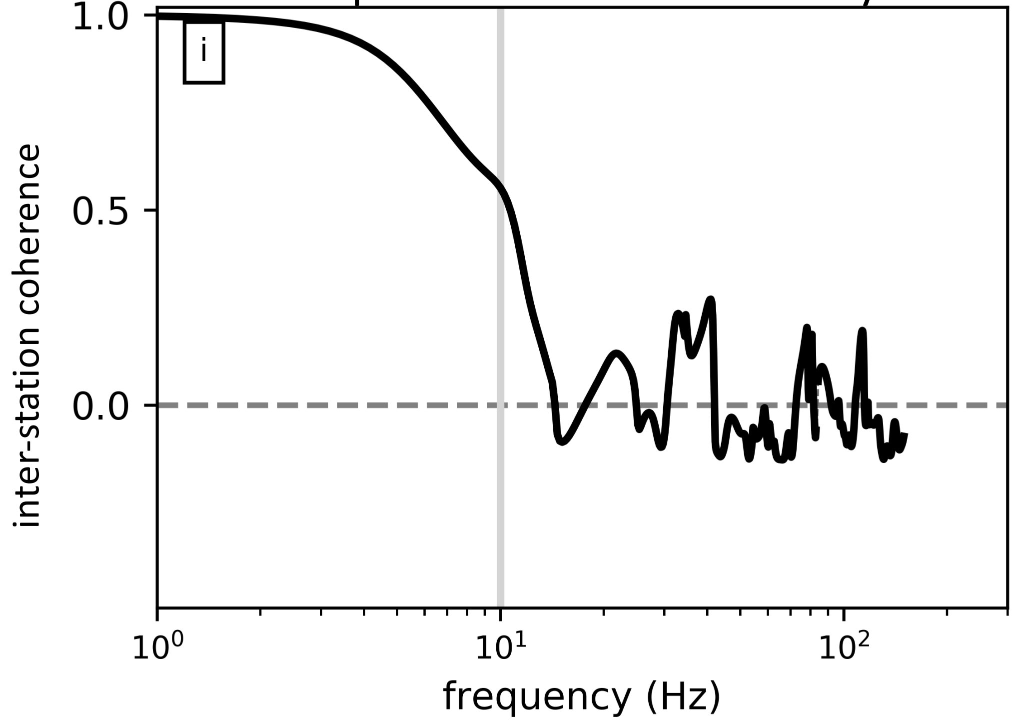
- Different at periods shorter than D / seismic wave speed
- Similar at longer periods

Synthetics for a 600-m wide earthquake

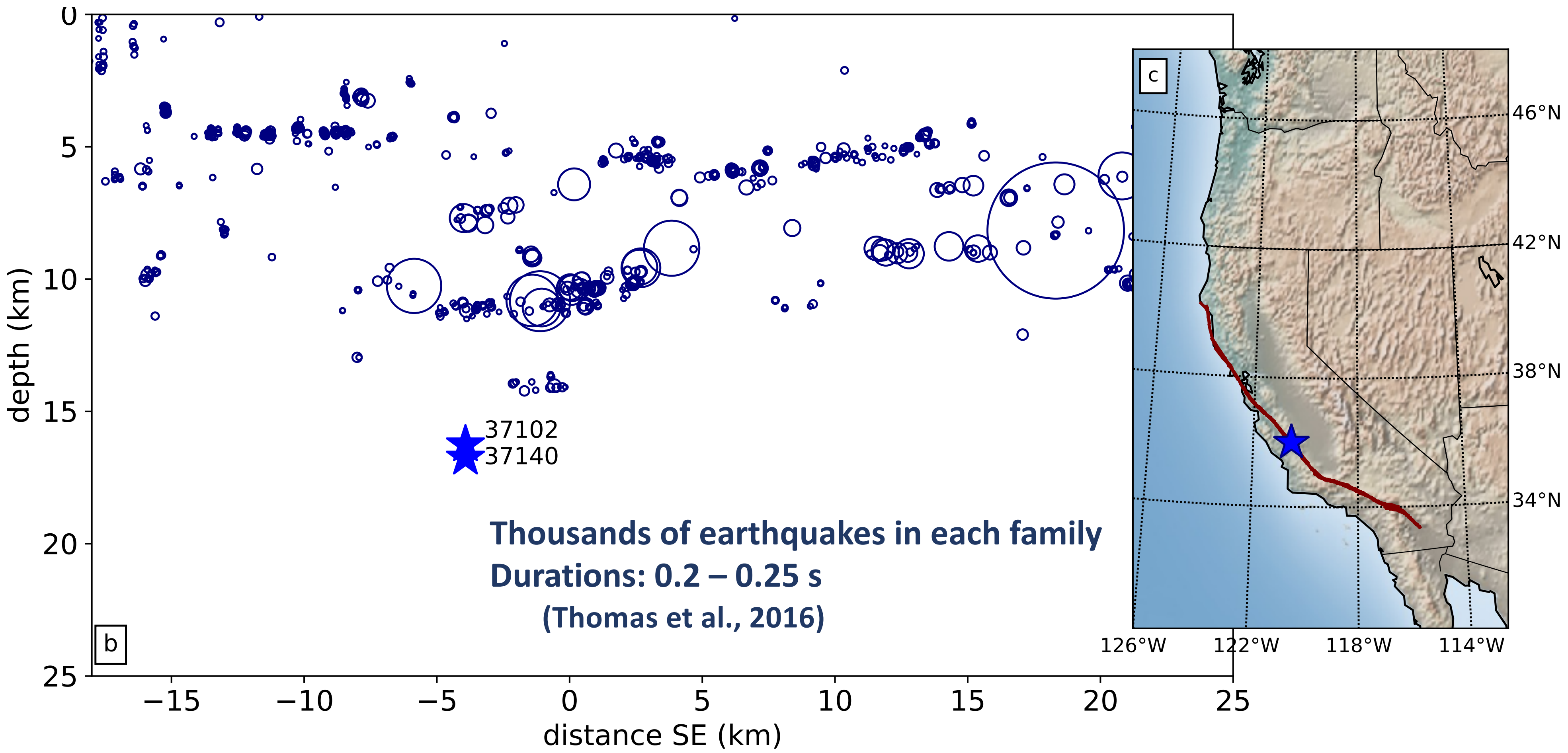
Apparent slip rate functions recorded at 7 stations, as shifted to account for source-station travel times



Slip rate functions' similarity



Tremor earthquakes near Parkfield, CA

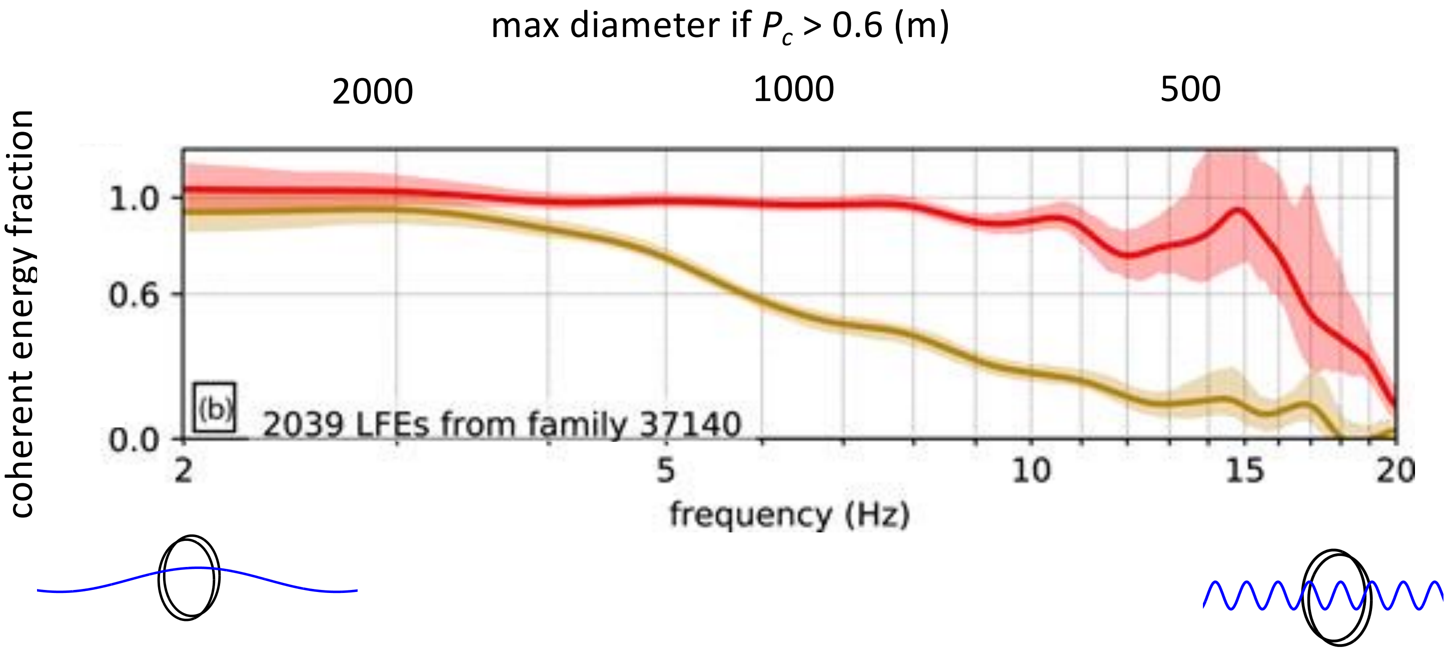


Thousands of earthquakes in each family
Durations: 0.2 – 0.25 s
(Thomas et al., 2016)

Coherent energy in one LFE family

Similar energy calculation to that used previously, compared with total energy

Most energy at frequencies less than 15 Hz is coherent across stations (red)
→ Diameter < 400 m



Combine with duration ≈ 0.2 s (Thomas et al, 2016)
→ Rupture speed < 0.6 (400 m) / (0.2 s) = 1200 m/s ≲ 0.3 × shear wave speed
→ Tremor less limited by seismic wave radiation than most earthquakes?

LFE and tremor properties so far

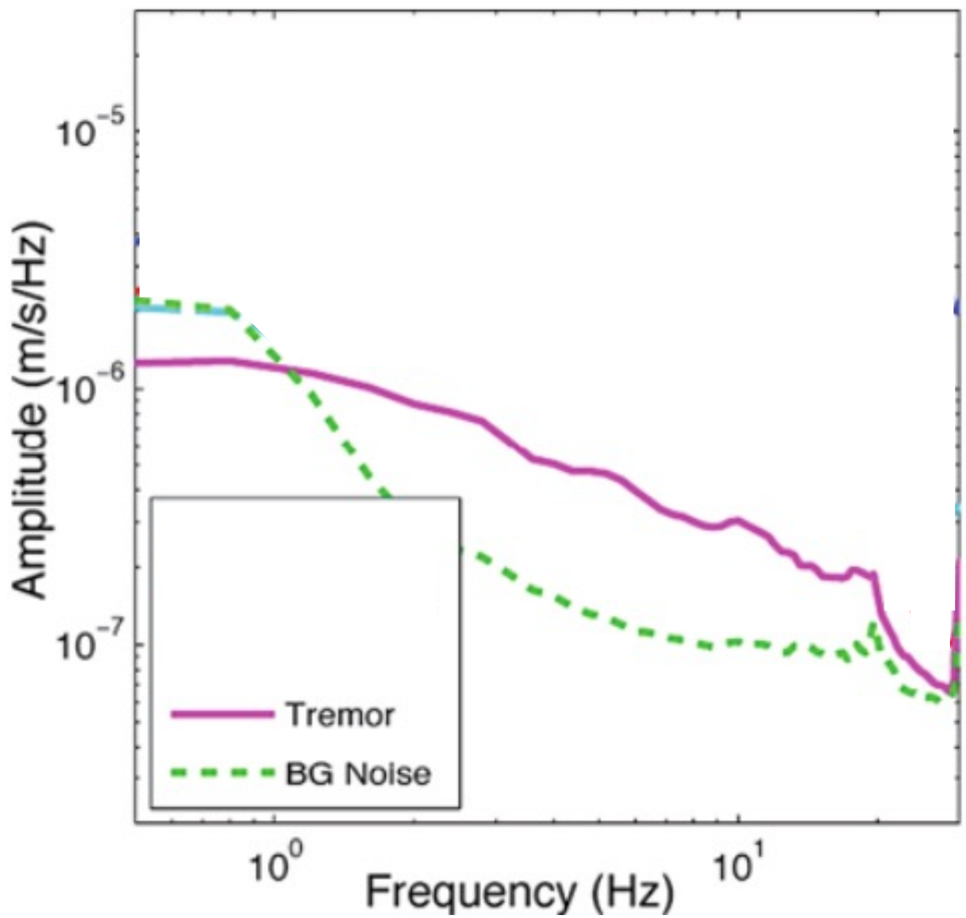
modified from Rubinstein et al, 2009

- *Dominantly in 1-10 Hz band*
- *M1 – 2.5*
- *0.2 – 0.5 s long*
- *Some < 400 m wide*
- *Some rupture at < 0.5 times shear wave speed*

Need precise, careful, and creative analysis

So what are LFEs?

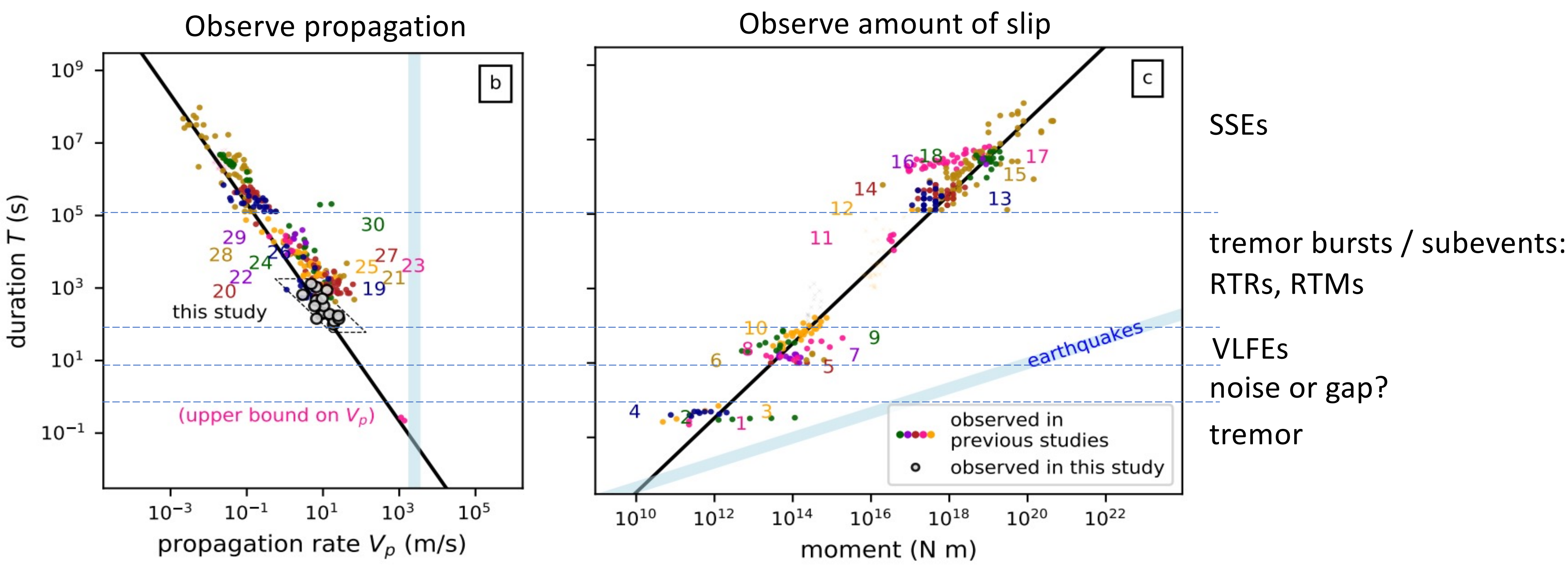
- Low stress drop earthquakes?
- Resonance in fault zone?
- Short slow slip events?



Are slow slip and tremor the same process?

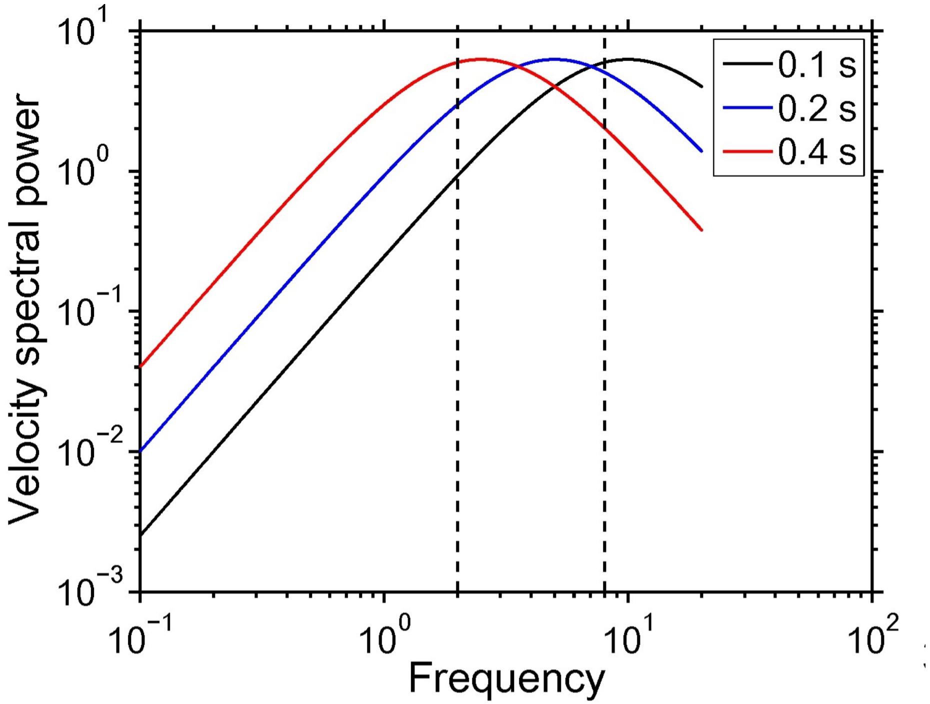
No: There's a gap between VLFEs and tremor. And **tremor's LFEs seem to have a characteristic moment and duration** in some observations.

Yes: They're on the right trend, and they're slow for some reason. Why not the same reason as slow slip? The gap is just because the ocean generates lots of 1-s seismic noise.



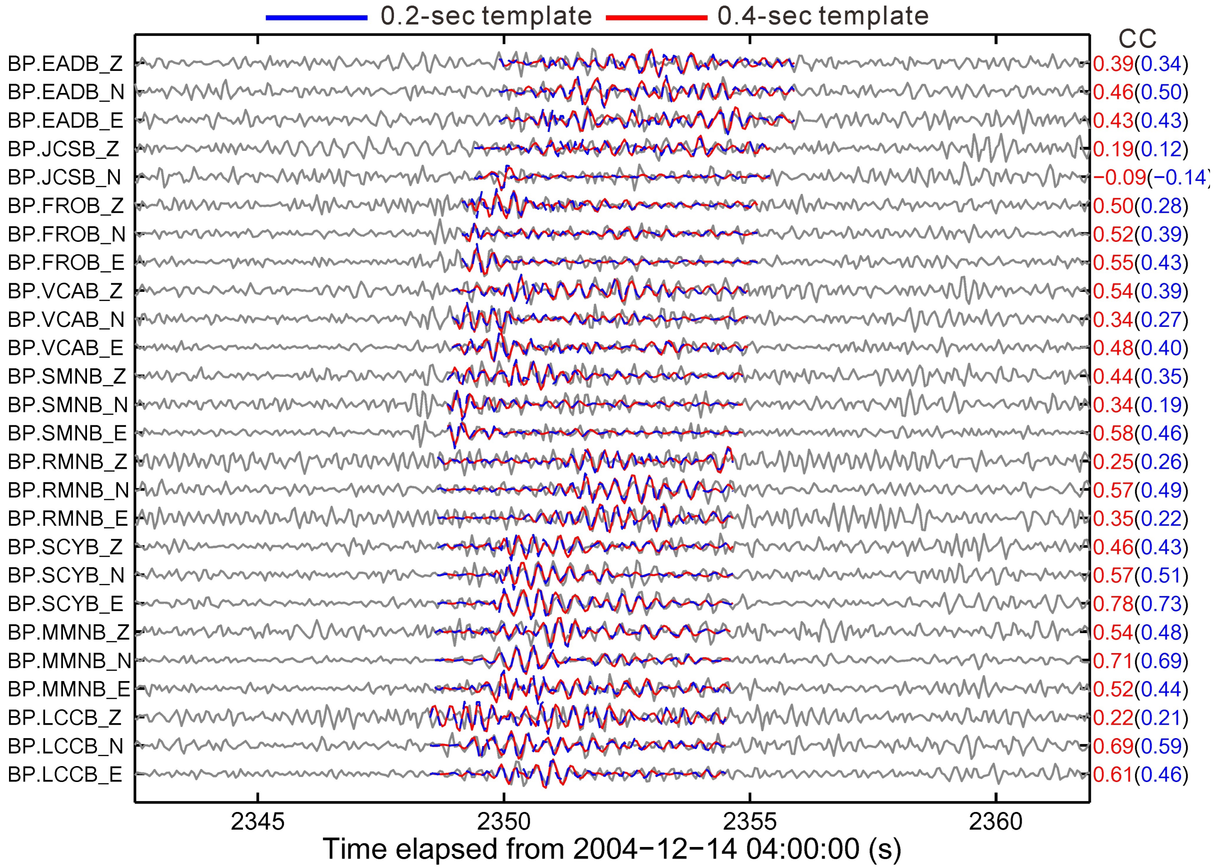
Or maybe longer events are just harder to find?

Work by Hui Huang:
Huang and Hawthorne, submitted



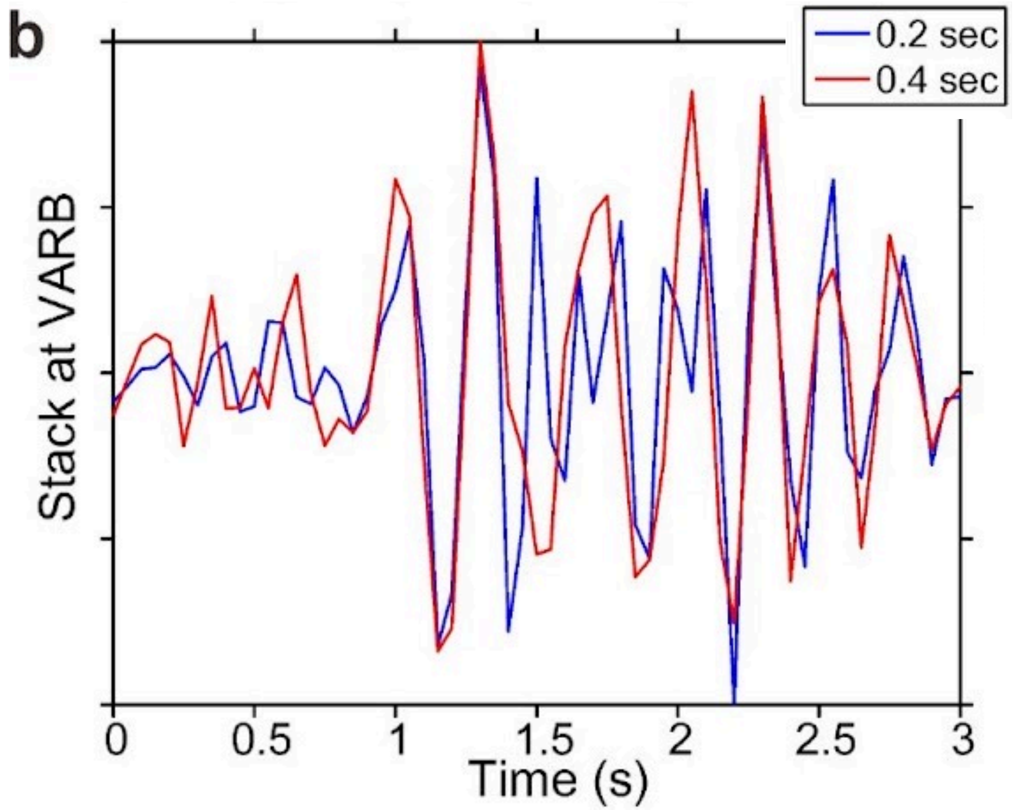
- Tend to work at 2-8 Hz frequencies because of noise at lower frequencies
- In that band, 0.2-s-long earthquakes are easiest to find

So let's look for longer events



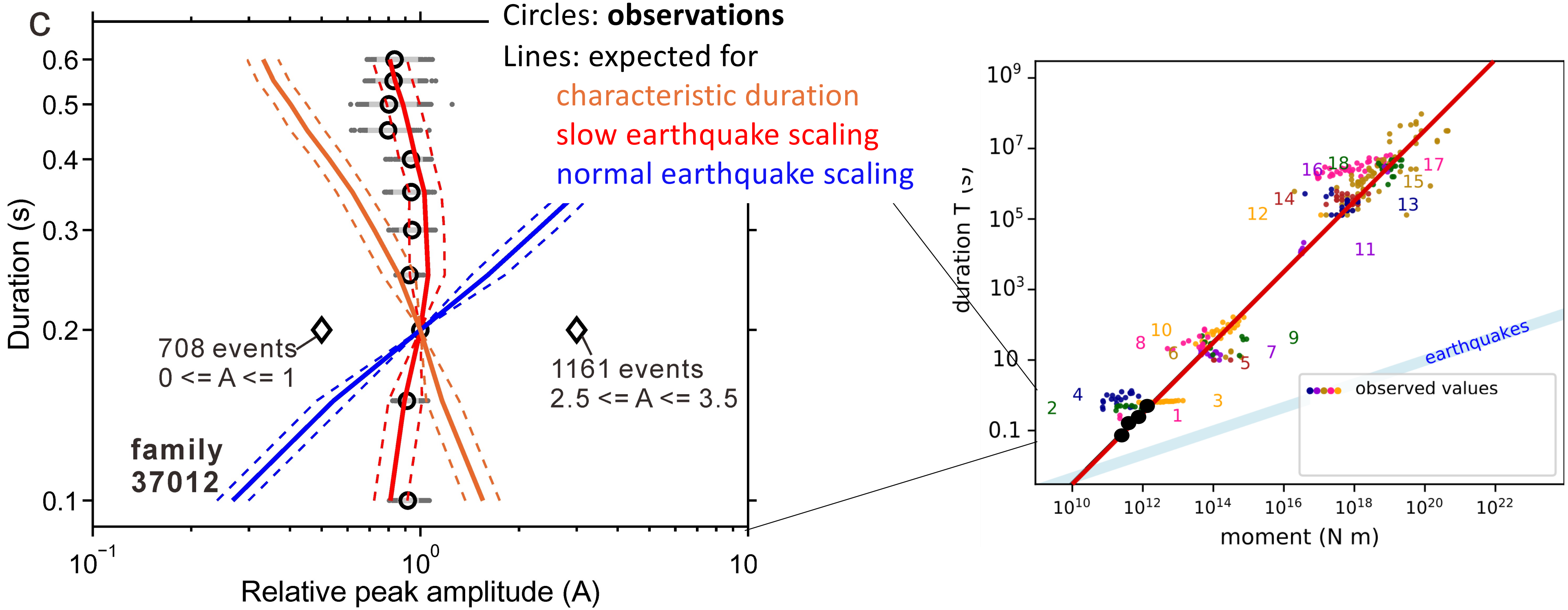
Create templates for 0.2-s and 0.4-s events and search through continuous seismic data
Stack identified events and estimate their amplitudes and durations

And we find longer LFEs!



- Differences are subtle but significant
- Detect at some stations, stack at others to be sure we're not biasing our result

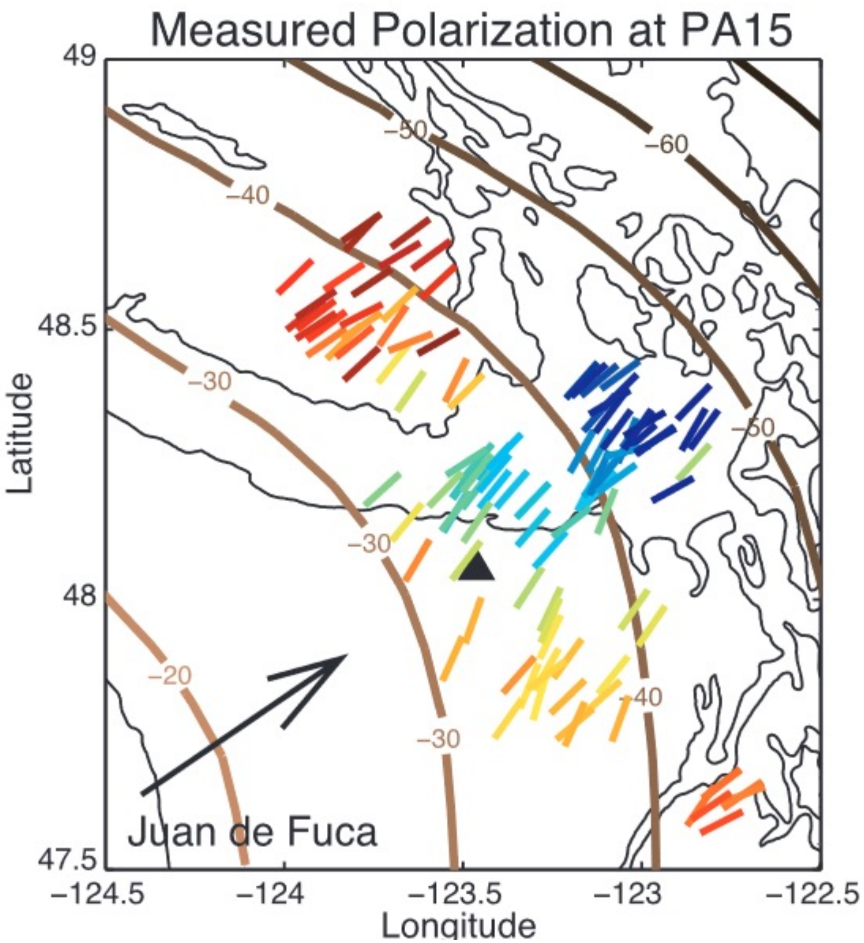
LFE moment-duration scaling



Observed scaling is the same as seen for longer slow earthquakes

→ Tremor earthquakes are short slow slip events?

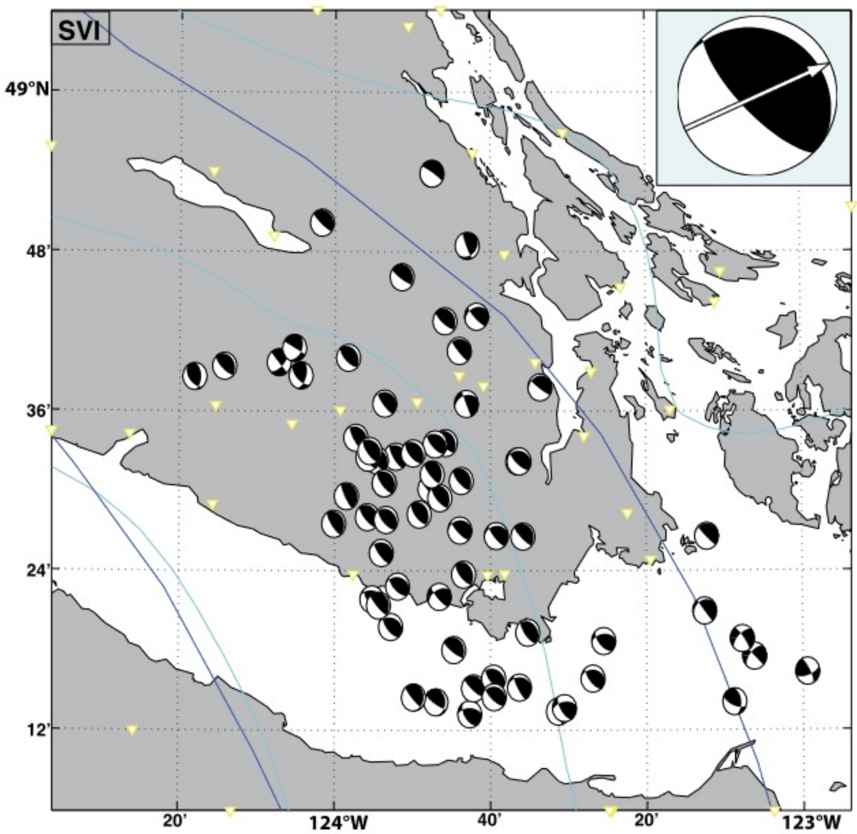
LFEs are mostly shear slip: polarization analysis

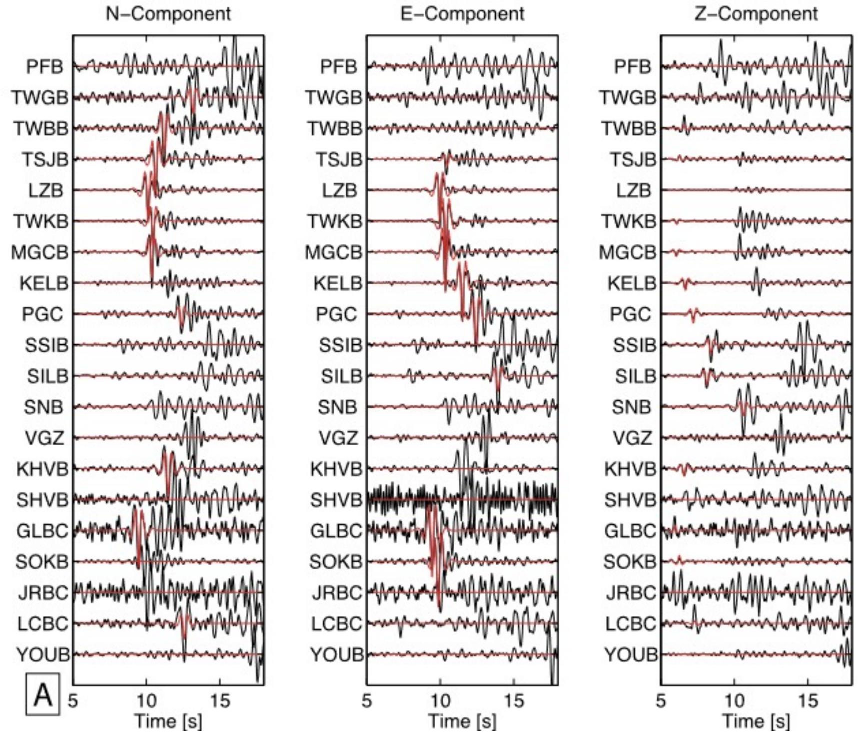


Measure orientation of S wave observed at the array (triangle) due to tremor centred on each of the lines.
All NE-SW, parallel to slip direction.

Wech and Creager, 2007

LFEs are mostly shear slip: focal mechanisms

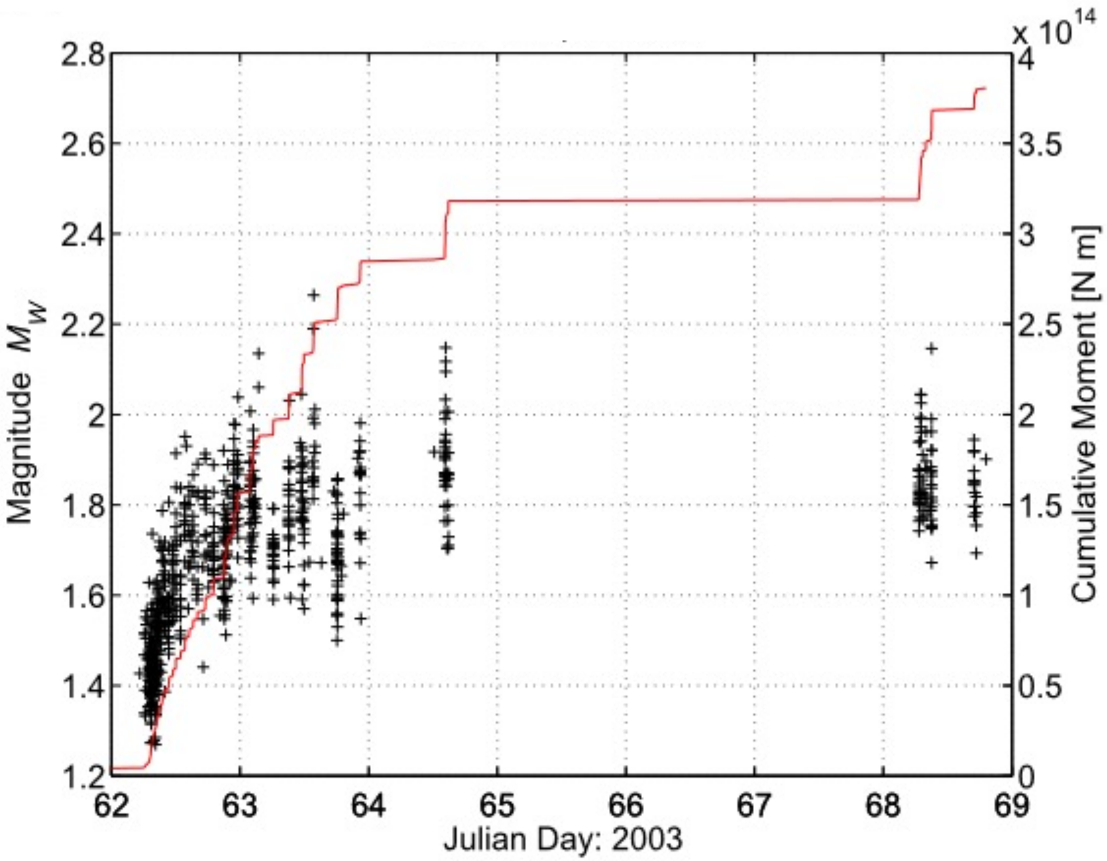




Compare observed waveforms to synthetics for a range of focal mechanisms

Royer et al, 2014

What about dilation?



Bostock et al, 2015

Moments at one location through time

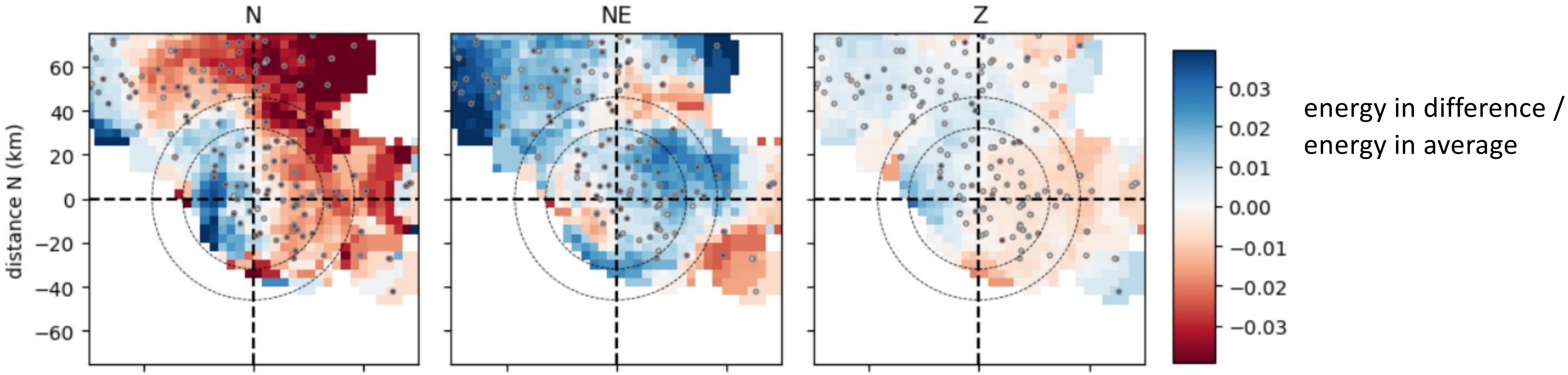
- Start small
- But increase as the main front moves farther ahead

→ A change in smoothness or permeability through time?

Maybe the later, bigger LFEs have less dilation because the permeability is higher?

Can we a see a difference in the focal mechanisms of early and late LFEs?

Energy in the difference



- Stack early LFEs (more dilation expected) and late LFEs (less dilation expected)
- Subtract the two stacks
- Examine the polarization of the difference: mostly N-S, NE-SW, vertical?

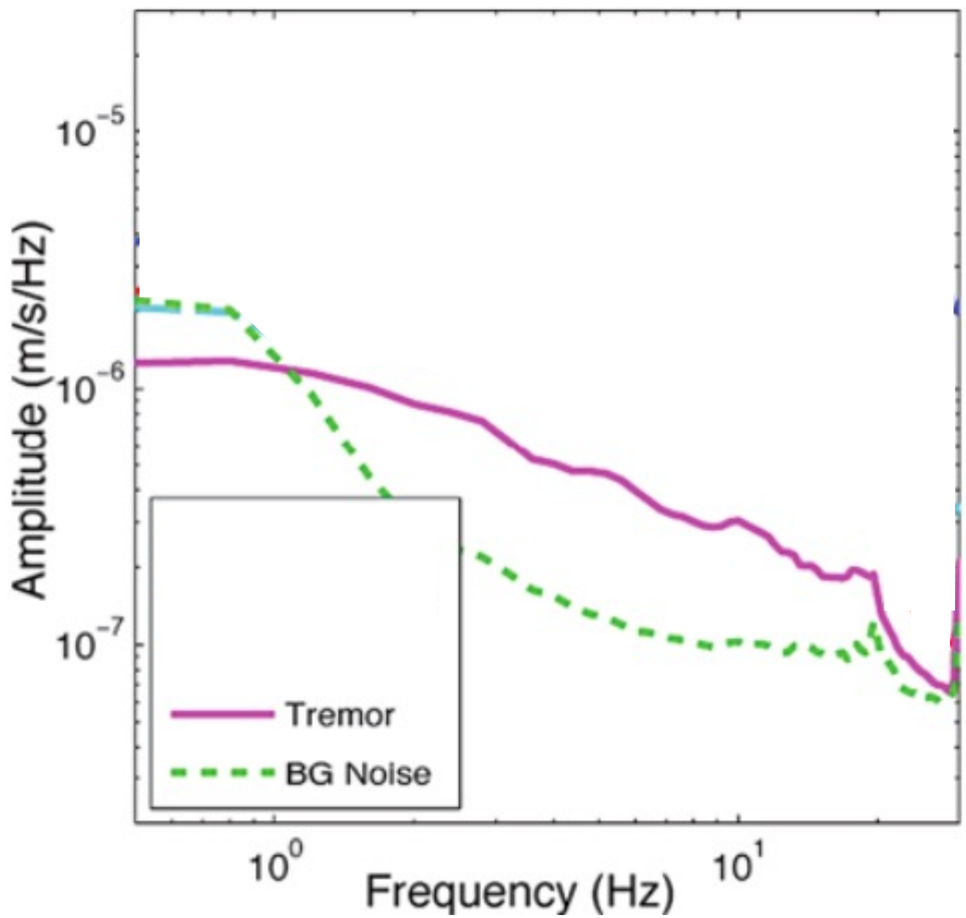
○ Difference is less than a few percent of the total energy
○ No obvious patterns

But just a few percent dilation is plausible; Need to try harder?

Tremor summary

modified from Rubinstein et al, 2009

- *Dominantly in 1-10 Hz band*
- *M1 – 2.5*
- *0.2 – 0.5 s long*
- *Some < 400 m wide*
- *Some rupture at < 0.5 times shear wave speed*
- *Possible detection bias, some longer LFEs*
- *Mostly shear slip*



Need more precise, careful, and creative analysis to determine what causes LFEs.