Observing and modelling the spectrum of a slow slip event
A single fault zone process for slow earthquakes?

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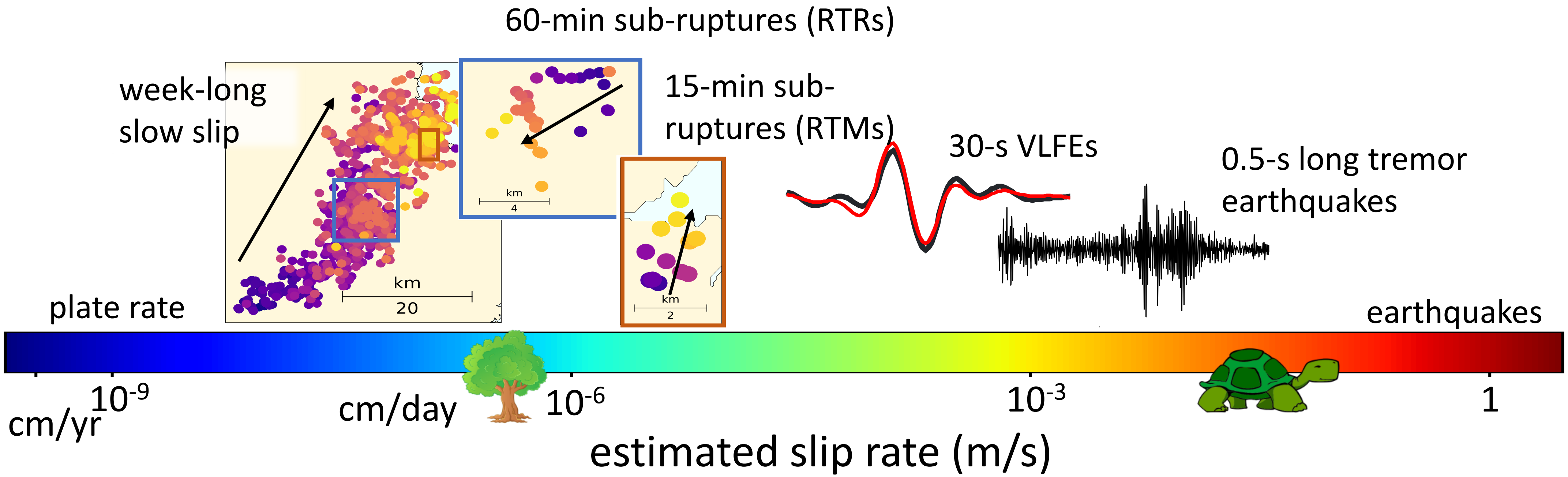
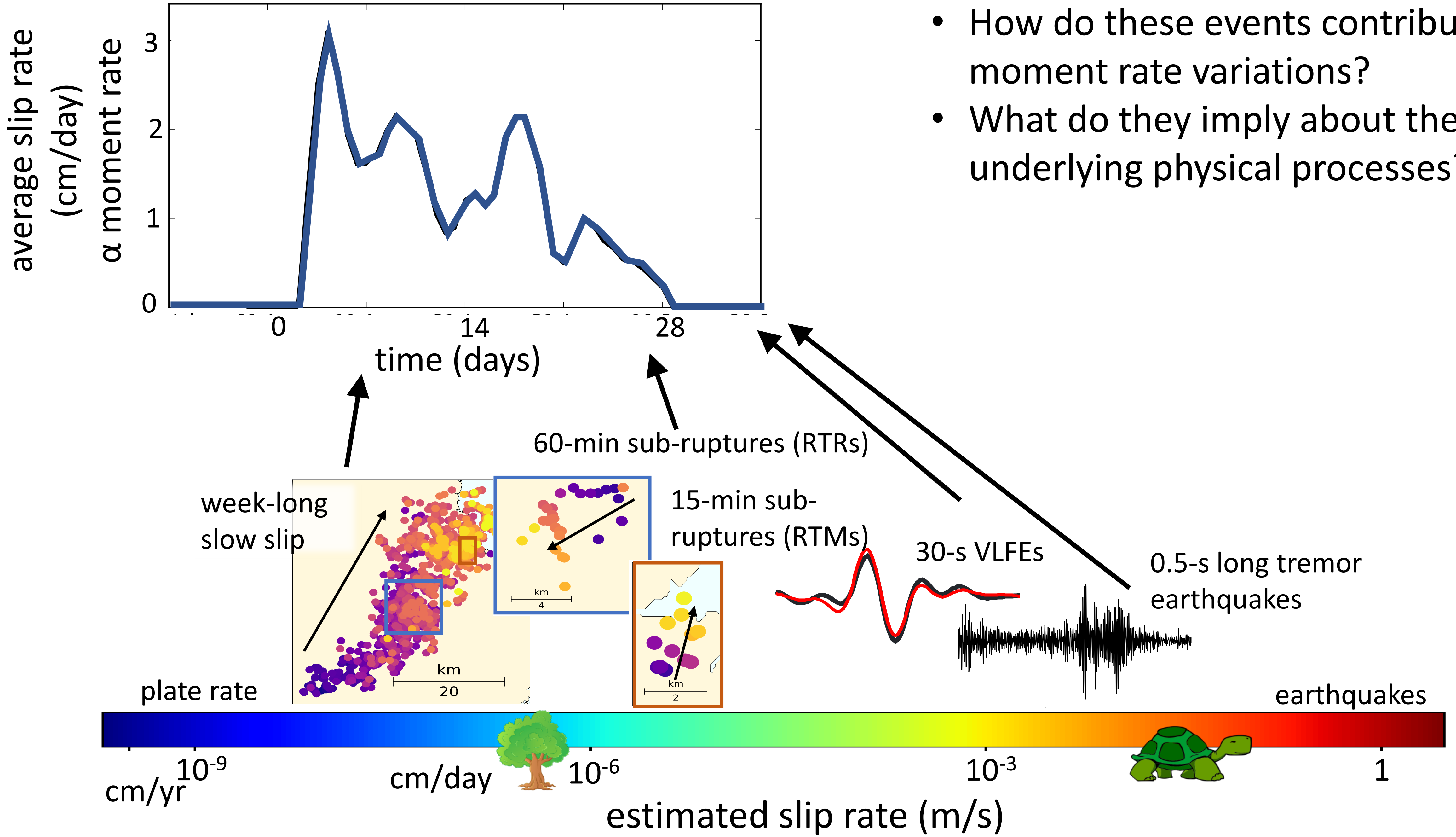
Noel Bartlow (Berkeley)



Tremor migration: Peng and Rubin; VLFEs: Yabe and Ide, 2014

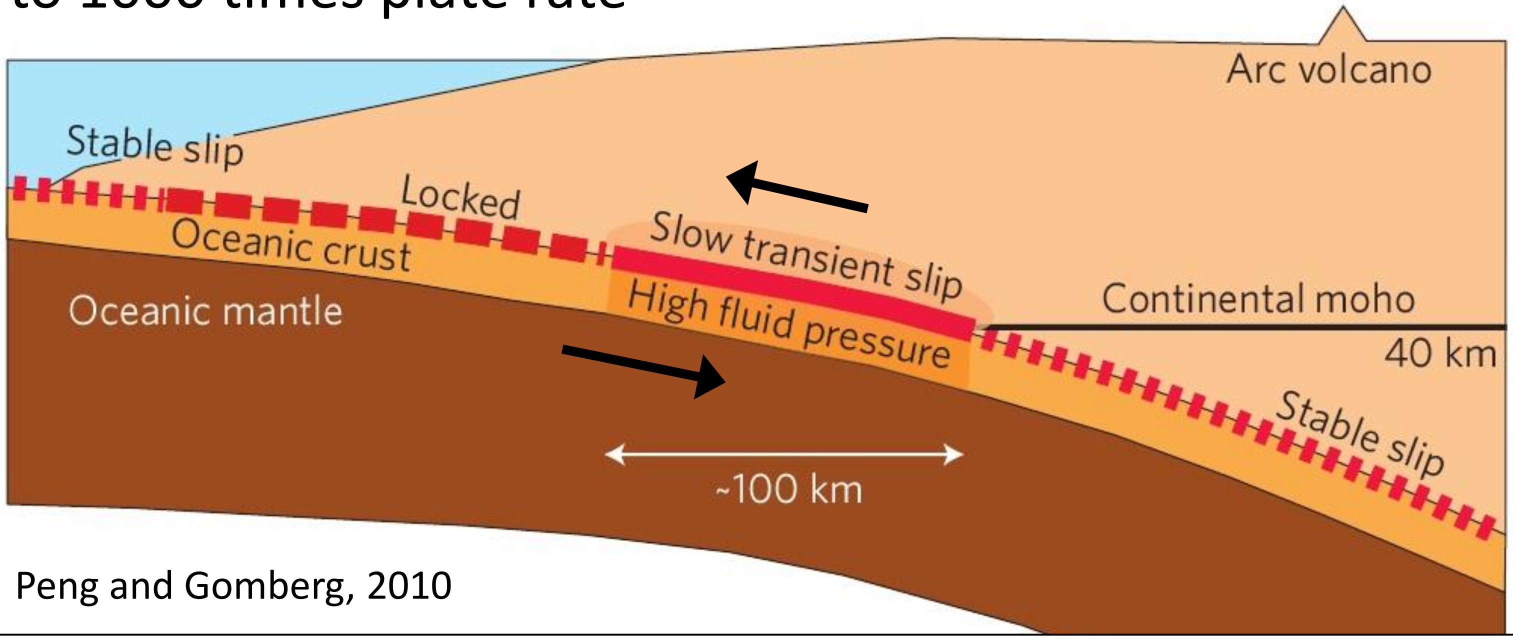
- How do these events contribute to moment rate variations?
- What do they imply about the underlying physical processes?



Tremor migration: Peng and Rubin; VLFEs: Yabe and Ide, 2014

Slow slip in Cascadia

- 1 month long, M 6.5 - 6.9, about 1 per year
- Slip rates $10^{-7} – 10^{-6}$ m/s,
  100 to 1000 times plate rate

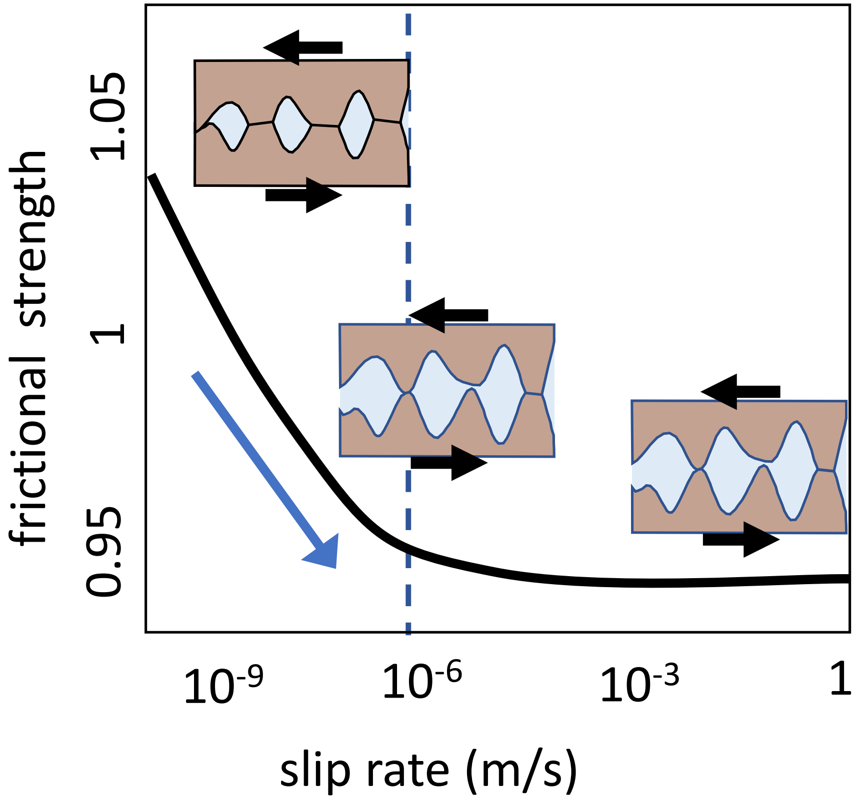


Peng and Gomberg, 2010

So which fault zone processes control these slip rates?

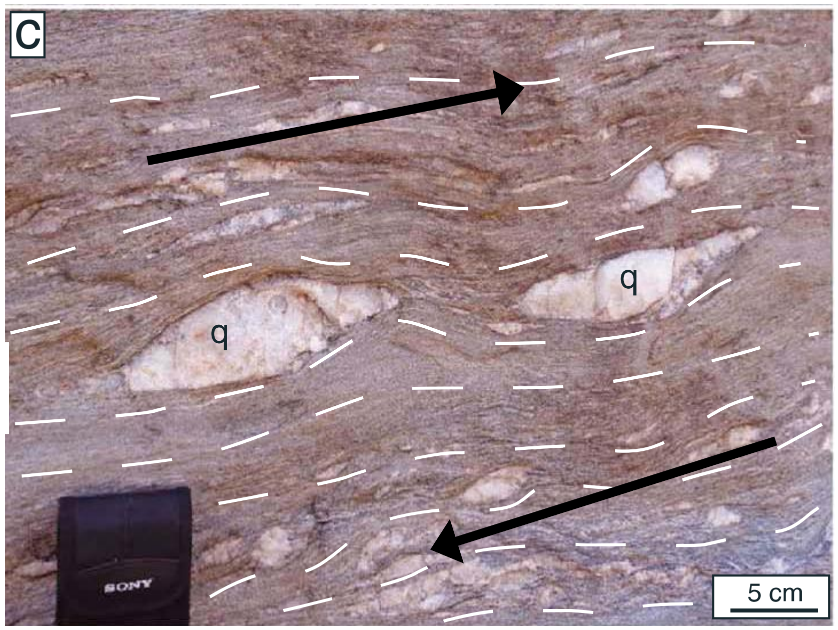
What could limit slow slip slip rates?

A limit on frictional weakening
from minimum asperity size



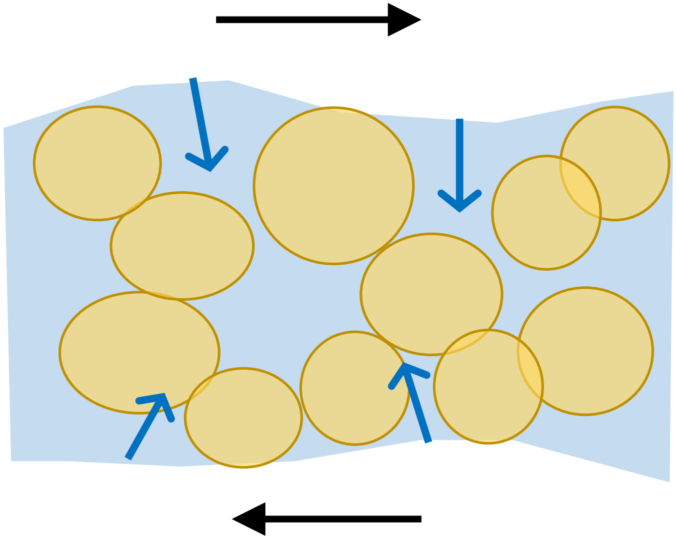
Shibazaki and Iio, 2003;
Hawthorne and Rubin, 2013

Mix of brittle and viscous deformation



Lavier et al, 2013; Fagereng et al, 2014;
Behr et al, 2018

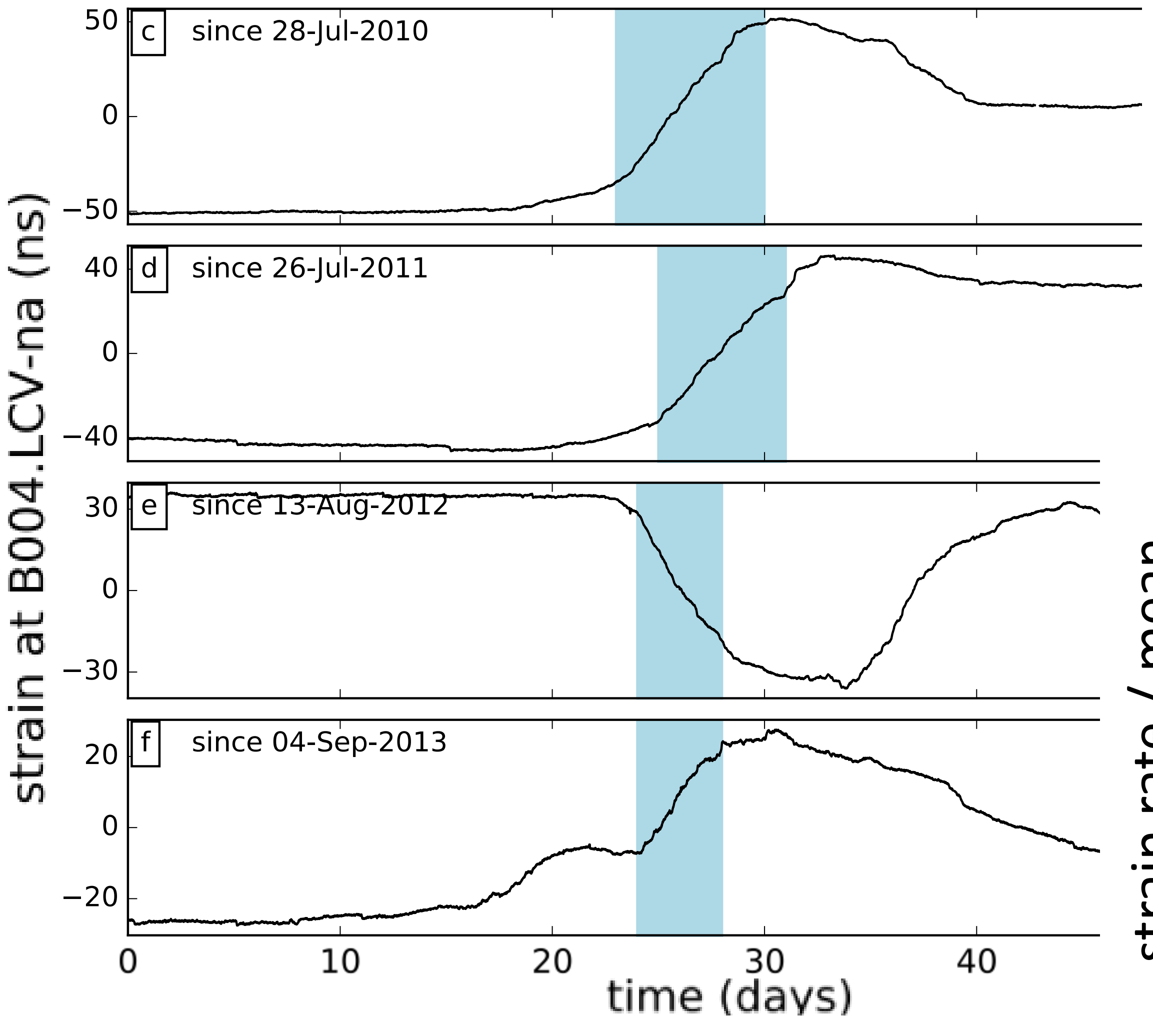
Shear-induced fluid pressure drops,
via dilatancy or fracture



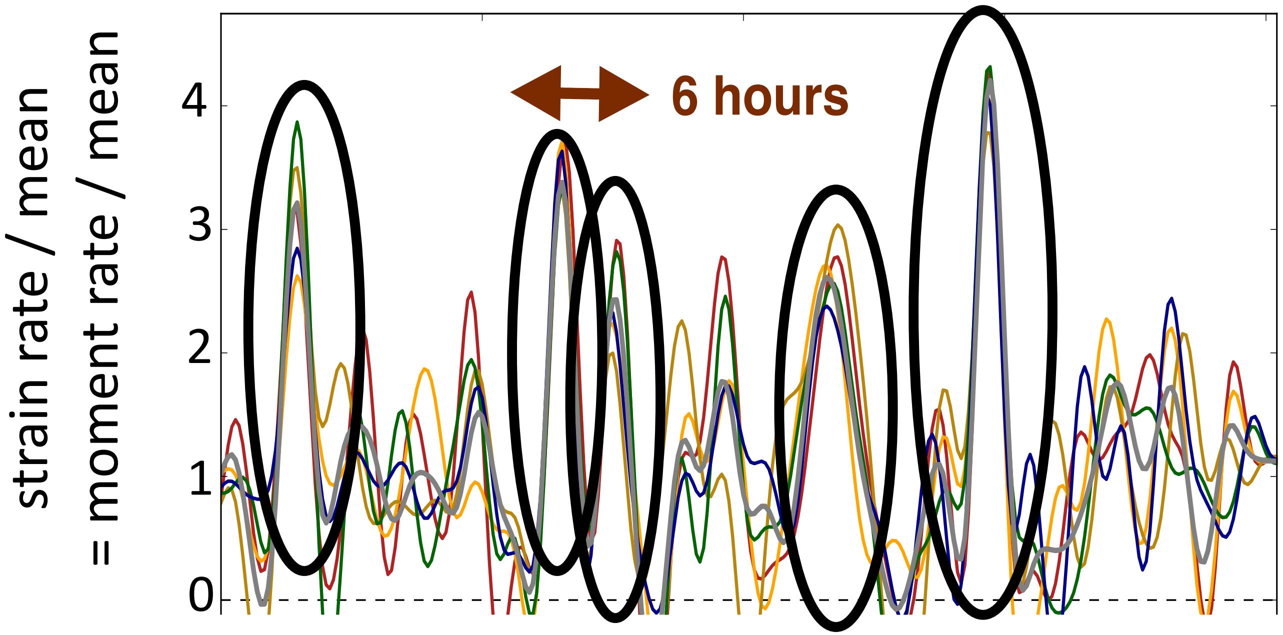
Liu and Rubin, 2010; Segall et al, 2010;
Moore and Piazolo, in review

Proposed mechanism	Creates slow earthquakes?	Creates abundant events?		
Minimum asperity size Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013	yes	yes		
Brittle and viscous deformation Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;	yes	yes?		
Shear-induced fluid pressure changes Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.	yes	yes		

Borehole strain-based observations of heterogeneity



How many physical processes have been shown to reproduce these moment rate bursts?

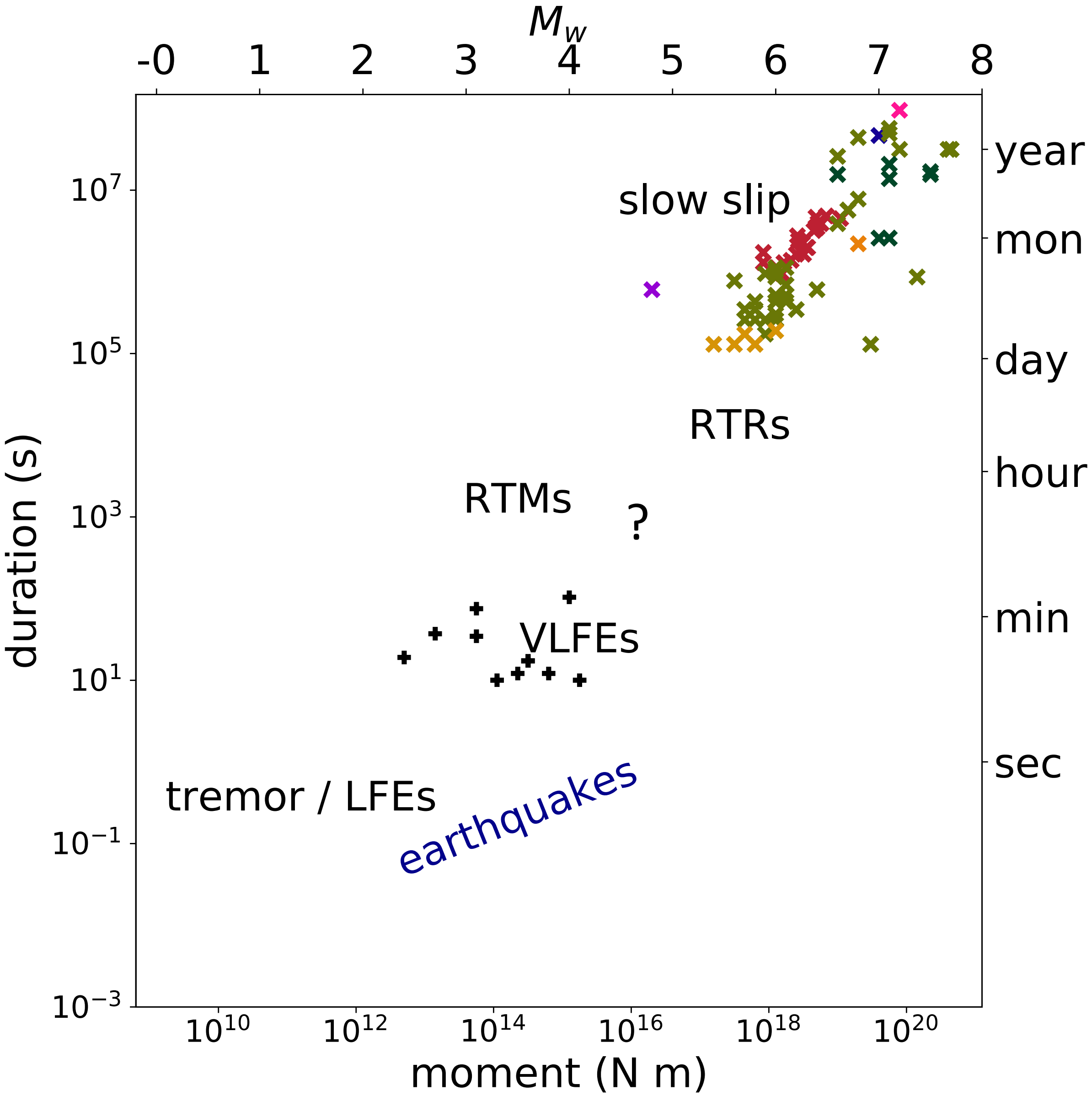


Proposed mechanism	Creates slow earthquakes?	Predicts abundant events?	Complexity on simple faults?	
Minimum asperity size Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013	yes	yes	no	
Brittle and viscous deformation Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;	yes	yes?	no?	
Shear-induced fluid pressure changes Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.	yes	yes	no	

Models appear too stable to allow heterogeneity on simple faults
→Fault networks are complex

But how can we measure and assess the heterogeneity?

A spectrum of slow earthquakes



Slow slip: a specific fault zone process
Tremor: low-stress drop earthquakes

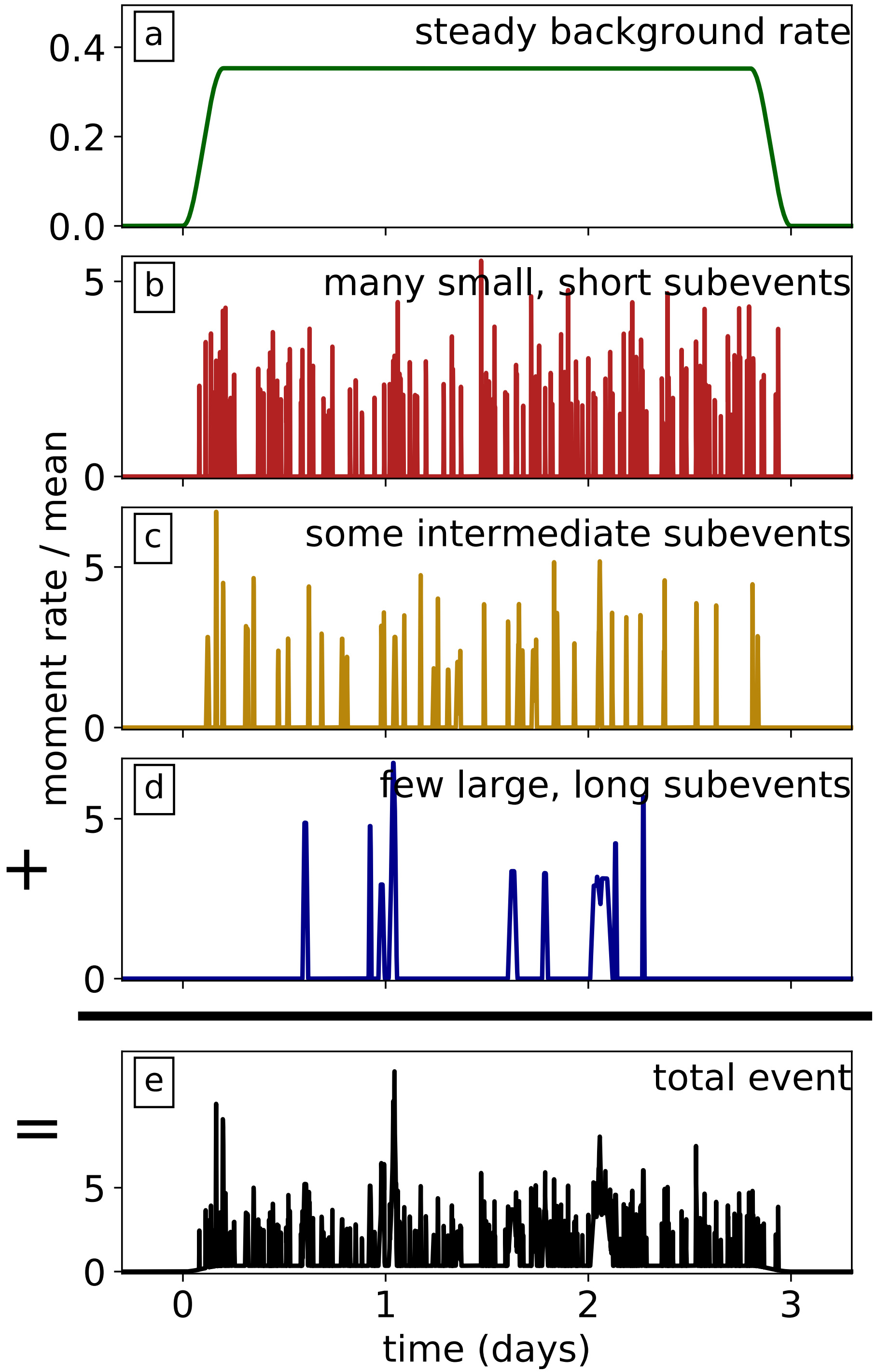
or

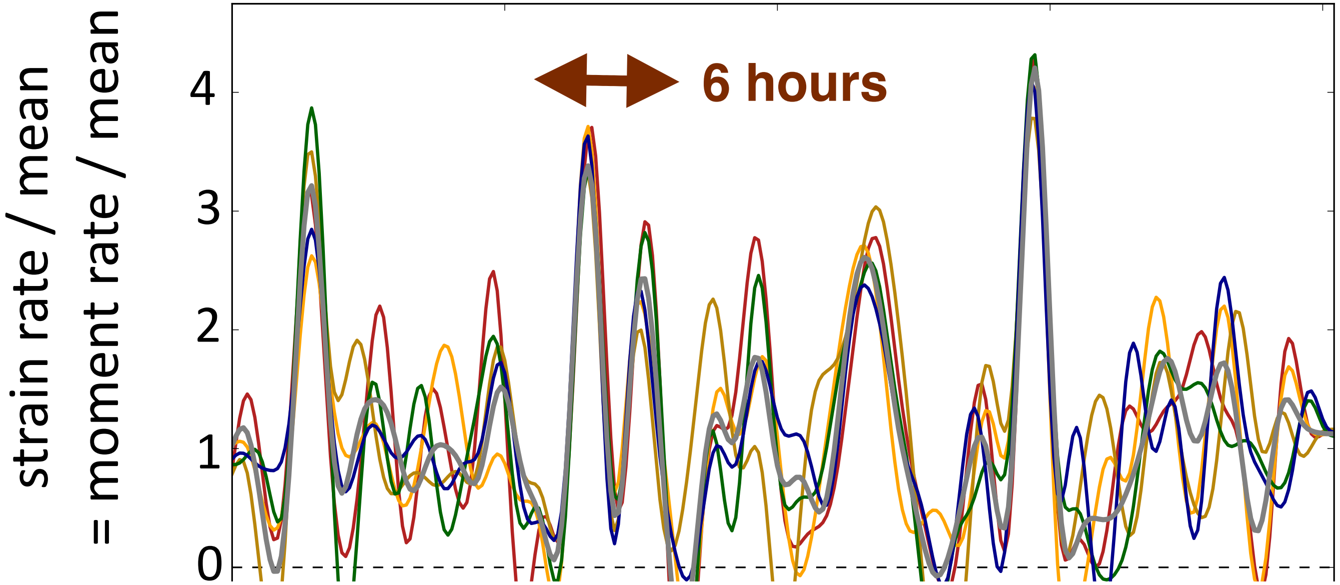
A continuum of slow slip events of different sizes

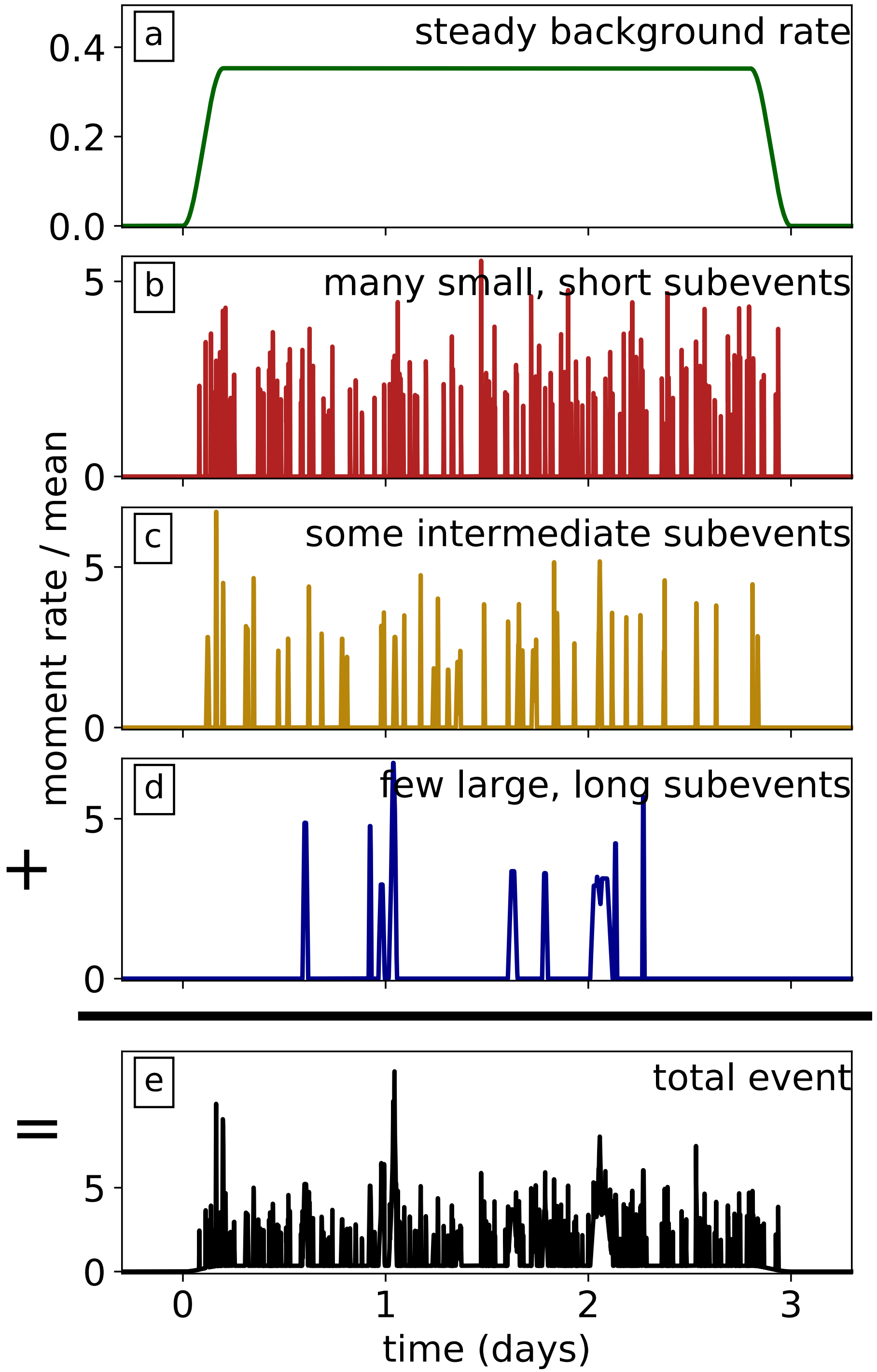
Where smaller events are faster!?

After Ide et al, 2007; Gao et al, 2012

Could we reproduce this variability with a collection of subevents?





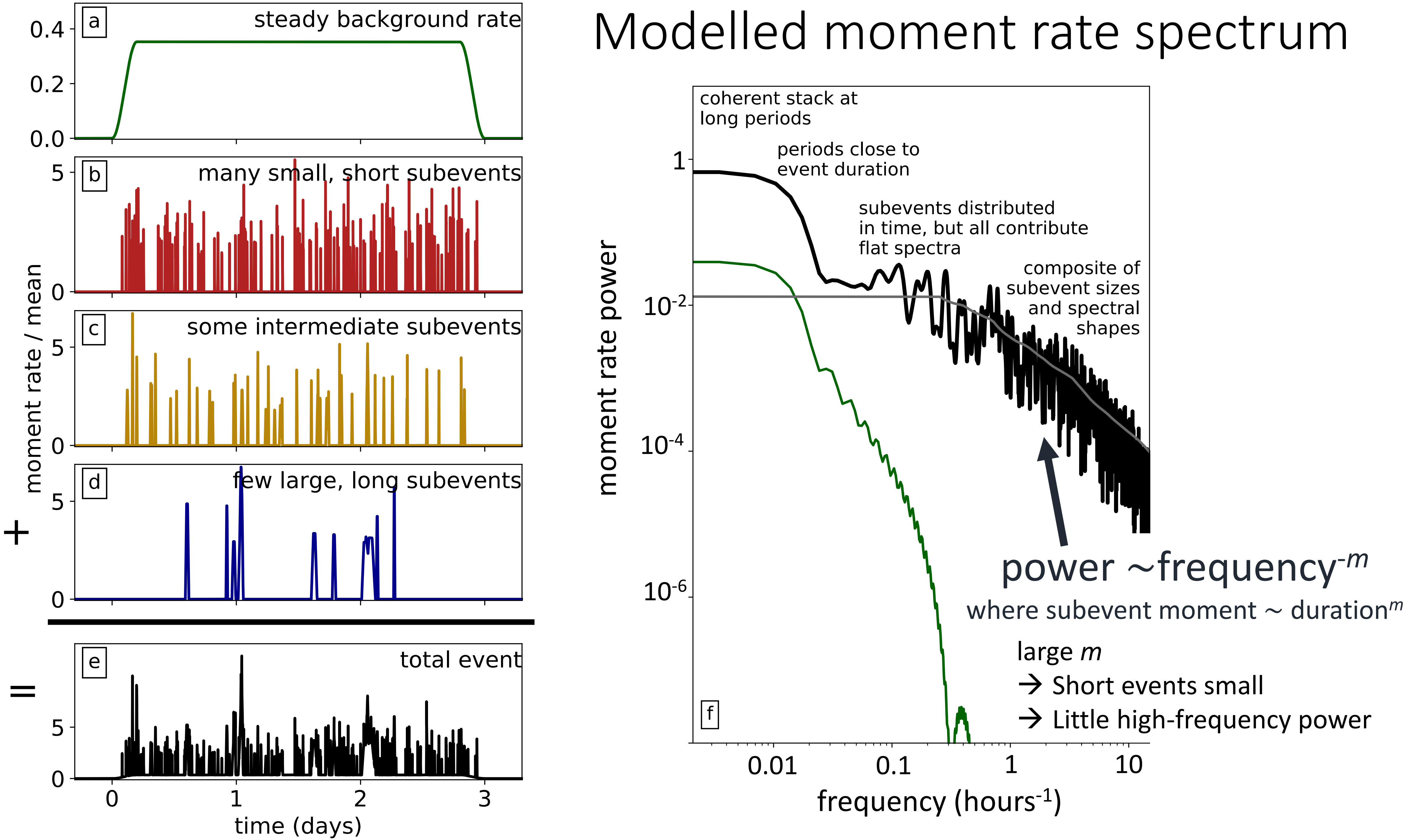


Could we reproduce this variability with a collection of subevents?

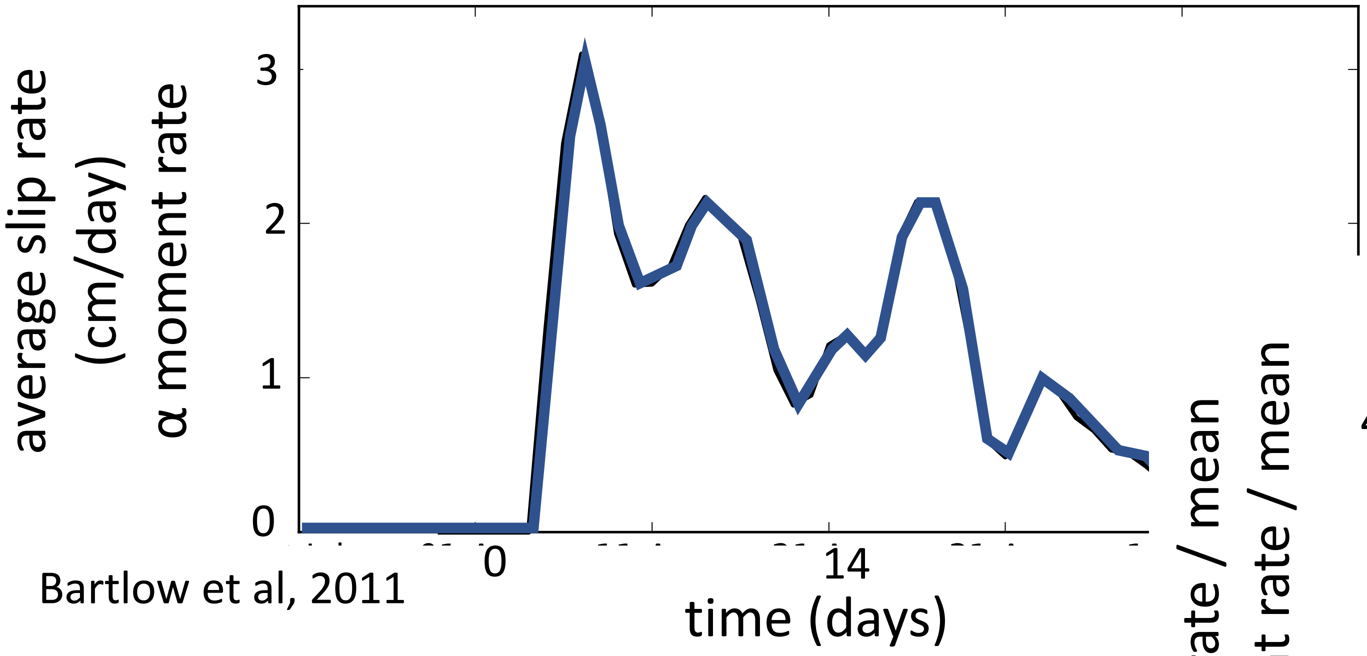
Need to choose

- Number of events of each moment
- Relationship: moment ~ duration^m

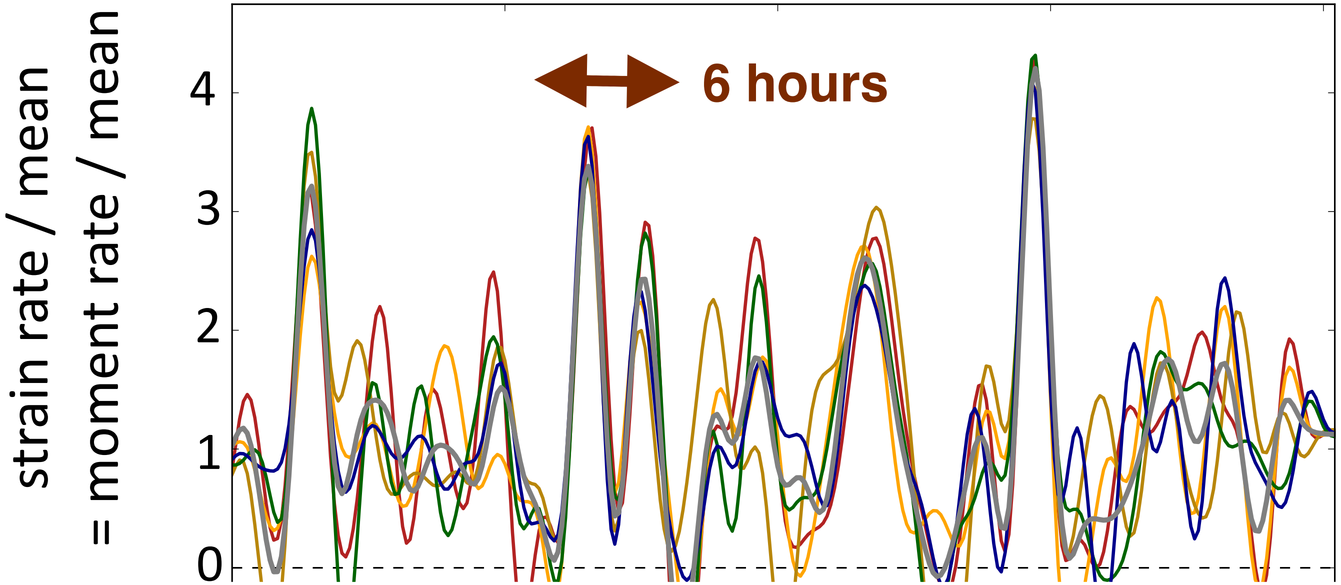
Modelled moment rate spectrum



How would our geodetic moment rate observations reflect subevents?

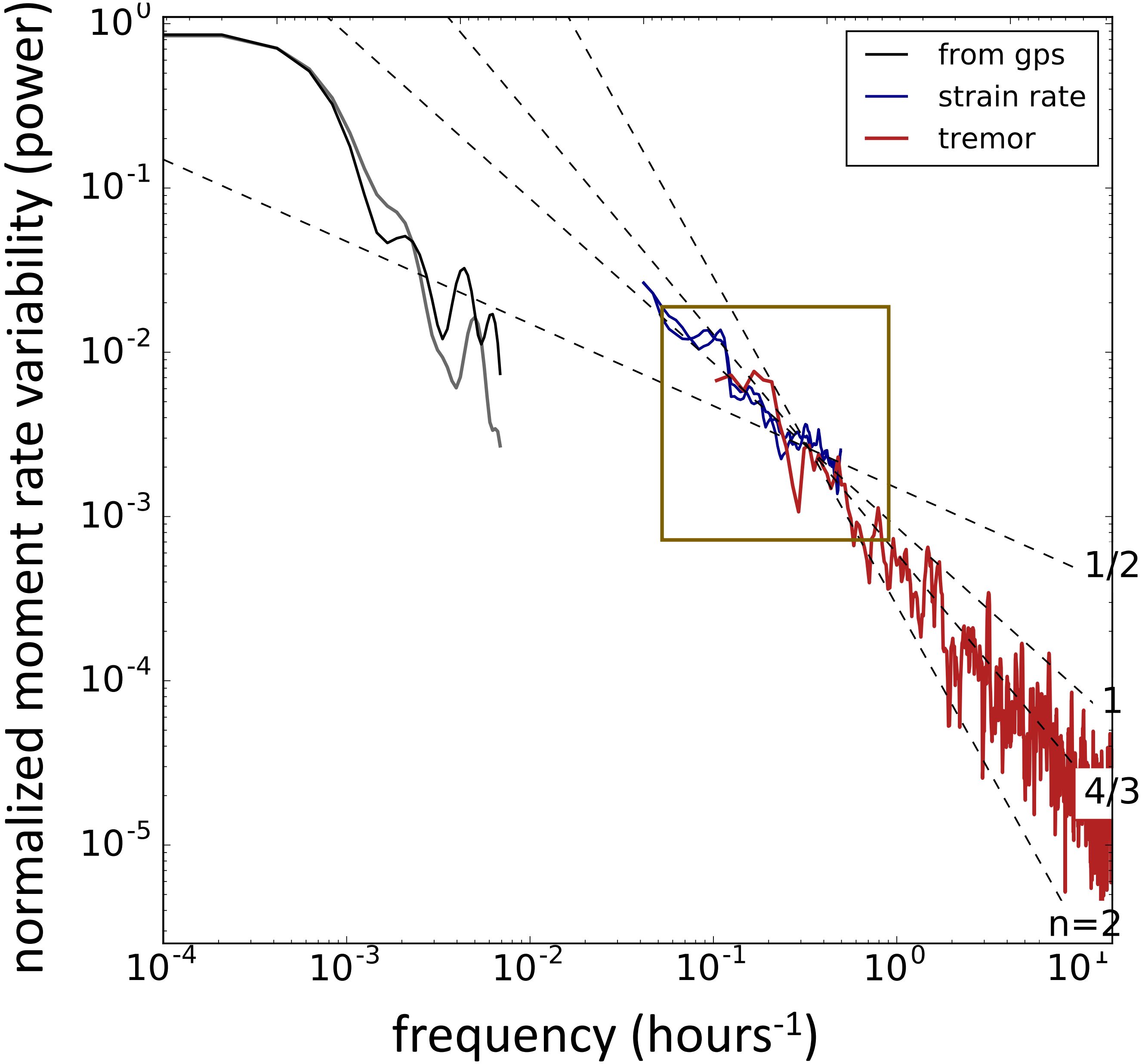


Bartlow et al, 2011

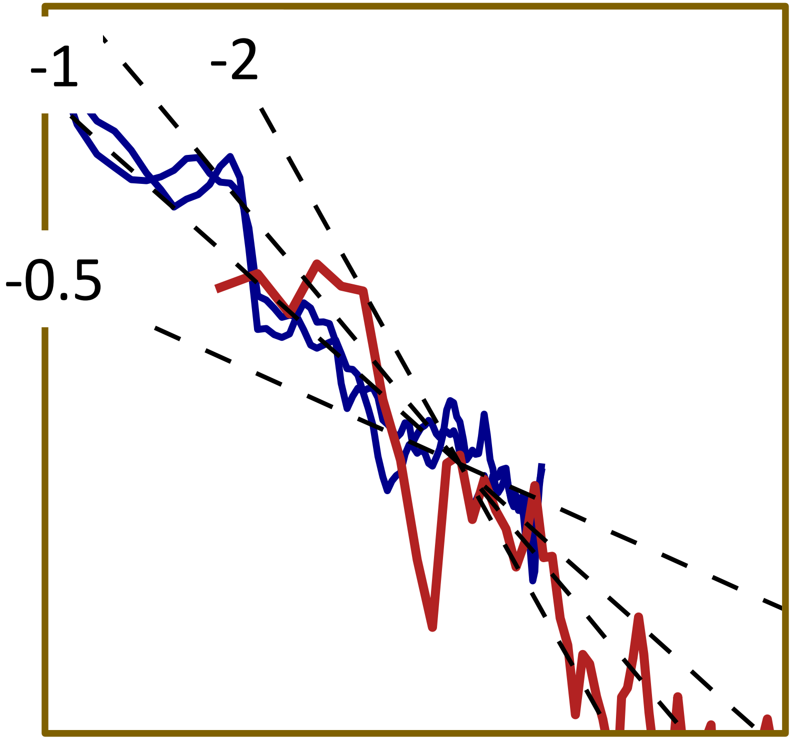


Can estimate amplitude of moment rate variability on a range of timescales.

Observed moment rate spectrum

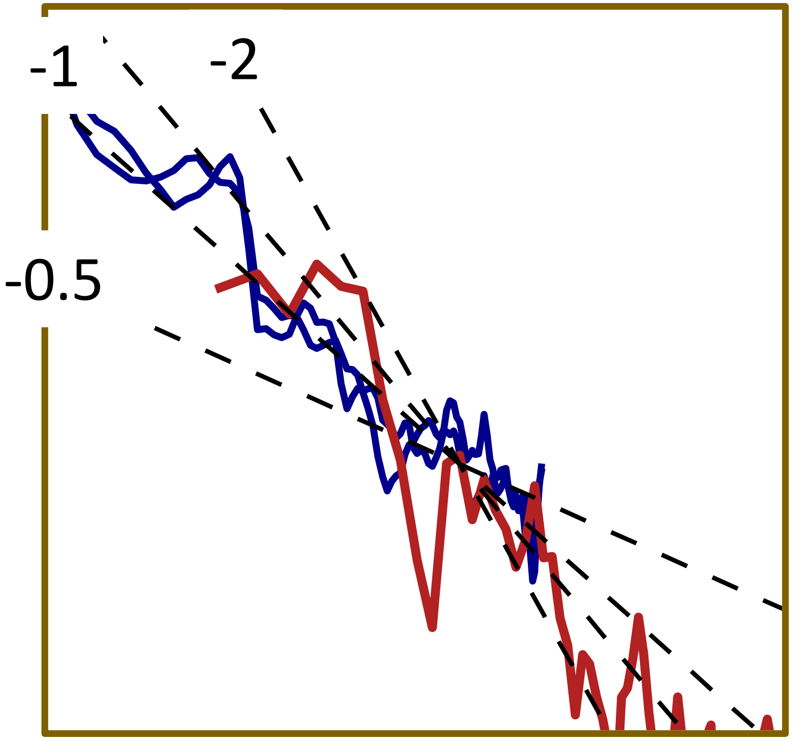


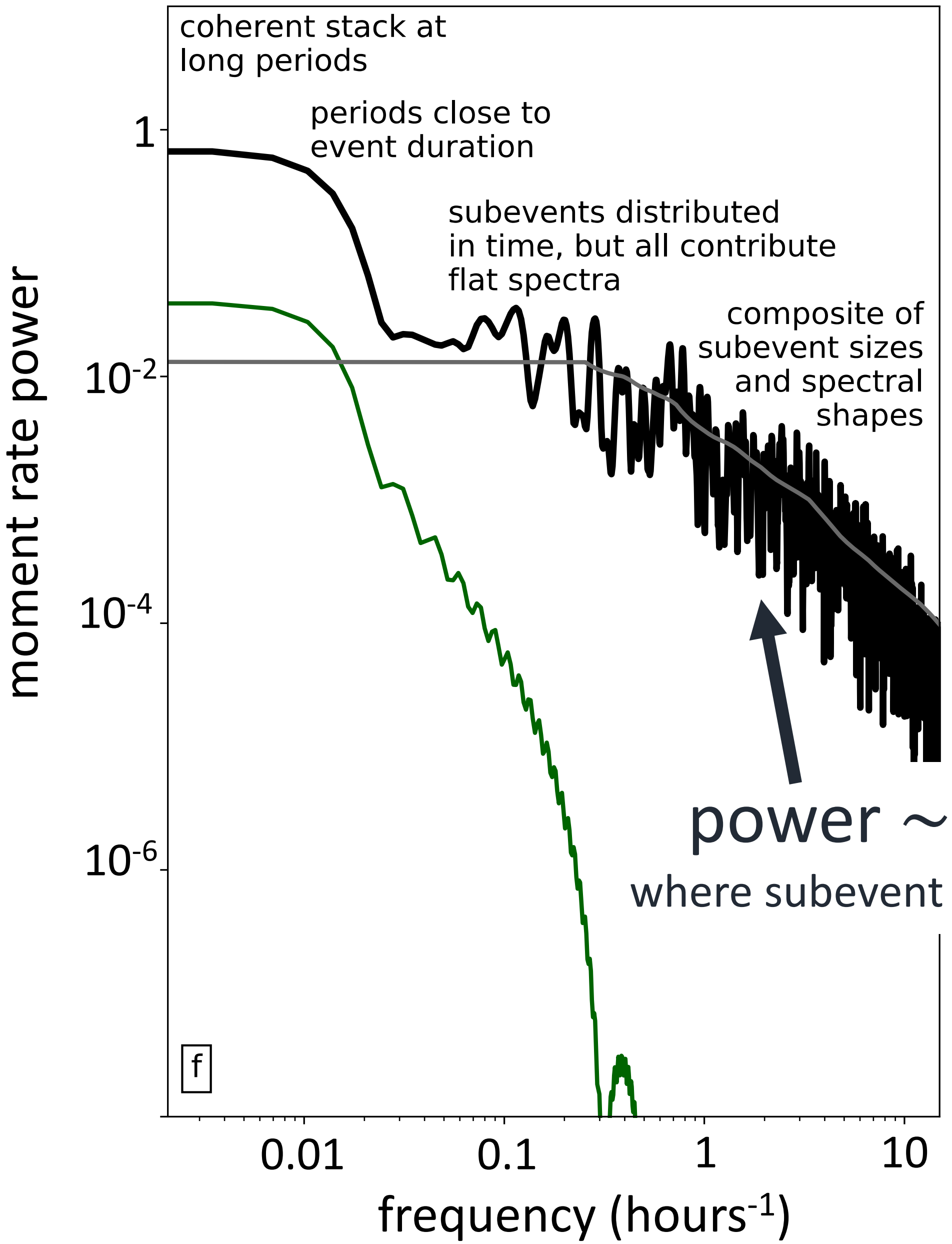
- Decays as frequency^{-1} at high frequencies



Modelled moment rate spectrum

- Data decays as frequency^{-1}



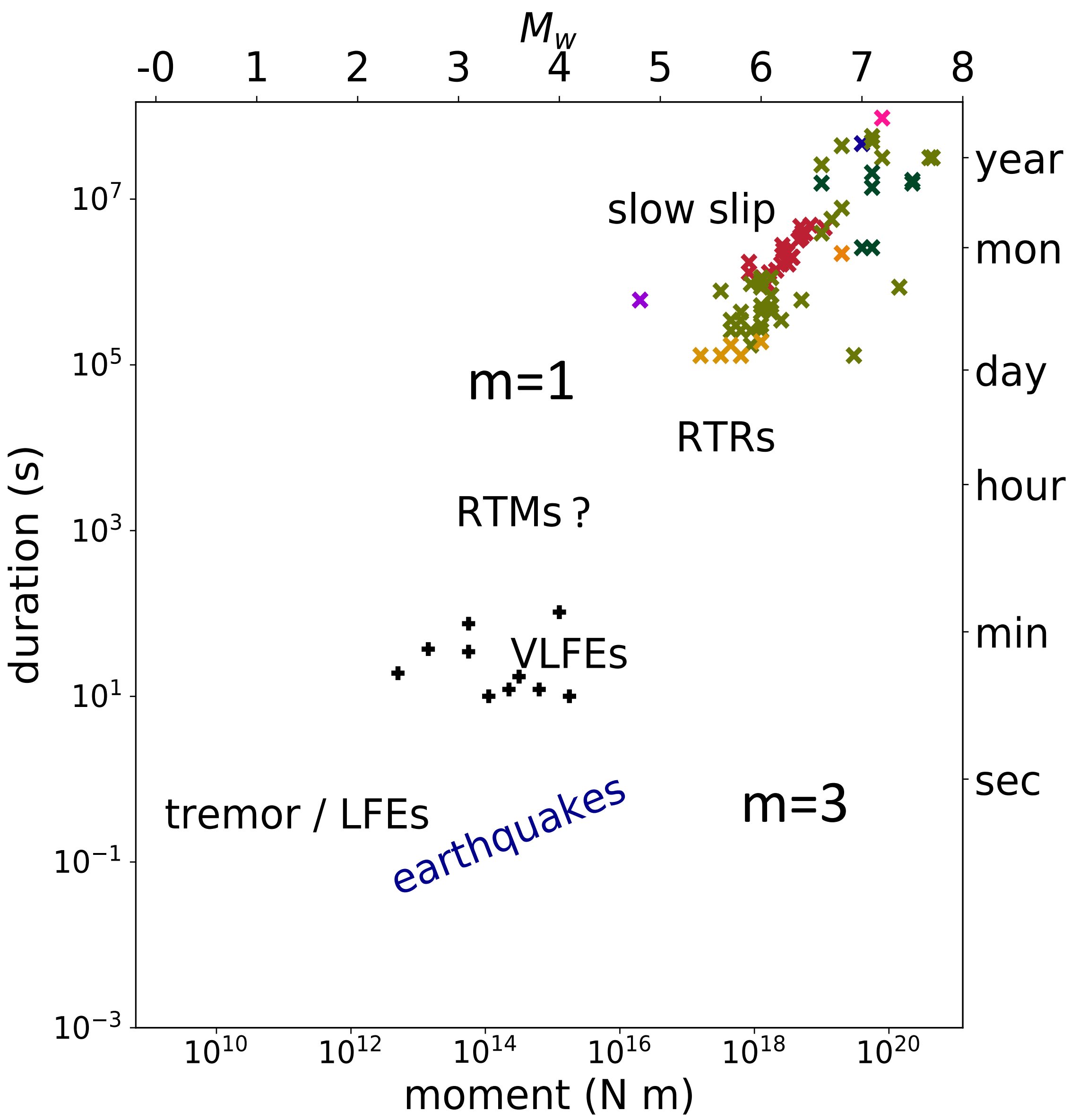


power ~frequency^{-m}

where subevent moment ~ duration^{m}

To match a frequency^{-1} decay, need m=1, consistent with the proposed continuum scaling

Slow slip and tremor: 1 continuum, 1 physical process?

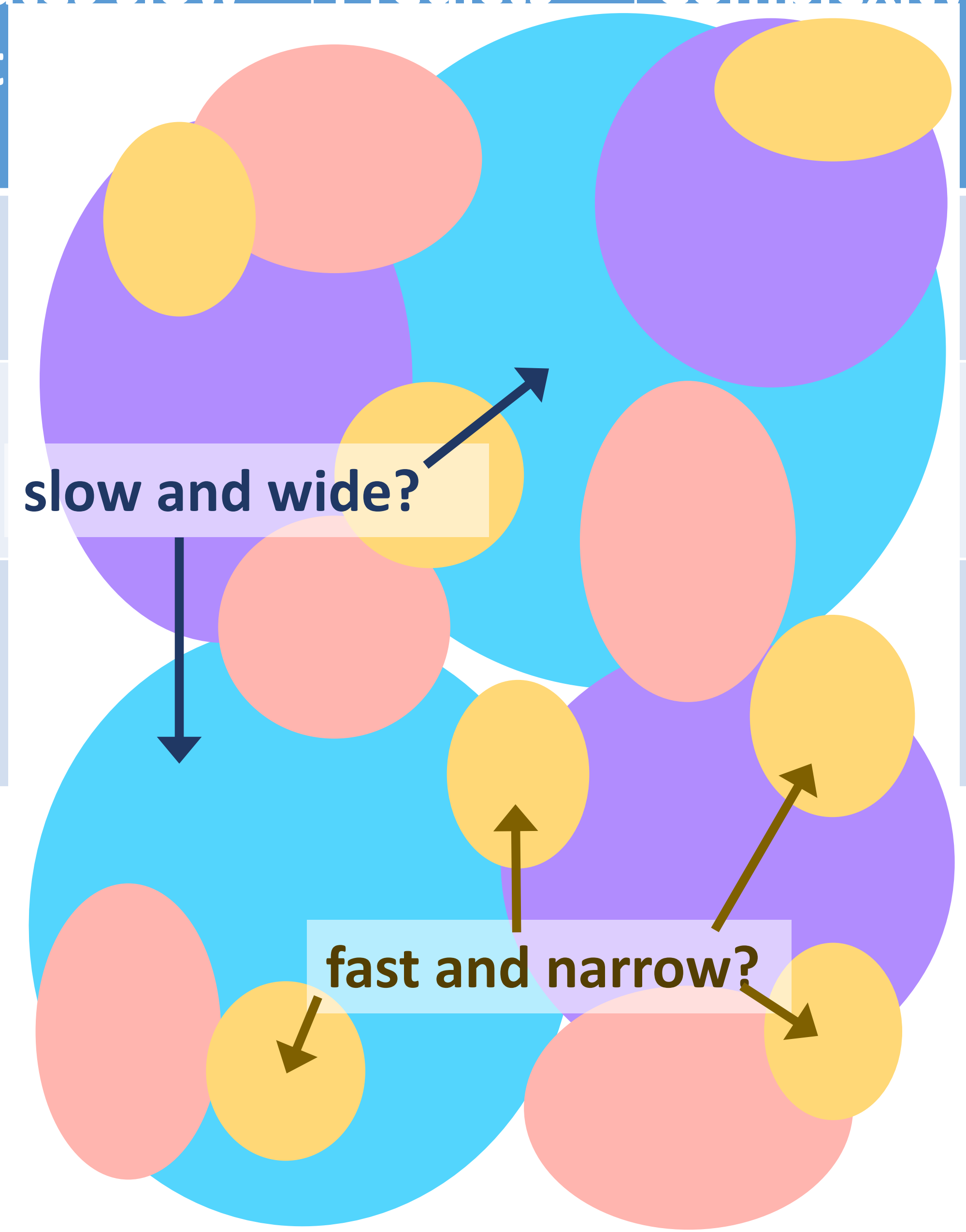


Moment rate variability *consistent* with a single continuum of slow earthquakes with moment ~ duration

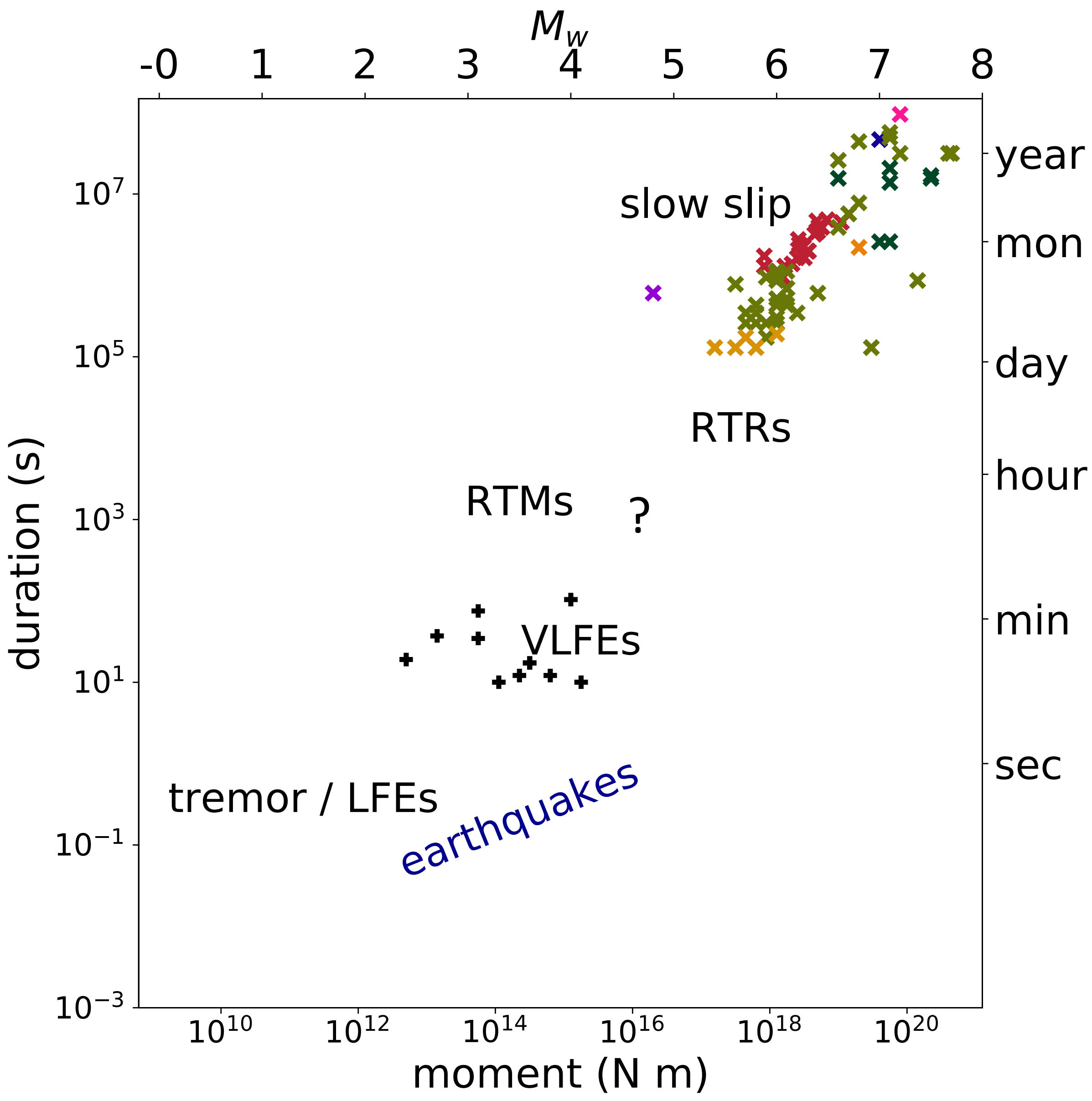
Which processes could produce a continuum where small events are faster?

After Ide et al, 2007; Gao et al, 2012

Proposed mechanism	Creates slow eart	Predicts	Complexity	Size-dependent slip rates?
Minimum asperity size Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013				no
Brittle and viscous deformation Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;				via fault viscosity
Shear-induced fluid pressure changes Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.				via fault width



Conclusions



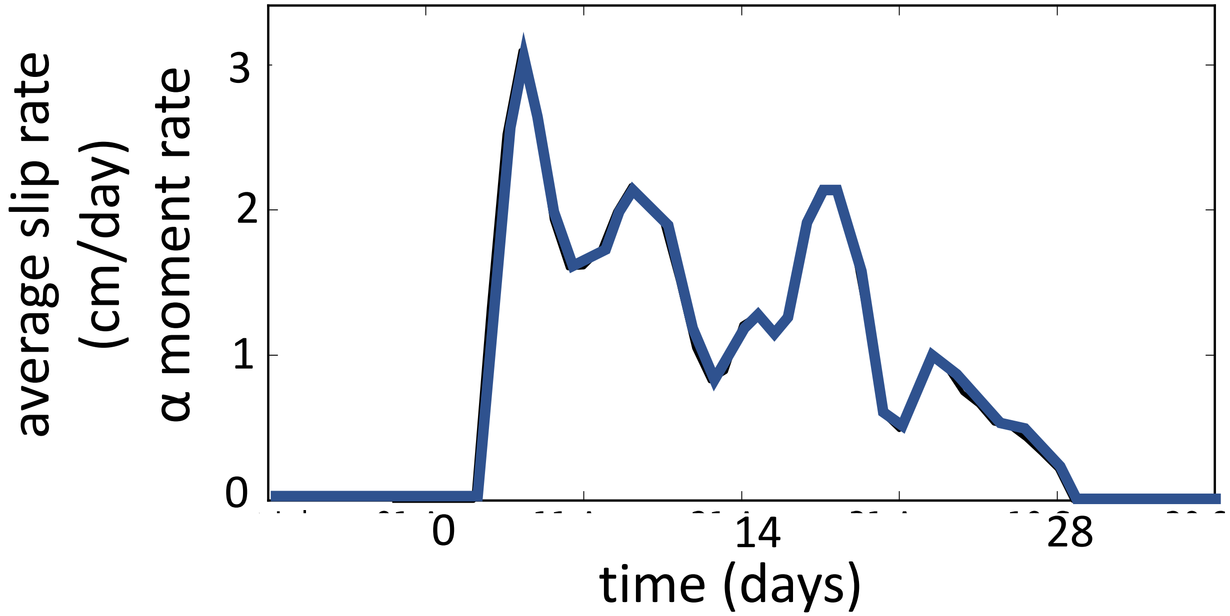
Slow earthquakes come in a range of sizes and durations

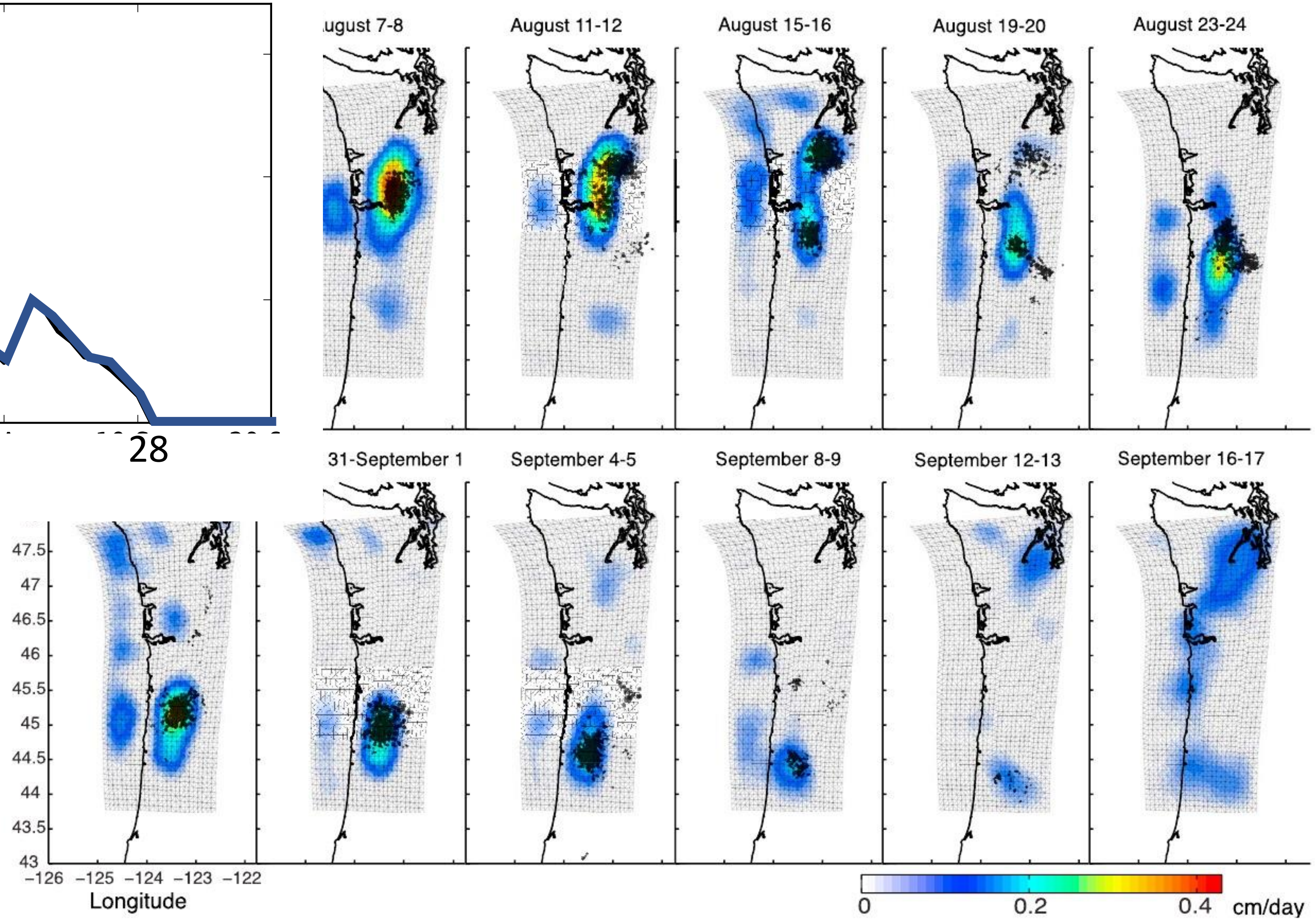
Moment rate spectra are *consistent* with a single continuum of slow earthquakes

The continuum would

- exclude several physical processes
- could indicate size-dependent shear zone properties

GPS-based observations of slow slip heterogeneity



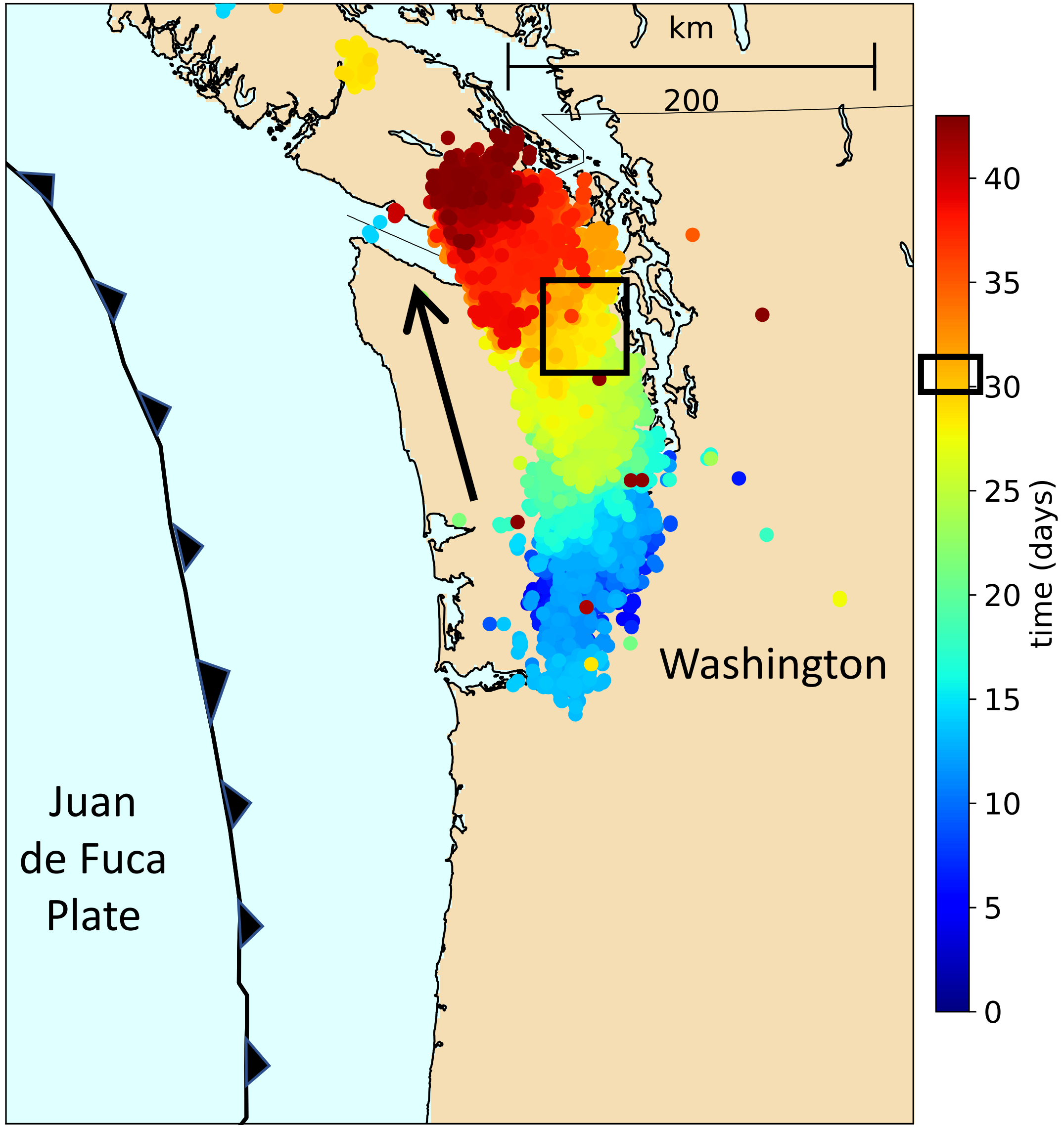


Bartlow et al, 2011

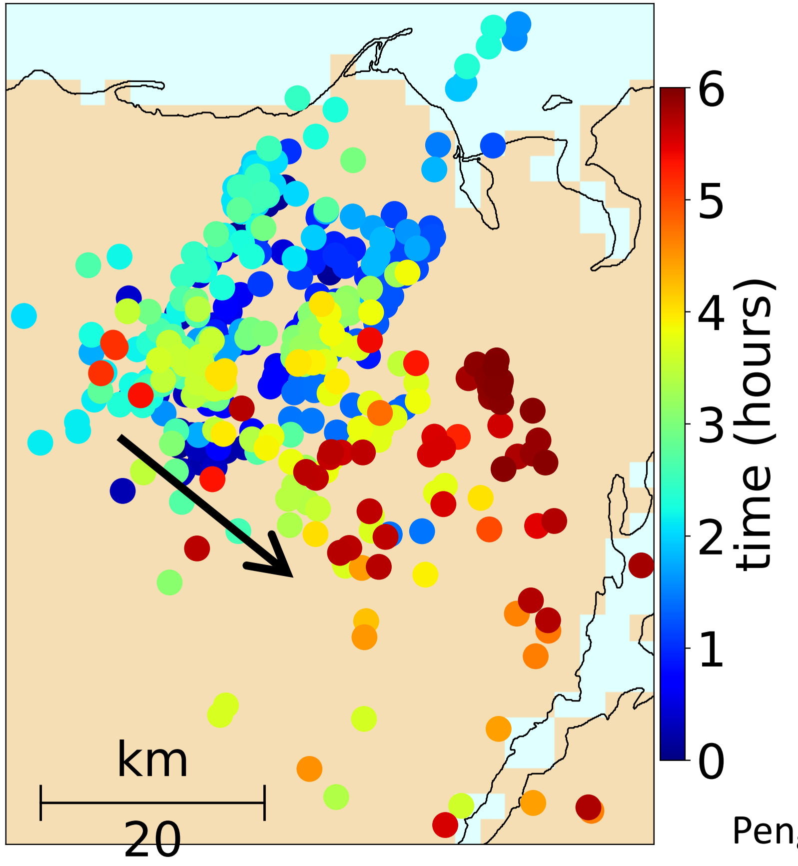
slip rate (cm/day)

Proposed mechanism	Creates slow earthquakes?	Predicts abundant events?	Complexity on simple faults?	Size-dependent slip rates?
Minimum asperity size Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013	yes	yes	no	no
Brittle and viscous deformation Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;	yes	yes	no?	via fault viscosity
Shear-induced fluid pressure changes Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.	yes	yes	no	via fault width
Frictional weakening and strengthening patches Skarbek et al, 2012; Luo and Ampuero, 2017; Yabe et al, 2017	yes	no	no?	via v-s fraction
Size-limited weakening areas? Liu and Rice, 2007; Rubin, 2008; Skarbek et al, 2012	yes	no	no	no
Fluid addition to viscous	yes	yes	??	??

Slow earthquake complexity: hours-long sub-ruptures



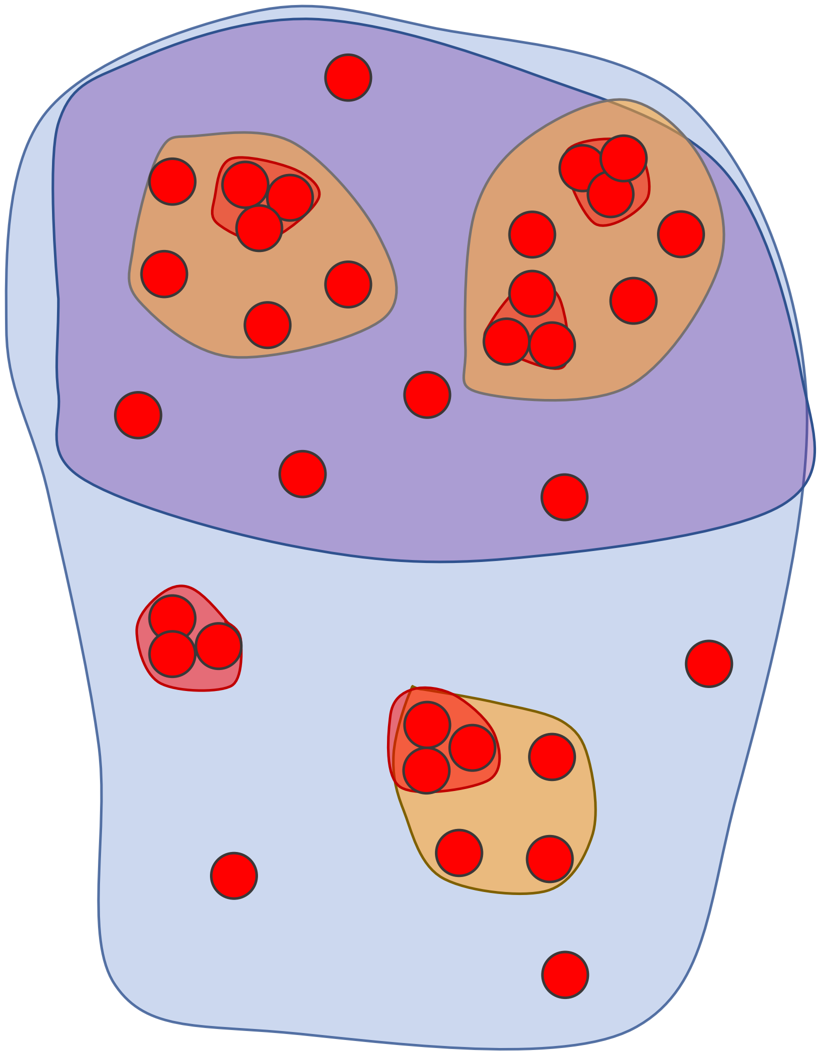
Wech et al, 2009



Peng and Rubin, 2016

Rupture speeds 10 to 50 times faster than main event

Option 1: Clusters of brittle failures

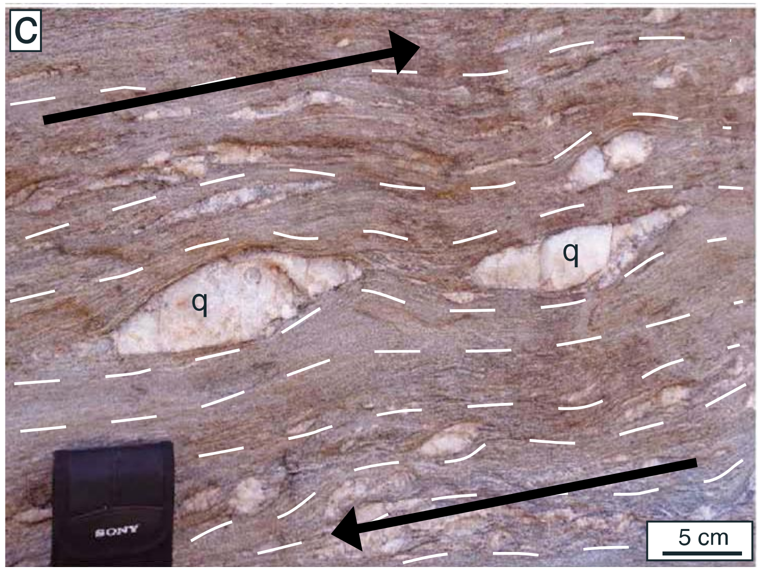


Whole slipping area: small brittle fraction → low slip rate

Upper half: moderate brittle fraction → moderate slip rate

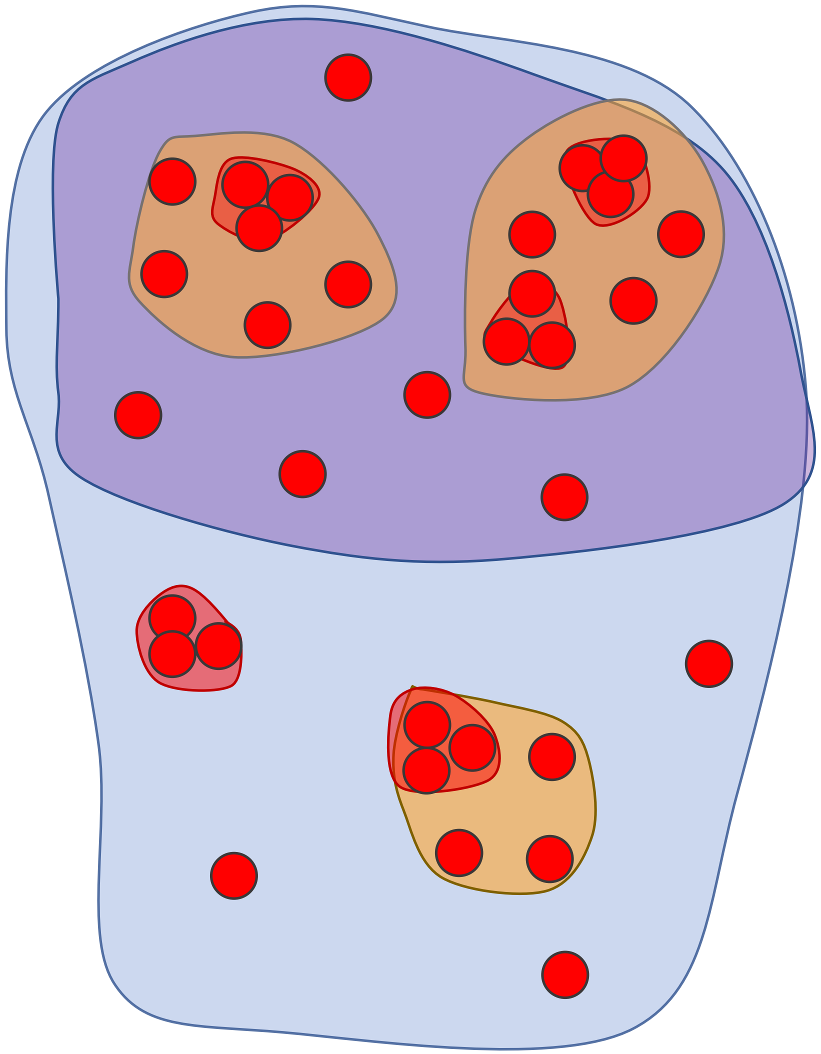
Smaller clusters: higher brittle fraction → higher slip rate

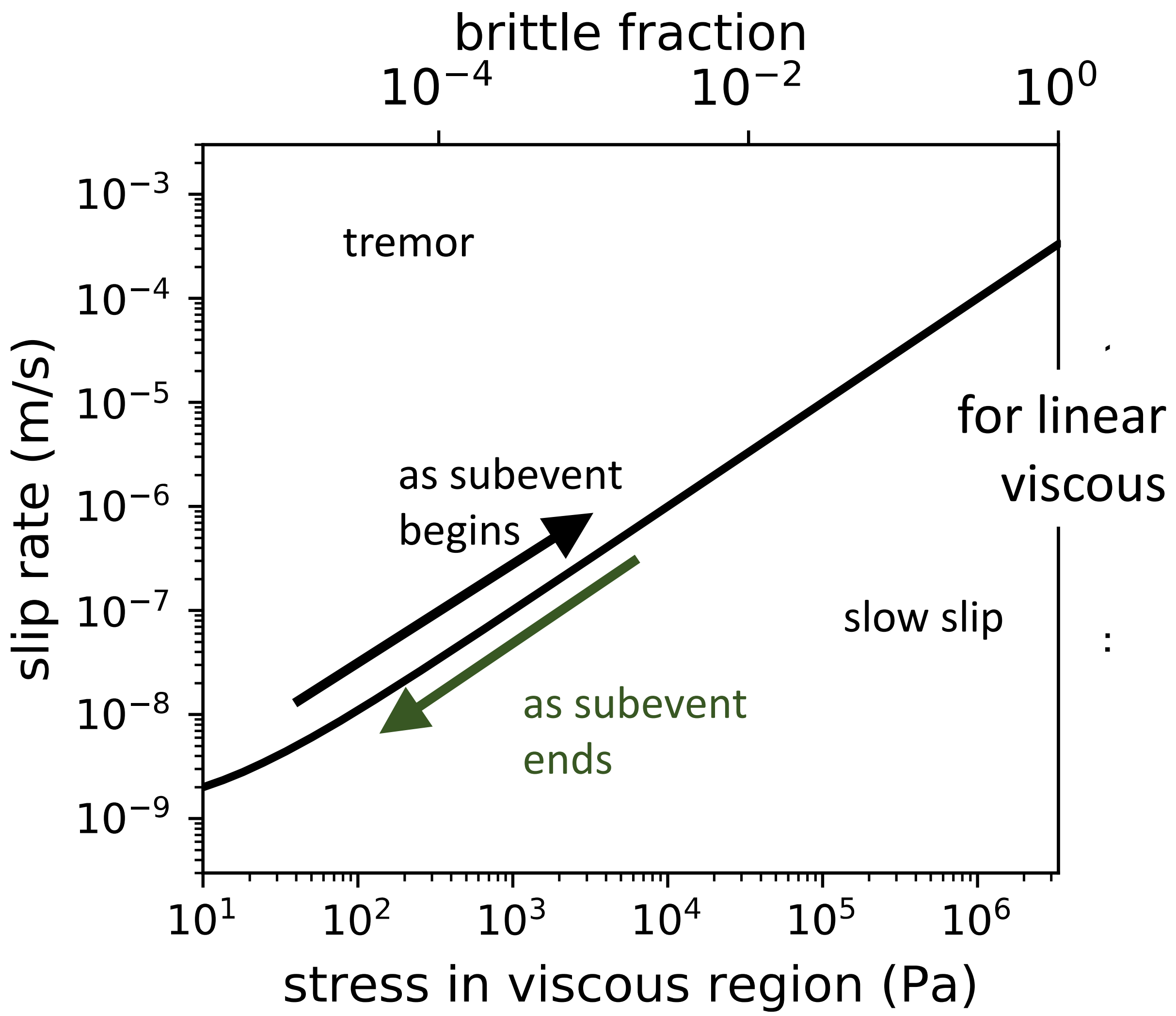
Smallest clusters: highest brittle fraction → highest slip rate



Fagereng et al, 2014

Option 1: Clusters of brittle failures

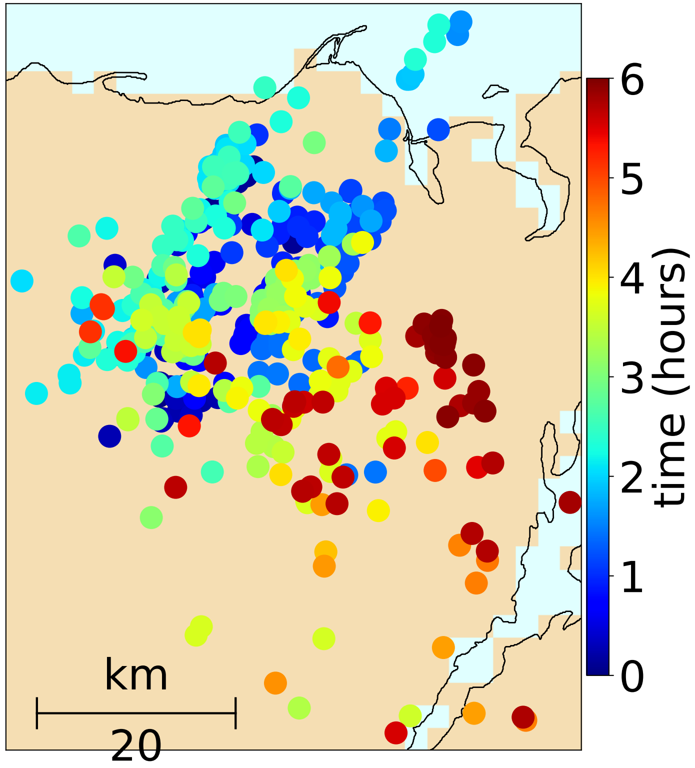




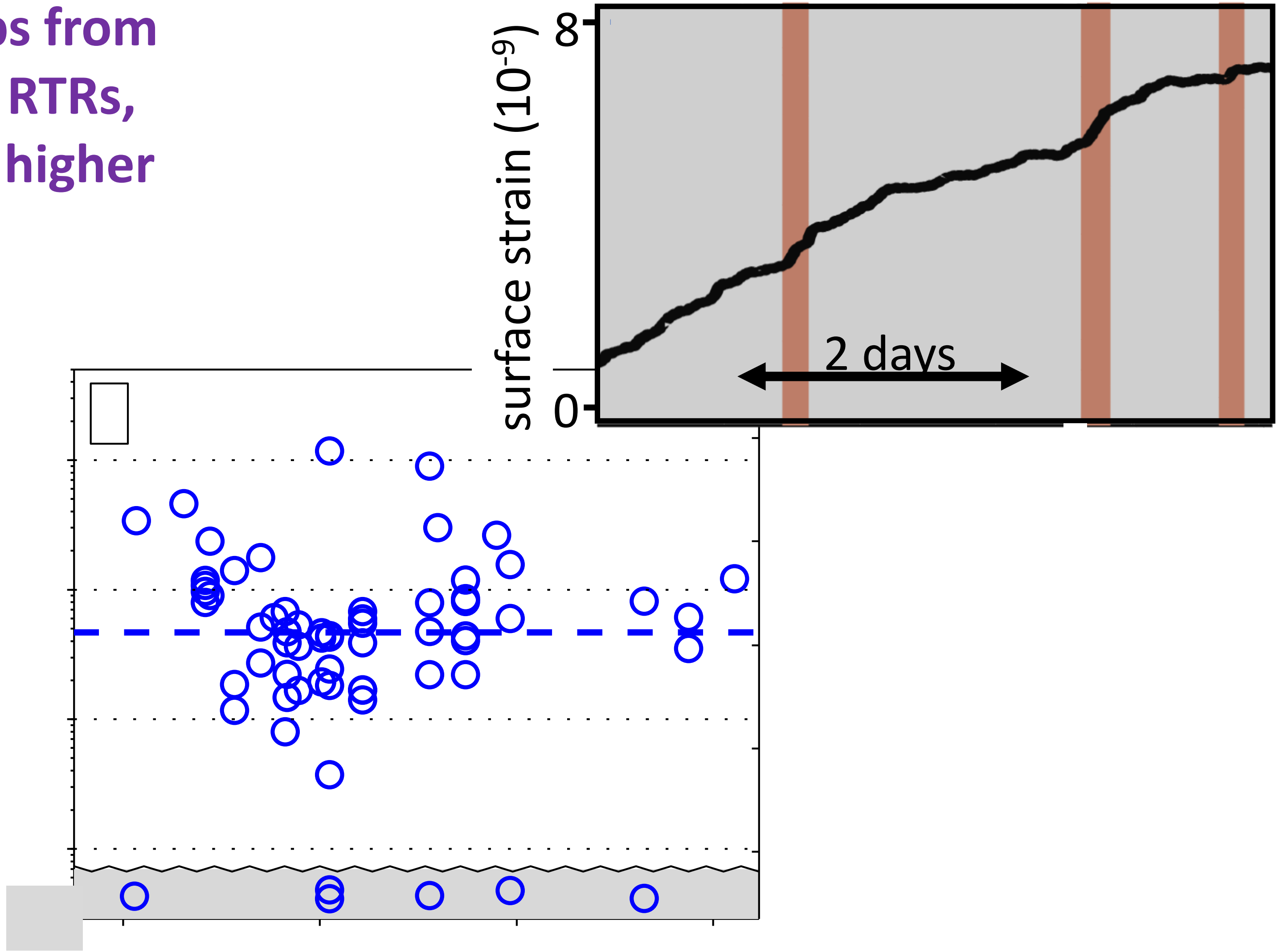
→ Larger stress drops in smaller, faster events?

Option 1: Clusters of brittle failures

But we don't infer high stress drops from strain observations of hours-long RTRs, even though slip rates are 5 times higher

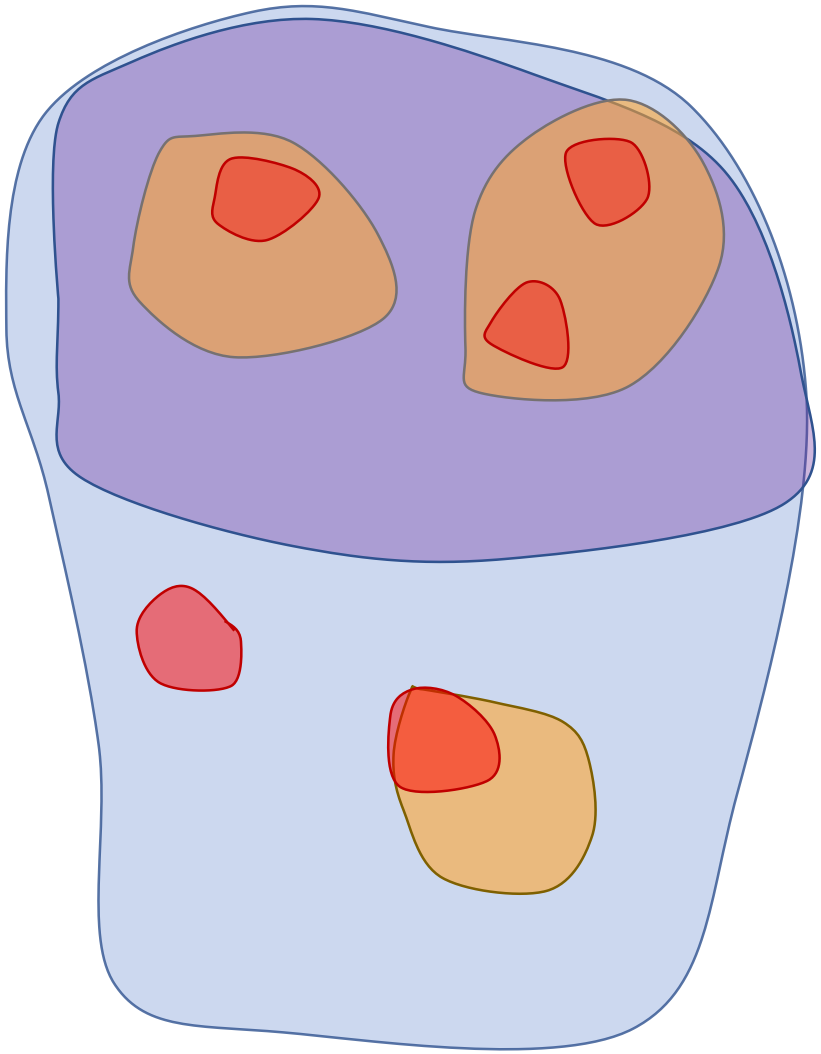


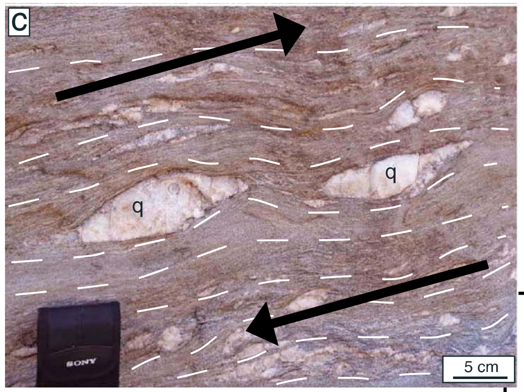
Peng and Rubin, 2016



Hawthorne et al, 2016

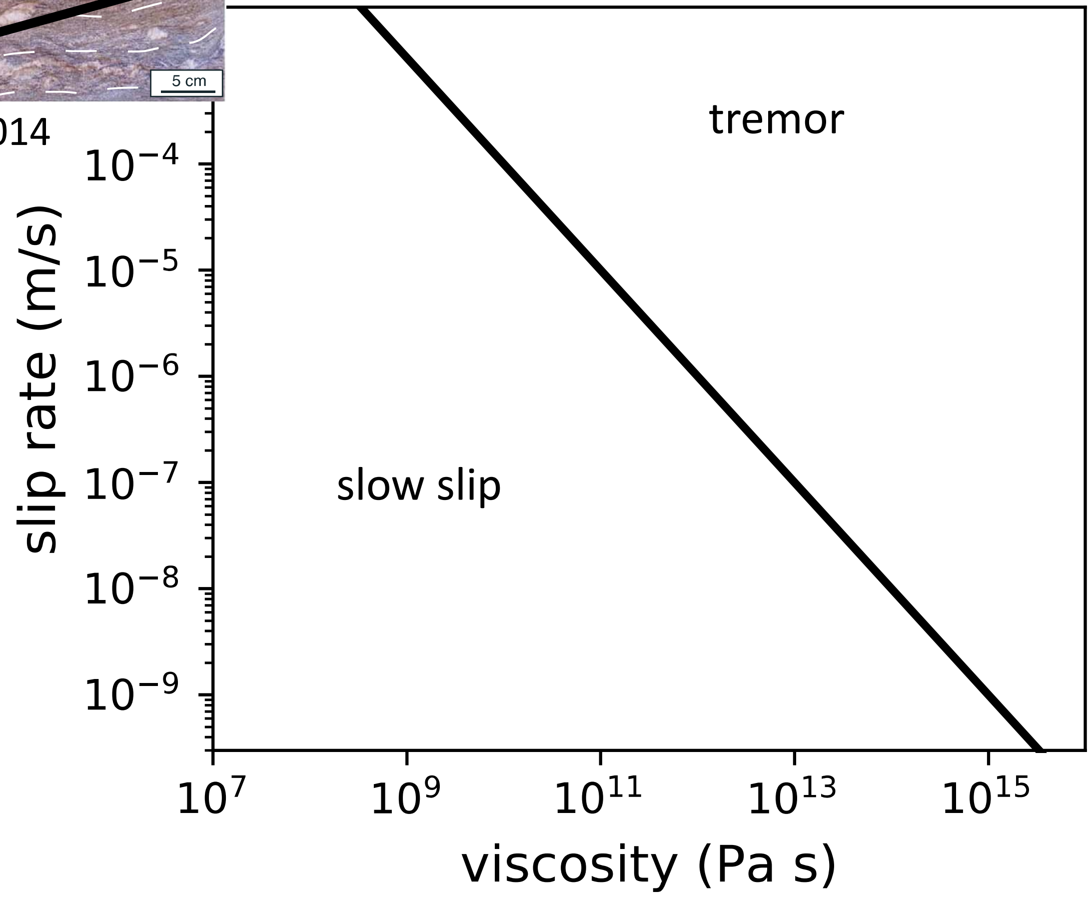
Option 2: Size-dependent fault properties





Fagereng et al, 2014

Smaller shear zones have lower viscosities?



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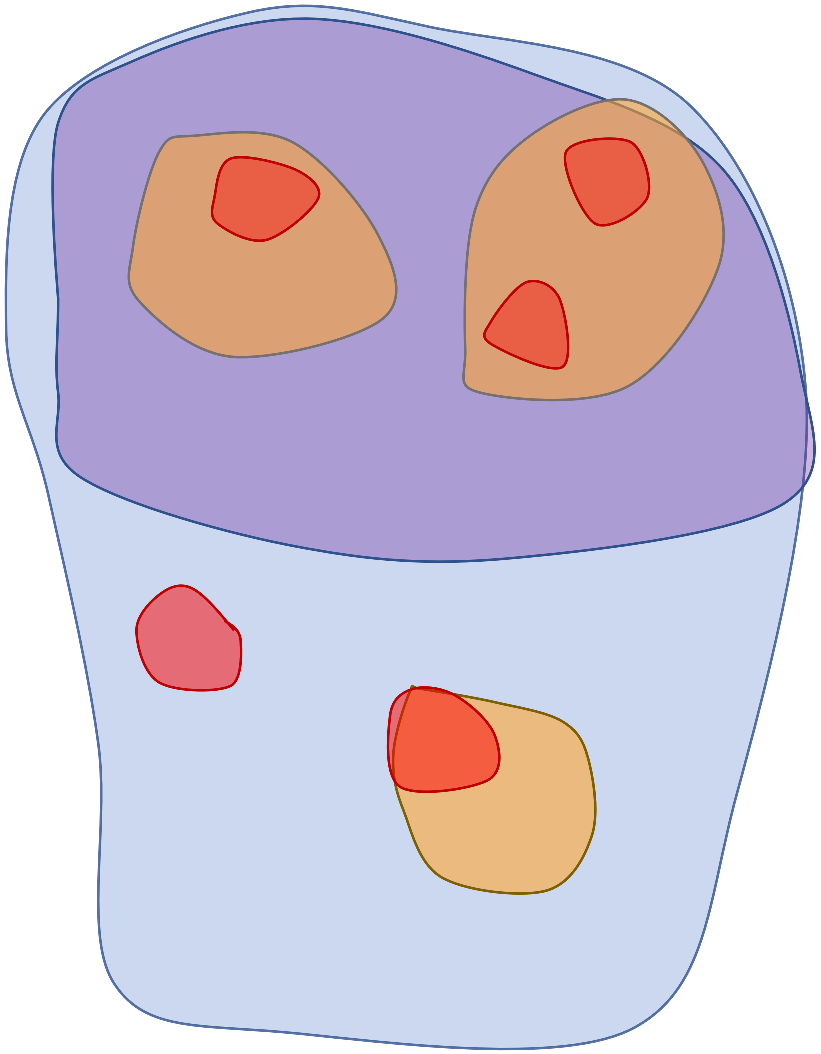
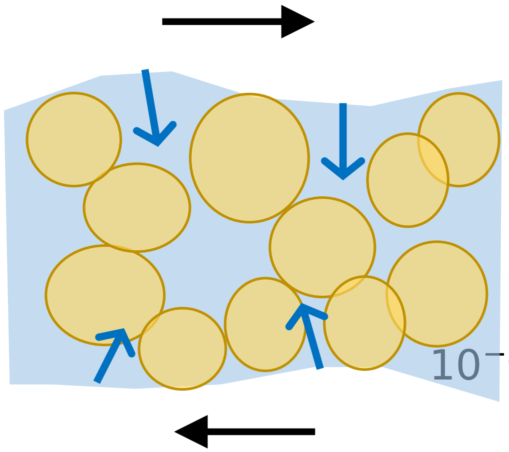
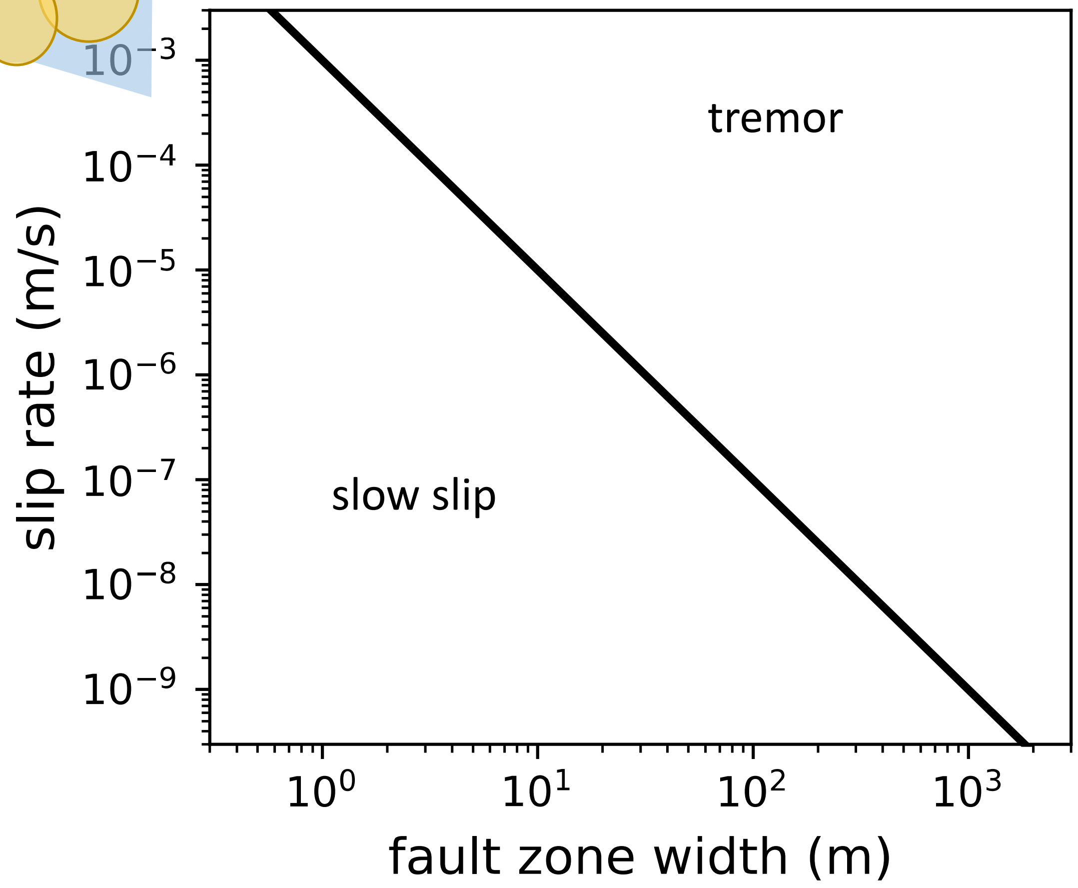




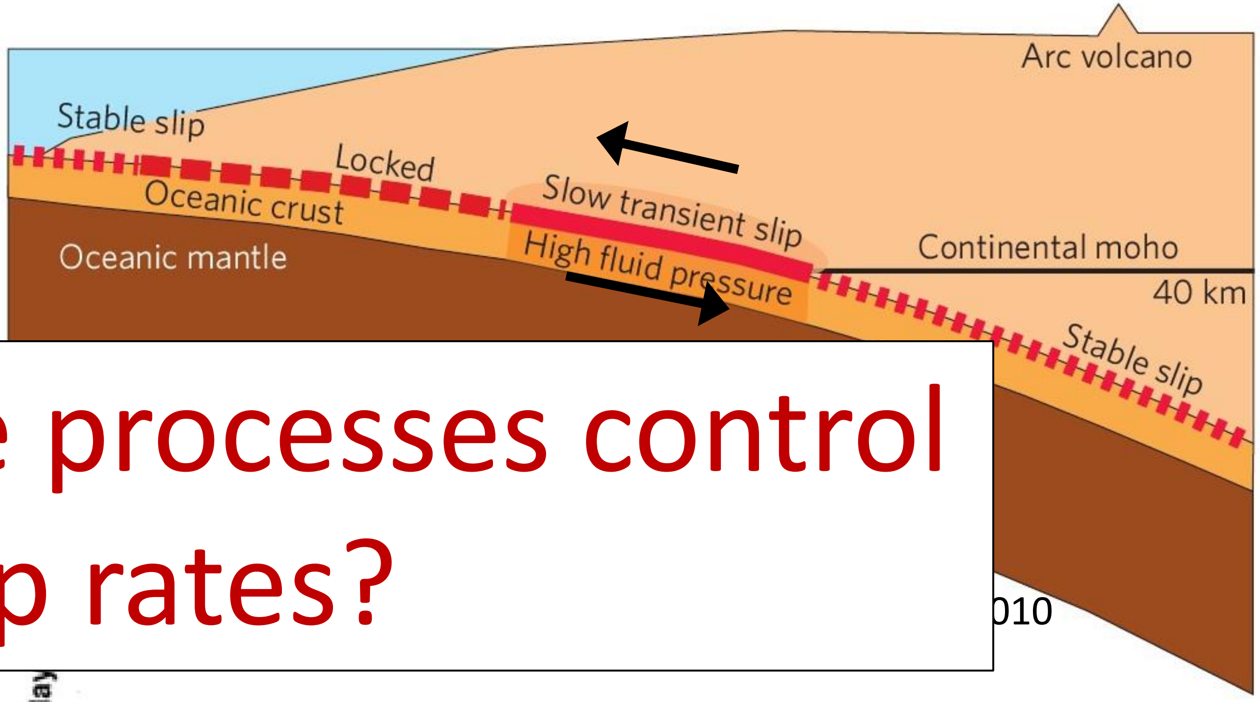
Smaller faults are narrower?
→ Faster fluid diffusion?



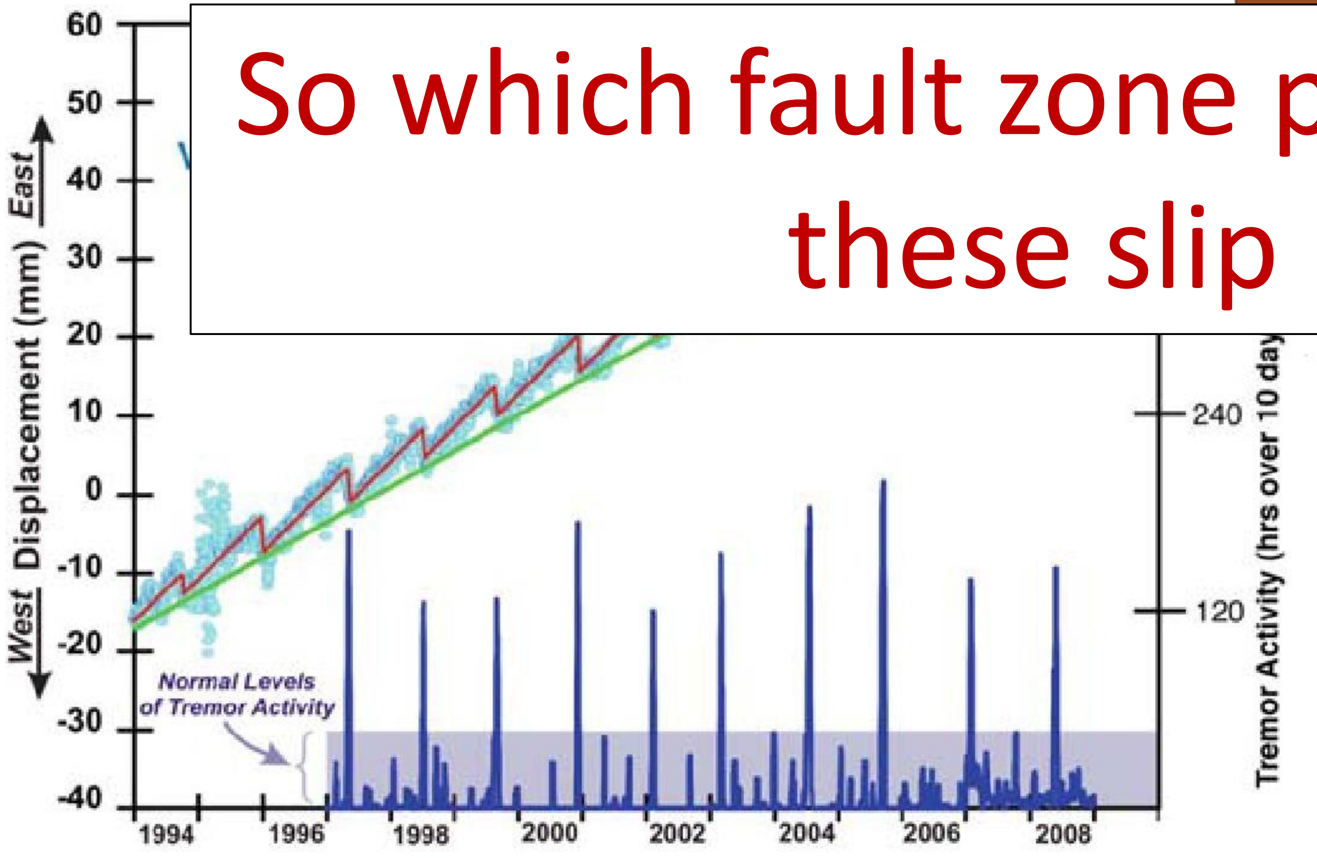
Slow slip and tremor in Cascadia

Slow slip: transient aseismic slip

- 1 month long, M 6.5 - 6.9
- Slip rates $10^{-7} – 10^{-6}$ m/s,
  100 to 1000 times plate rate



So which fault zone processes control these slip rates?



Rubinstein, 2009

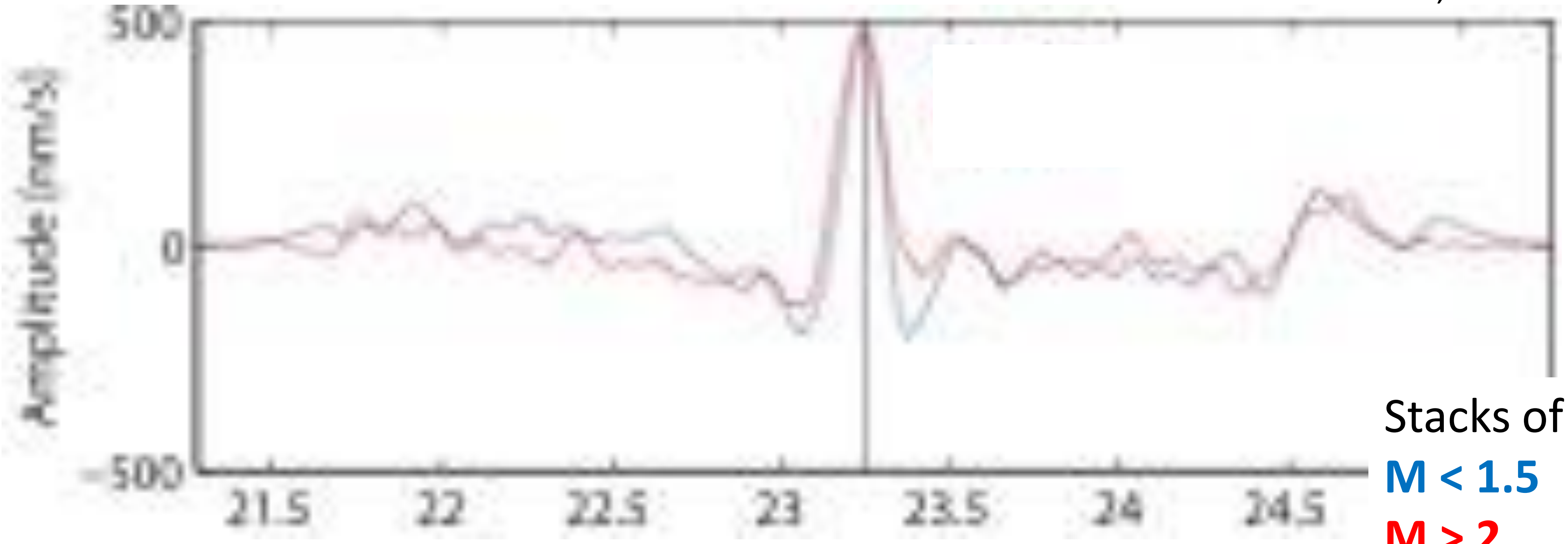
Tremor: many small but slow earthquakes

- Mostly 0.5 seconds long, *M* 1 – 2.5
- Slip rates probably 10^{-4} to 10^{-3} m/s
- 10 to 1000 times slower than most seismic wave-limited earthquakes

What about tremor's characteristic durations?

Within in the tremor band, duration appears independent of moment

Bostock et al, 2015



Stacks of LFEs with
M < 1.5
M > 2

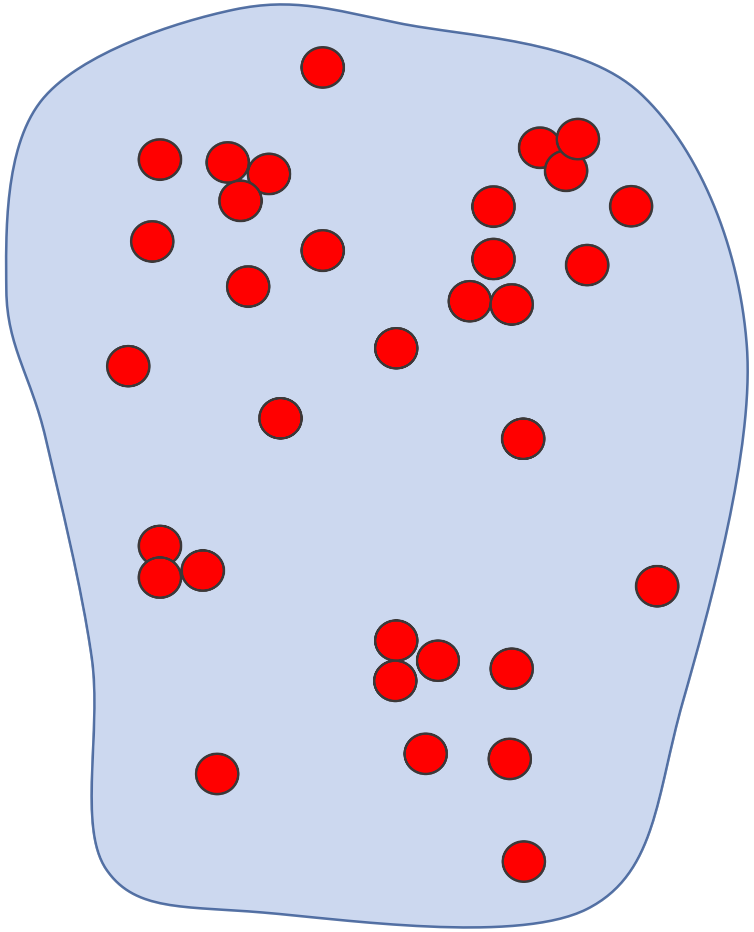
→Tremor is different from slow slip?

→Slow earthquakes occur on asperities, and we've only identified some of them?

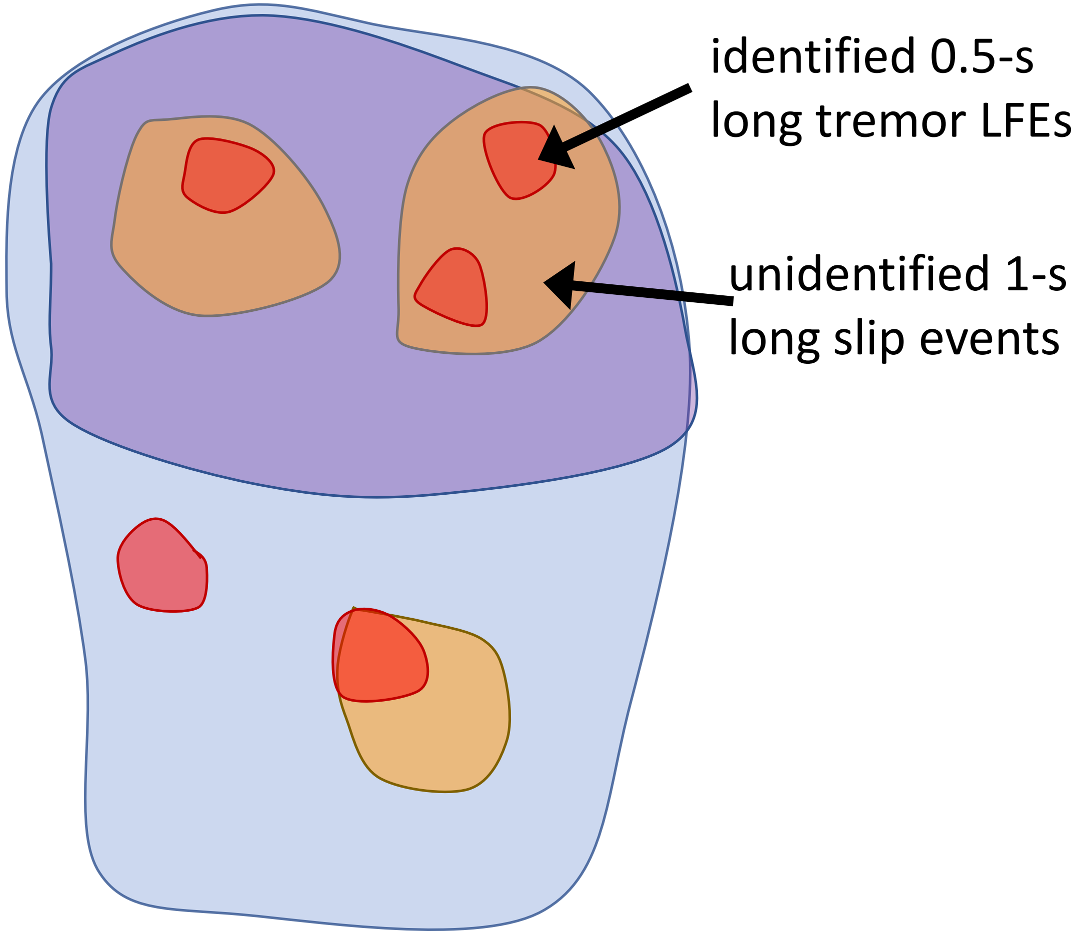
What about tremor's characteristic durations?

Within in the tremor band, duration appears independent of moment (Bostock et al, 2015)

→Tremor is different from slow slip?

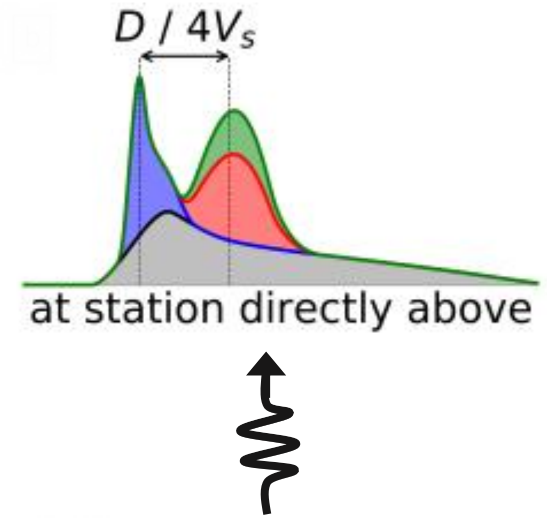


→Slow earthquakes occur on asperities?



Is tremor really fast enough to be an earthquake?

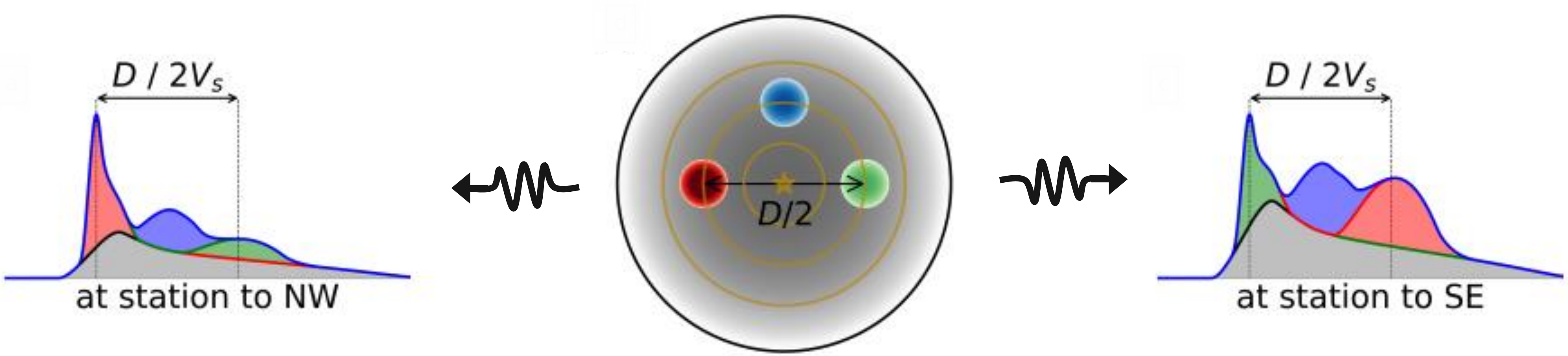
Does it rupture at near-shear wave speeds?



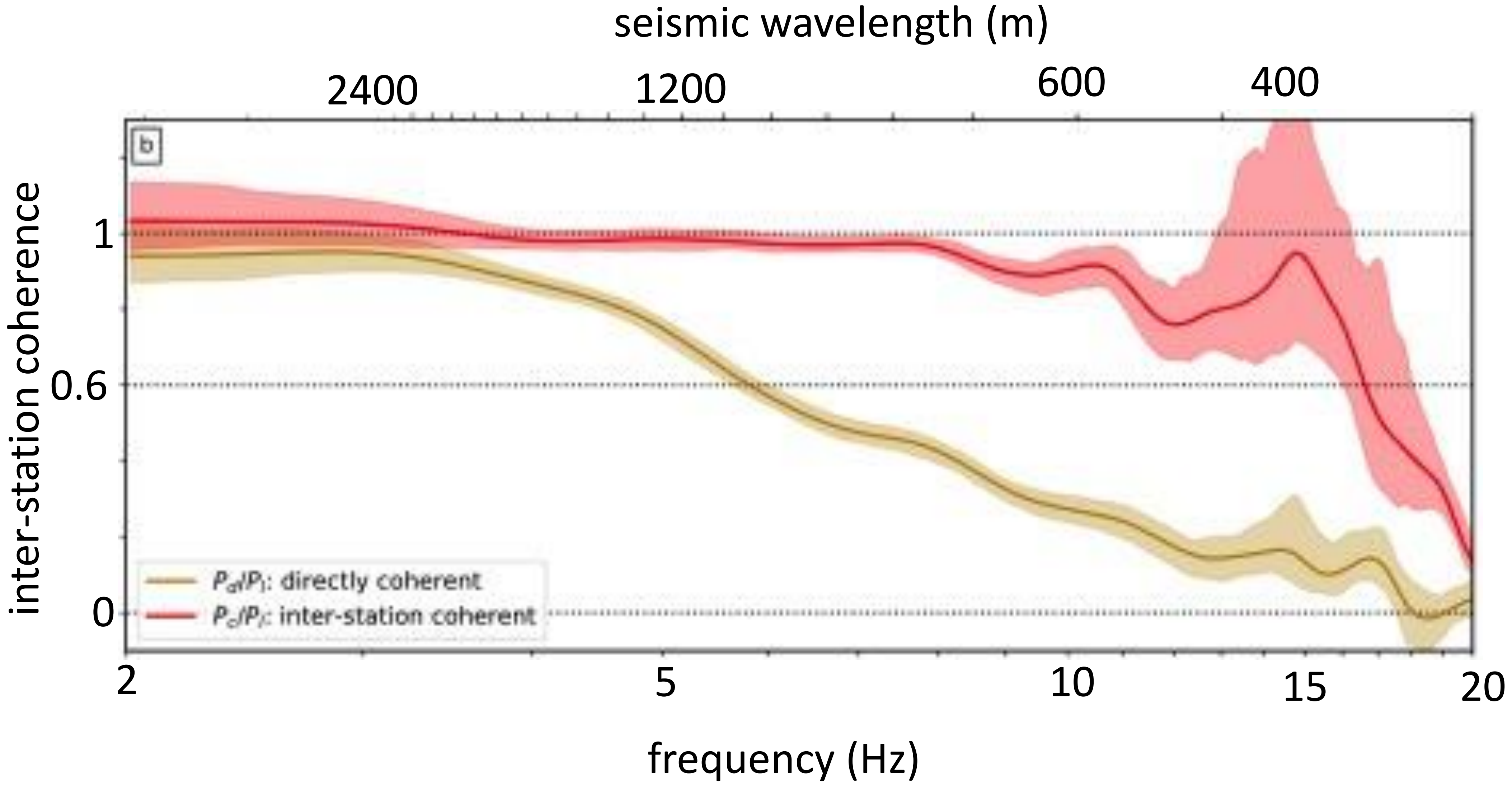
LFE durations in Parkfield: 0.2 s (Thomas et al, 2016)

To estimate rupture extent, look for seismic waves generated at a range of locations

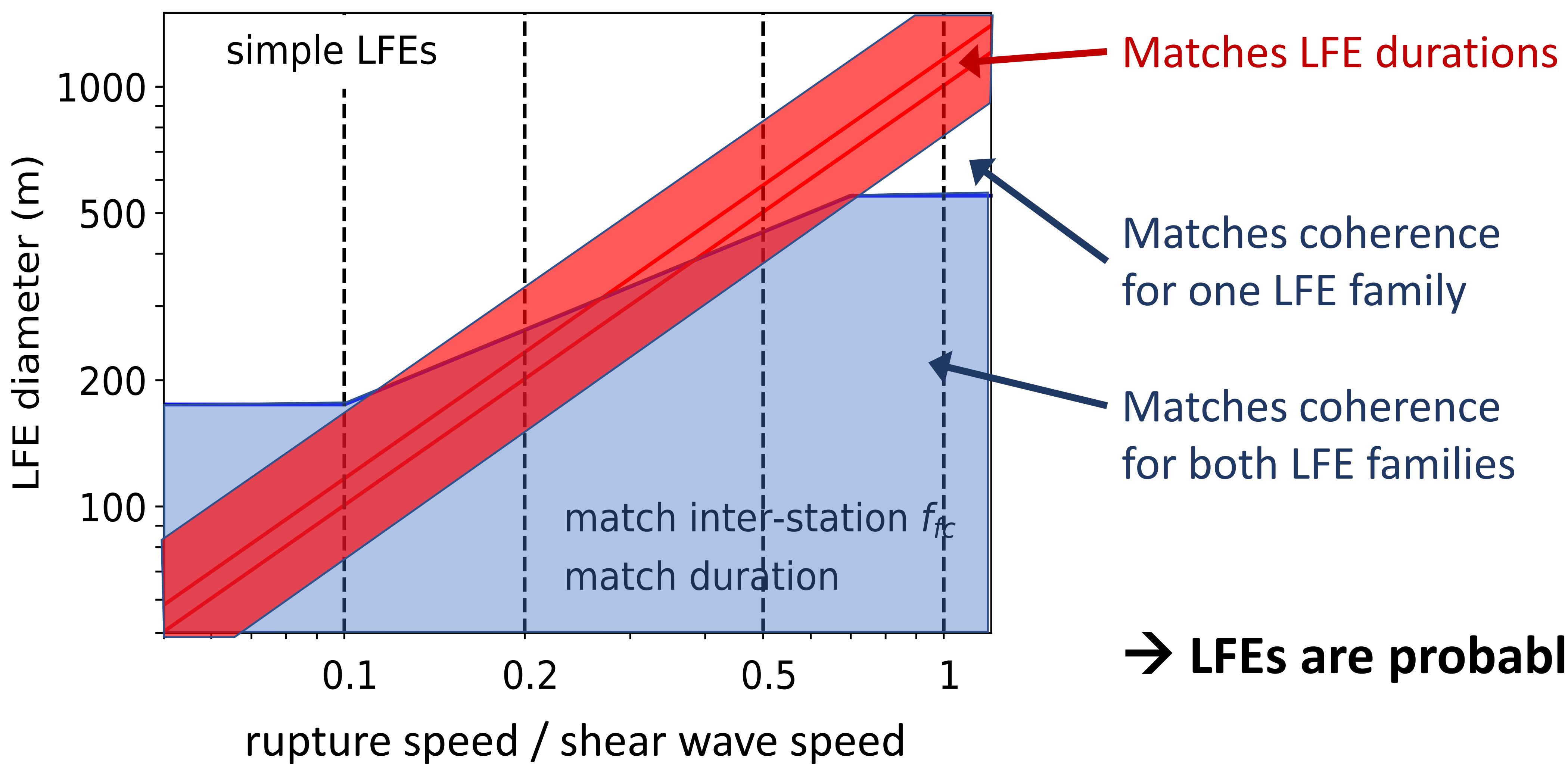
- Inter-station differences visible only at high frequencies, at seismic wavelengths shorter than D



Inter-station coherence

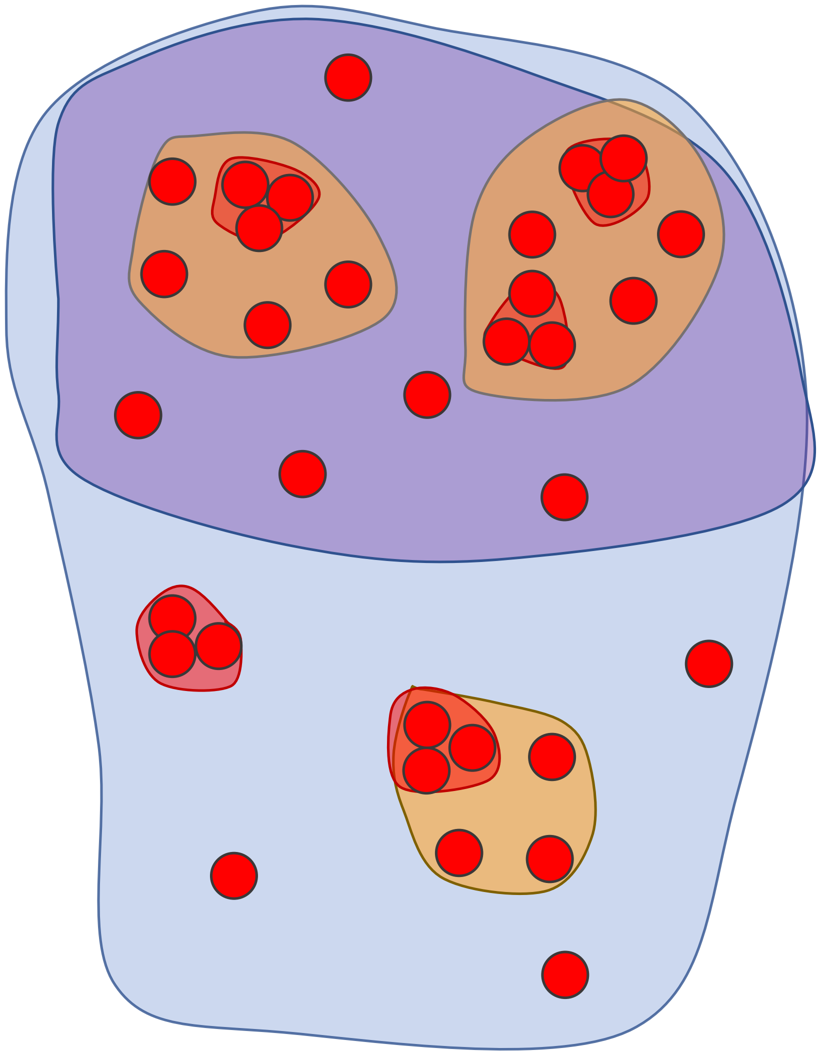


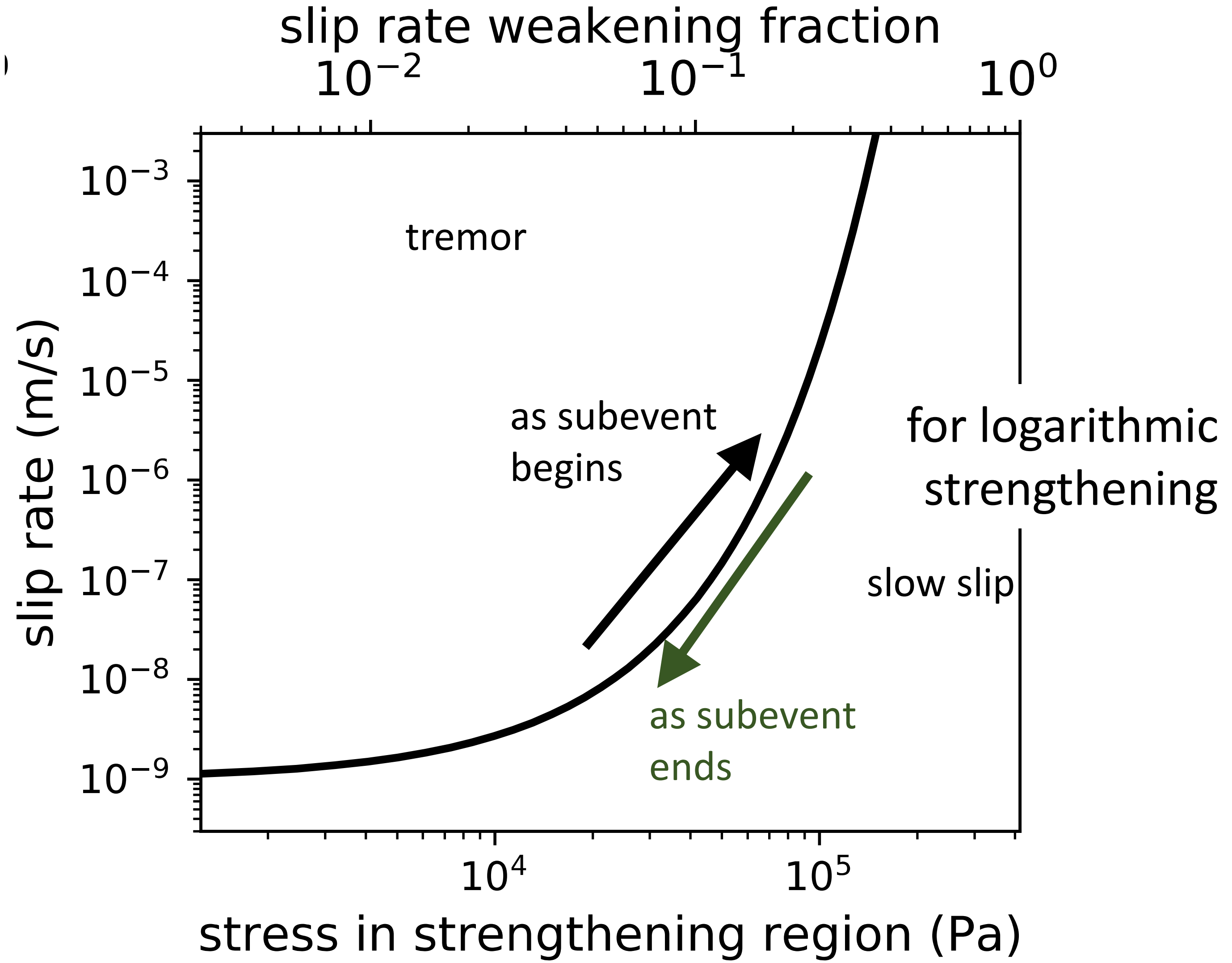
Allowable diameters and rupture speed



→ LFEs are probably slow

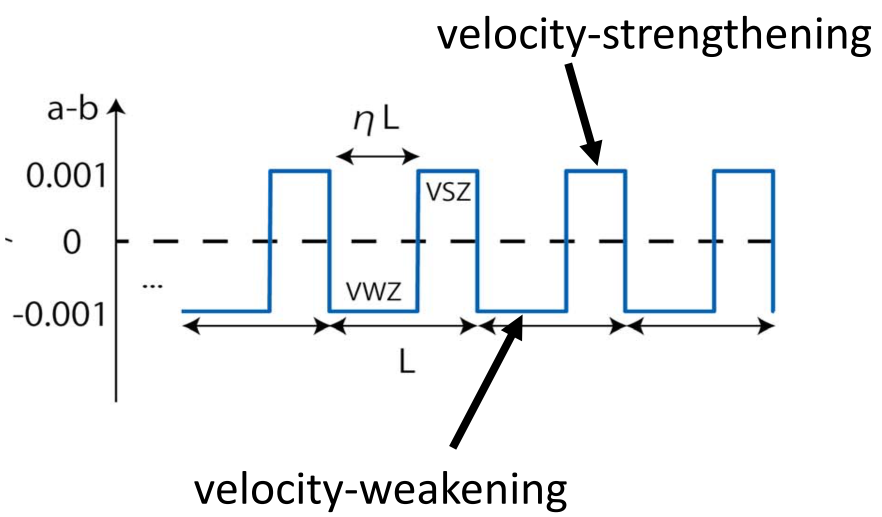
Option 1: Clusters of brittle failures

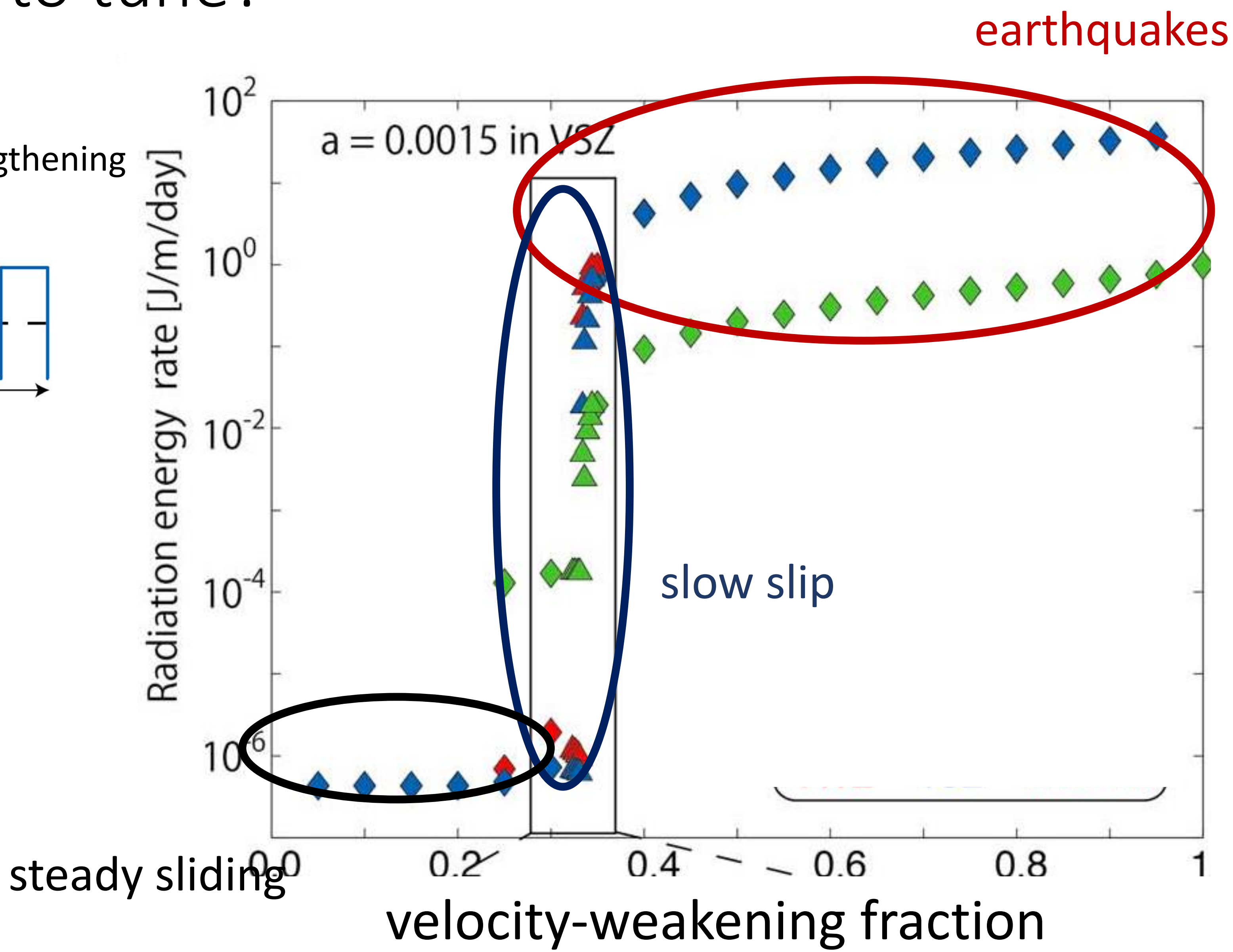




→ Stress drops okay, but hard to tune

Mixed frictional weakening and strengthening: too hard to tune?





Yabe and Ide, 2017

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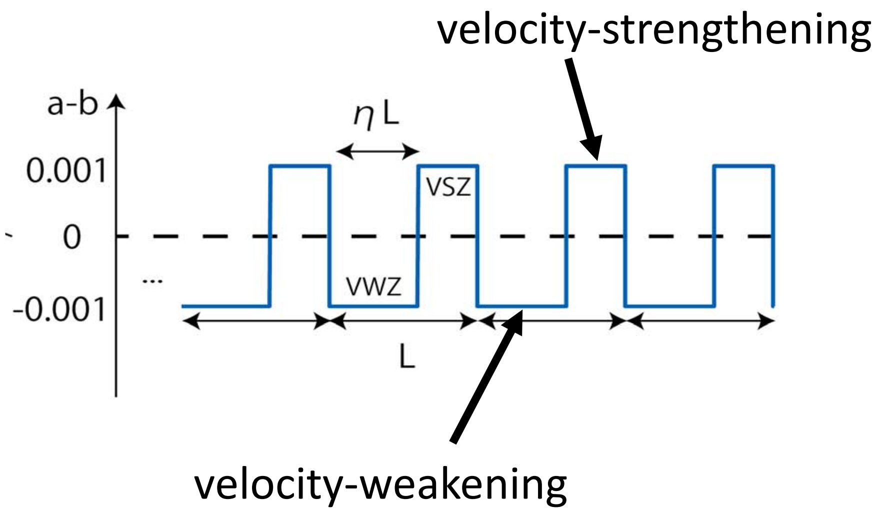
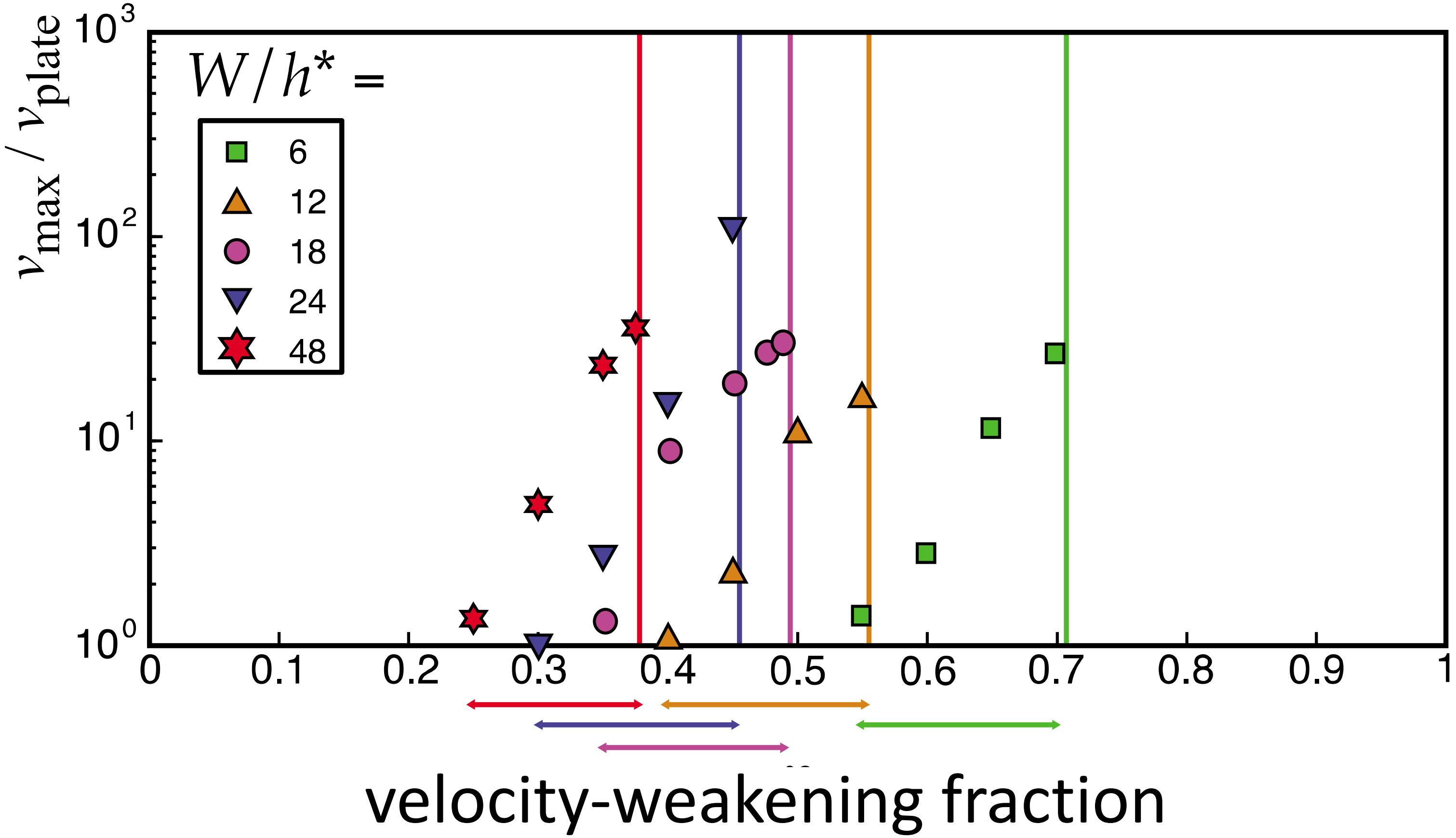


Yabe and Ide, 2017

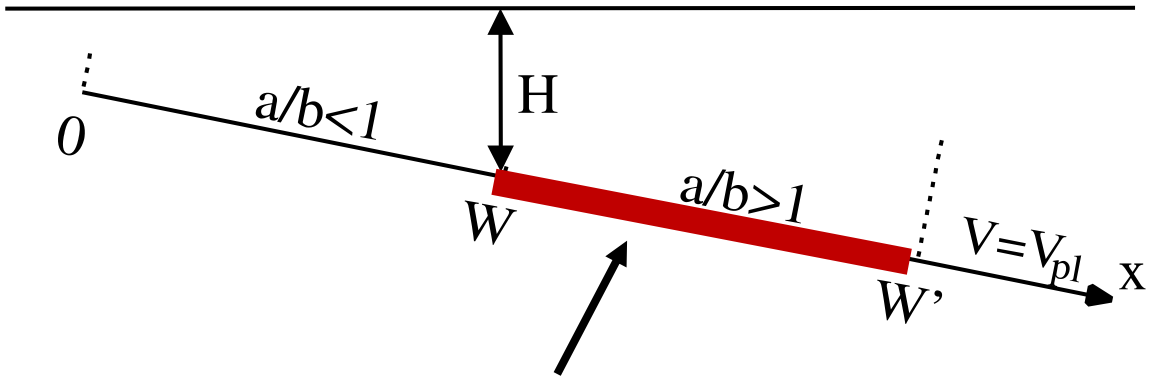


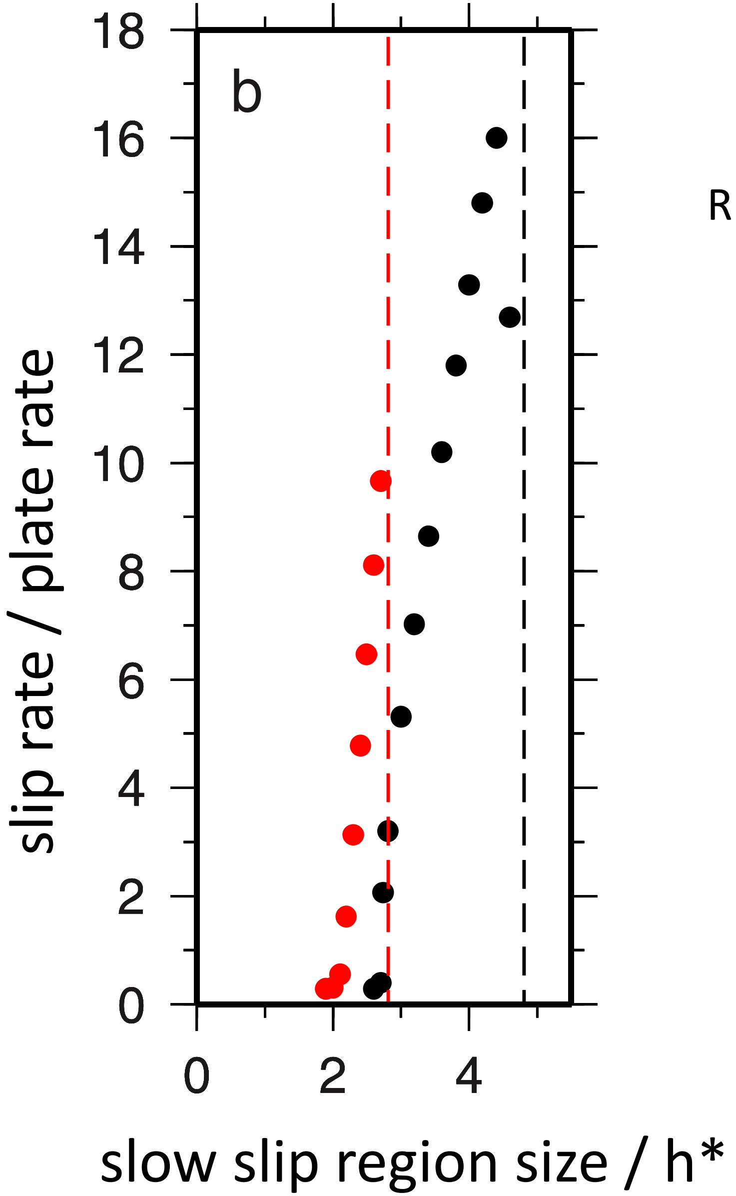
Skarbek et al, 2012

Characteristically sized velocity-weakening segment: too hard to tune?

Large enough for acceleration, too small for instability?

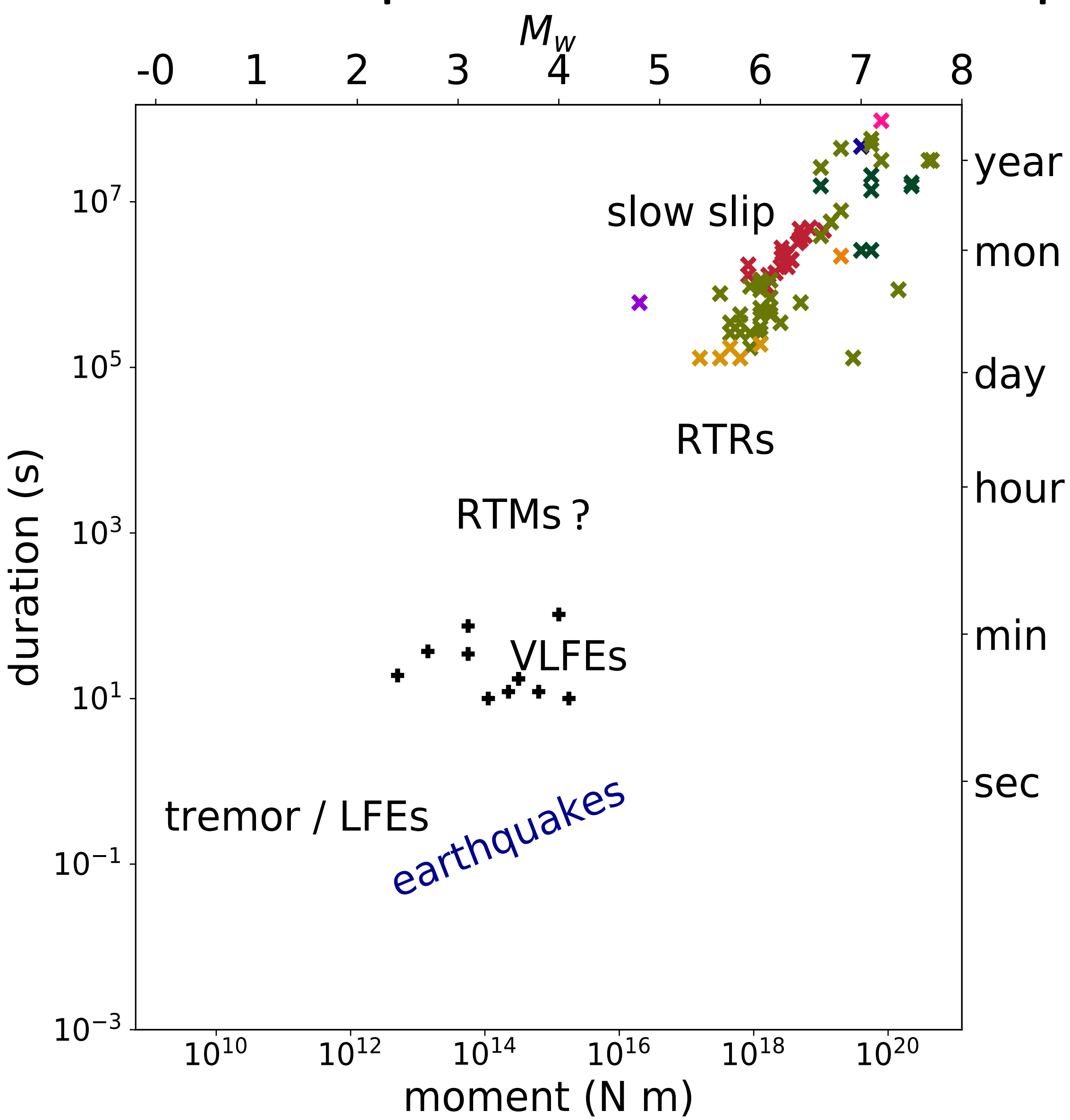
Liu and Rice, 2005, 2007





Rubin, 2008

Slow slip and tremor: 2 processes or 1 continuum?



Moment rate variability consistent with a single continuum of slow earthquakes with moment ~ duration

After Ide et al, 2007; Gao et al, 2012

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Tremor: numerous small but slow earthquakes

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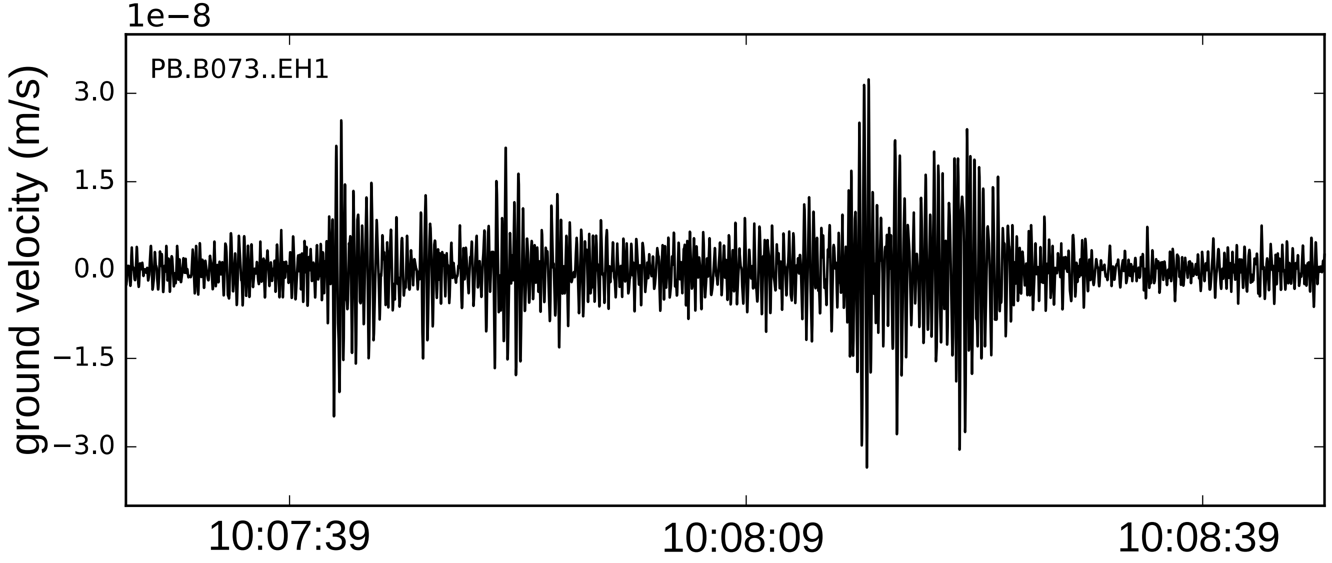
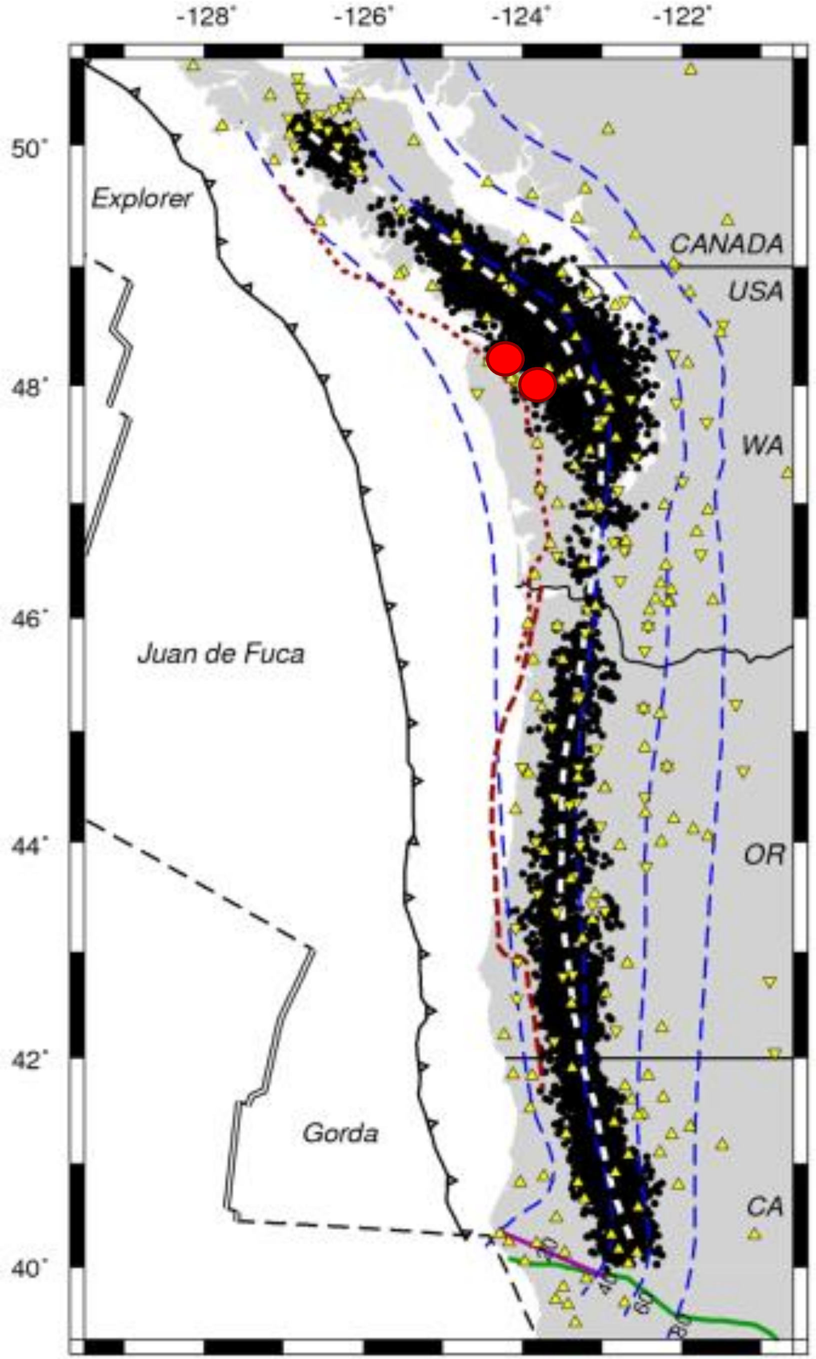
- Slip rates probably 10^{-4} to 10^{-3} m/s

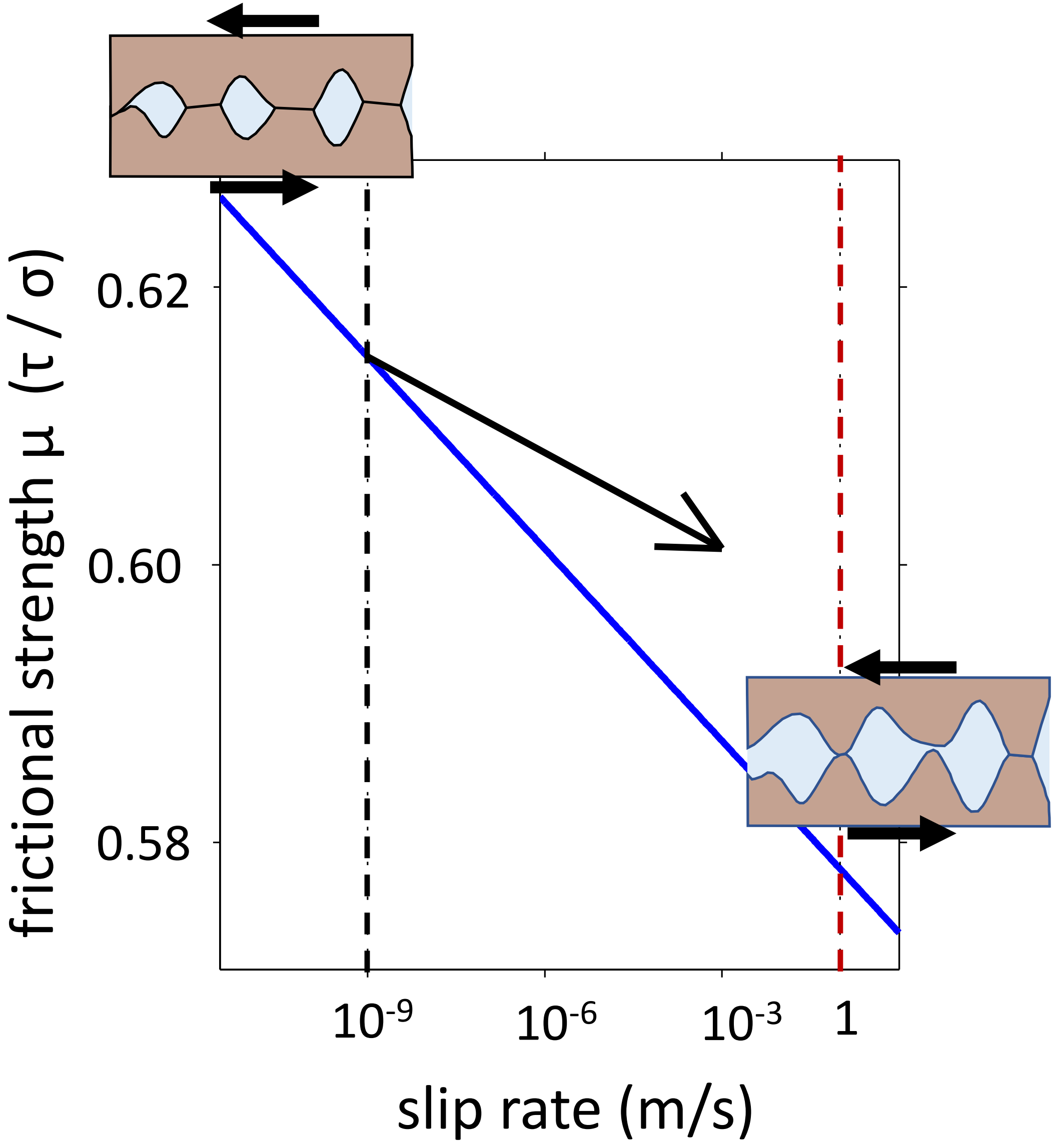




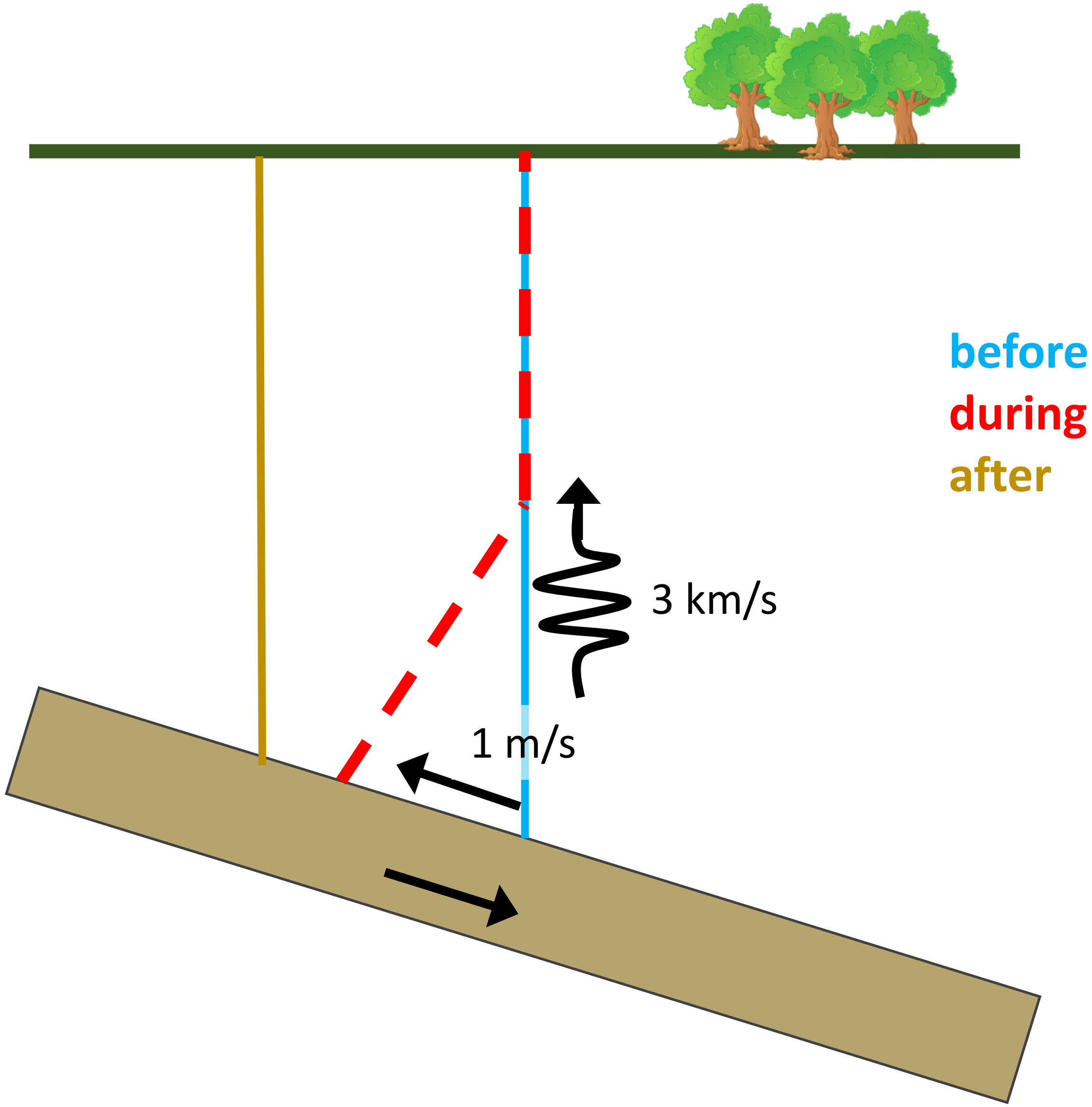
So which physical processes control these slip rates?

Boyarko et al, 2015

What limits earthquake slip rates?



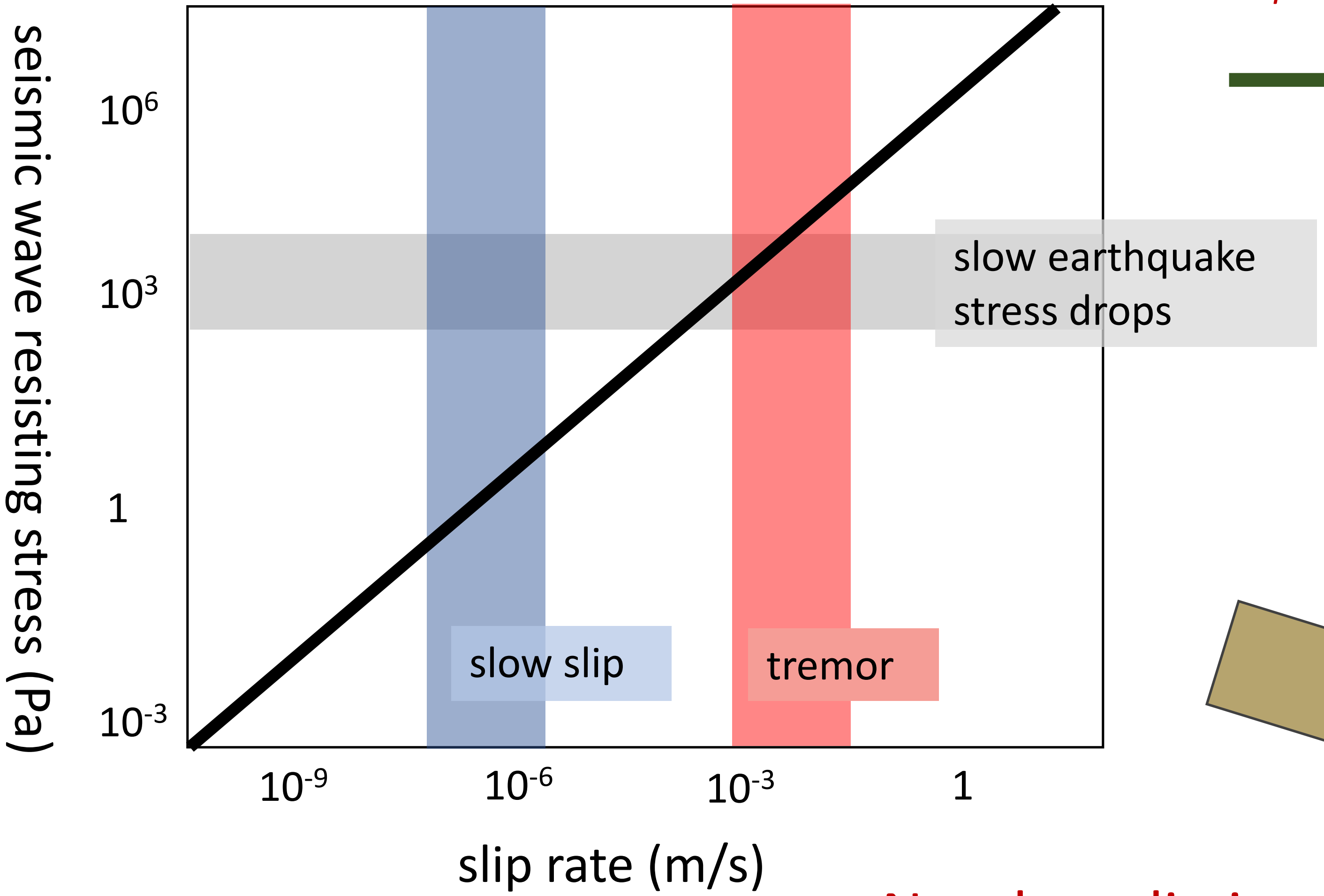
Seismic waves

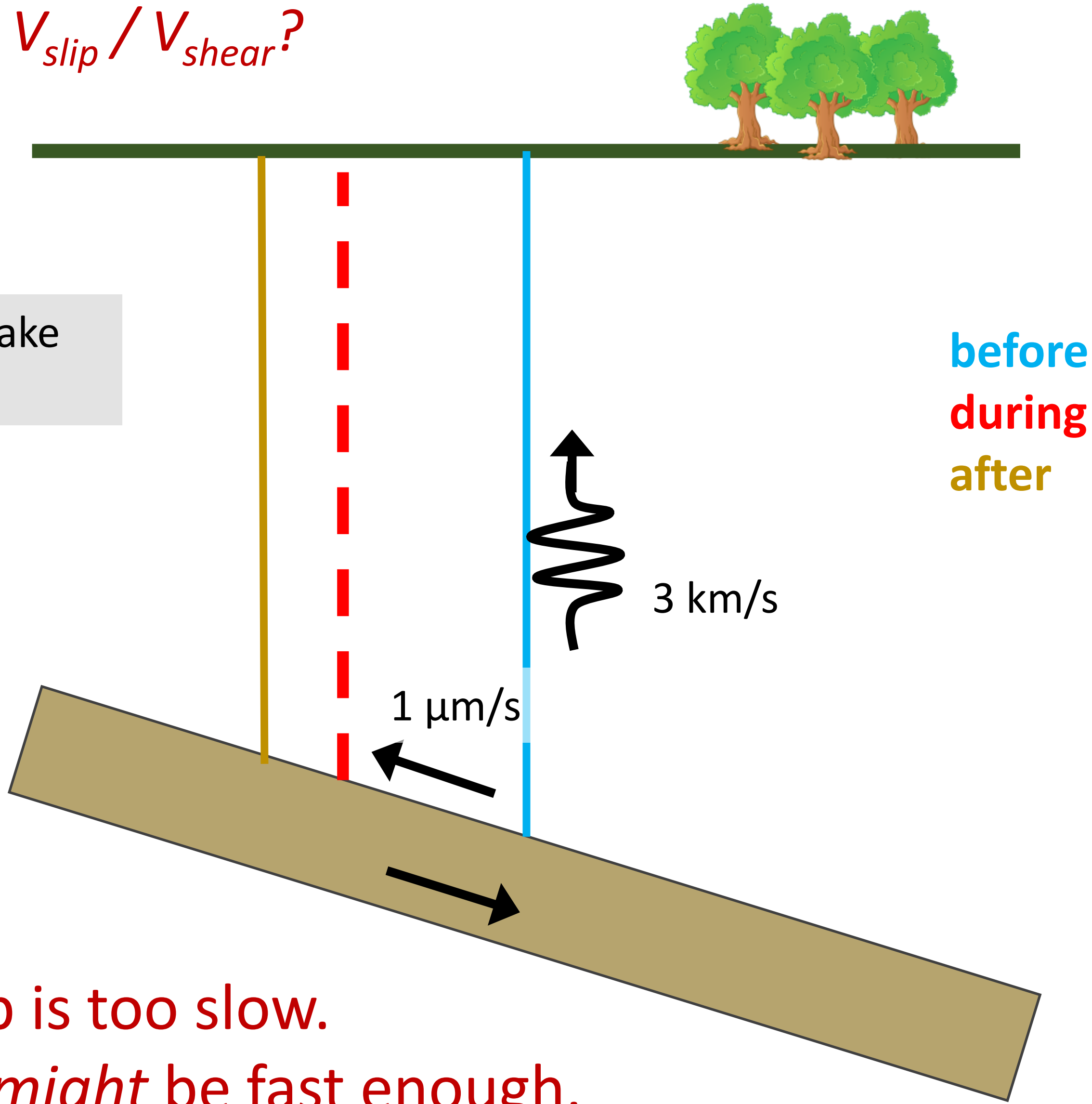


Do seismic waves limit slow slip slip speeds?

frictional weakening = elastodynamic stress?

stress drop = $G\ V_{slip} / V_{shear}$?





No, slow slip is too slow.

But tremor *might* be fast enough.

Abundant slow earthquakes