Earthquake physics from small to global scales

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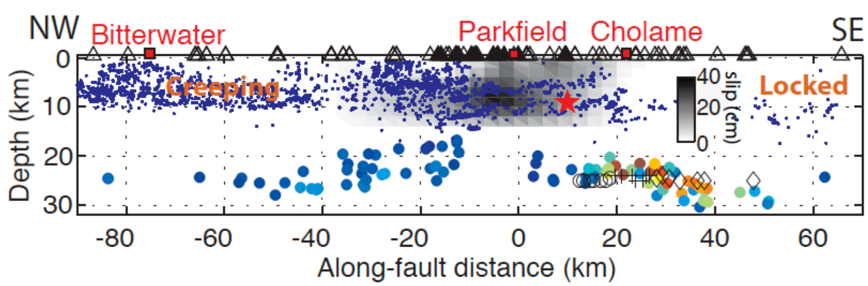
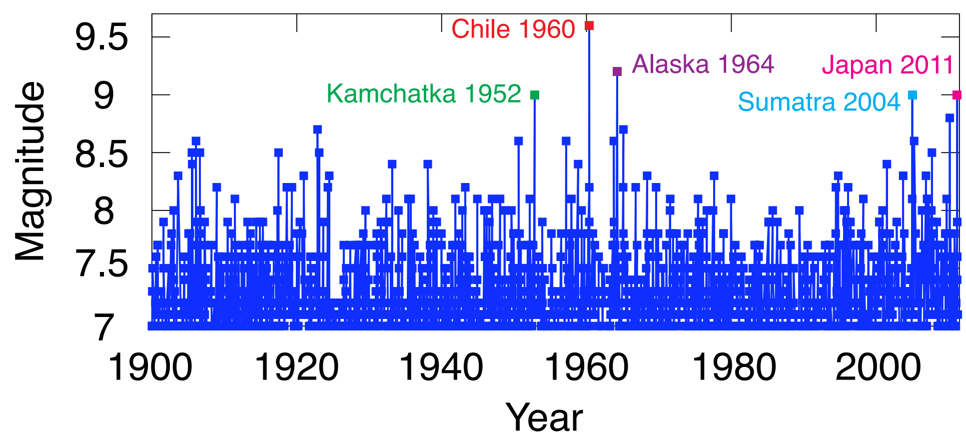
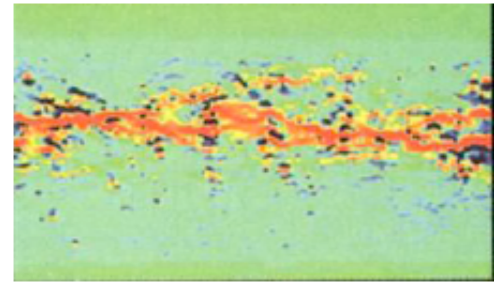
Small scales – tectonic tremor



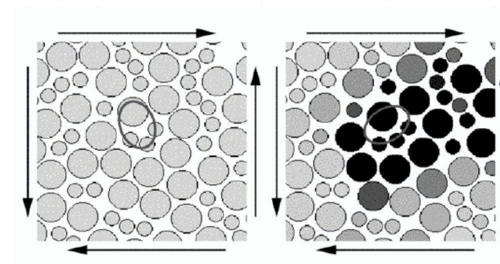
Global scales – megaquakes

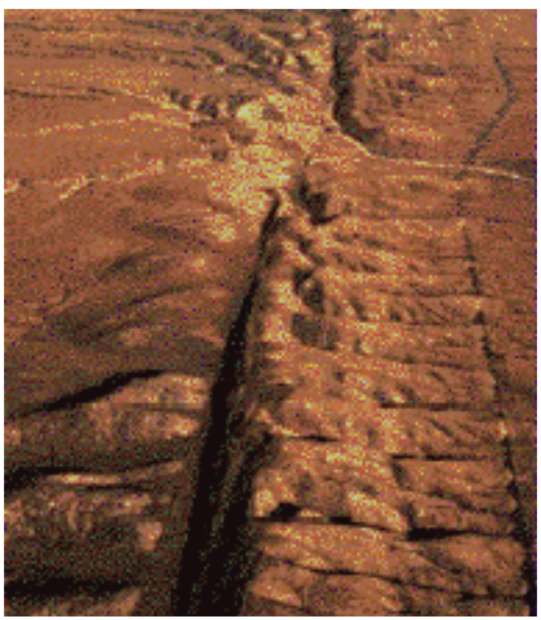


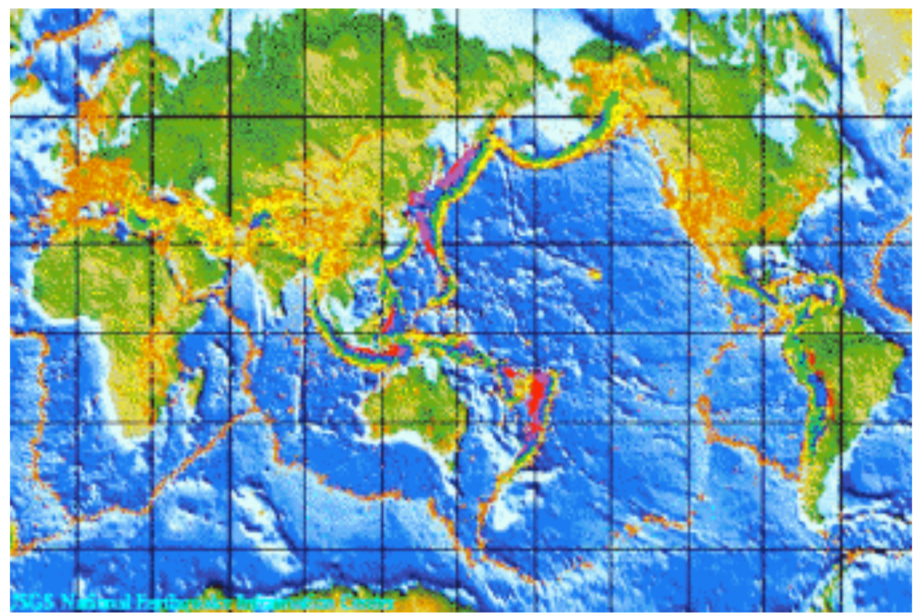
Goal: improve our understanding of the basic physics of earthquakes.



Interdisciplinary problem -- draws on physics, seismology, materials science, engineering, etc.



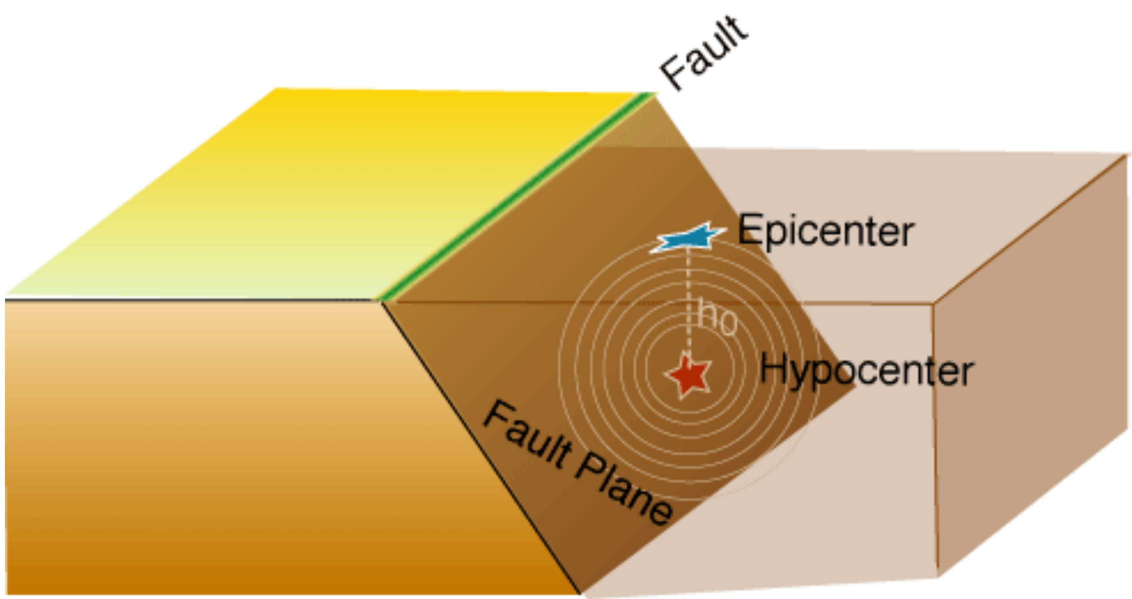


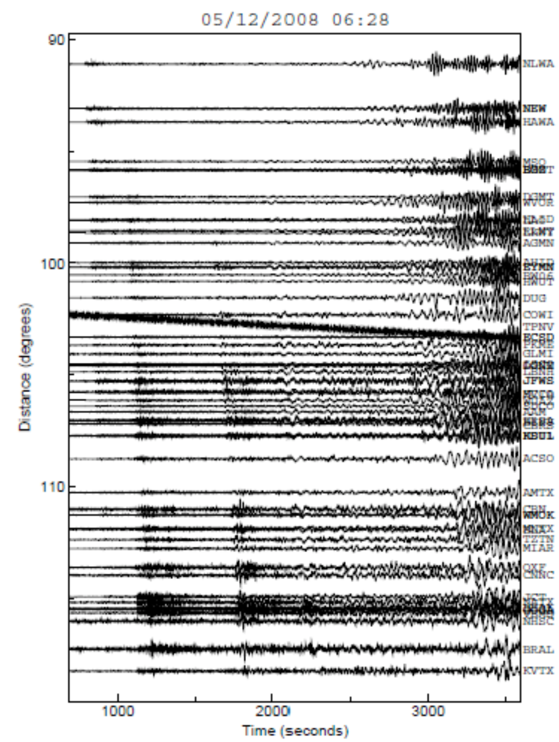


Physics of Earthquakes

Seismologists do not have a complete description of the physics governing earthquake rupture. Why?

1st Problem: Earthquakes happen deep in the earth's crust, and we can't observe them directly





Look at seismic waves instead.

Physics of Earthquakes

Seismologists do not have a complete description of the physics governing earthquake rupture. Why?

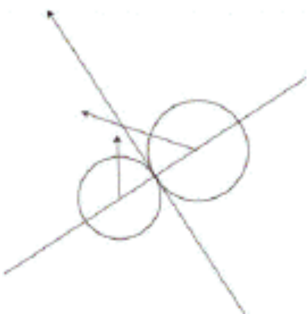
2nd Problem: Occur at extreme physical conditions (hard to replicate in lab experiments)

- Large slip velocities (~1 m/s), Large slip (up to 20 m)
- Large confining pressures (~100 MPa), fluids present
- All current data compromises on at least one of these conditions

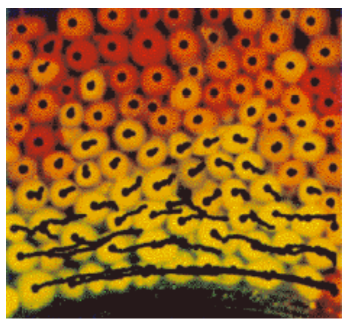
Physics of Earthquakes

But even if we knew all the basic physics, we're still faced with the problem that earthquakes are complex systems, with a huge range of important length and time scales:

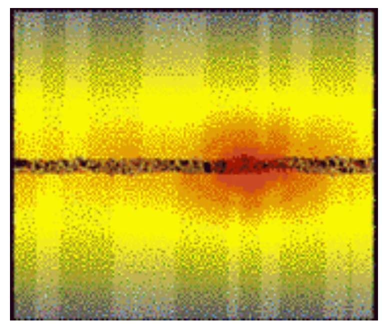
Contacts



Grains

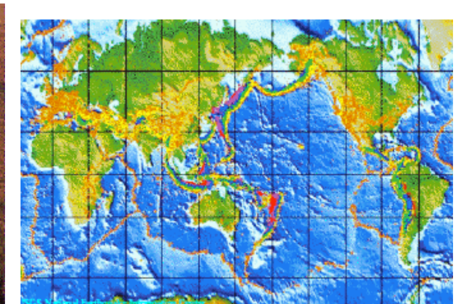


Friction



Faults

Networks

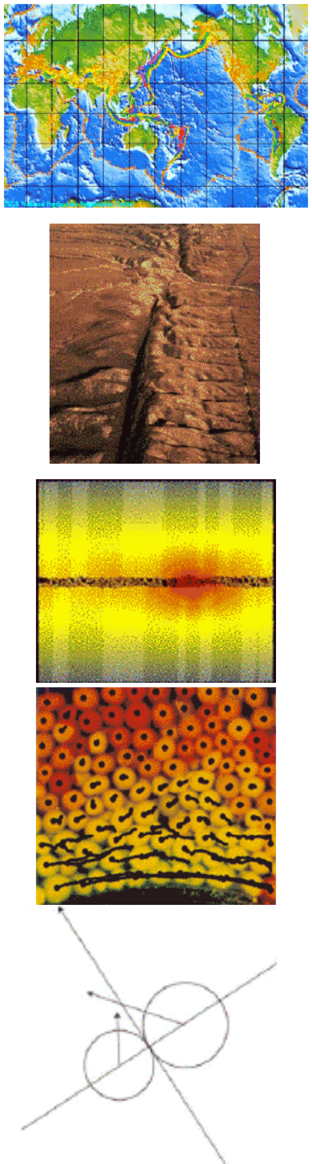


Increasing length scales

Increasing time scales

Multi-Scale Earthquake Problem

Time & Space



Networks

Faults

Friction

Grains

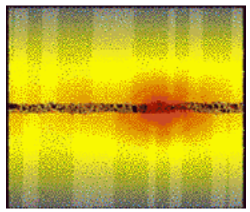
Contacts

"Vertical:" connect different scales

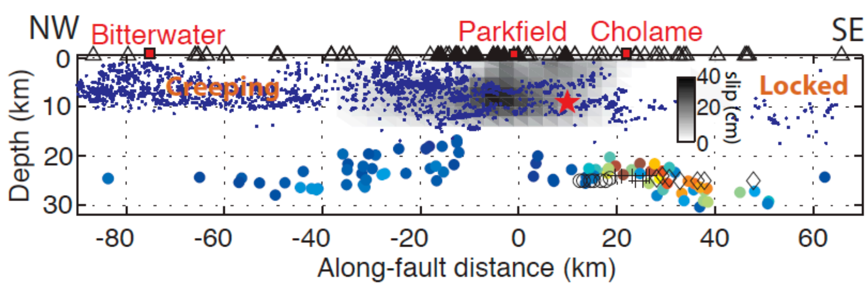
"Horizontal:" each level is a complex, often heterogeneous, dynamical system, with rich behavior, and many unknowns

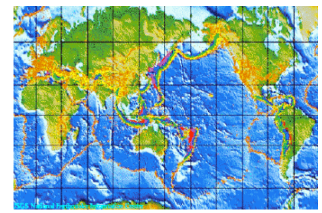
In this talk, "horizontal" approach at two different scales: Friction and Networks.

Multi-Scale Earthquake Problem

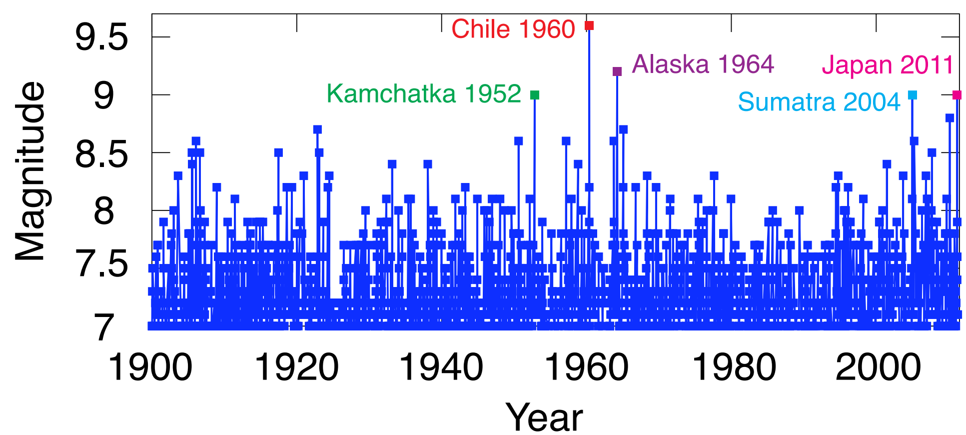


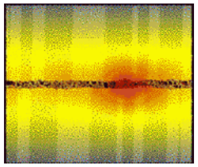
At friction scale, use observations of nonvolcanic tremor (tiny earthquakes occurring deep in the crust) to learn about the nature of friction in the earth.





At network scale, look at occurrence of largest earthquakes to determine if there is correlation between them.

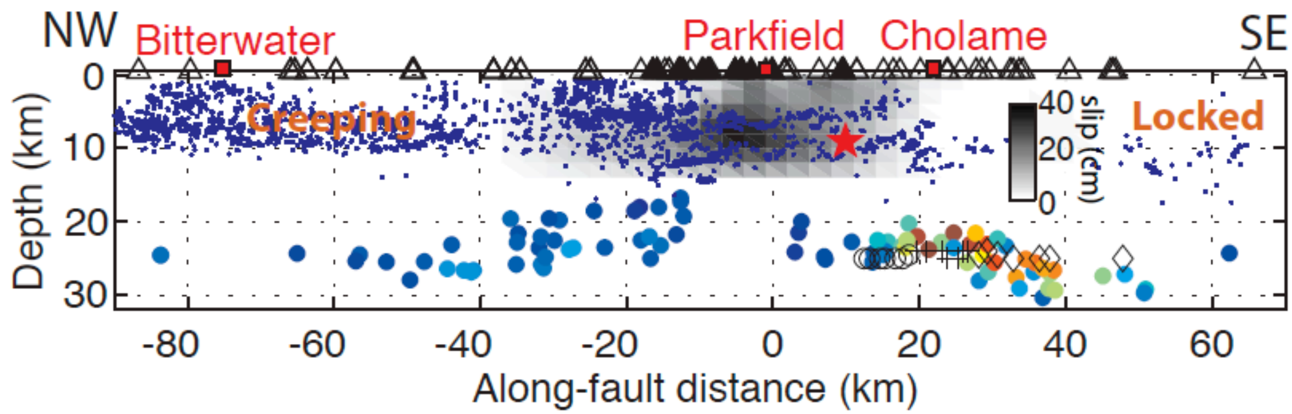




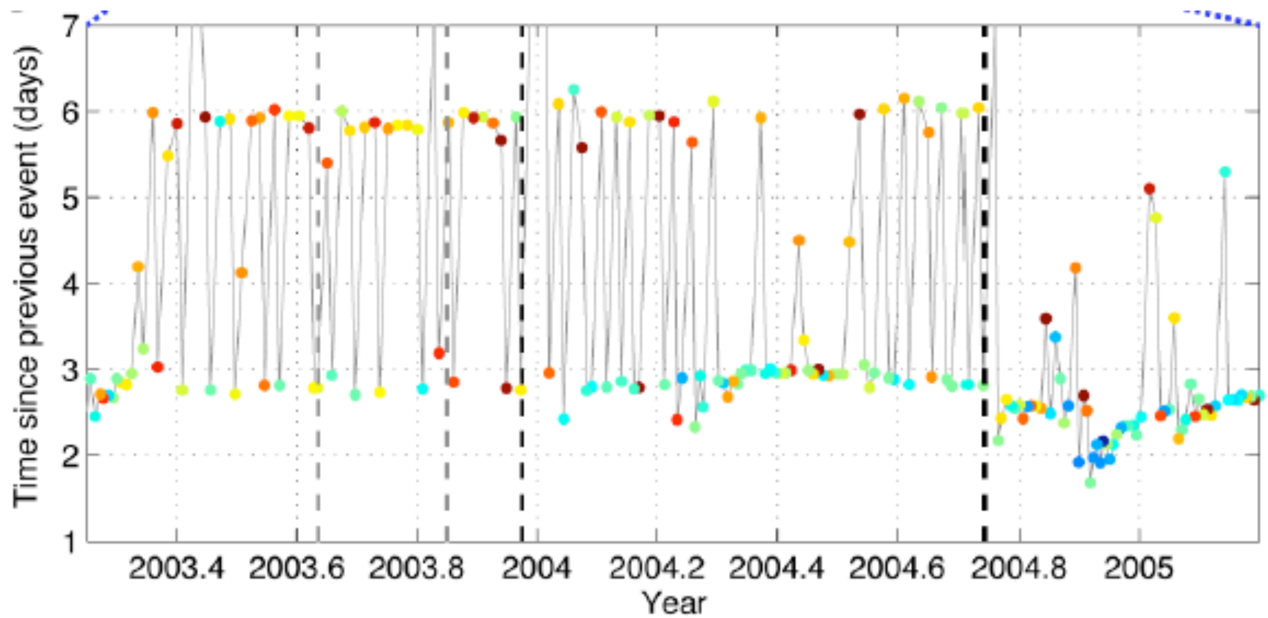
Nonvolcanic Tremor

Parkfield, CA

Shelly and Hardebeck, GRL, 2010

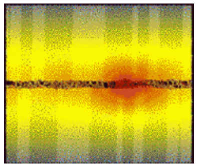


Shelly, Science, 2010

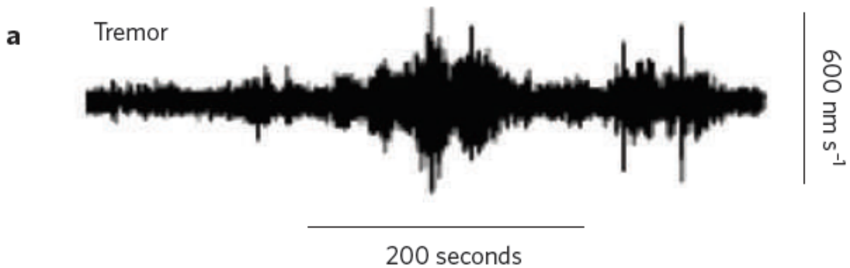


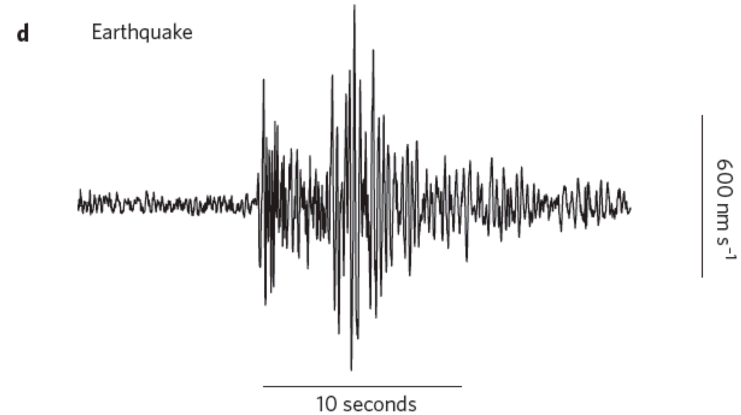
However, there are tiny earthquakes that occur deep in the crust – "Nonvolcanic Tremor"

Occur frequently (days between events instead of years), so we have better data on their occurrence.



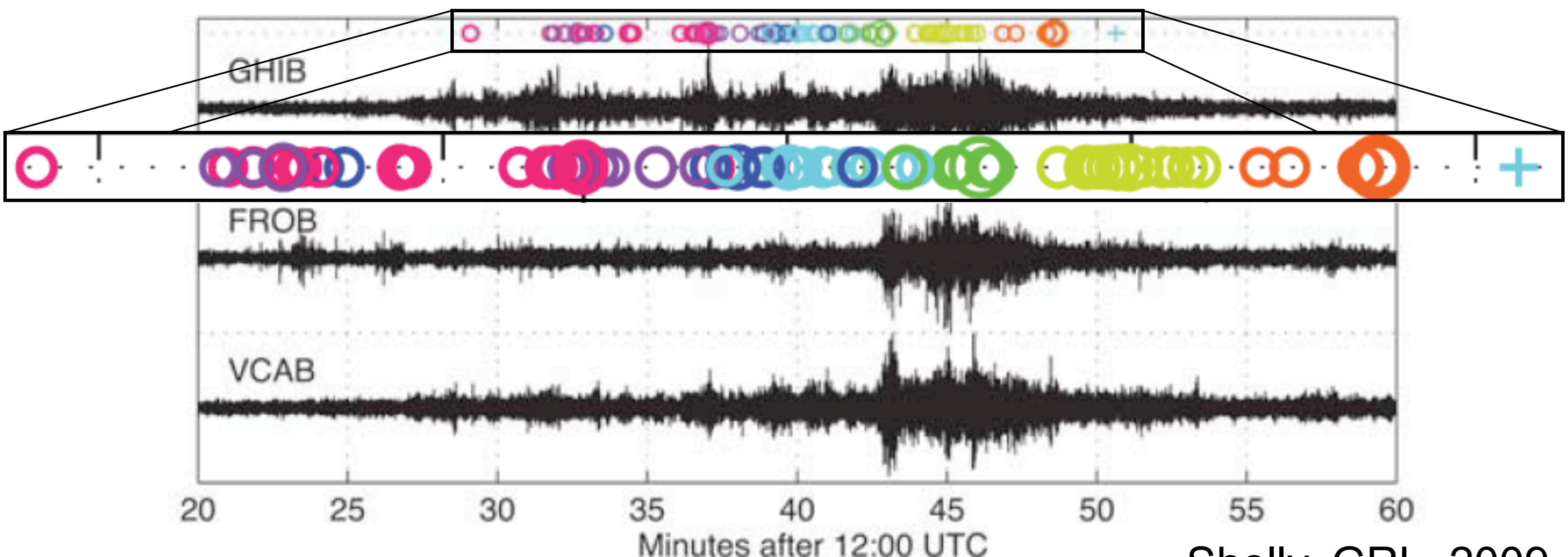
What is unique about tremor?



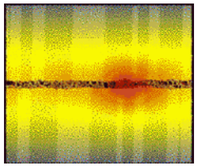


Different types of seismic signals, and events occur in “bursts” of activity.

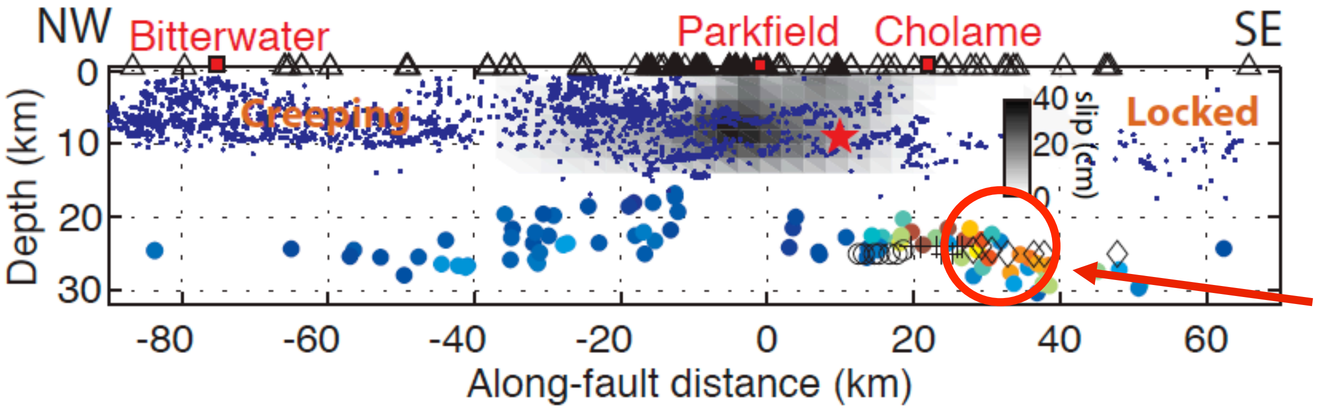
Peng and Gomberg, 2010



Shelly, GRL, 2009



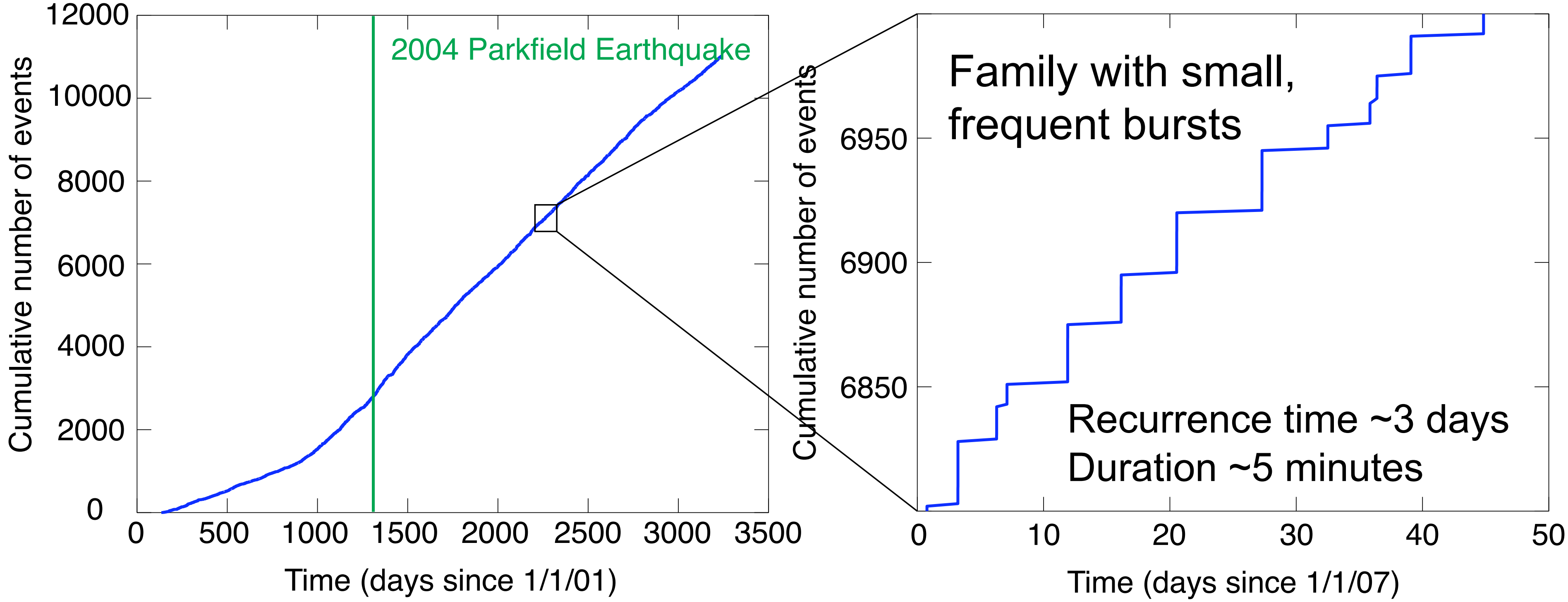
Tremor behaviors



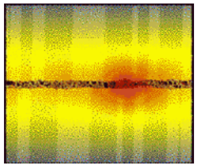
Look at an example tremor family.

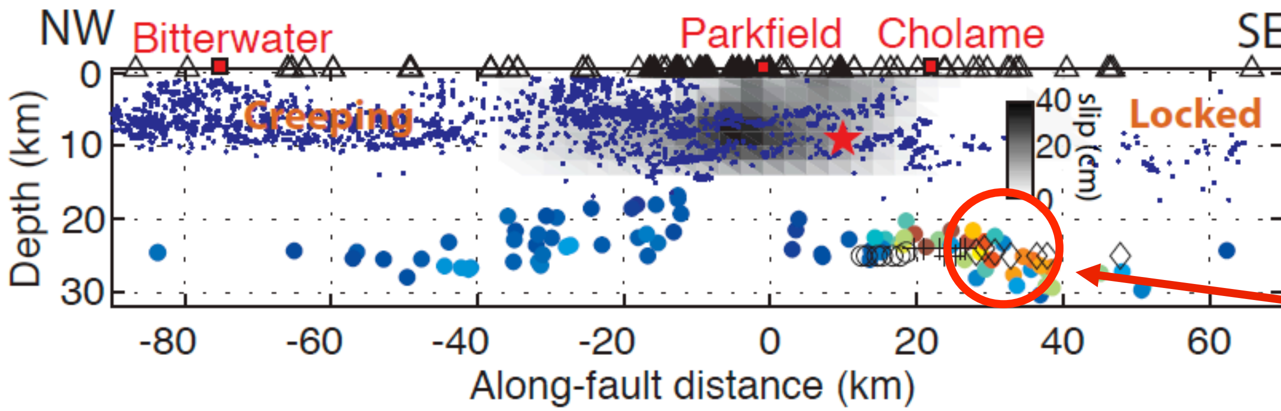
Located in this patch of tremor, one of the deeper examples.

Family 19165 (27.5 km depth)



Tremor behaviors

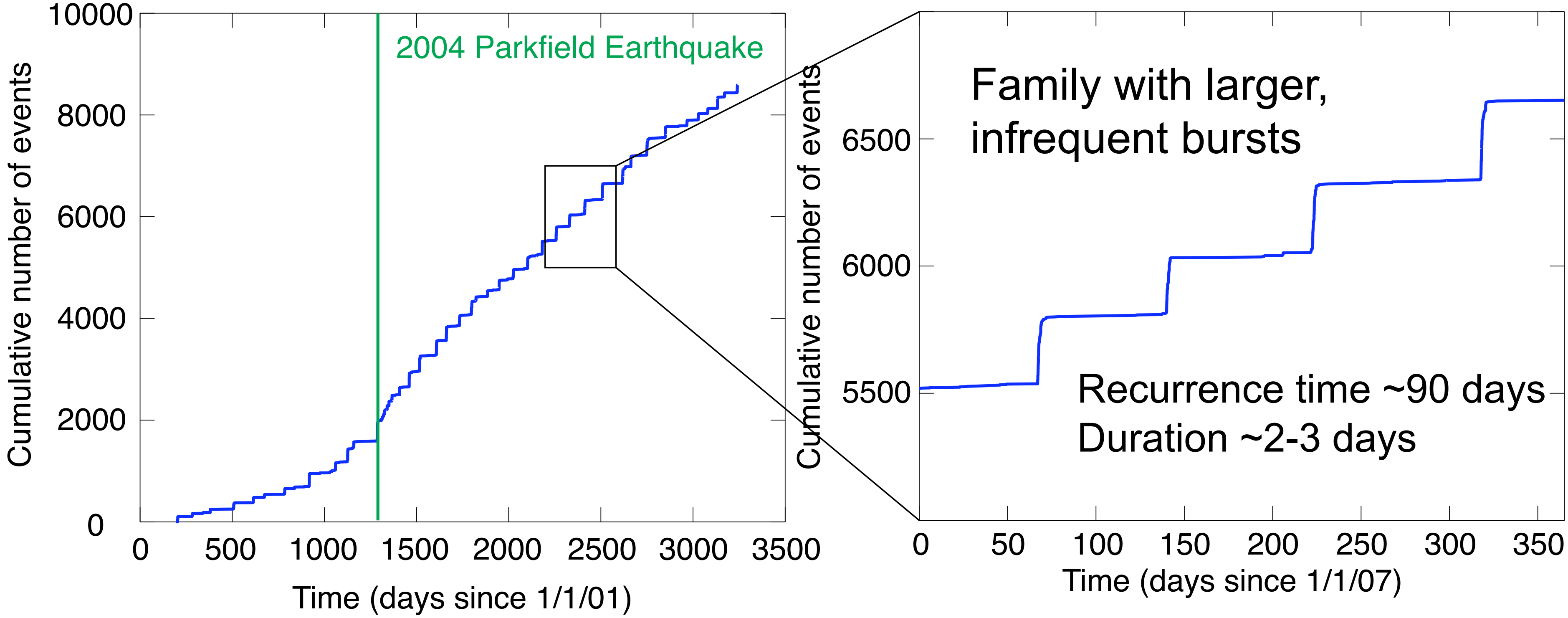


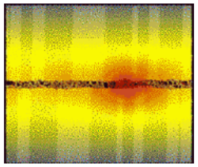


Look at a second family with different dynamics.

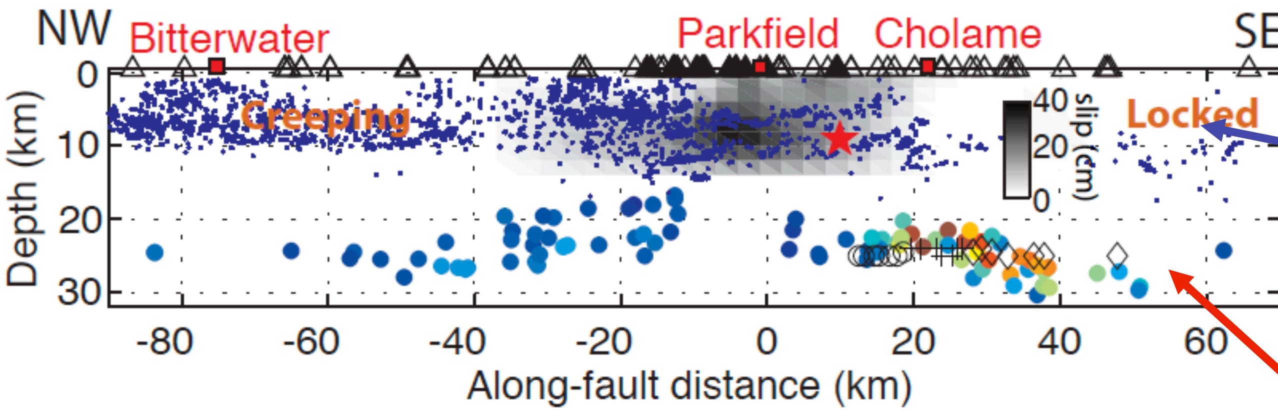
Shallower, but same part of the fault.

Family 68539 (21 km depth)





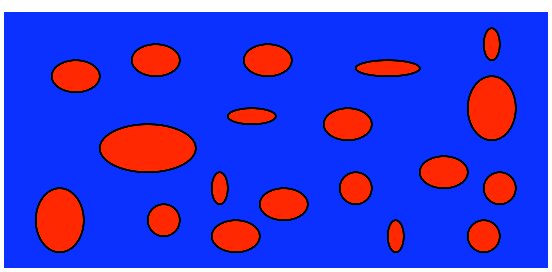
Modeling Tremor



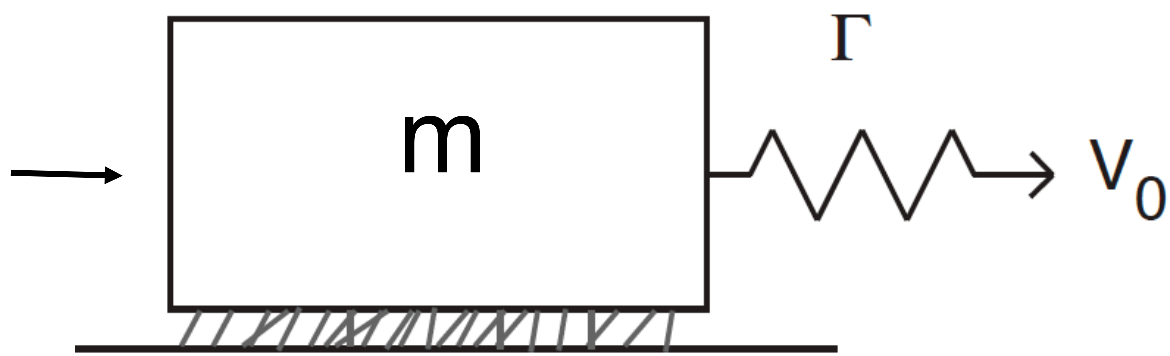
Earthquakes occur in the brittle upper ~15 km of crust.

Friction gradually changes from brittle to ductile in lower crust, where tremor occurs

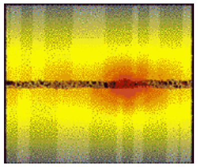
Idea: friction at depth is both brittle and ductile. Develop a simple model for this, and use observations to determine frictional properties at depth.



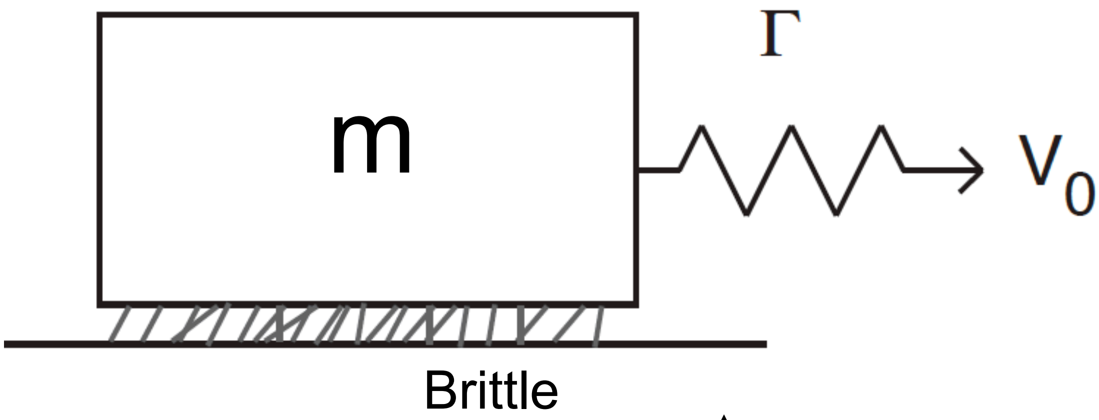
Brittle patches Ductile fault



(Top view of fault plane)

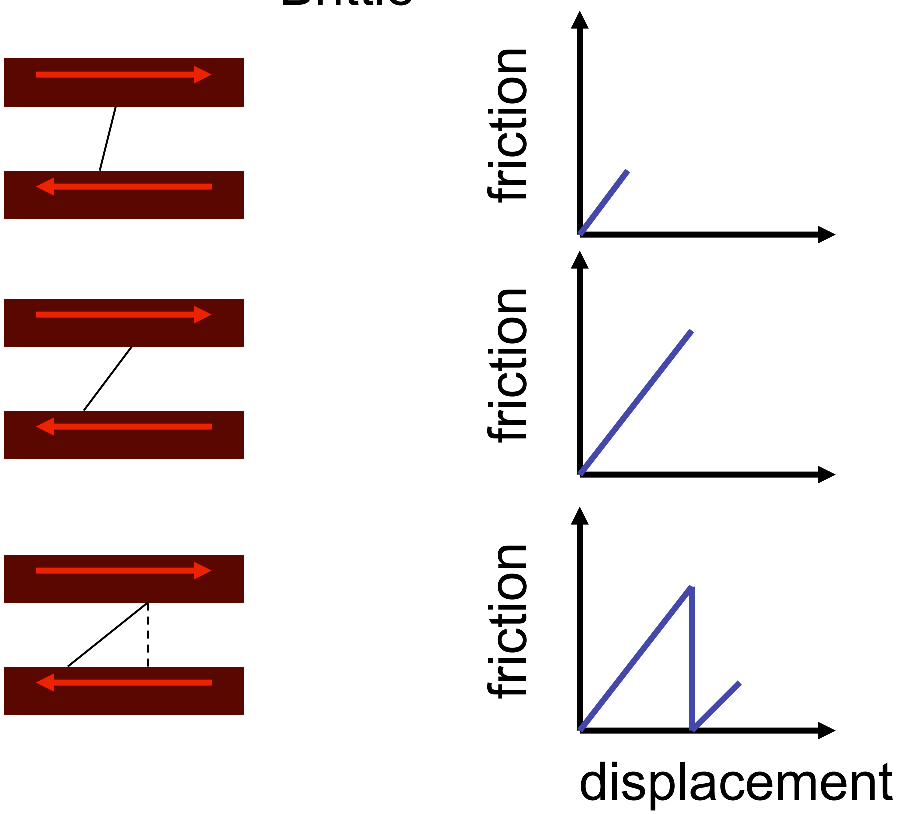


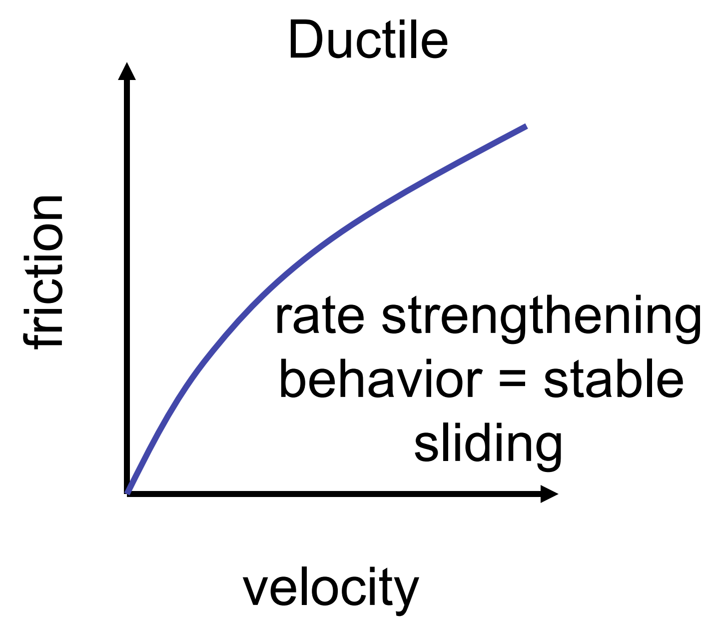
Brittle-Ductile Friction Model

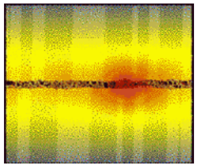


Idea: bristles represent brittle fault patches (resist motion, then fail). Other patches behave in a ductile manner (slide stably).

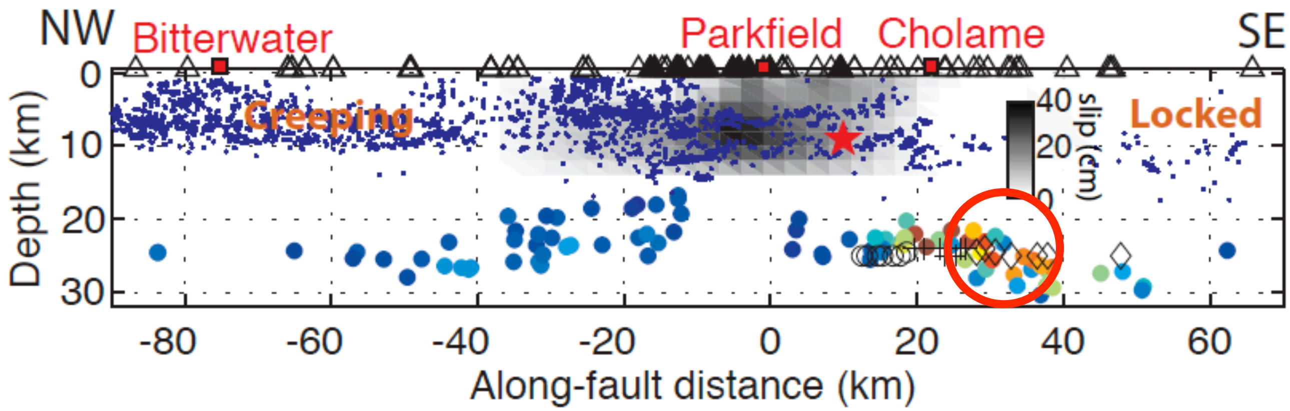
Friction is the sum of brittle and ductile parts.







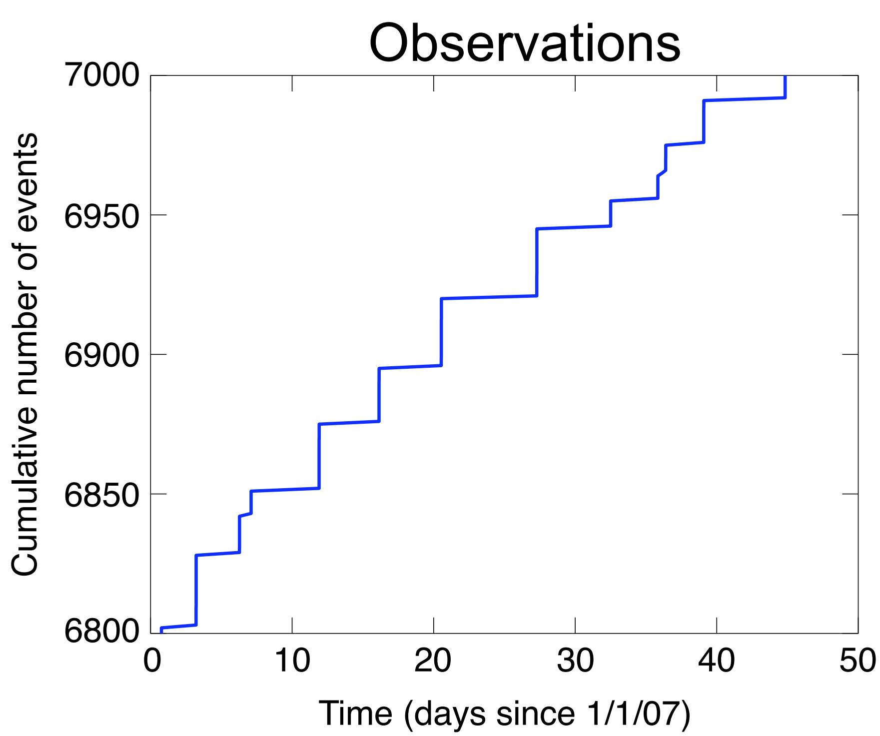
Comparison with observations

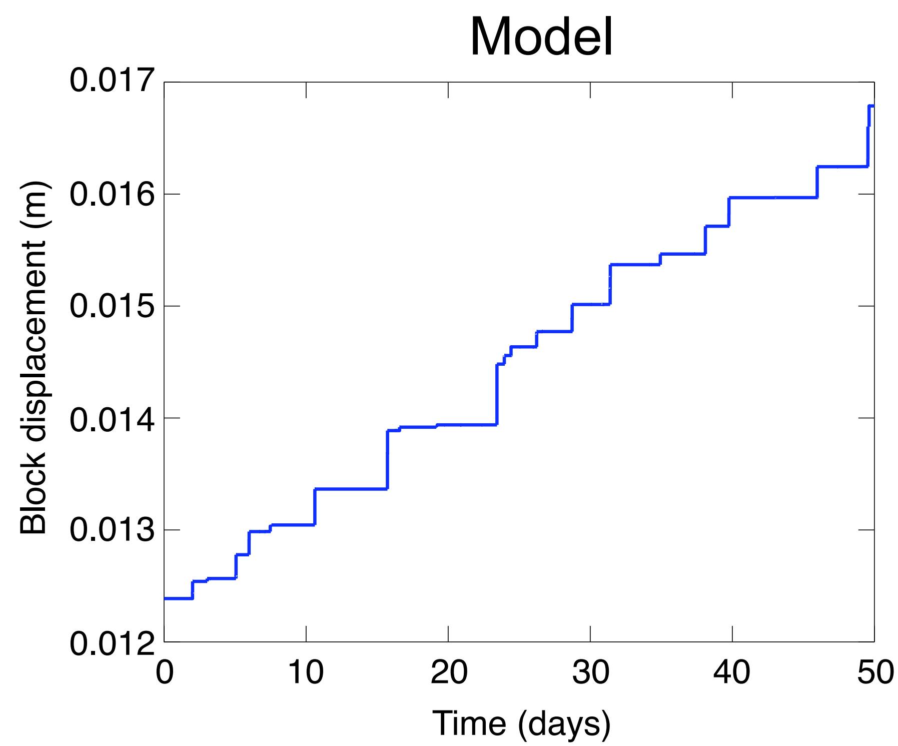


Frictional resistance has =small brittle and ductile components

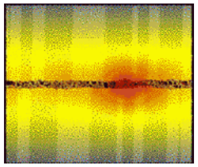
Patch failure lengths have narrow range (1-7.5 microns)

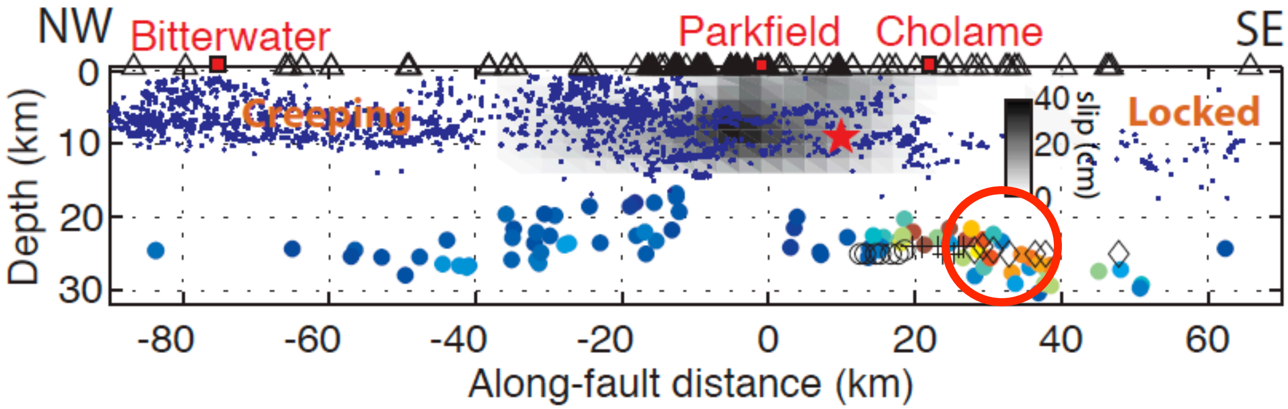
Family 19165 (27.5 km depth)





Comparison with observations



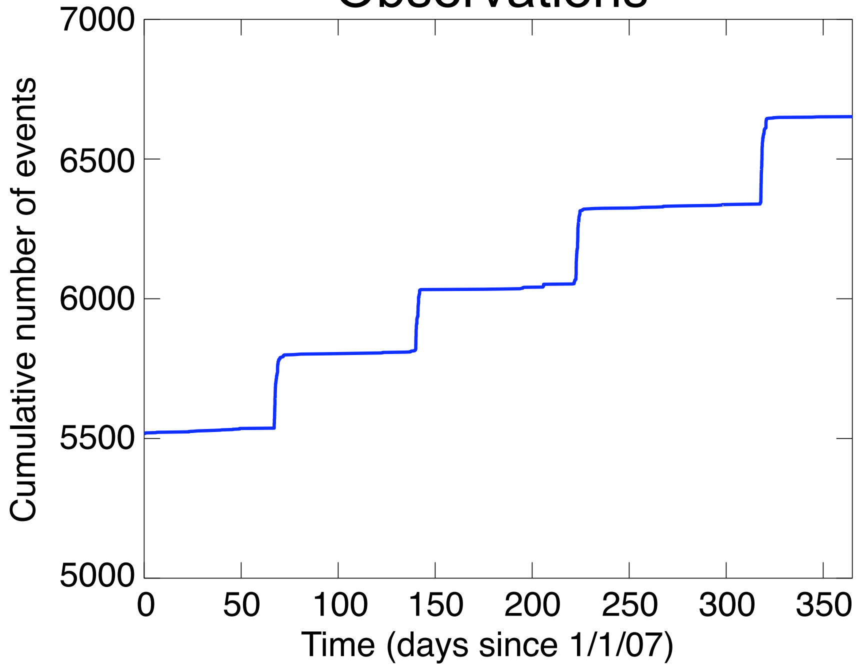


Both brittle and ductile strengths are larger

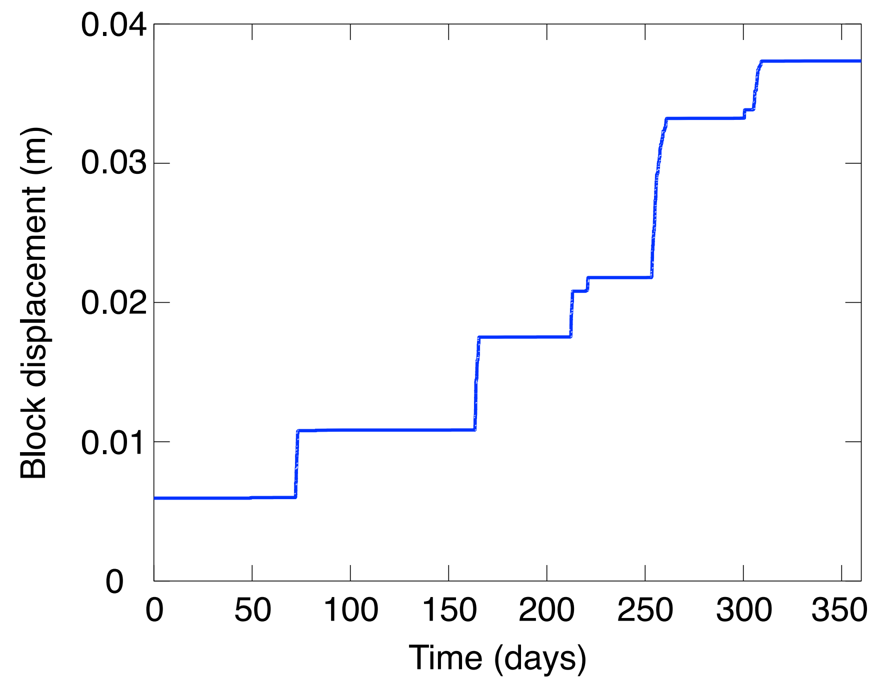
Patch failure lengths have broad range (1-320 microns)

Family 68539 (21 km depth)

Observations

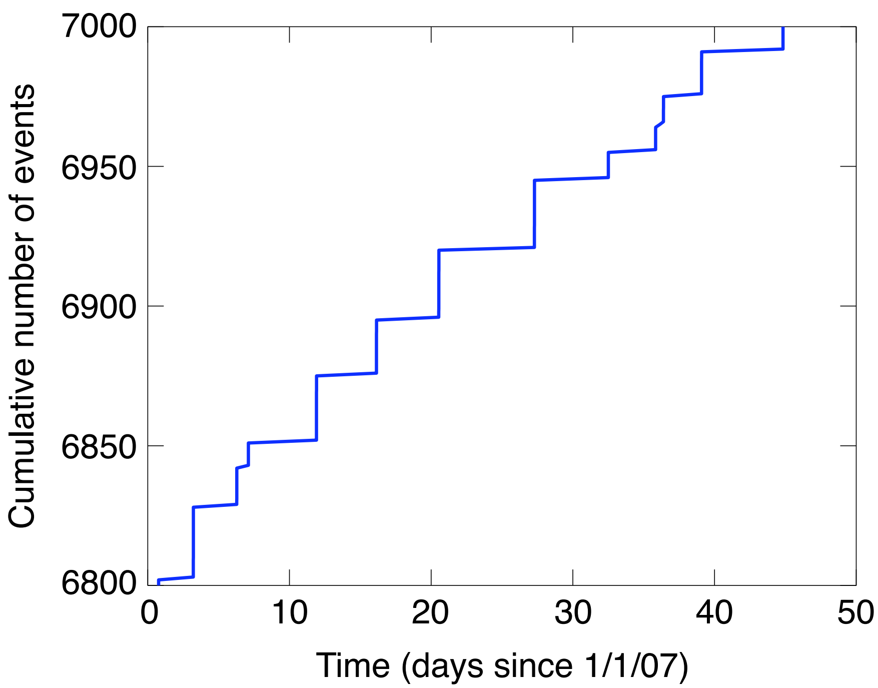


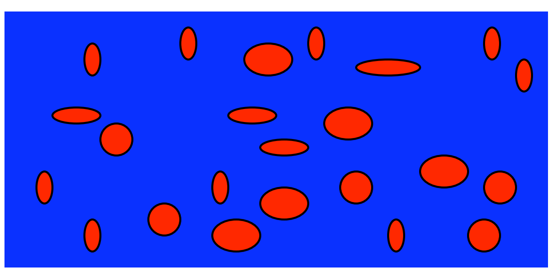
Model



What controls tremor behavior?

Deeper Tremor (27.5 km depth)

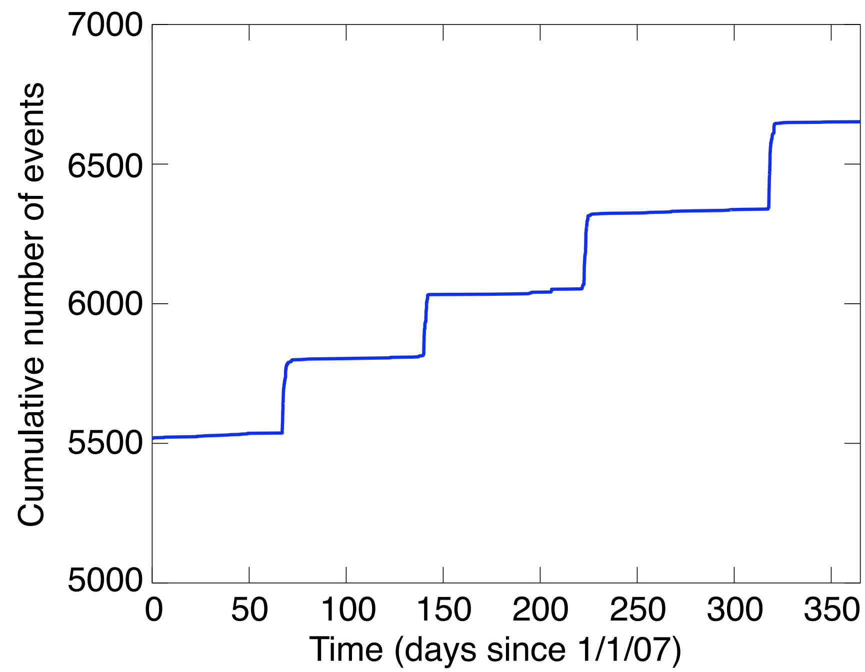


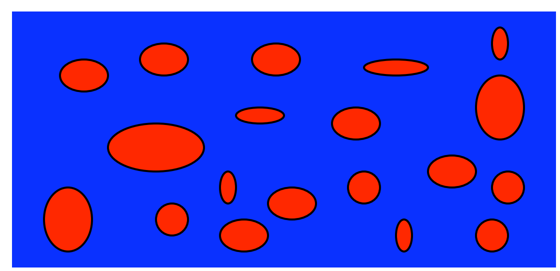


Weaker, uniform size brittle patches

Weaker ductile background

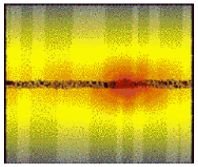
Shallower Tremor (21 km depth)





Stronger, broad sized brittle patches

Stronger ductile background

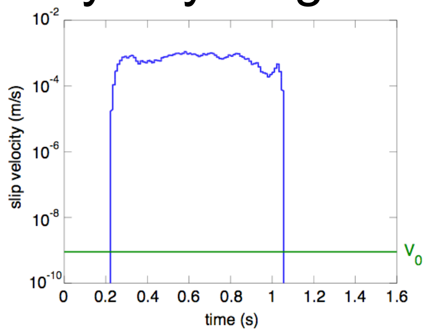


Model Dynamics

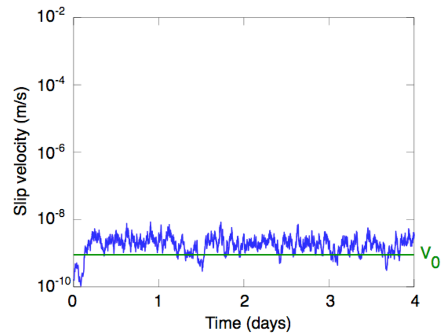
(Daub et al., GRL, 2011)

Can we say anything more general about the dynamics?

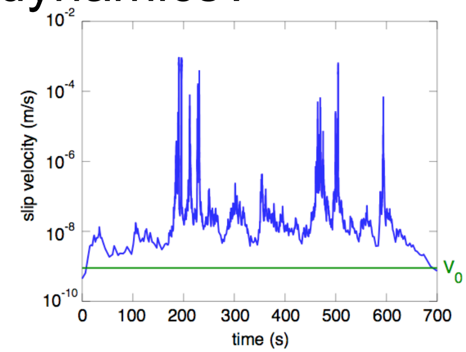
Vary brittle/ ductile strengths to see type of resulting dynamics:



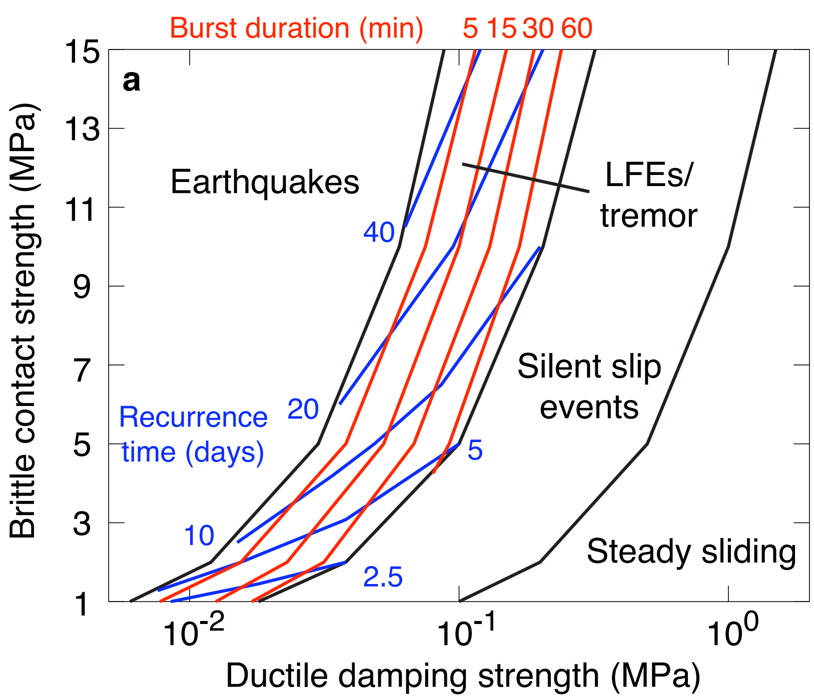
Earthquake

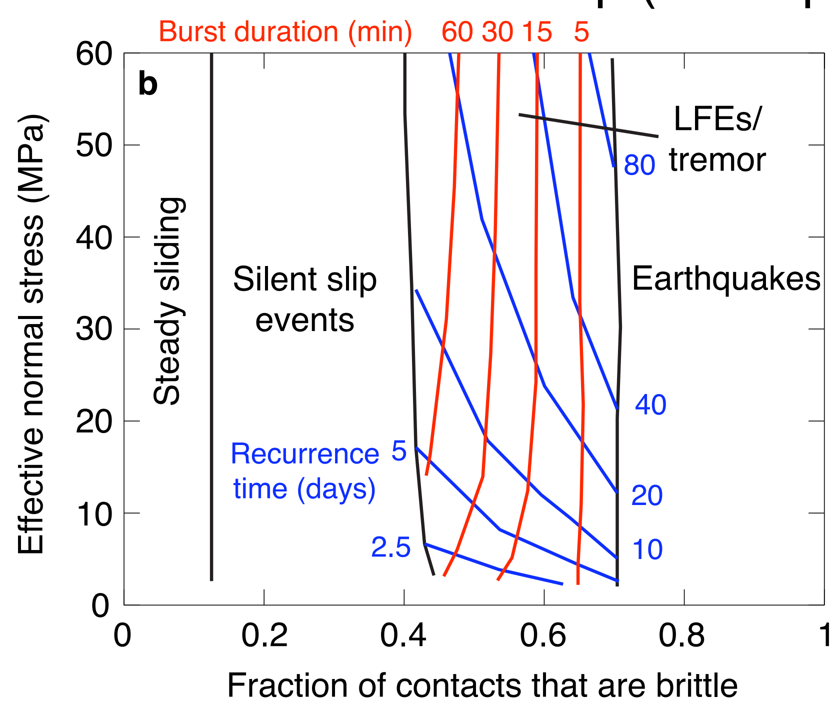


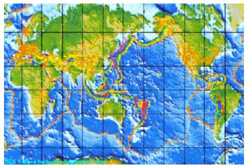
Steady sliding



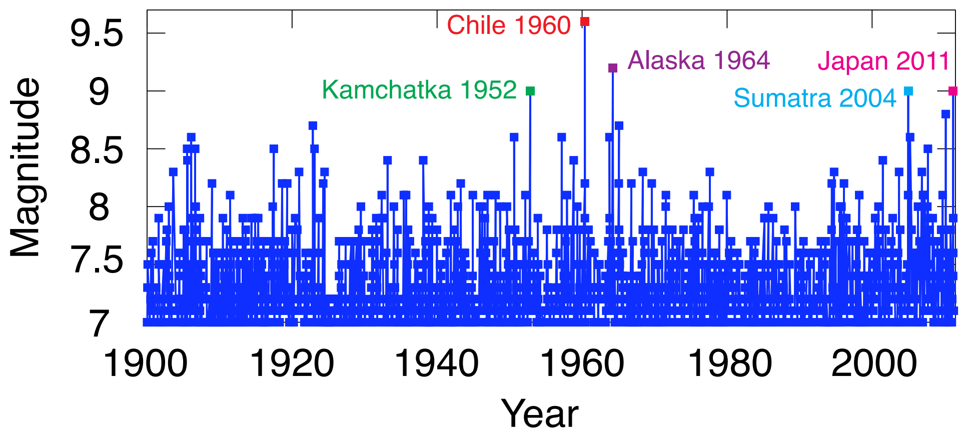
Tremor (high slip rate)
Silent slip (low slip rate)

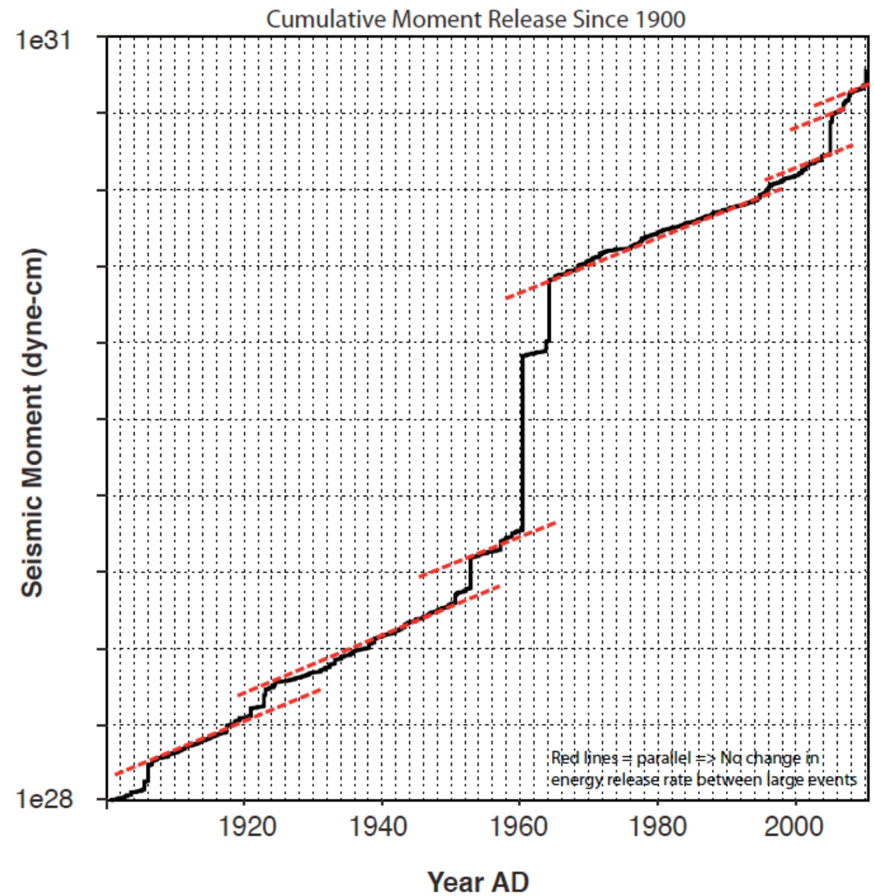






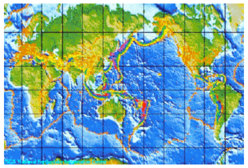
Clustering of Large Earthquakes?



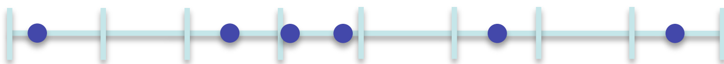


Do the largest earthquakes cluster in time? See increased number in 60's and again in 2000's.

Mixed opinions in the literature (Bufe and Perkins, 2005; Michael, 2011). Investigate this using earthquake record.



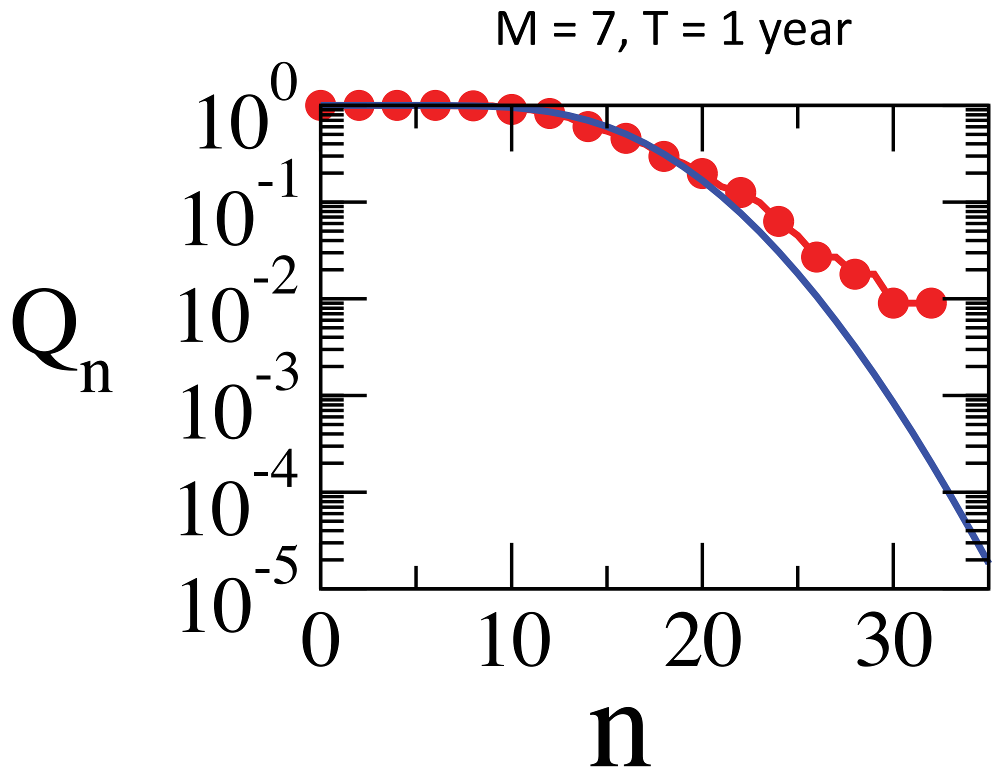
Analysis Methods



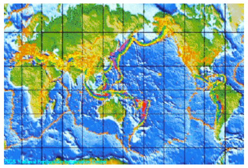
Time

Simple approach: for a magnitude threshold M, divide catalog into bins of length T. Count number of events in each bin.

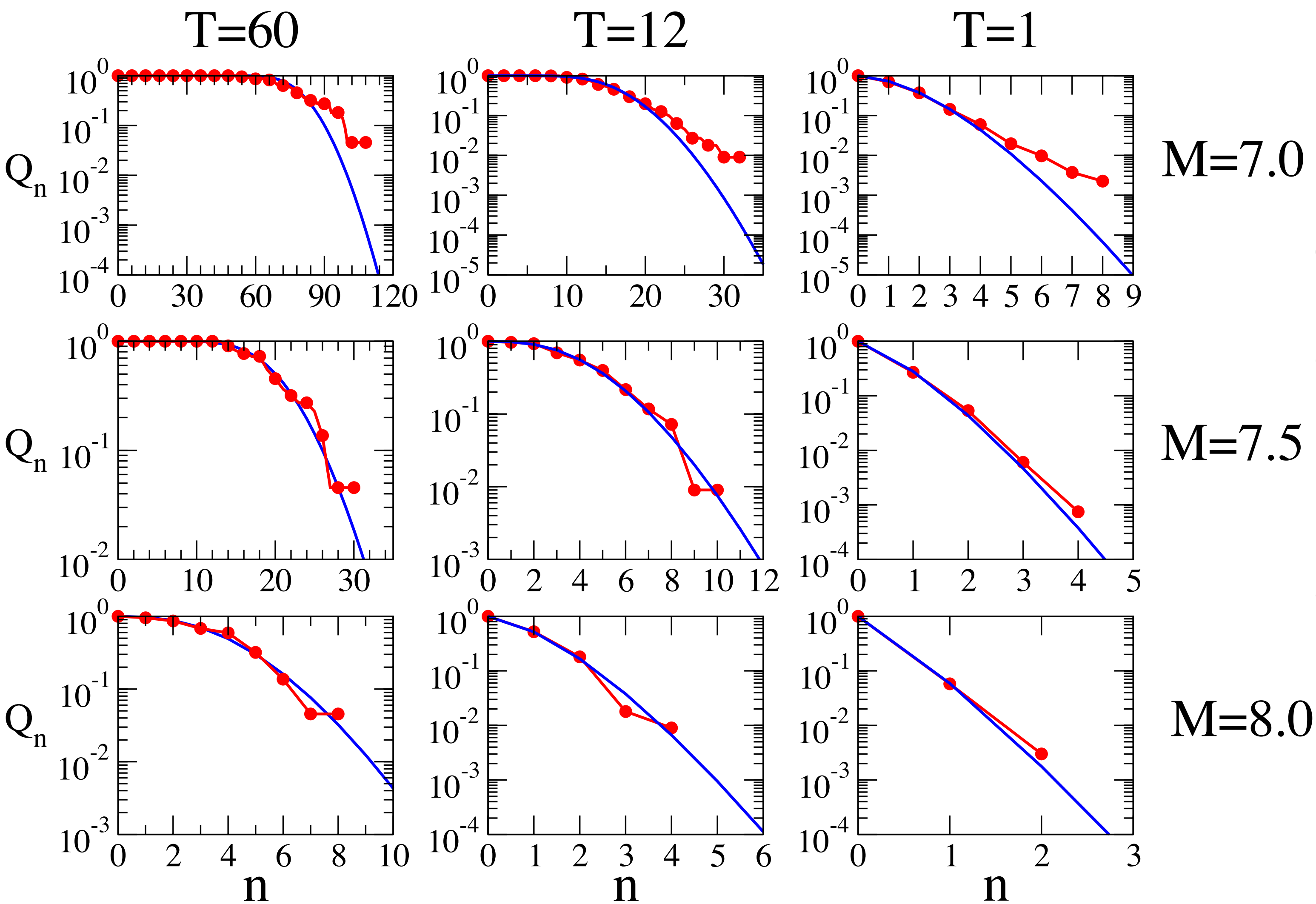
Compare cumulative distribution of bin occupation numbers from data (red curve) to distribution expected for Poisson statistics (blue curve).



Plot shows clustering in catalog. More bins with large number of events than expected if earthquakes are random.

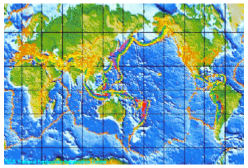


PAGER Catalog Analysis



Observe clustering for M = 7 earthquakes

Larger magnitudes appear Poissonian.



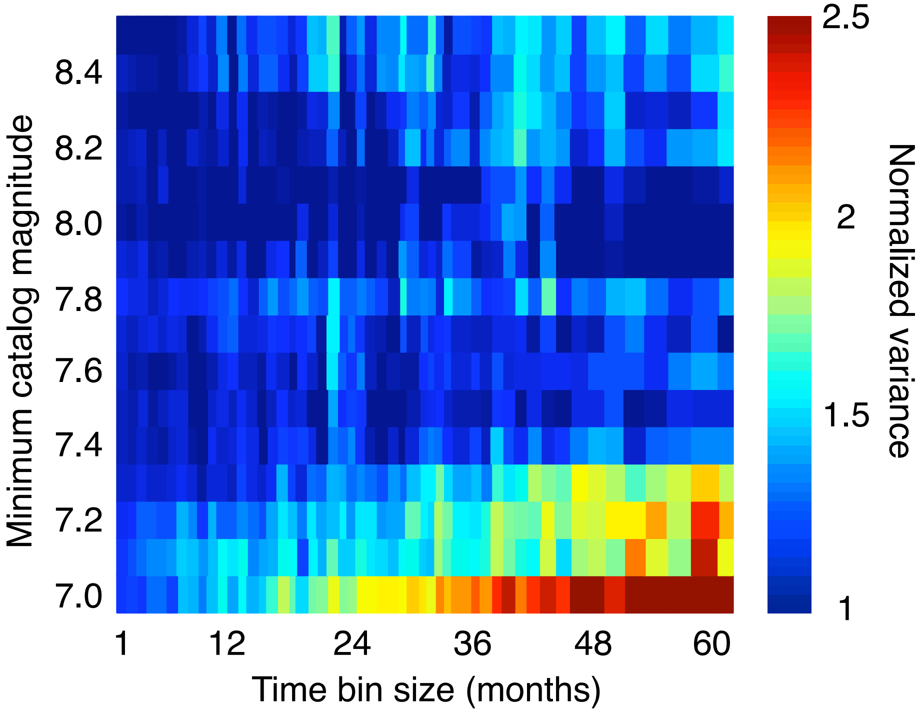
Is this statistically significant?

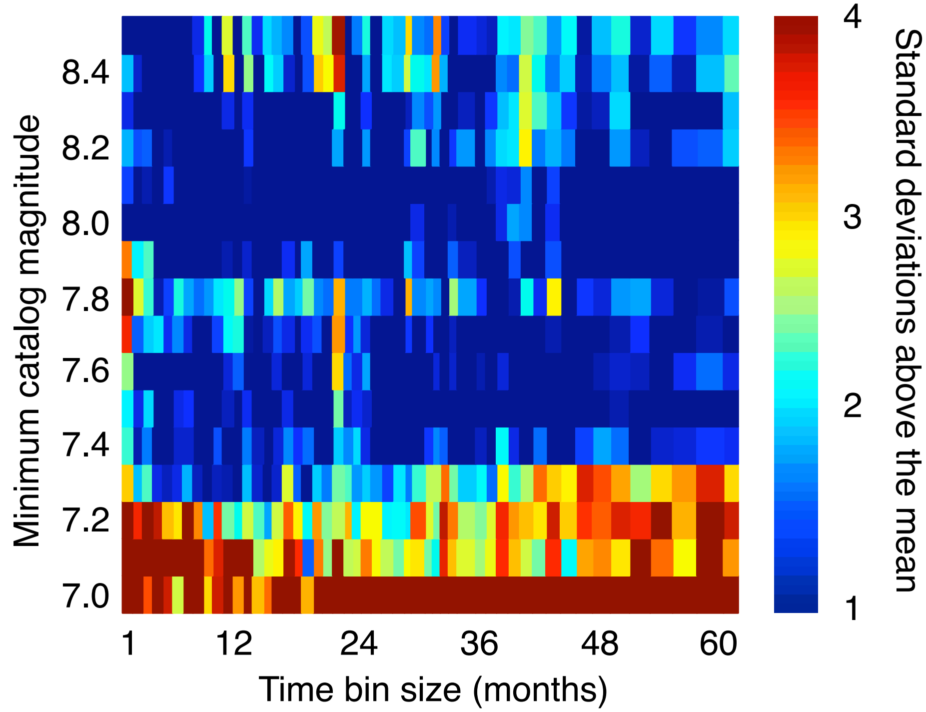
Compare data to many (10^6) synthetic catalogs to determine how likely the clustering is.

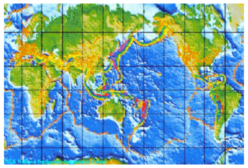
Use scalar measure of clustering: variance normalized by the average (=1 for Poisson, >1 if clustered)

$$V = \frac{< n^2 > - < n >^2}{< n >}$$

Compare to statistics of 10^6 synthetic catalogs.



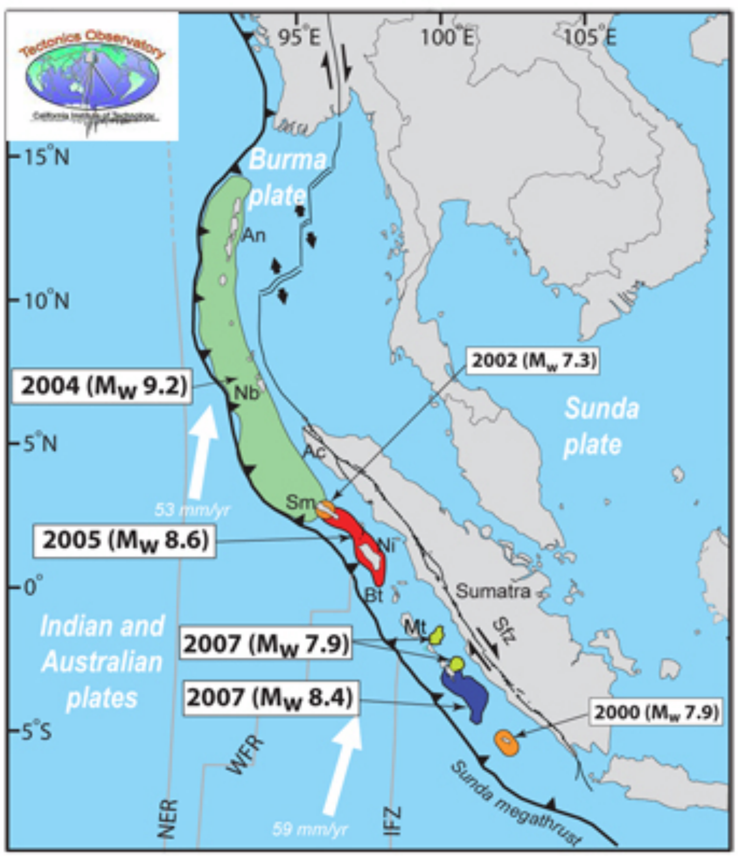




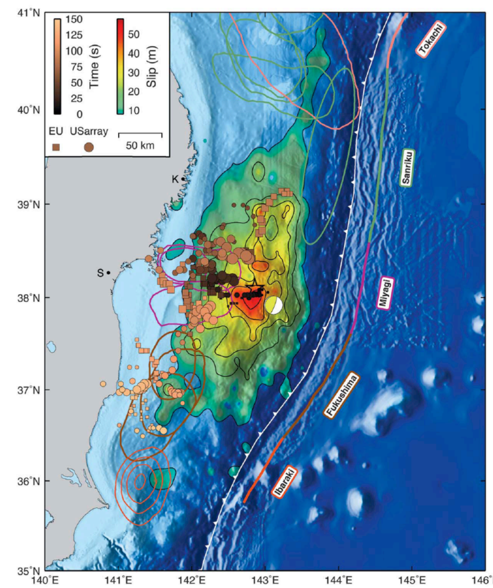
Aftershocks?

Is clustering due to aftershocks? Large earthquakes can have large aftershocks.

Remove aftershocks using a simple window method (Knopoff and Gardner, 1974).

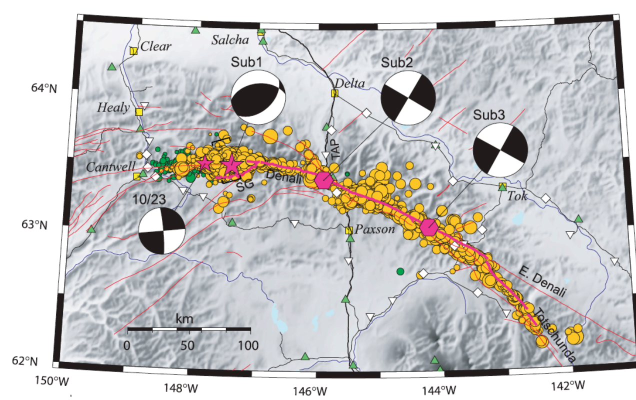


However, subject to arbitrary assumptions as catalog contains a mixture of faulting types with variable rupture lengths:

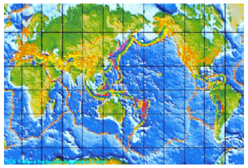


Both rupture lengths ~300 km!

Tohoku 2011 (M9)



Denali 2002 (M7.9)

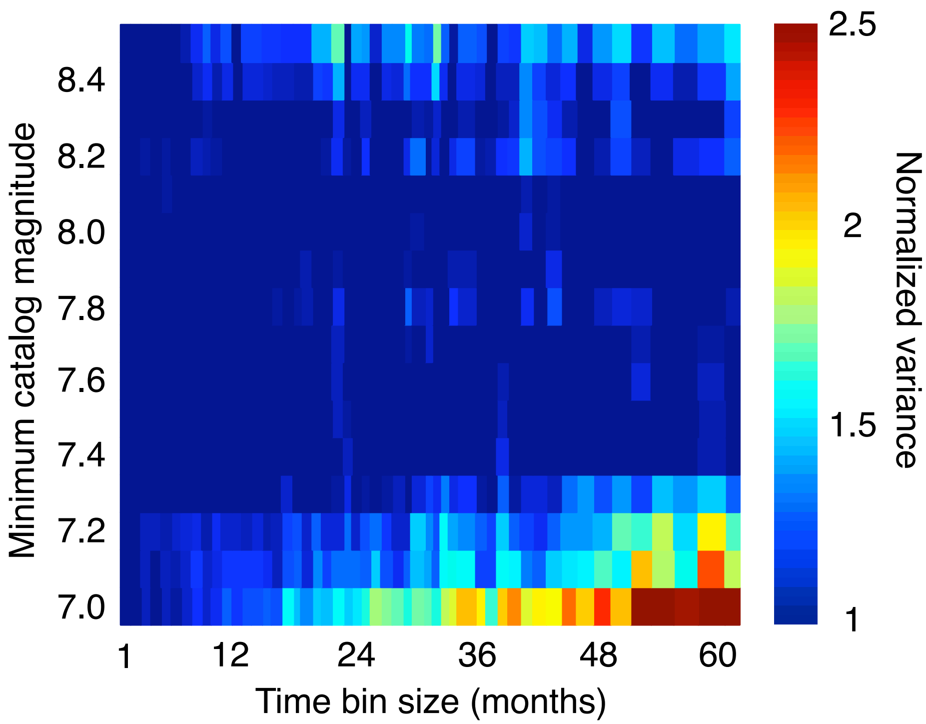


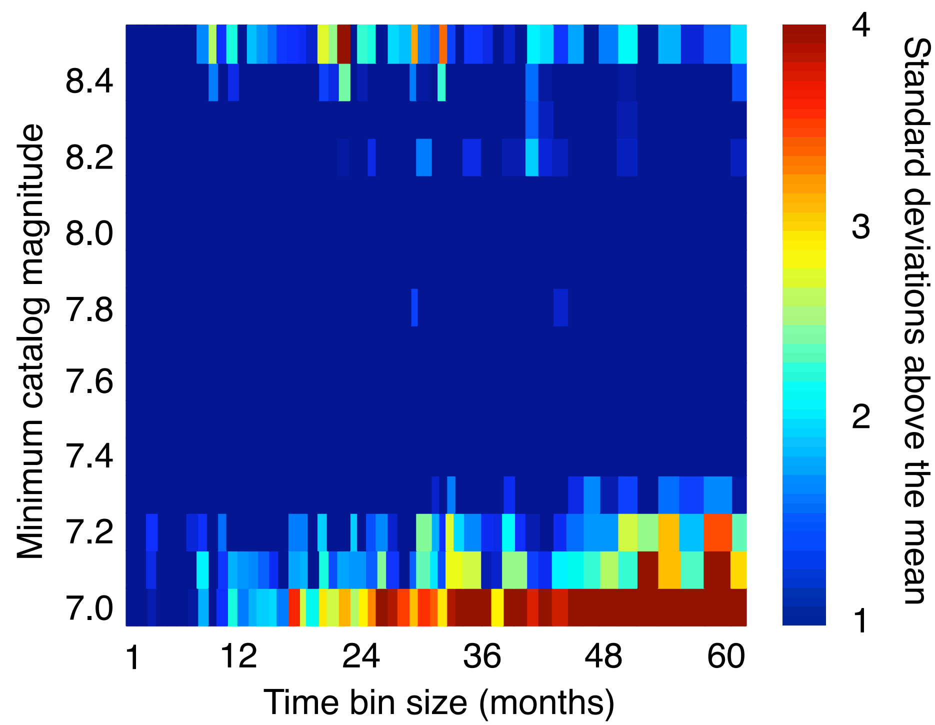
Clustering without aftershocks?

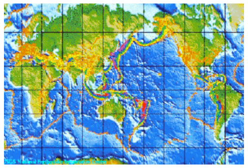
Repeat analysis with catalog with aftershocks removed.

Most of the clustering goes away – only systematic clustering is observed at M7 for long time windows.

M7 clustering at long time windows occurs in early part of century when magnitudes are uncertain, so unclear if this is real.





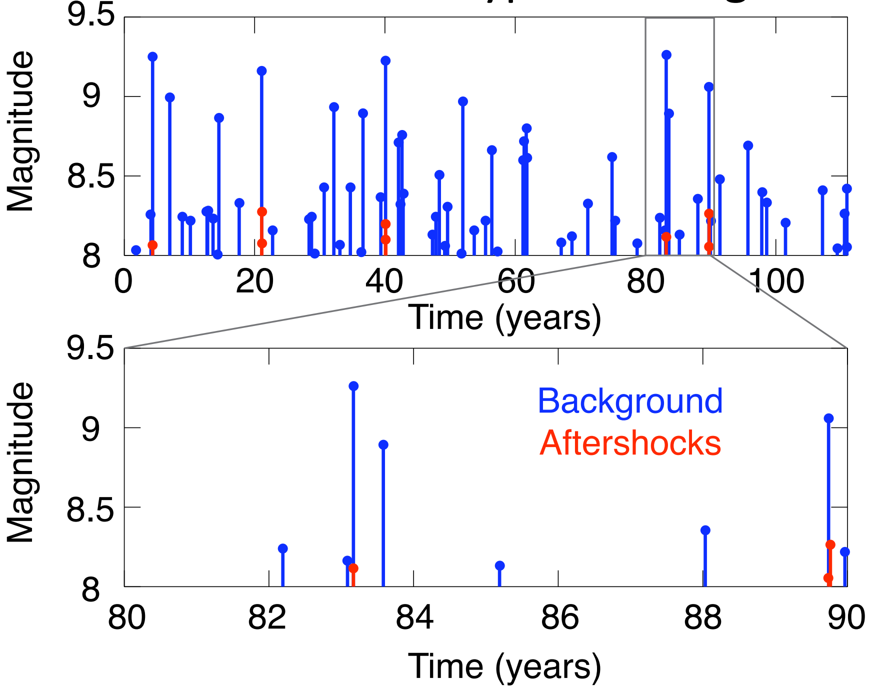


What does this mean?

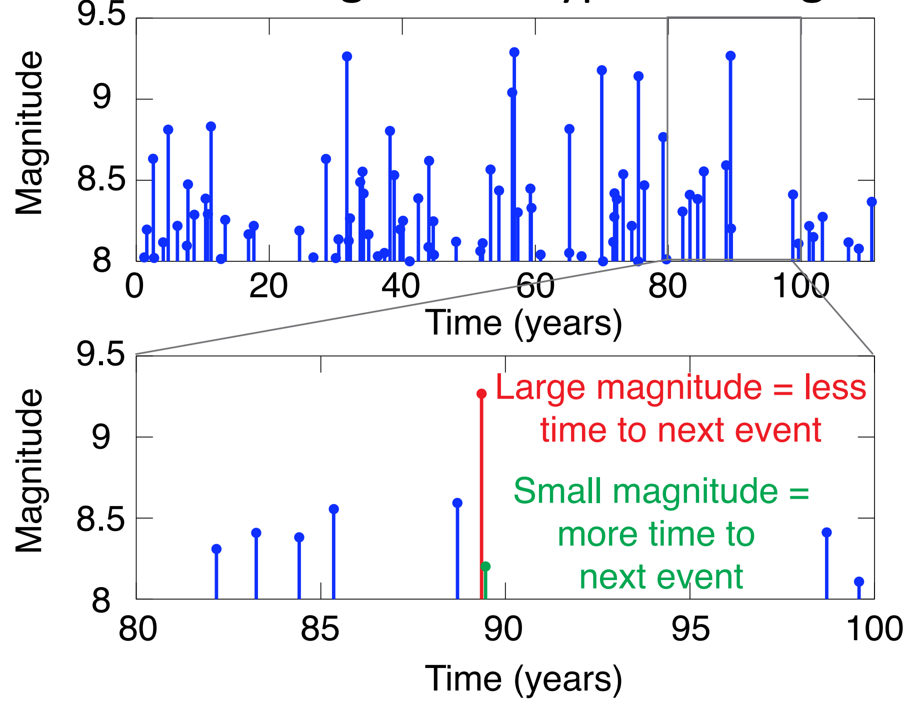
Earthquake catalog appears to be random in time.

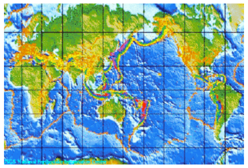
But data is limited – how much can 110 years of data tell us about the biggest earthquakes (say M8 and above, 80 events in PAGER)? Perform statistical tests on two synthetic catalogs that contain clustering.

“Aftershock-type” catalog



“Inhomogeneous-type” catalog





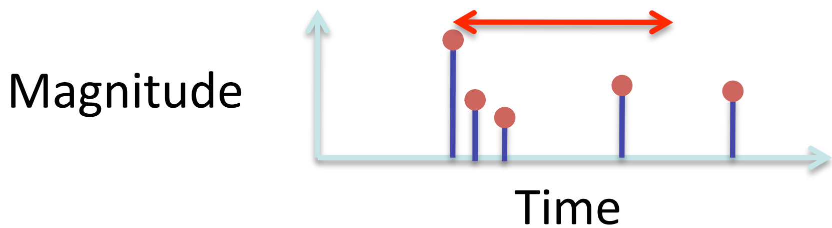
Statistical Tests

Perform several tests on ensembles of clustered catalogs.

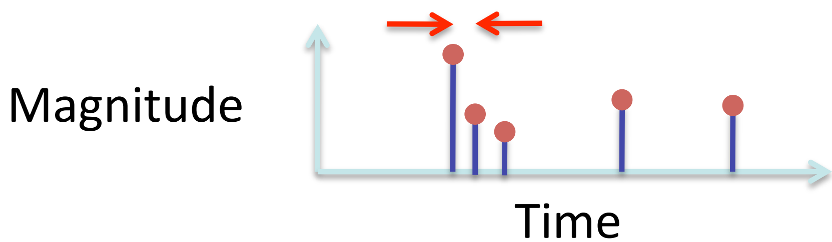
1. Variance test (used in analysis of PAGER catalog). General indicator of clustering.

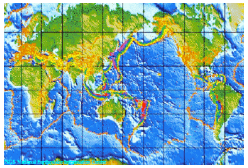
$$V = \frac{< n^2 > - < n >^2}{< n >}$$

2. “Window test.” Compare event rate in ½ year after biggest earthquakes to background. Should work well on Aftershock-type catalog.

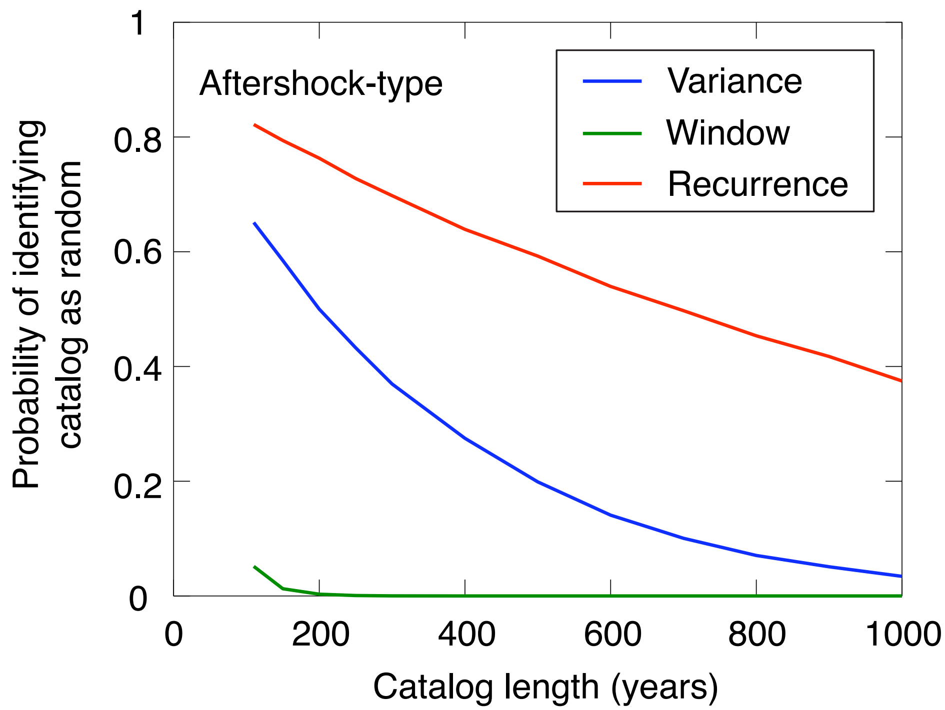


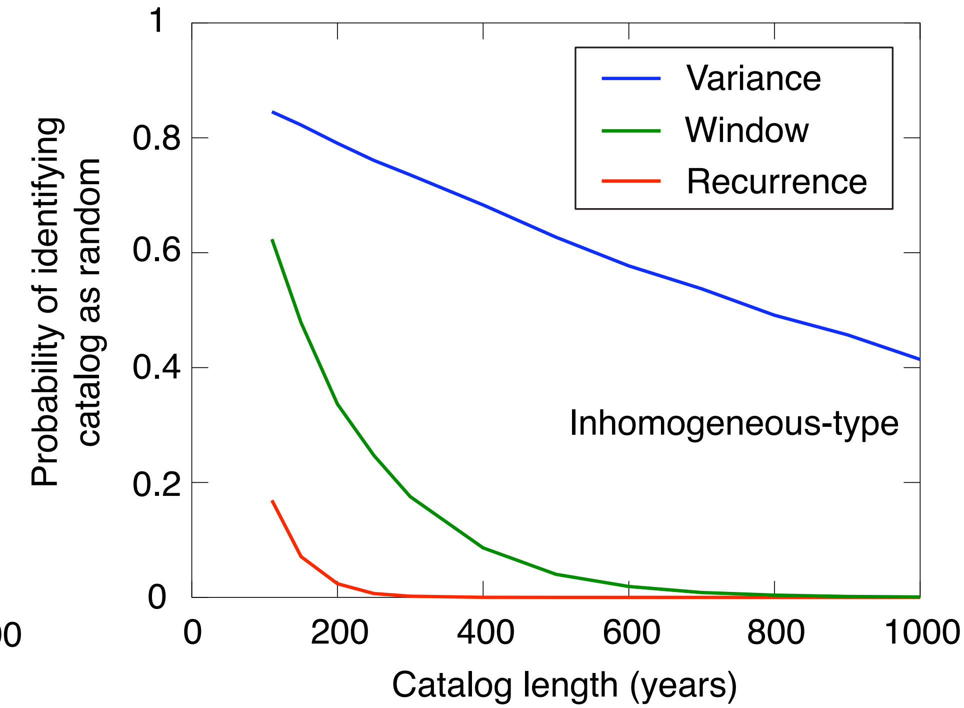
3. “Recurrence test.” Compare interevent time following the biggest earthquakes to average recurrence. Should work well on Inhomogeneous-type catalog.





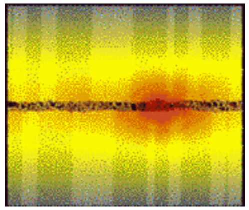
Results of Statistical Tests



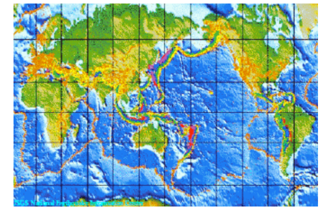


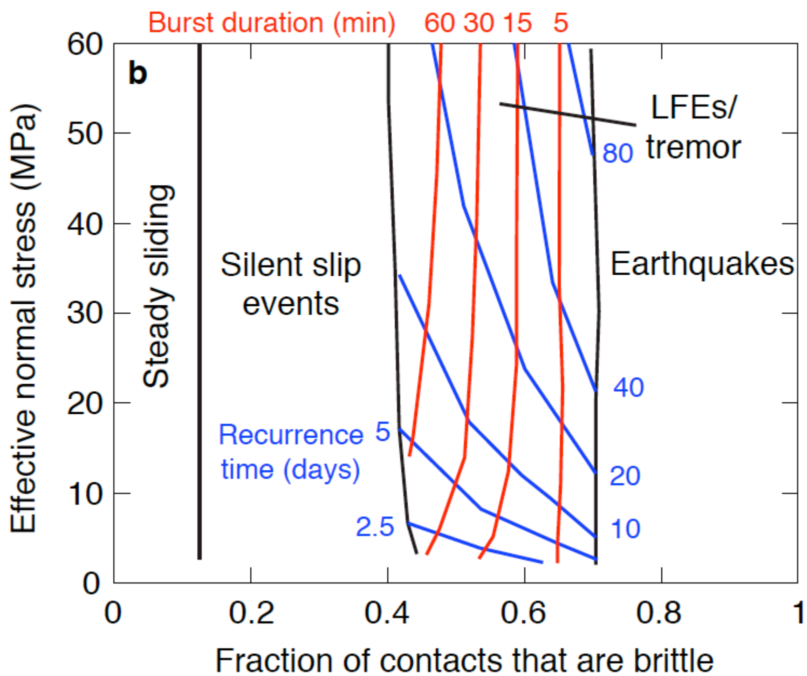
Things to note:

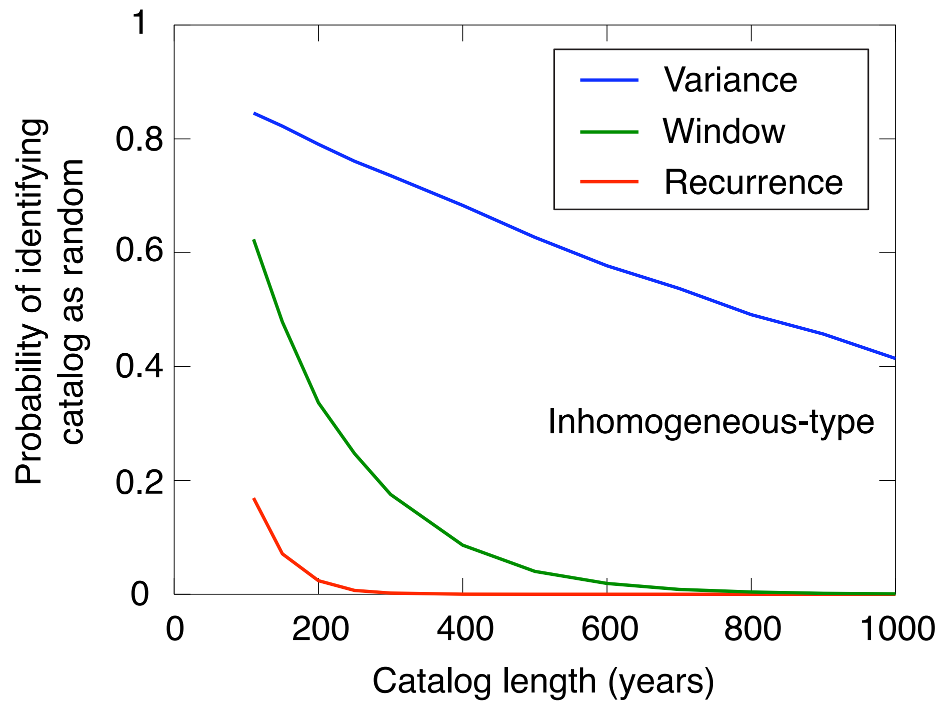
1. Variance misses most clustered catalogs with only 110 years of data!
2. Specific tests fare much, much better with little data. Physical insight into clustering can help devise better statistical tests.
3. All catalogs improve with additional data, but improvement can be slow.



Recap







- Model captures dynamics of tectonic tremor at Parkfield
- Differences in tremor behavior captured by varying strength of brittle fault patches and ductile background
- Model can capture full range of observed faulting behaviors

- Large earthquakes are random
- This could be because we have so little data
- Physics-specific tests can distinguish better than generic ones