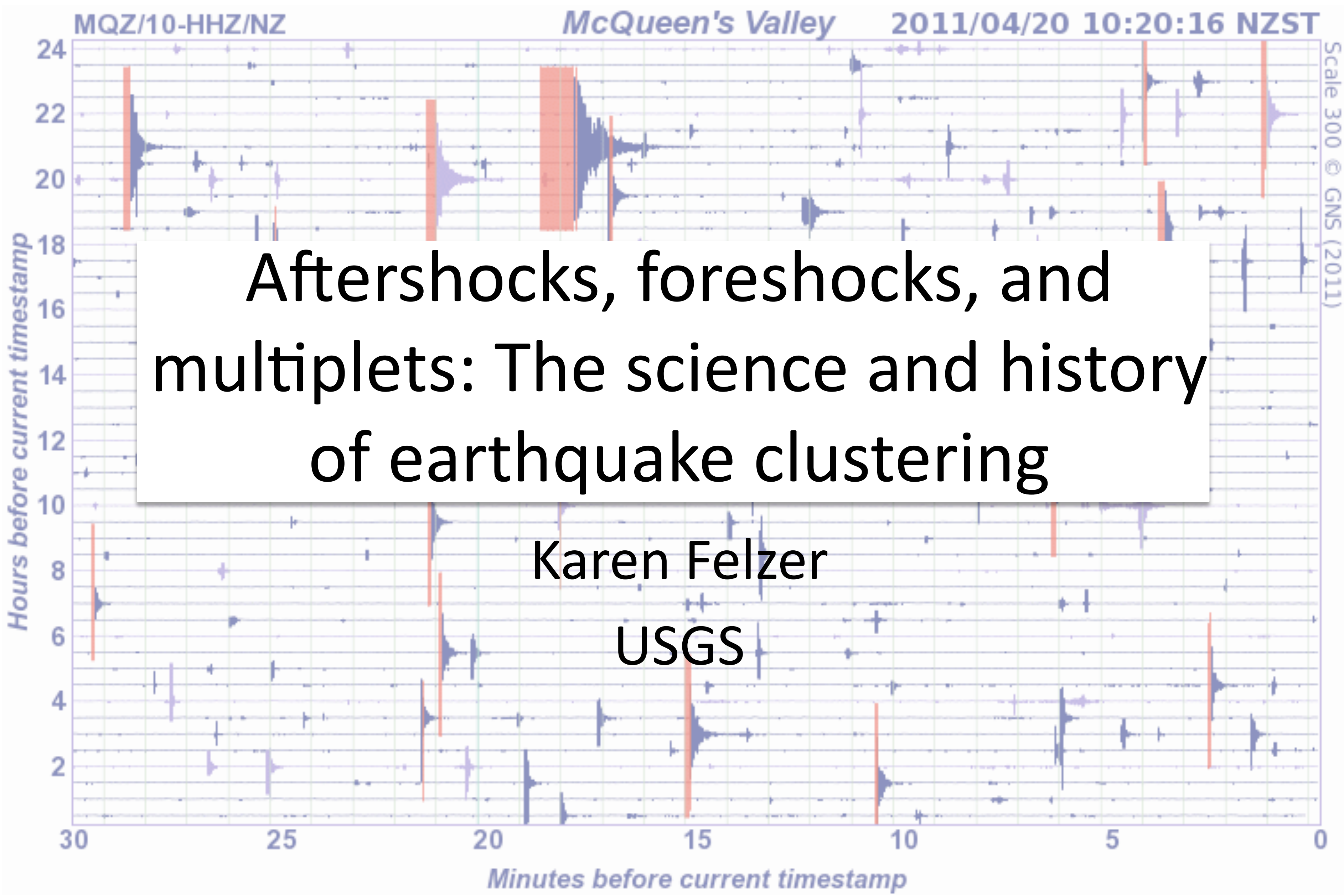
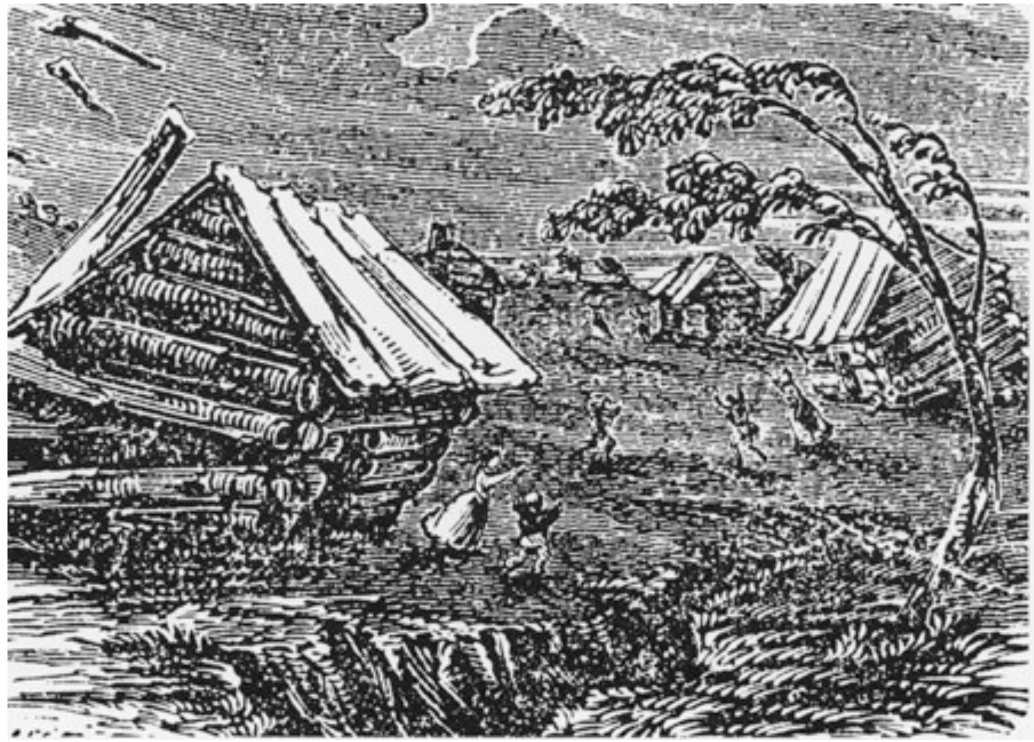


Aftershocks, foreshocks, and multiplets: The science and history of earthquake clustering

Karen Felzer

USGS



Wood cut of the New Madrid earthquake

“There was a great shaking of the earth this morning. Tables and chairs turned over and knocked around - all of us knocked out of bed. The roar I thught would leave us deaf if we lived. It was not a storm. when you could hear, all you cold hear was screams from people and animals. It was the worst thing that I have ever wittnesed. It was still dark and you could not see nothng. I thought the shaking and the loud roaring sound would never stop. You could not hold onto nothing neither man or woman was strong enough - the shaking would knock you lose like knocking hicror nuts out of a tree. I don't know how we lived through it..” *–George Heinrich Crist, 16 December 1811, Kentucky*

The Mississippi river after the New Madrid earthquakes

"What are we gonna do? You cannot fight it cause you do not know how. It is not something that you can see. In a storm you can see the sky and it shows dark clouds and you know that you might get strong winds but this you can not see anything but a house that just lays in a pile on the ground - not scattered around and trees that just falls over with the roots still on it. The earth quake or what ever it is come again today. It was as bad or worse than the one in December [….]Some thinks that this is the beginning of the world coming to a end." *George Heinrich Crist, 23 January 1812, Kentucky*

Trees thrown over by the Ned Madrid earthquakes

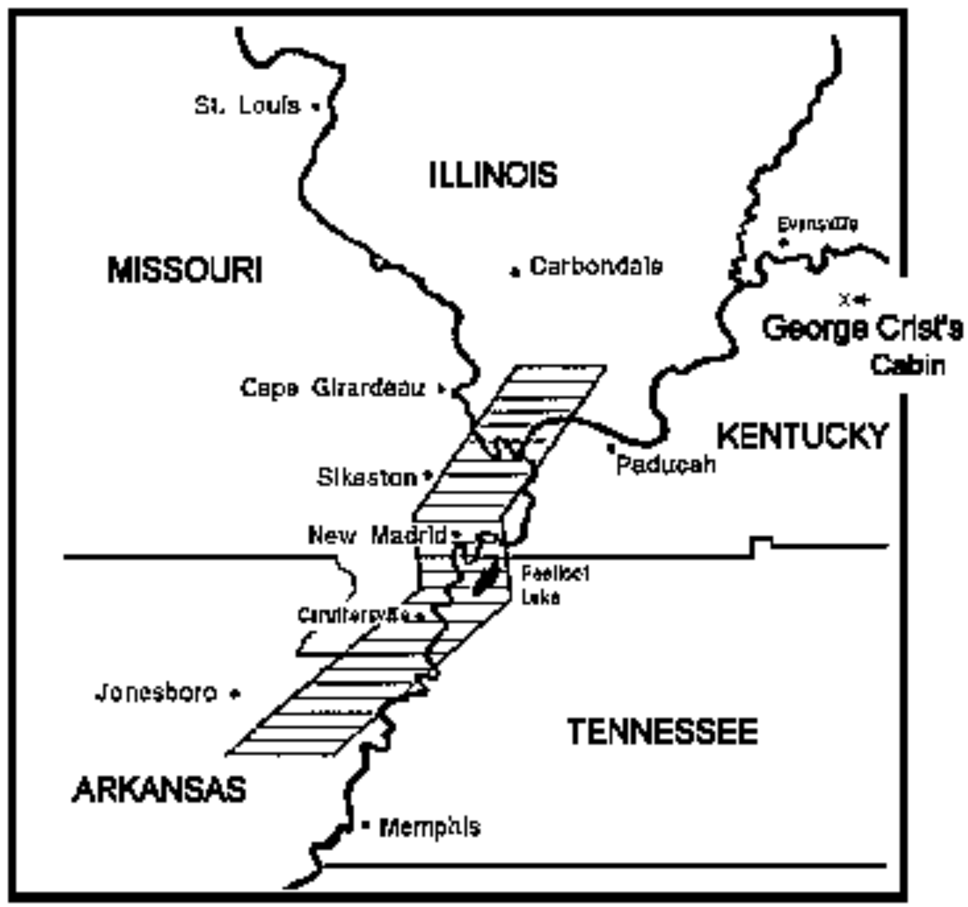
"If we do not get away from here the ground is going to eat us alive. We had another one of them earth quakes yesterdy and today the ground still shakes at times. We are all about to go crazy - from pain and fright. We can not do anything until we can find our animals or get some more. We have not found enough to pull he wagons." " *–George Heinrich Crist, 8 February 1812, Kentucky*

New Madrid Earthquake Cluster

December 16, 1811, 2:15	**M 6.7—6.9**
December 16, 1811, 7:15	M 6.5—6.7
January 23, 1812, 9:15	M 6.5—7.0
February 7, 1812, 3:45	M 7.1—7.3

Magnitudes from *Hough and Page* (2011)

Location of the New Madrid Earthquakes



Map from http://hsv.com/genlintr/newmadrid

Closer to home: the Landers earthquake cluster

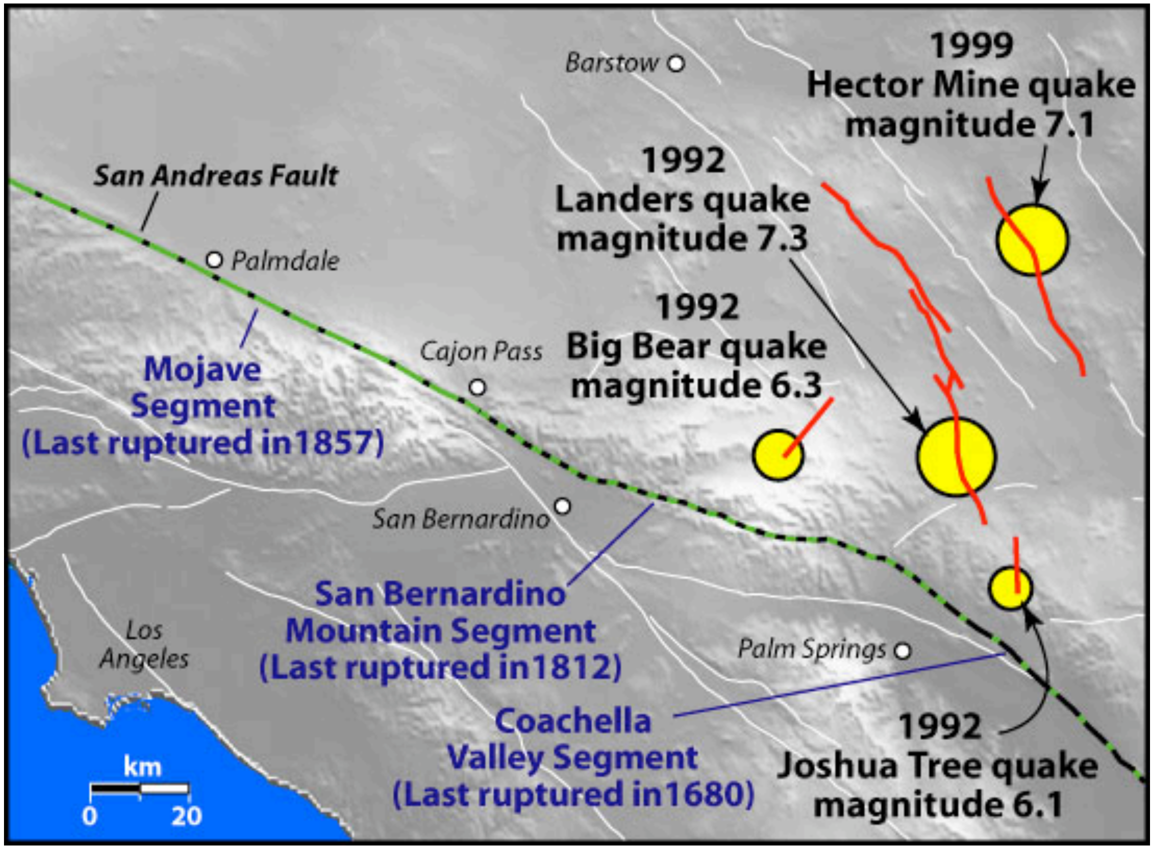


Figure by Andrew Freed, taken from *Oceanus*

More recently: The New Zealand Canterbury/Christchurch sequence

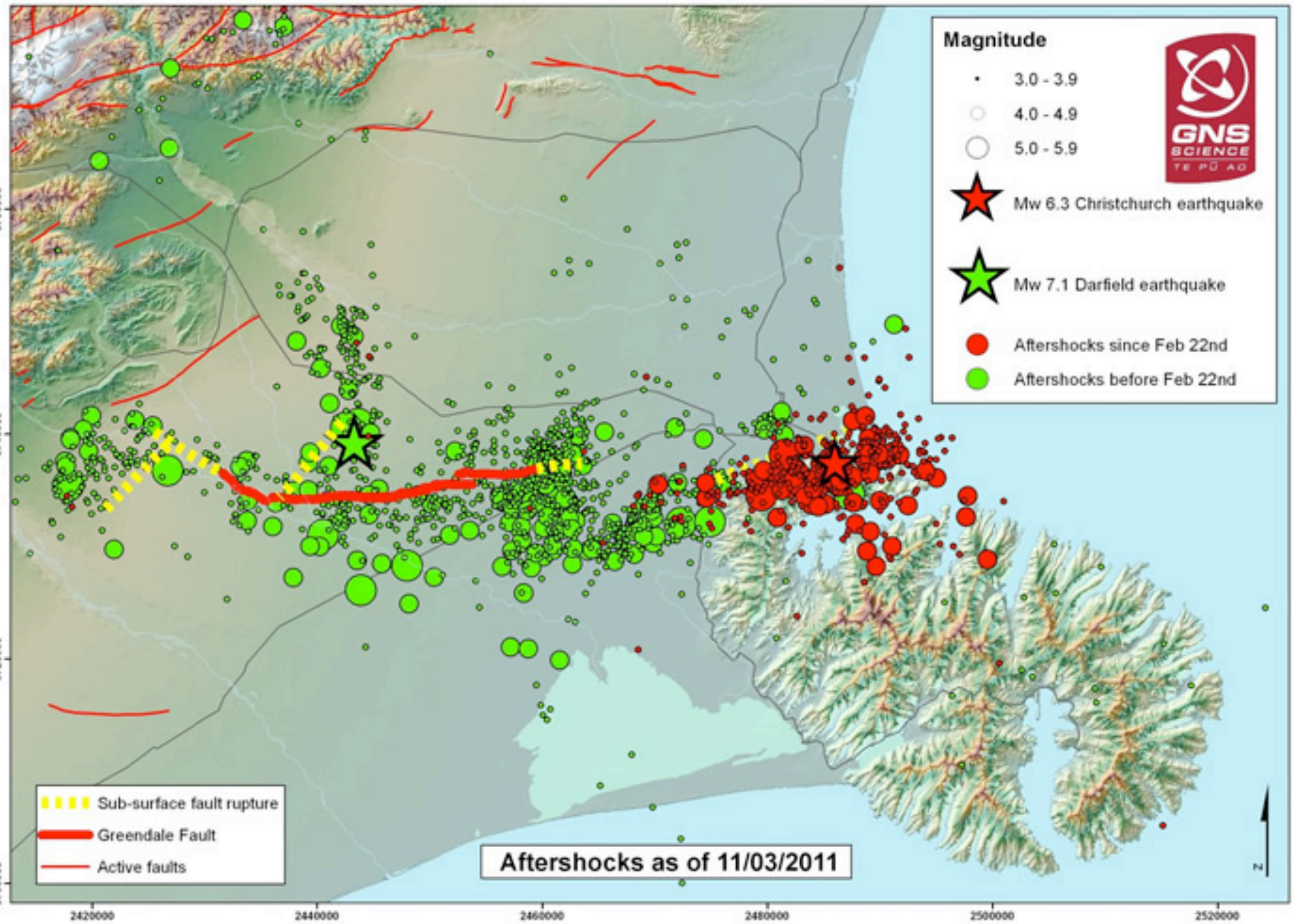


Figure by Rob Langridge and William Ries, GNS Science

Closer in time: the Tohoku-Oki Japan 2011 sequence

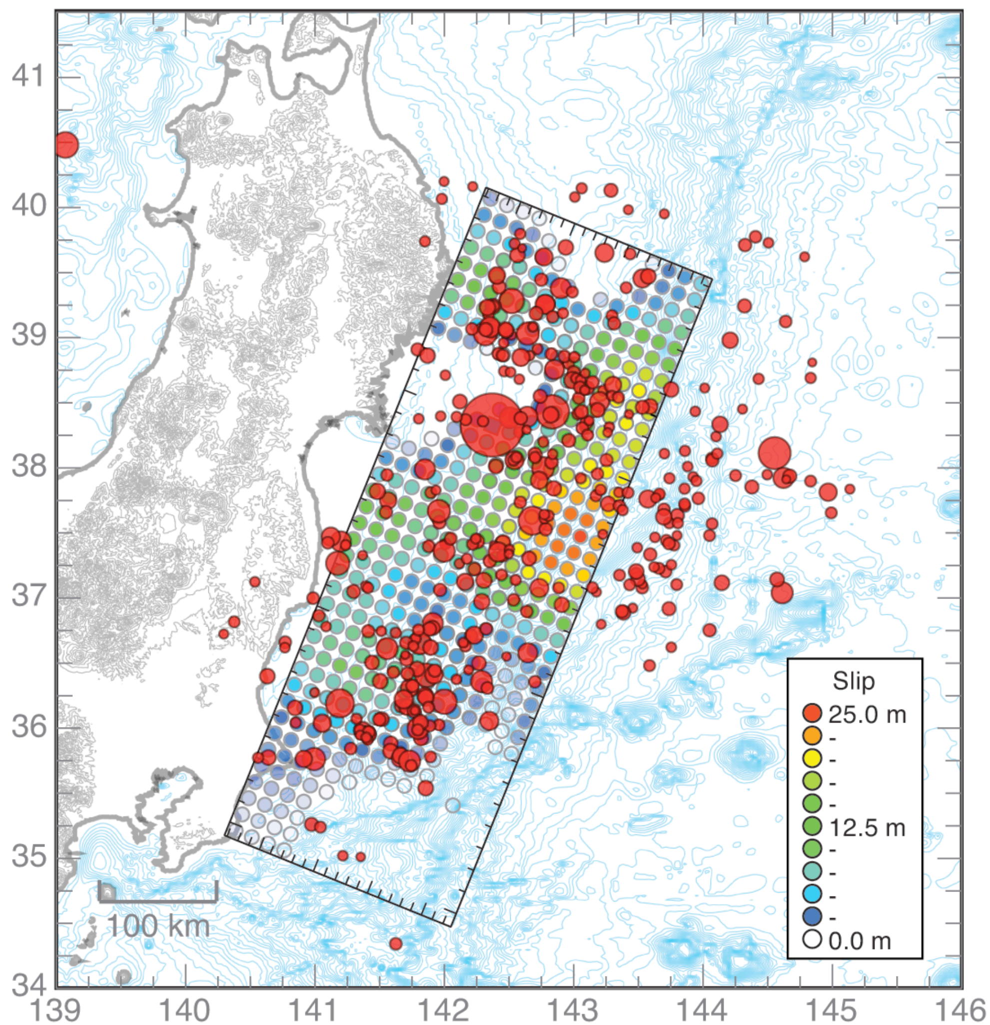
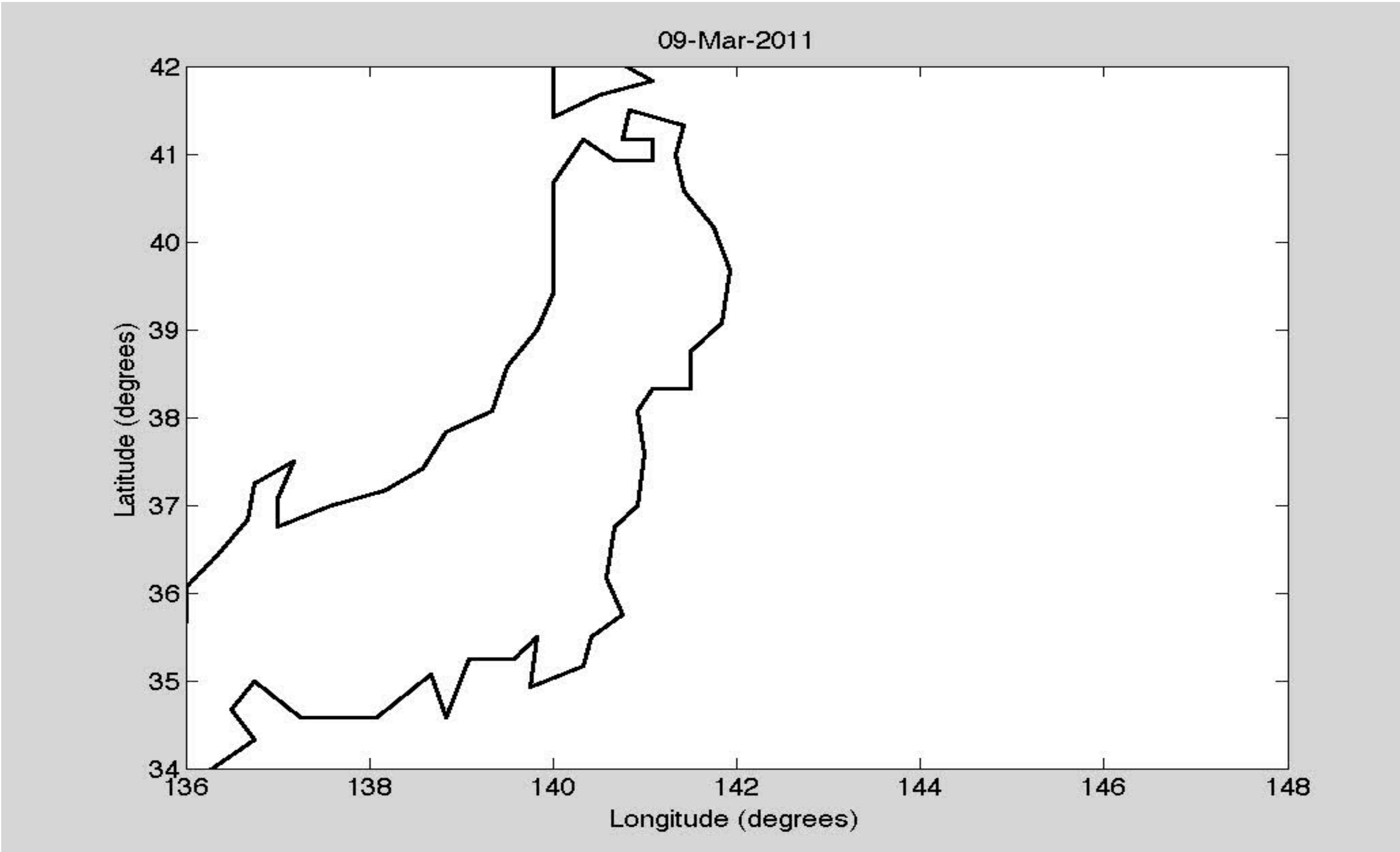


Figure by C. J. Ammon, Penn State

Tohoku-Oki aftershock sequence

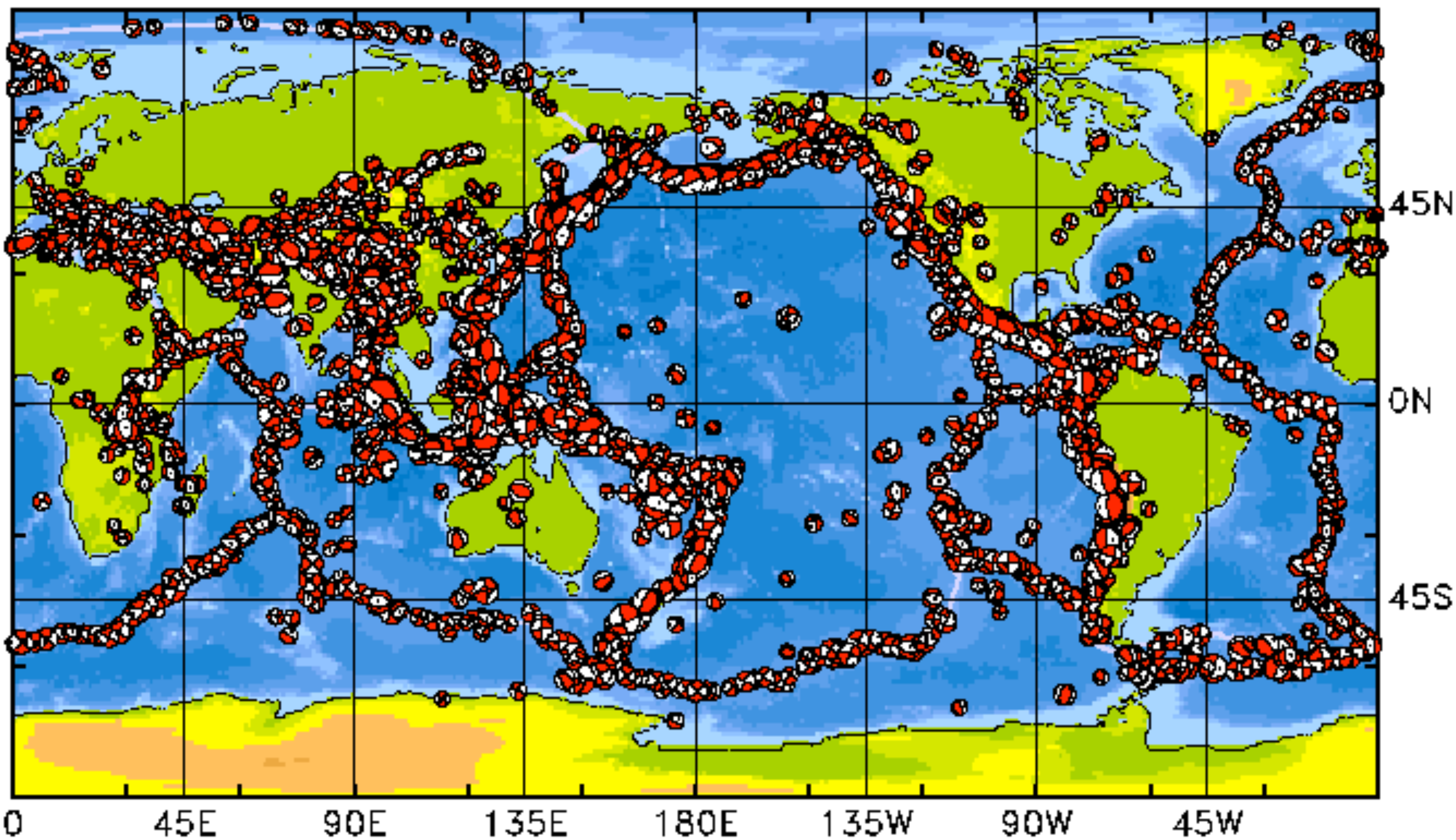


movie by Morgan Page

Earthquake clusters are common

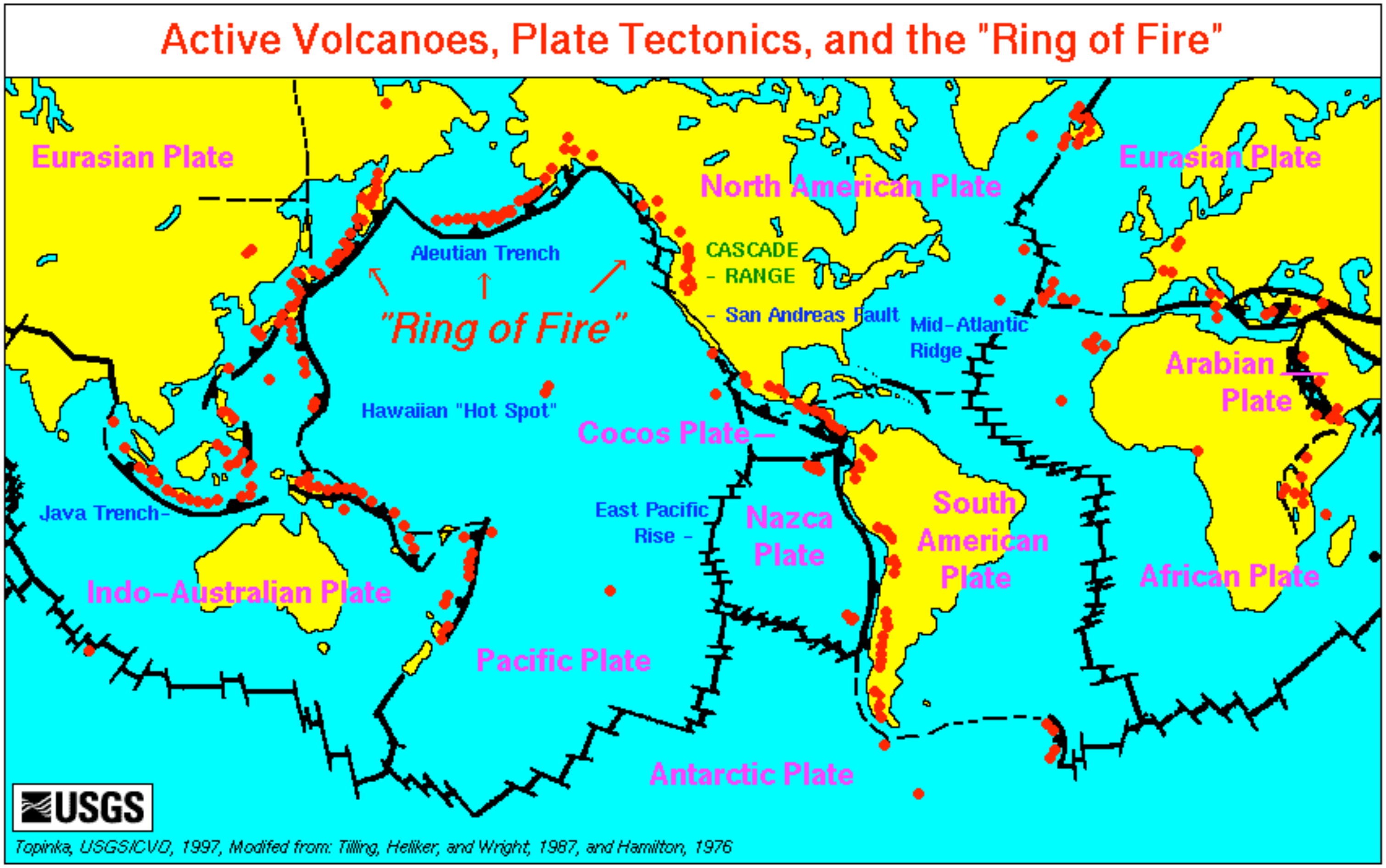
- ~**10%** of all earthquakes occur close in time and space to another earthquake of similar magnitude (within one magnitude unit)
- **>60%** of all earthquakes occur as aftershocks, foreshocks, or multiplets
- Earthquakes cluster because the occurrence of one earthquake triggers others.
- Earthquake clustering creates significant issues for efforts to forecast earthquakes.

The world's earthquakes

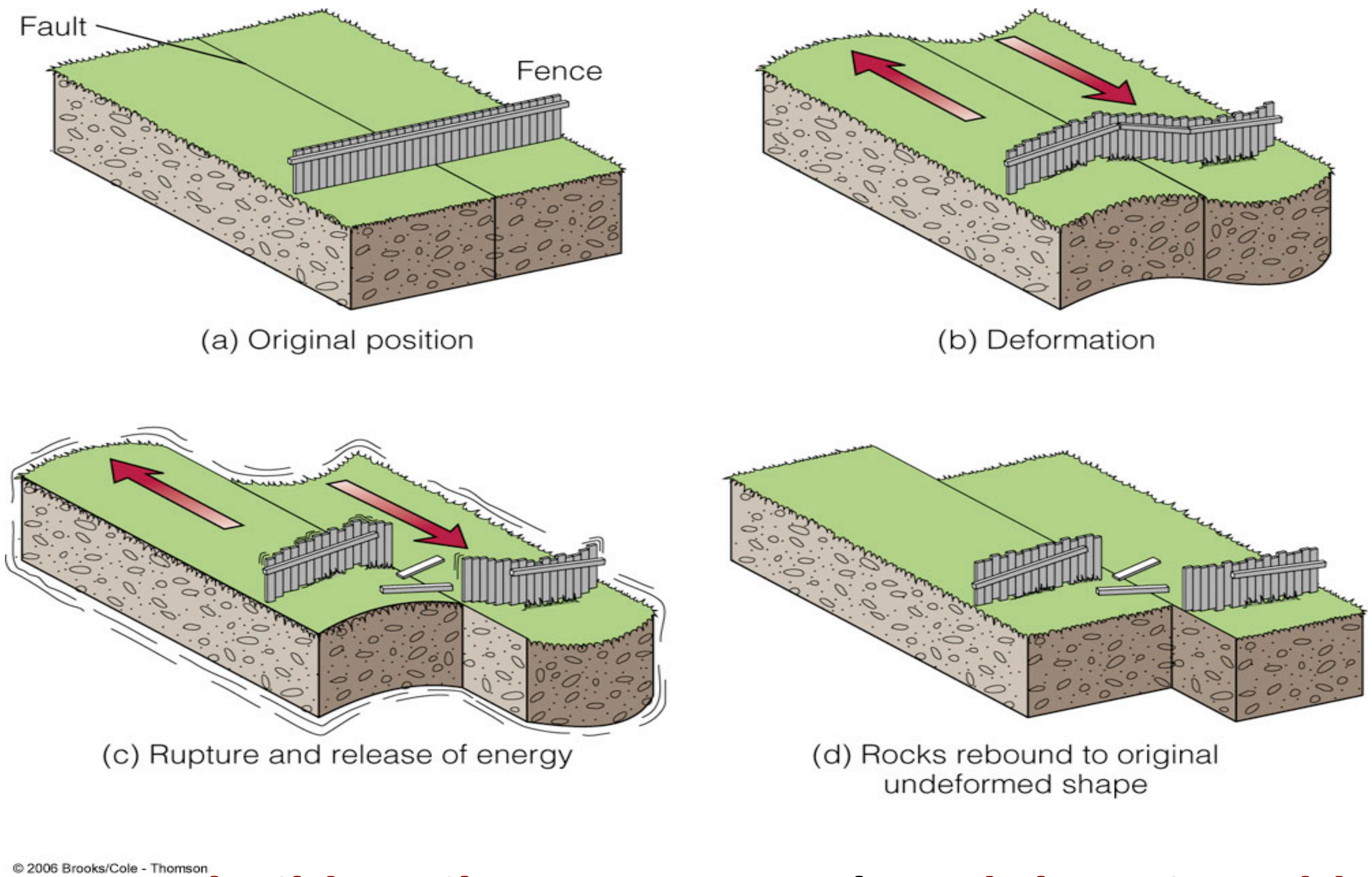


Shallow seismicity, 1976-2005, from the Global CMT project

Most earthquakes occur where one plate moves past another

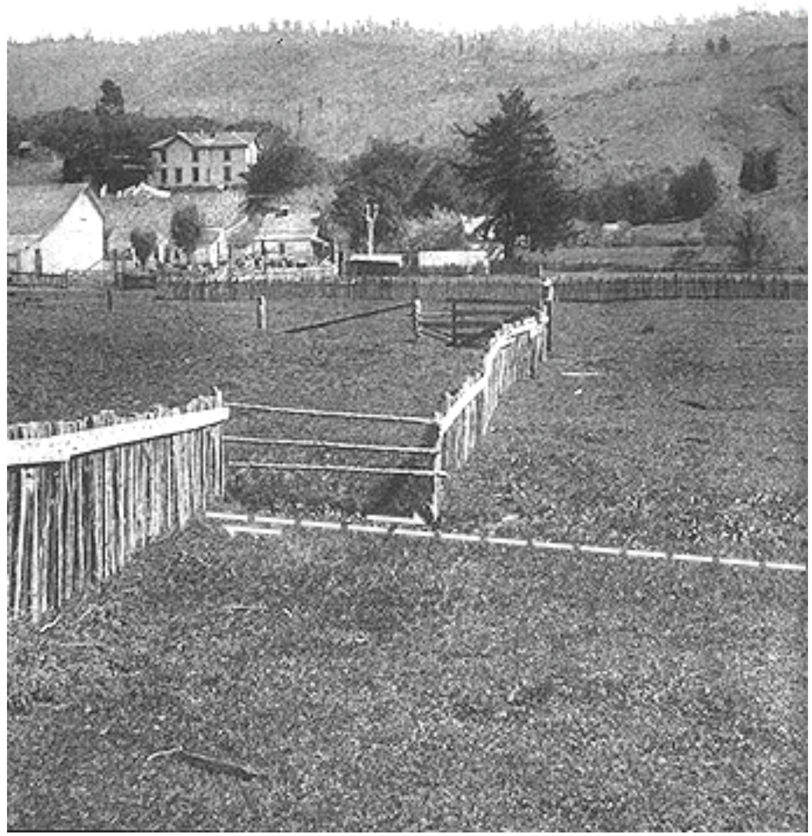


Where the tectonic plates meet they sometimes stick



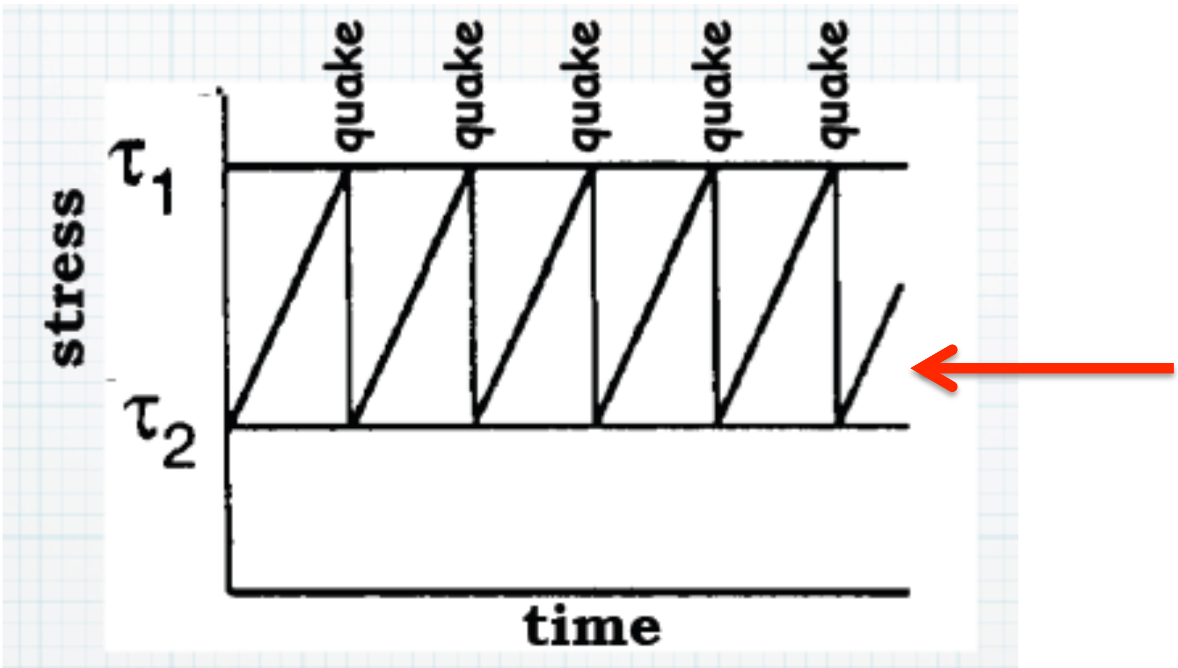
Stresses build until stress=strength and there is sudden movement in an earthquake

This model of how earthquakes occur is known as elastic rebound



The model was formulated by Harry F. Reid after observing displacements associated with the 1906 San Francisco earthquake

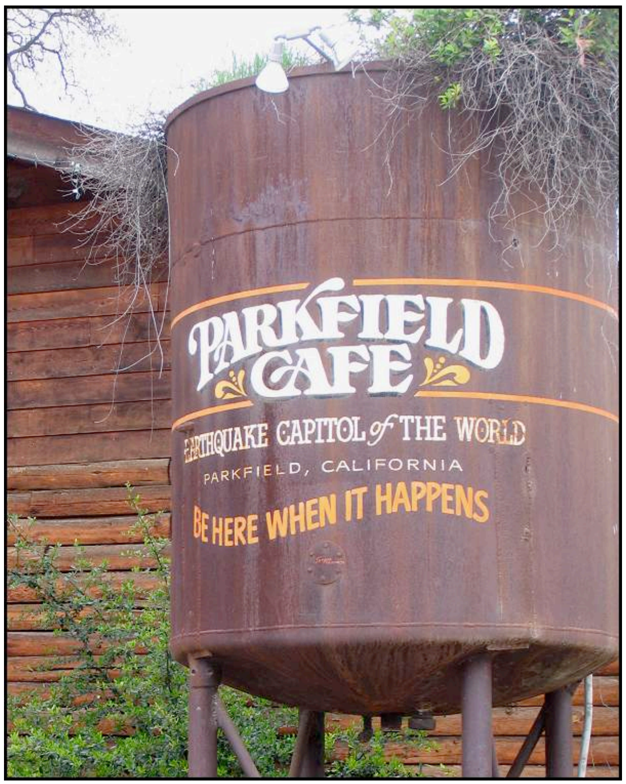
The tectonic plates move at a slow, constant rate



The seismologist's dream

So elastic rebound should allow us to easily forecast earthquake times

But repeated attempts to use elastic rebound to forecast earthquakes have not met with success



The Parkfield Prediction: 95% chance of a M 6 earthquake by January **1993** (*Bakun and Lindh*, 1985)

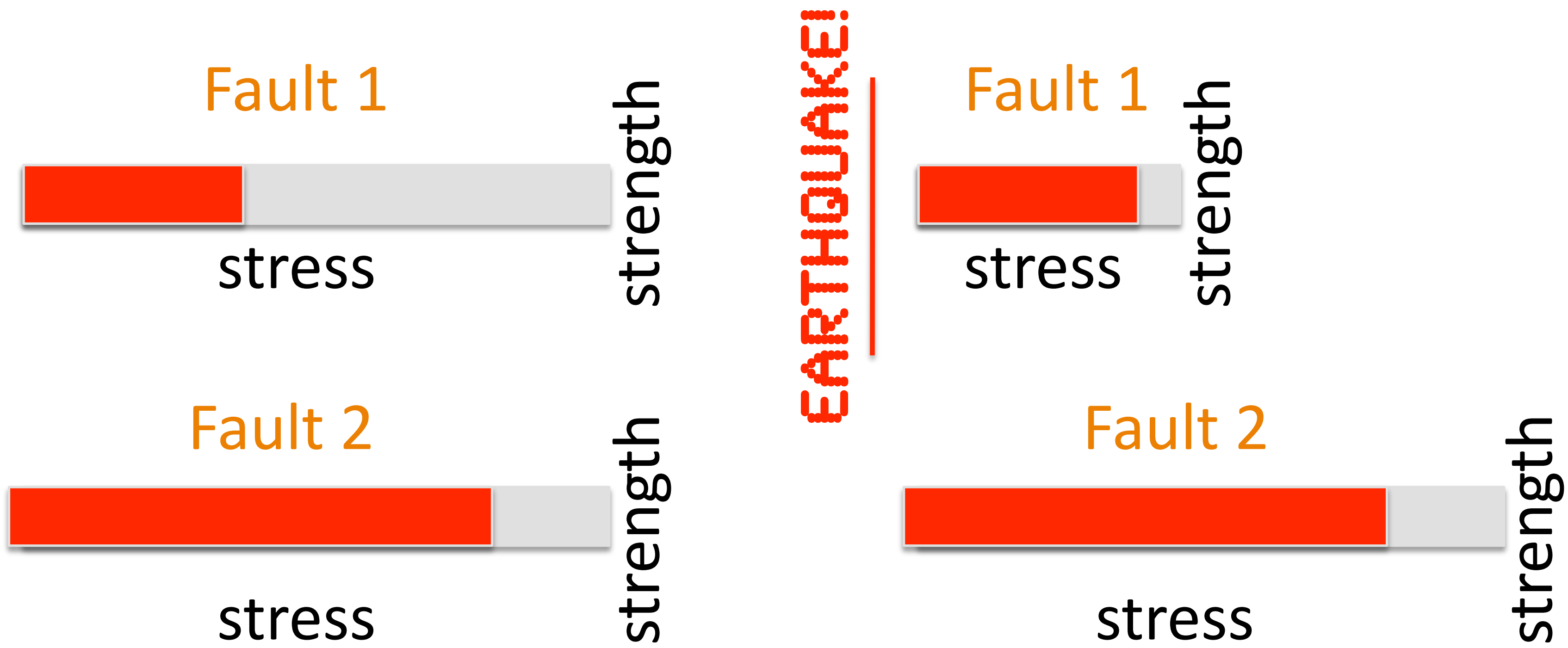
Reality: No M≥6 earthquake until **2004**

My hypothesis: Elastic rebound forecasts fail because the shaking from one earthquake can cause catastrophic loss in strength in locations on neighboring faults

House with loss of strength due to earthquake shaking

This causes the stress=strength relationship to be satisfied on triggered faults much more rapidly, and results in earthquakes occurring in clusters rather than at regular repeating intervals

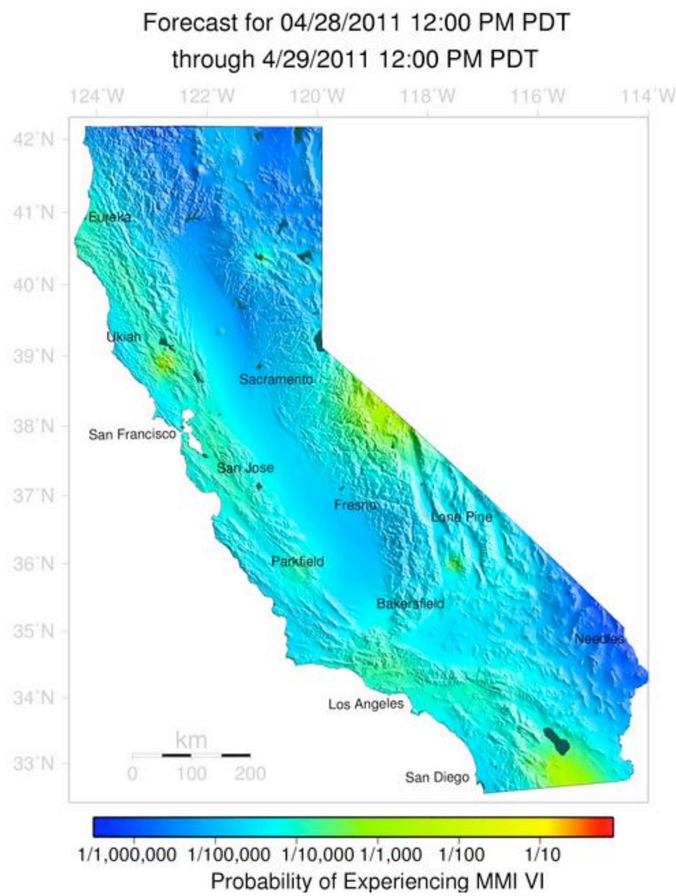
How earthquake triggering usurps elastic rebound based forecasting



Before triggering, Fault 2 should rupture first

But after an earthquake occurs near Fault 1, it goes first

So: Our understanding of earthquake clustering may be our most powerful forecasting tool

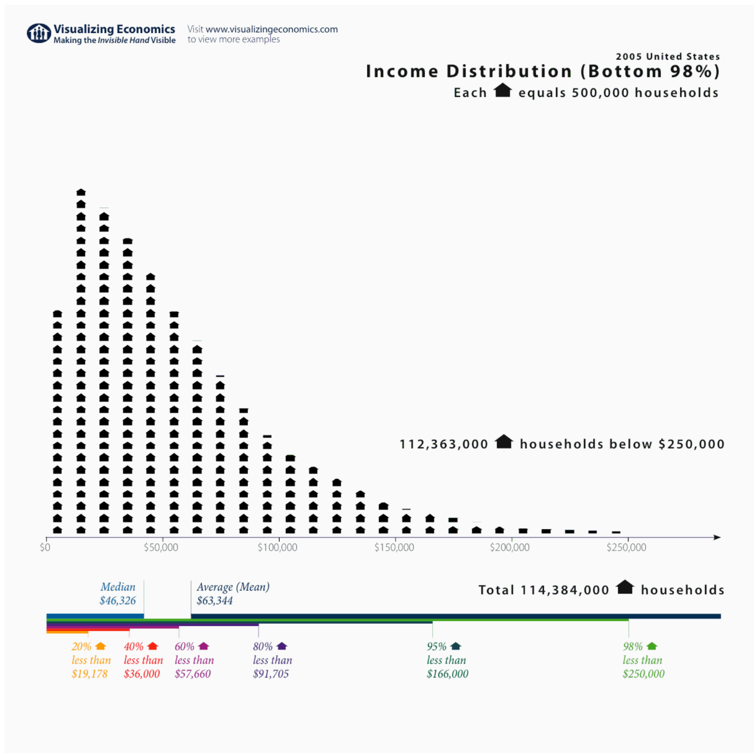


USGS STEP aftershock forecast for 4/28/2011

Aftershock forecasts are made possible by the fact that aftershocks are good at adhering to the same statistical distributions in:

- **Time**
- **Magnitude**
- **Space**

Example of a statistical distribution: Incomes in the United States

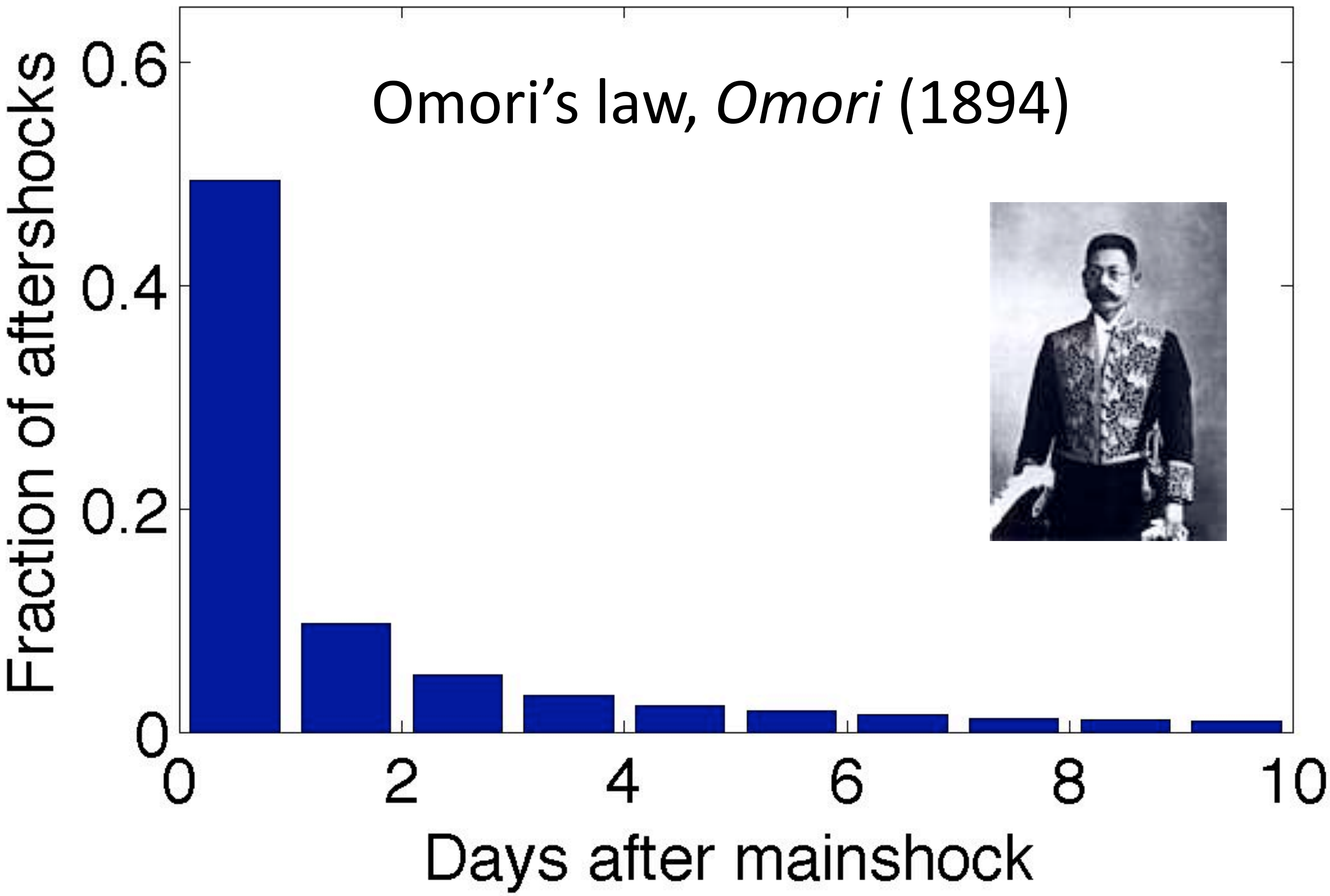


2005 Income Distribution, from Visualizing Economics

- If I had a long list of random names, the income distribution tells me that 60% earn <$57,600, 5% >$166,000, etc.
- But the distribution doesn't tell me which individuals are in that top 5%, or who I should call for a big donation!

Aftershock distributions #1: Time

The number of aftershocks varies as 1/time



Application of Omori's law: The fraction of the aftershock sequence that is over at different times

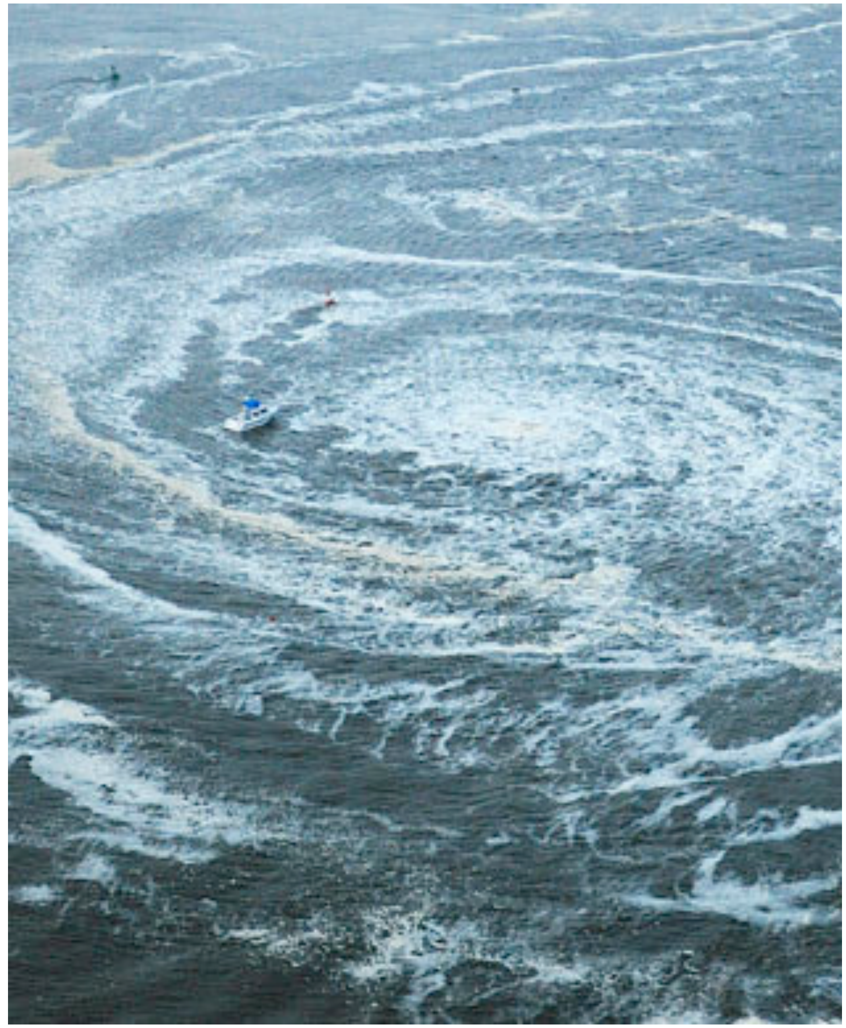
10 minutes	12%
1 hour	21%
1 day	49%
1 week	73%
1 year	95%
50 years	>99%

Note: Late large aftershocks do happen!

The **M 7.1** Hector Mine aftershock occurred 7 years after the **M 7.3** Landers mainshock

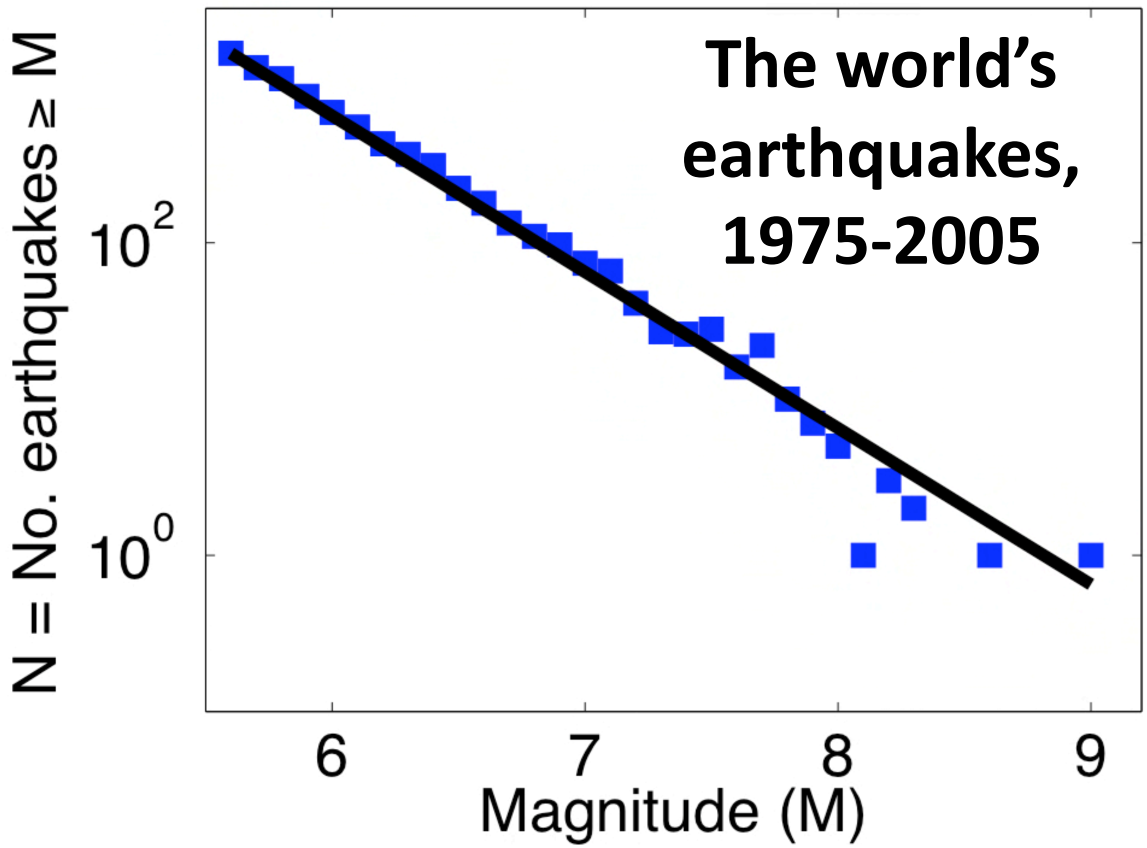
Aftershock distributions #2: Magnitude

Chino Hill, M 5.4



Japan, M 9.0

The distribution of aftershock magnitudes is the same as the distribution of all earthquake magnitudes, world-wide



Data from the Global CMT catalog

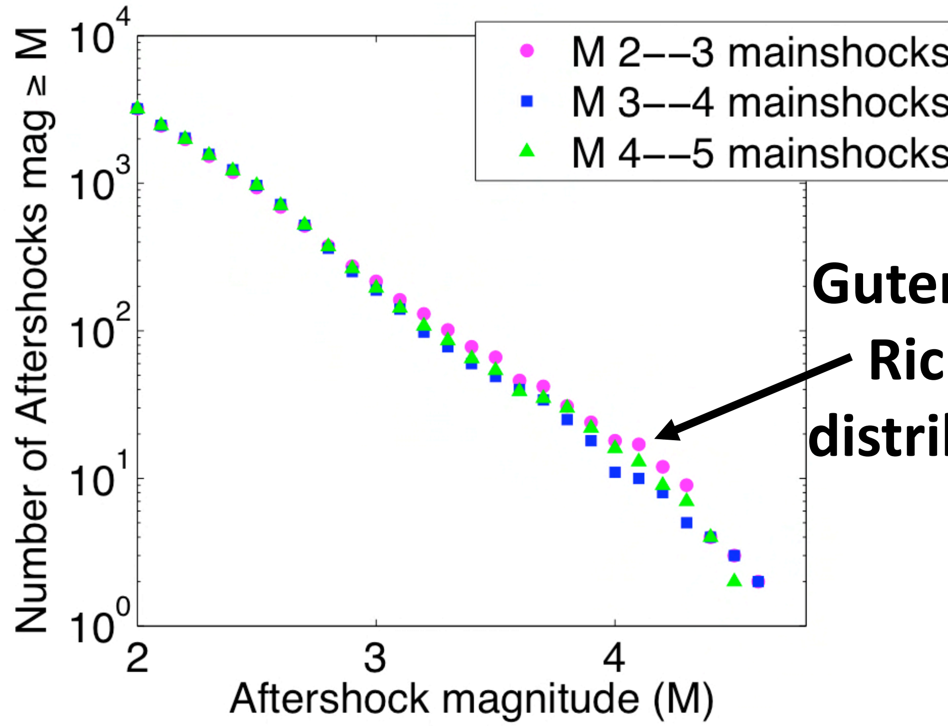
The Gutenberg-Richter distribution

For each 10 earthquakes of magnitude M, there is 1 eq of magnitude M+1

Chino Hill, M 5.4

Christchurch, M 6.3

Aftershock magnitude distribution is independent of mainshock magnitude



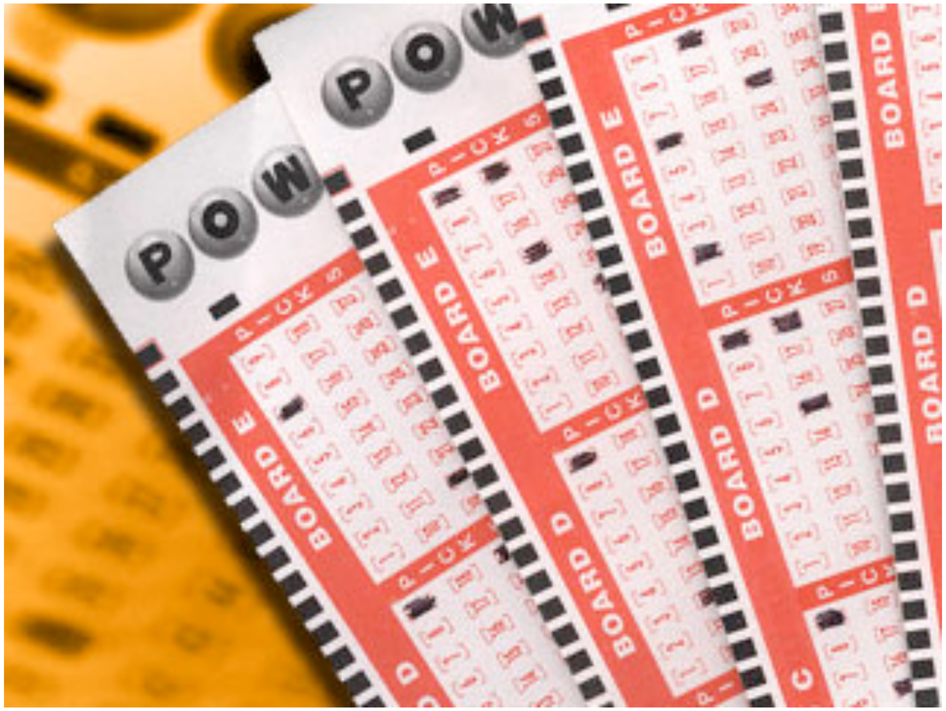
Gutenberg-Richter distribution

Sometimes an aftershock is larger than the earthquake that triggered it, which is then renamed a **"foreshock"**

Larger mainshocks do have larger aftershocks *on average* because they have more aftershocks

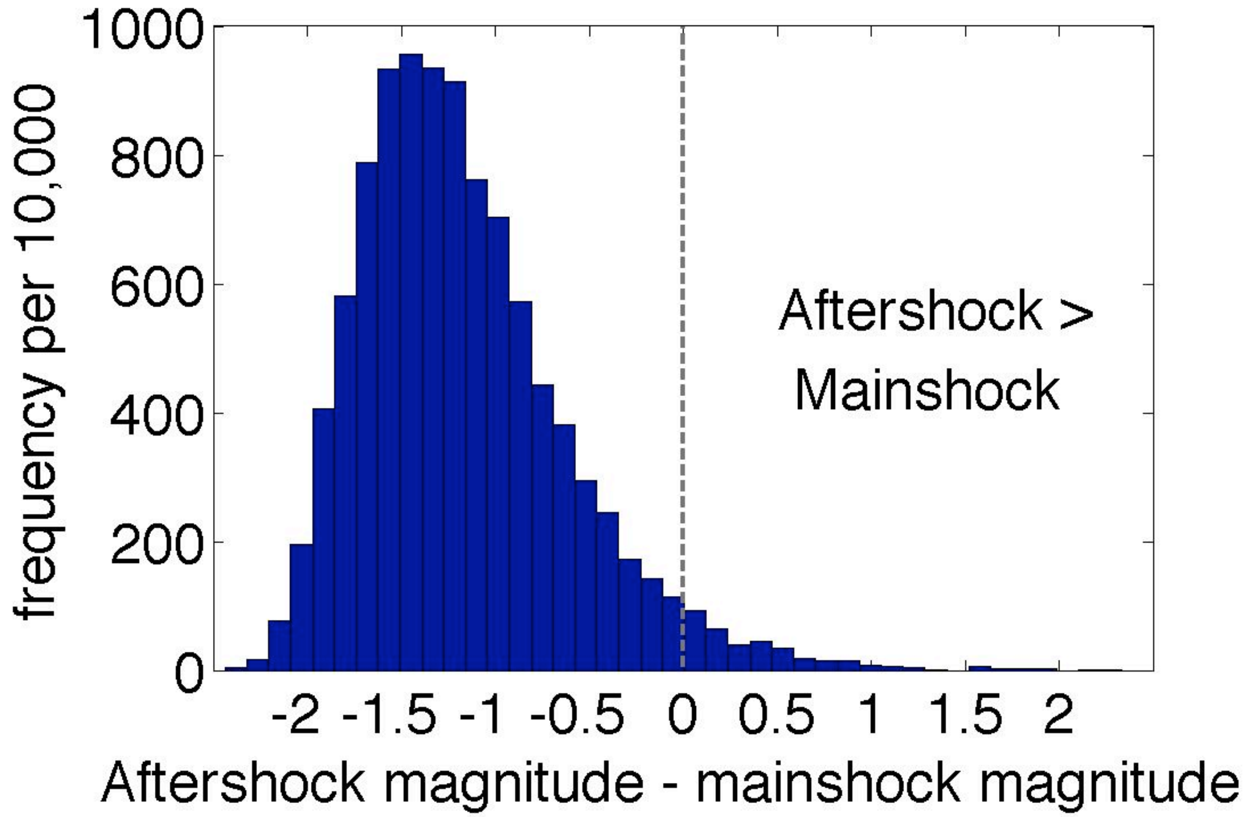
Mainshock magnitude	**Average number of aftershocks M≥3.5**
M 6	20
M 7	200
M 8	2,000
M 9	20,000

Having more aftershocks produces a larger probability of triggering a large one



Analogy: Large earthquakes buy more lottery tickets, so have a larger chance of "winning"

Probability distribution for the largest aftershock magnitude



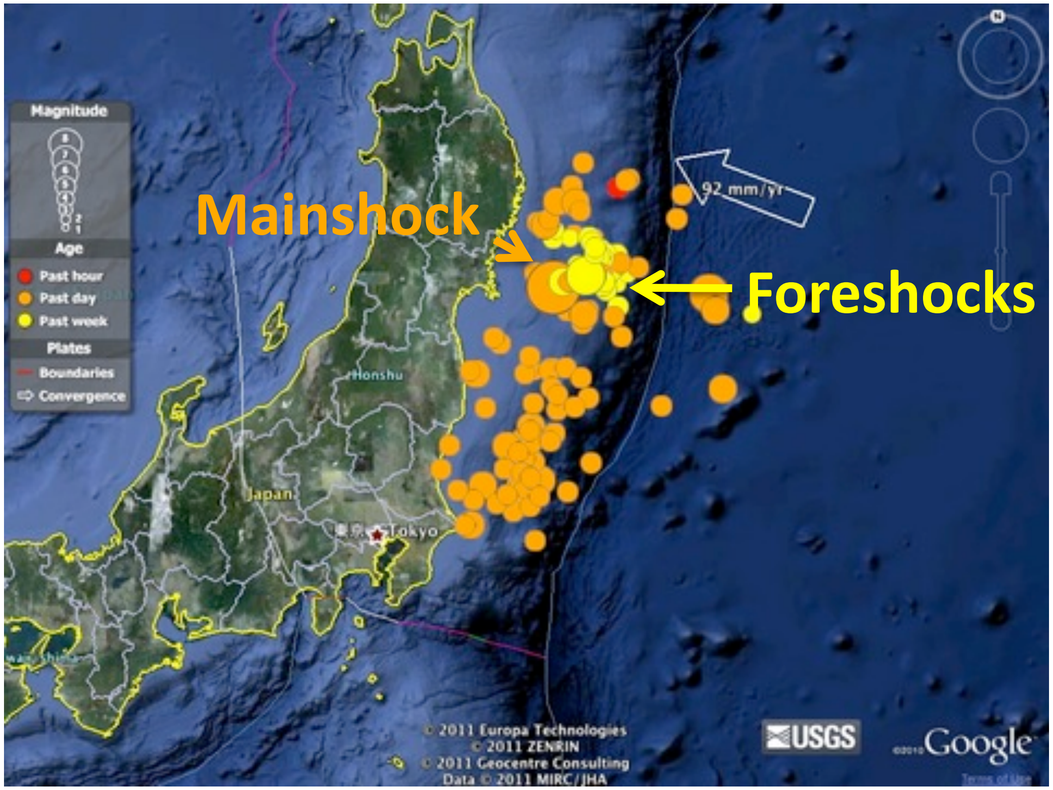
The **mean** mainshock mag – largest aftershock mag = 1.2
(Båth's law, *Båth,* (1965)

Example: Expectations for the largest aftershock after an M 7 earthquake

Largest aftershock	Probability
M>8	0.5%
M>7	5%
M>6.5	12%
M>6	31%
M>5.7	53%
M<5.0	2%

A smaller earthquake triggering a larger one: example from Japan

- A M 7.2 foreshock occurred on March 9, two days before the mainshock.



- During an average week, the chance of a M 9 somewhere near Japan is ~ **1 in 50,000**

- After any M 7.2 we know that the probability of an M 9 occurring (because it may be triggered) rises to **1 in 1000** (50 times more probable than usual).

Use of this information would result in 999 false mass evacuations per success

Evacuation from Hurricane Rita

We can't do any better because we do not know which individual earthquakes will be large. Why can't we figure this out??

All earthquakes actually start or "nucleate" at a tiny point on a fault, known as the hypocenter

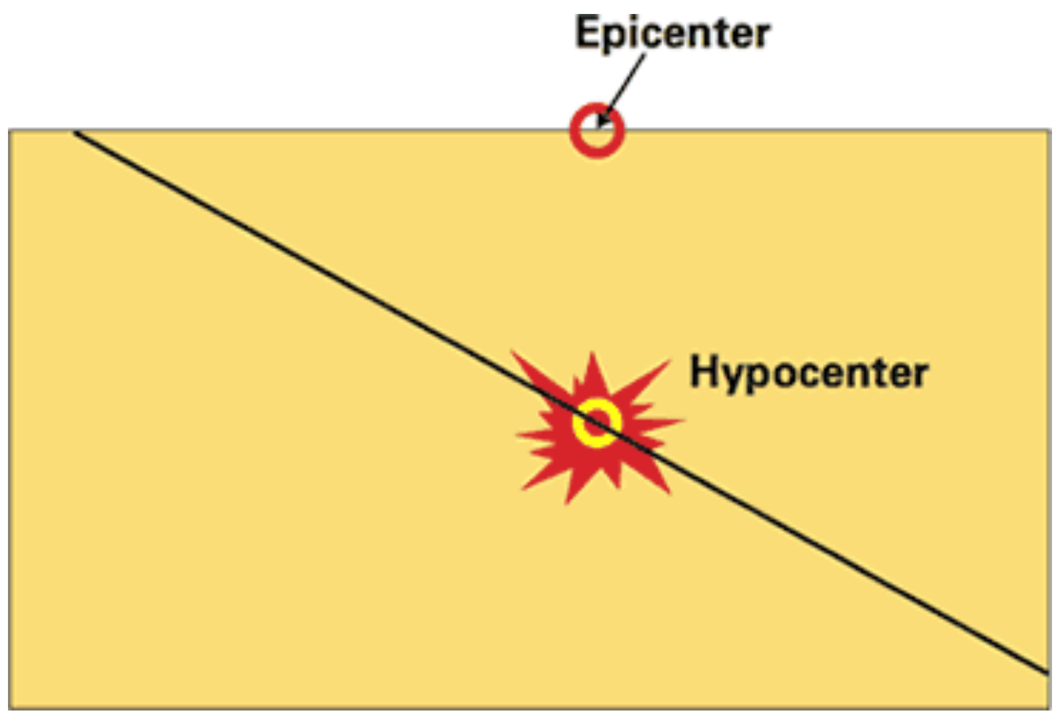


Figure by Charles Ammon

Fault slip occurs at the hypocenter, which triggers surrounding fault to slip next. The earthquake grows as the total area and amount of fault slip gets larger.

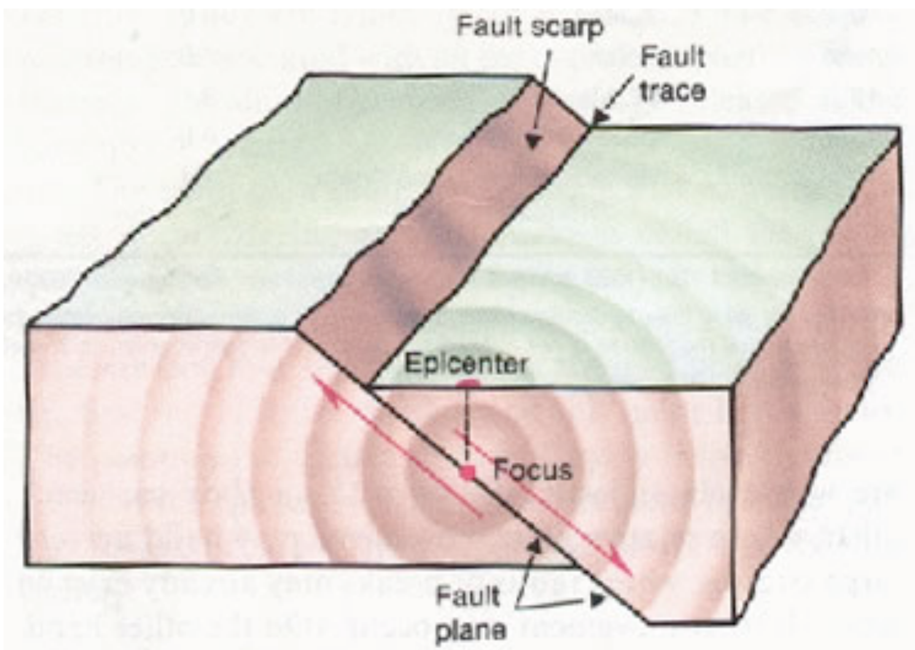
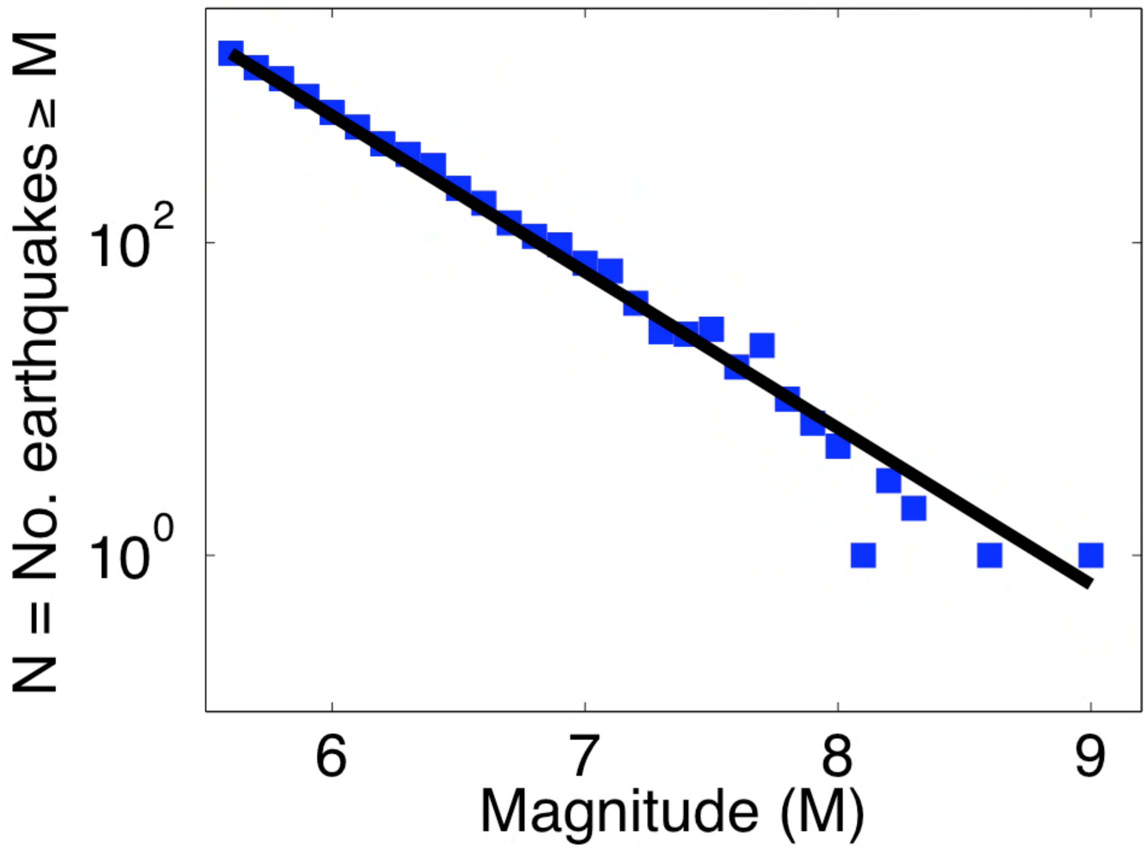


Figure by Kian H. Chong

As earthquakes propagate, however, they encounter many barriers on the fault that try to stop growth

As a result most earthquakes only rupture a small area of the fault. They produce a tiny amount of shaking and are not felt.

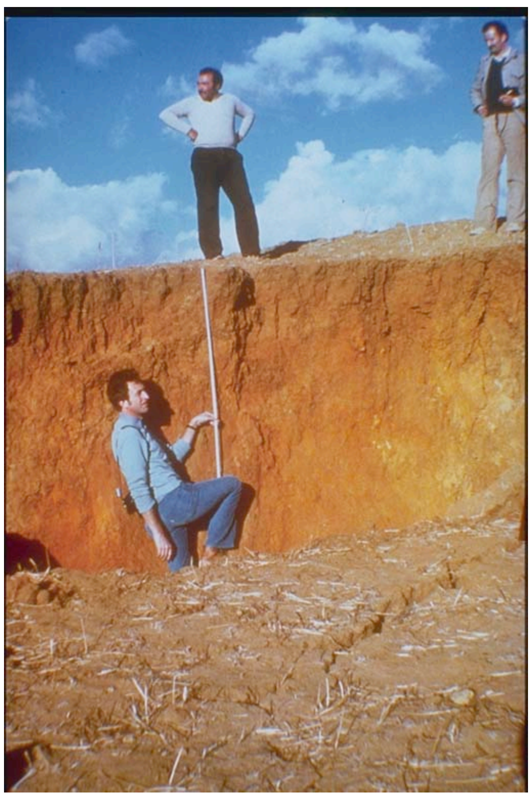
Most earthquakes are small



The Gutenberg-Richter distribution

Data from the Global CMT catalog

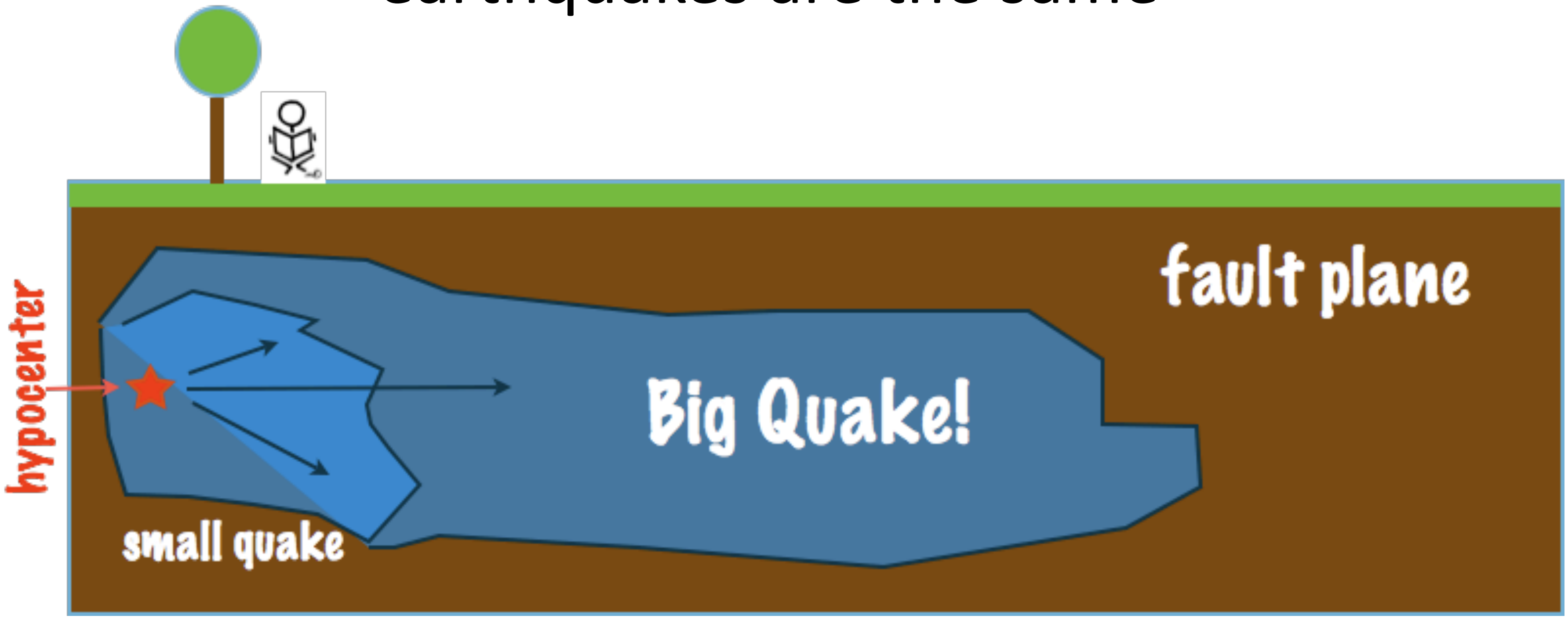
A few earthquakes manage to overcome the odds and produce large slip over a large area, and devastating shaking



1980, El Asnam, Algeria, M 7.3

Image from NOAA website

Important for our story: Triggering occurs at the hypocenter. At this point small and large earthquakes are the same



How large the earthquake becomes is the result of complex dynamic interactions after the initial triggering

The triggering cascade

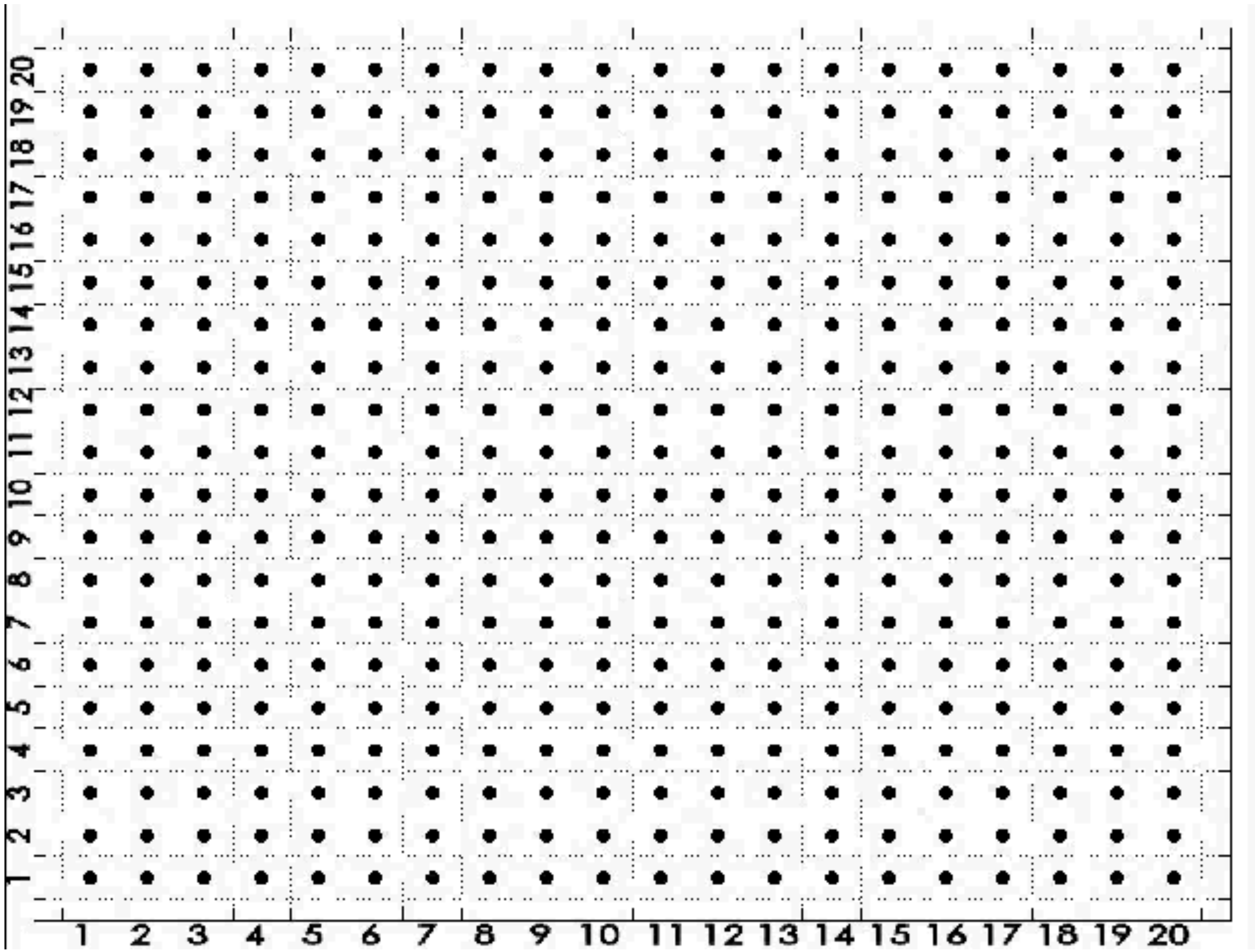
- Karen’s model: The mainshock weakens a small fault area right around the hypocenter.
- Dynamic waves produced by rupture at the hypocenter weakens surrounding fault area.
- If the rupture spreads, additional fault is weakened by the additional dynamic waves.
- How far this process will continue before it is stopped cannot be anticipated.

How large an earthquake will grow is as predictable as flipping pennies…

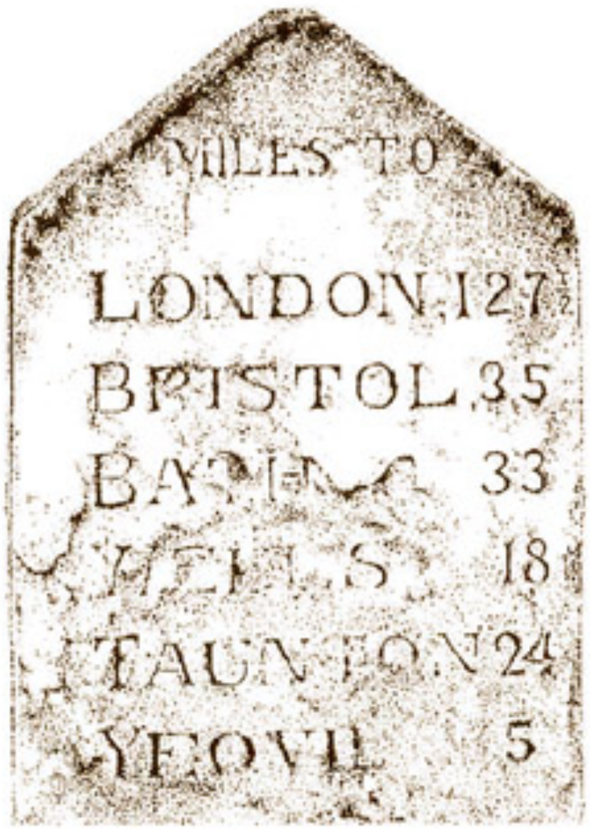
You flip a penny 100 times. On each flip there is an equal 50% chance of getting heads

Earthquake size ~ number of heads in a row

Getting a large event is unlikely -- but it happens under the same starting conditions as smaller events

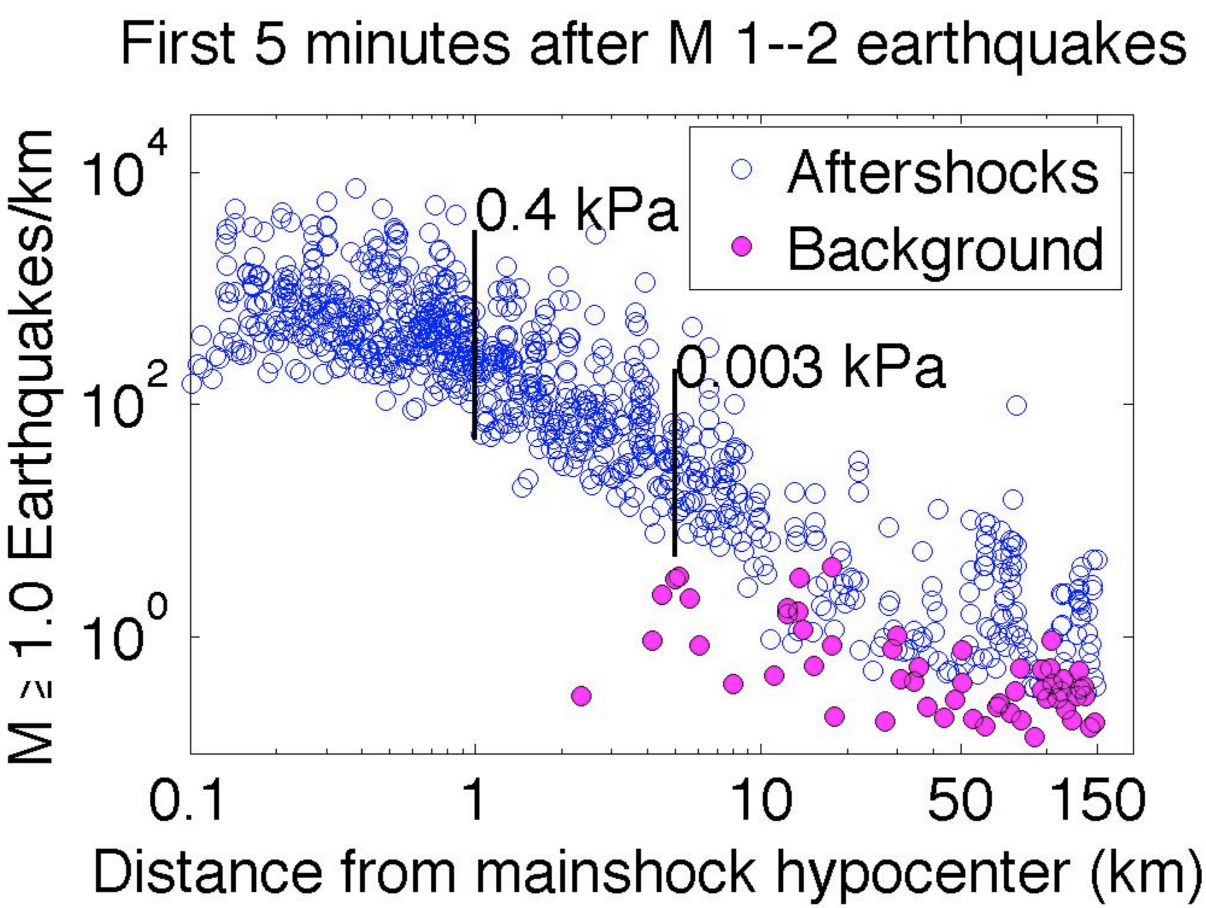

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Aftershock distributions #3: Distance



Old Milestone

The density of aftershocks decays as ~1/distance from the mainshock fault plane

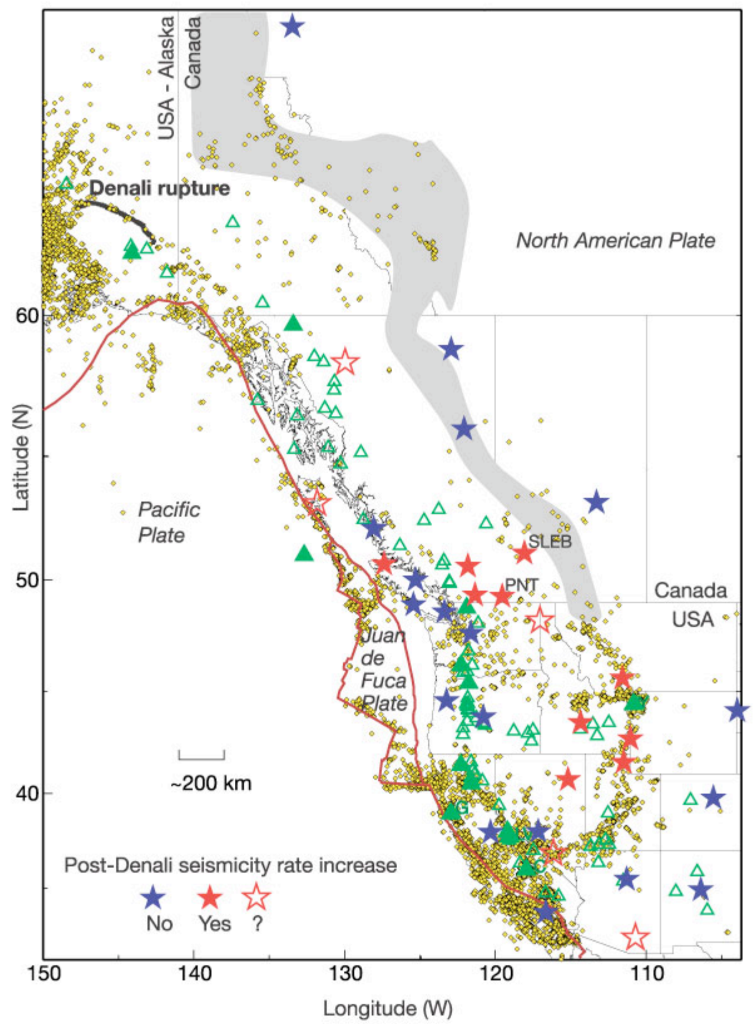


8656 M 1—2 Northern California mainshocks from the NCSN catalog, not preceded by larger event for 3 days/200 km

Put on own slide

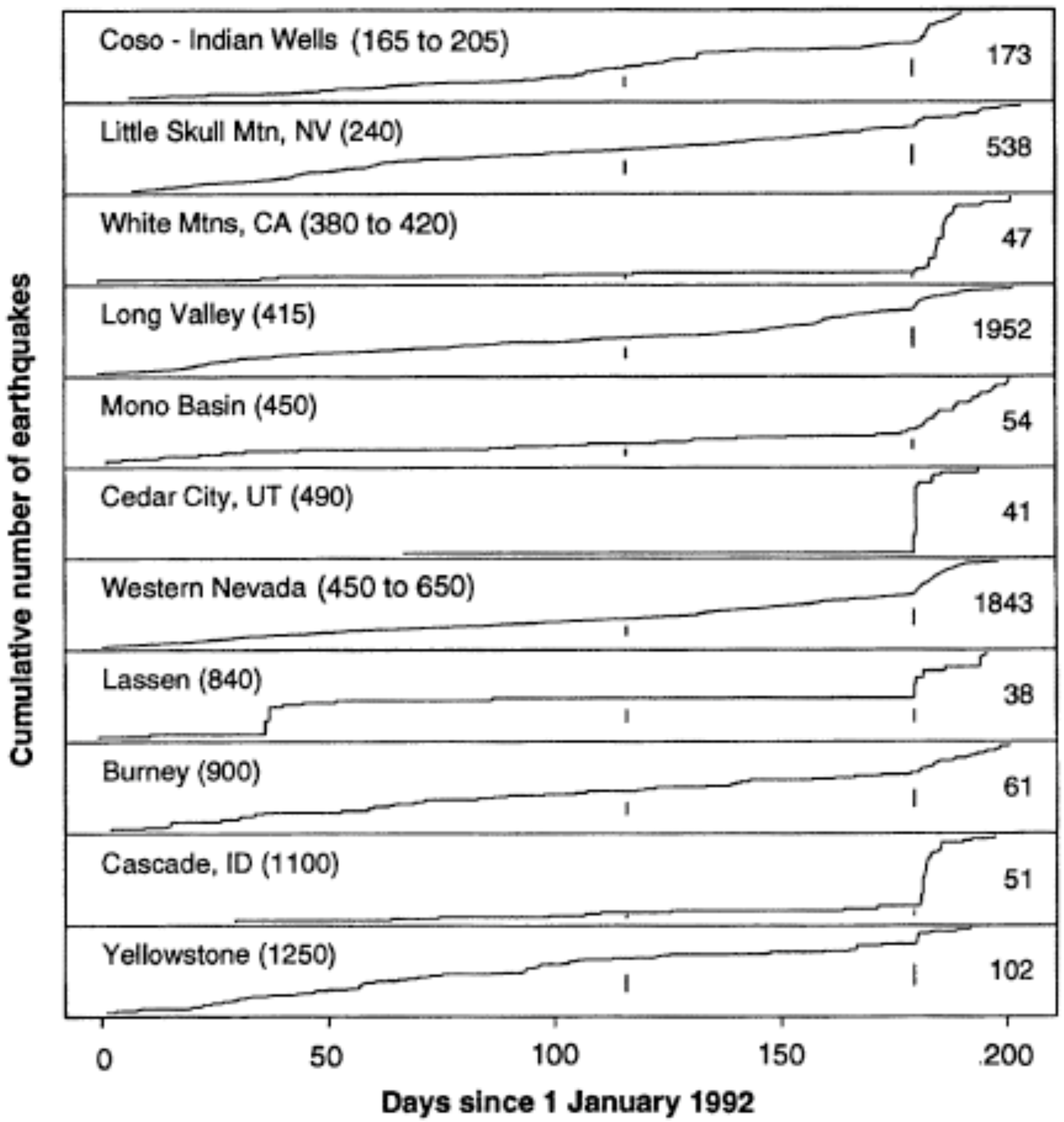
Earthquakes of all magnitudes produce aftershocks out to distances of ≥ 50--100 km (*Felzer and Brodsky,* 2006)

M≥7 earthquakes trigger seismicity worldwide



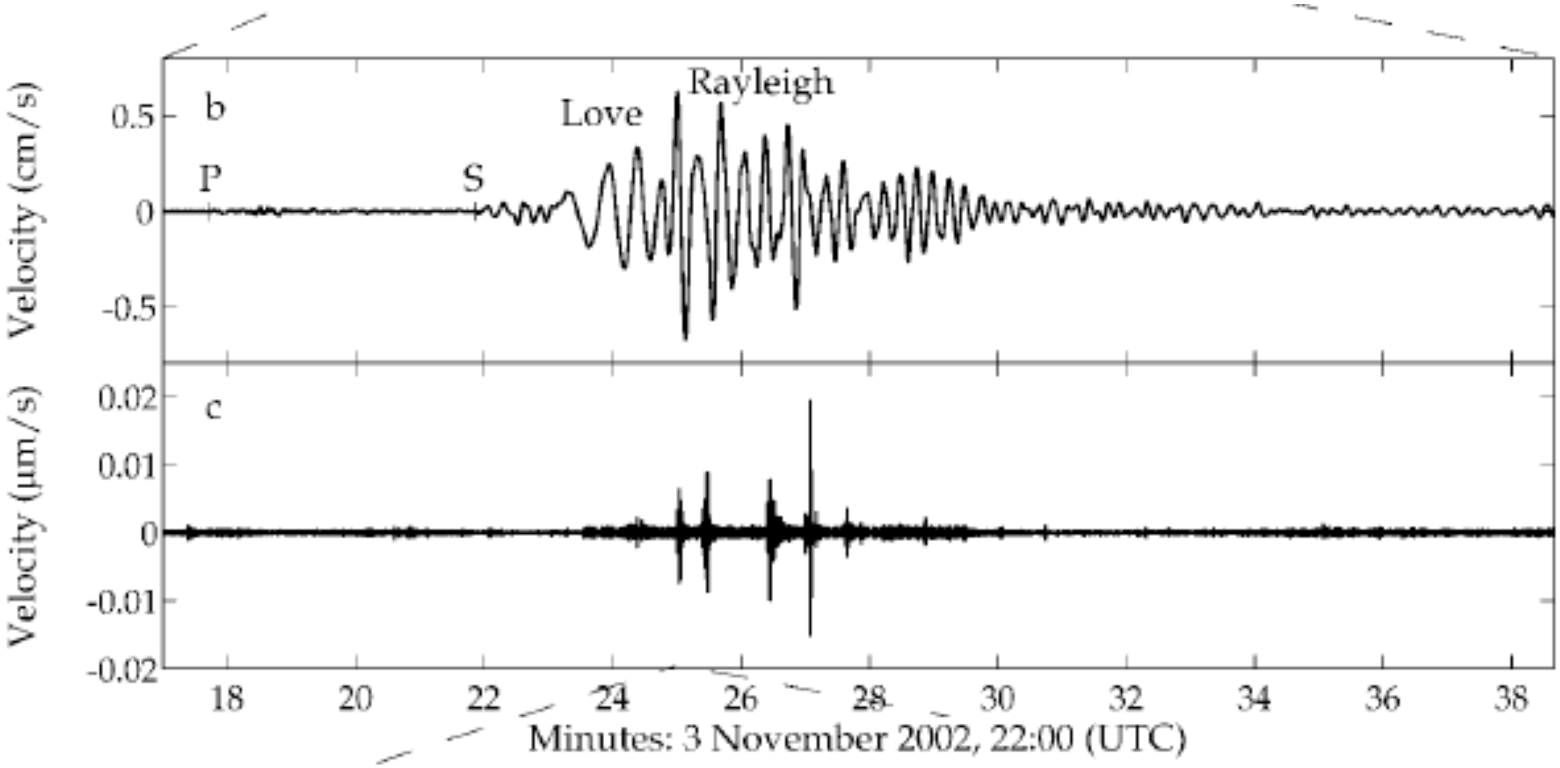
Earthquakes triggered in North America by the Denali, Alaska earthquake (*Gomberg et al.* , 2004)

Distant earthquake triggering can be detected from increases in the amount of catalogued seismicity at different locations



Distant triggering by the 1992 M 7.3 Landers earthquake, from *Hill et al* (1993)

The triggering can also be observed by high frequency filtering of seismograms at distant locations



Triggering at Mt. Ranier by surface waves of the Denali earthquake, from *Prejean et al*. (2004).

Distant triggering probably represents a different physical process than aftershock zone triggering

- Distant triggering occurs at a very low rate. Stress change is both very low at distance, and appears to be less effective at triggering seismicity than it is in the near field(*Van Der Elst and Brodsky,* 2010).
- Distantly triggered earthquakes show a strong preference for volcanic and geothermal areas.
- The occurrence of distant triggering is statistically significant only for small (M<5) earthquakes (*Michael,* 2010; *Parsons and Velasco*, 2011).

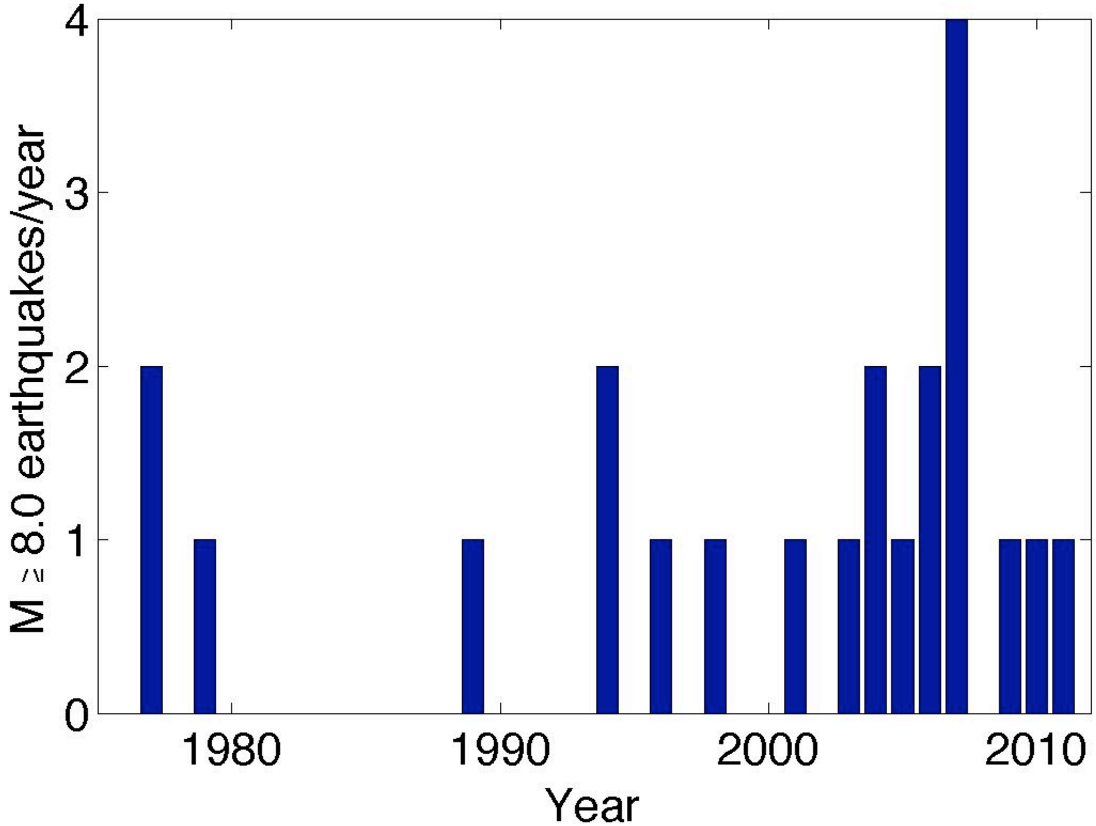
There are some enticing examples of large far apart earthquakes occurring close together in time

- 1901: August 9, M ~8 earthquakes in Vanuatu and the Kuriles separated by 5 hours.
- 1902: M ~8 earthquakes off of the Marianas and Mexico separated by 1 day.
- 1906: M ~8 earthquakes in the Aleutians and Chile separated by **30 minutes**.
- 2004: M 8.1 north of MacQuarie Islands and M 9.0 Sumatra earthquake separated by 3 days

Google maps

We could not calculate directions between **Aleutians West, Alaska** and **Sumatra**.

It has seemed like we are currently in a global “mega-cluster”



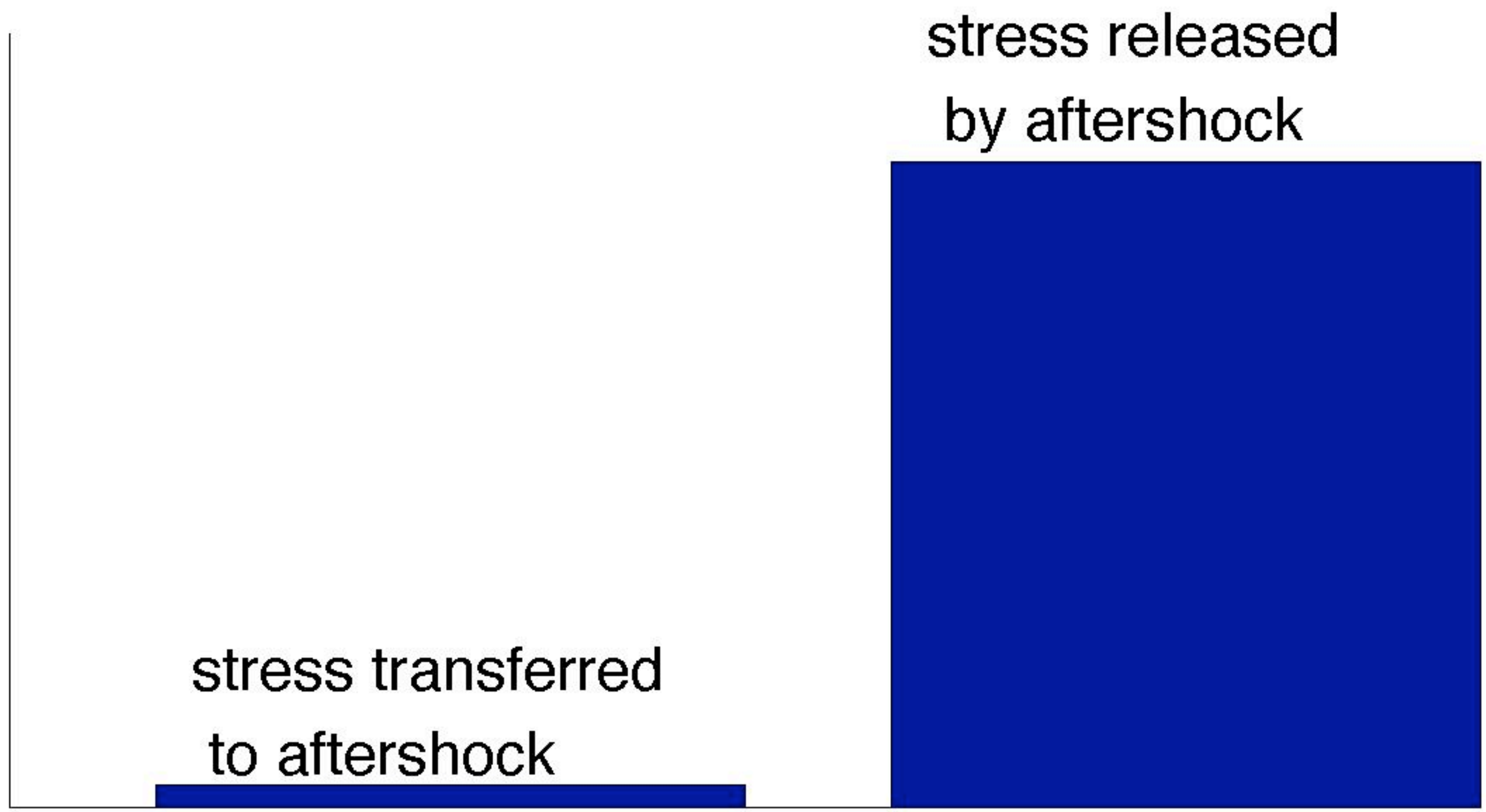
But the number of large earthquakes that have occurred so far, outside of each other’s aftershock zones, are also consistent with **purely random occurrence**

Conclusions

- >60% of all earthquakes occur as aftershocks, foreshocks, or multiplets. Earthquakes cluster because the occurrence of one earthquake triggers additional earthquakes to occur.
- We have good constraints on the how many earthquakes will turn out to be foreshocks, but no way to know ahead of time which ones will be foreshocks.
- Most earthquake triggering occurs over very short distances, but some triggering over very large distances also occurs. Whether large earthquakes can be triggered this way has yet to be determined.

To find a possible answer, we inspect some aftershock and earthquake conundrums

Conundrum #1: The static stress transferred from the mainshock is << than aftershock stress release



So it seems that the aftershocks were about to go on their own – but this is inconsistent with how many earthquakes are aftershocks

Conundrum #2: The average fault should need **>60 MPa** of shear stress before an earthquake

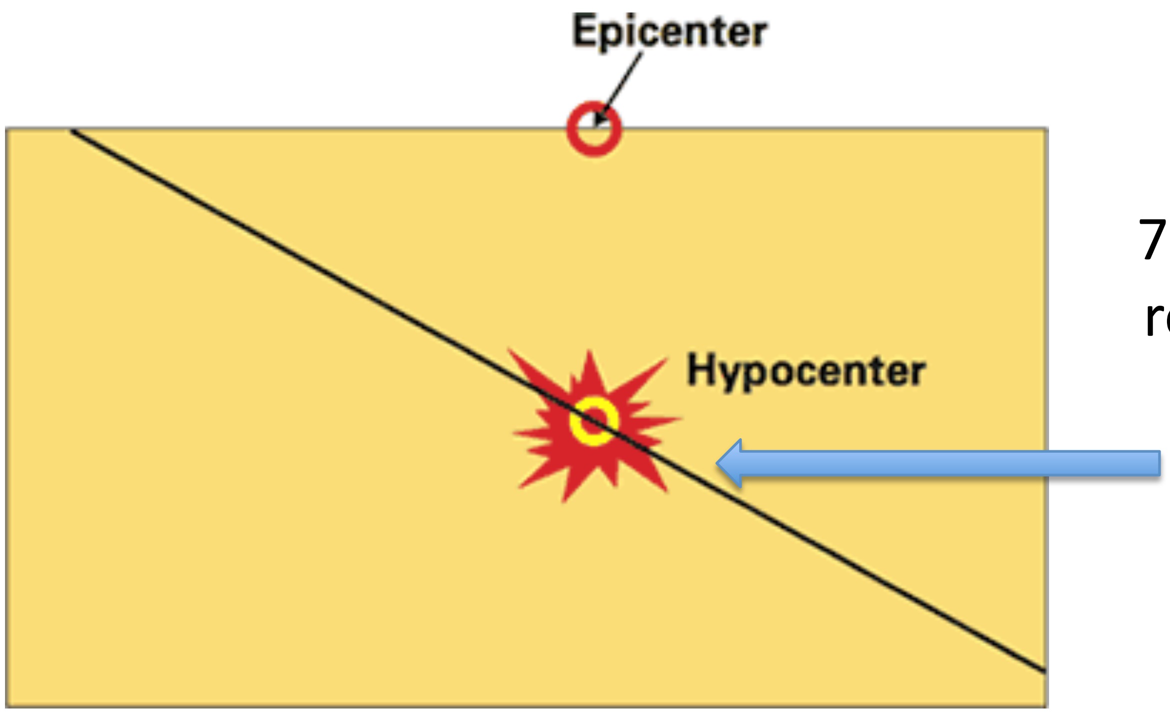
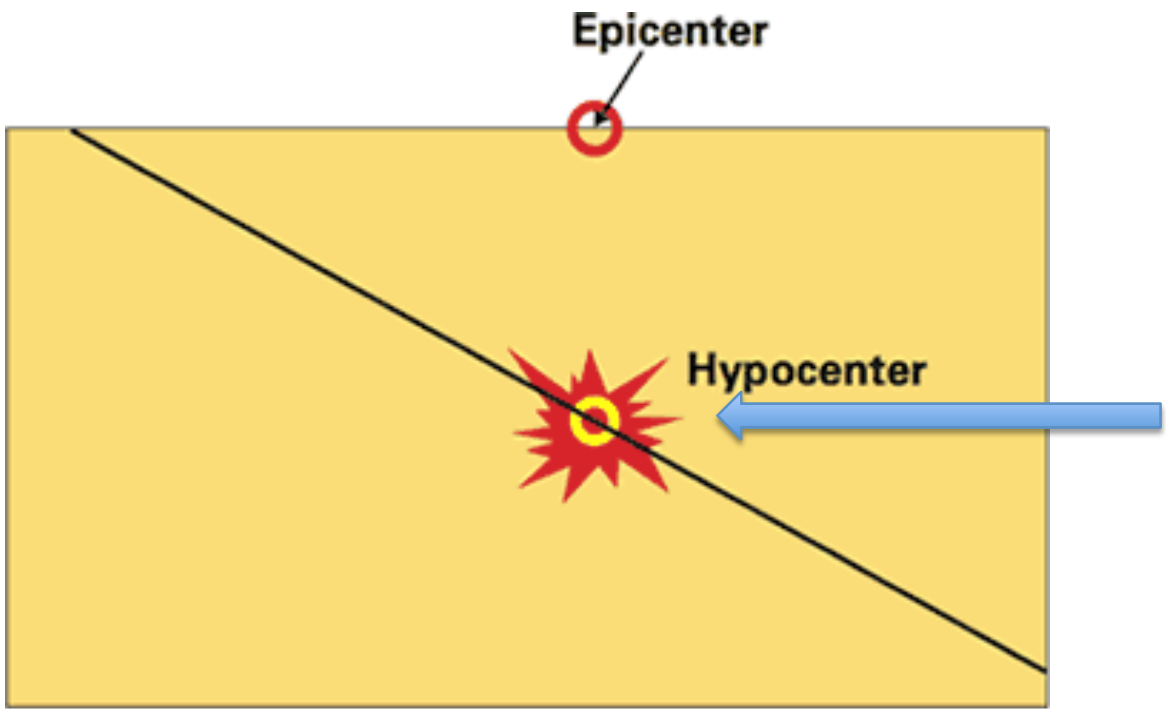


Figure by Charles Ammon

7 km of overlying rock and water = 100 MPa x 0.6 coefficient of friction

but the shear stress on most faults at rupture is only ~**10 MPa** (e.g. *Hardebeck and Hauksson*, 2001)

Karen's solution:



Shaking from the mainshock can severely weaken tiny volumes, allowing earthquakes to start under low stress

Figure by Charles Ammon

=>There is a long period of time during which a fault is far from the stress that would allow it to rupture spontaneously, but may rupture if triggered

Analogy: This building may have taken a long time to fall down without an earthquake

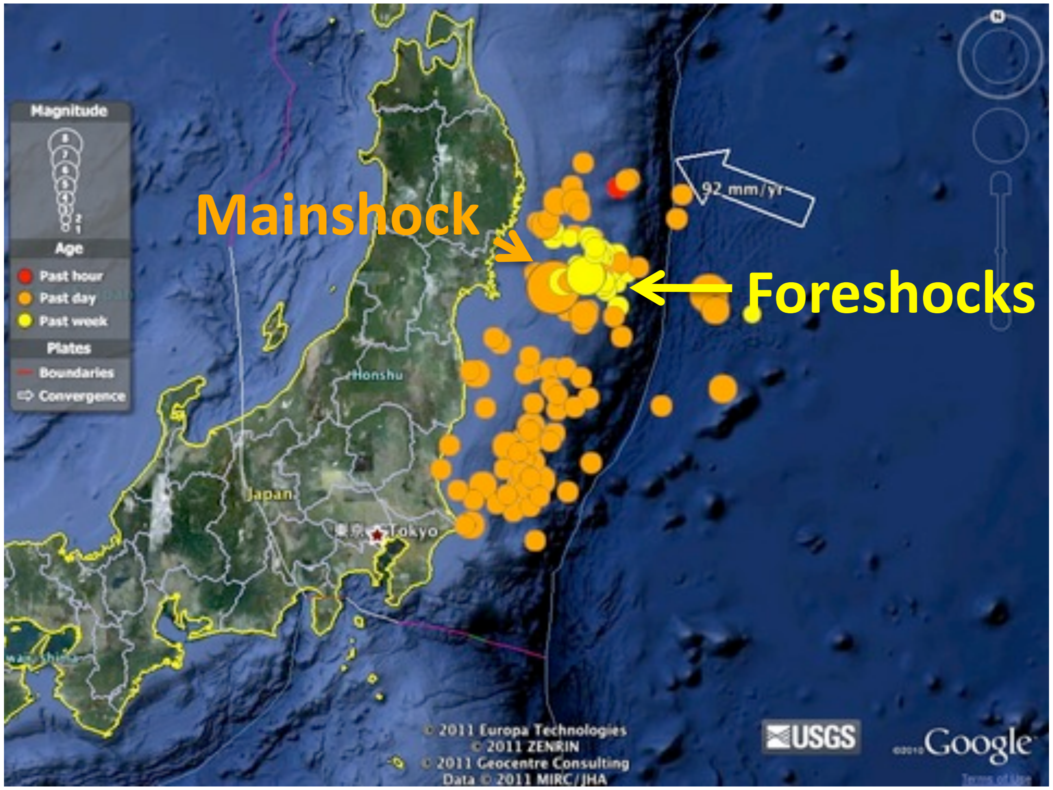
but after seismic shaking a stiff breeze might cause more damage

Hot topics in earthquake clustering:

Can we predict which earthquakes will be foreshocks?

Example from Japan

- A M 7.2 foreshock occurred on March 9, two days before the mainshock.



- During an average week, the chance of a M 9 somewhere near Japan is ~ **1 in 50,000**

- After any M 7.2 we know that the probability of an M 9 occurring (because it may be triggered) rises to **1 in 1000** (50 times more probable than usual).

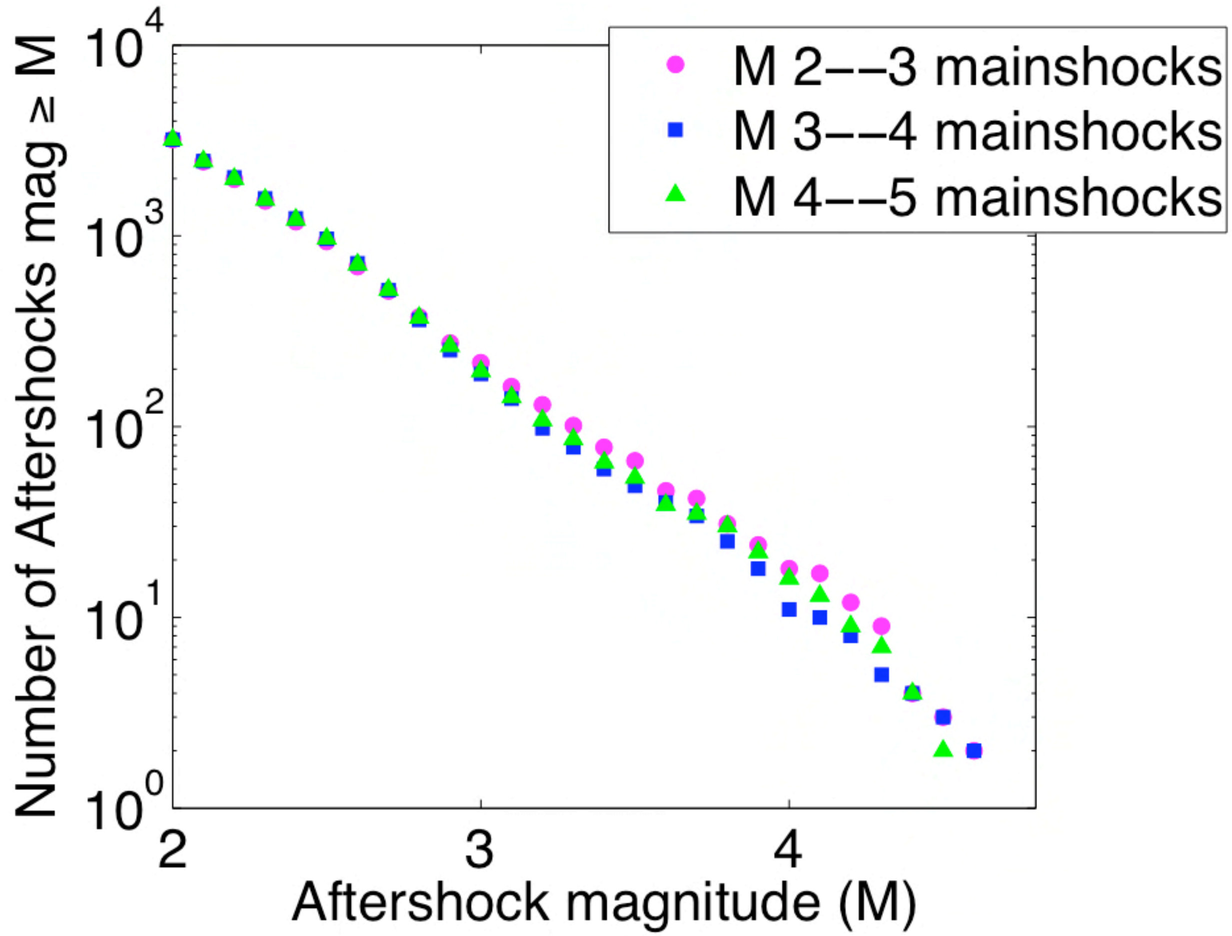
- The occurrence of any earthquake warrants heightened awareness that a larger quake might follow (each earthquake has a ~5% chance of triggering something larger than itself).

- But the probability that a random earthquake will be a foreshock is generally too low to justify mass public actions.

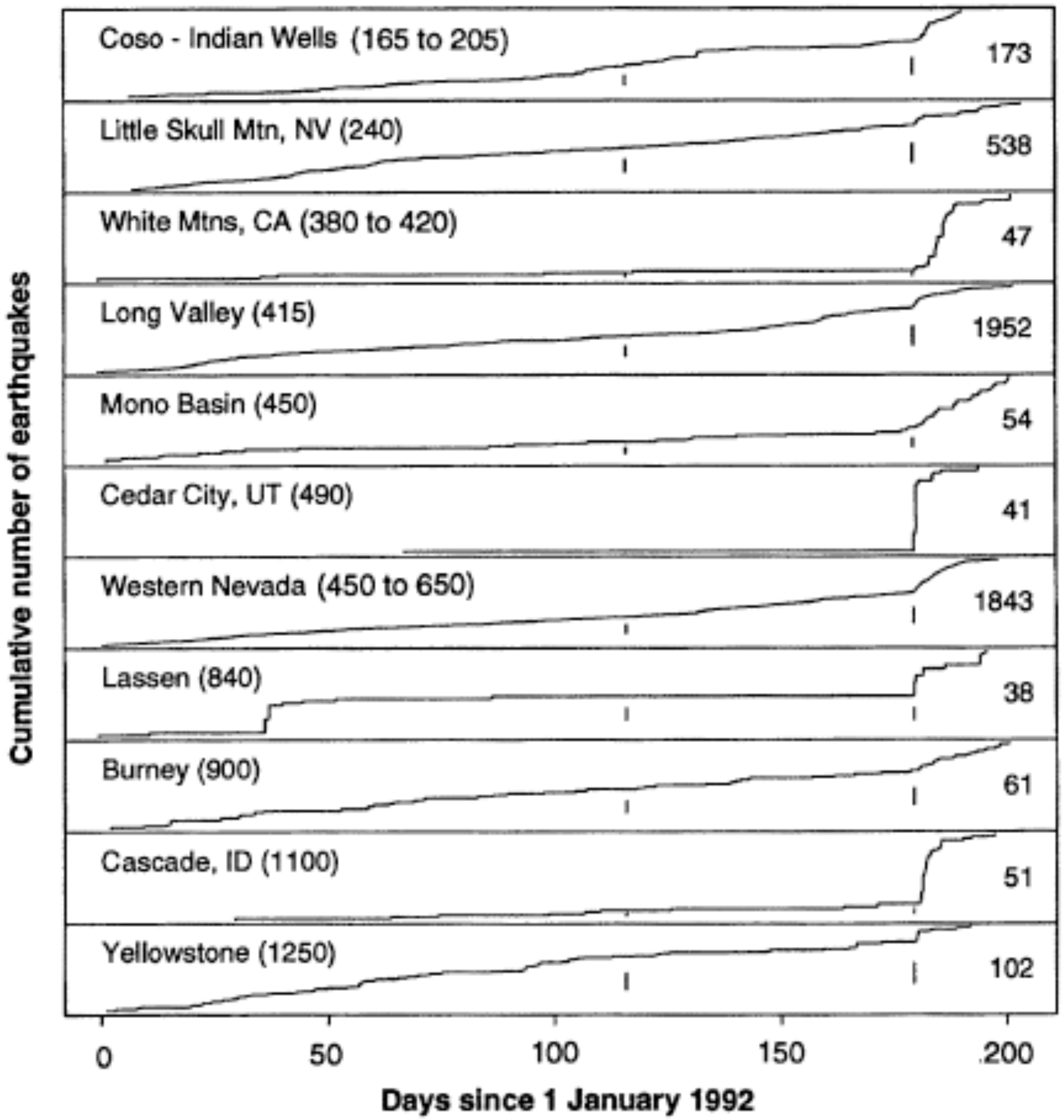
Conclusions

- Earthquake clustering is common. >60% of all earthquakes occur as aftershocks, foreshocks, or multiplets. Earthquakes cluster because the occurrence of one earthquake triggers additional earthquakes to occur.
- The majority of triggered earthquakes occur close in time and space to their trigger.
- We have good constraints on the how many large earthquakes will be triggered over many sequences, but no way to say which particular times, locations, or sequences will contain these events.

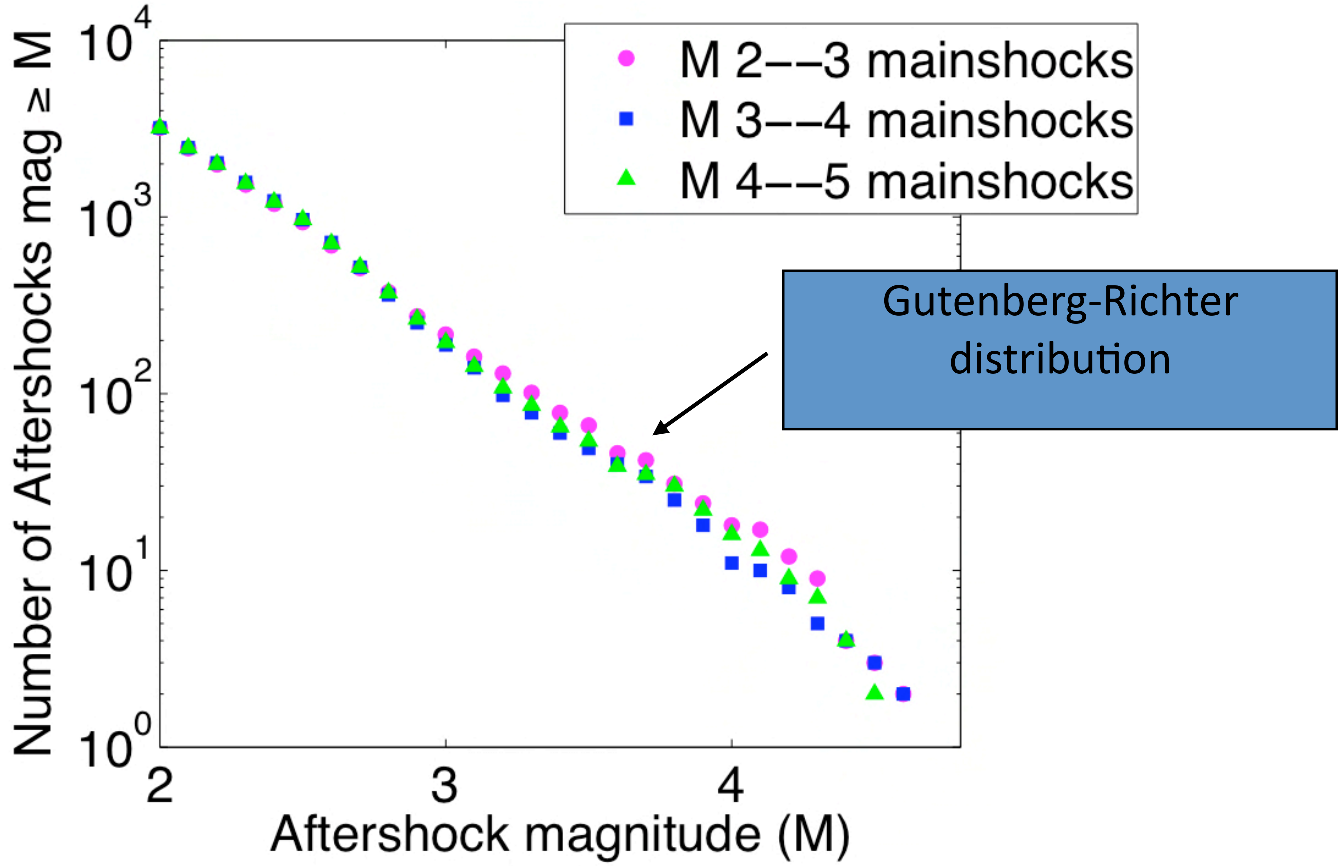
Aftershock magnitude distribution is independent of mainshock magnitude



Hill et al. 1993



Evidence for Statistic #2: Aftershock magnitude distributions are independent of mainshock magnitude



Aftershocks taken from 2 days/5 km around each mainshock. 3,200 aftershocks in each distribution

Foreshock rates can be accurately predicted from the rate of aftershocks smaller than the mainshock

1. No. aftershocks ≥ M = $F(M_{main})10^{-bM}$ ← GR distribution
2. $F(M_{main}) \sim 10^{Mmain - 1.3}$ in California, for aftershocks within 1 day and 1 fault length of mainshock; b=1.

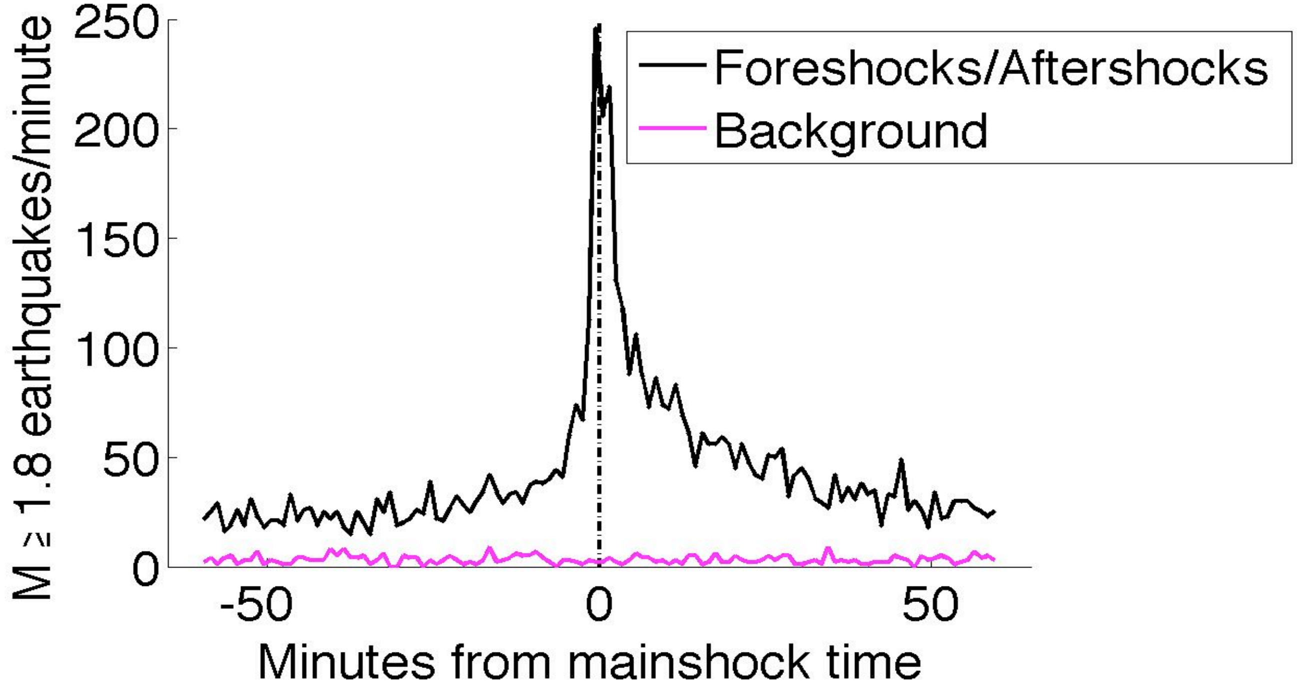
Predicted rate that an earthquake will produce an aftershock larger than itself within one day:

$$=10^{Mmain-1.3-M} = 10^{Mmain-1.3-Mmain} = 0.050$$

Observed rate: 0.047 +- 0.0054

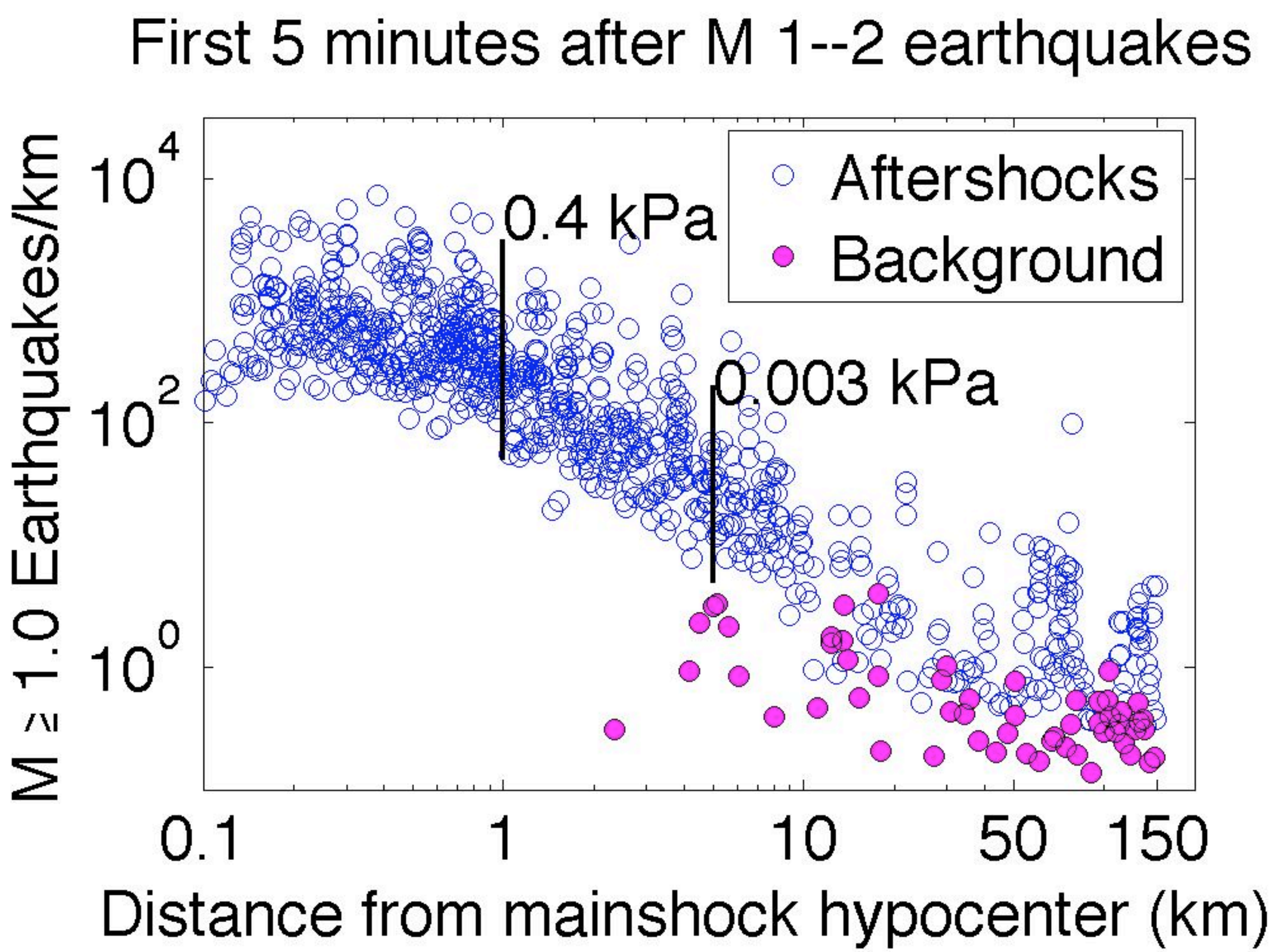
(6,086 M ≥ 3 California earthquakes, 1984-2004)

Southern California M 1.8—4.0 mainshocks (all depths) produce **0.254—0.259** M≥1.8 aftershocks/M=3 mainshock in the first hour



The calculation uses a total of 17,021 mainshocks from the 1984-2009 SCSN catalog that are not preceded by a larger earthquake over 3 days/100 km. There are 3199 after-quakes, 156—203 of which may be background earthquakes.

No: Aftershock triggering at <150 km where mainshock-induced static stress changes are tiny suggest that these stresses are not needed



8656 M 1—2 Northern California mainshocks from the NCSN catalog, not preceded by larger event for 3 days/200 km

The problem is that the earthquake rupture process is very complex, so whether or not an earthquake will continue to grow past any given point can only be given by a probability, not a certainty.

Alternative: The "Harold Lloyd" Model
Binary, not proportional, stress response

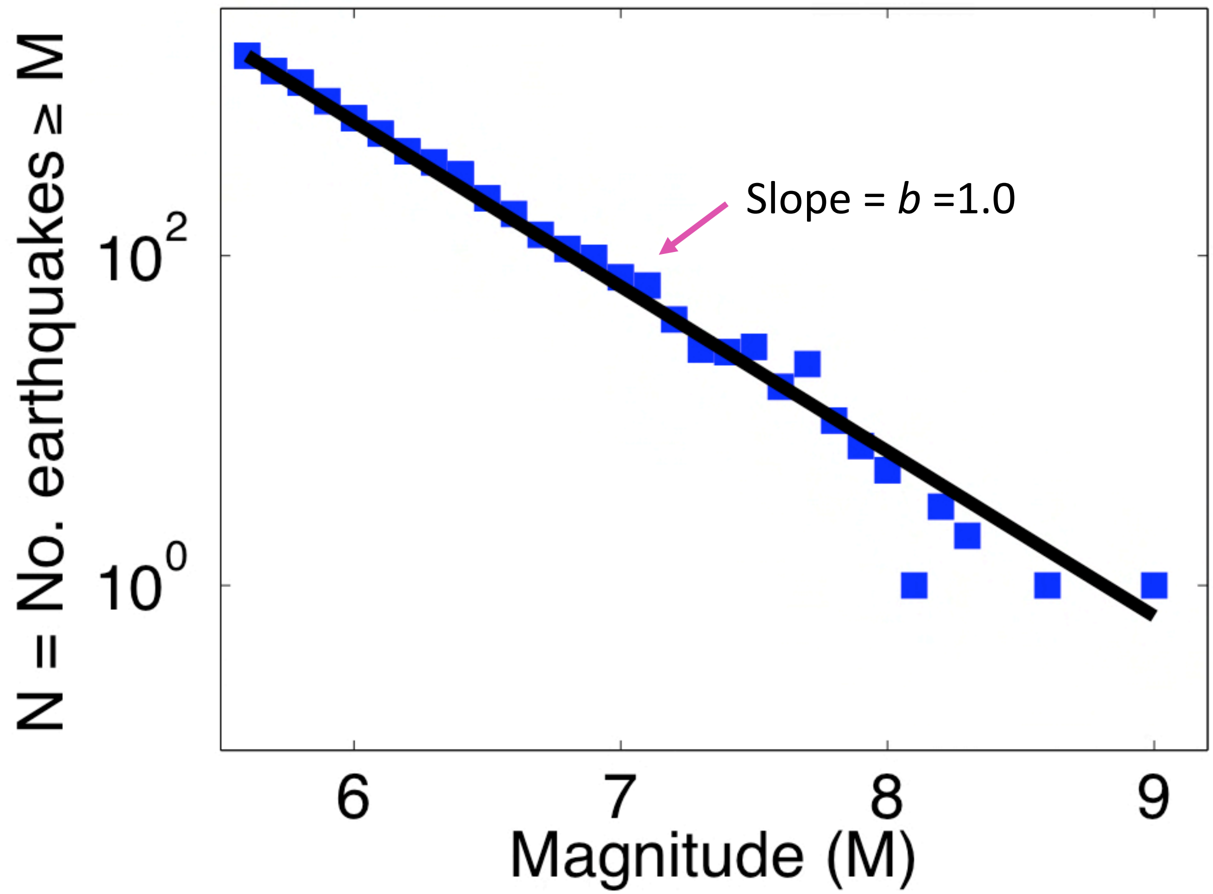
Option 1: Stiff clock or light Harold => no clock advance

Option 2: The hand gives way maximum clock advance

- If Harold is heavier, a clock advance is more likely
- But Harold's weight ≠ clock advance size

The Gutenberg-Richter magnitude frequency relationship

1976-2005 Global CMT catalog

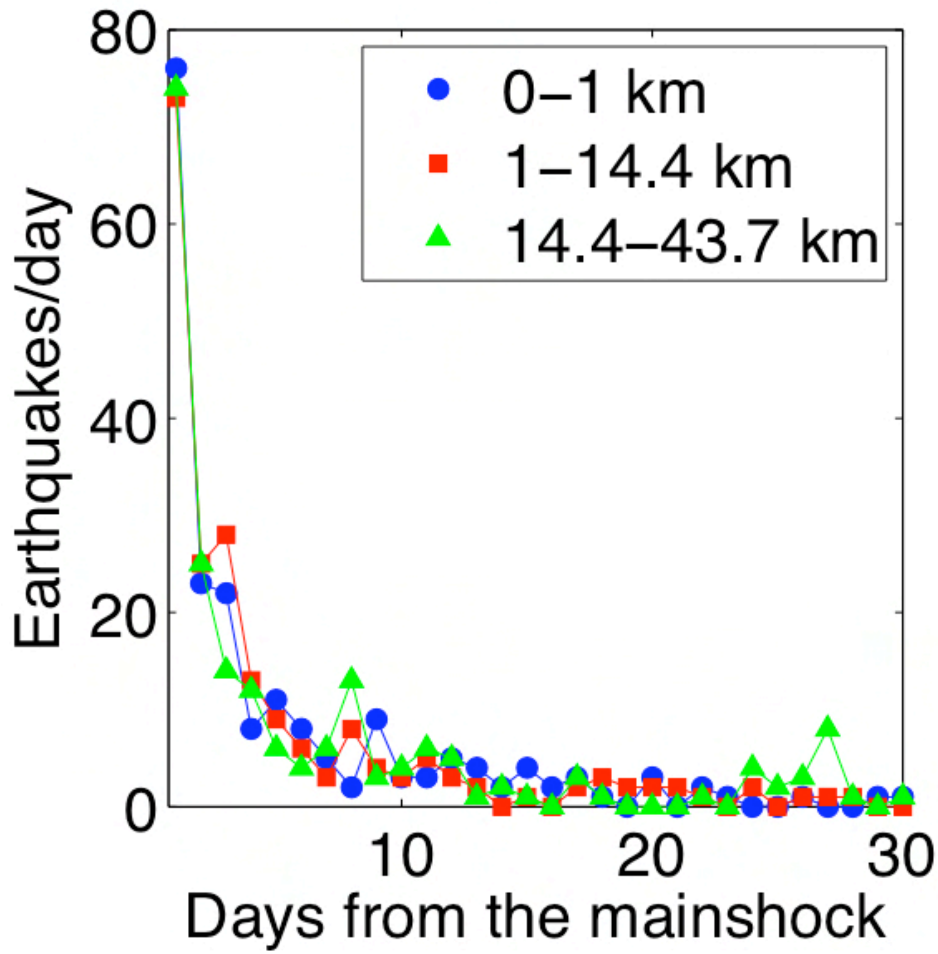


$$\log(N) = a - bM$$

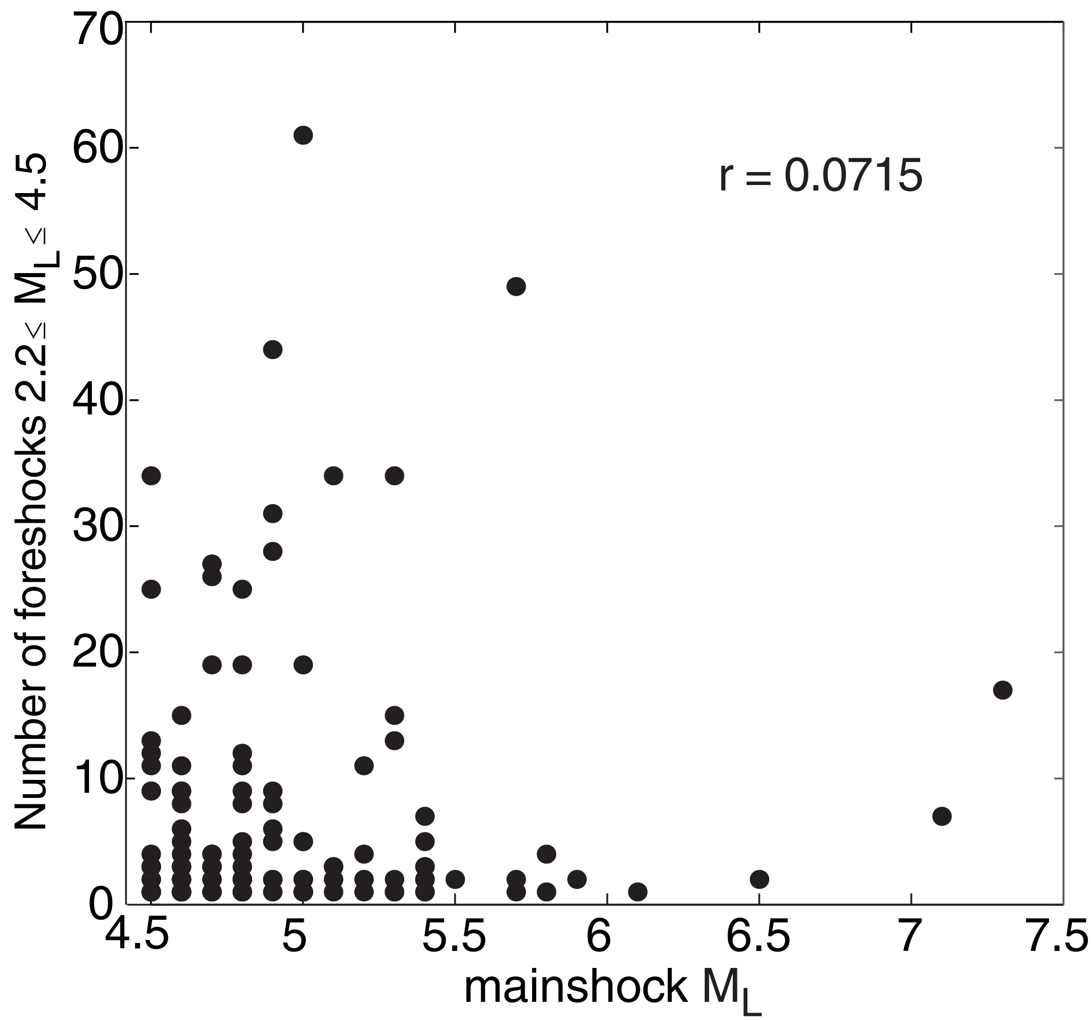
"Earthquake prediction provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers."

-Charles Richter

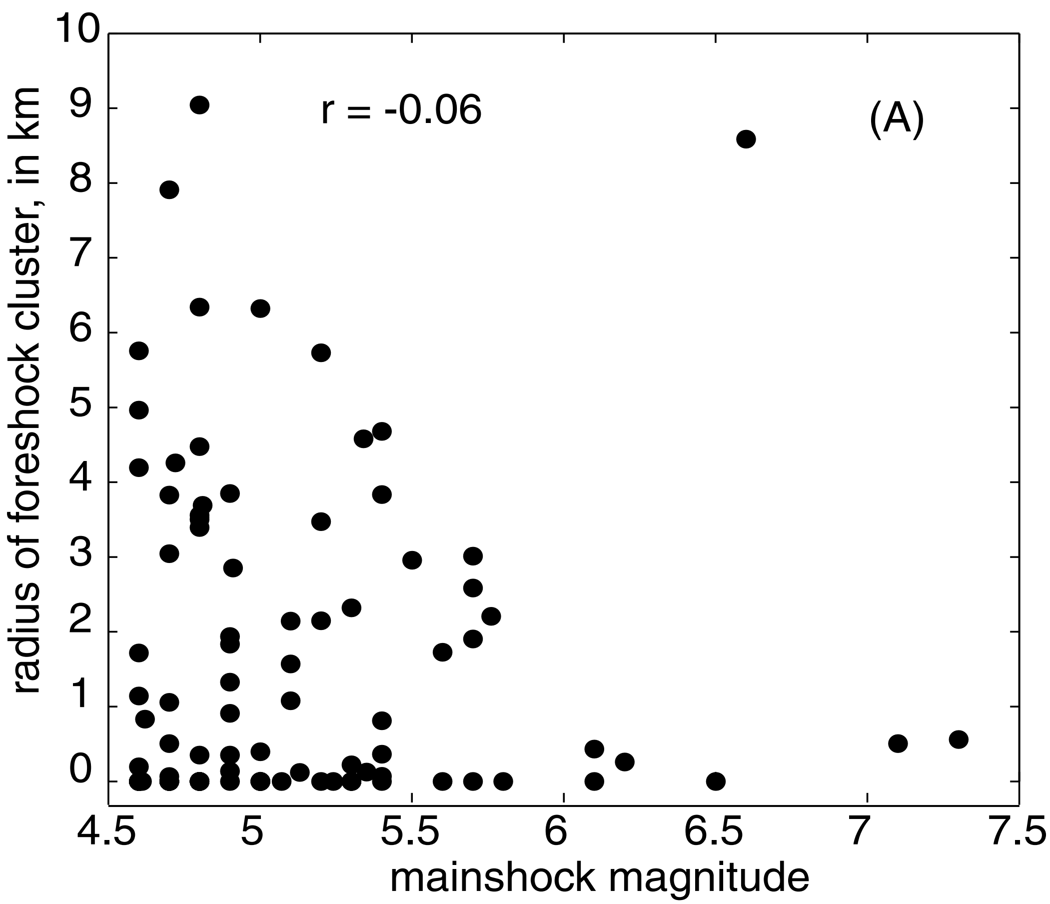
Landers mainshock: Groups of 200 aftershocks at different distances show the same number of aftershocks/day



Kolmogorov Smirnoff Test: All distributions similar at 95% confidence



r = 0.0715
Number of foreshocks 2.2≤ M_L ≤ 4.5
mainshock M_L
0
10
20
30
40
50
60
70
4.5
5
5.5
6
6.5
7
7.5



Foreshocks are events within 10 km , 2 days

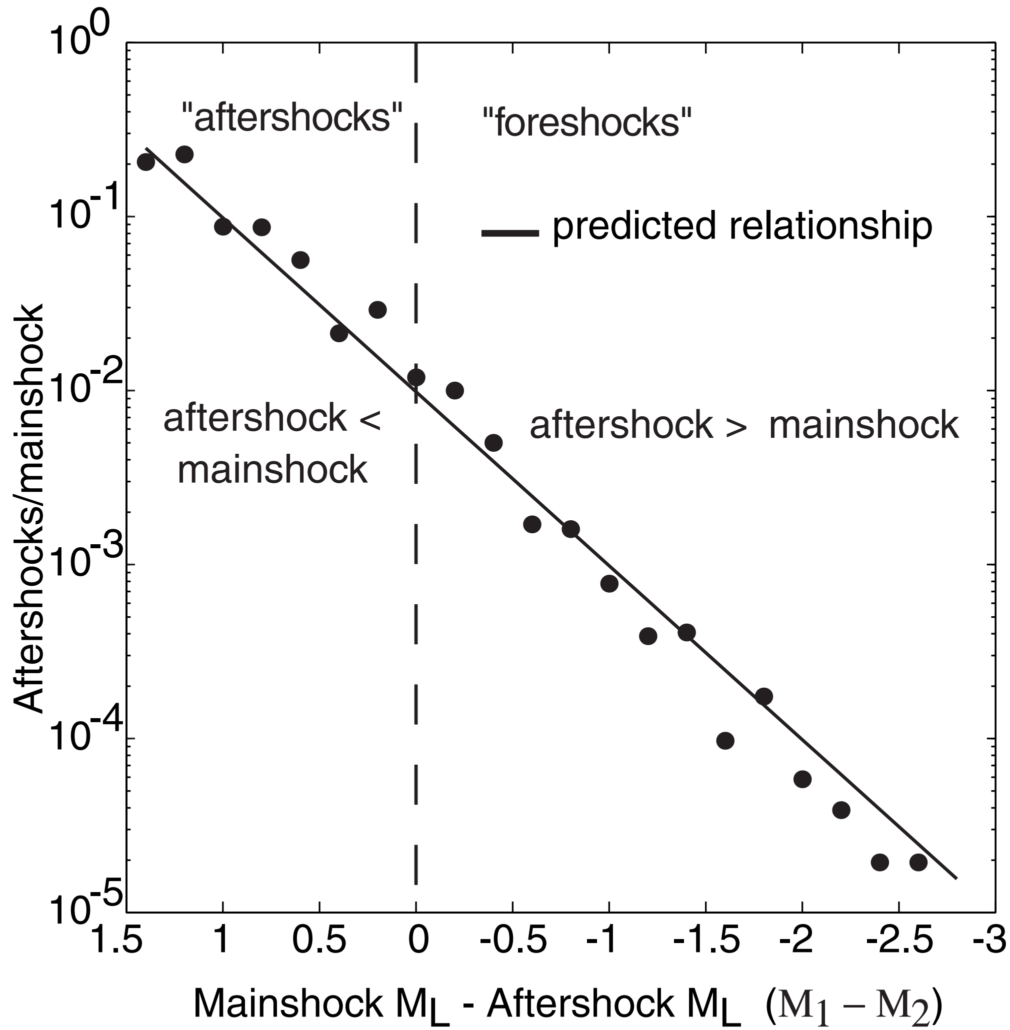


Figure uses 101,680 M>2.2 earthquakes from California, 1975-2001

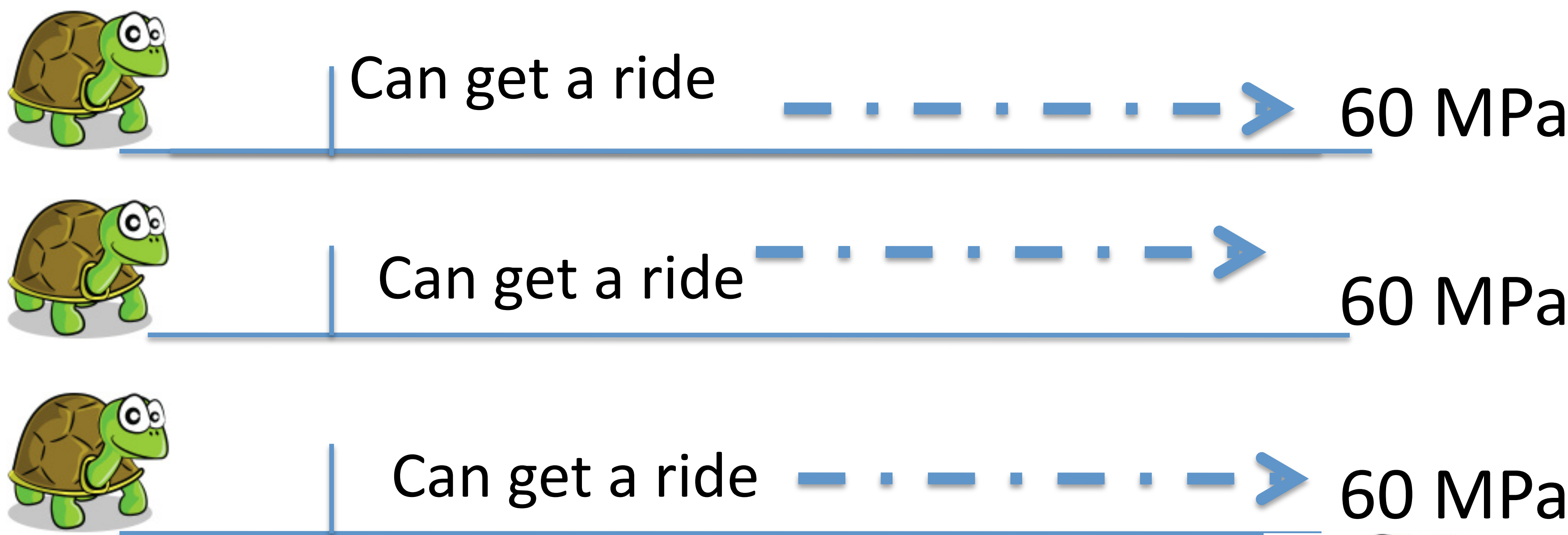
Earthquake cluster definitions

- **Aftershock**: An earthquake that follows a larger earthquake.
- **Multiplet**: An earthquake that occurs with other earthquake(s) of similar magnitude.
- **Foreshock**: An earthquake that precedes a larger earthquake.
- **Swarm**: The rapid occurrence of a series of earthquakes of similar, and generally small, magnitude (usually geothermal/volcanic).

outline

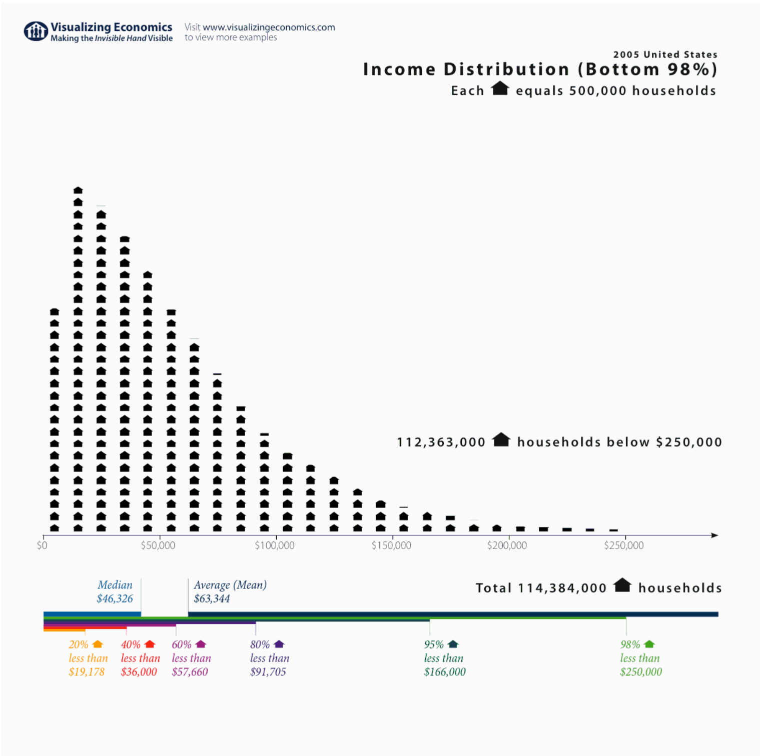
- The only short term predictability of earthquakes is that they tend to occur in clusters
- Some how the stress released by one earthquake encourages others to occur in a statistically predictable fashion. In fact, at least 60% of earthquakes occur this way – and possibly many more. It might be very difficult for an earthquake to nucleate without stressing from a prior event, because of total stress drop vs. high normal stress at depth.
- But not all large earthquakes are followed by other large earthquakes. The rules of numbers and chance, adding up to 100% if all earthquakes were aftershocks.
- What can I expect in an aftershock sequence: The aftershock sequence, close and far, power law decay, magnitude independence with time, the nearness factor, mga saturation, what can I expect to feel, the distant triggered event – go back to original sequences for this.
- How foreshocks come into the equation, the postdiction illusion, the landers story
- Rehash – what we can forecast, what are the absolute limitations, why clusters matter to you.

Analogy: A bunch of turtles are on a long race. They can finish by plodding the whole way or taking a ride from a bird after they've gone at least 10 ft



If the bird comes by frequently enough most turtles will end up taking a ride – like most faults will be triggered while their stress is still low rather than remaining stationary until high stress can accumulate

What does it mean to "know a distribution"?



2005 Income Distribution, from Visualizing Economics

- If I had a long list of random names, the income distribution tells me that 60% earn <$57,600, 5% >$166,000, etc.
- But the distribution doesn't tell me which individuals are in that top 5%, or who I should call for a big donation!

Aftershock statistics that we know

- The **distribution** of aftershock times
- The **distribution** of aftershock magnitudes
- The probability that an aftershock will be larger than it's mainshock
- The **distribution** of aftershock locations

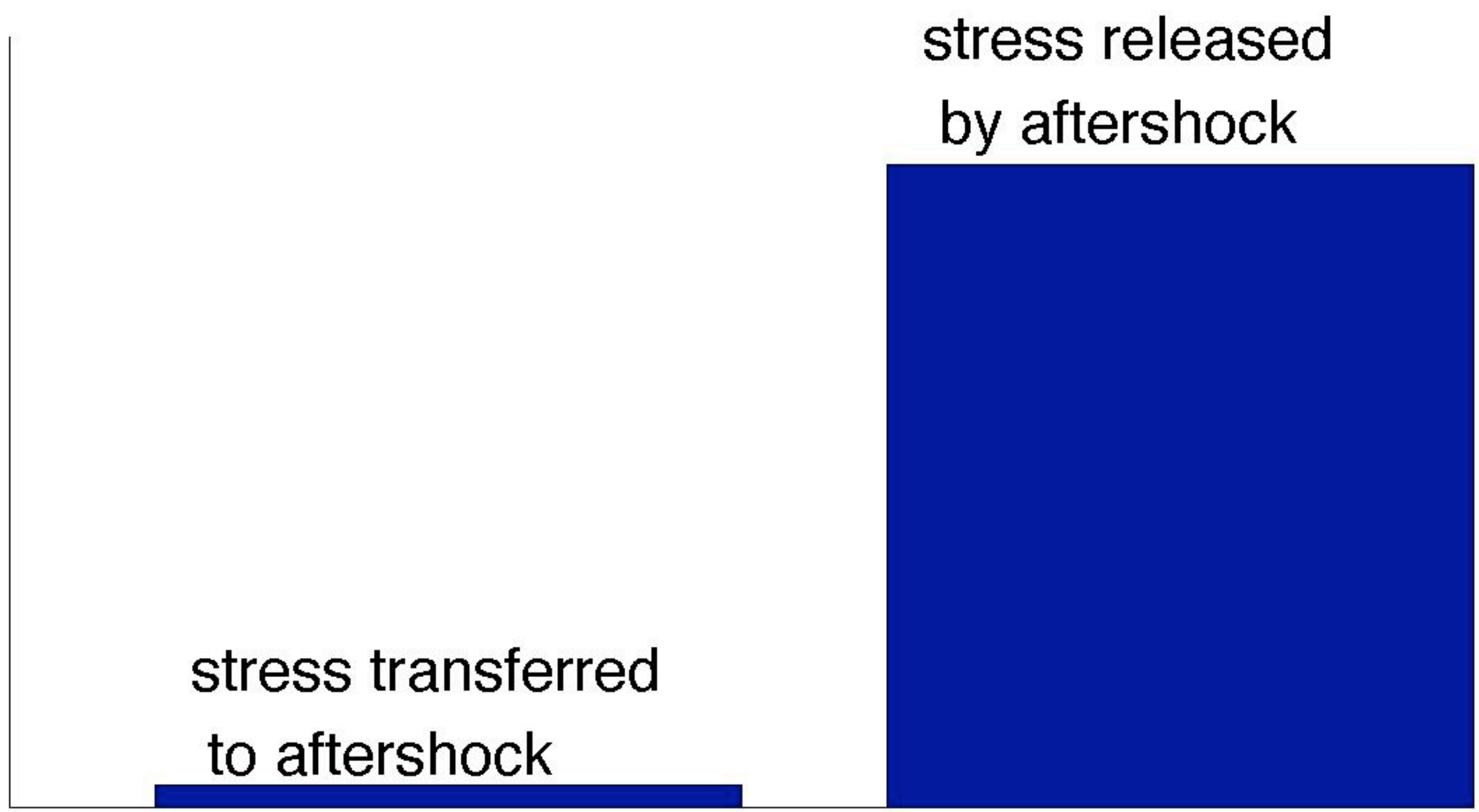
Applying Omori's Law

Example #1: Average number of M≥3.5 aftershocks after an M 6.5 mainshock

0 – 10 minutes	8 (48/hour)
10 minutes – 1 hour	5-6 (6.8/hour)
1 hour – 1 day	19 (0.8/hour)
1 day – 1 week	16 (0.11/hour)
1 week – 1 year	14-15 (0.002/hour)
1 year – 50 years	3-4 (0.000008/hour)

- Karen's solution is motivated by the finding of *Hardebeck and Hauksson* (2001) that the **shear stress on faults tends to be << ordinary fault strength at the time of rupture**
- This suggests that something may be causing an unusual decrease in fault strength right before rupture occurs

The static stress transferred to most aftershocks << stress released by the aftershock



What is going on?