Two tests to determine the cause of intermediate range aftershocks

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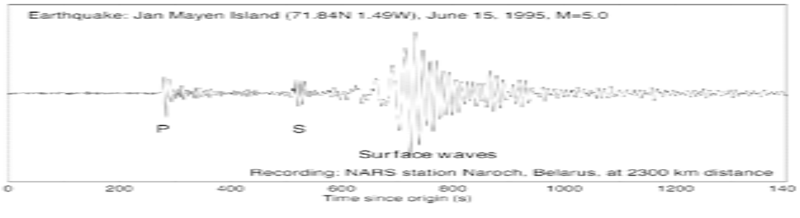
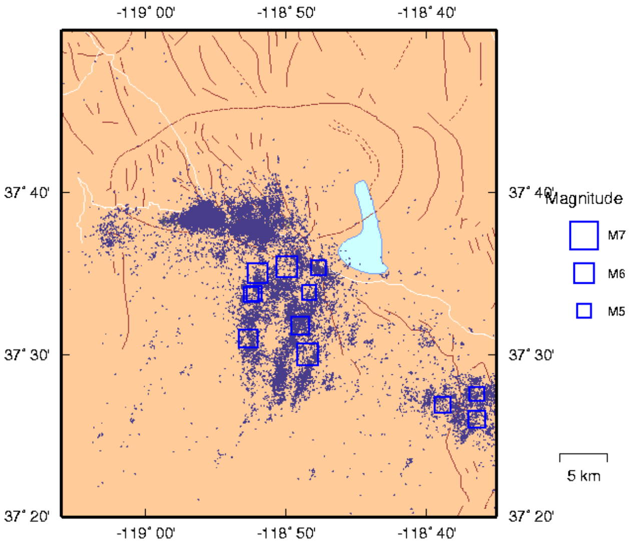
Are aftershocks triggered by

Static stresses?

Dynamic stresses?



Far field aftershocks
(>>100 km)
Dynamic Triggering



Seismicity 1970-2003

Long Valley

Near field aftershocks
(<0.5 – 1 fault length)
Too complicated to tell

1906 Fault Trace

Intermediate field aftershocks ??

Focus of this talk

Differences between static and dynamic triggering

	Static triggering	**Dynamic triggering**
Stress Shadow	Exists	Doesn’t Exist
Decay of aftershocks with distance	$\frac{1}{\text{Distance}^3}$	$\frac{1}{\text{Distance}}$

Stress Shadow Test

- A stress shadow is a regional decrease in the seismicity rate following a neighboring earthquake

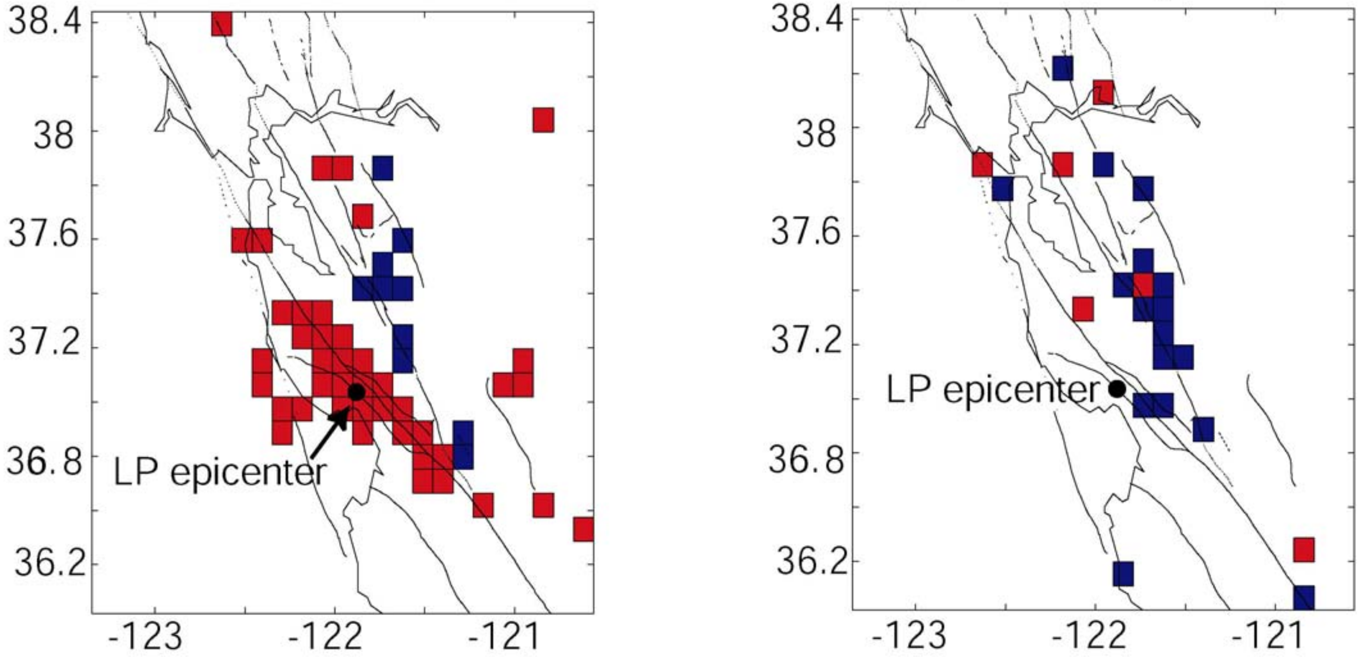
Static triggering = stress shadow

Dynamic triggering = no shadow

Common Test: Look for time averaged rate decreases in declustered catalog
(*Reasenberg and Simpson*, 1992; *Wyss and Wiemer*, 2000)

1 yr after the Loma Prieta earthquake (10/18/89, M_W 7.0) /previous 6 yrs

10/1/88-10/1/89 /previous 6 yrs



Declustered catalog of M>1.5 earthquakes; 49% of earthquakes removed

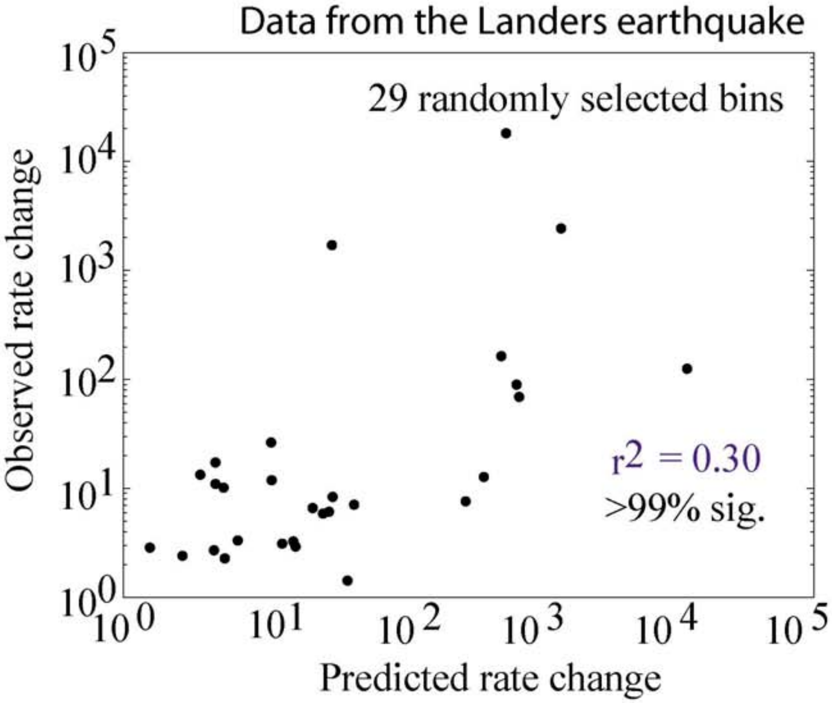
Plotted rate changes are significant at the 95% confidence level, assuming that the declustered catalogs are Poissonian

🟦 rate decrease
🟥 rate increase

Problem: Significant rate decreases are common

Our Original idea: Is there a correlation between the amplitude of predicted and observed rate decreases?

Correlation is clearly observed for rate increases

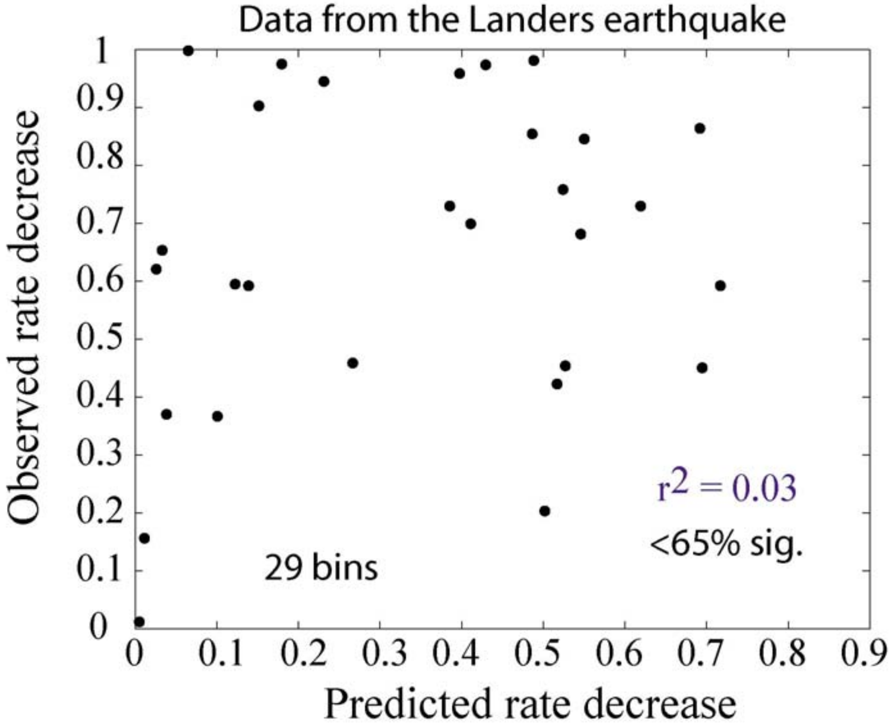


Calculations done in 2.5 x 2.5 km bins, experiencing 0.1 to 8 bars of stress increase from the mainshock

Rate Change predictions from Coulomb static stress change (calc. by *Stein et. al.*) and rate and state friction equations (*Dieterich, 1994*)

Our Original idea: Is there a correlation between the amplitude of predicted and observed rate decreases?

No correlation is observed for rate decreases



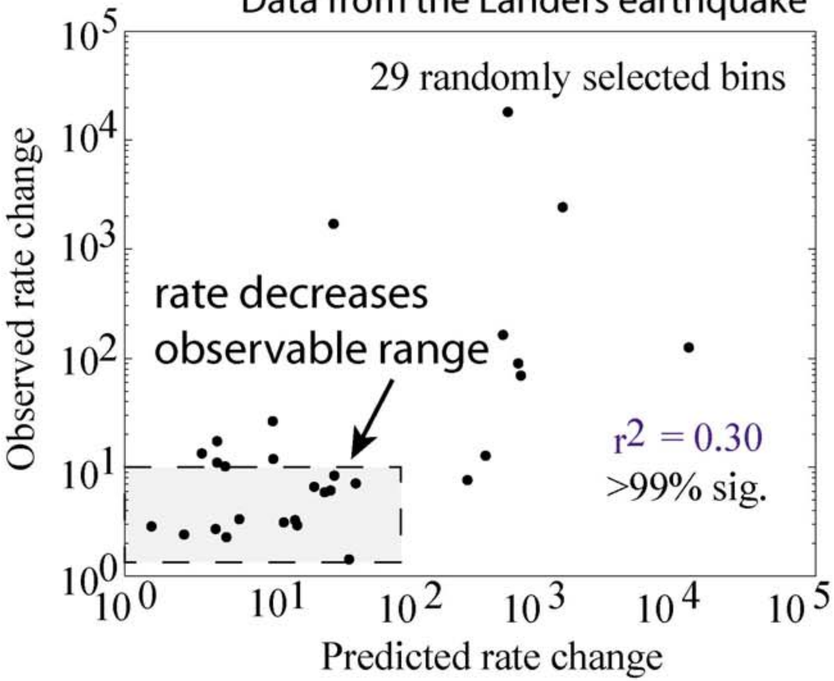
Calculations done in 2.5 x 2.5 km bins experiencing **-8 to -0.1 bars** *of stress decrease from the mainshock*

Rate Change predictions from Coulomb static stress change (calc. by *Stein et. al.*) and rate and state friction equations (*Dieterich, 1994*)

Our Original idea: Is there a correlation between the amplitude of predicted and observed rate decreases?

But the positive correlations are not significant over the limited range in which rate decreases can be measured

Data from the Landers earthquake



Calculations done in 2.5 x 2.5 km bins, experiencing 0.1 to 8 bars of stress increase from the mainshock

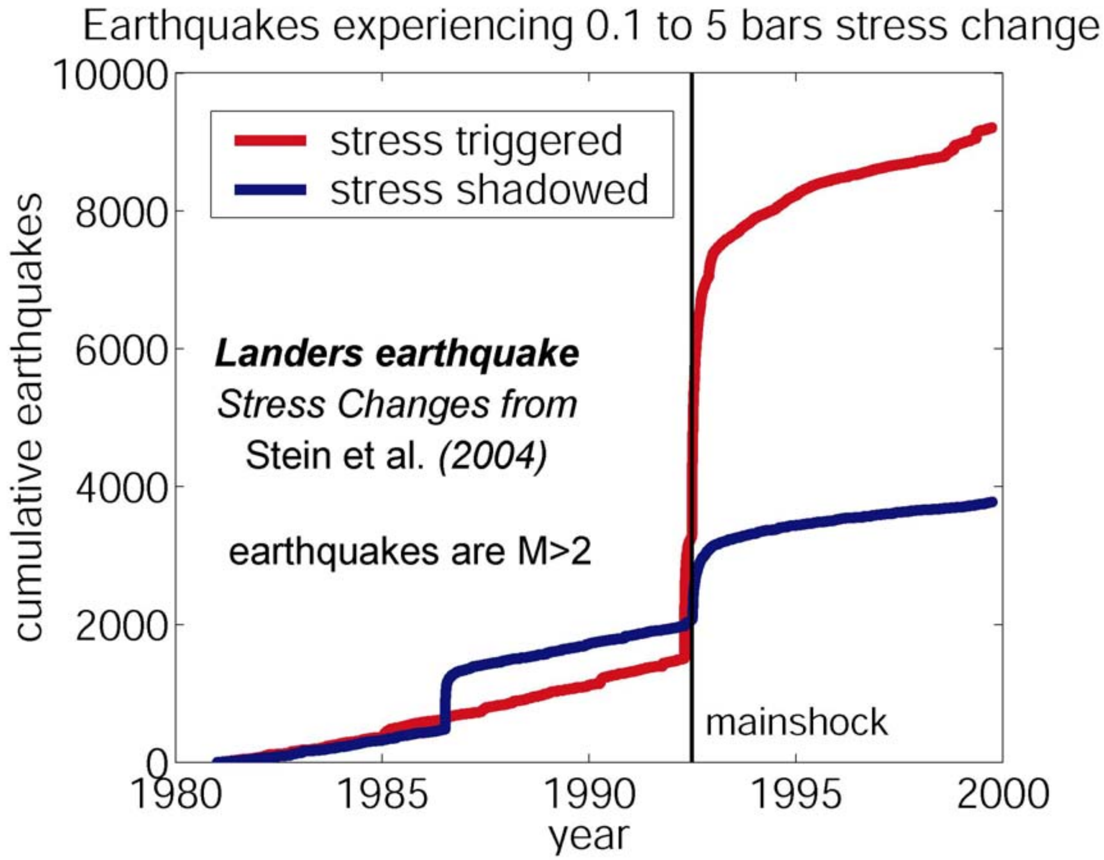
Rate Change predictions from Coulomb static stress change (calc. by *Stein et. al.*) and rate and state friction equations (*Dieterich, 1994*)

Problem: Rate/Stress change calc errors obscure signal over this range

Alternative Method: Look for sudden rate drop at time of mainshock

Issue: How to identify expected stress shadow area

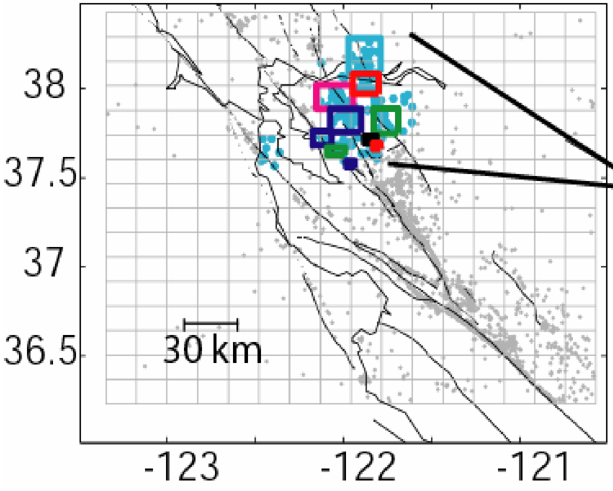
Method 1: Use stress change calculations



Problem: Modeled shadows always contain aftershocks

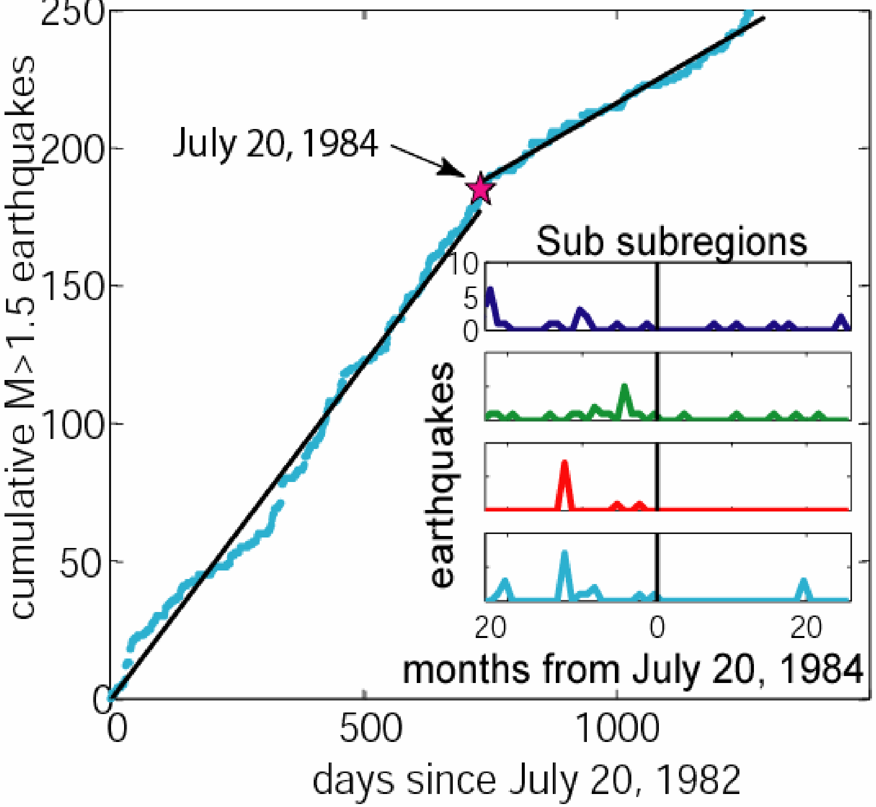
Method 2: See if a subregion of the modeled shadow has a rate decrease

(Parsons et al. 1999; Stein 1999; Wyss & Wiemer, 2000; Toda and Stein, 2003)



There was no large earthquake on July 20, 1984

Time series of entire subregion



Problem: Localized sudden rate decreases are common

Method 3: Use new earthquake time ratio test to empirically find entire region where there are no aftershocks

1) Divide region into spatial bins

2) Calculate **R** for each bin

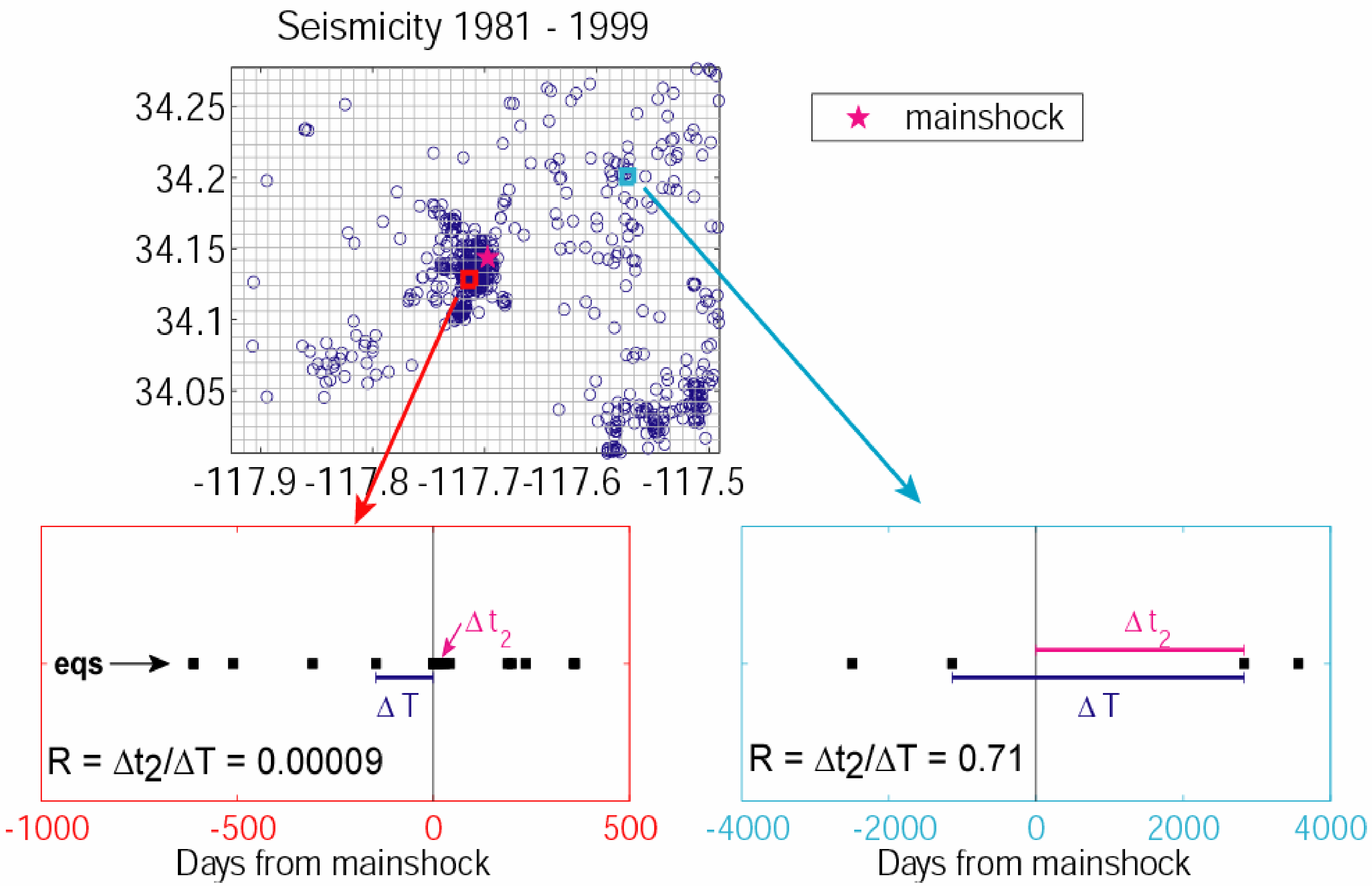
$$R = \frac{\Delta t_2}{\Delta T}$$

Δt_2: time from mainshock to first earthquake after mainshock

ΔT: time from last earthquake before mainshock to first earthquake after mainshock

3) When aftershocks are present: Most $R << 1$

Example: Using the time ratio **R** to identify regions with aftershocks of the 1990 M 5.4 Claremont Earthquake


Seismicity 1981 - 1999

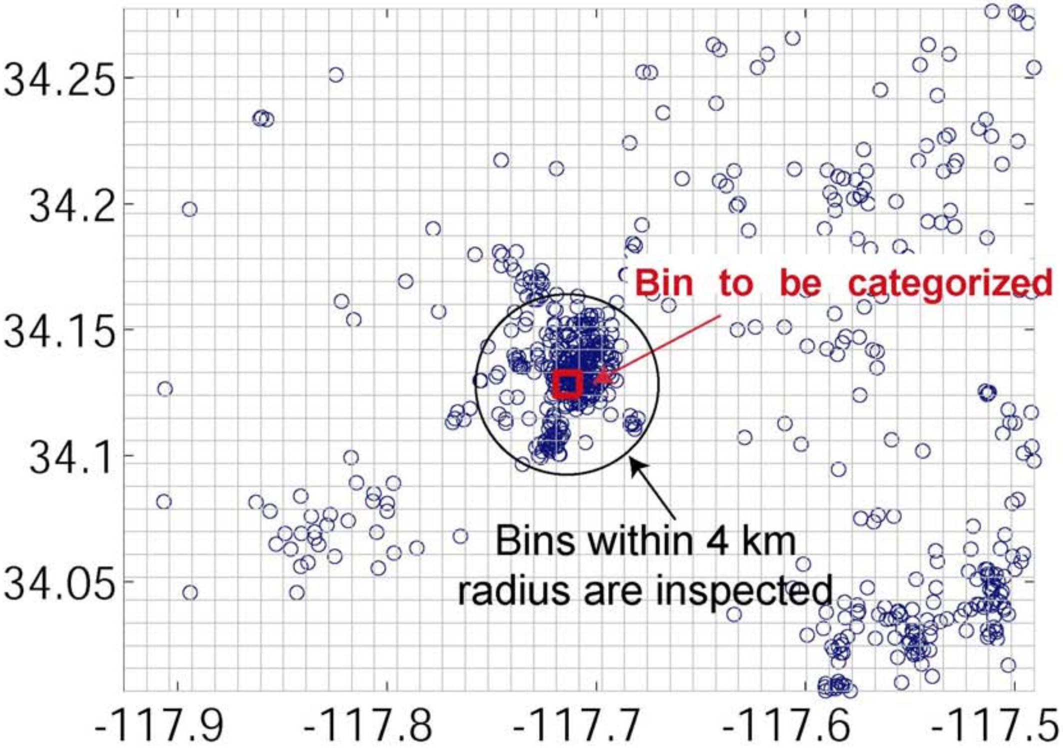
R<<1: Aftershocks

R not <<1: Not Aftershocks

Continuation of time ratio example

Issue: Some bins with late aftershocks do not have small time ratios

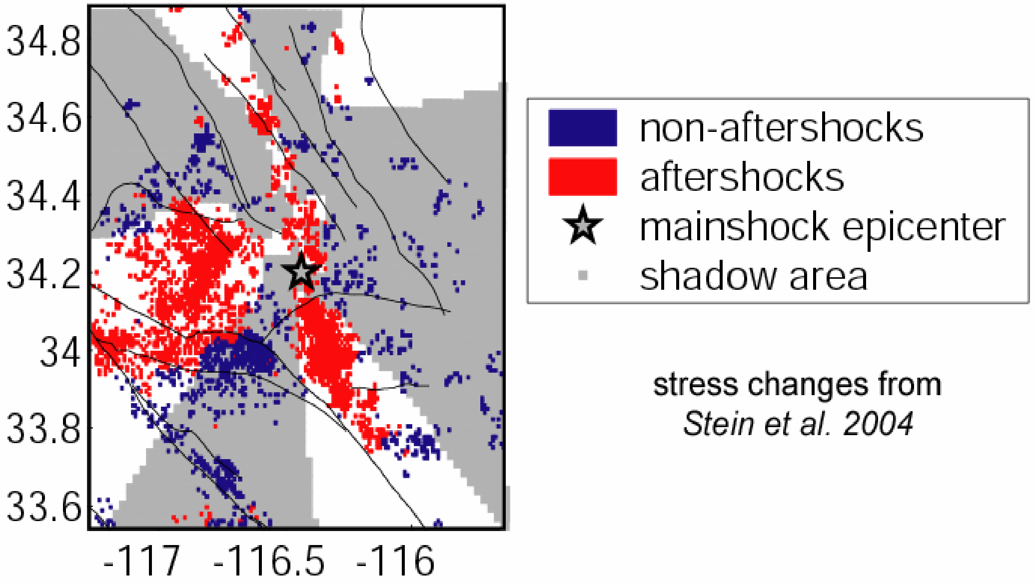
Solution: Since aftershocks cluster, a bin is classified as containing aftershocks if a significant percentage of bins within 4 km have a small time ratio **R**.



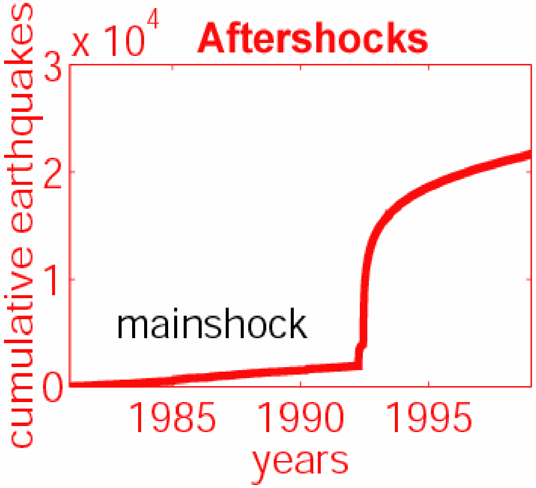
Test of the Time Ratio Method

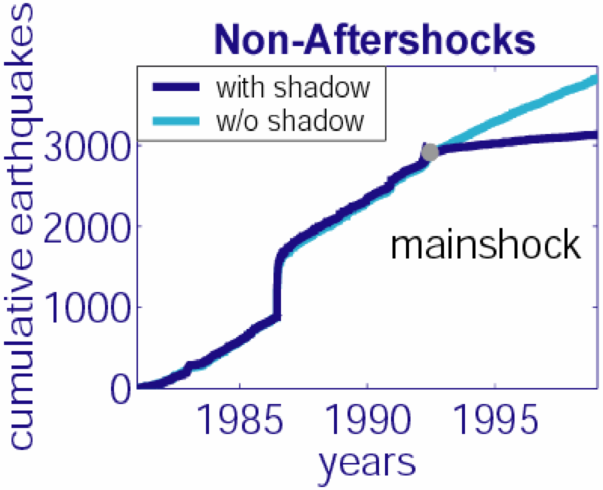
The ratio can identify a simulated Landers stress shadow

Error Rate:
2.3% of
aftershocks
are missed



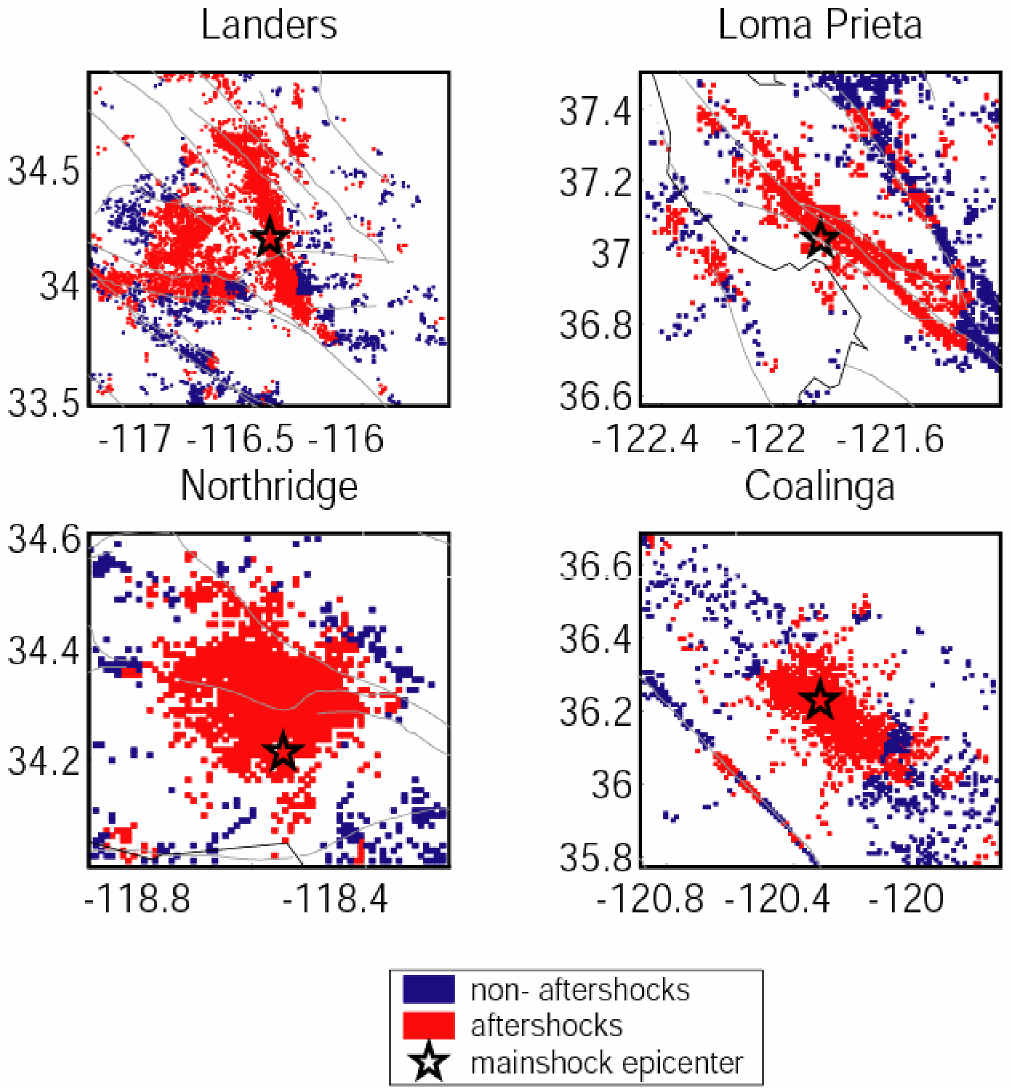
stress changes from
Stein et al. 2004



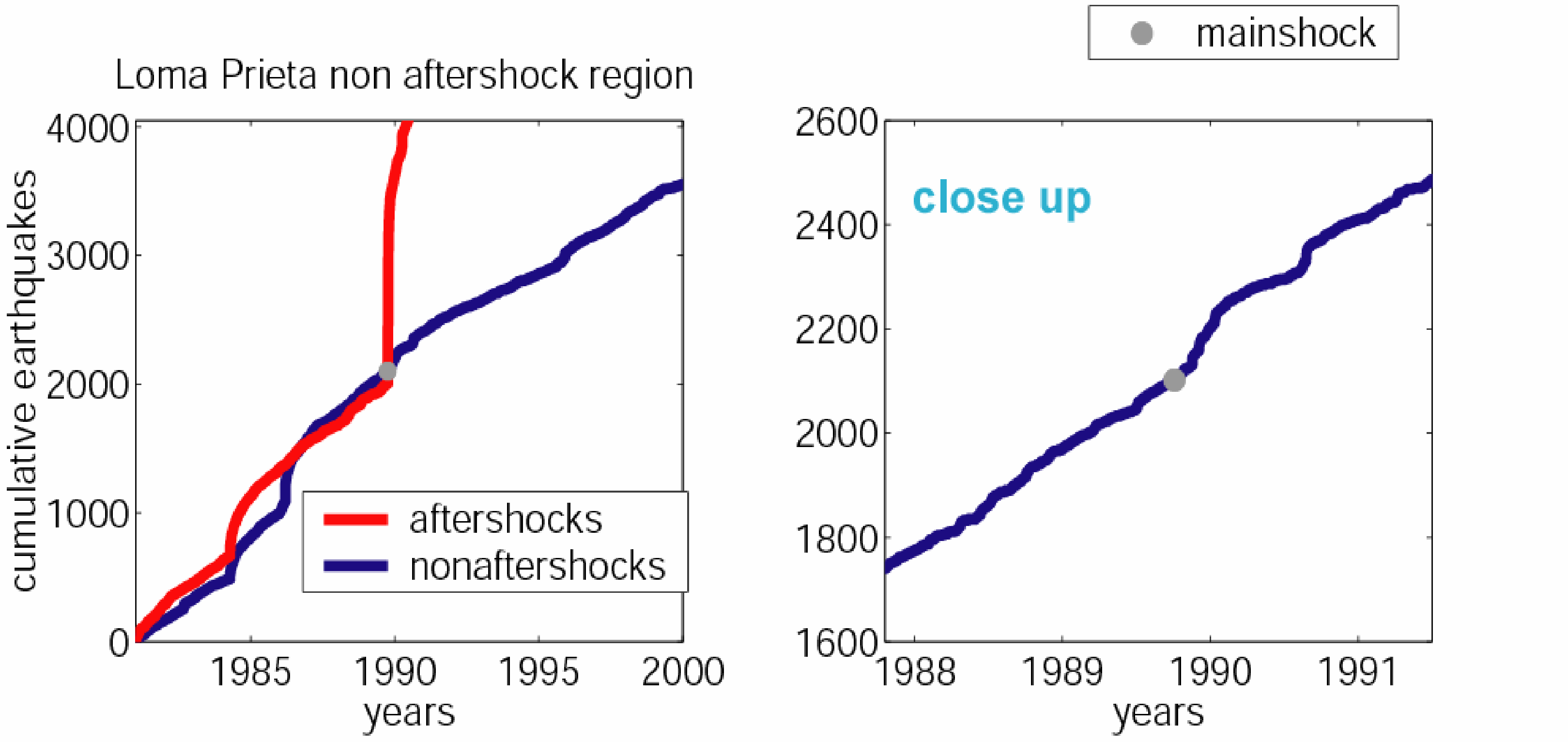


Using the time ratio to look for predicted stress shadow regions

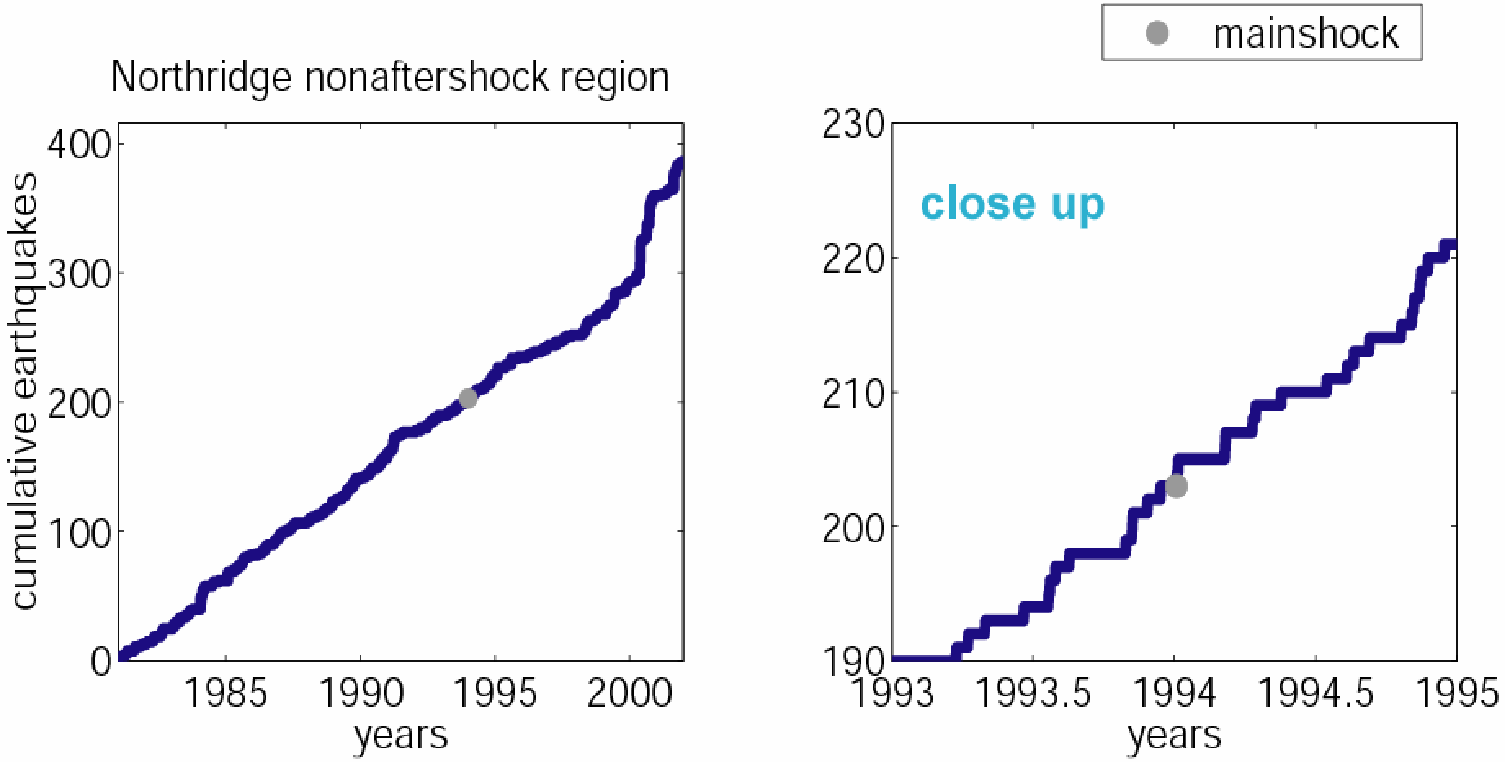
catalog data



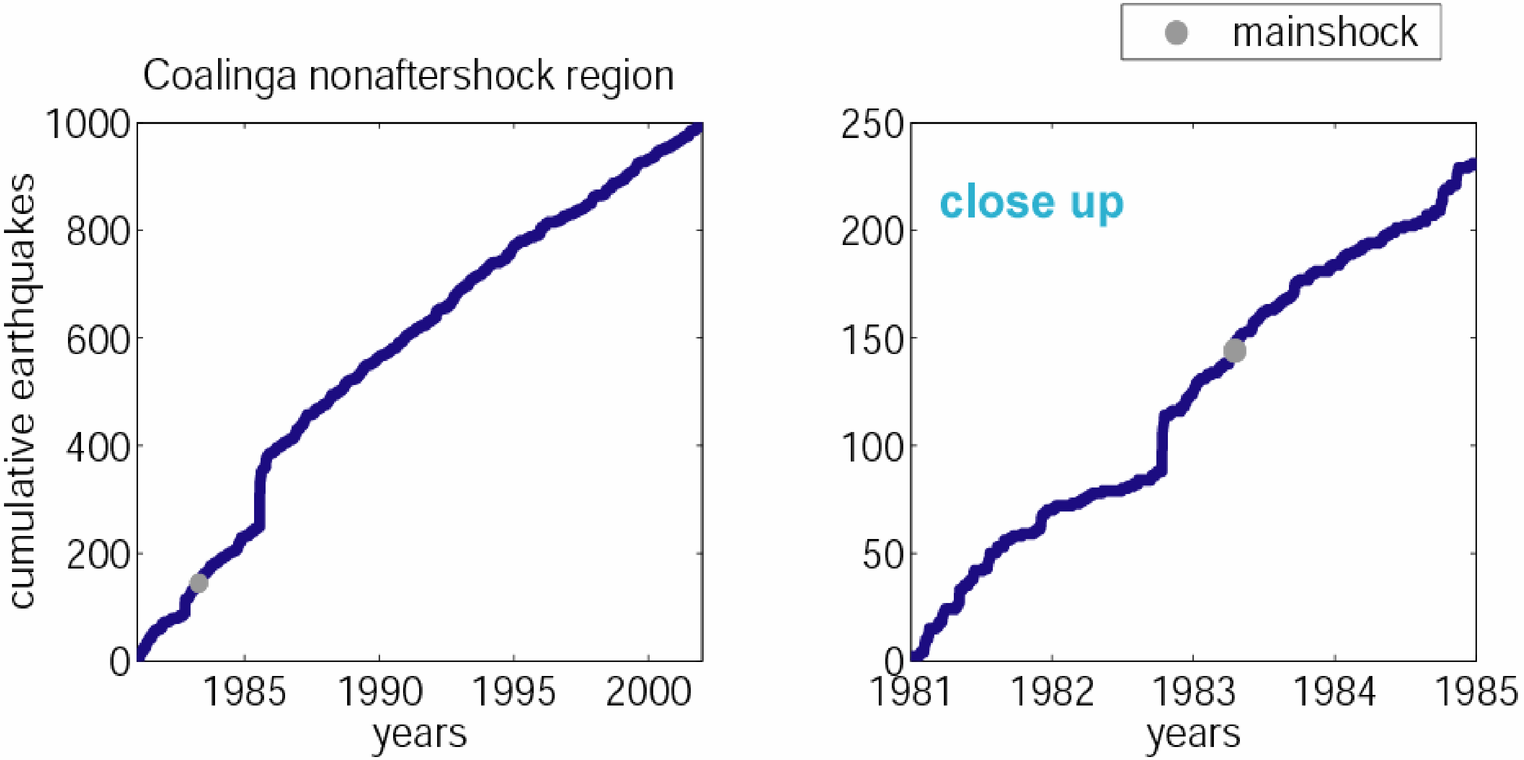
Results 1: No sign of a stress shadow after the 1989 M 7.1 Loma Prieta earthquake



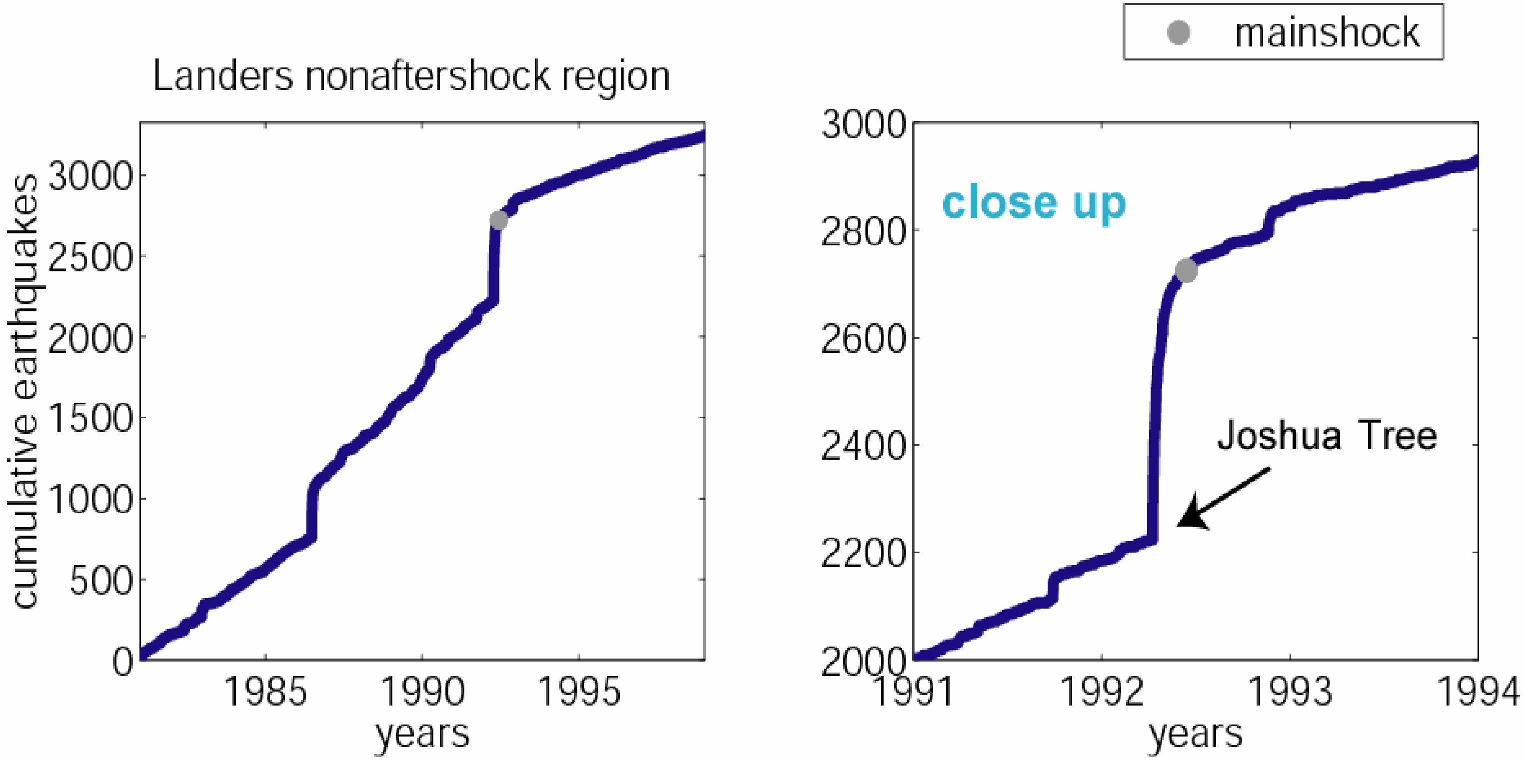
Results 2: No sign of a stress shadow after the 1994 M 6.7 Northridge earthquake



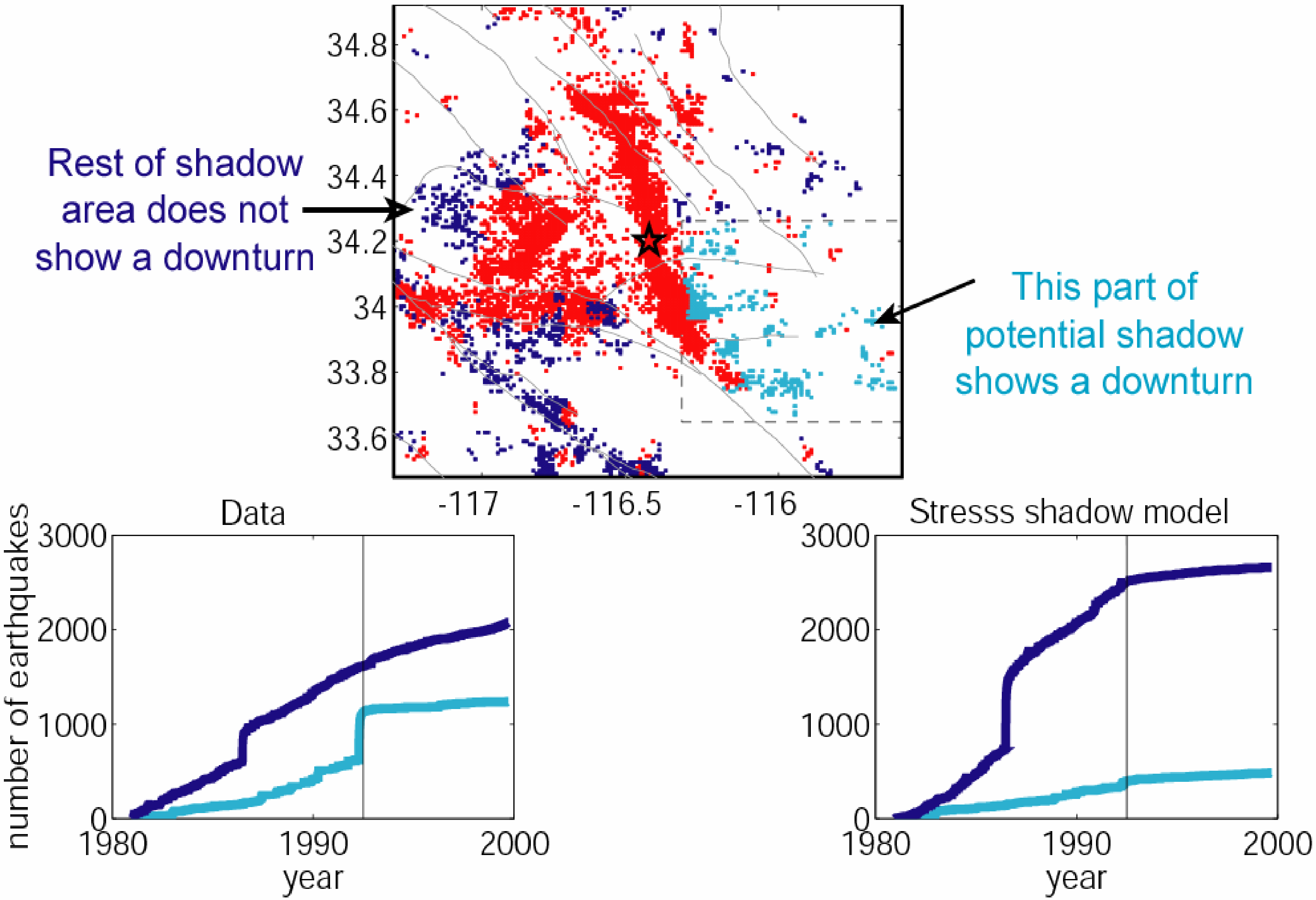
Results 3: No sign of a stress shadow after the 1983 M 6.4 Coalinga earthquake



Results 4: Small decrease in slope after the 1992 M 7.3 Landers earthquake?



Dealing with Landers: Downturn for 1992 Landers earthquake is spatially isolated, inconsistent with stress shadow model



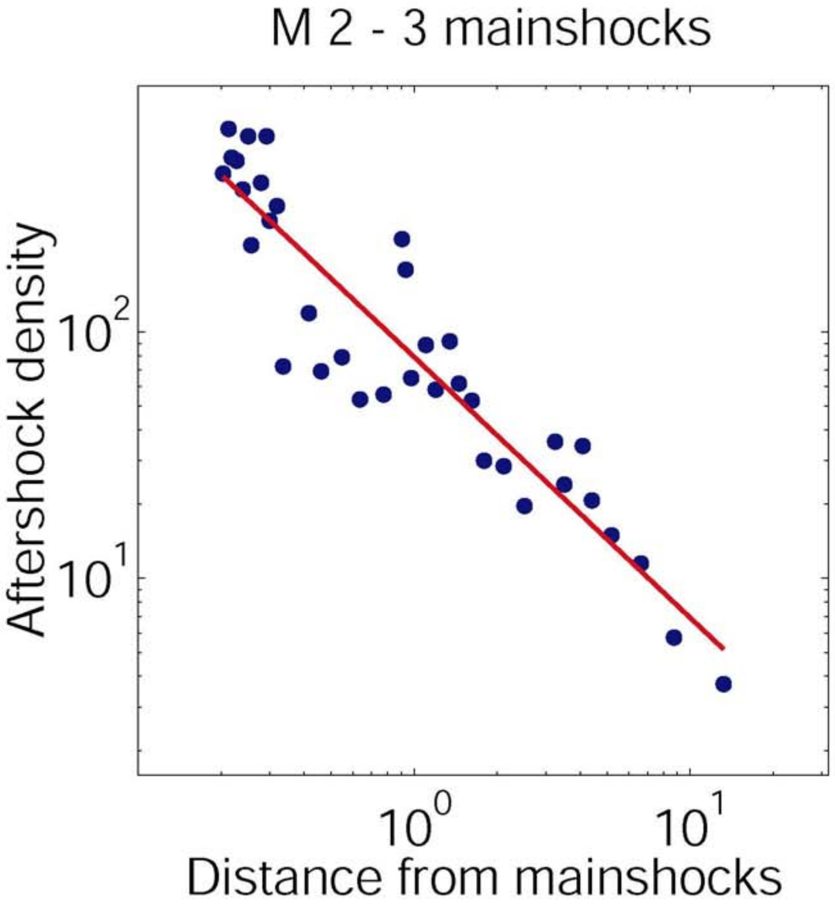
Rest of shadow area does not show a downturn

This part of potential shadow shows a downturn

Aftershock Triggering

	Static triggering	**Dynamic triggering**
Stress Shadow	~~Exists~~	Doesn't Exist **probably!**
Decay of aftershocks with distance	$\frac{1}{\text{Distance}^{3}}$	$\frac{1}{\text{Distance}}$

Aftershock Decay with Distance Test



If aftershock density varies linearly with stress change amplitude:

We expect a relationship of the form:

$$\rho = r^{-m}$$

ρ = Aftershock density
r = Distance from mainshock

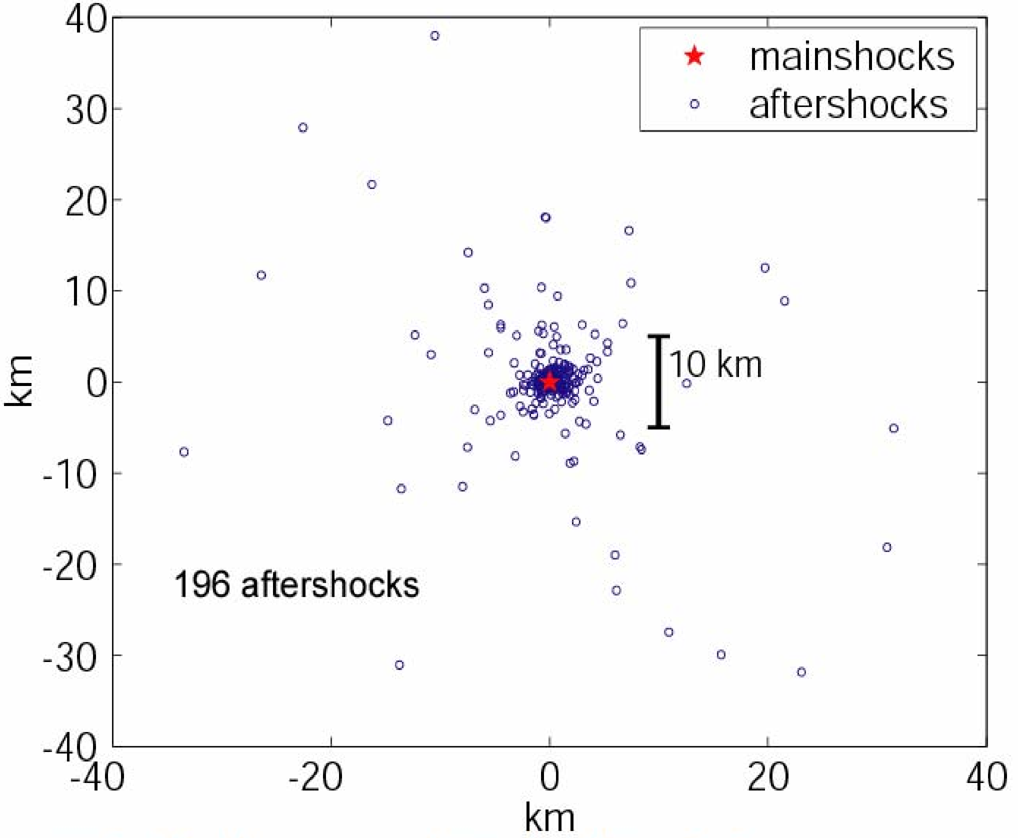
For Static stress: m = **3**
For Dynamic stress: m = **1**

Choosing a data set to solve for m

-We use the relocated *Shearer et al*. (2003) Southern California catalog

-We use small mainshocks because they can be considered point sources

Map of 2141 M 3-4 mainshocks w. first 30 minutes of M>2 aftershocks



*note that *mainshocks are centered at the origin* = "aftershock stacking"

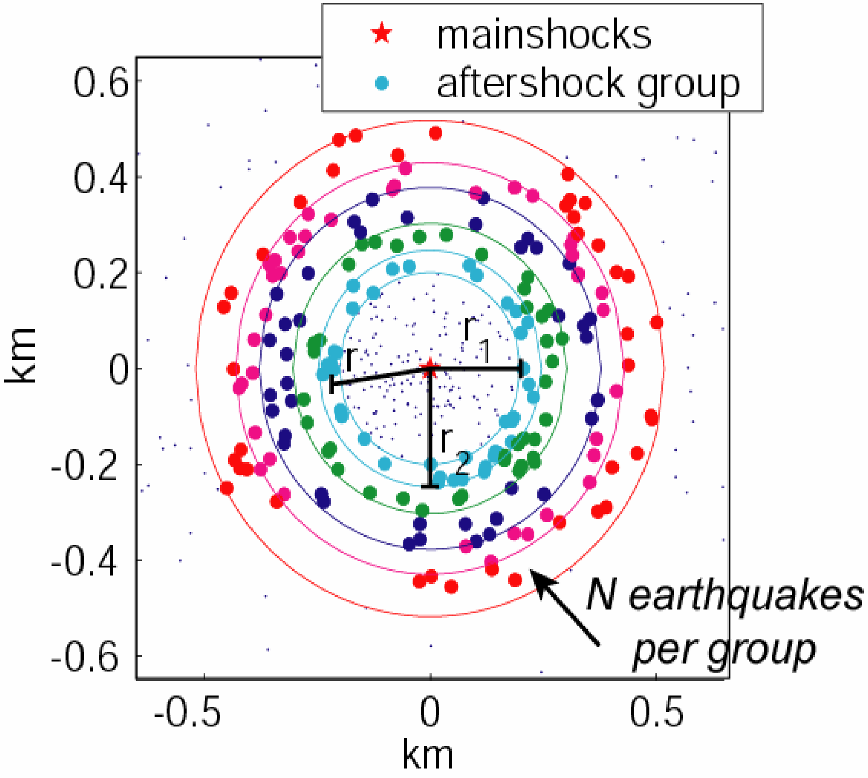
Measuring aftershock distance (**r**) and density (ρ)

1) Place aftershocks in groups of *N* by distance from mainshocks

2) For each group calculate:

r = Average distance from mainshock

ρ = density = $N/(r_2^{\gamma} - r_1^{\gamma})$



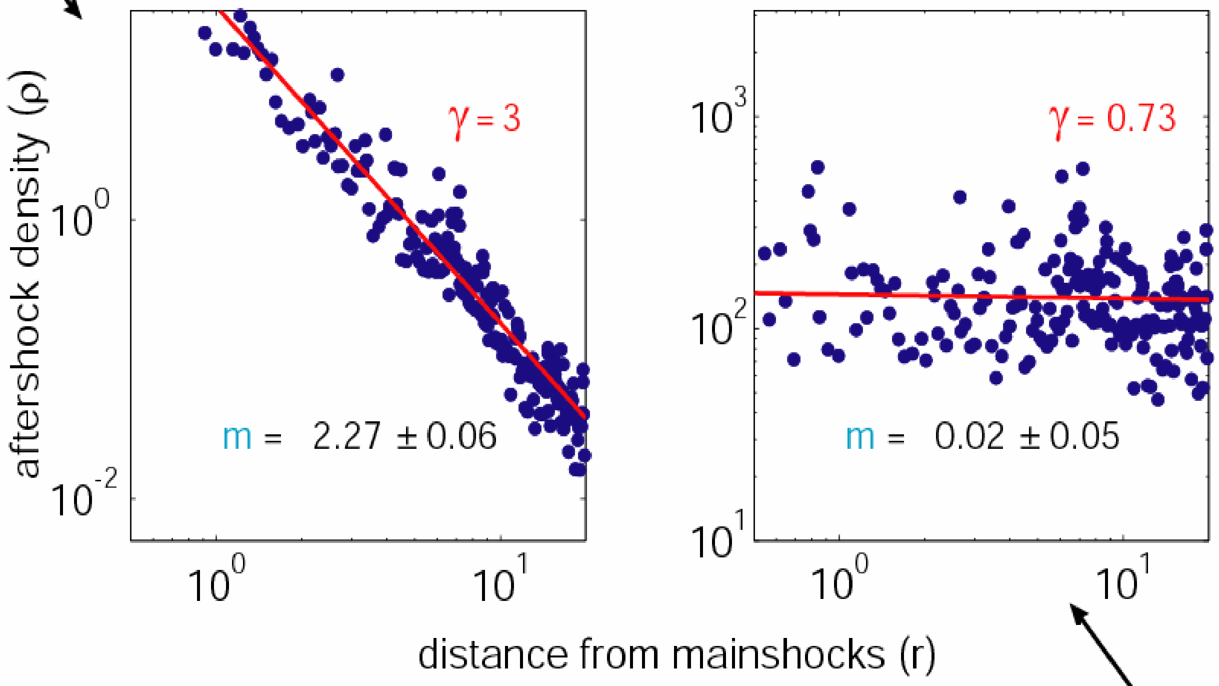
N earthquakes per group

Correcting for fractal fault structure

We solve for aftershock density as: $\rho = N/(r_2^{\gamma} - r_1^{\gamma})$

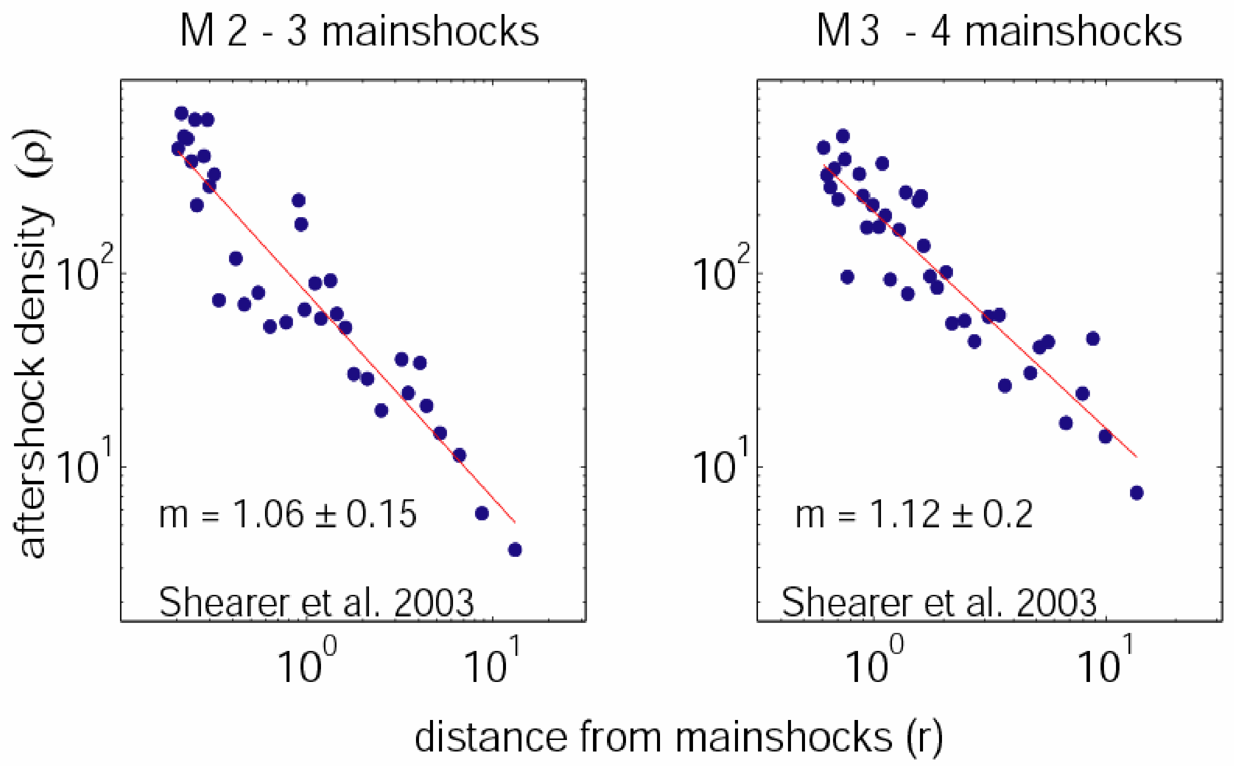
Choosing $\gamma=3$ (assuming faults are uniformly distributed in a volume) produces a sharp decay even in earthquakes occuring before the mainshock

Earthquakes occurring 4-5 days before M 3-4 mainshocks.



Using $\gamma = 0.73$ accounts for fault clustering, giving **m**=0 for pre-mainshock earthquakes

Distance vs. Density for first 30 minutes of aftershocks, So Cal



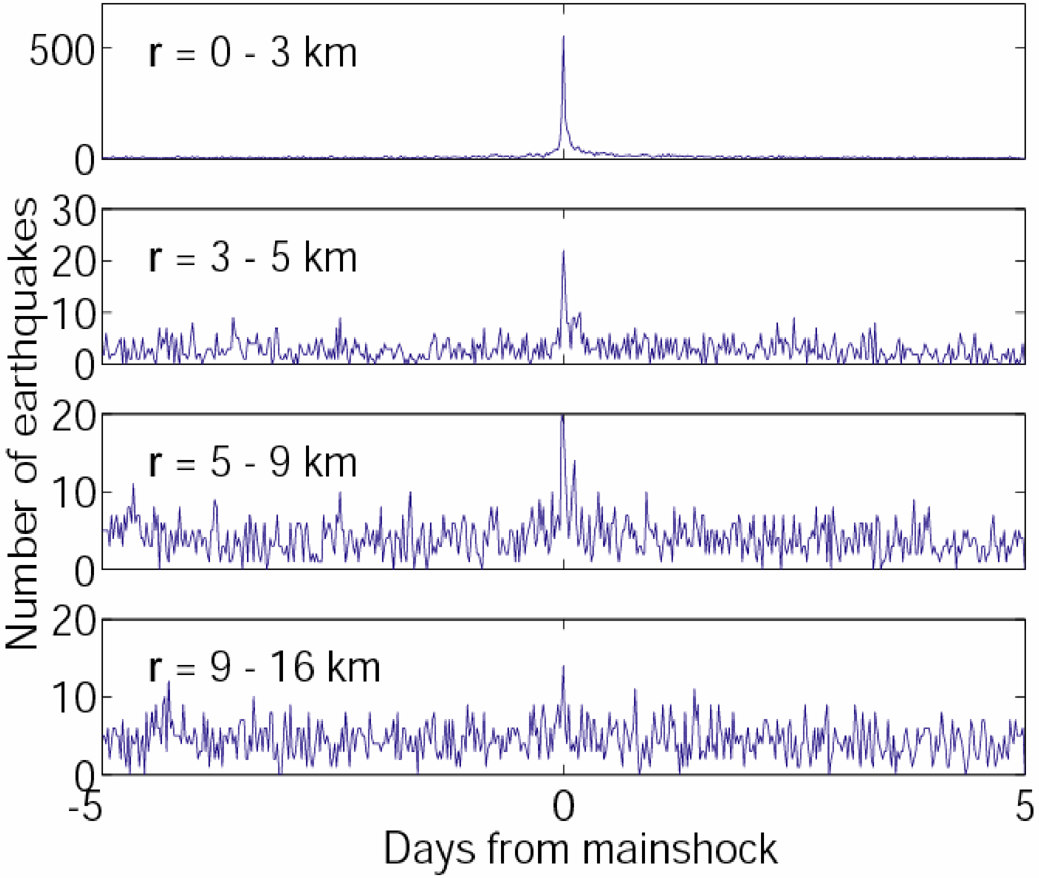
180 aftershocks,
9843 mainshocks

196 aftershocks,
2141 mainshocks

Distances are between mainshock and aftershock hypocenters

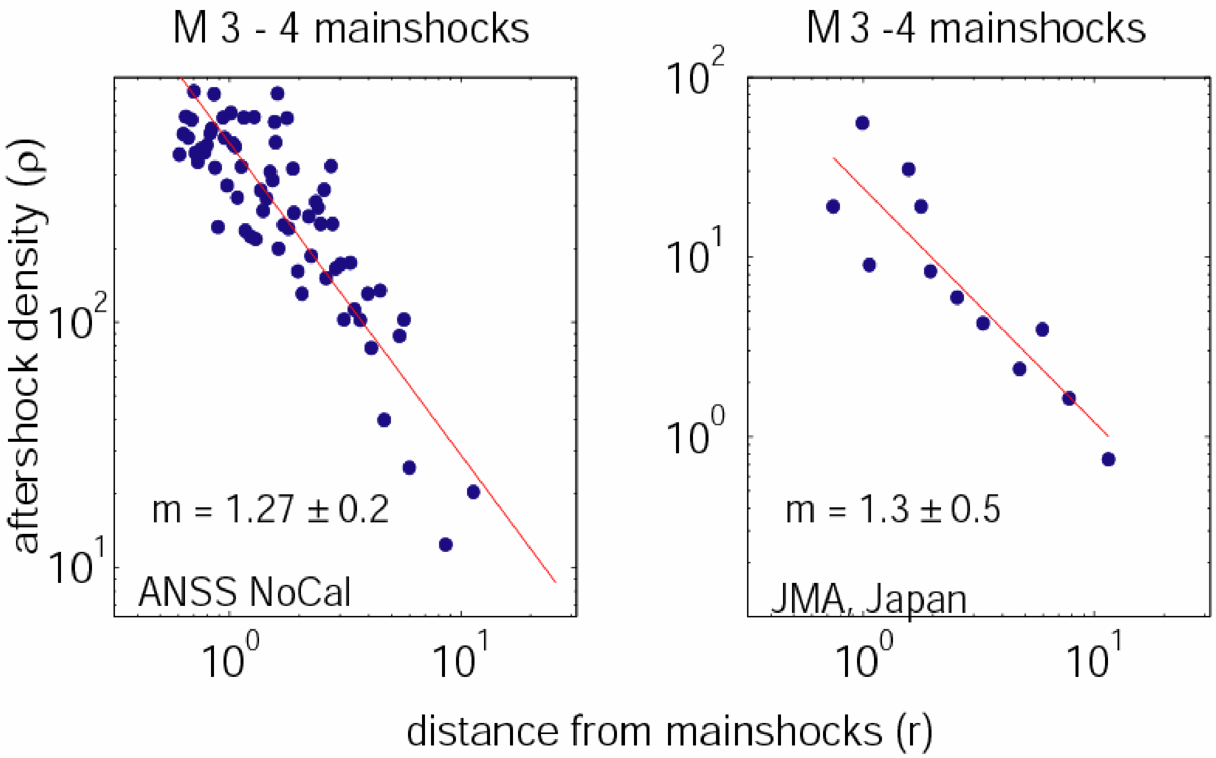
Distant aftershocks are real

Time series of stacked aftershocks of M 3-4 mainshocks shows that aftershocks occur out to 16 km (14 fault lengths)



Each data point in time series = 30 minutes

Distance vs. density for first 30 minutes of aftershocks, other regions



511 aftershocks,
1734 mainshocks

67 aftershocks,
977 mainshocks

Distances are between mainshock and aftershock epicenters

Conclusions

	Static triggering	**Dynamic triggering**
Stress Shadow	~~Exist~~	Doesn’t Exist **probably!**
Decay of aftershocks with distance	$\cancel{\frac{1}{\text{Distance}^3}}$	$\frac{1}{\text{Distance}}$