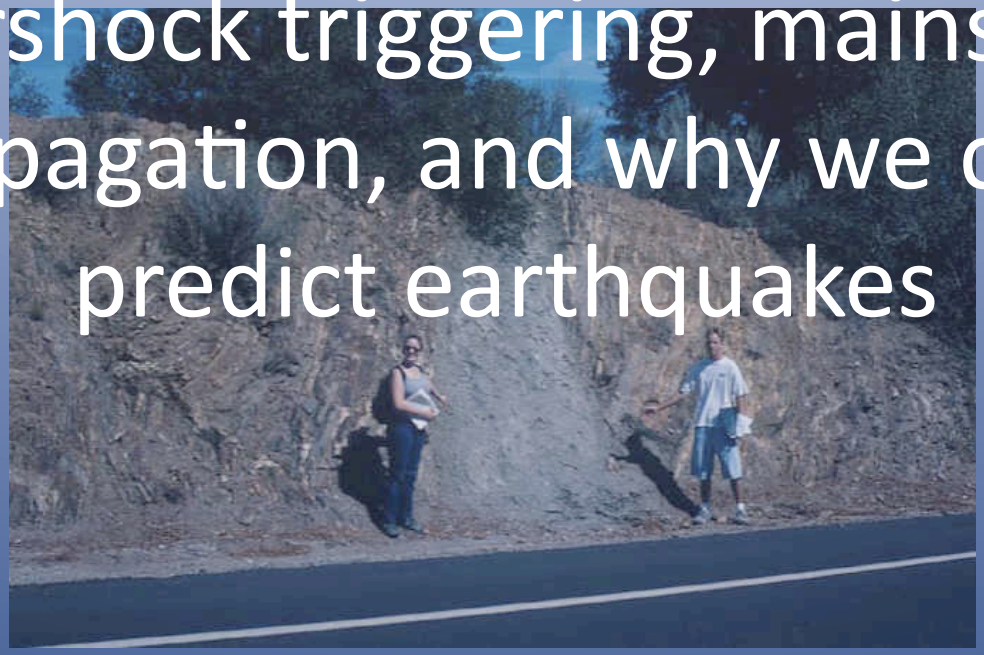
The pulverization hypothesis of aftershock triggering, mainshock propagation, and why we can't predict earthquakes

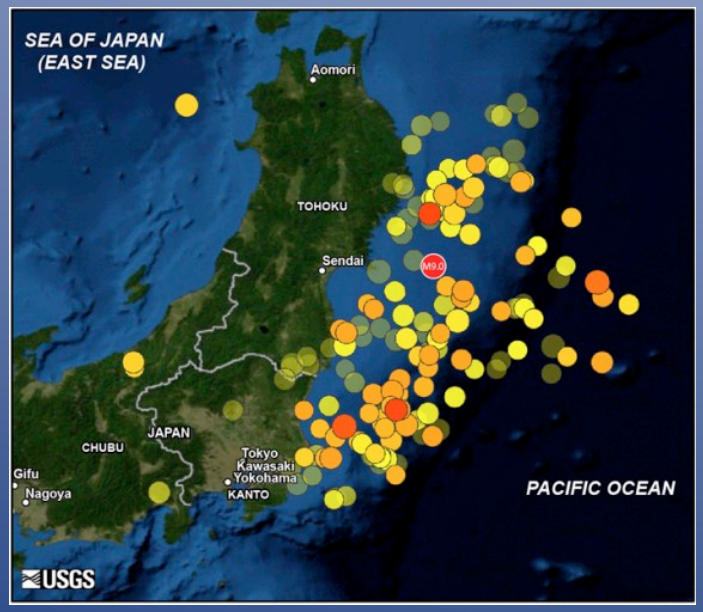


Elsinore Fault Gouge, photo by Bruce Perry

Karen Felzer
Pasadena Field Office

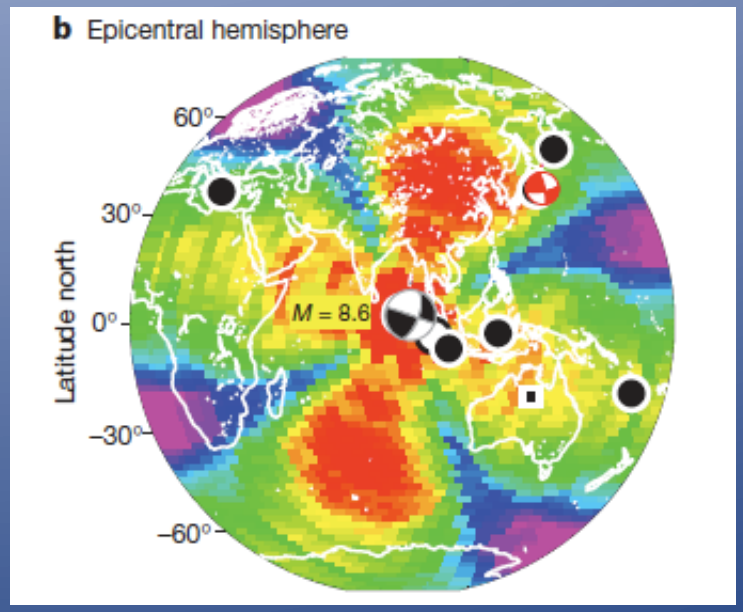
We can usually forecast that earthquakes will be followed by more earthquakes. The encore is composed of:

Aftershocks (<~100 km)



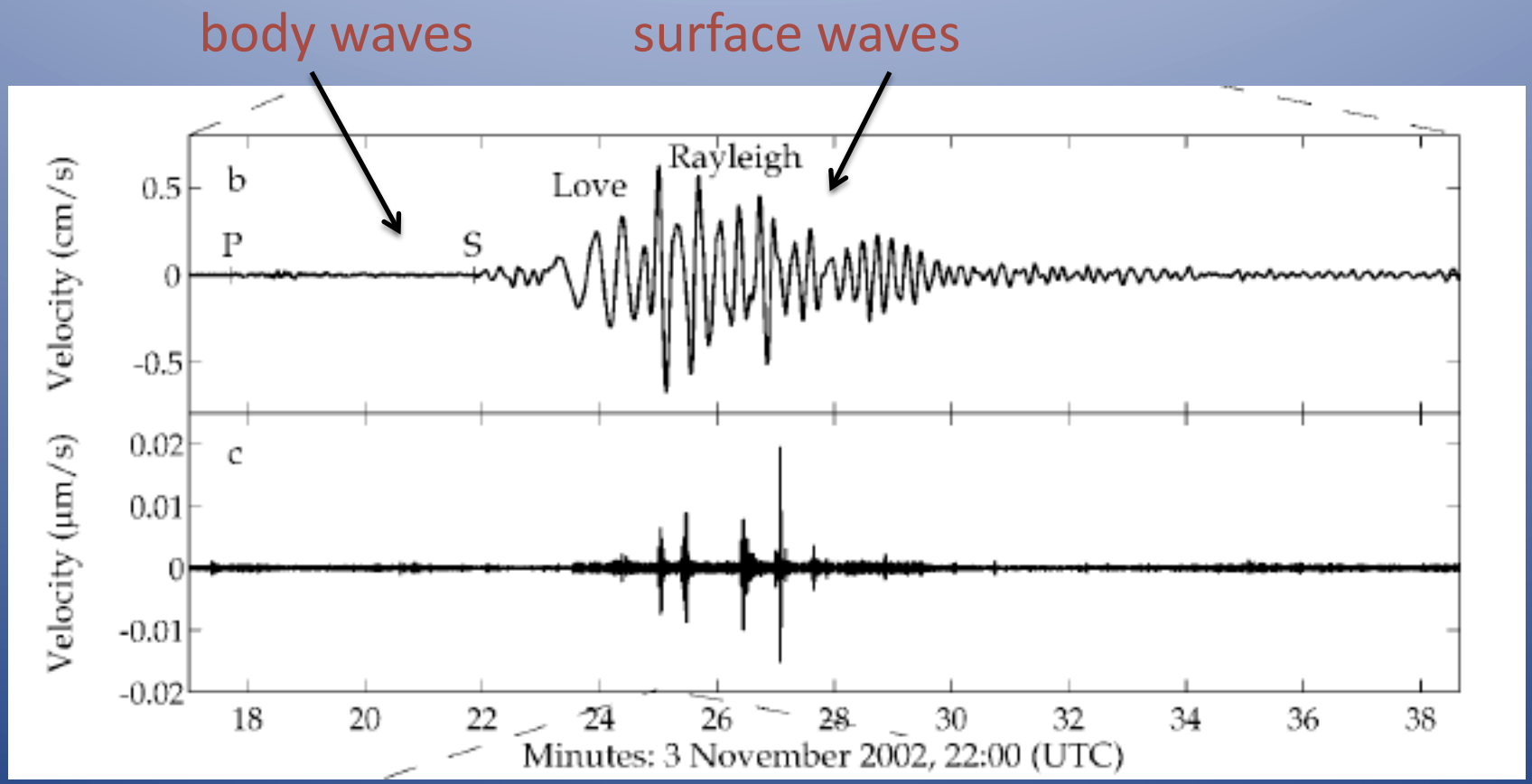
Tohoku aftershocks

Triggered earthquakes

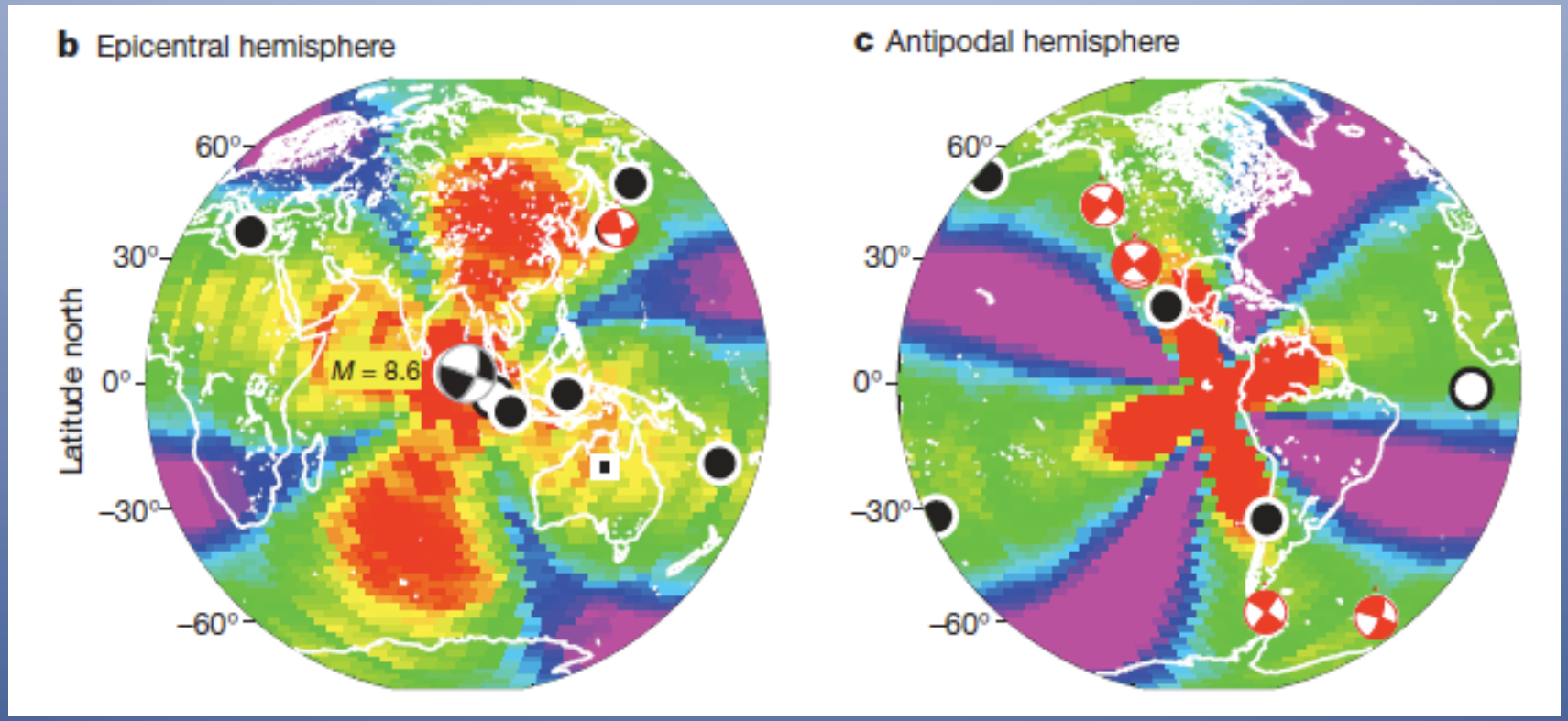


Earthquakes triggered by the 2012 East Indian Ocean Eq, *Pollitz et al*. (2012)

Distant triggered earthquakes are clearly triggered by surface waves



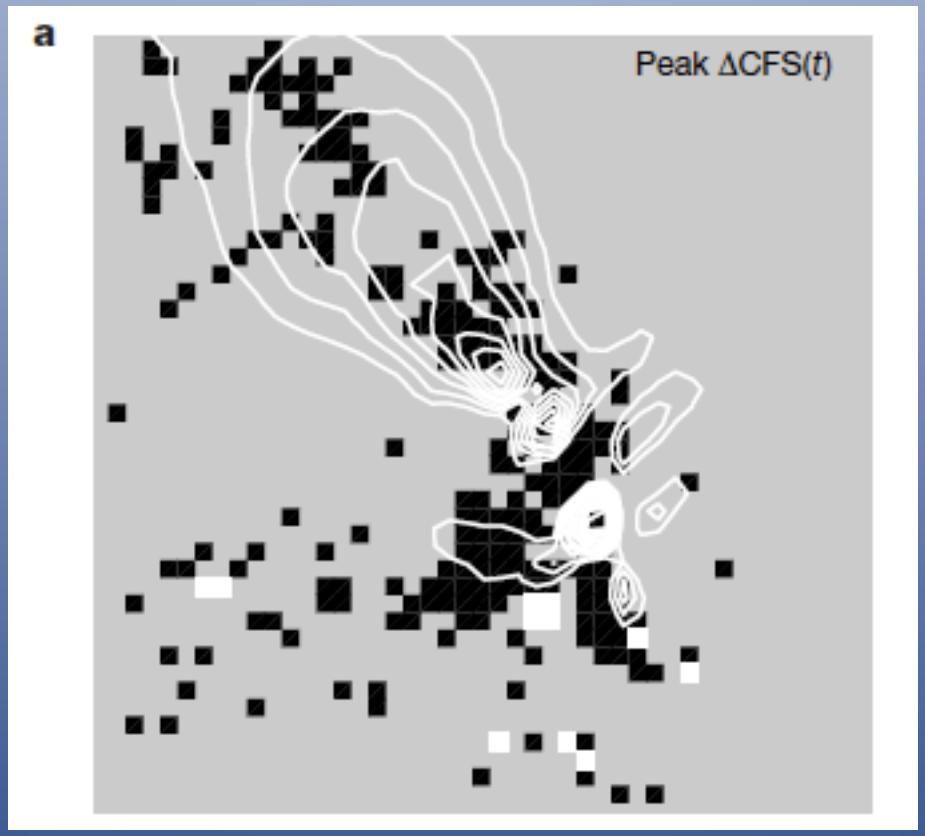
Triggering at Mt. Ranier by surface waves of the Denali earthquake, from *Prejean et al*. (2004).



Pollitz et al. (2012)

Triggered earthquakes of the 2012 Indian Ocean Earthquake agreeing with the surface Love wave radiation pattern

Near field aftershocks also follow the peak dynamic strain pattern

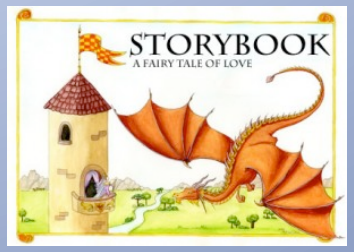


Aftershocks of the 1992 Landers earthuqake, from *Kilb et al.* (2000)

Yet agreement between near field aftershocks and dynamic strain is puzzling --

- Near field dynamic shaking is primarily body waves, not surface waves. Body waves are known to be ineffective triggers in the far field.
- There are various time delays between the mainshock and near field aftershocks. It is not clear how a dynamically triggered phenomena can be time delayed.

The story



- Near field aftershock triggering is driven by the high frequency component of body waves. Body waves are not efficient triggers in the far field because the high frequencies attenuate.
- High frequency acceleration weakens nucleation zones by pulverizing fault gouge. But the faults do not actually rupture until they are pushed to failure by afterslip/other aseismic processes. This creates the time delay.

Postseismic deformation and aftershocks follow a similar decay rate

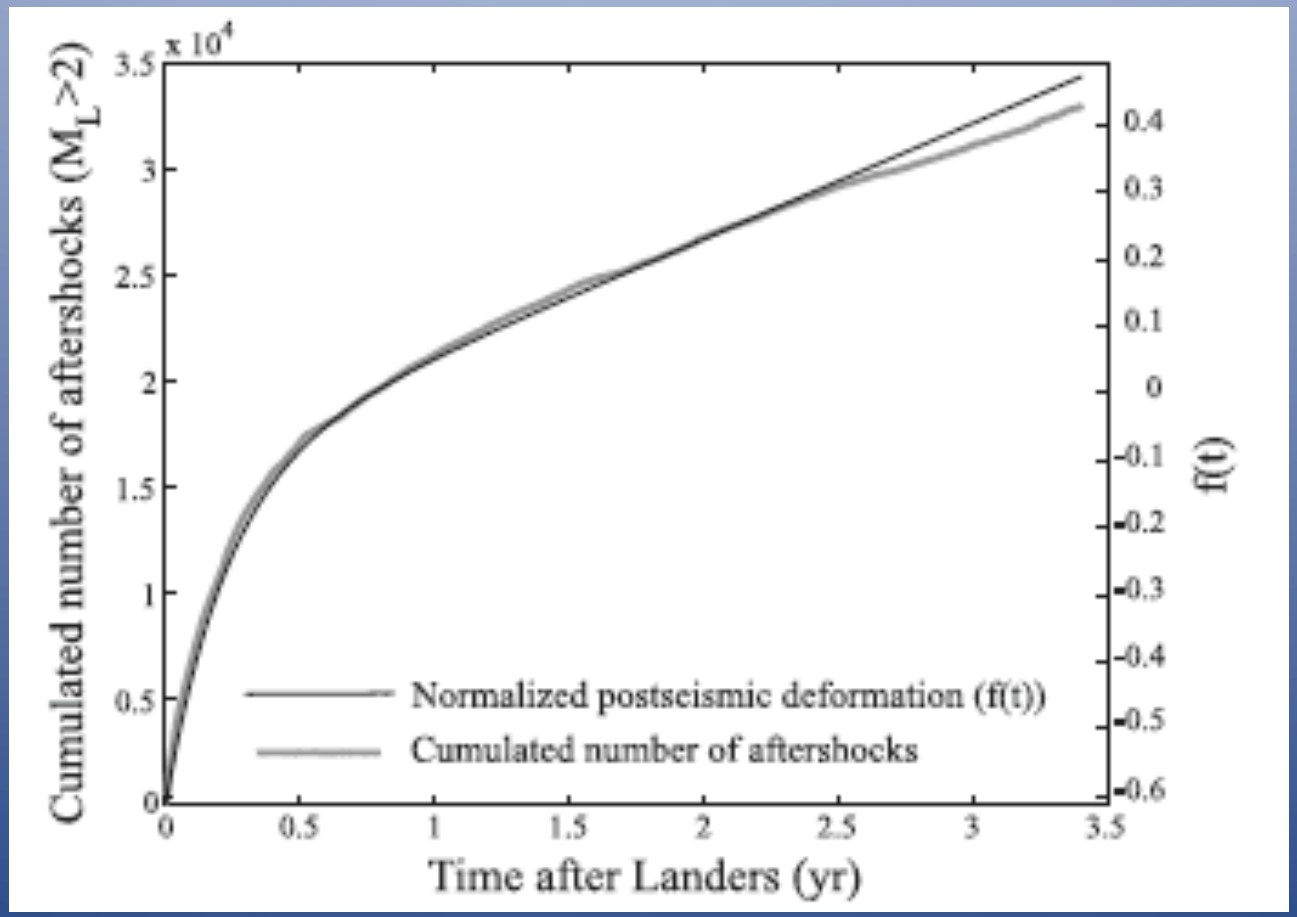
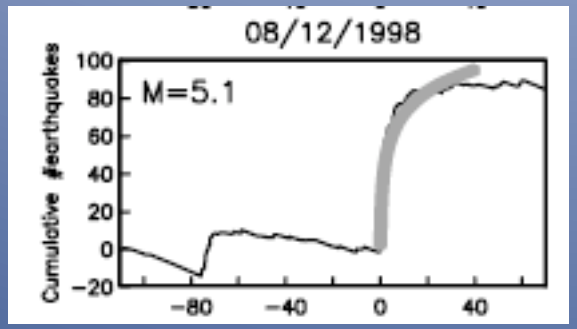


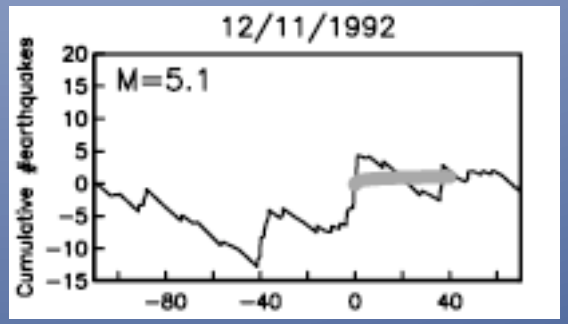
Figure from *Perfettini and Avouac* (2007)

Support for the story: High frequencies are the missing ingredient in things that trigger few aftershocks

Impulsive event



Aseismic event



Pollitz and Johnston (2006)

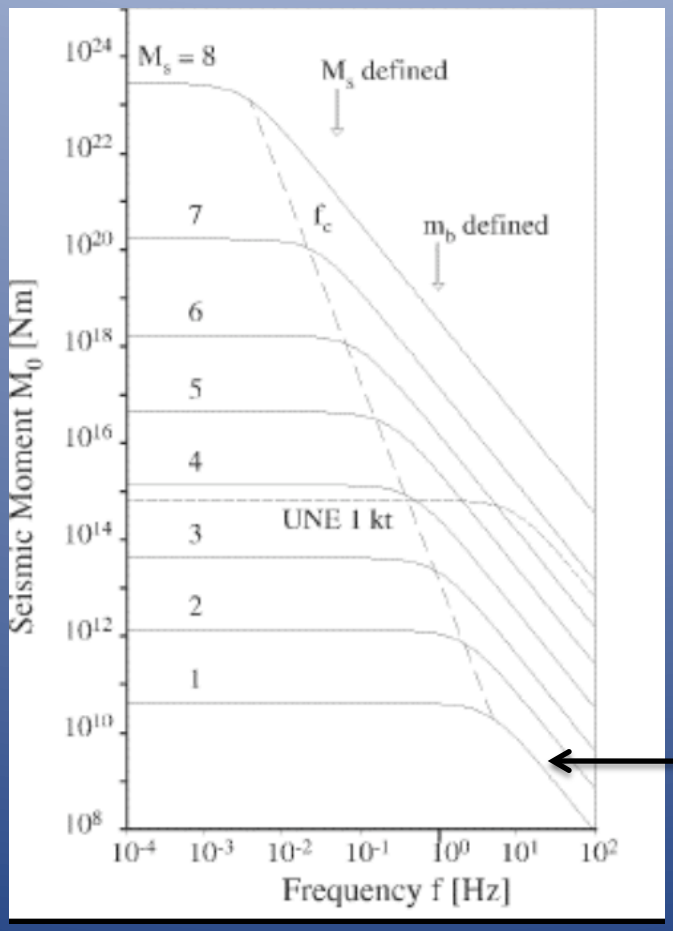
Aseismic slip events alone are ineffective at triggering aftershocks

High frequencies are the missing ingredient in things that trigger few aftershocks

Nuclear blasts trigger few aftershocks
(*Parsons and Velasco*, 2009)

Triggering by high frequencies is required to reproduce observed aftershock scaling relationships

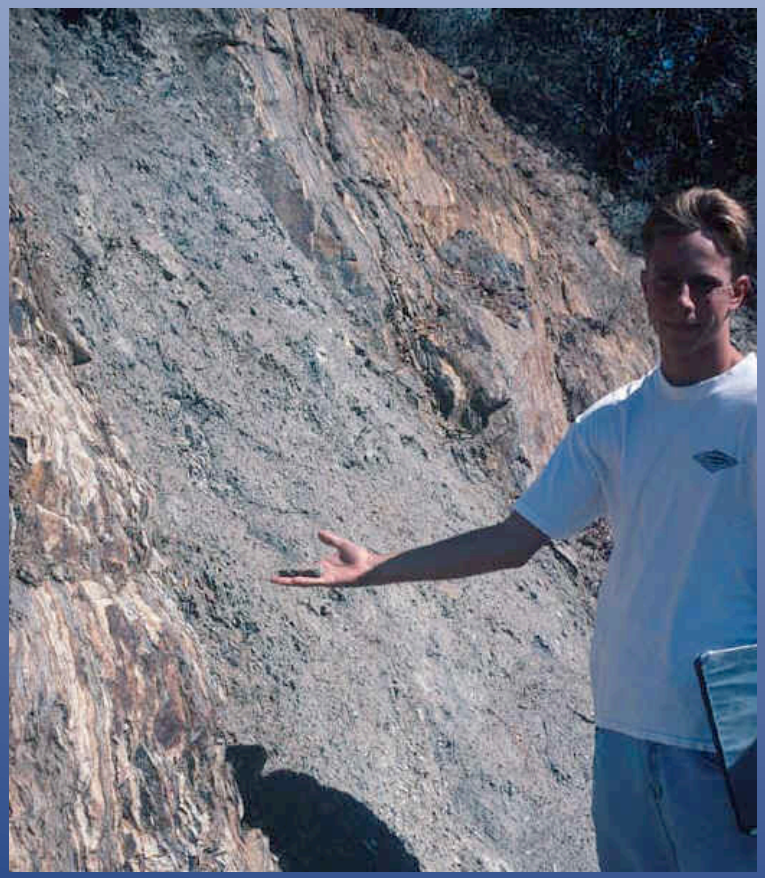
Earthquake Source Spectra



Consistent aftershock productivity scaling as 10^M requires triggering by frequencies above the highest corner frequency

From the website of Eric Bergman

Pulverization is a phenomena uniquely linked to high frequencies



Elsinore Fault, photo by Bruce Perry

Pulverization leads to the formation of fault gouge (*Wilson et al.*, 2005)

Creating fresh, incohesive fault gouge is like inventing the wheel

We now have rolling and powder lubrication=> significantly weaker fault

The gouge weakening effect was documented in the lab by *Reches and Lockner* (2010)

"… At modest slip speeds of 10-60 mm/s this newly formed gouge organized itself into a thin deforming layer that reduced the fault's strength by a factor of 2-3. After slip the gouge rapidly "aged" and the fault regained its strength in a matter of hours to days. Therefore only newly formed gouge can weaken the experimental faults"

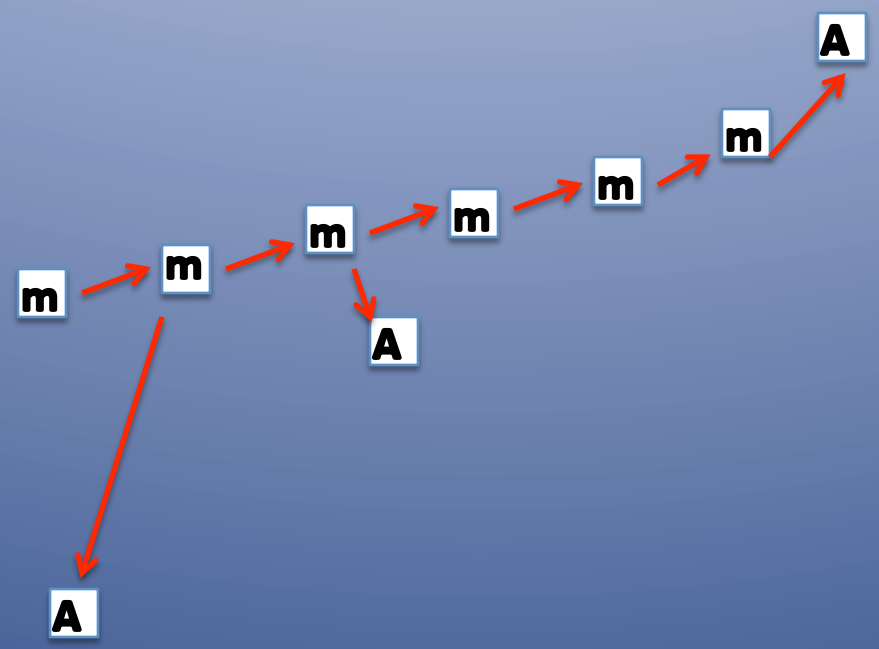
The pulverization hypothesis can explain many things -

1. Unification between the physics of aftershock production and mainshock propagation.
2. The failure of the time predictable earthquake model.
3. The San Andreas Fault heat flow paradox.

1) Unification of the physics of aftershock production and mainshock propagation

- *Kagan and Knopoff* (1981) found evidence in seismic waveforms and aftershock statistics that mainshock propagation and aftershock triggering represent a single continuous process.
- *Reches and Dewers* (2005) found that pulverization occurs out in front of a growing rupture. This provides the basis for a link.

We can visualize that pulverization causes the weakening of small cracks ahead of the fault tip



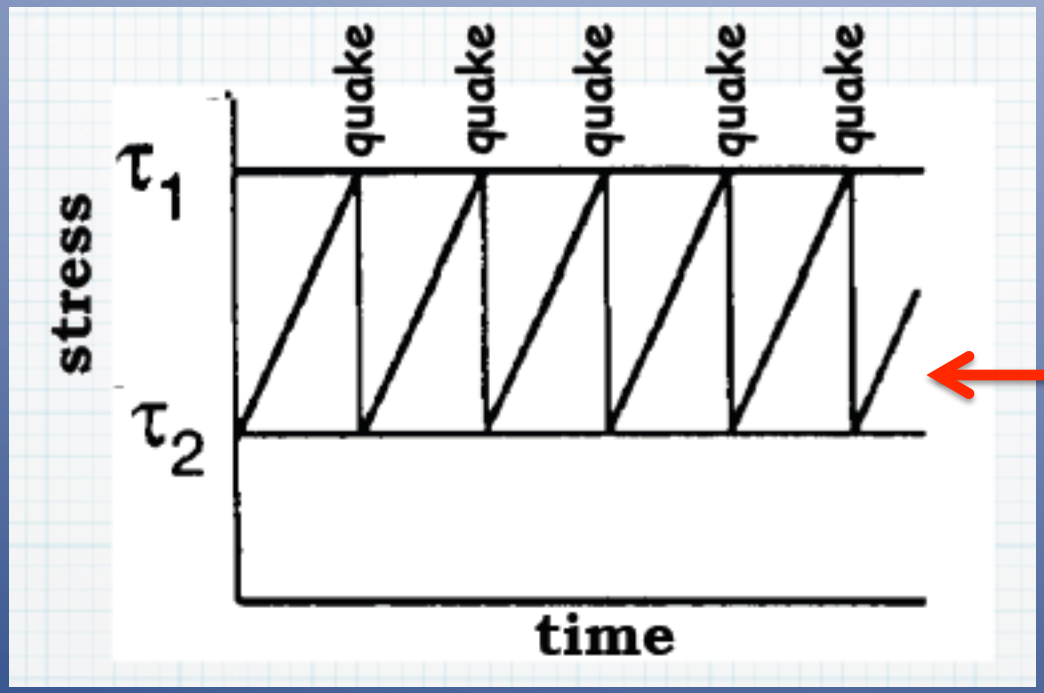
Depending on local stress/strain conditions these cracks either join the mainshock (m) or fracture later as aftershocks (A).

Recent laboratory support for the pulverization model of earthquake growth

- "Rapid acceleration leads to rapid weakening in earthquake-like laboratory experiments", *Chang et al.* (2012). Documents rapid weakening via gouge formation and powder lubrication when there are high accelerations at the rupture front

Laboratory gouge, *Reches and Lockner* (2010)

2) The failure of time predictable/seismic gap models



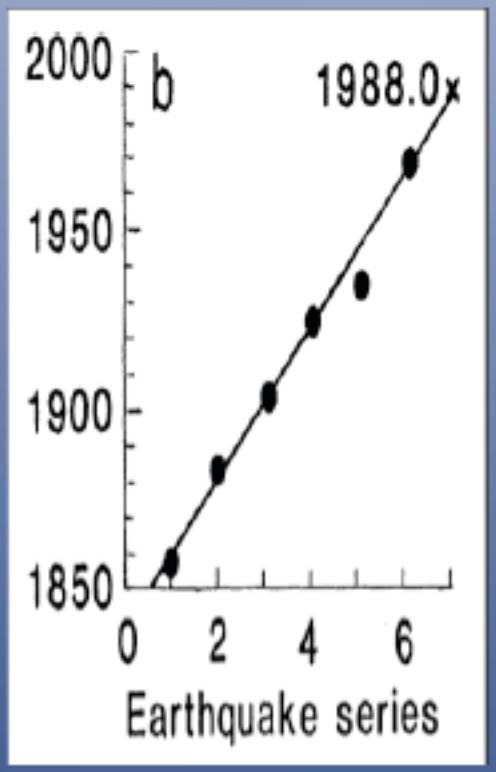
What seismologists wish for…

In the seismic gap model stress builds from baseline to fault strength during the earthquake cycle. Faults that have been quiet for > average cycle have the highest risk.

Media interpretations of the seismic gap model

- "Scientists say the Hayward fault is overdue for a major earthquake" – ABC news
- Geologists uncover earth's secrets, says Southern California is overdue for a major earthquake - University News
- The [San Andreas Fault] is 10 months pregnant! – guardian.co.uk

The most official, prospective seismic gap prediction was made at Parkfield, California



Bakun and Lindh (1985) predicted a M 6 Parkfield earthquake every 22 years. The next earthquake was to occur by 1993 at 95% confidene

There was no M≥6 earthquake at Parkfield until 2004

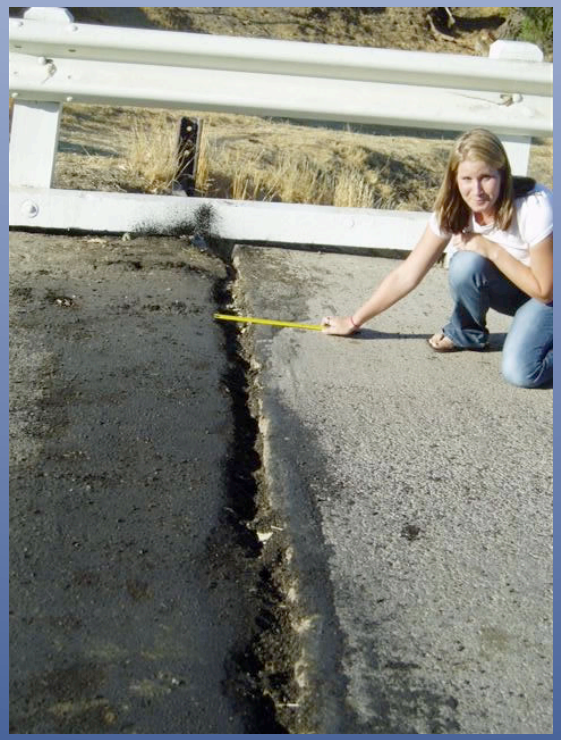
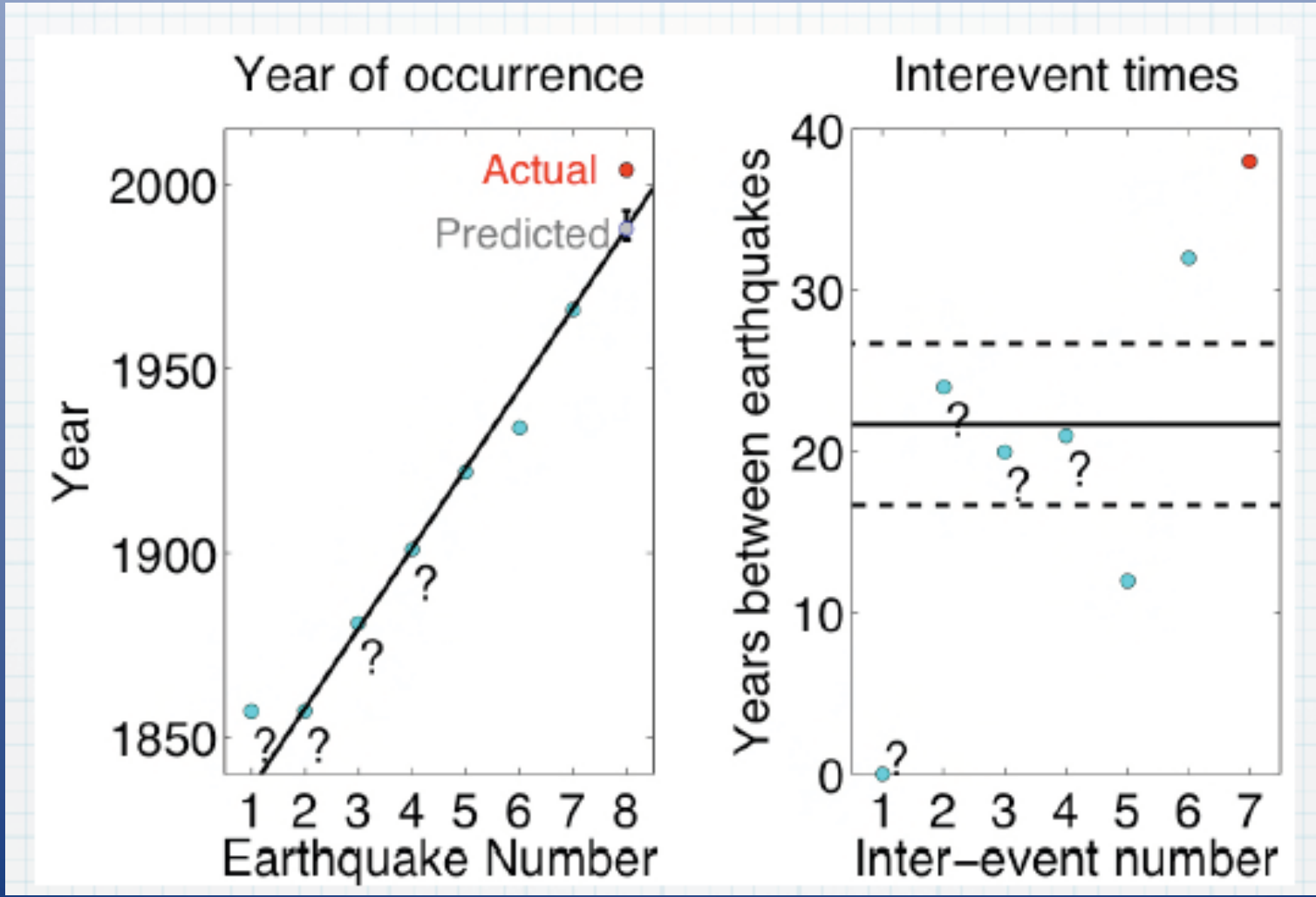


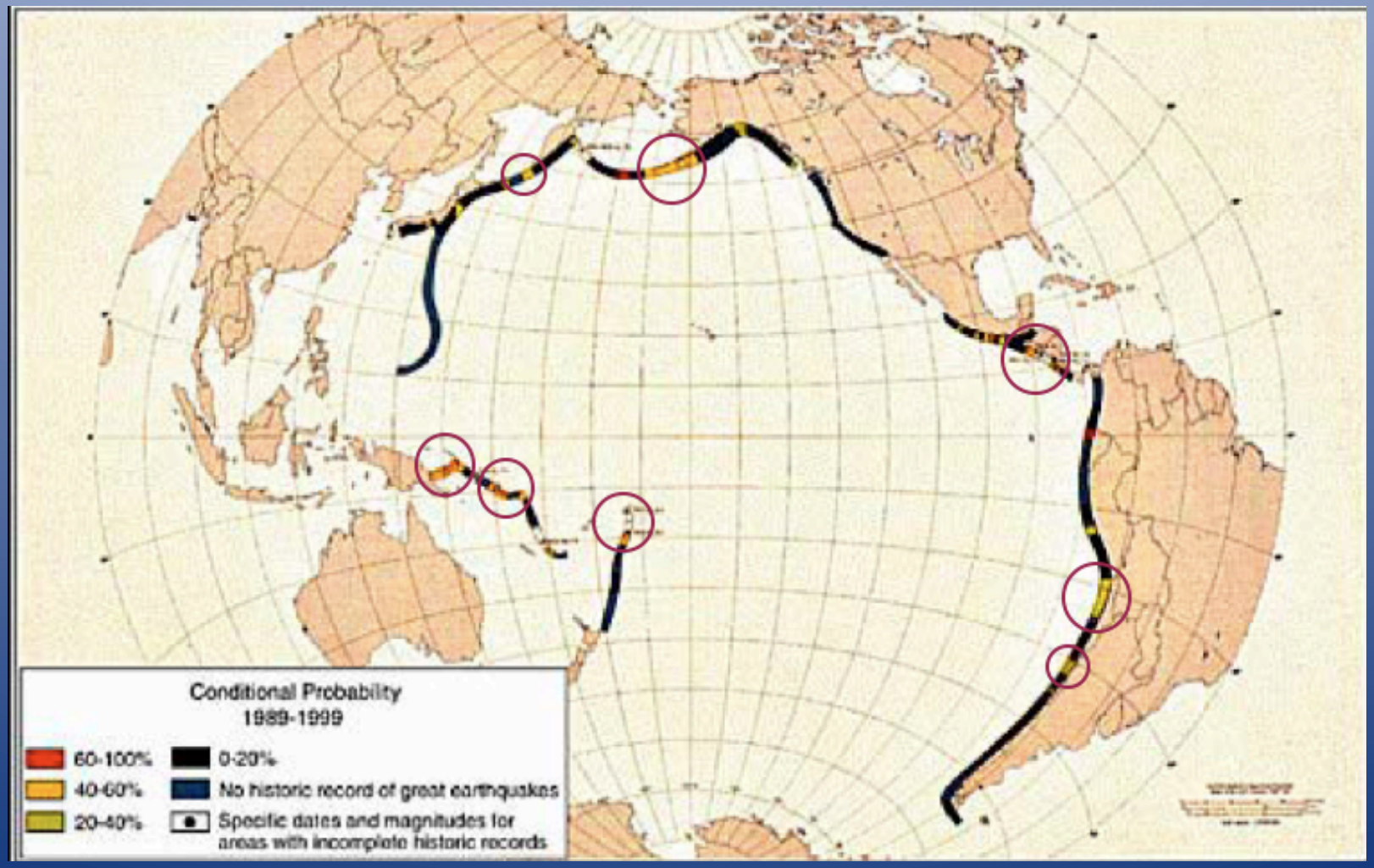
Photo by Pacific Earthquake Engineering Research Center

99.75% chance that the time predictable model for Parkfield is wrong

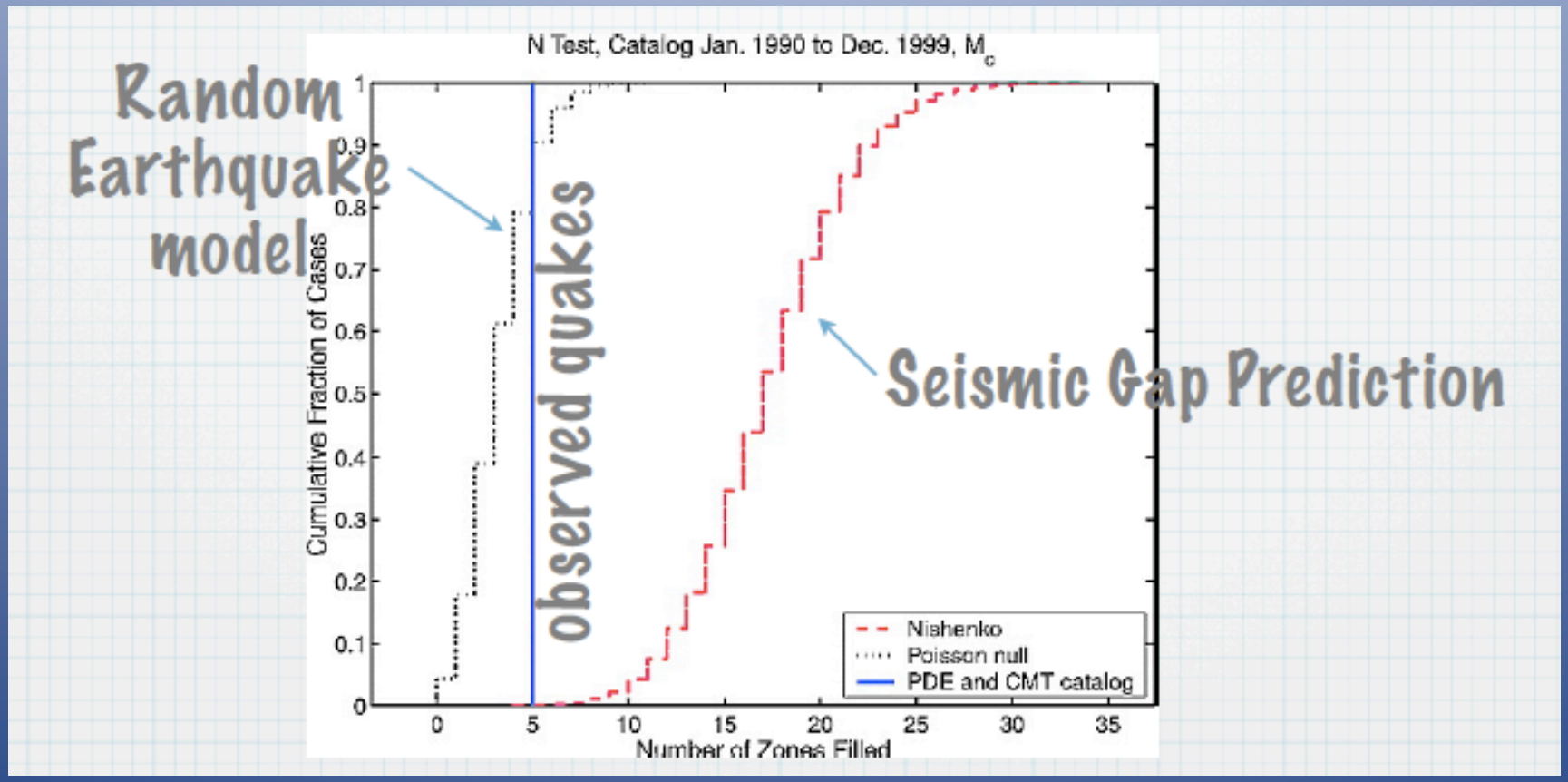
Parkfield earthquakes may not have been so periodic to begin with



Nishenko (1991) made a global seismic gap forecast



The Nishenko forecast also failed

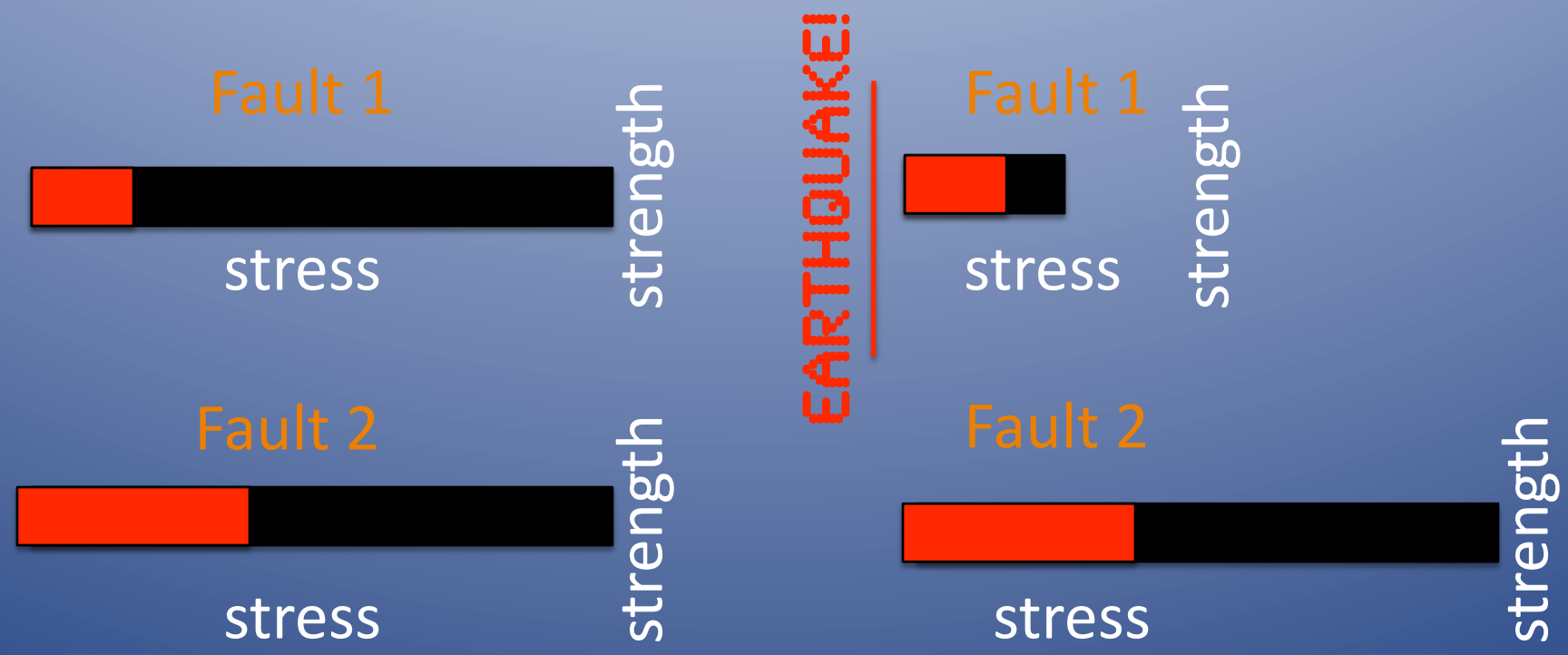


Rong et al. (2003)

Explaining the failure of the time predictable model with the pulverization model

- The time predictable model assumes that fault stress is brought close to fault strength by tectonic loading, a gradual, predictable process.
- In the pulverization model fault stress is ordinarily far below fault strength. A drop of fault strength due to pulverization from another event almost always occurs before stress can build to the original strength level.
- In effect we are arguing that all earthquakes are aftershocks… in fact ~70-90% are (*Sornette and Werner*, 2005). The rest probably occur in swarms – topic of another talk!

Explaining the failure of the time predictable model with the pulverization model



Before triggering, Fault 2 should rupture first

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

3. The San Andreas Heat Flow Paradox

Borehole measurements find the crust to be strong – hydrostatic pore pressure, frictional coefficient ~0.6—1.0. If this strength was maintained at the time of rupture nucleation, ~100MPa of shear stress would be required to start rupture.

But a heat flow anomaly is not seen around the San Andreas Fault

Observation: No variation of heat flow across the San Andreas

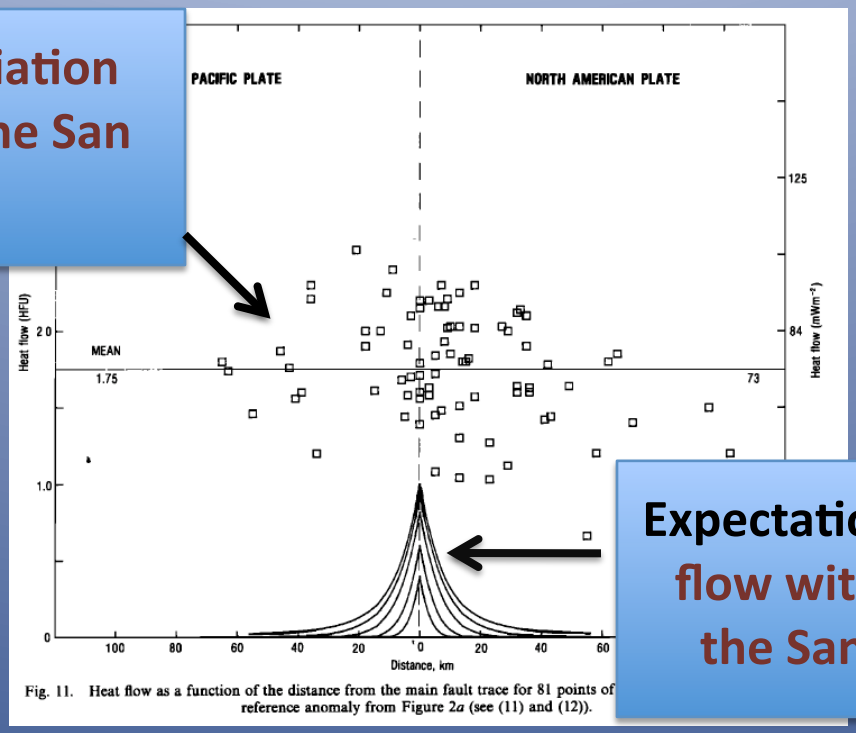


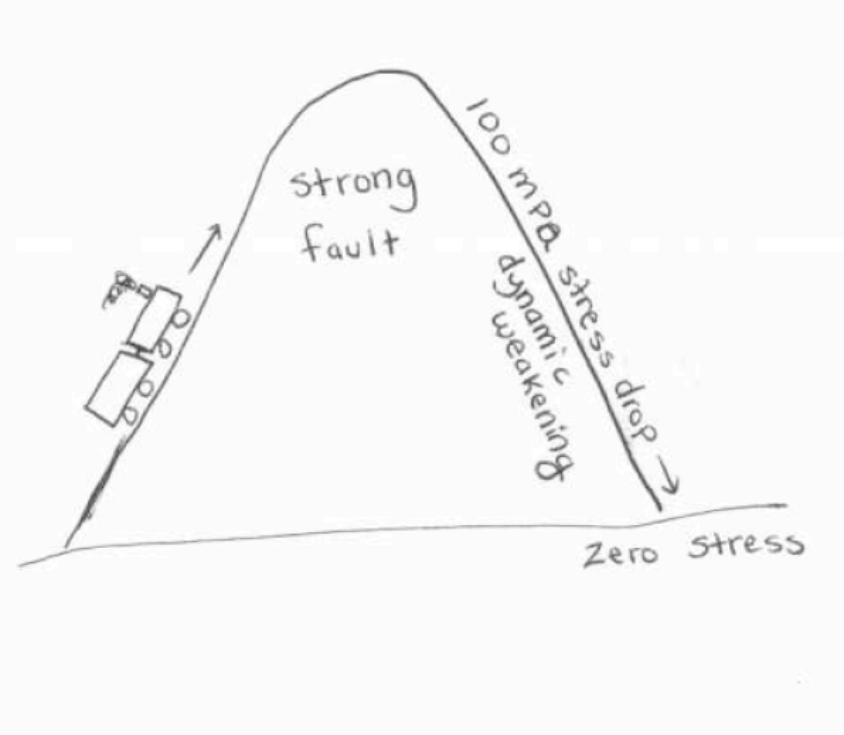
Fig. 11. Heat flow as a function of the distance from the main fault trace for 81 points of reference anomaly from Figure 2a (see (11) and (12)).

Expectation: Decay of heat flow with distance from the San Andreas fault

Lachenbruch and Sass (1980)

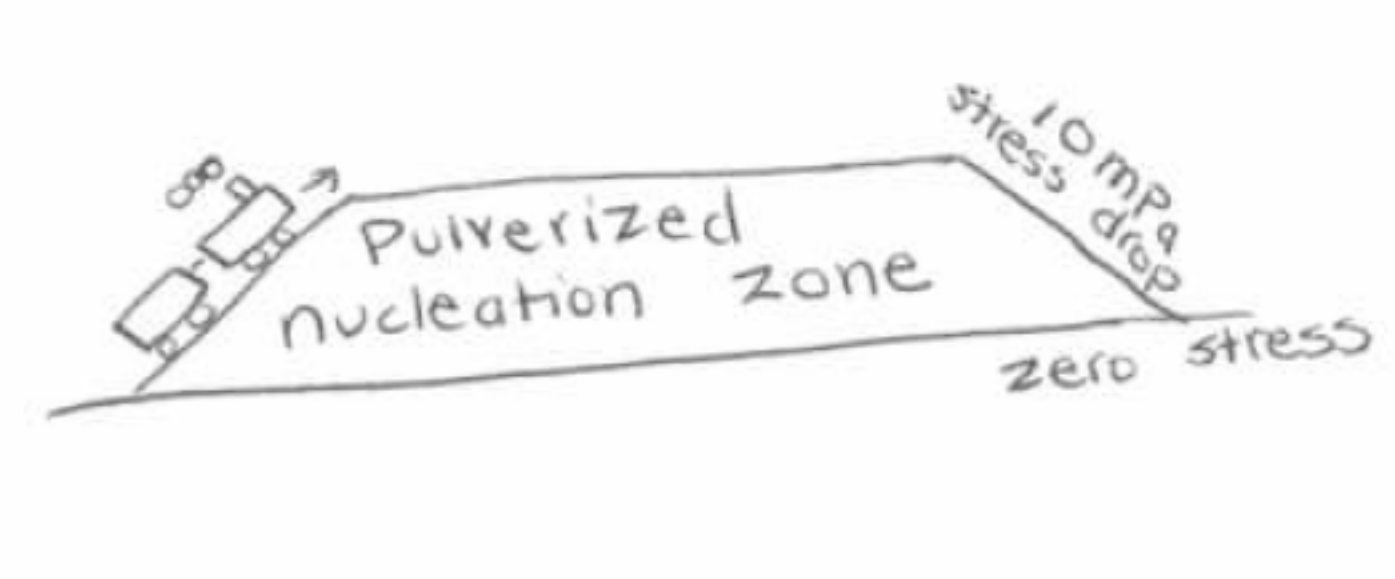
This indicates that shear stress at rupture is no more than 10 MPa. This agrees with stress drop observations for all earthquakes, and measurements across active faults.

Severe weakening probably occurs during seismic rupture



But weakening during rupture could explain the heat flow observations only if we had 100 MPa stress drops

All of the observations can be explained if there is pulverization-induced weakening of the normally strong fault immediately before seismic failure



Conclusions

- Most active faults have very low shear stress in comparison to their strength.
- Failure – either the initiation of an aftershock or the propagation of an ongoing earthquake – occurs when pulverization coupled with a small amount of aseismic afterslip cause dramatic fault weakening
- The model explains why aseismic slip/static stress change alone triggers few aftershocks, the failure of the time predictable model, and the heat flow paradox.

Outstanding Problems

- Laboratory experiments show that the pulverization weakening mechanism only drops fault strength by a factor of 2—3; we need a factor of 10. This may be due to the different conditions at seismogenic depths and the presence of pore fluids.
- We need to make, and test, predictions of how swarm earthquakes can fit into this model.

Thank you!

Structure weakened by high frequency acceleration