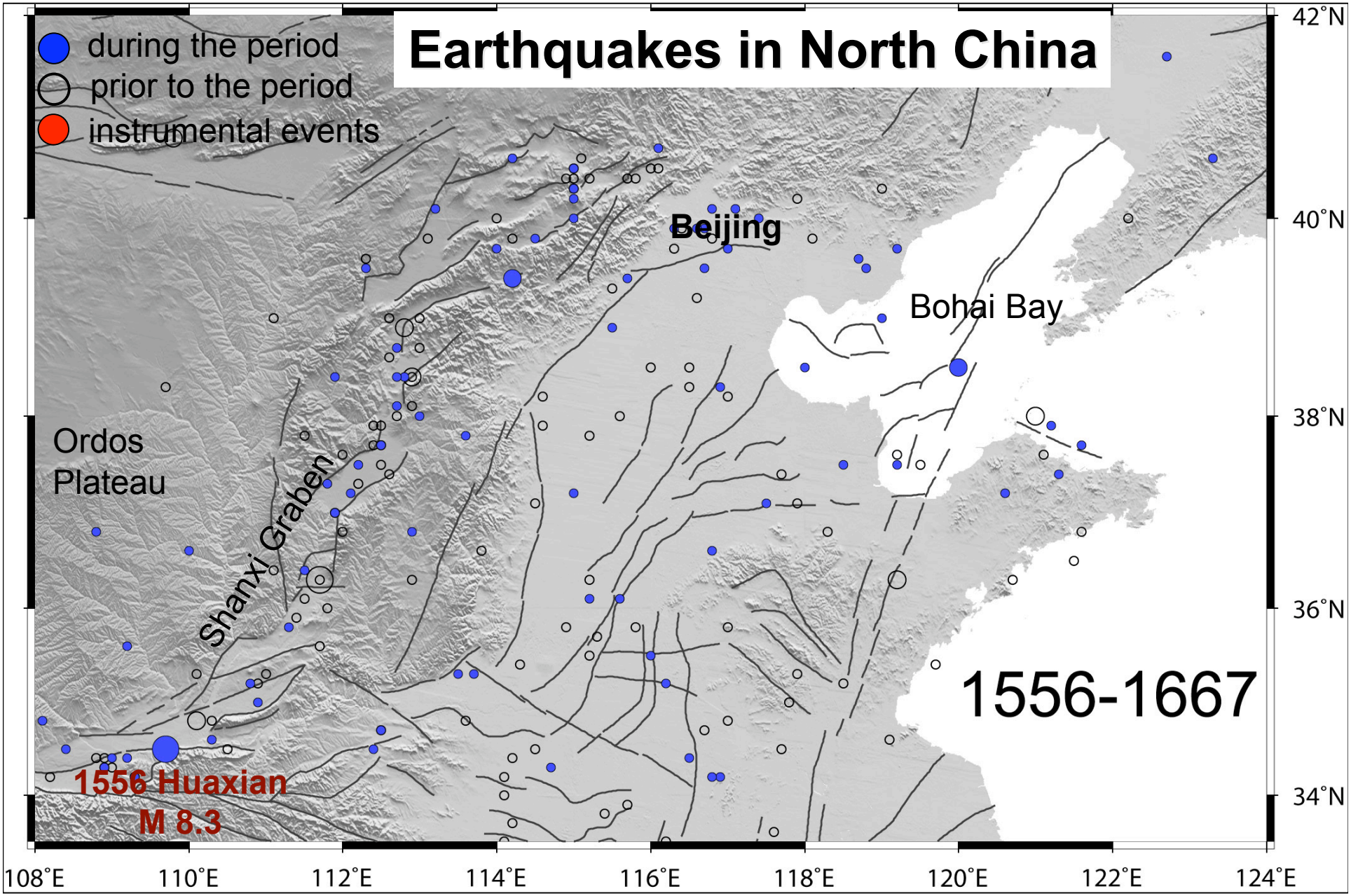
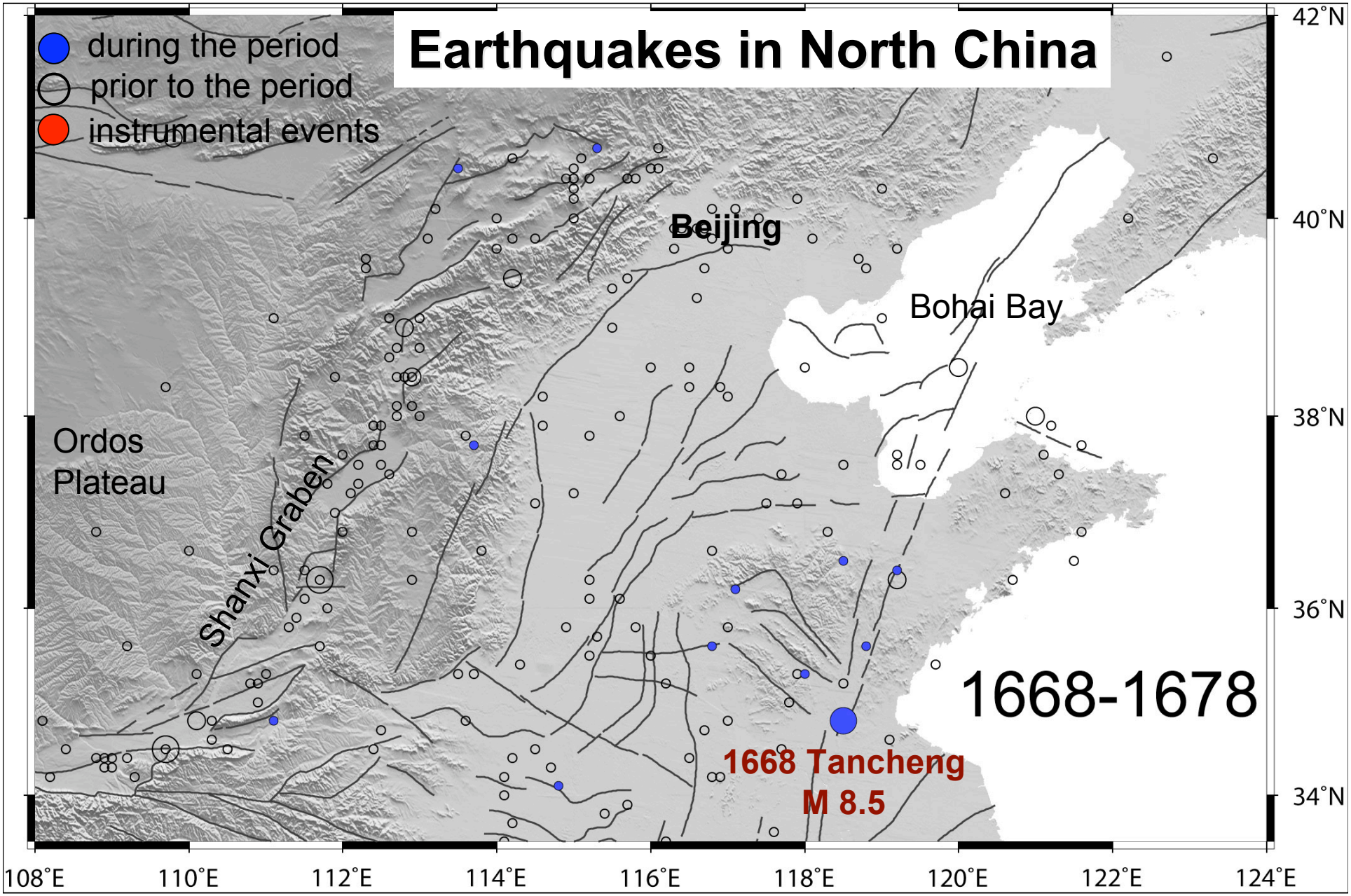
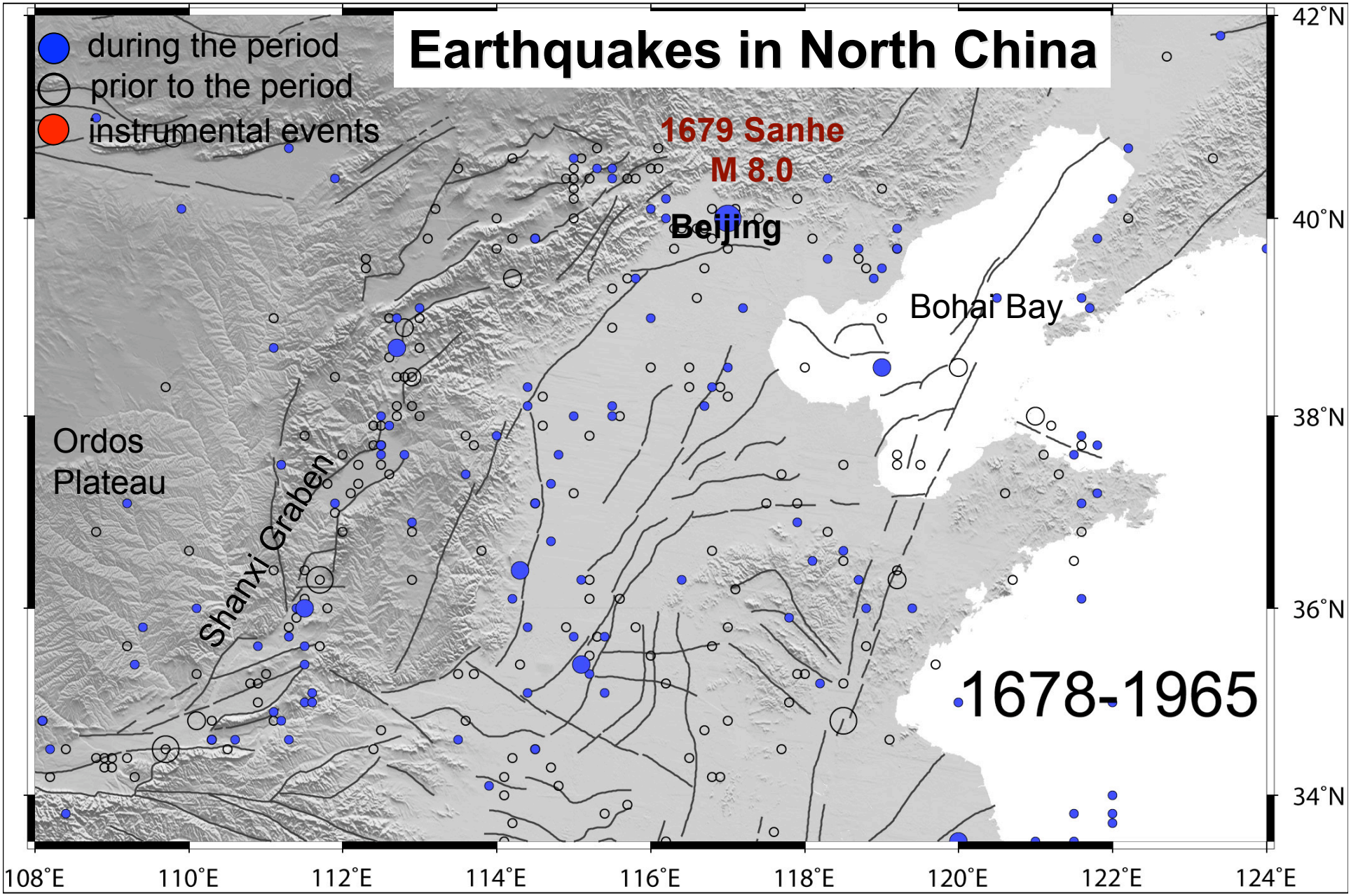


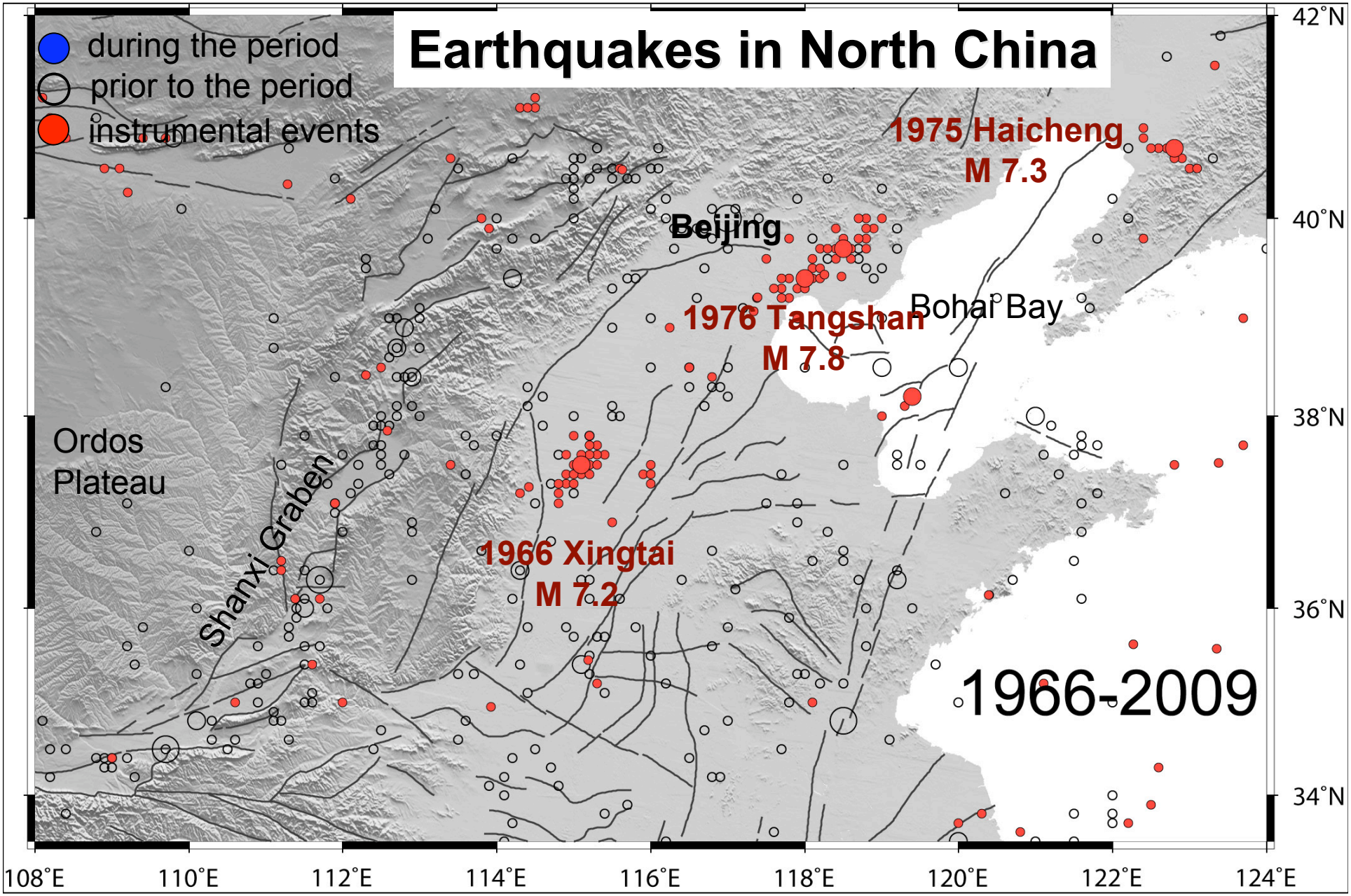

**Large events often pop up where there was little seismicity!**




**Large events often pop up where there was little seismicity!**

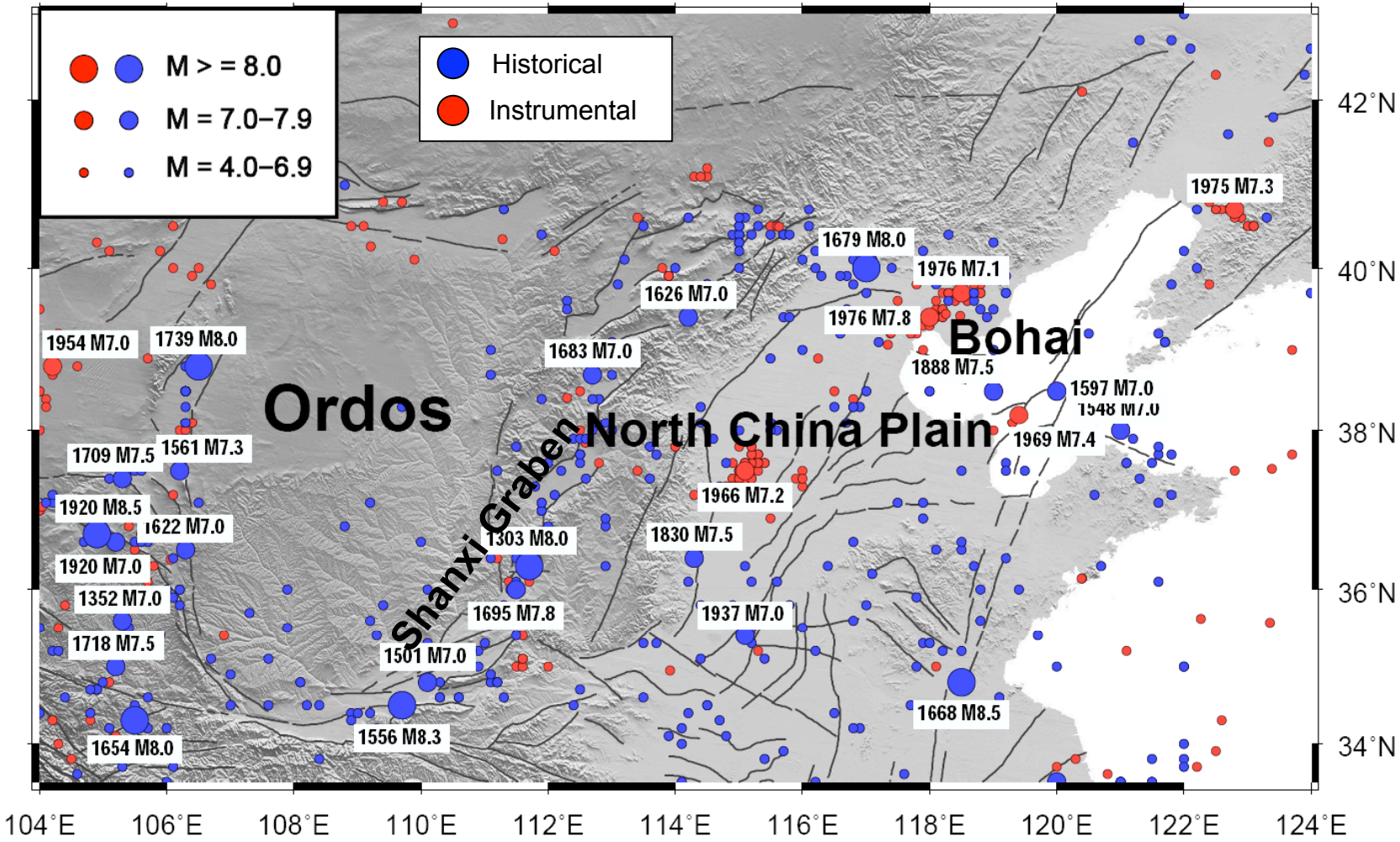



**Large events often pop up where there was little seismicity!**




**Large events often pop up where there was little seismicity!**

# No large (M>7.0) events ruptured the same fault segment twice in N. China since 1303

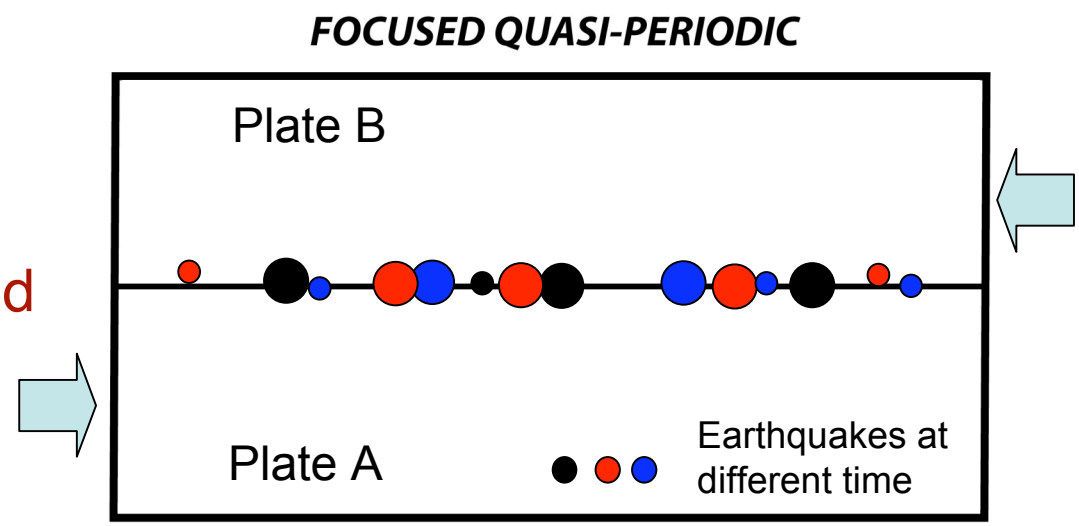



In past 200 years, quakes migrated from Shanxi Graben to N. China Plain

## Plate Boundary Earthquakes

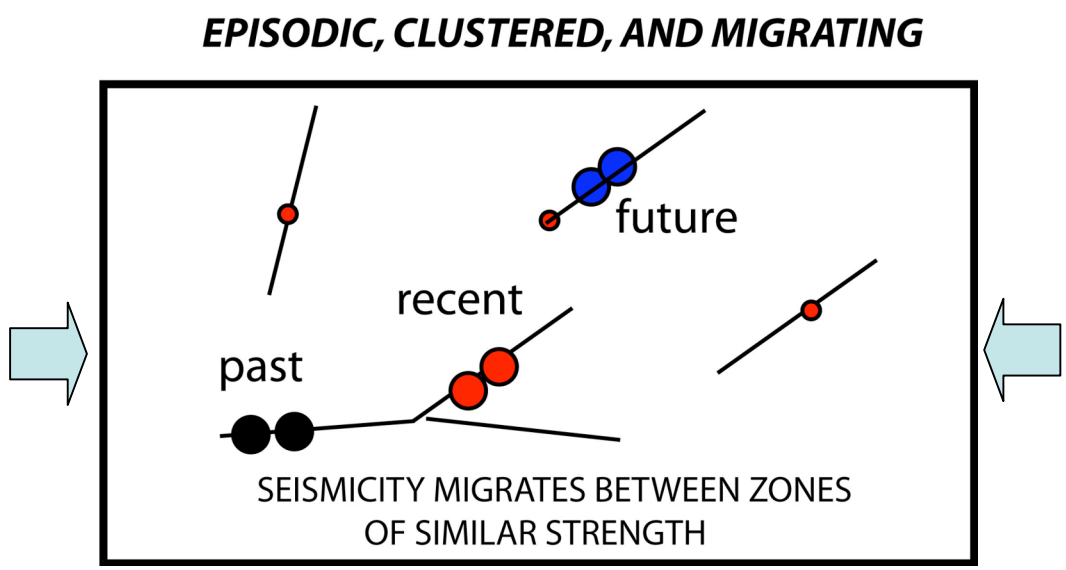
•Fault loaded rapidly at constant rate

•Earthquakes spatially focused & temporally quasi-periodic




## Intraplate Earthquakes

•Tectonic loading collectively accommodated by a complex system of interacting faults
•Loading rate on a given fault is slow & may not be constant
•Earthquakes can cluster on a fault for a while then shift
***Past can be poor predictor***



**Faults in a region form a complex system whose evolution cannot be understood by considering an individual fault.**

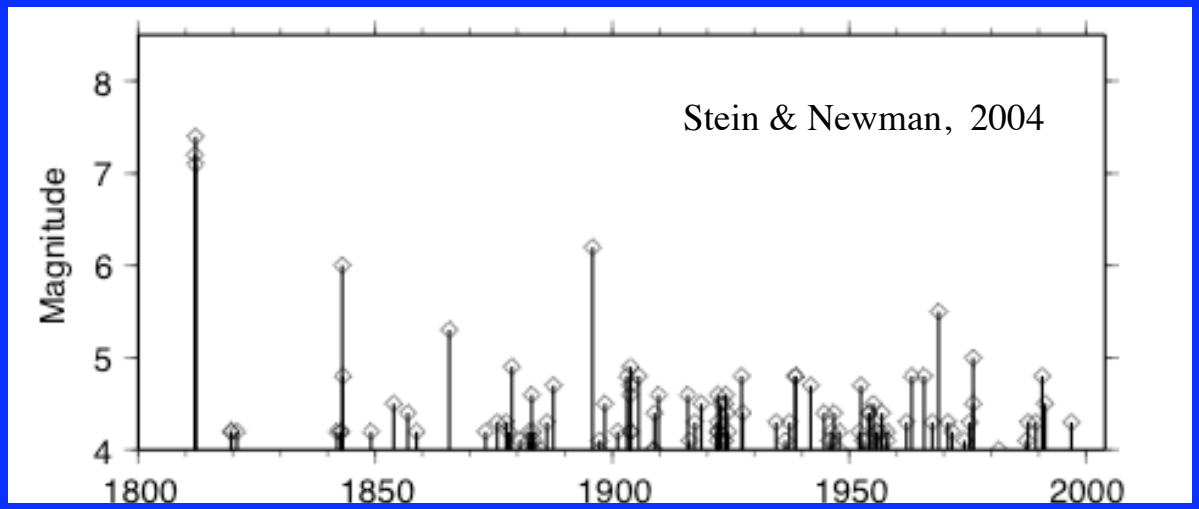
In complex systems, the whole behaves in ways more complicated than can be understood from analysis of its component parts.

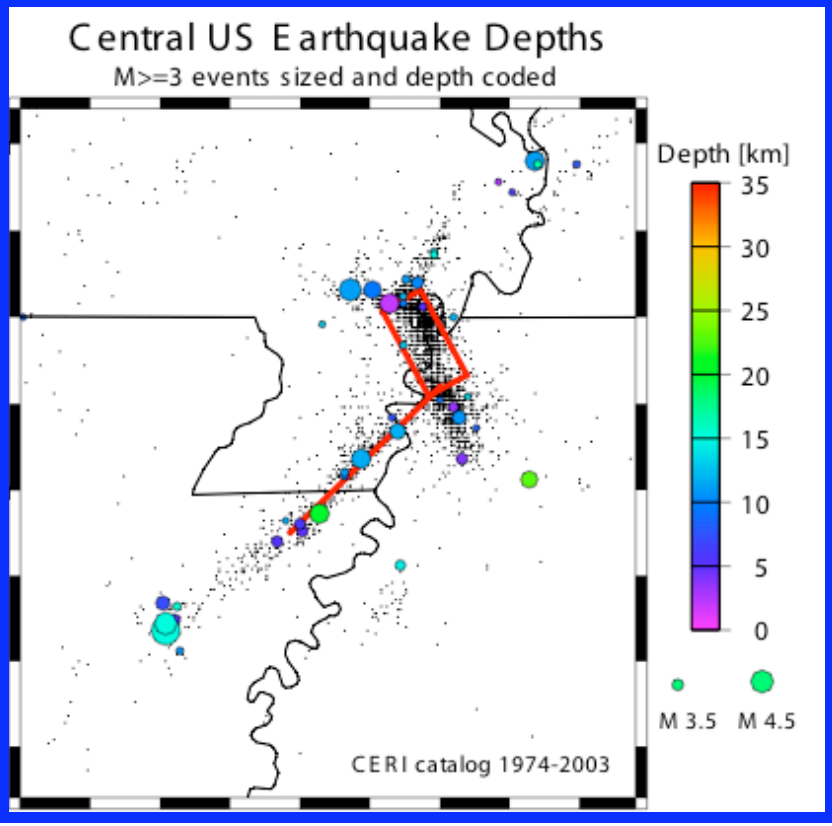
A human body is more complicated than we can understand by studying individual cells, the economy is more complicated than explained by individual business transactions, and studying one ant doesn't tell how a colony behaves.

Studying such systems requires moving beyond the traditional reductionist approach, which focuses on the system's simplest component, understands it in detail, and generalizes it for the entire system. The system is viewed as a totality, so local effects in space and time result from the system as a whole.

*These effects have been recognized at plate boundaries, but are crucial in continental plate interiors.*

# NEW MADRID SEISMICITY: 1811-12 AFTERSHOCKS?




Instead of indicating locus of future large earthquakes, ongoing seismicity looks like aftershocks of 1811-12

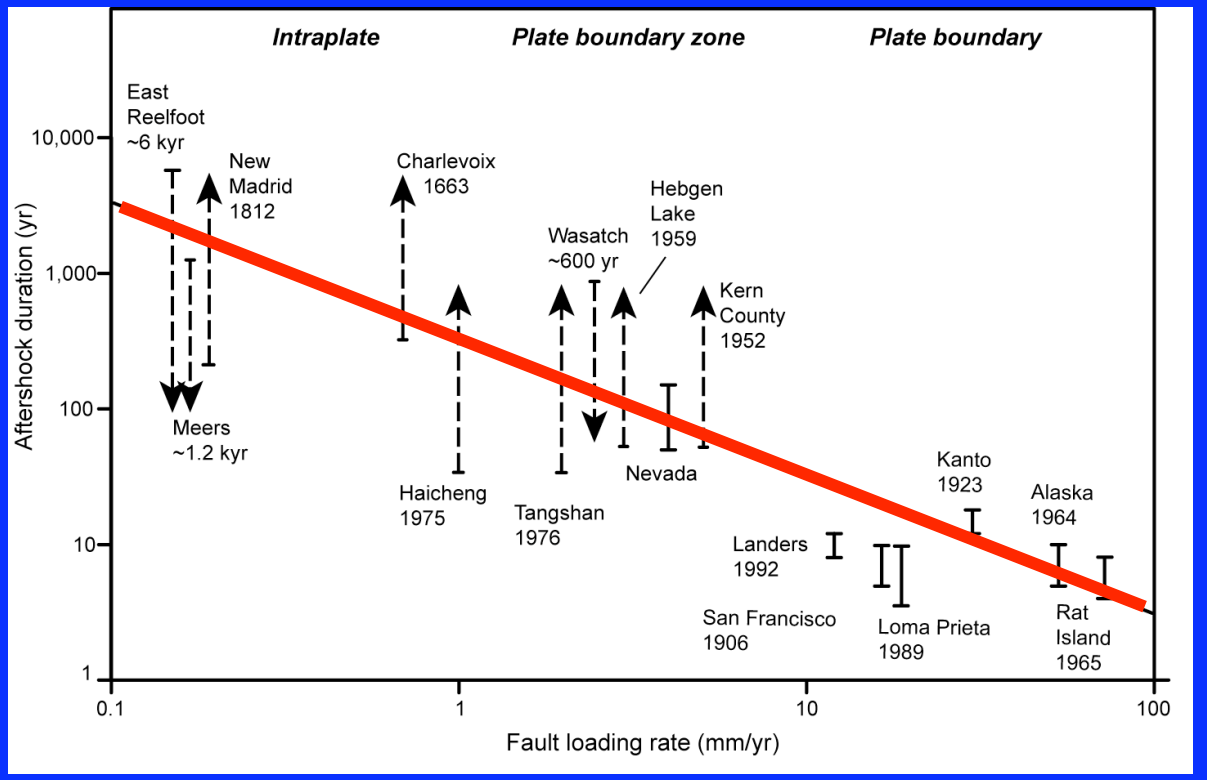
- used to delineate 1811-12 ruptures
- rate & size decreasing
- largest at the ends of presumed 1811-12 ruptures

# LONG AFTERSHOCK SEQUENCES IN SLOWLY DEFORMING CONTINENTAL INTERIORS

Faults at plate boundaries quickly reloaded by steady plate motion after large earthquake

Faults within continents reloaded much more slowly, so aftershocks continue much longer

Current seismicity likely to be largely aftershocks rather than implying location of future large events



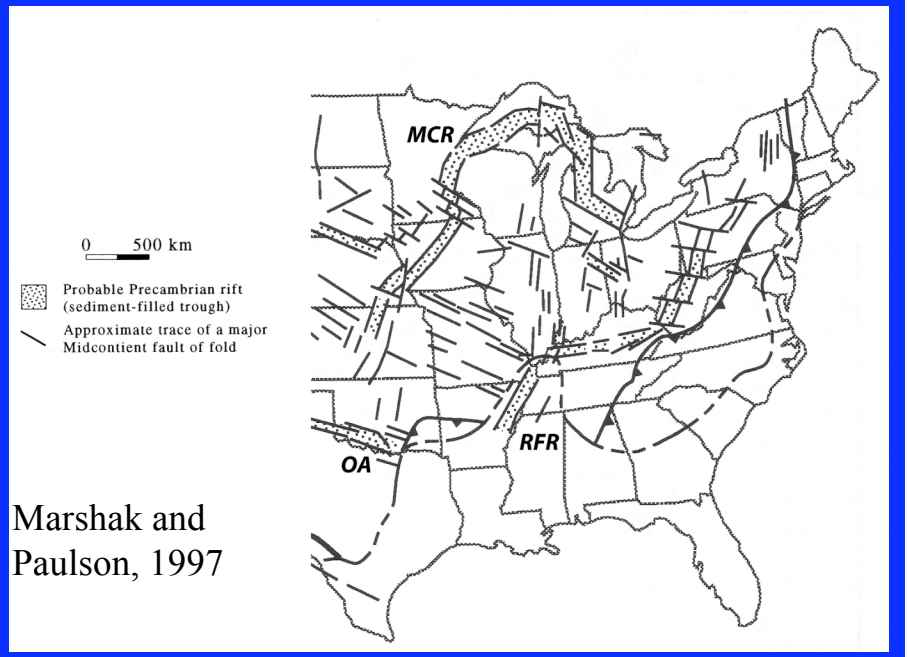

Stein & Liu, 2009

# CAUSES OF INTRAPLATE EARTHQUAKES

GPS shows at most slow platewide deformation

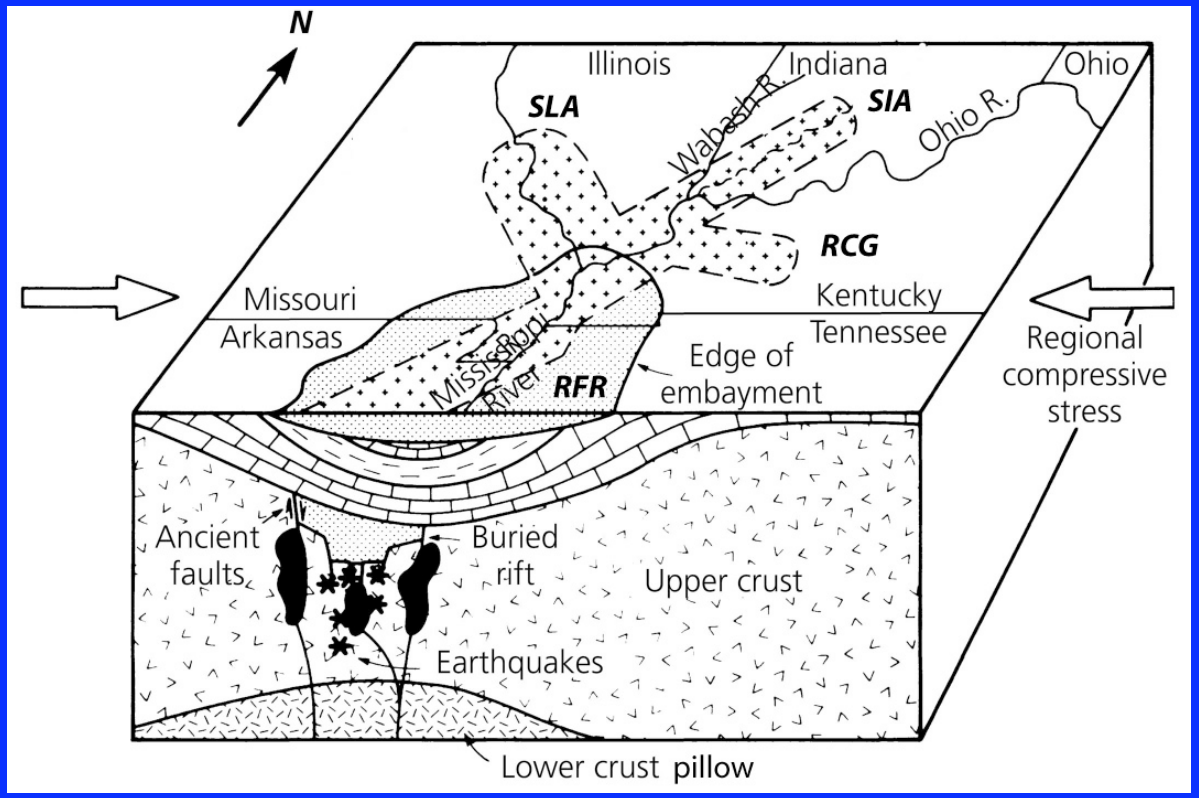
Plate interior contains many fossil faults developed at different times with different orientations but only a few appear active today

*Time- and space- variable deformation can't only reflect platewide tectonic stresses, which change slowly in space and over millions of years*




Marshak and Paulson, 1997

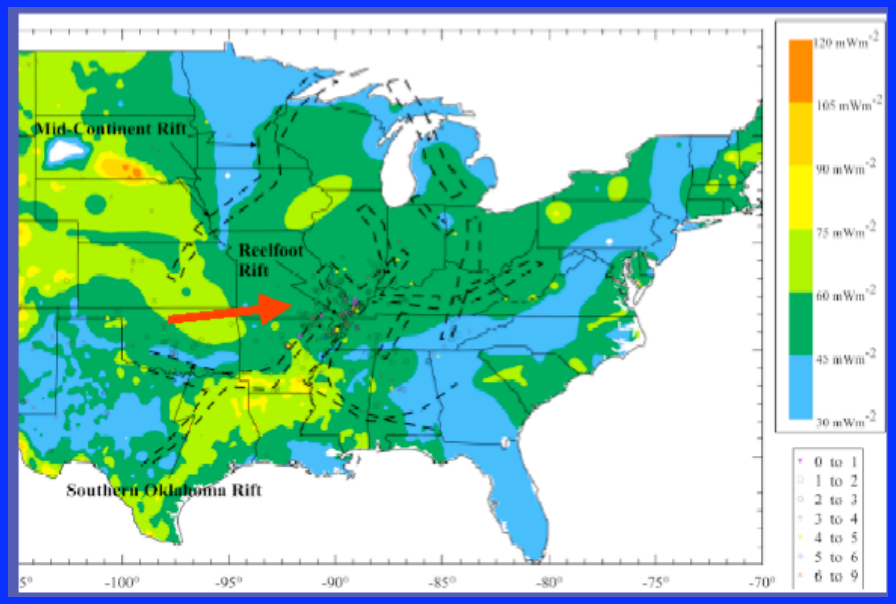
*Earthquakes reflect localized stress sources & fault interactions*

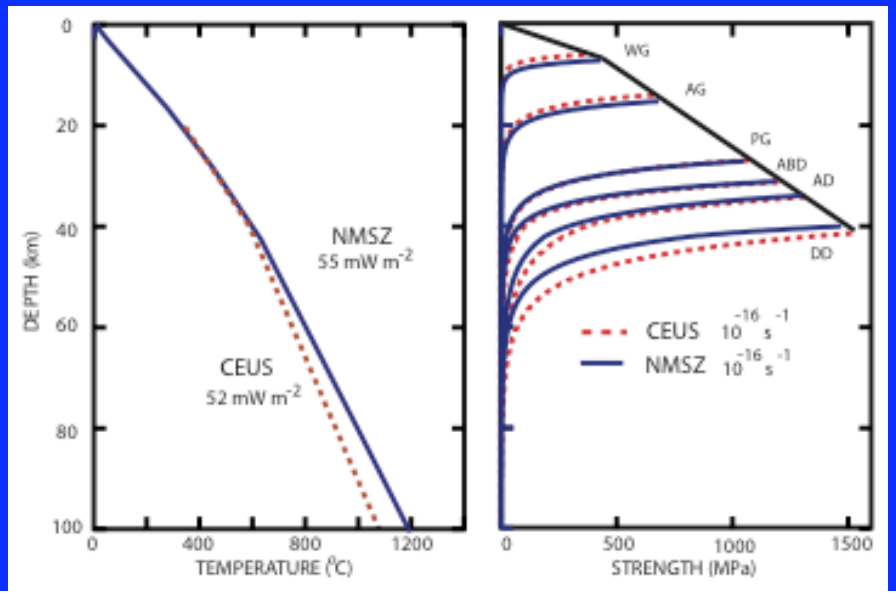



Braile et al., 1986

Although New Madrid earthquakes probably occur by reactivation of faults associated with Paleozoic rifting, stress *localized in space and time* must have recently triggerred these particular faults.

# NMSZ NOT HOT, WEAK, OR SPECIAL




Liu & Zoback (1997) argue for NMSZ heat flow ~15 mW/m$^2$ higher making area weaker than surroundings

Reanalysis finds anomaly zero or much smaller (3+/-23 mW/m$^2$), so the NMSZ and CEUS *have essentially the same temperature & thermally-controlled strength*

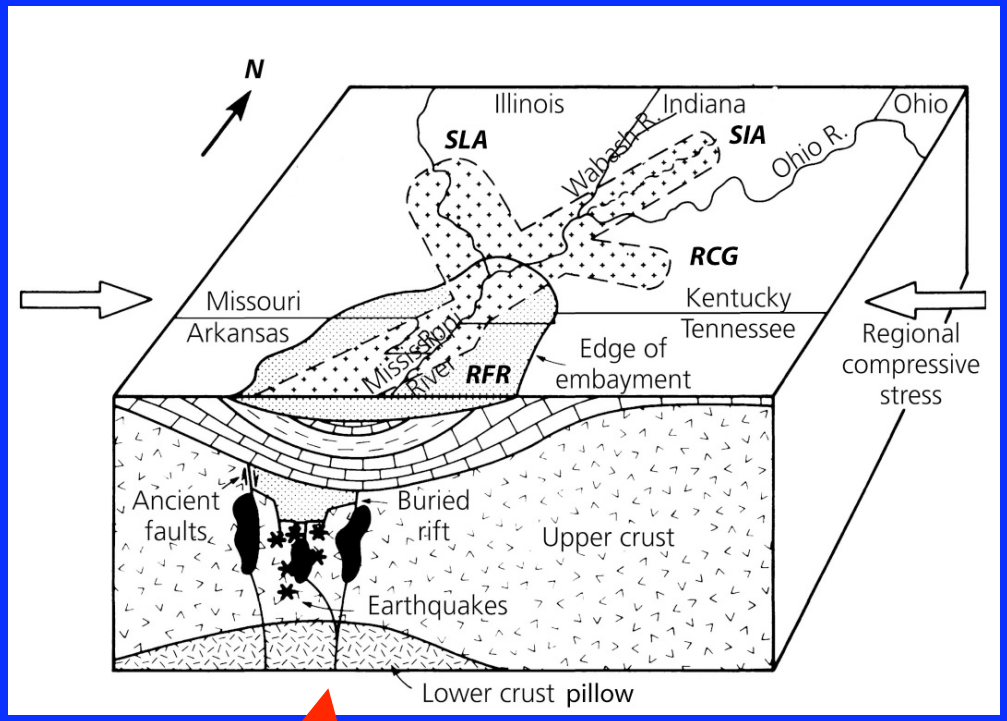
No strength reason for platewide stresses to concentrate in NMSZ rather than other faults

McKenna, Stein & Stein, 2007

# POSSIBLE LOCAL STRESS SOURCE FOR SEISMICITY: RIFT PILLOW SINKING

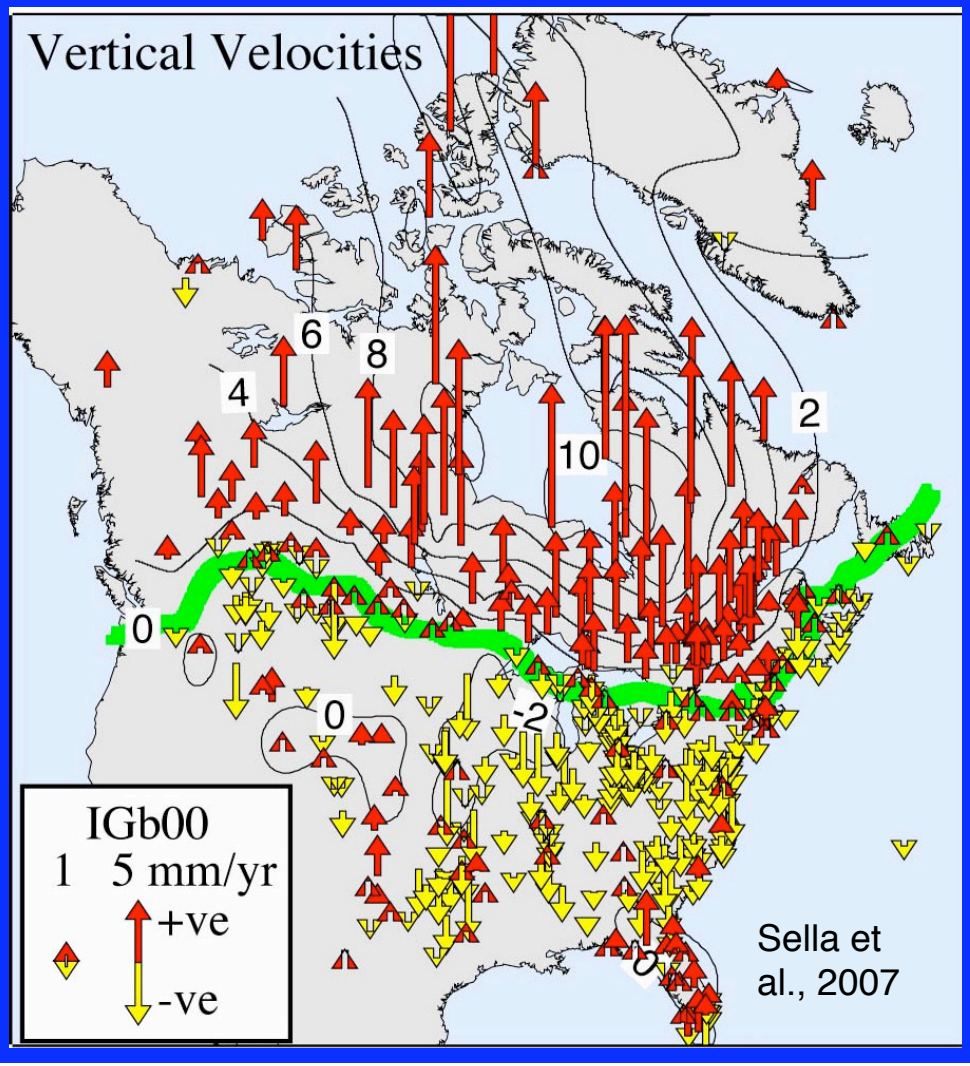
Ancient high density mafic body (Grana and Richardson, 1996; Stuart et al., 1997) sinks due to recent weakening of lower crust in past 9 kyr (Pollitz et al., 2001)

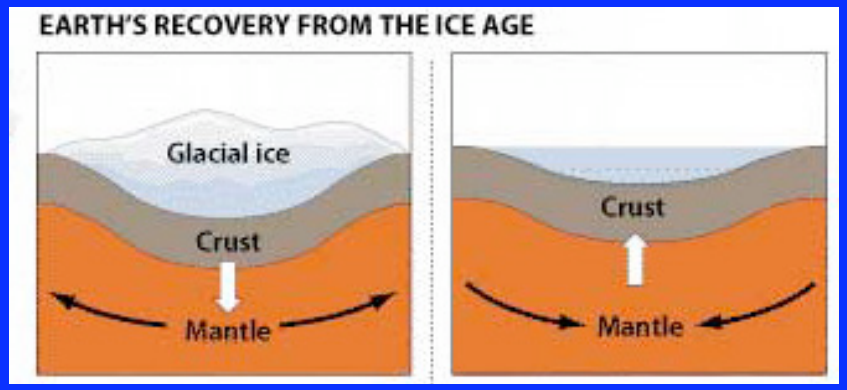
Problems: no evidence for a weak zone and no obvious reason for why weakening occurred in this place at this time




Braile et al., 1986

# POSSIBLE STRESS SOURCE FOR SEISMICITY: GIA - GLACIAL ISOSTATIC ADJUSTMENT




May explain seismicity along old ice sheet margin in Eastern Canada & elsewhere (Stein et al., 1979; 1989; Mazzotti et al., 2005)

Stresses decay rapidly away from ice margin, so can't explain NMSZ (Wu and Johnson, 2000) unless upper mantle and lower crust there two orders of magnitude weaker than surroundings (Grollimund and Zoback, 2001)

No evidence for such weakening

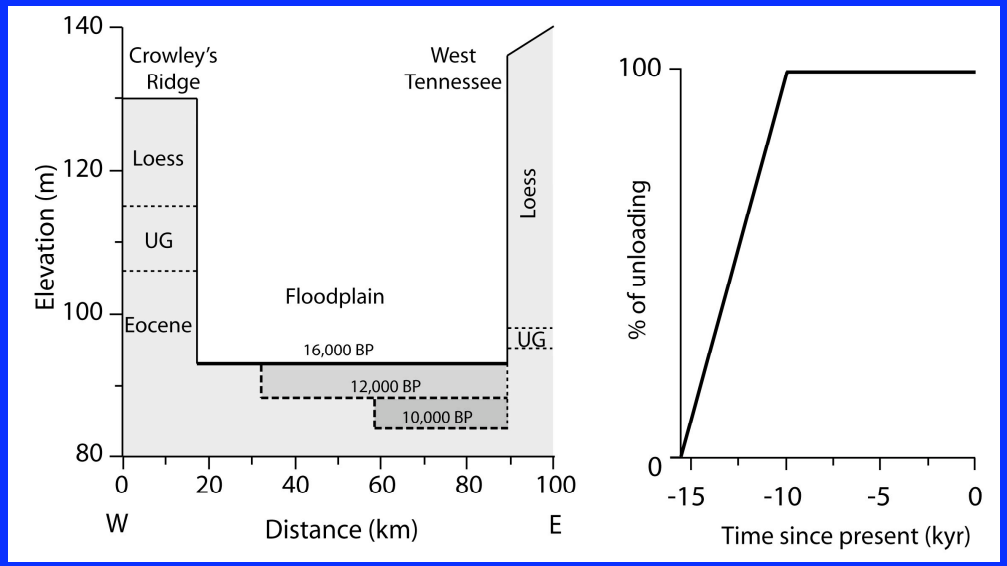
# POSSIBLE LOCAL STRESS SOURCE FOR SEISMICITY: POSTGLACIAL EROSION IN MISSISSIPPI EMBAYMENT

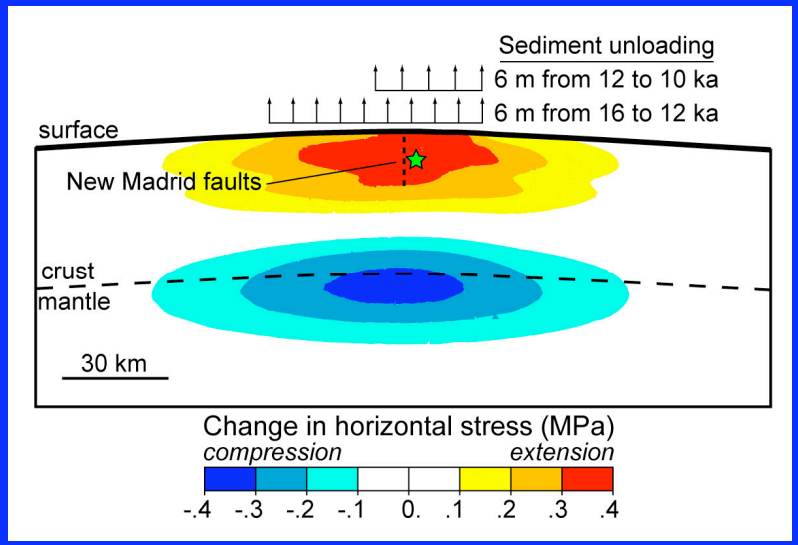
Flexure caused by unloading from river incision 16 - 10 ka reduces normal stresses sufficiently to unclamp pre-existing faults

Fits timing of recent seismicity

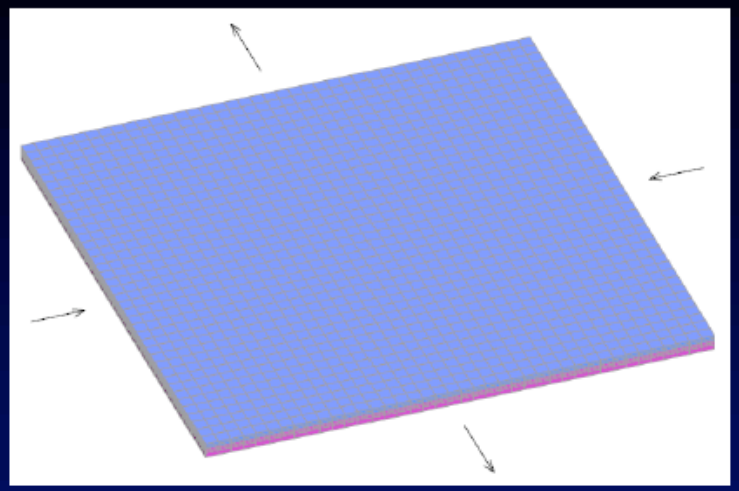
Doesn't require weak zone

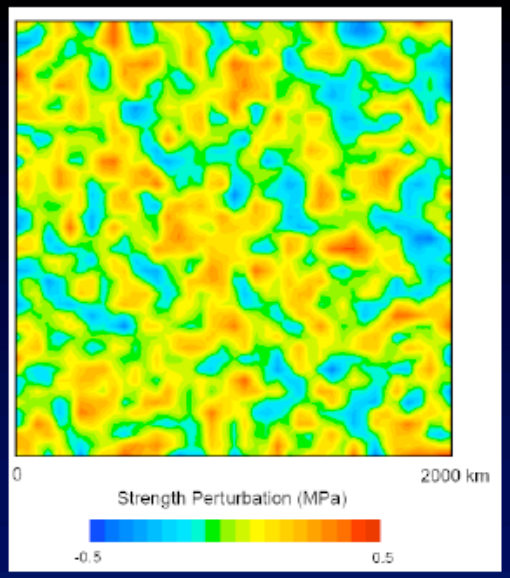
Fault segments that ruptured unlikely to fail again




Calais, Freed, Van Arsdale & Stein, 2010



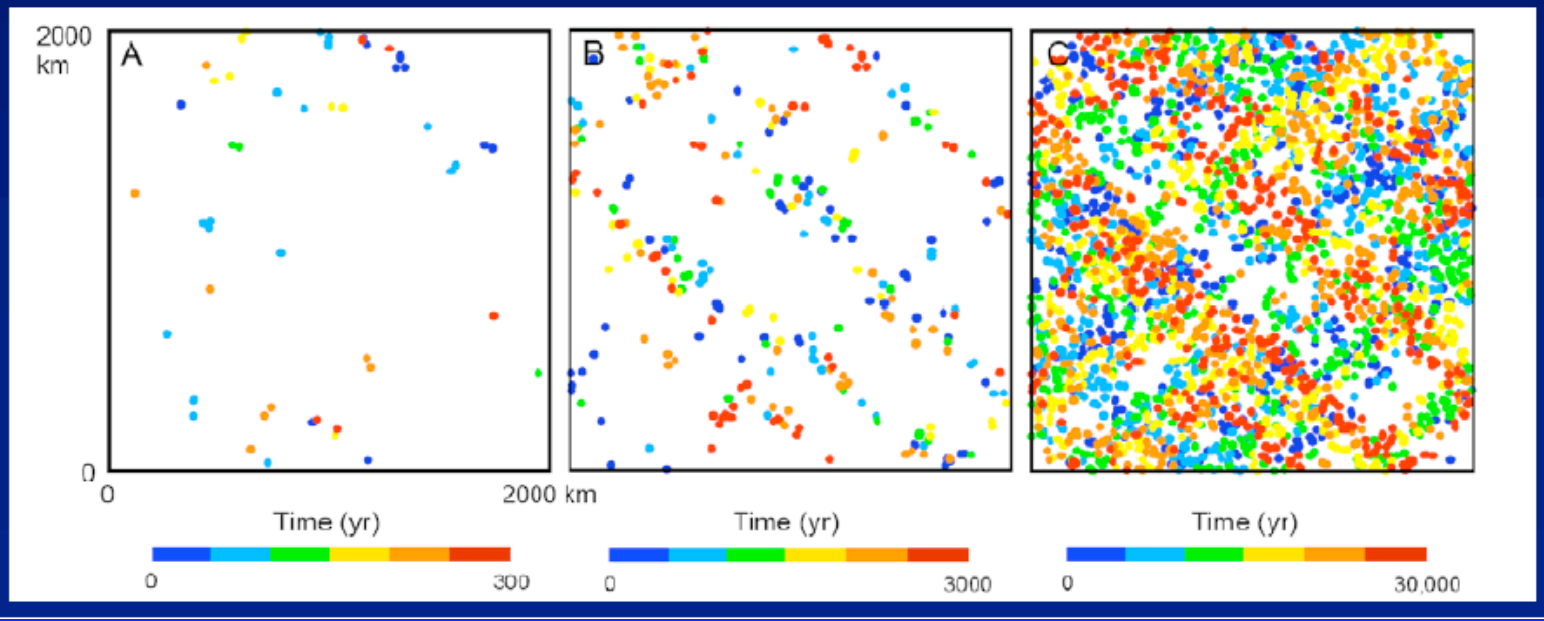



# NUMERICAL MODEL

# FOR INTRAPLATE EARTHQUAKES

Li, Liu & Stein, 2008

In a few hundred years, earthquakes appear to be clusters scattered in the region. In few thousand years, clusters connect and form belts. In tens of thousands of years, earthquakes are scattered in the whole region.



# EFFECTIVE SEISMIC HAZARD ESTIMATION IN CONTINENTS REQUIRES RECOGNIZING SPACE-TIME VARIABILITY

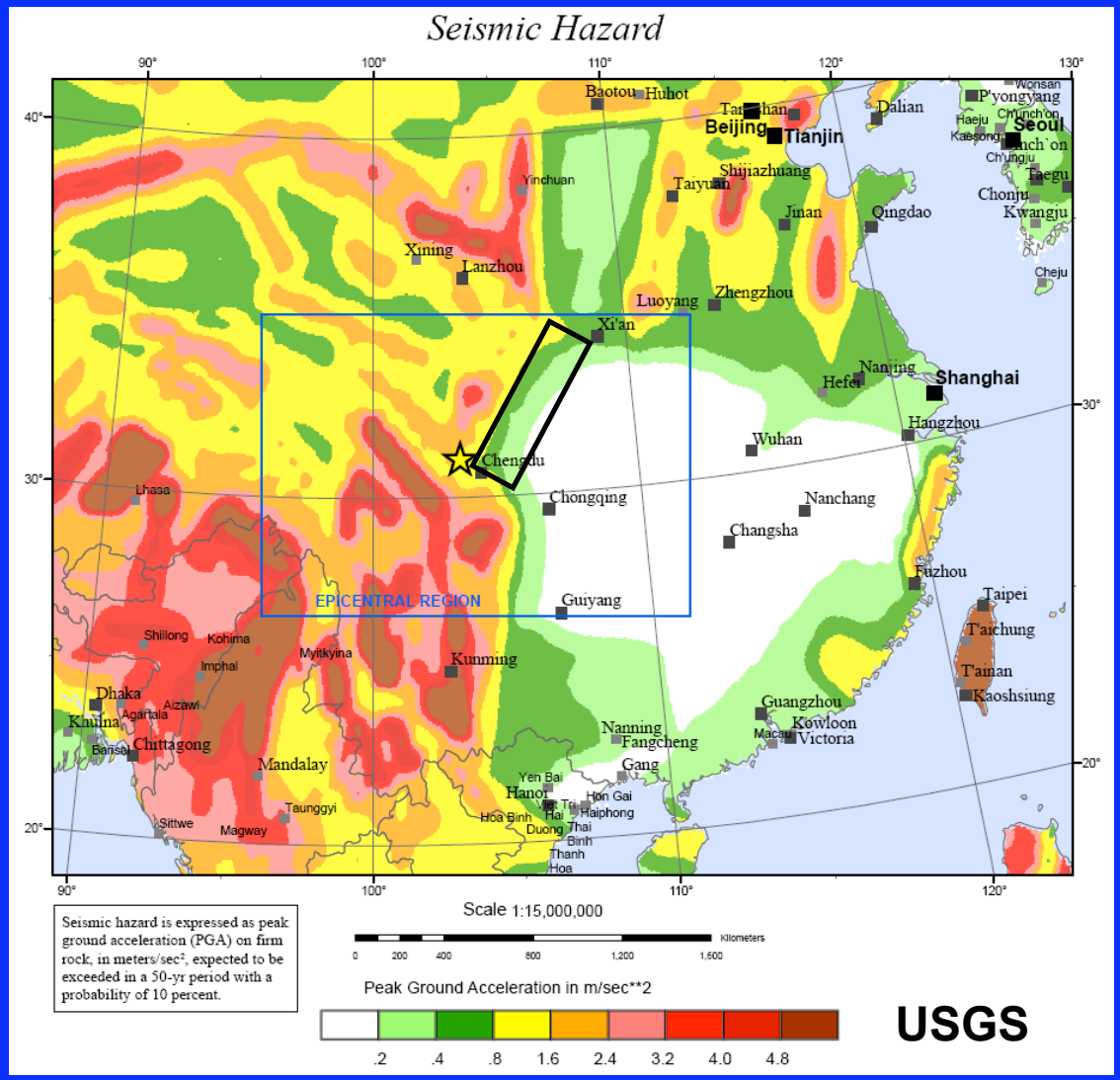
Complex spatiotemporal patterns of large earthquakes & long durations of their aftershocks make assessing hazards difficult

Locations of small earthquakes in short historical record often don't reflect continuing deformation that will cause future large earthquakes

Need geodetic & seismological data to identify where strain accumulates, geologic data to define history, & models of the migration process to understand what observations mean

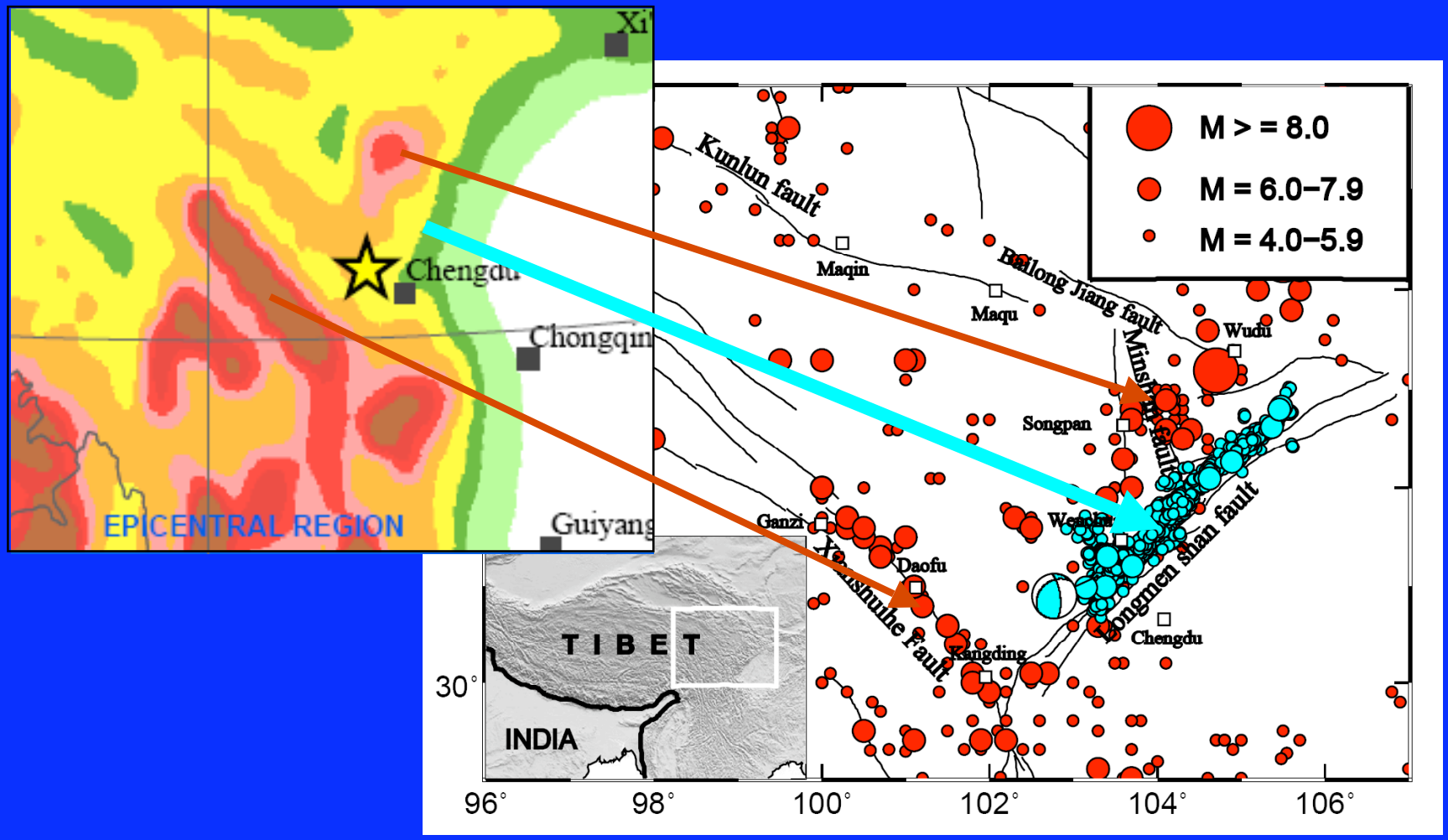
Relying unduly on recent seismicity to predict locations of future large earthquakes *overestimates hazard in some places and leads to surprises elsewhere*

# 2008 Wenchuan earthquake (Mw 7.9) was not expected: map showed low hazard



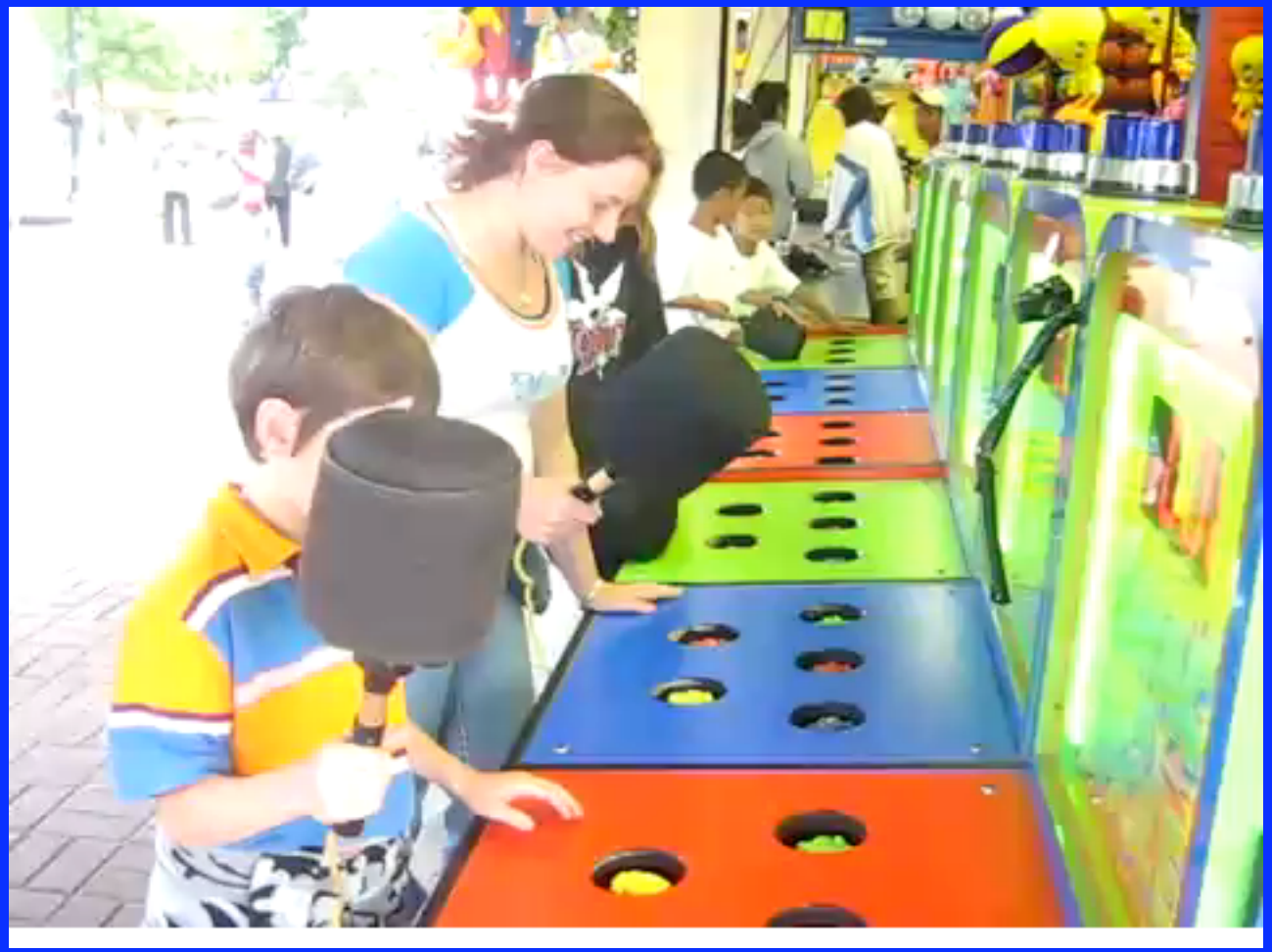
# Hazard map ignored variability - assumed steady state - relied on lack of recent seismicity

## Didn't use GPS data




- Earthquakes prior to the 2008 Wenchuan event
- Aftershocks of the Wenchuan event delineating the rupture zone

Neglecting variability is like ‘Whack-a-mole’ - you wait for the mole to come up where it went down,  but it’s likely to pop up somewhere else.



# NMSZ MORE DANGEROUS THAN CALIFORNIA?

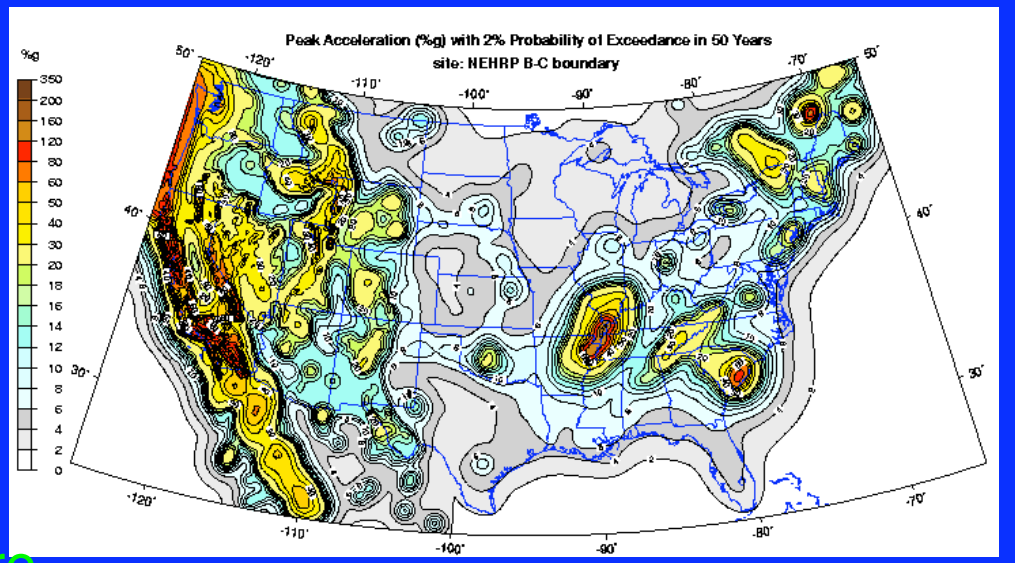
## Hazard defined as maximum acceleration predicted in some time period

*Need to assume:*

Where and when earthquakes will occur

How large they will be

Ground motion they will produce




These aren't well understood, especially in intraplate regions where large earthquakes are rare, so hazard estimates have considerable uncertainties and it will be a long time before we know how good they were

"A game of chance against nature of which we still don't know all the rules"
(Lomnitz, 1989)

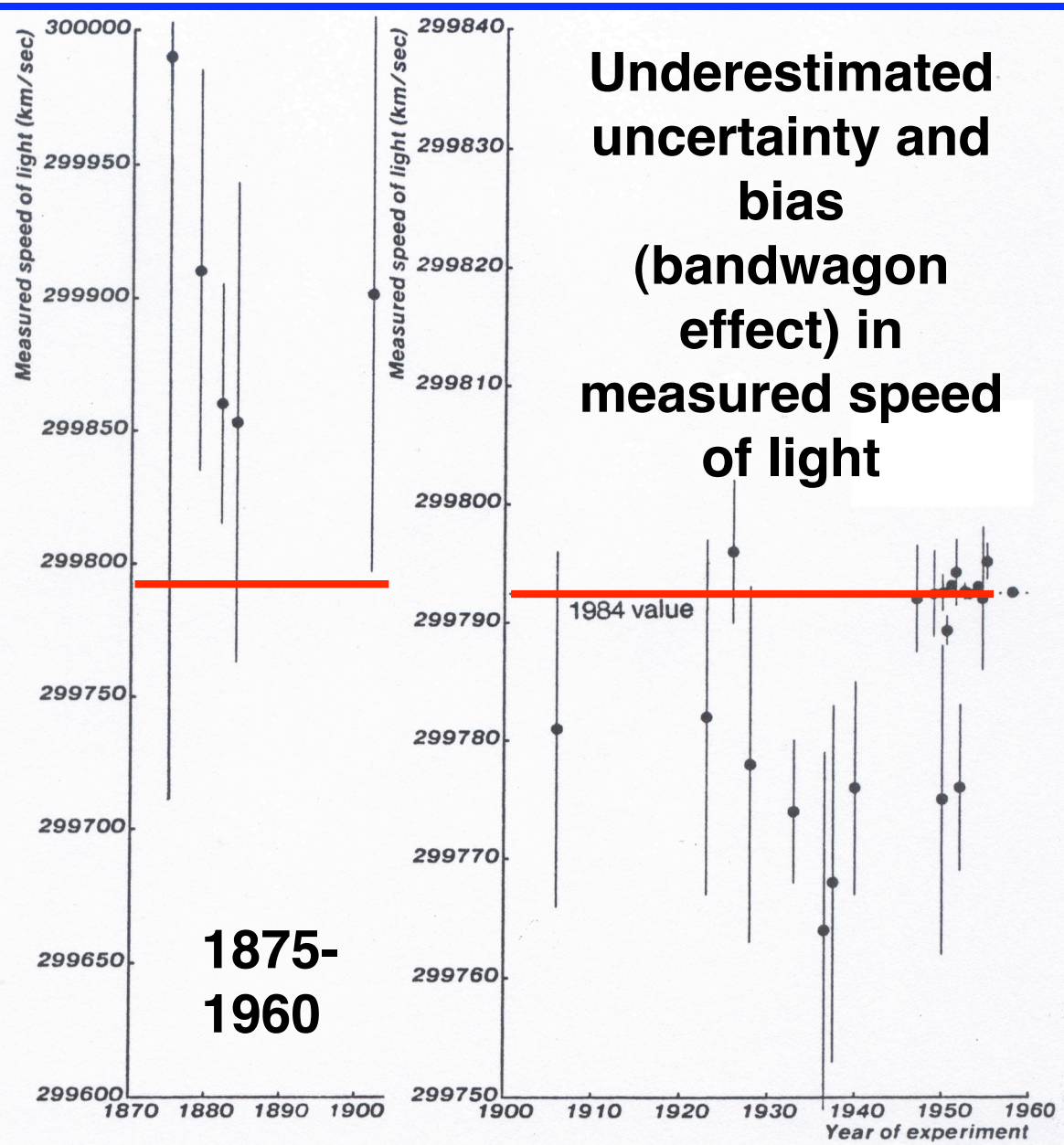
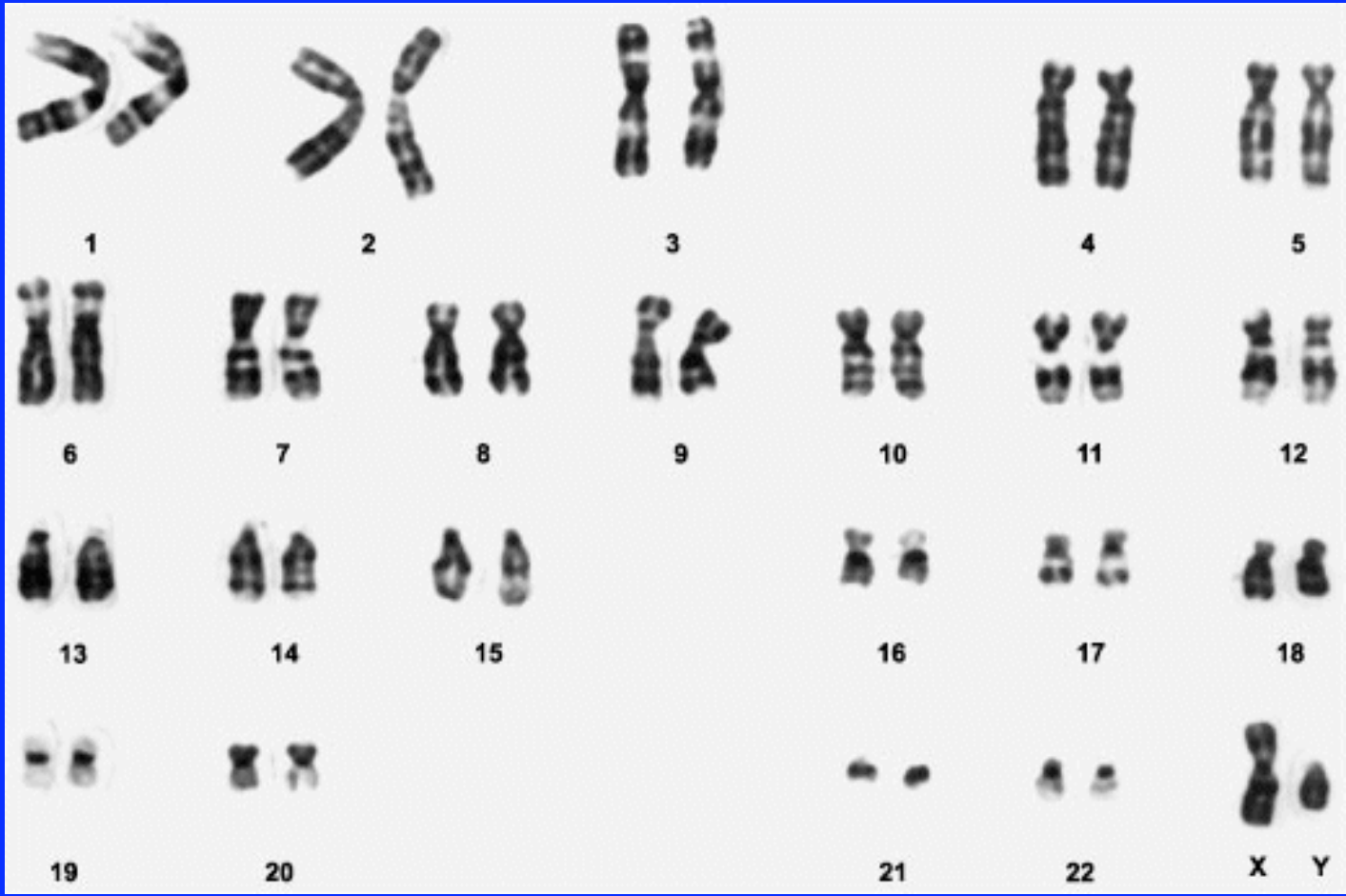



Figure 4.1. Experimental measurements of the speed of light between 1875 and 1960. Vertical bars show reported uncertainty as standard error. Horizontal dashed line represents currently accepted value. Less than 50% of the error bars enclose the accepted value, instead of the expected 70%. From Henrion and Fischoff, 1986.

**Uncertainties are hard to assess and generally underestimated**

**Systematic errors often exceed measurement errors**

# Number of human chromosome pairs




1921-1955: 24 Now: 23

# HIGH MODELED NMSZ HAZARD RESULTS FROM HIGH-END ASSUMPTIONS

*Systematic*

- Future earthquakes will be like past ones in location & timing

Doesn't consider space-time variability

- Redefined from maximum acceleration predicted at 10% probability in 50 yr to 2% in 50 yr (1/ 500 yr to 1/2500 yr)

Arbitrary choice on policy grounds; no benefit/cost analysis

*Measurement*

- Large magnitude of 1811-12 and thus future large earthquakes

Uncertainty in interpreting intensity data

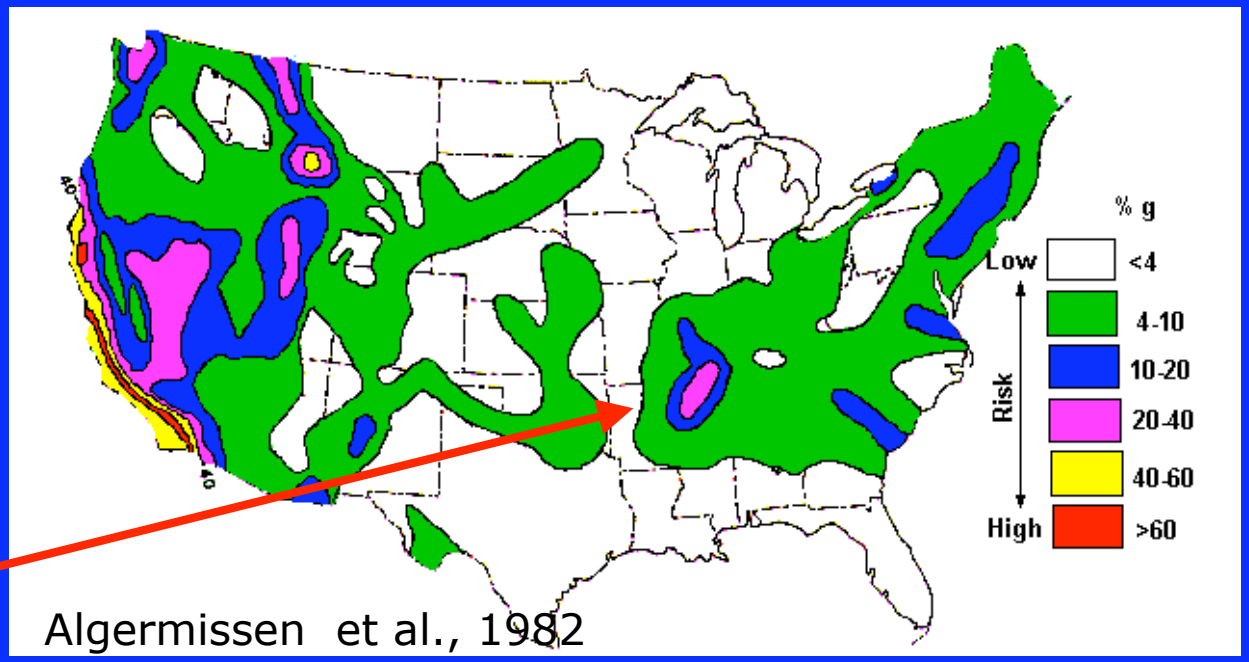
- High ground motion in large events

Lack of data, chose high model

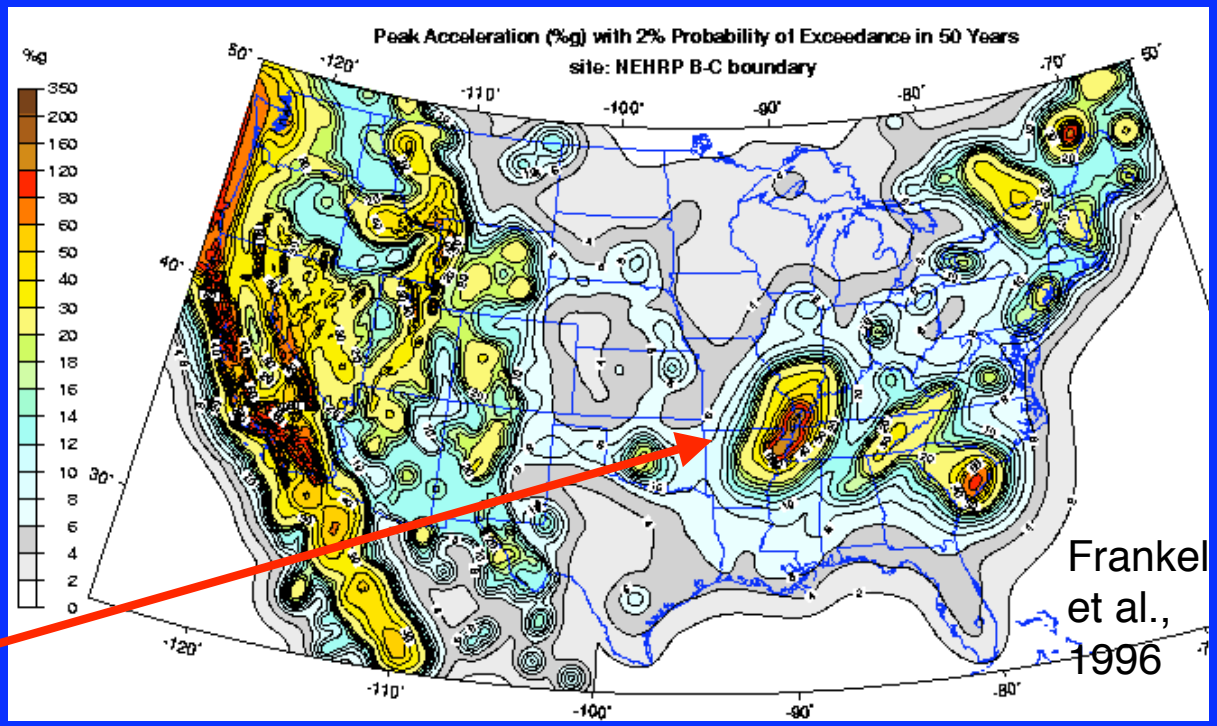
# Hazard redefined with longer window

from maximum acceleration predicted at 10% probability in 50 yr (1/ 500 yr )

to much higher 2% in 50 yr (1/2500 yr)




Algermissen et al., 1982




Frankel et al., 1996

# Expect New Madrid hazard much less than California

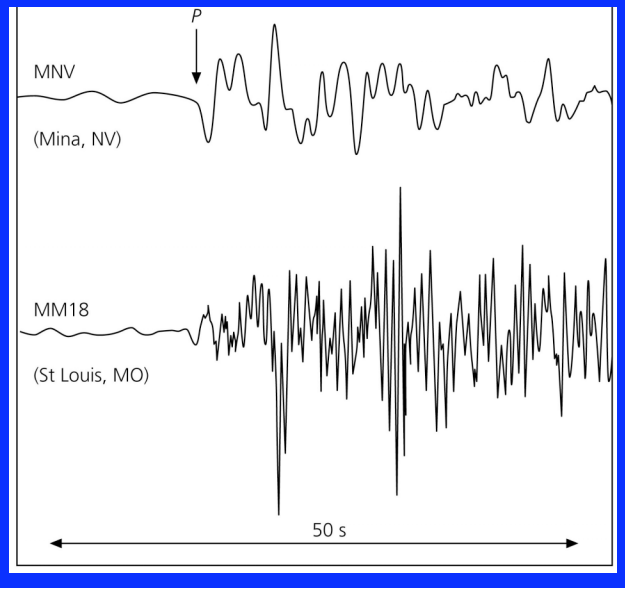
## Seismicity 1/30-1/100 California rate, due to different motion rates

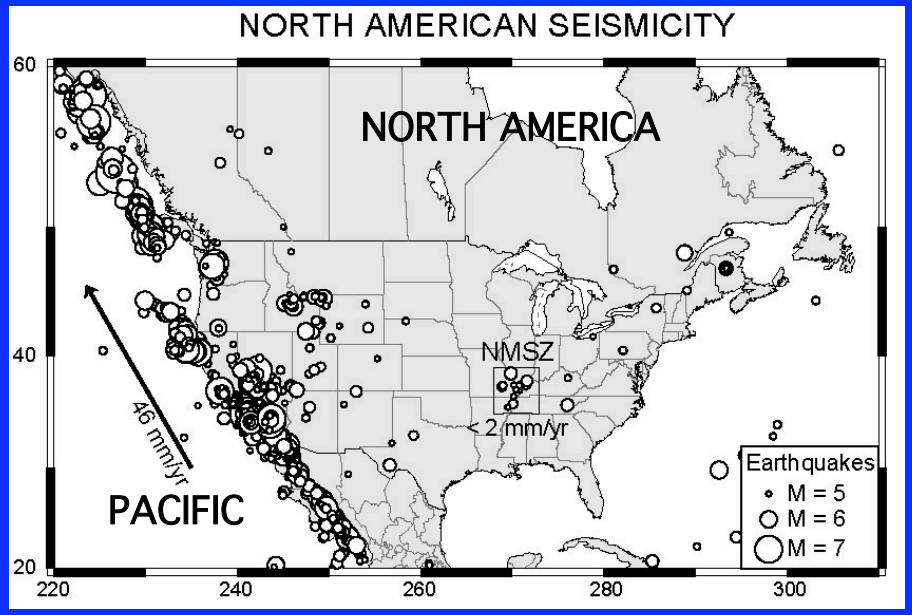
M>5 ~ every 15 yr

M>6 ~ every 150 yr

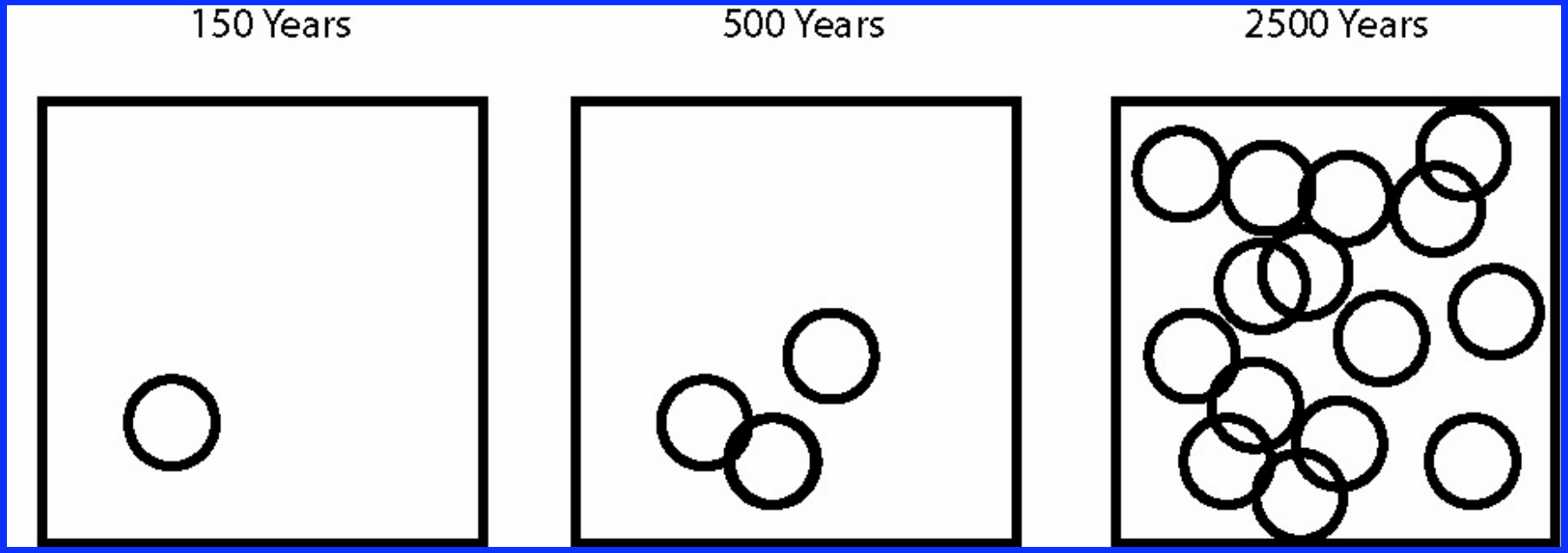
M>7 in 1811-12

Seismic energy propagates better than in California



# NEGLECTING VARIABILITY, ASSUMED HAZARD GROWS WITH TIME WINDOW




Strongly shaken areas MMI > VII for M 6

Over time, more earthquakes hit and larger portion of area shaken at least once. Some places shaken a few times.

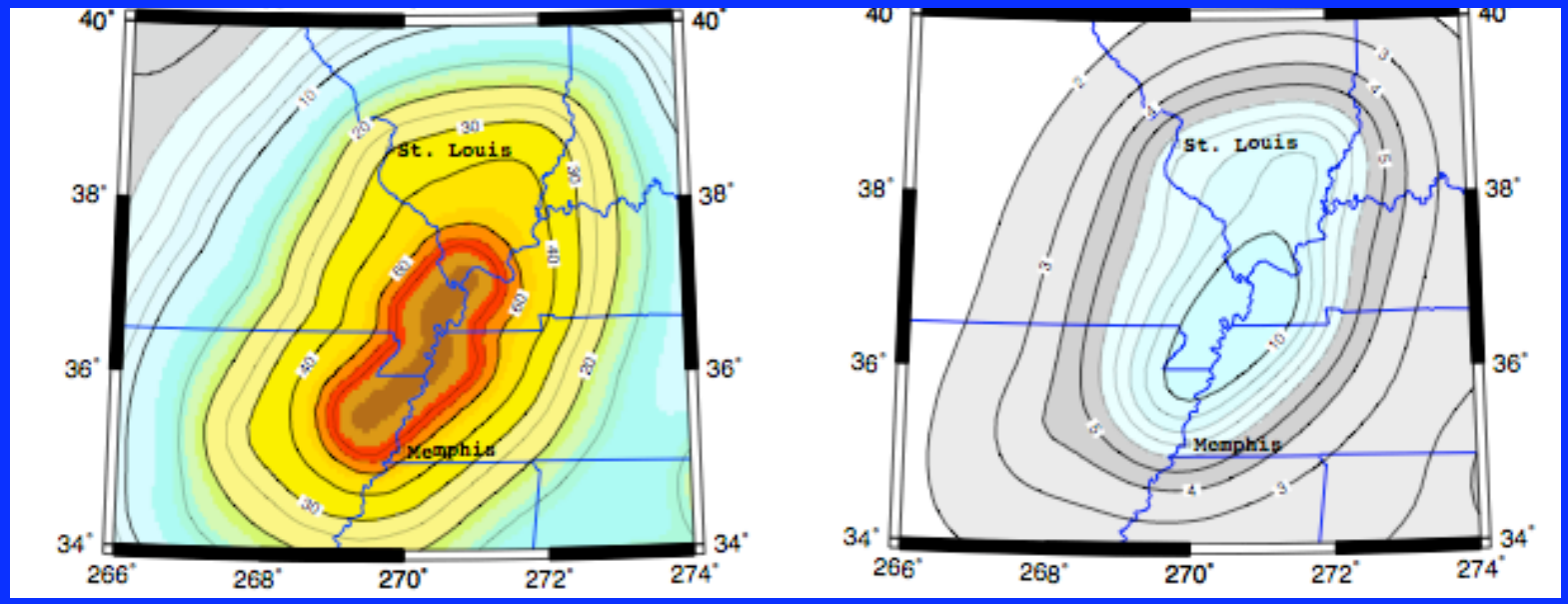
*Maps covering longer times look scarier.*

Typical building life 50-100 years, so almost all in NMSZ will be replaced before they're strongly shaken, much less damaged

**Assume from GPS no M7 on the way**

**Hazard from quakes up to M ~ 6.7**

***~ 1/10 that of USGS prediction***




*USGS, 2500 yr, assumes M 7 coming*

*GPS, 500 yr, assumes no M 7 coming*

*Need continuing GPS to assess possible hazard of M7 here & on other faults*

*No evidence, but can't exclude until we understand mechanics*

## *Current status*

GPS data show no strain accumulation in NMSZ

Recent cluster of large events doesn't reflect long-term fault behavior and seems to be ending

Continental intraplate earthquakes often episodic, clustered & migrating

How and why this occurs needs study

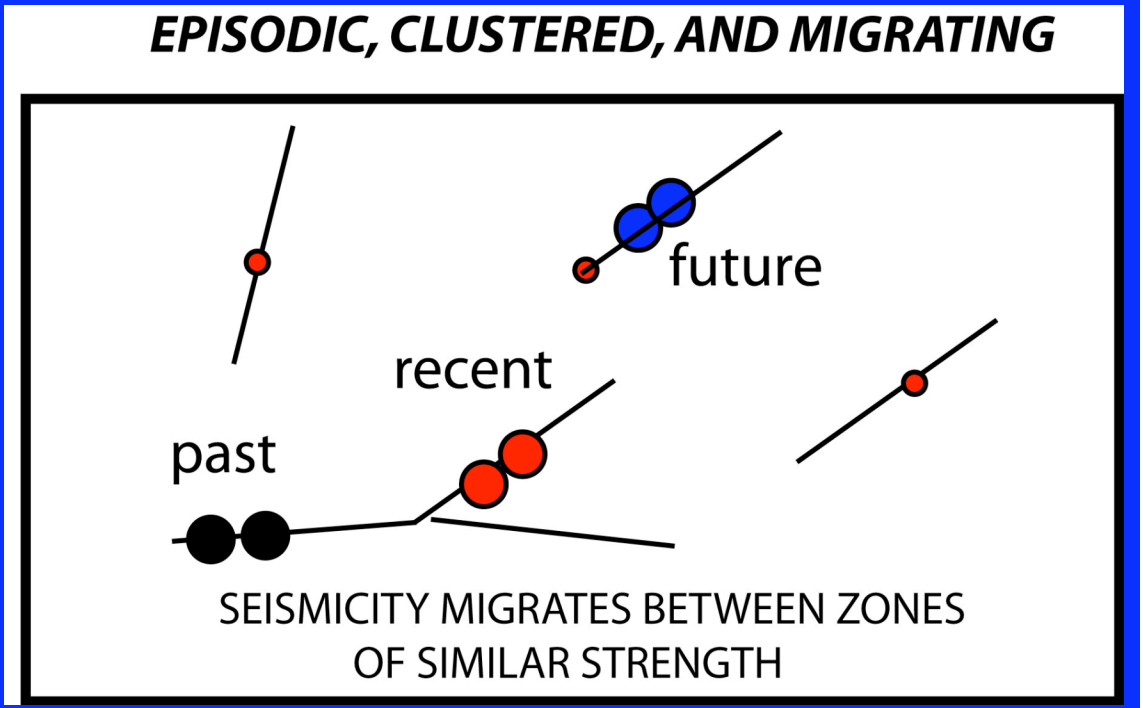
New Madrid earthquake hazard overestimated

Need careful analysis for cost-effective mitigation policy

Science issues remaining unresolved needed to improve hazard estimate

*More scientific than hazard issue*

# COMPLEXITY CALLS FOR HUMILITY




"Complexity demands attitudes quite different from those heretofore common in physics. Up till now, physicists looked for fundamental laws true for all times and all places. But each complex system is different; apparently there are no general laws for complexity. Instead one must reach for 'lessons' that might, with insight and understanding, be learned in one system and applied to another. Maybe physics studies will become more like human experience."

Goldenfeld & Kadanoff, 1999