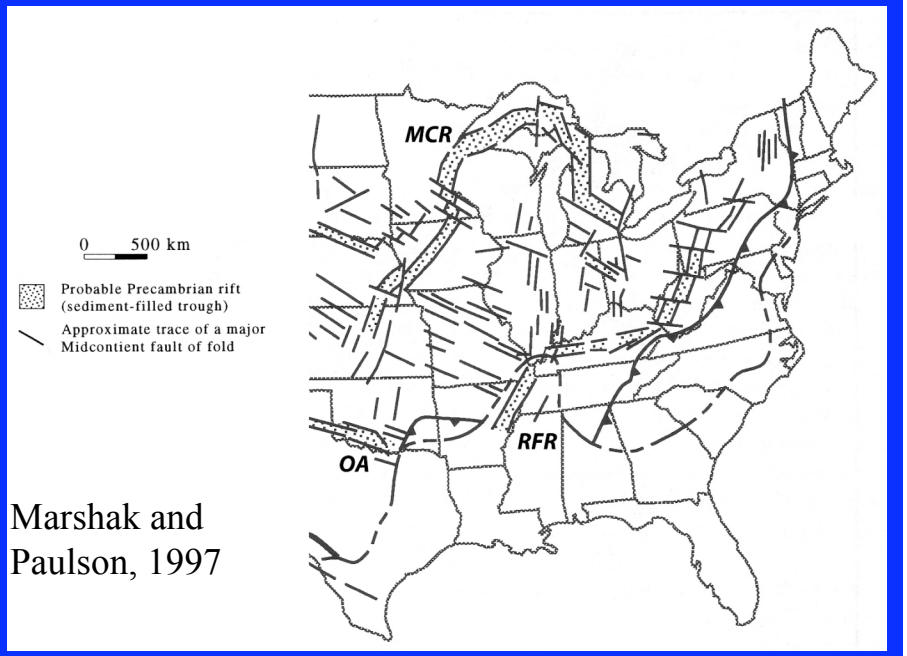
CAUSES OF INTRAPLATE EARTHQUAKES

GPS shows at most slow platewide deformation

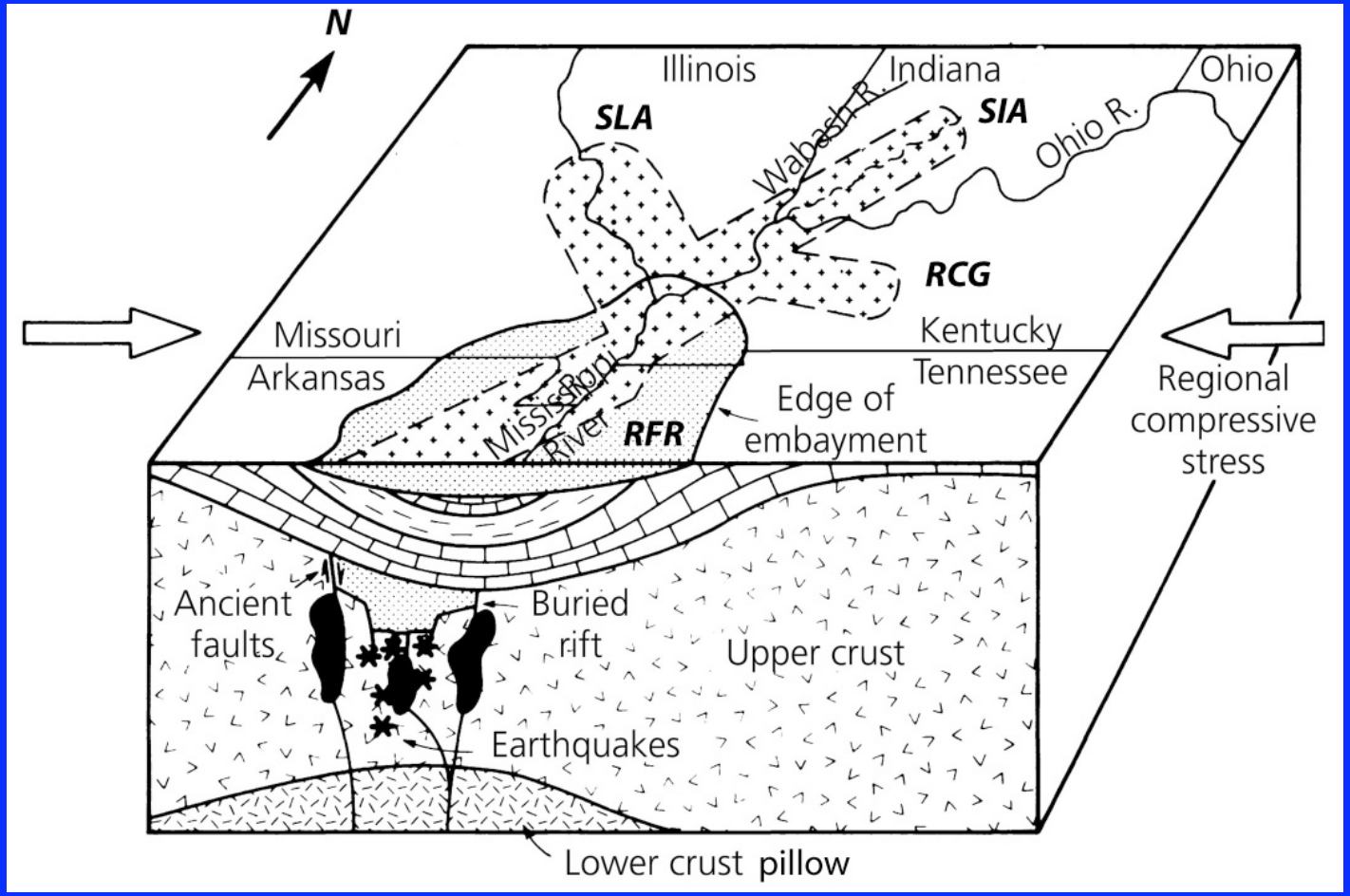
Plate interior contains many fossil faults developed at different times with different orientations but only a few appear active today

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

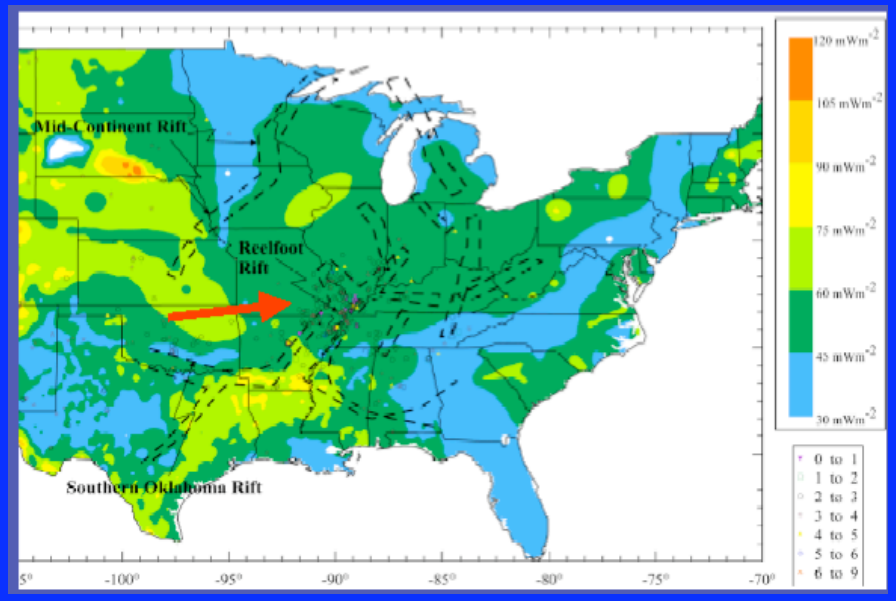
Earthquakes reflect localized stress sources & fault interactions

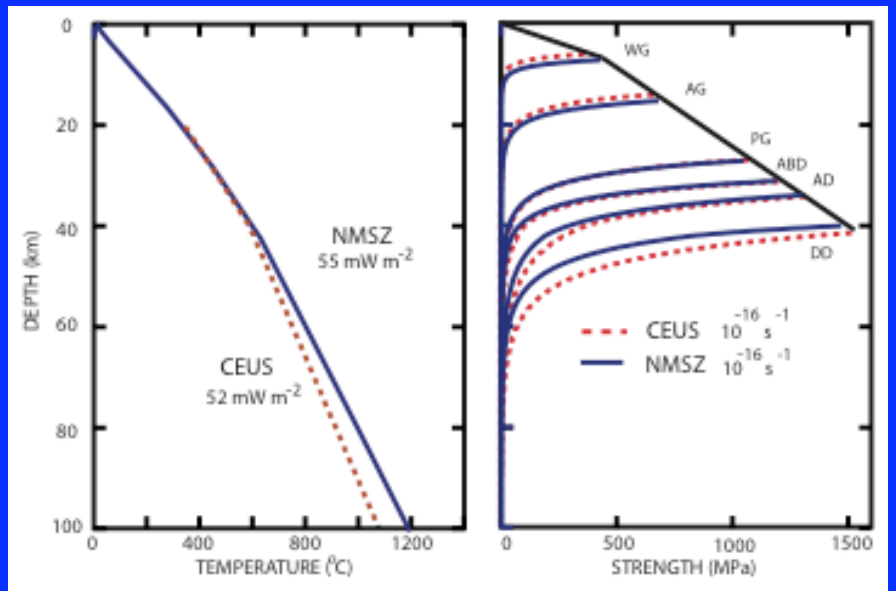


Braile et al., 1986

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





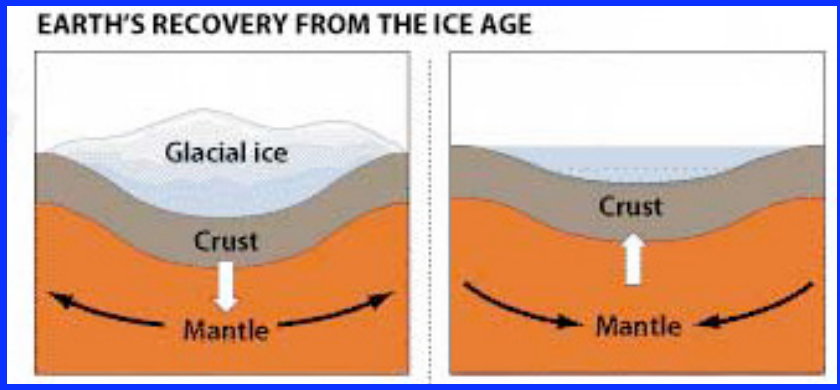
Liu & Zoback (1997) argue for NMSZ heat flow ~15 mW/m^2 higher making area weaker than surroundings

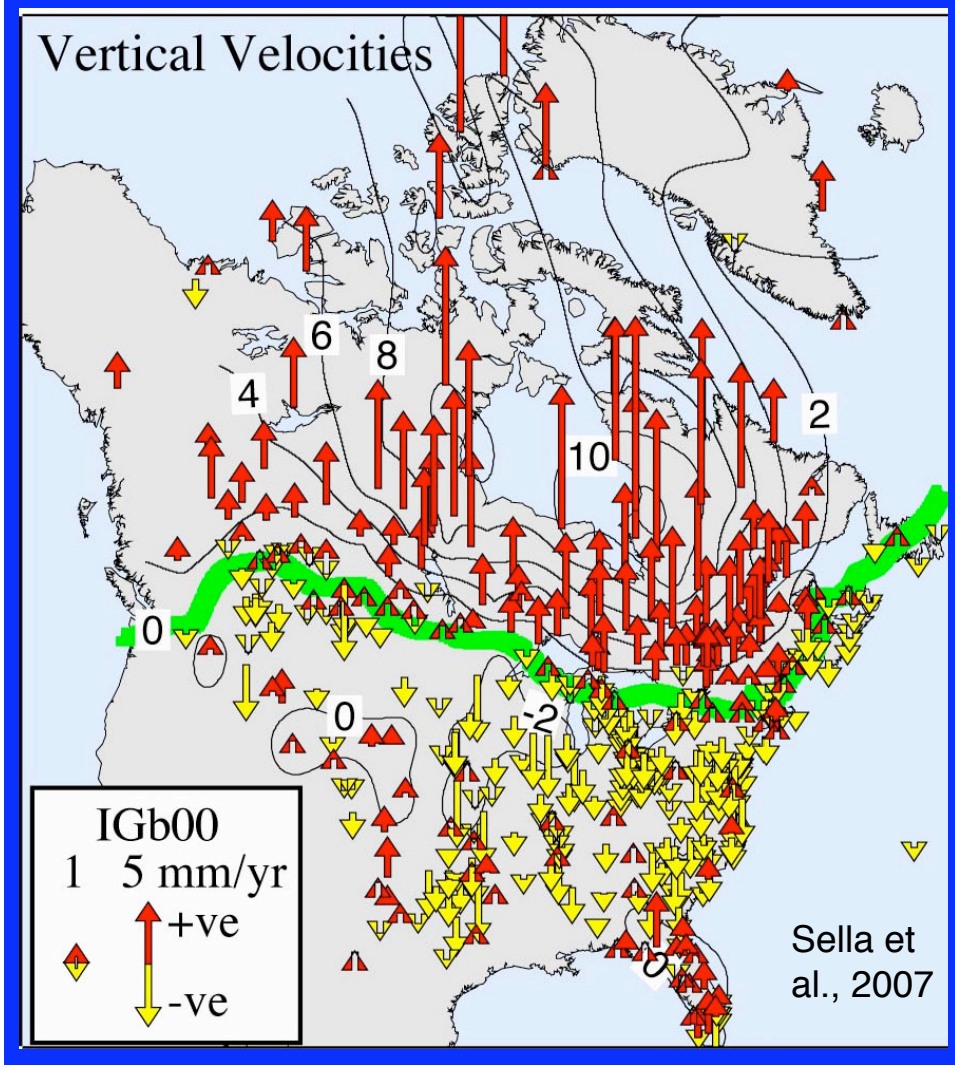
Reanalysis finds anomaly zero or much smaller (3+/-23 mW/m^2), so the NMSZ and CEUS *have essentially the same temperature & thermally-controlled strength*

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

McKenna, Stein & Stein, 2007

POSSIBLE 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)

GPS shows nothing unusual at New Madrid

Stresses decay rapidly away from ice margin, so can't explain NMSZ (Wu and Johnson, 2000) unless order of magnitude weaker than surroundings (Grollimund and Zoback, 2001)

No evidence for such weakening

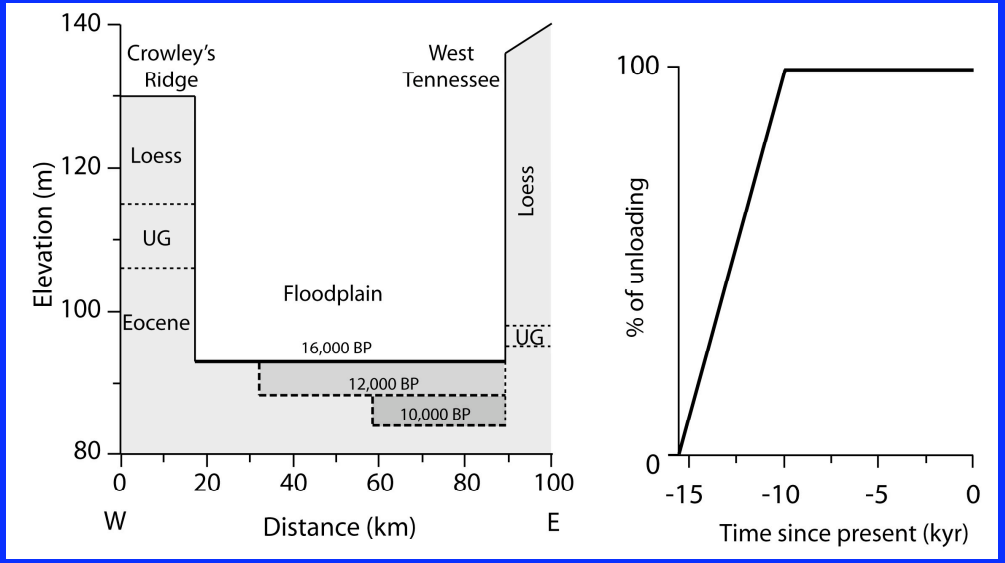
POSSIBLE LOCAL STRESS SOURCE FOR SEISMICITY:
POSTGLACIAL EROSION IN MISSISSIPPI EMBAYMENT

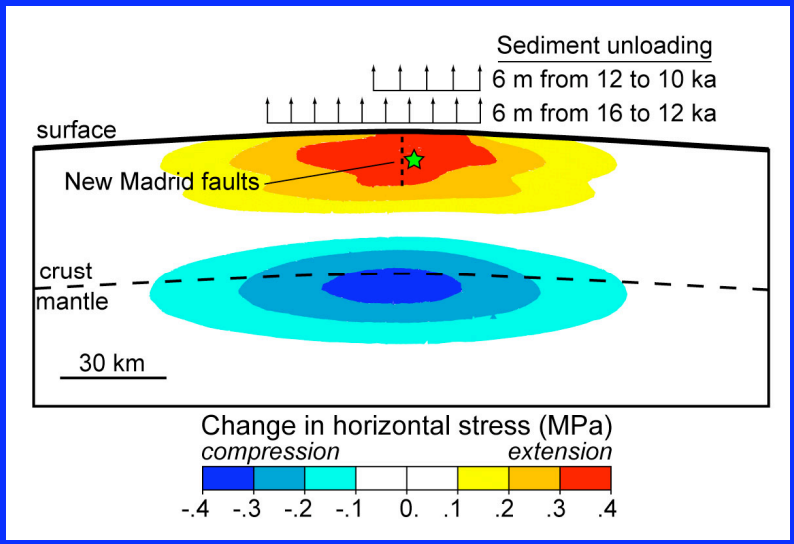
Flexure caused by unloading from river incision 16 - 10 ka reduces normal stresses sufficiently to unclamp pre-existing faults

Fits timing of recent seismicity

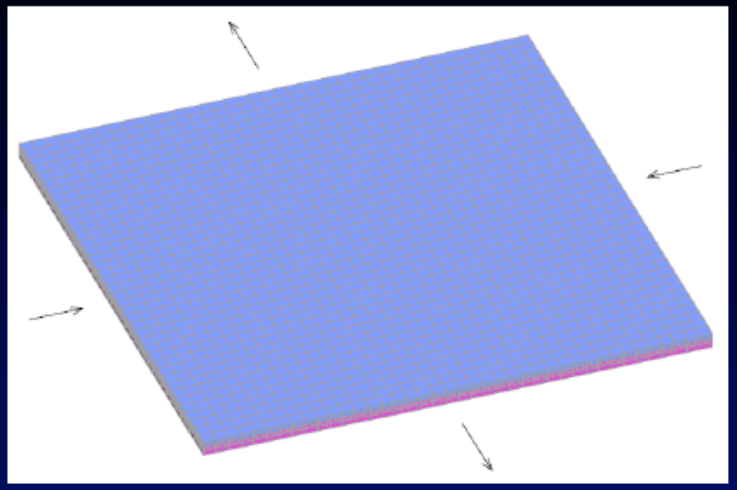
Doesn't require weak zone

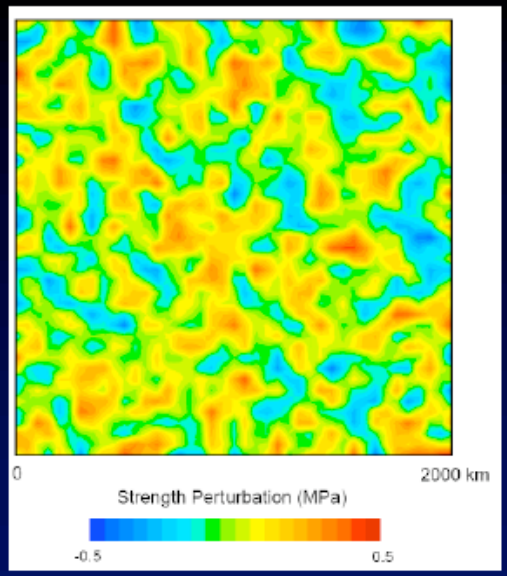
Fault segments that ruptured unlikely to fail again





Calais, Freed, Van Arsdale & Stein, 2010



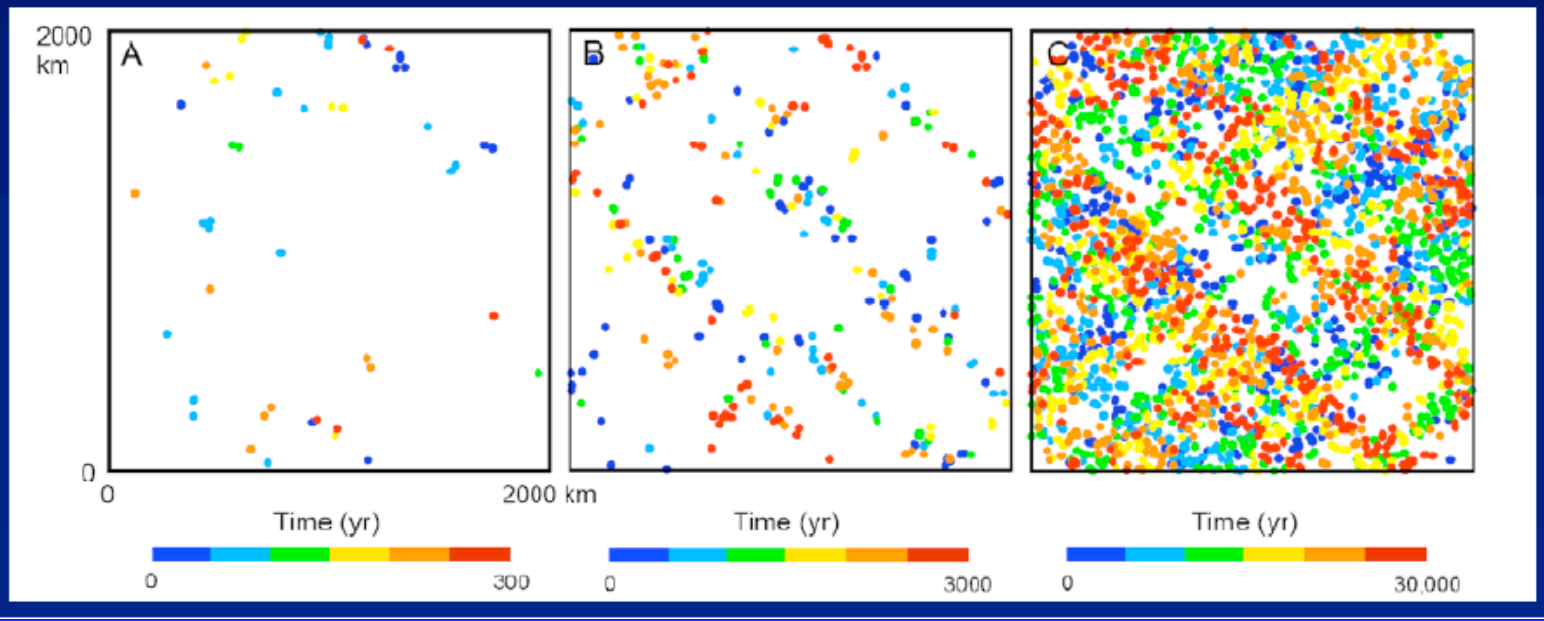


NUMERICAL MODEL

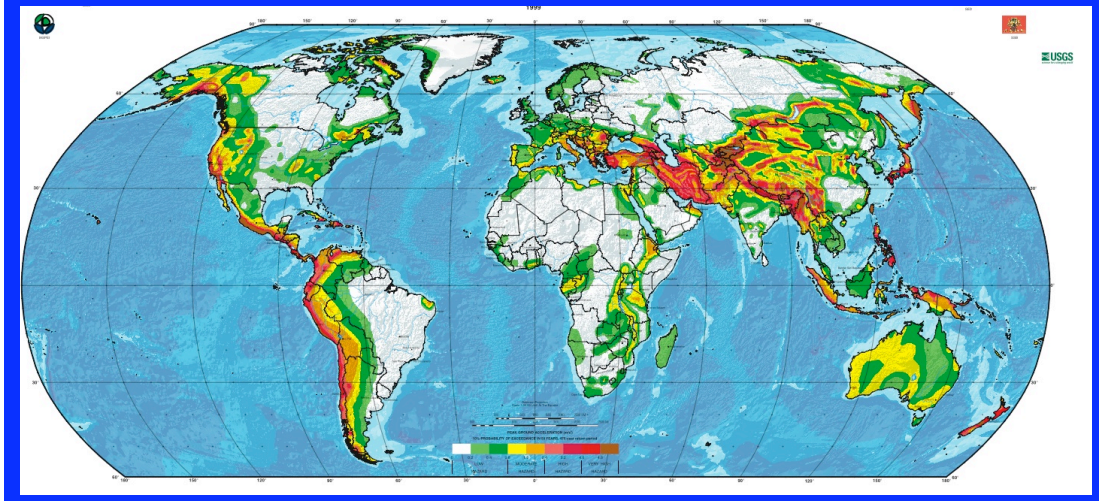
FOR INTRAPLATE EARTHQUAKES

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.



Hazard defined as maximum acceleration predicted in some time period



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

Need to assume:

Where and when large 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

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

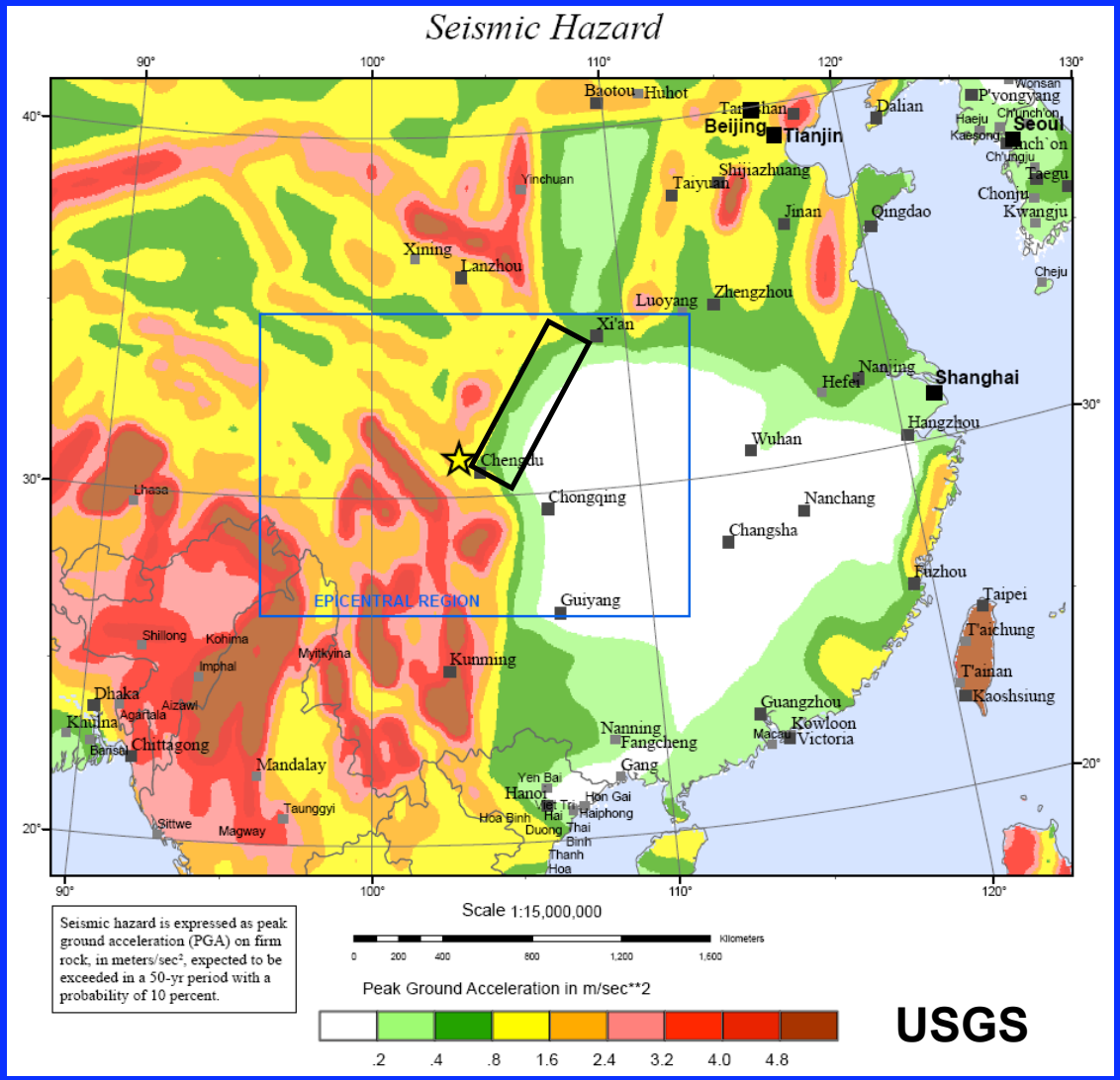
Complex spatiotemporal patterns of large earthquakes & long durations of their aftershocks make assessing hazards difficult

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

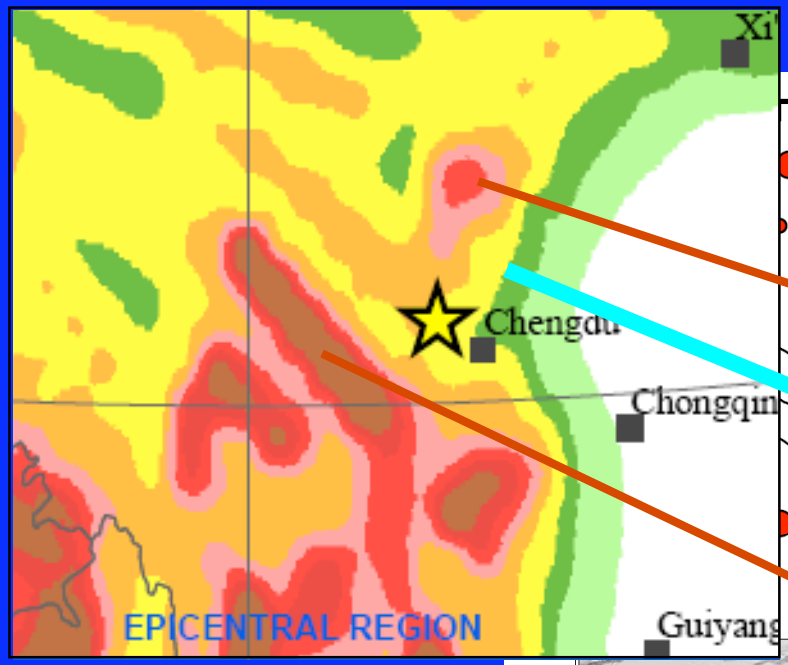
Relying unduly on recent seismicity to predict locations of future large earthquakes *overestimates hazard in some places and leads to surprises elsewhere*

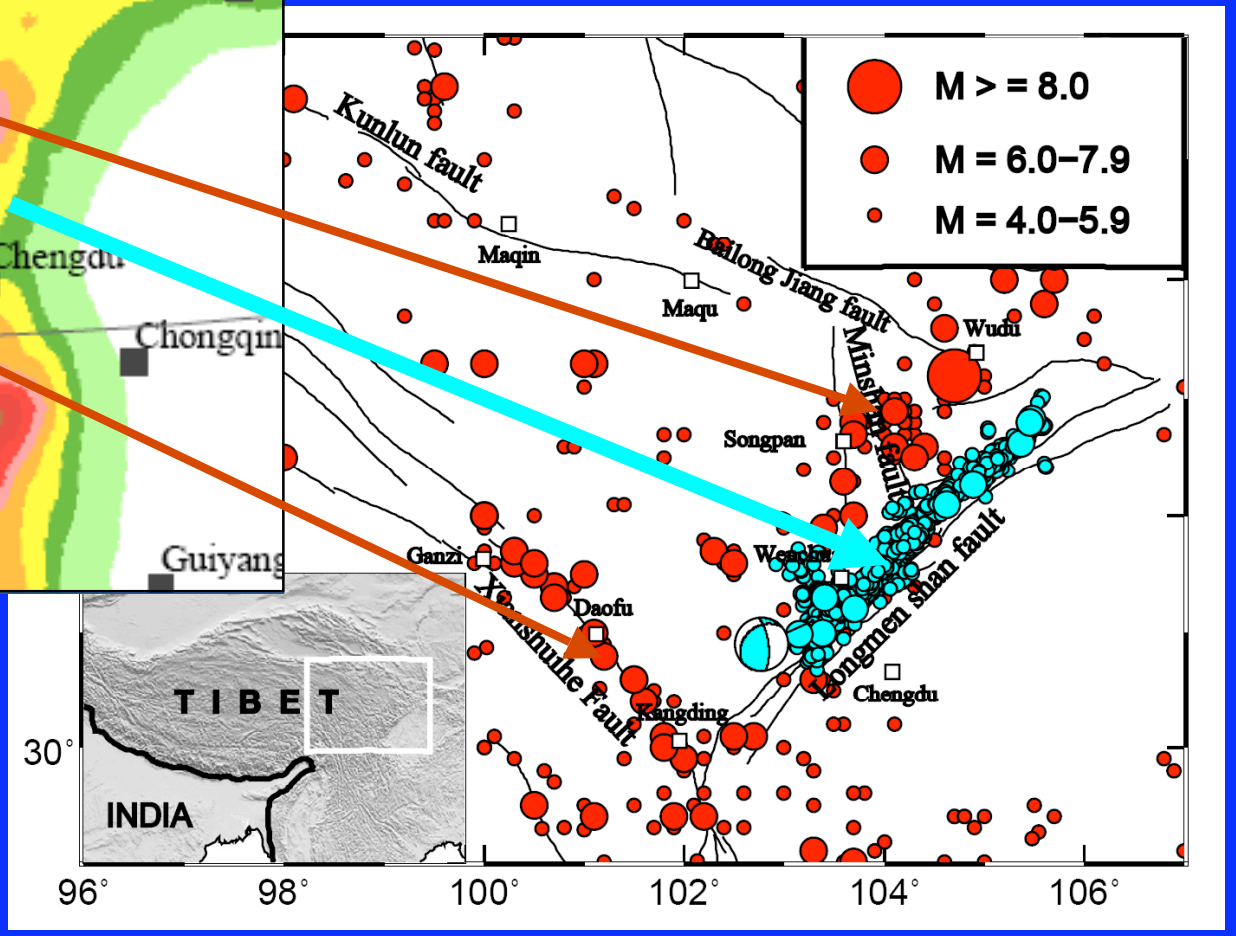
2008 Wenchuan earthquake (Mw 7.9) was not expected: map showed low hazard



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

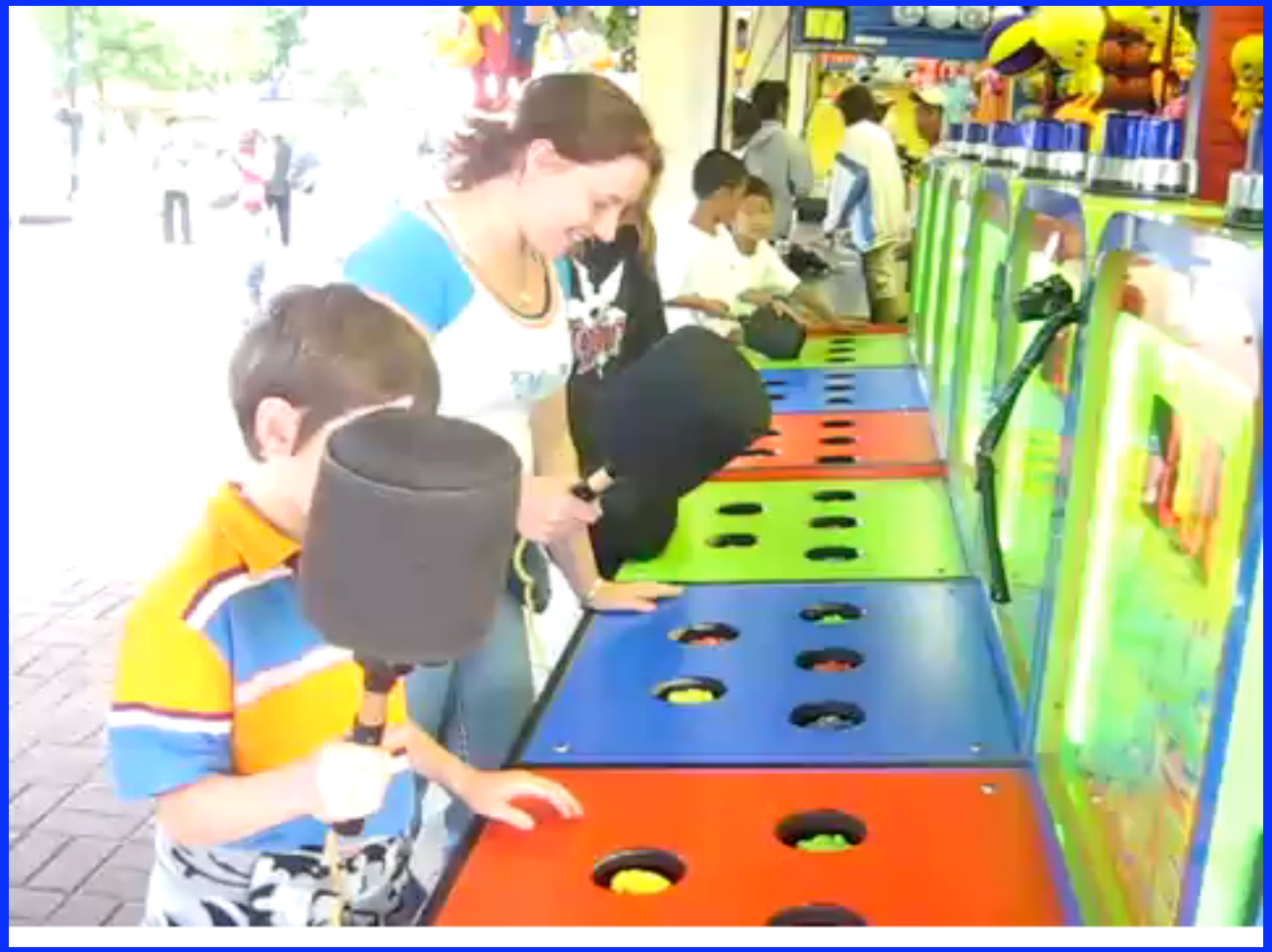
Didn't use GPS data



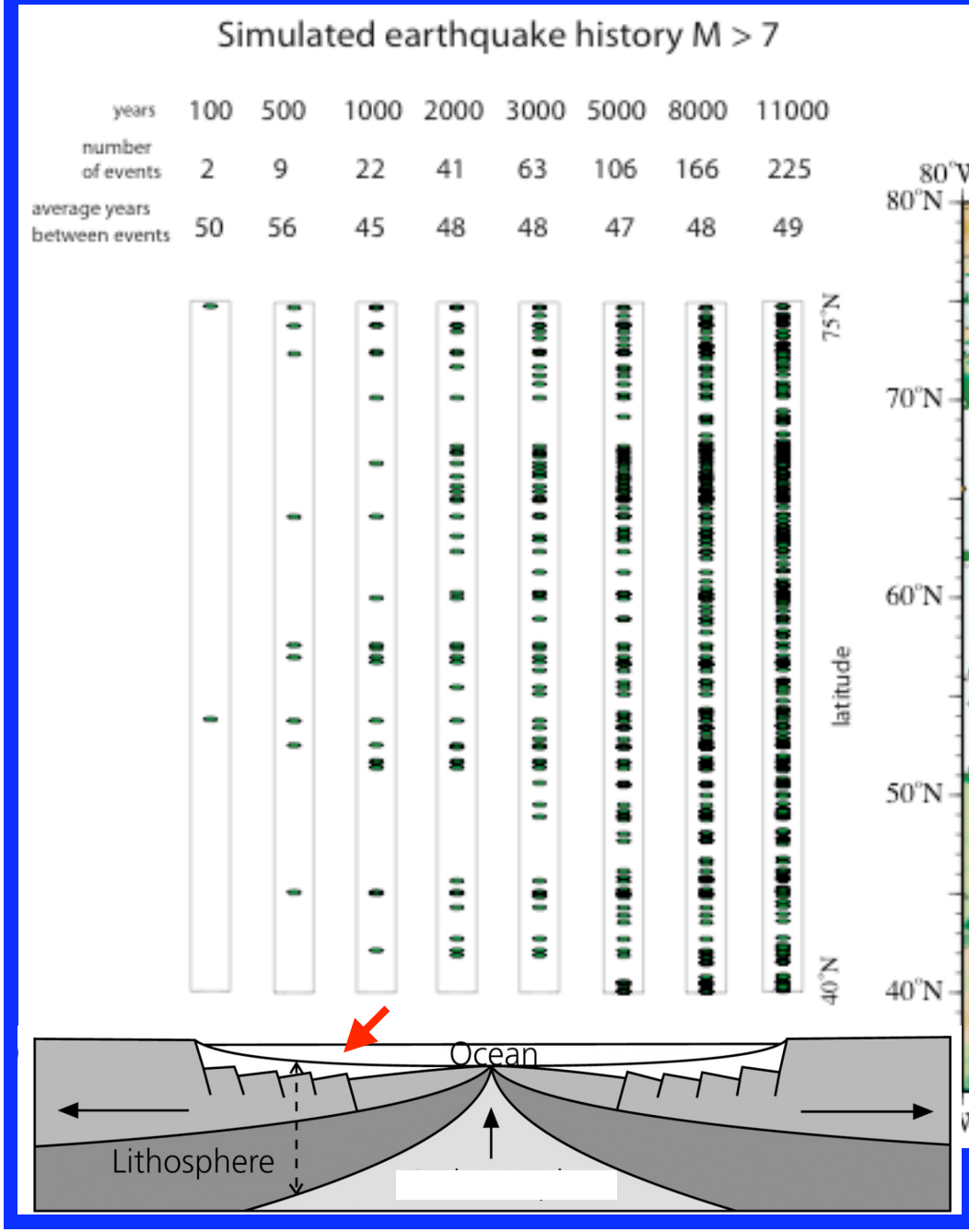


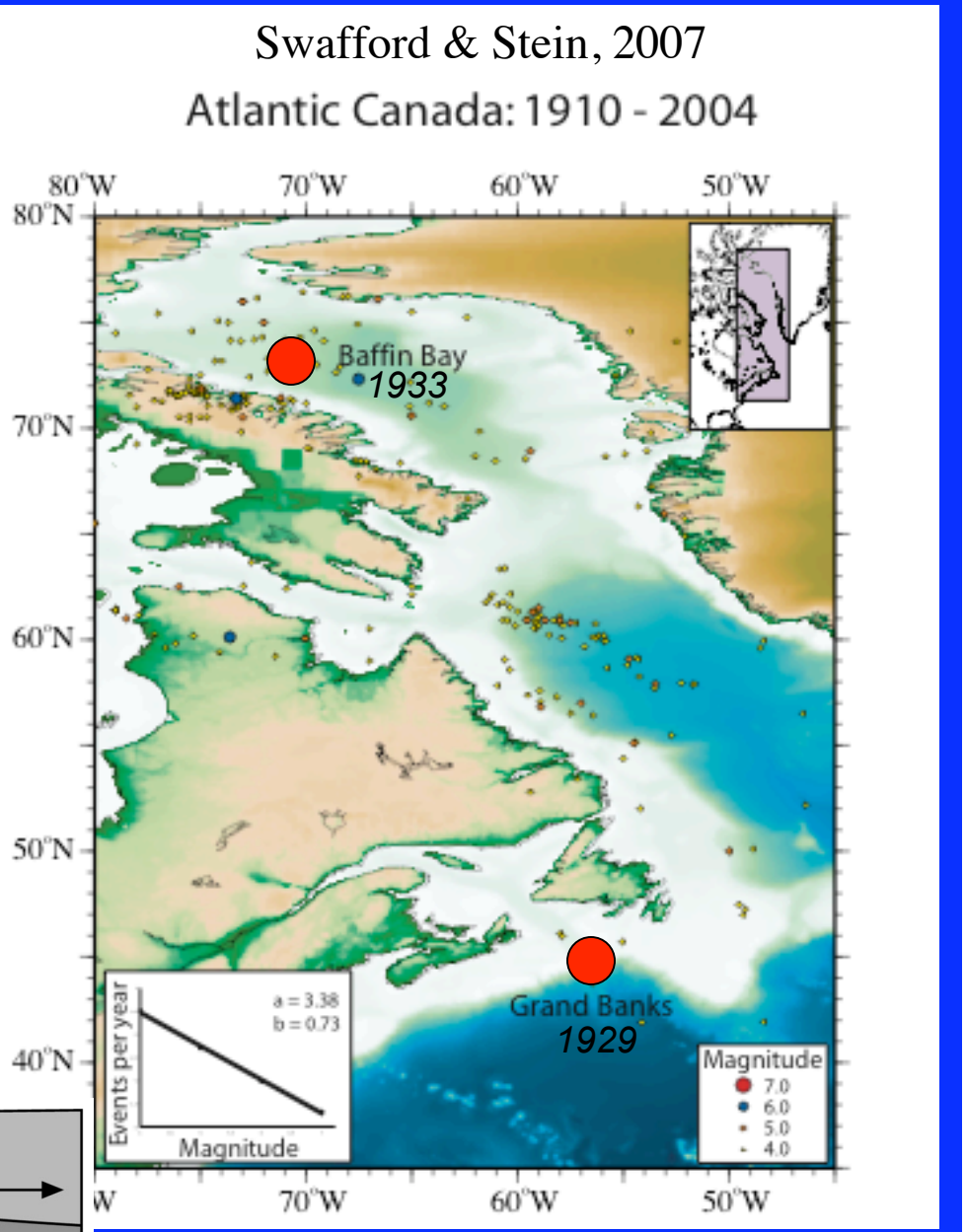
- Earthquakes prior to the 2008 Wenchuan event
- Aftershocks of the Wenchuan event delineating the rupture zone

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.



Long record needed to see real hazard



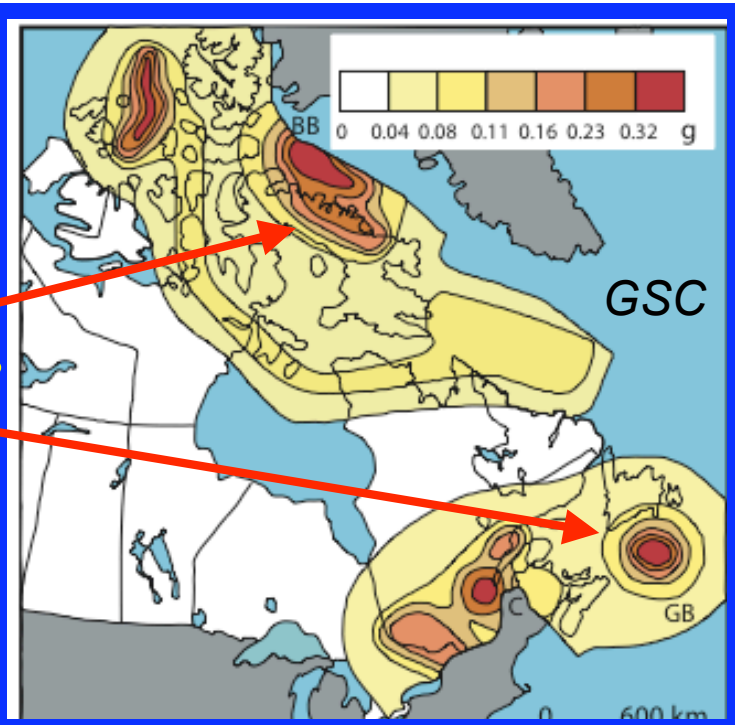


"Our glacial loading model suggests that earthquakes may occur anywhere along the rifted margin which has been glaciated."

Stein et al., 1979

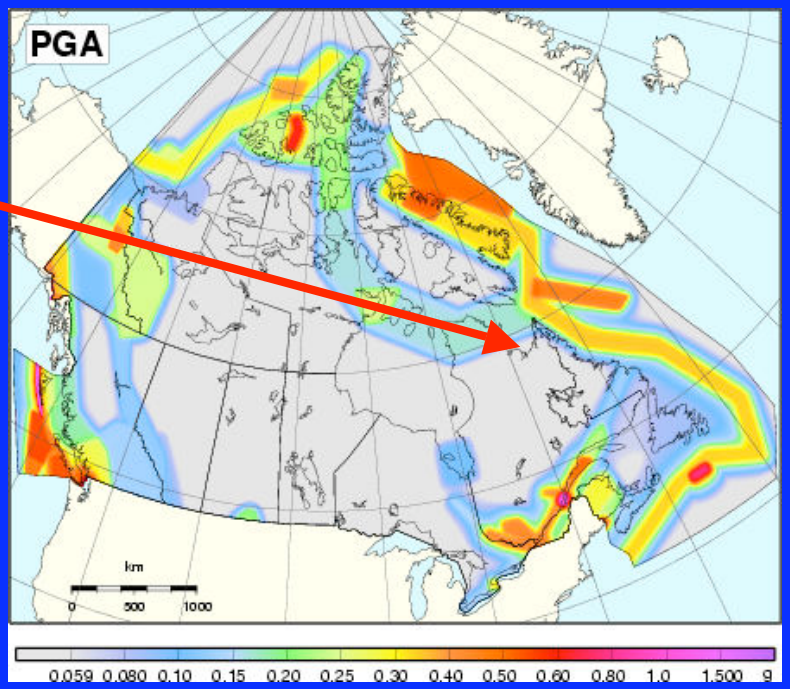
1985

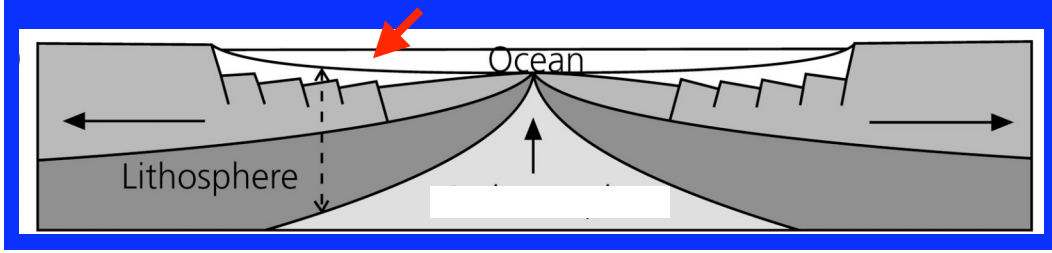
Concentrated hazard bull's-eyes at historic earthquake sites



2005

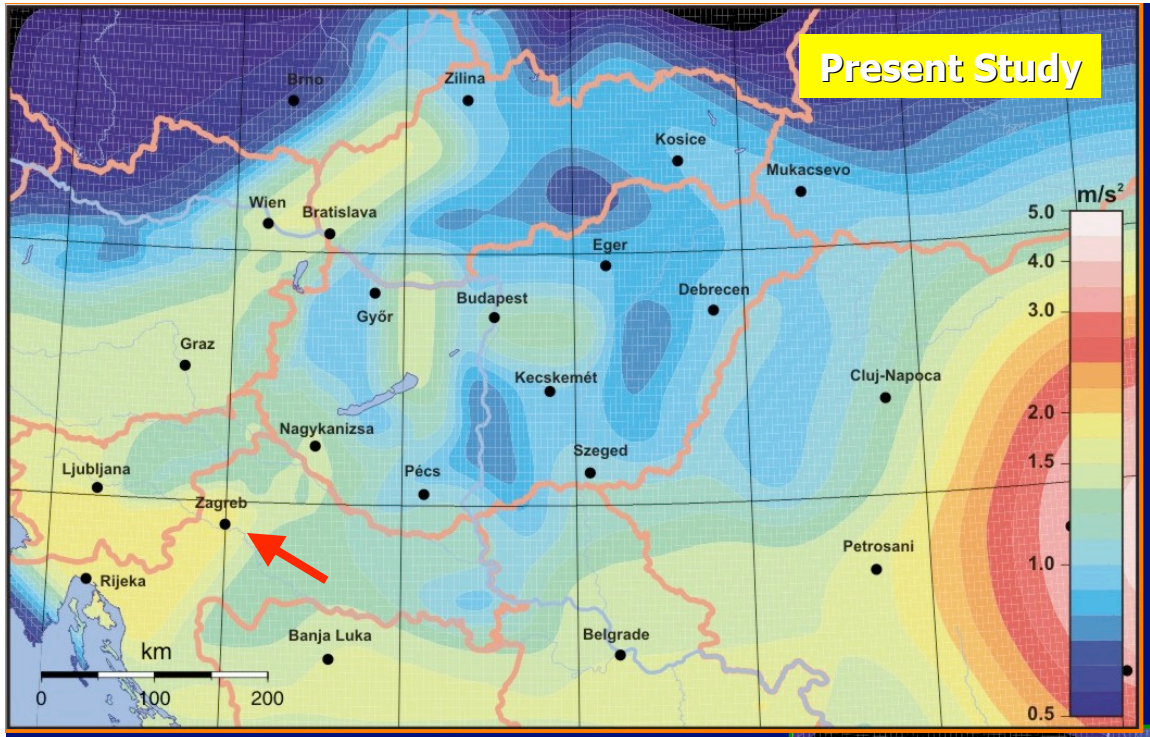
Diffuse hazard along margin





HUNGARY: ALTERNATIVE HAZARD MAPS

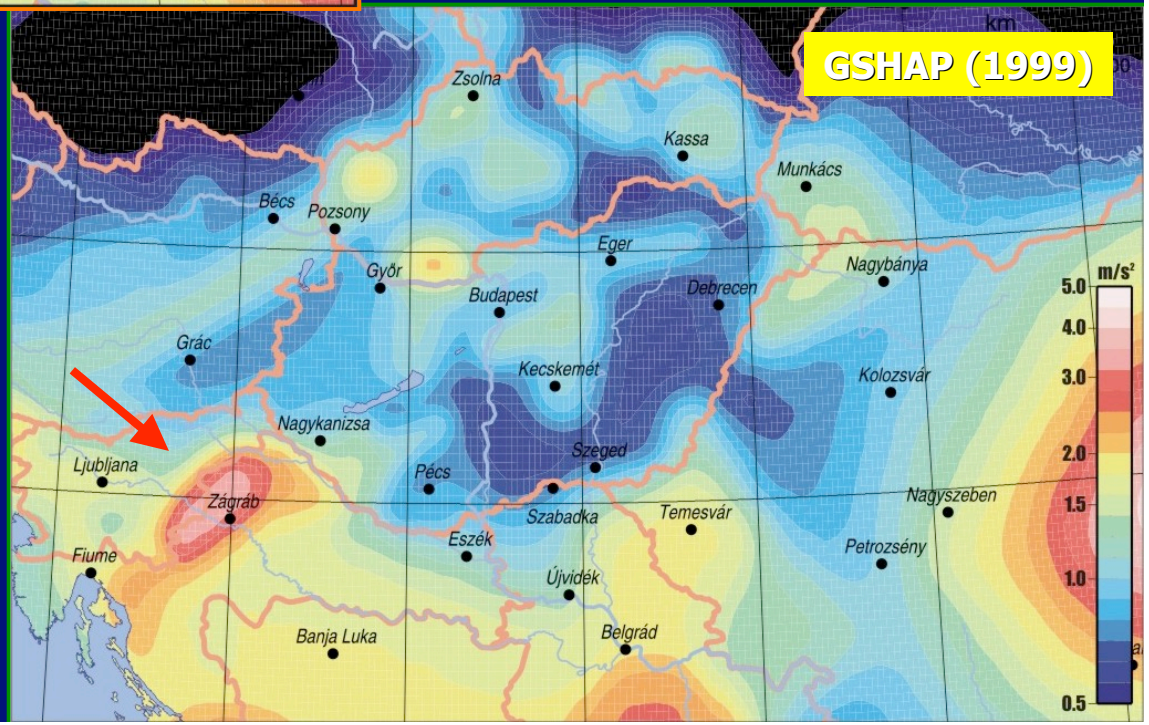
Peak Ground Acceleration
10% probability of
exceedance in 50 years
(once in 500 yr)



Diffuse hazard inferred incorporating geology

Concentrated hazard inferred from historic seismicity alone

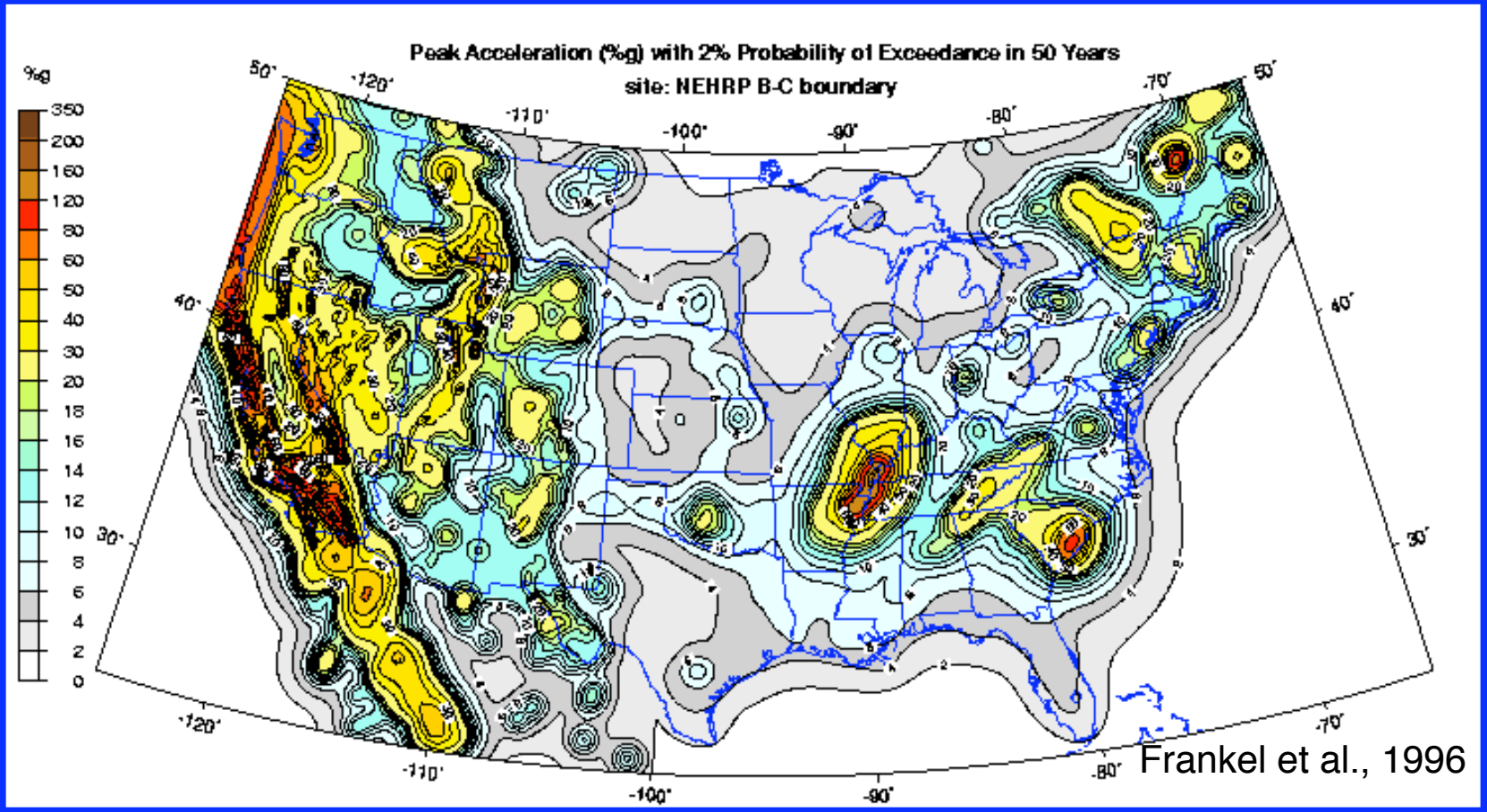
Toth et al., 2004



NEW MADRID SAID TO BE AS HAZARDOUS AS CALIFORNIA

Buildings should be built to same standards

How credible is this map?



Frankel et al., 1996

$100M retrofit of Memphis VA hospital, removing nine floors, bringing it to California standard

Such measures would cost $billions over 100s of years & likely yield little or no benefit during buildings' life

Is this a wise use of resources compared to alternatives that could do more good?

Impact of Earthquakes on the Central USA

Scenario assumes 1811-12 style events recur

936 pages list types of buildings damaged, injuries, tons of rubble, and deaths.

For example, in Arkansas 37,244 people are predicted to be looking for shelter, 50,159 buildings are predicted to be destroyed, 574 deaths occur, etc…

High *precision* (# of digits)
Need to consider *accuracy* (how real)

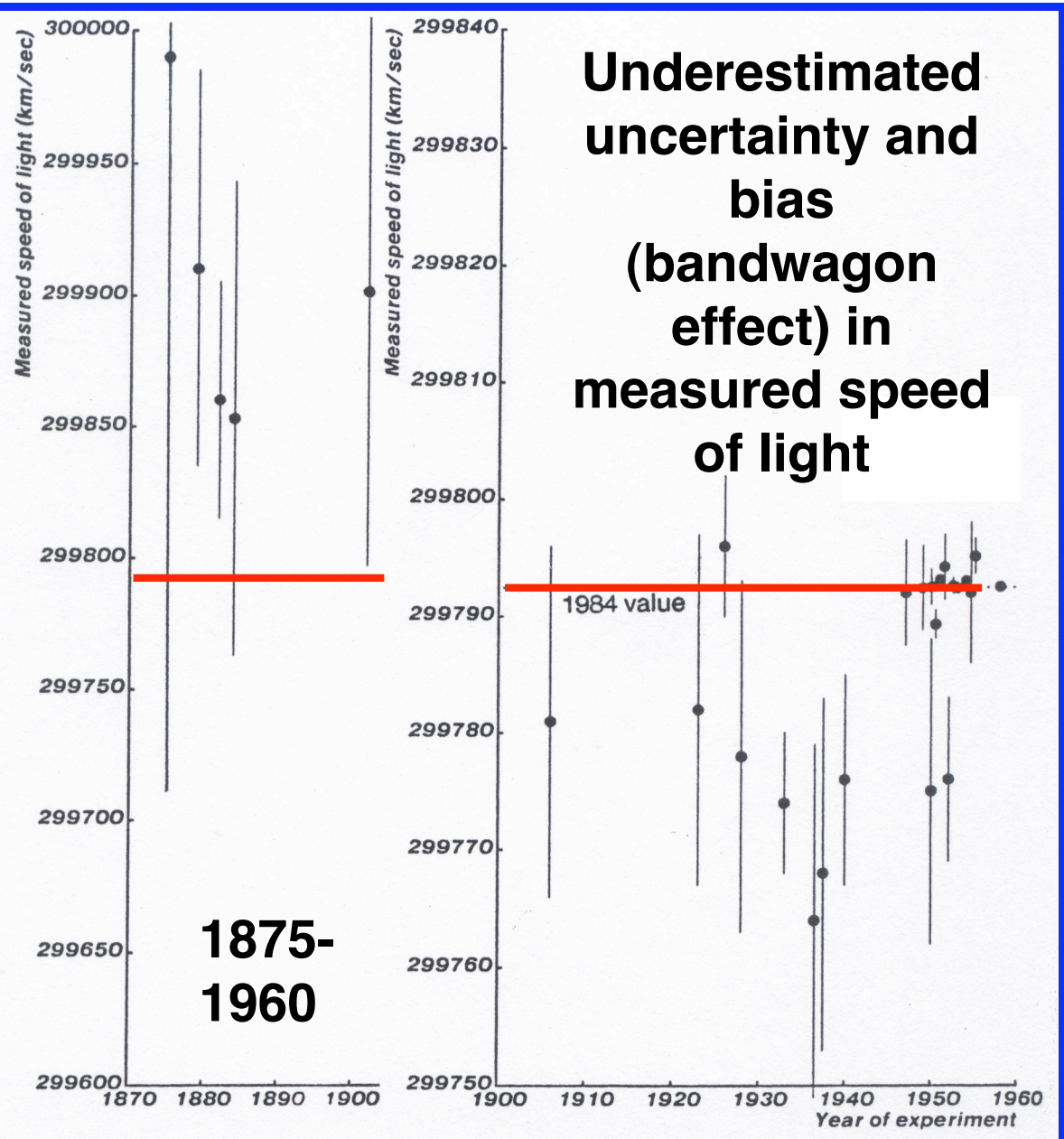
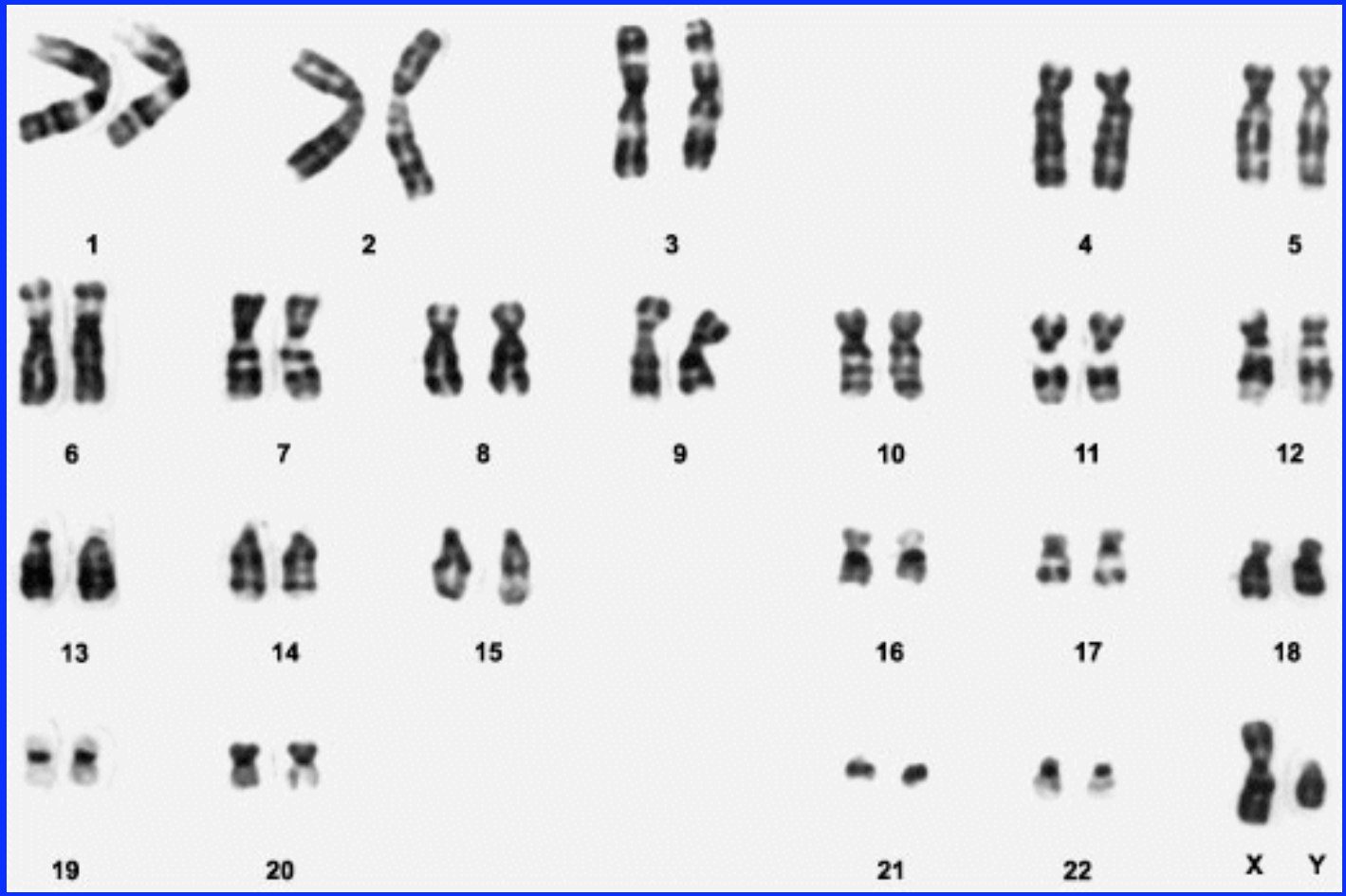


Figure 4.1. Experimental measurements of the speed of light between 1875 and 1960. Vertical bars show reported uncertainty as standard error. Horizontal dashed line represents currently accepted value. Less than 50% of the error bars enclose the accepted value, instead of the expected 70%. From Henrion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

HAZARD OVERESTIMATED: Y2K

Much ado made that on January 1, 2000 computer systems would fail, because dates used only two digits

U.S. & other governments established major programs

Estimated $300 billion spent on preparations

Few major problems occurred, even among businesses and countries who made little or no preparation

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

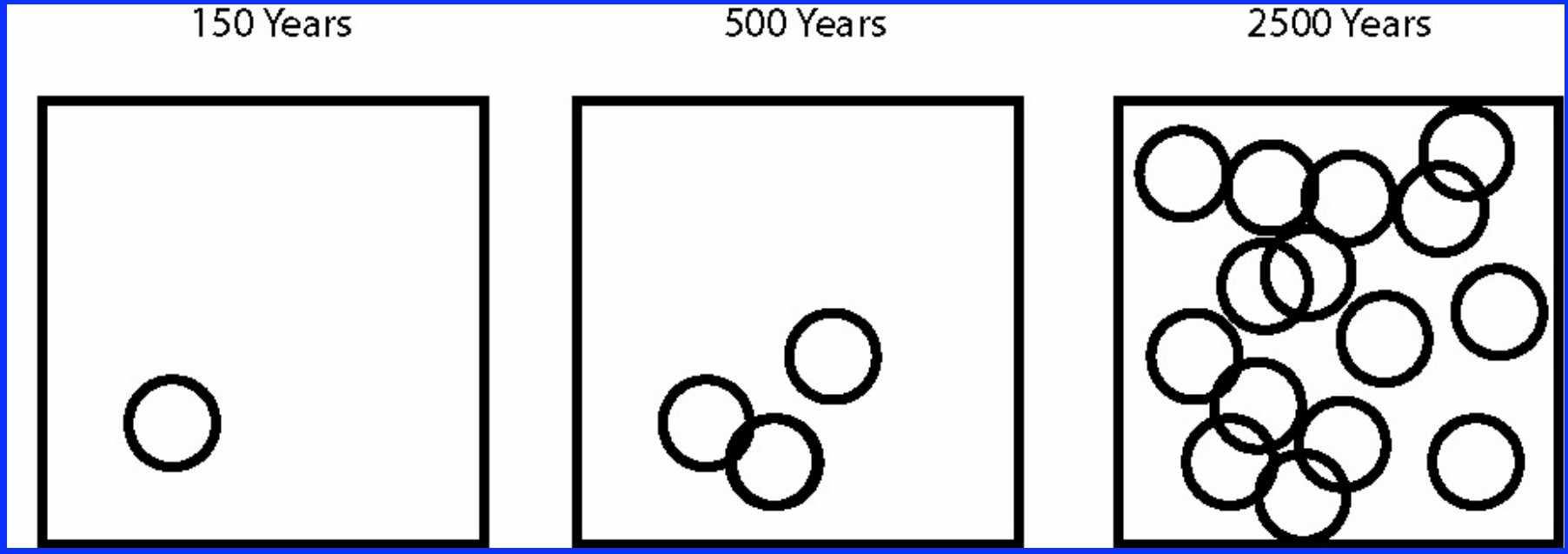
- Large magnitude of 1811-12 and thus future large earthquakes

Uncertainty in interpreting intensity data

- High ground motion in large events

Lack of data, chose high model

Assume that an earthquake of a certain size will strike in a certain time and cause shaking within a certain area.



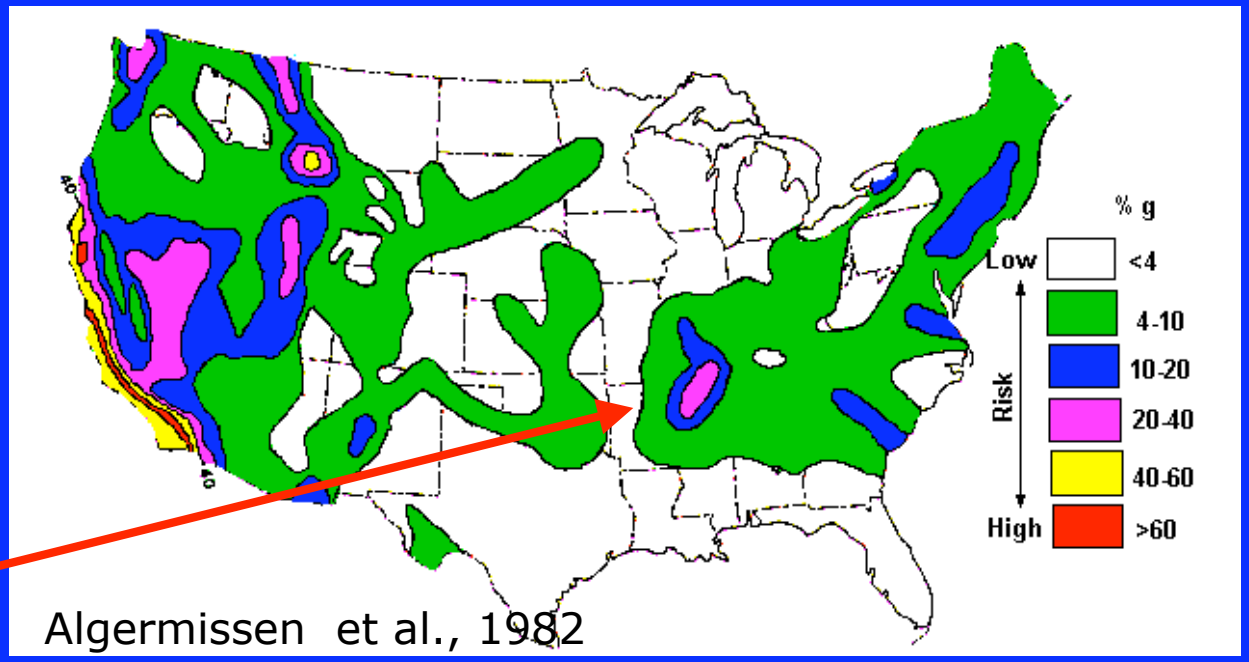
Strongly shaken areas MMI > VII for M 6

Include earthquakes of different magnitudes, assume some areas more likely to have earthquakes, and have stronger shaking close to the epicenter. Hazard at a given location is described by the maximum shaking due to earthquakes that is predicted to happen in a given period of time. Thus it increases for longer time windows / lower probabilities

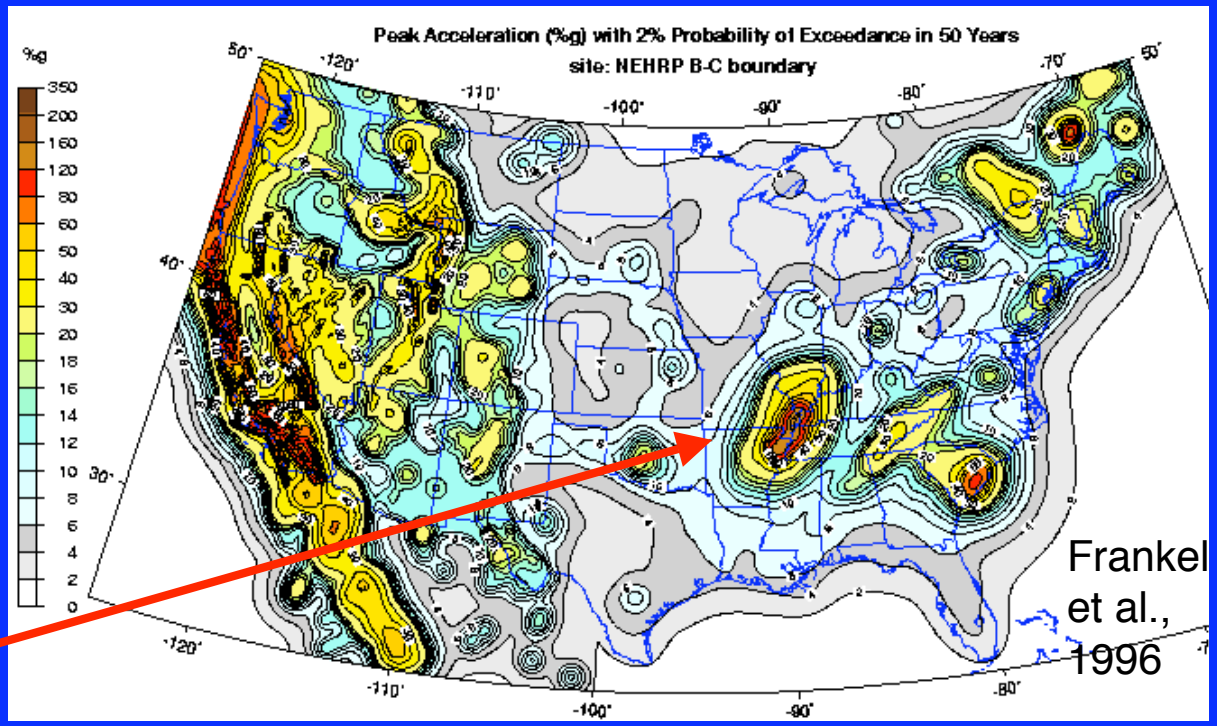
Hazard redefined with longer window

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

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

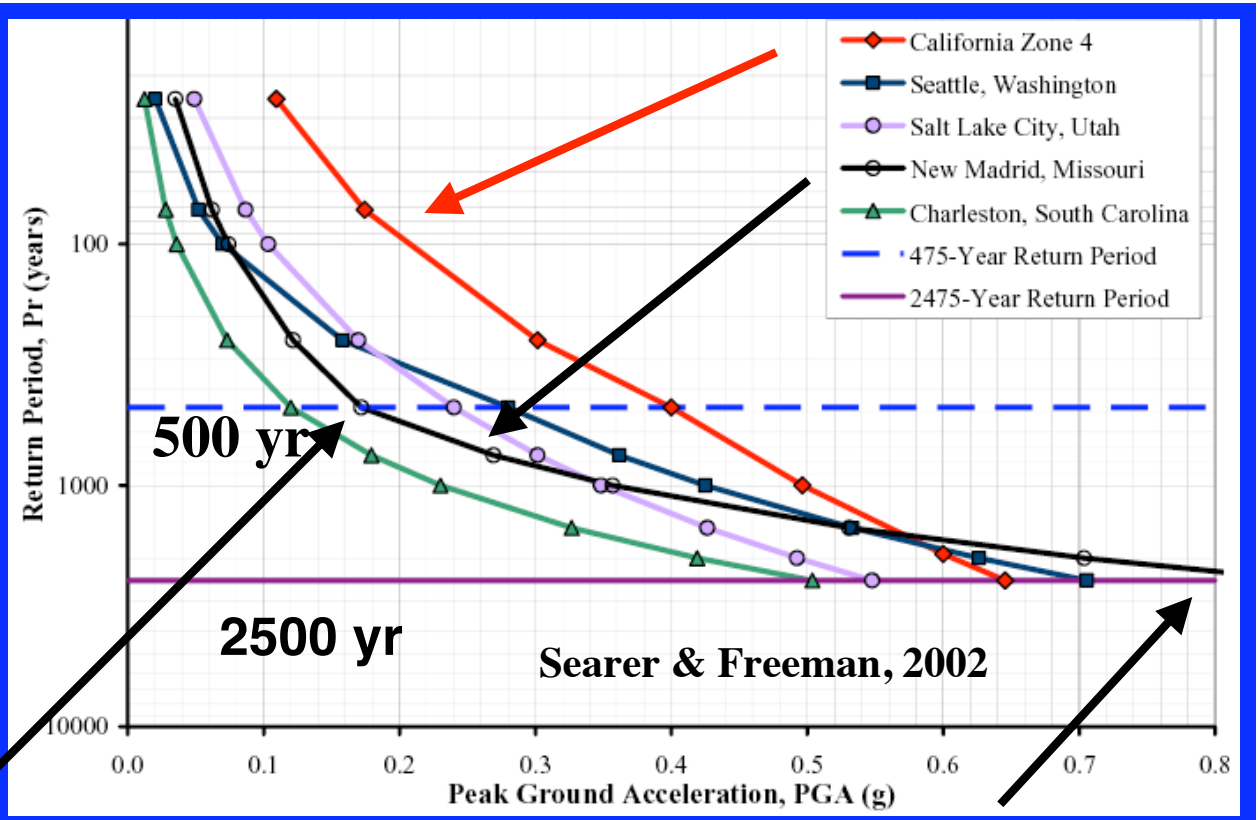


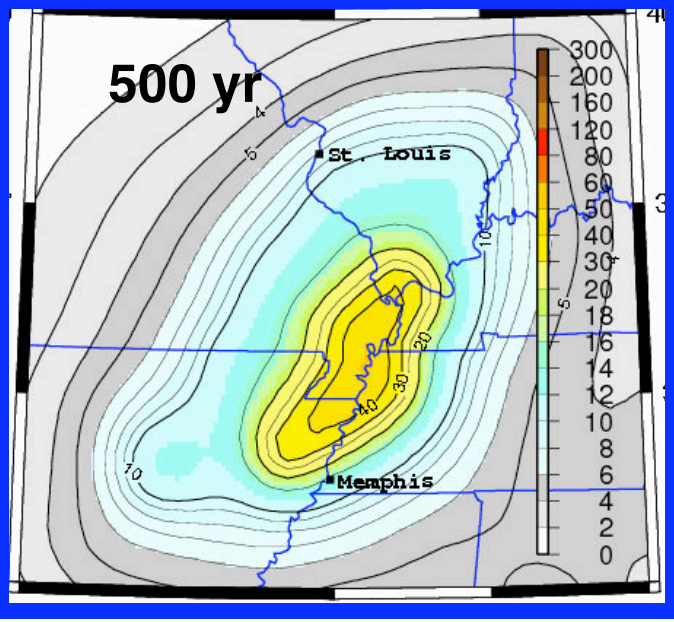
Algermissen et al., 1982



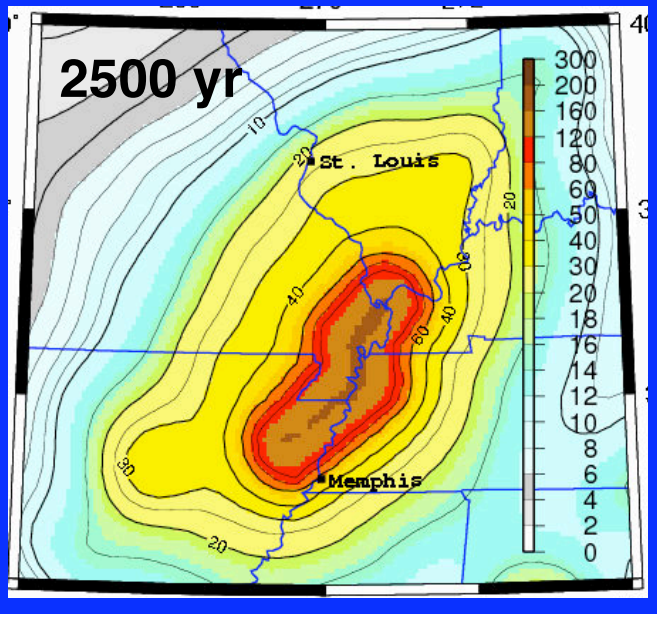
Frankel et al., 1996

New Madrid hazard higher than California results largely from redefining hazard as largest shaking expected every 2500 yr: Not so for 500 yr





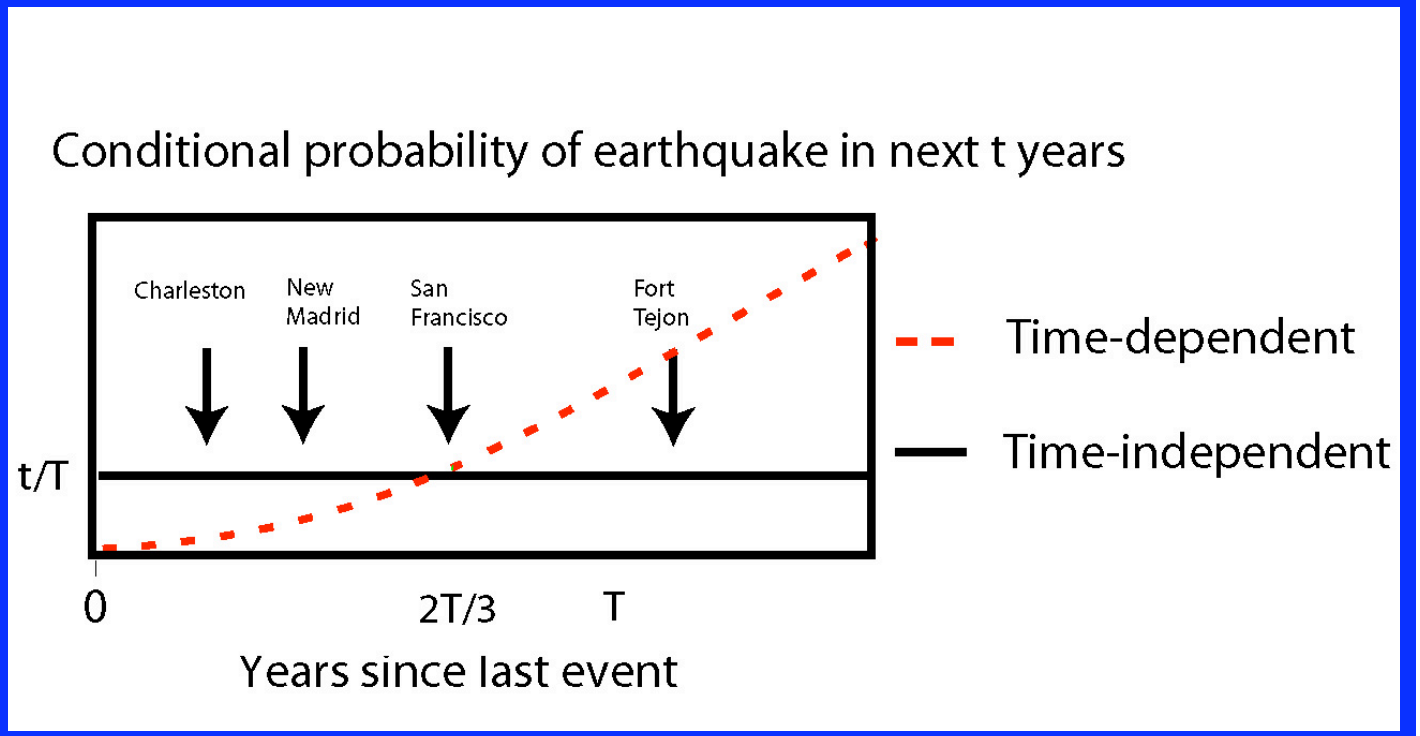
400%



RELATIVE PREDICTED HAZARD DEPENDS ON POSITION IN EARTHQUAKE CYCLE

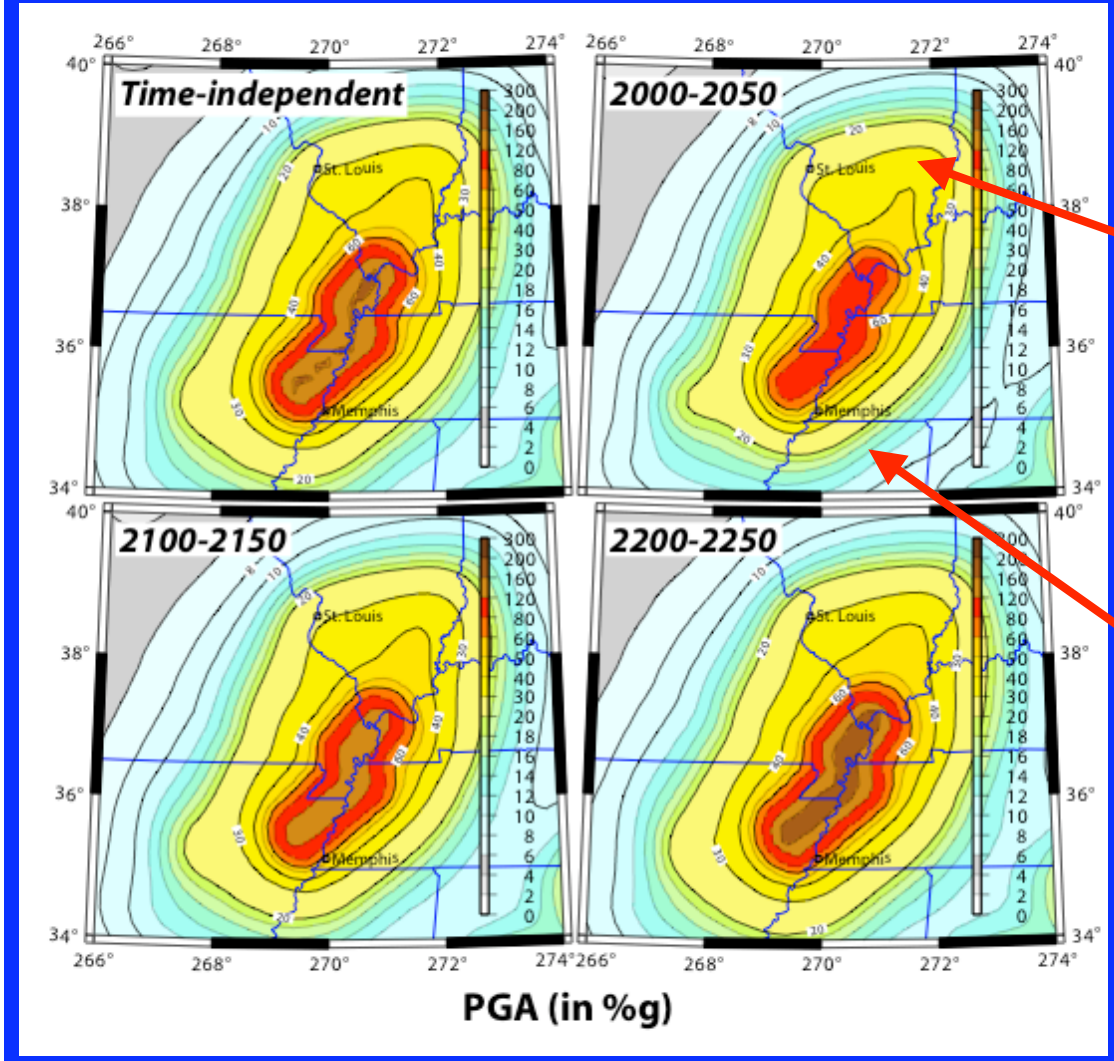
Time dependent lower until ~2/3 mean recurrence

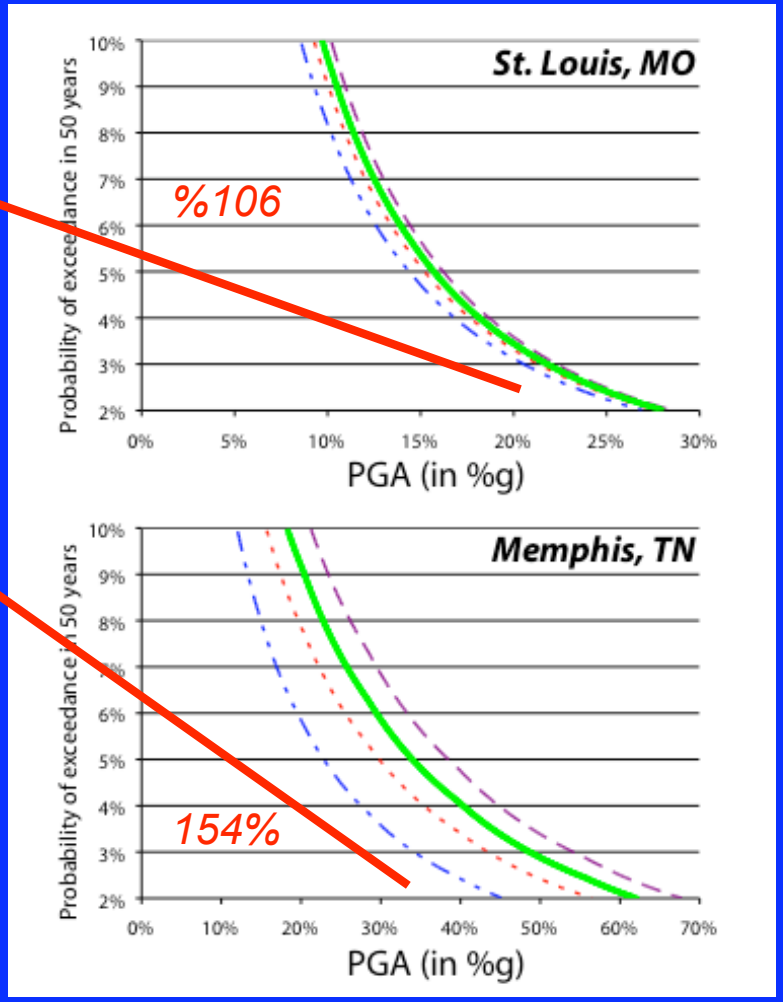
New Madrid in mid-cycle so USGS time independent assumption predicts higher hazard



Hebden & Stein, 2008

NEW MADRID





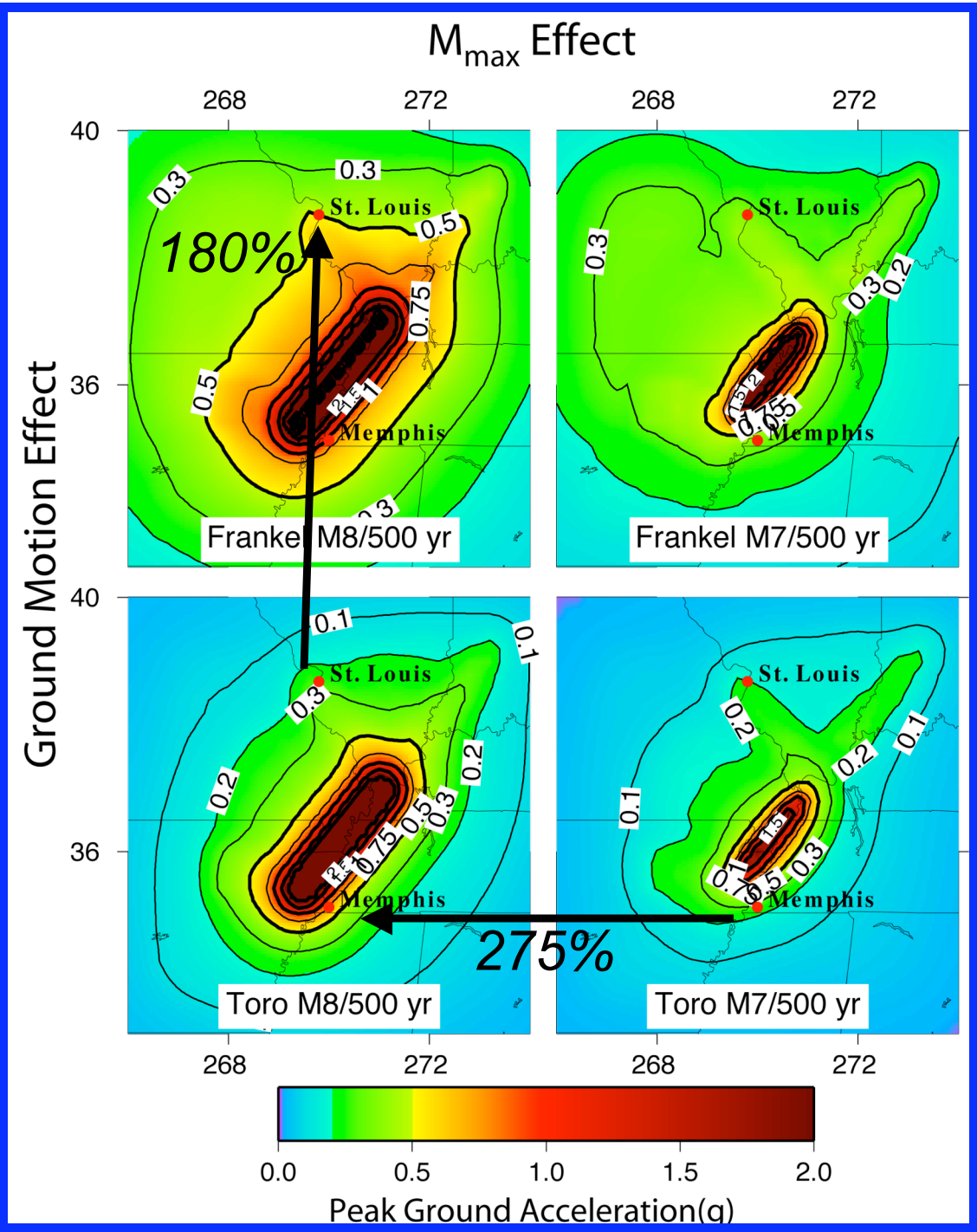
2% in 50 yr (1/2500 yr)

2000-2050 2100-2150 2200-2250 Time-independent

PREDICTED HAZARD DEPENDS ON

- Assumed maximum magnitude of largest events
- Assumed ground motion model

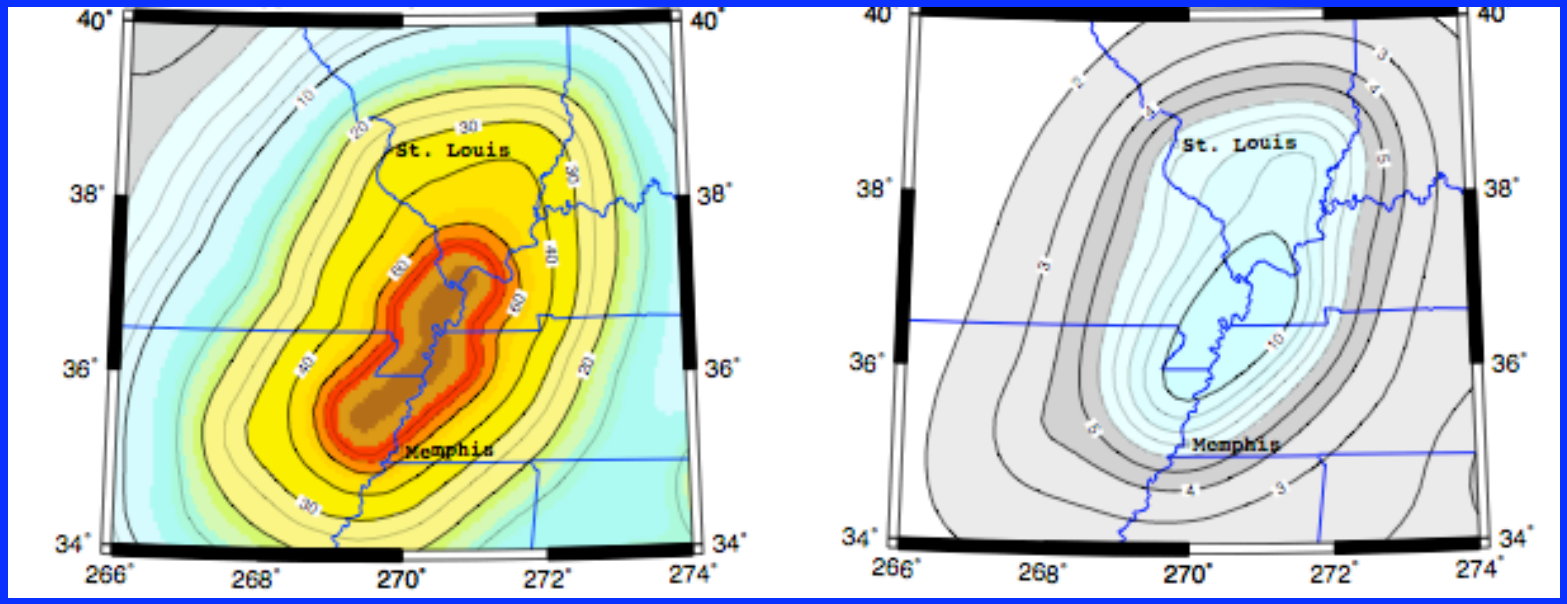
Newman et al., 2001



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

Continental earthquakes: what to do while waiting for rare large earthquakes

Analyze small earthquakes, some of which may be aftershocks

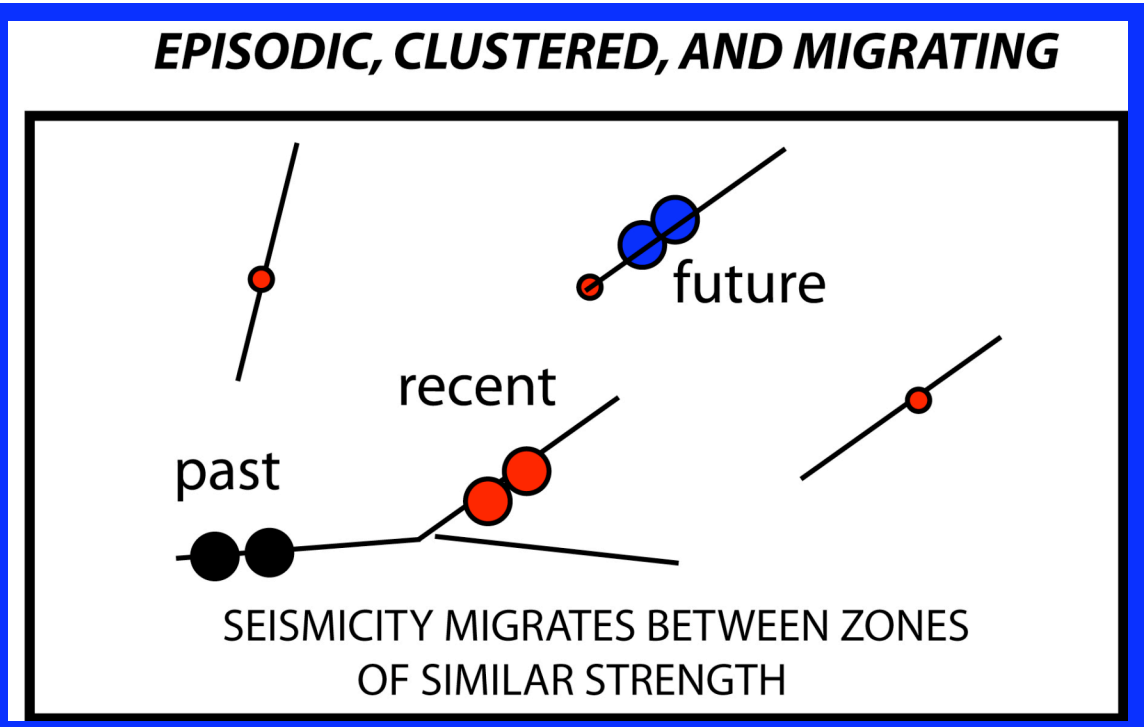
Use GPS data to see if/where strain's accumulating

Use paleoseismic & shallow seismic data to establish faulting histories in broad region

Use geologic data to understand regional stress evolution

Develop testable models of how & on what timescales stress concentrations, physical conditions & fault interactions cause episodic, clustered & migrating earthquakes

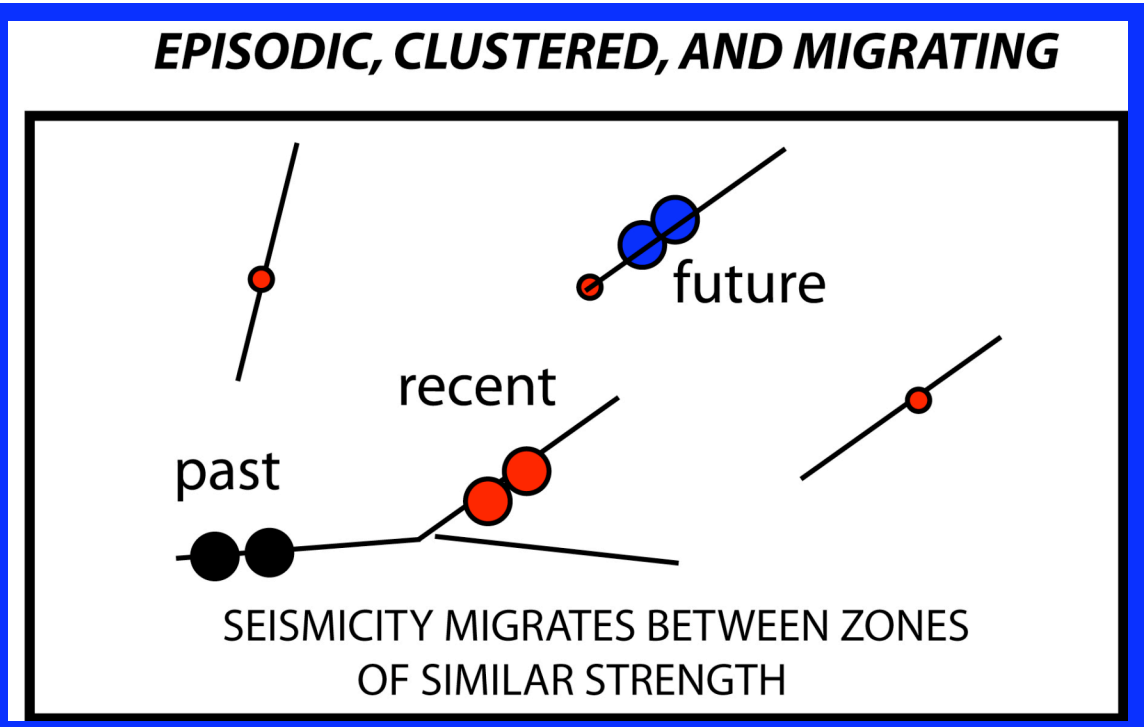
COMPLEXITY CALLS FOR HUMILITY



"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

COMPLEXITY CALLS FOR HUMILITY



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OVERESTIMATED HAZARD

1976 SWINE FLU *"APORKALPSE"*

CDC reported "strong possibility" of epidemic. HEW thought "chances seem to be 1 in 2" and "virus will kill one million Americans in 1976."

President Ford launched program to vaccinate entire population despite critics' reservations

40 million vaccinated at cost of millions of dollars before program suspended due to reactions to vaccine

About 500 people had serious reactions and 25 died, compared to one person who died from swine flu