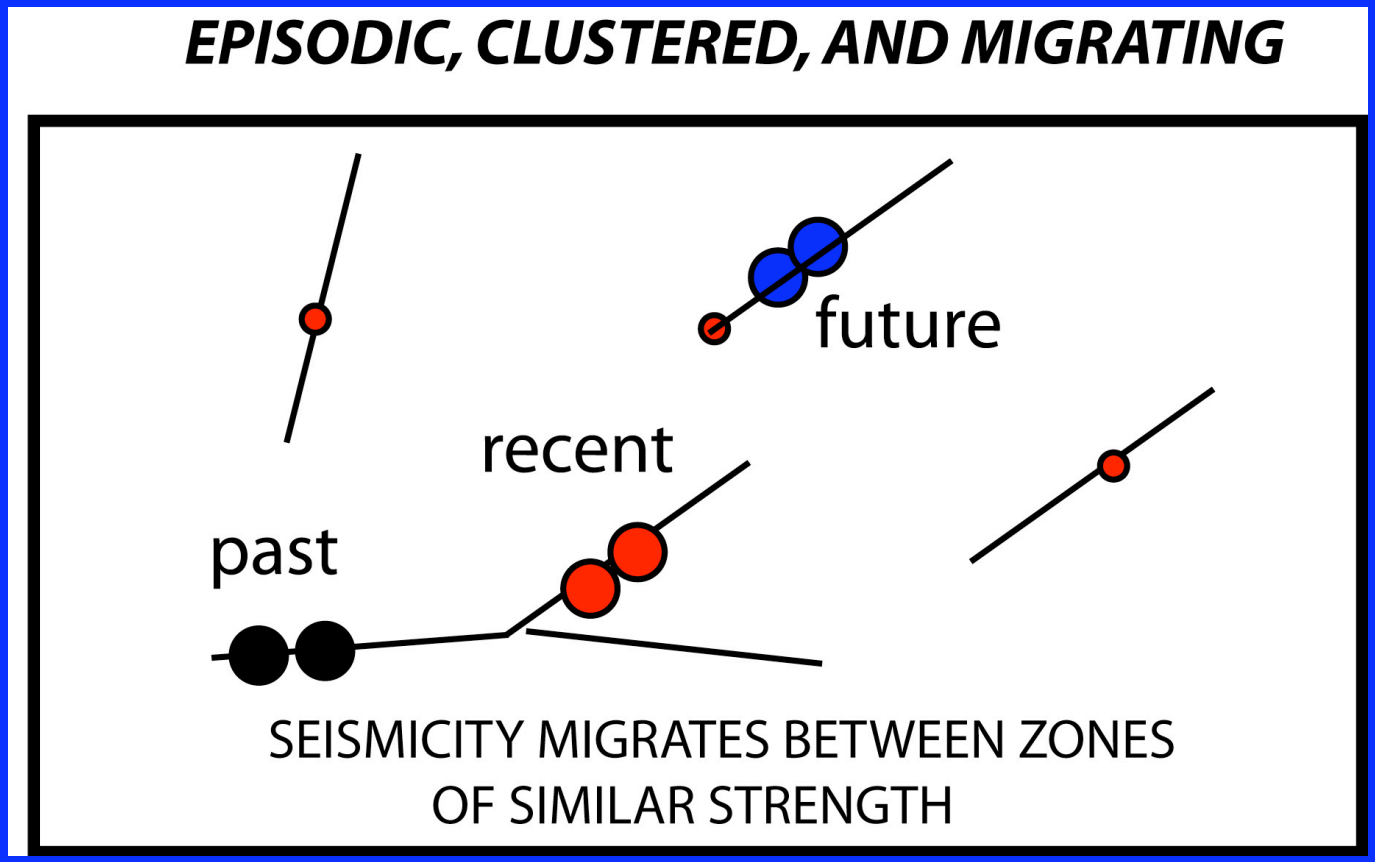
New view of New Madrid:
little motion, complex faults, small hazard

Seth Stein
Northwestern

Eric Calais
Purdue

Qingsong Li
LPI

Mian Liu
University of Missouri



"How wonderful that we have met with a paradox. Now we have some hope of making progress." Niels Bohr

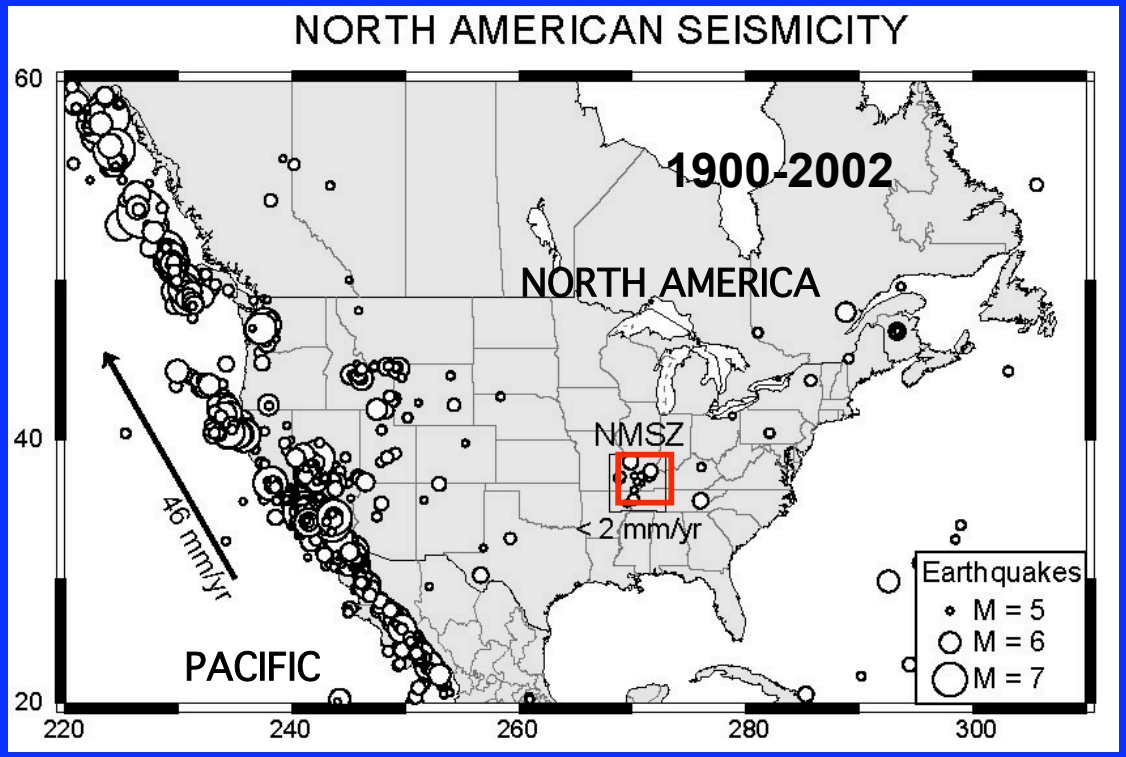
New Madrid seismic zone

M 7 earthquakes in 1811-12

Small earthquakes continue

Big ones might happen again

Don't know why, when, how dangerous



Still, somehow

1811-12 events acquired image as almost mythical cataclysms

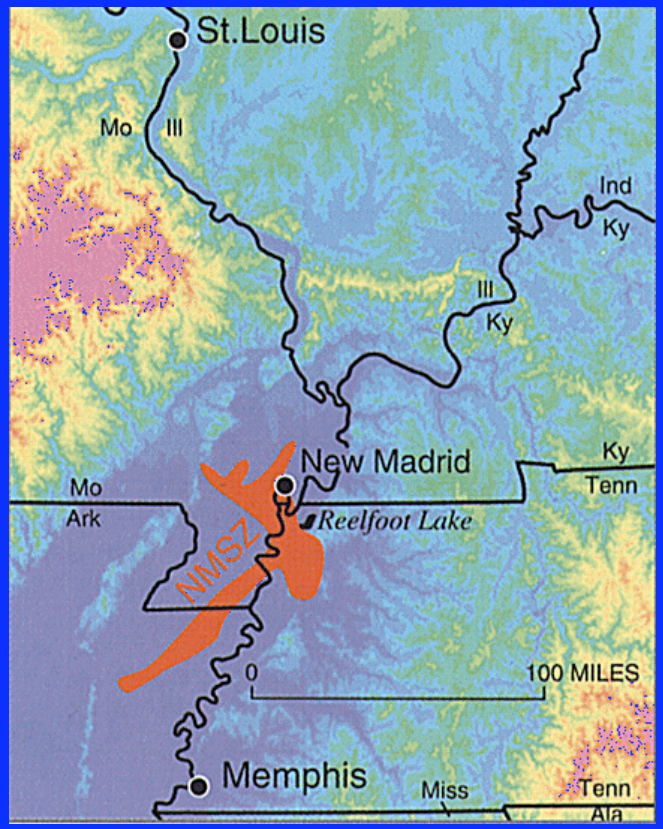
Hazard said comparable to or greater than California

New Madrid earthquakes can be considered

- Minor curiosity showing that plates differ slightly from ideal model of no internal deformation

- Type example of continental intraplate earthquakes

- Opportunity to explore how continental interiors deform, since little's known



What happened in 1811-12

What GPS data show about ongoing deformation

Model for intracontinental earthquakes

Implications for seismic hazards & policy

Collaborators 1990-present

Northwestern

PhD students
Andrew Newman (now Georgia Tech)
John Weber (now Grand Valley State)
Joe Engeln (now Missouri DNR)

Postdocs
Giovanni Sella (now National Geodetic Survey)
Resty Pelayo

Undergrad/Ms
James Hebden

Grad student field assistants
Gary Acton, Lisa Leffler, Lynn Marquez, Richard Sedlock, Mark Woods

Others

Tim Dixon & Ailin Mao (Miami)
John Schneider (Geoscience Australia)
Joseph Tomasello (Reeves Firm)
Andres Mendes (AON)
Mike Bevis (Ohio State)
Ken Hudnut (USGS)
Glen Mattioli (Arkansas)

Undergrad field Assistants
Grand Valley State

Field engineers
UNAVCO, JPL

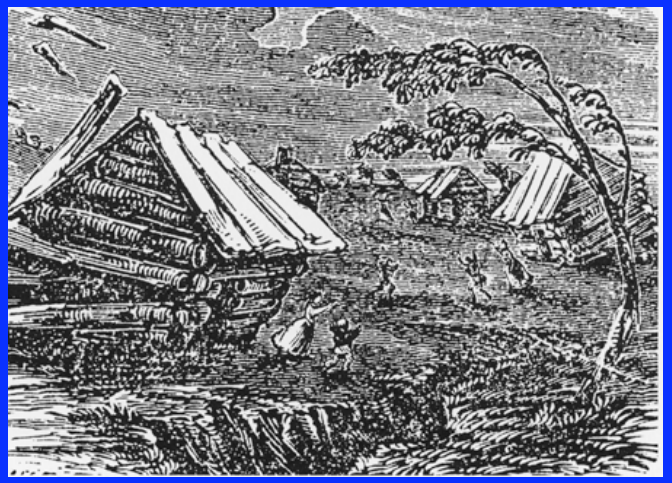
New Madrid:

December 16, 1811: "The house danced about, and seemed as if it would fall on our heads. I soon conjectured the cause of our trouble, and cried out that it was an Earthquake, and for the family to leave the house, which we found very difficult to do, owing to its rolling and jostling about. The shock was soon over, and *no injury was sustained, except the loss of the chimney*."

The earthquakes went on and on. Most were small, but one on January 23, 1812 was large enough to disrupt riverbanks and create more sand blows.

February 7, 1812 : " A concussion took place much more violent than those preceding." The town's houses, which sustained some damage like broken chimneys in the previous earthquakes but had not collapsed, *were "all thrown down*."

Sequence of earthquakes over months, with three major shocks

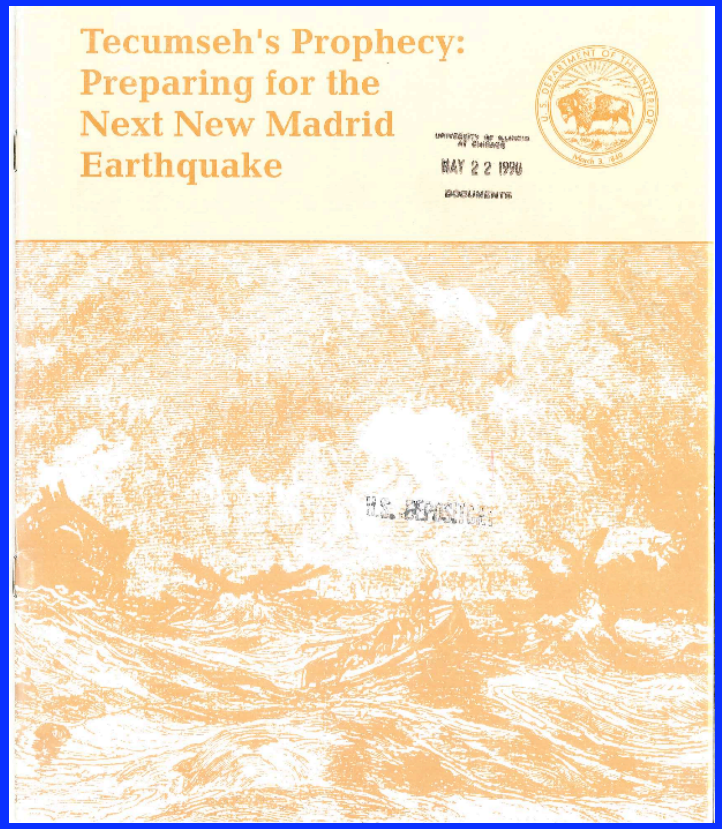


Historical Society of Missouri

Postdiction, not prediction

Shawnee chief Tecumseh didn't prophecy the 1811-12 earthquakes

Addressing tribes *after the earthquakes, he pointed to what had happened* as divine support for his cause: "The Great Spirit is angry with our enemies. He speaks in thunder, and the earth swallows up villages."



Penick, 1981; Hough & Bilham, 2006

Recent analysis of shaking Intensity (Hough et al., 2000) yields low/mid-magnitude 7 first inferred (Nuttli, 1973), not subsequently quoted 8 (Johnston, 1996)

St. Louis

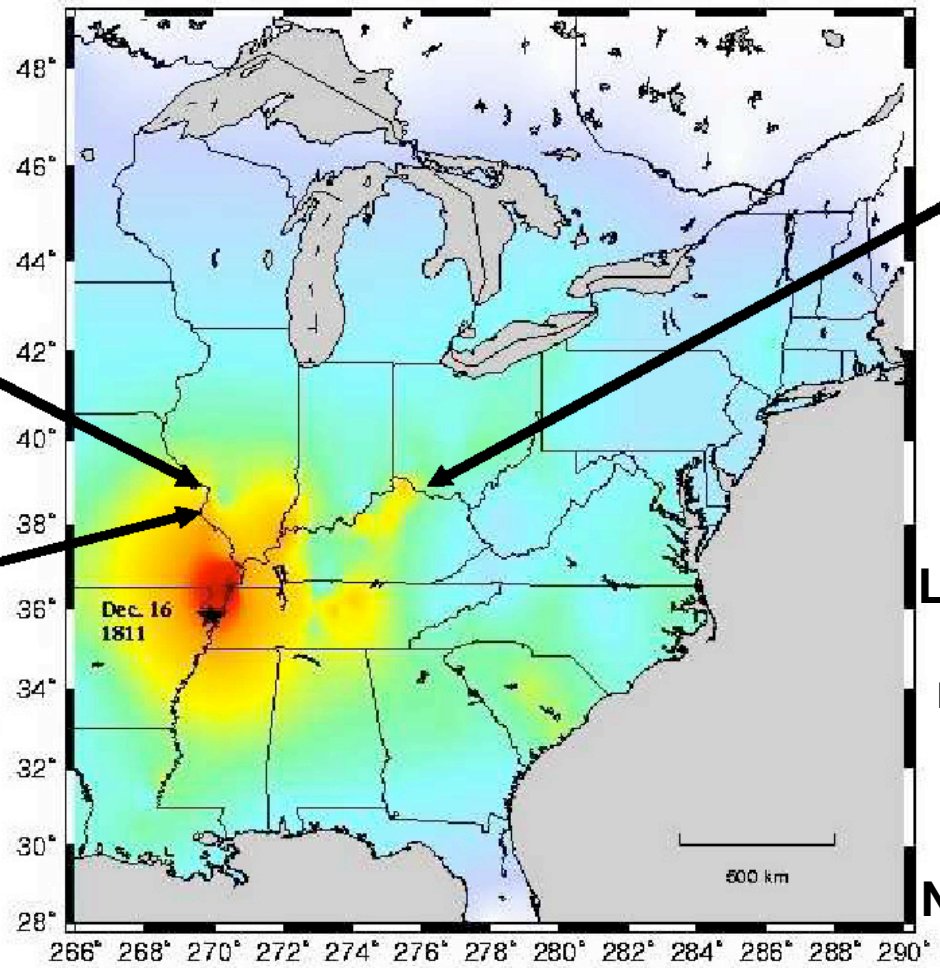
No lives have been lost, nor has the houses sustained much injury, a few chimneys have been thrown down.

Louisiana Gazette, Dec. 21, 1811

Ste. Genevieve

Shocks felt, caused no damage

Rozier, 1850



Kentucky hills south of Cincinnati:

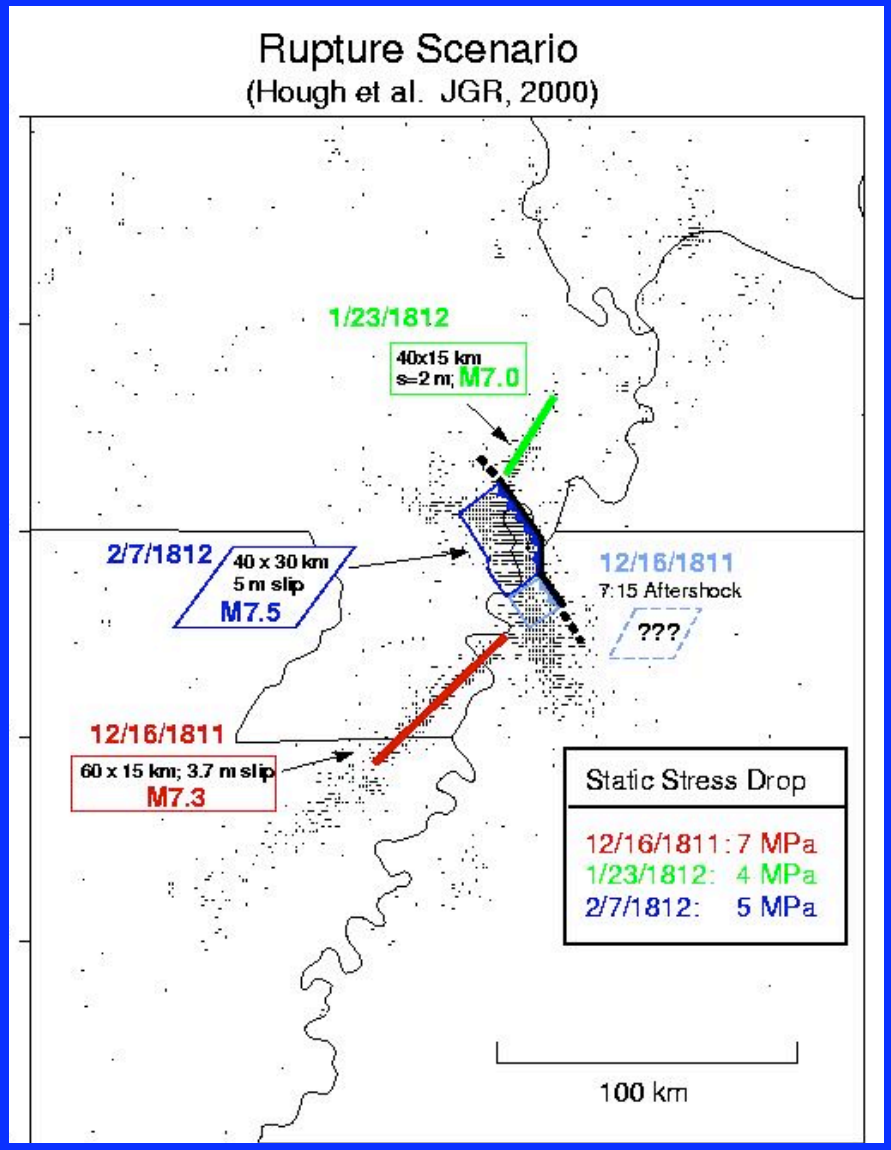
Many families ...slept during the shock...

Daniel Drake, 1815

Log cabin damage at New Madrid; minor damage in St Louis, Nashville, Louisville, etc. No Boston church bells ring

S. Hough

These were big earthquakes



Hidden Fury

The New Madrid Earthquake Zone

The danger posed by the New Madrid earthquake zone along the Mississippi River.

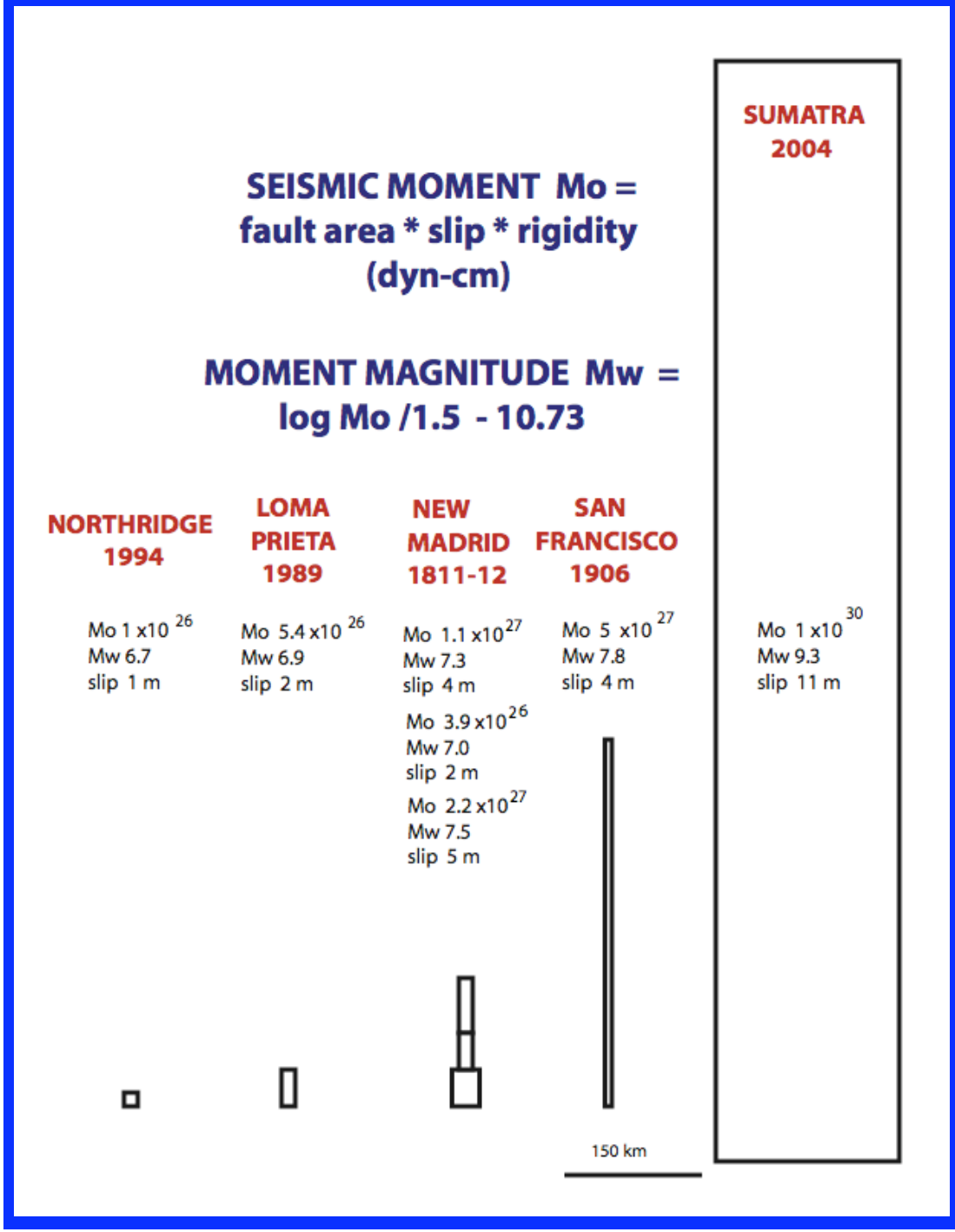
27 minutes
DVD-R version available
Color
Closed Captioned
Grade Level: 7-12, College, Adult
US Release Date: 1993
Copyright Date: 1993
ISBN (VHS): 1-56029-468-X
ISBN (DVD): 1-59458-441-9

"Interesting, easy to follow, full of good information."
****** Journal of Geological Education*

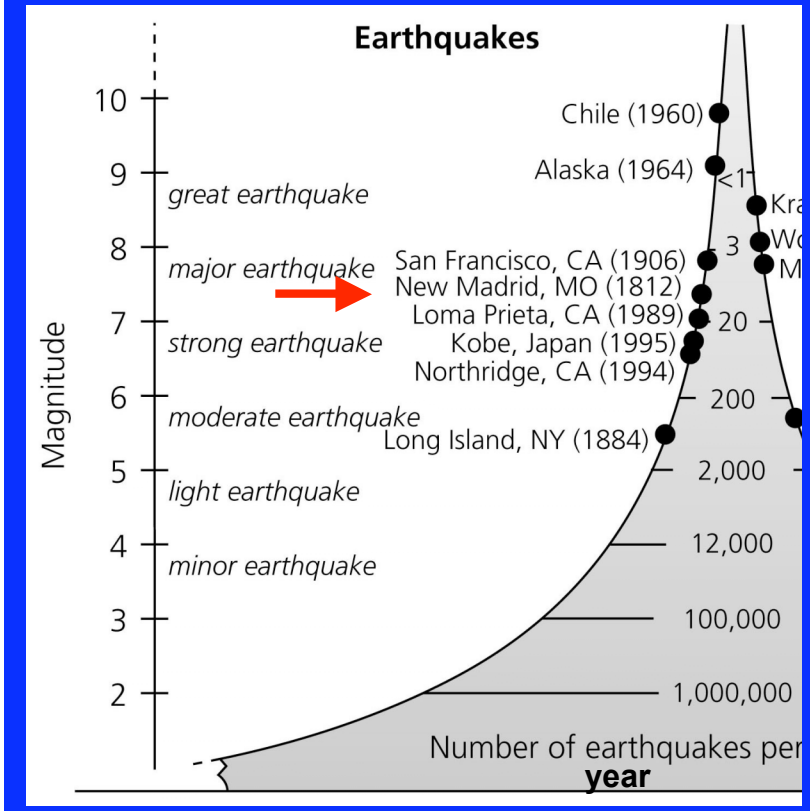
Produced by Doug Prose/Earth Images Foundation

The New Madrid earthquake zone, located along the Mississippi River near Memphis, Tennessee, has received little attention in recent years. But in 1811 it was the site of the most powerful series of earthquakes ever known on earth. Some two million square miles were affected, and shocks were felt as far away as Montreal, Canada - 1,200 miles from the epicenter.

But a lot smaller & more common than often stated

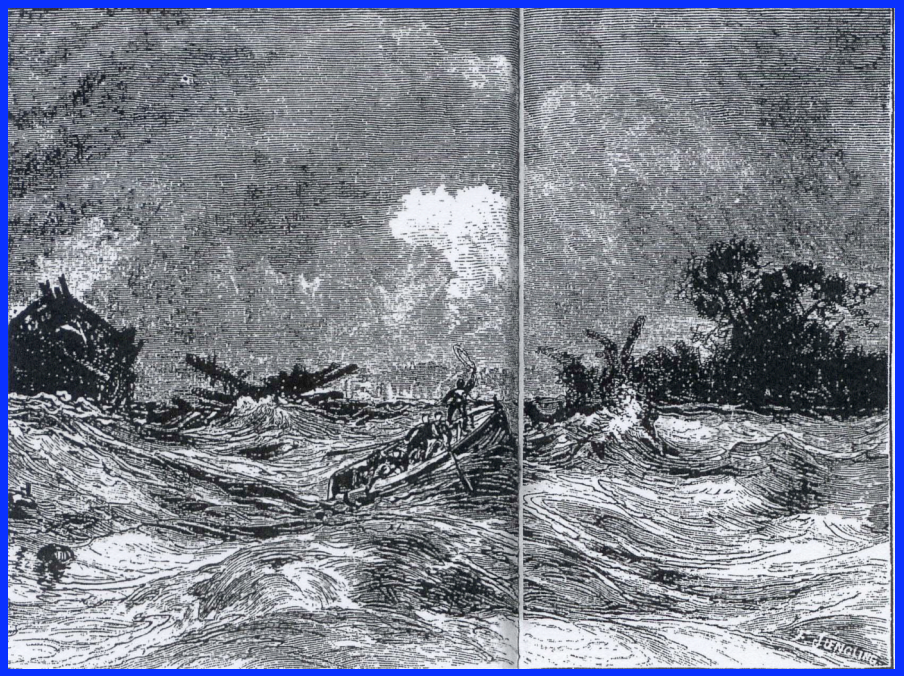


5-10 earthquakes of this size occur each year



Stein & Wysession (2003)
after IRIS

Did the Mississippi run backwards after February shock?



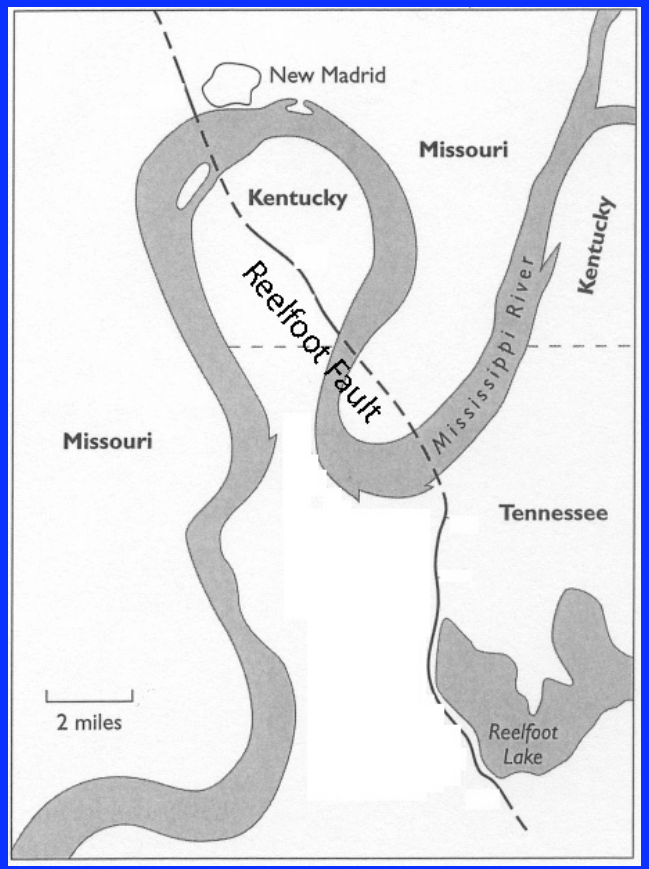
Historical Society of Missouri

"The current of the Mississippi was driven back upon its source with the greatest velocity for several hours in consequence of the elevation of its bed. But this noble river was not to be stayed in its course. Its accumulated waters came booming on, and over topping the barrier thus suddenly raised, carried everything before them with resistless power."

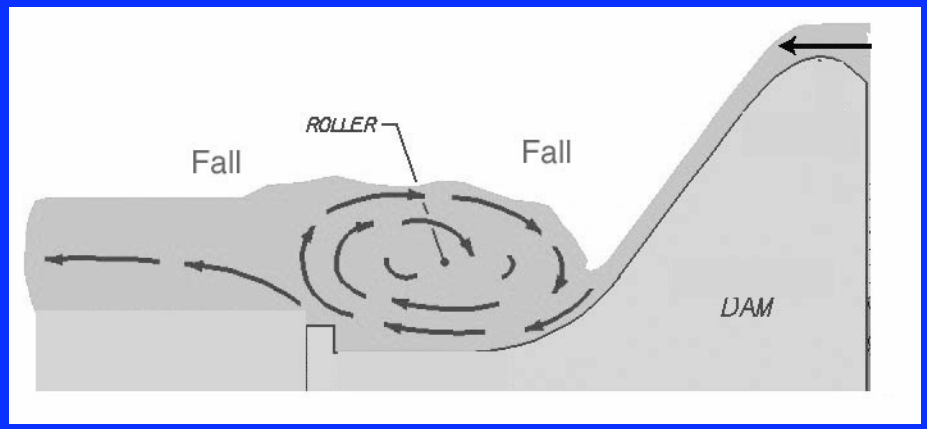
The reverse current lasted a few hours.

Real or legend?

Vertical motion on Reelfoot fault probably created temporary dams on riverbed that disrupted flow until current cleared them away



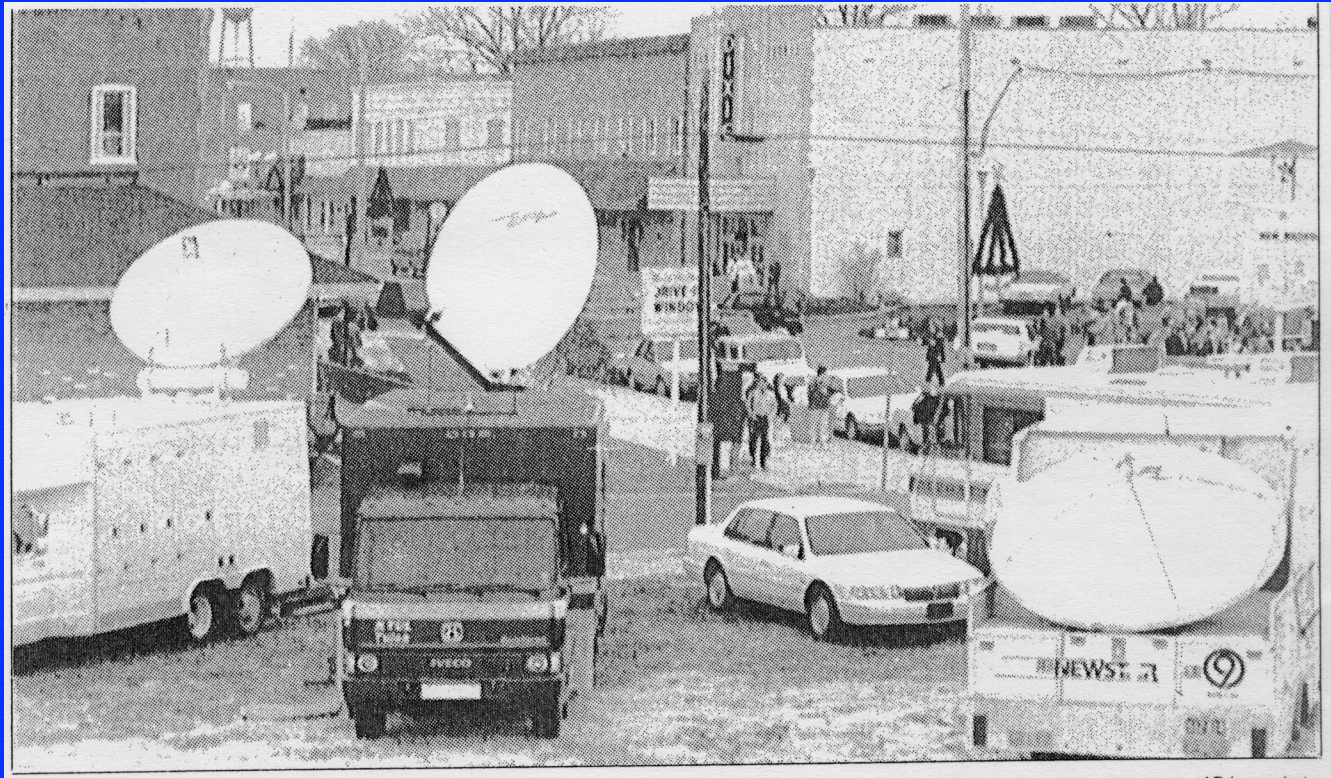
Sieh and LeVay, 1998



Flow over low head dam creates zone where surface water flows backwards, with waterfalls on upstream and downstream sides.

Boatmen perhaps encountered bigger & more complicated version, with back flow downriver from the first natural dams and slower current extending upriver.

Public fear 1811-12 recurrence



AP Laserphoto

Television trucks near Main Street in New Madrid, Mo., Sunday afternoon are just part of the flood of media that has poured into the town on the now-famous fault for the predicted quake.

Earthquake predicted for December 1990 by Iben Browning didn't happen

But earthquake fears are continually fed

Central United States Earthquake Consortium

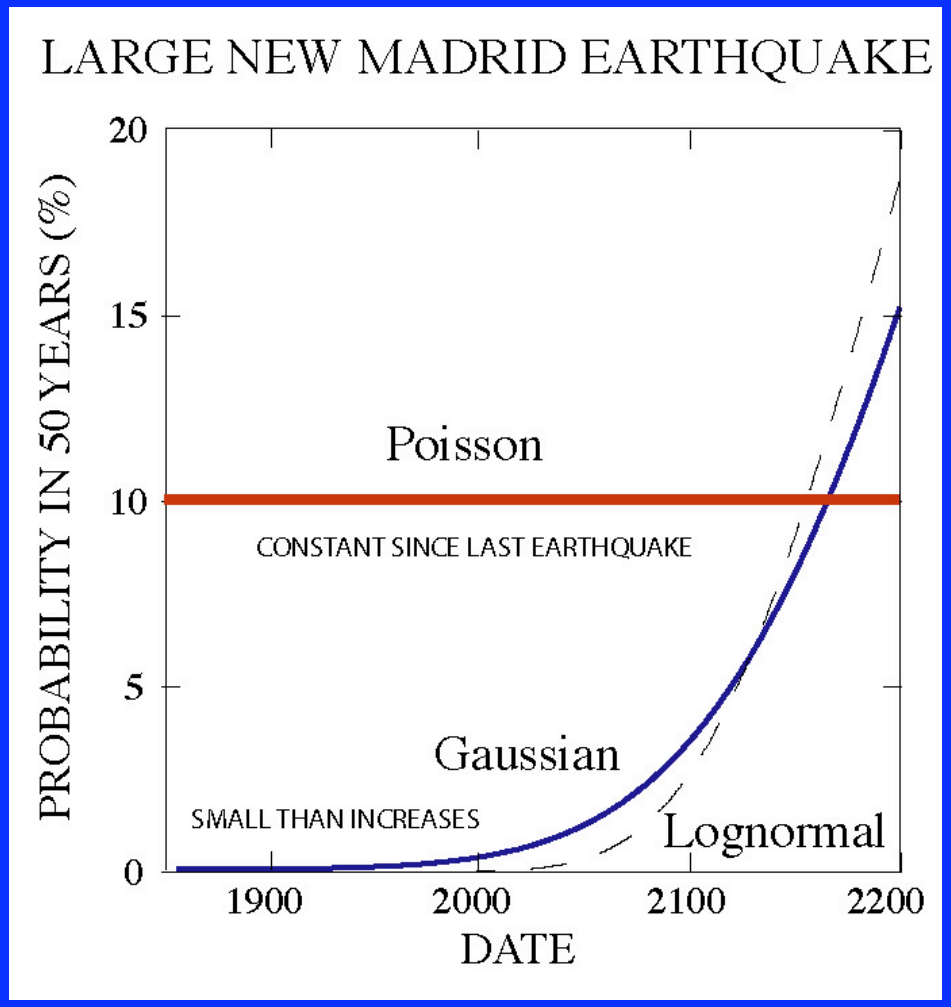
...a partnership to mitigate disasters and save lives

| HOME | EVENTS | PUBLICATIONS | SEARCH |

Can get any value, depending on assumptions of magnitude and recurrence

"Seismologists have predicted a 40-60% chance of a *devastating* earthquake in the New Madrid seismic zone in the next ten years. Those odds jump to 90% over the next 50 years. The potential magnitude of a *catastrophic* New Madrid quake dictates that we approach the preparedness on a regional basis"

Press release, 2000



Stein et al., 2003

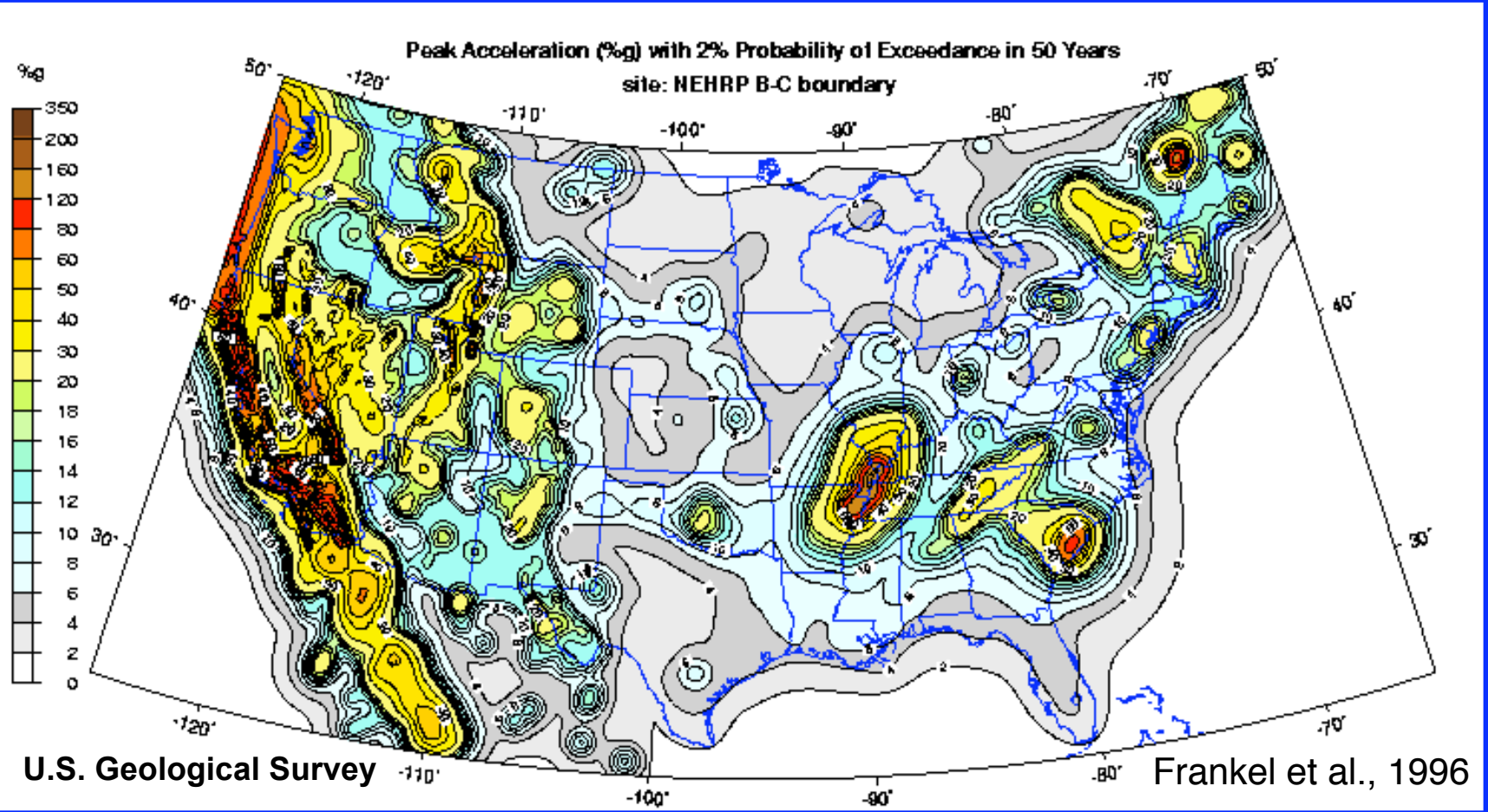
“Catastrophic” & “devastating” defined as M>6 which occurs ~ every 150 years somewhere in the New Madrid zone - most of which isn’t densely populated

Largest in the past century, 1968 (M 5.5) Illinois earthquake, caused no fatalities.

Damage consisted of fallen bricks from chimneys, broken windows, toppled television aerials, and cracked or fallen brick & plaster.

NEW MADRID SAID TO BE AS HAZARDOUS AS CALIFORNIA

Buildings should be built to same standards (FEMA)



U.S. Geological Survey

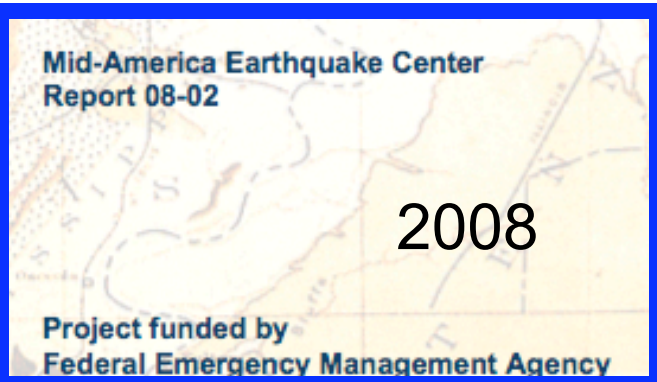
Frankel et al., 1996

CONSEQUENCE

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

J. Tomasello

Impact of Earthquakes on the Central USA



Scenario for 1811-12 style events

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)

"Apocalyptic claims do not have a good track record… arguments that simple, easily understood numbers are proof that the future holds complex, civilization-threatening changes deserve the most careful inspection."

More Damned Lies and Statistics by J. Best

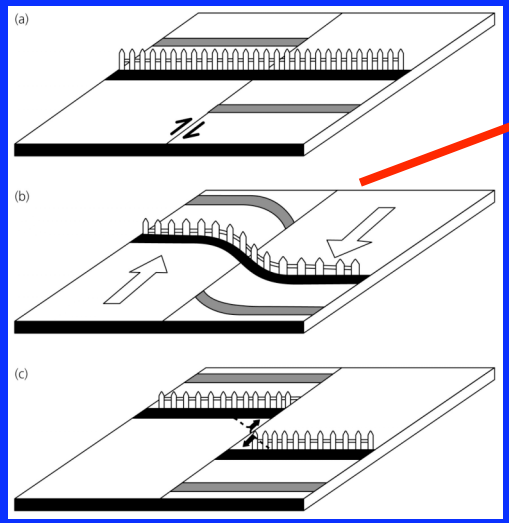
Impending doom scenarios assume 1811-12 size earthquakes will occur soon

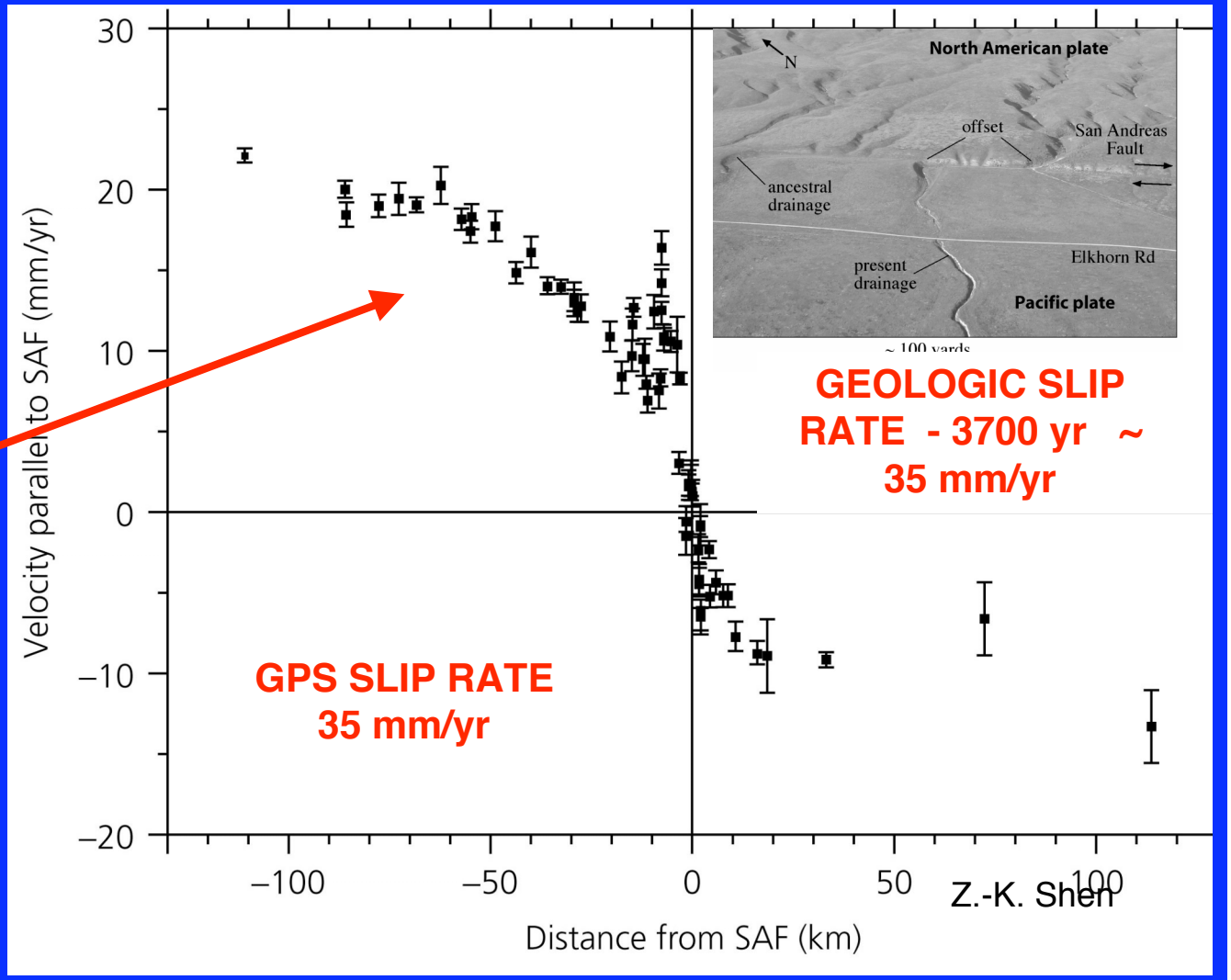
Before GPS, all we could say was that the future might be like the past…

Now we can test this hypothesis

San Andreas: GPS site motions show deformation accumulating that will be released in future earthquakes

Like a deformed fence

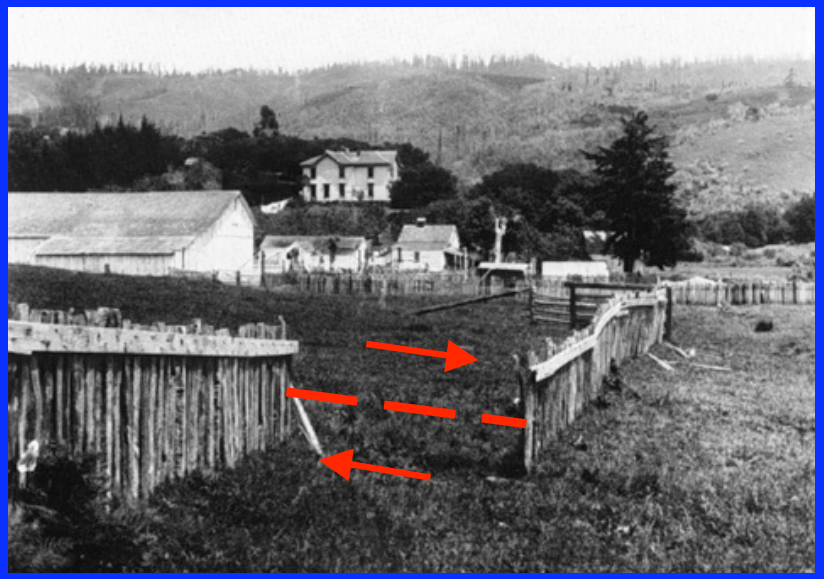


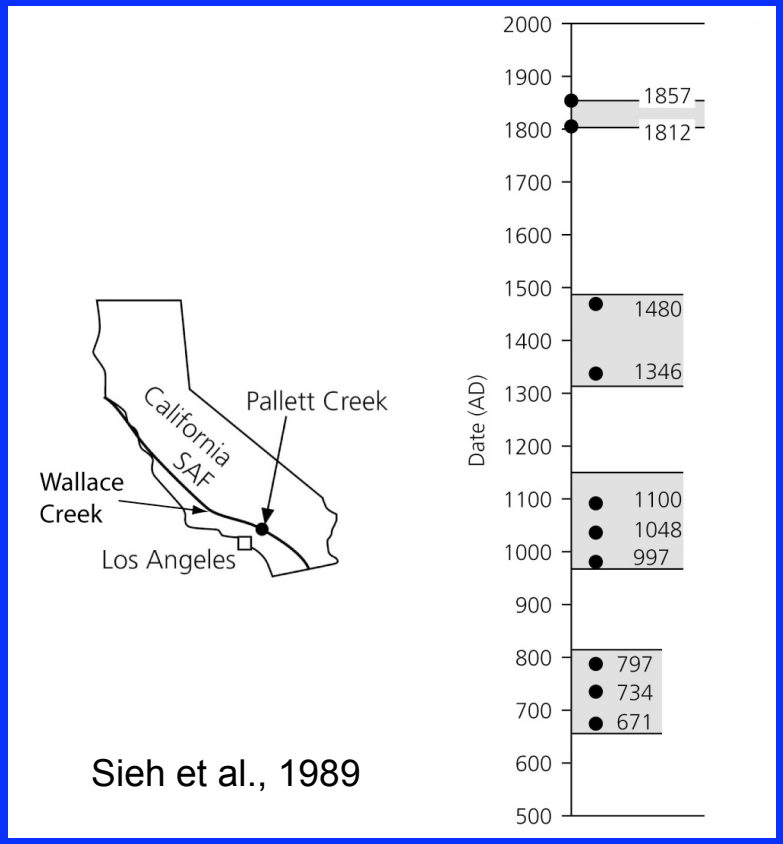


Geodetic, geologic, & plate motion rates agree

GPS site motions consistent with paleoseismic earthquake recurrence, showing steady motion

1906 San Francisco
M 7.7 Slip 4 m

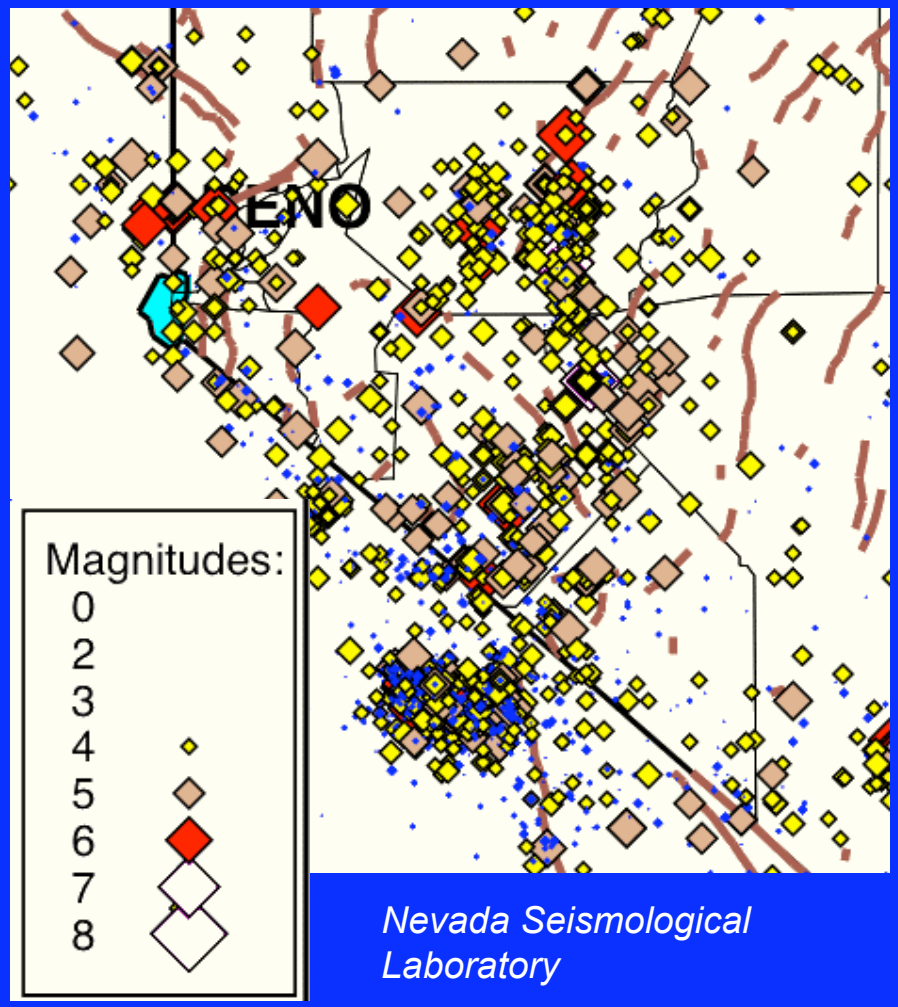




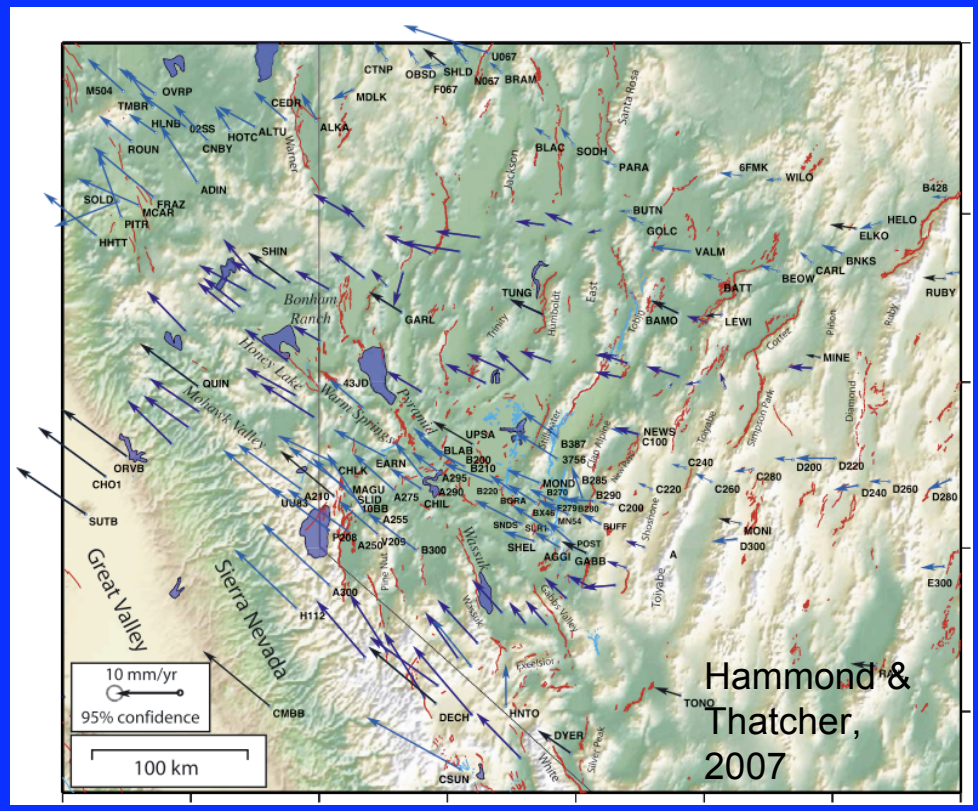
Expect earthquakes about every 4 m / 35 mm/yr or ~ 144 years

M >7 mean 132 yr

Nevada: GPS site motions show 2-3 mm/yr deformation accumulating that will be released in future large earthquakes



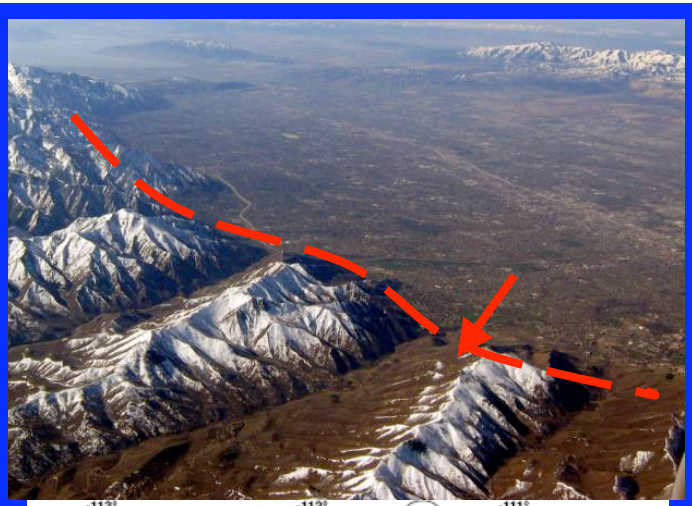
Nevada Seismological Laboratory

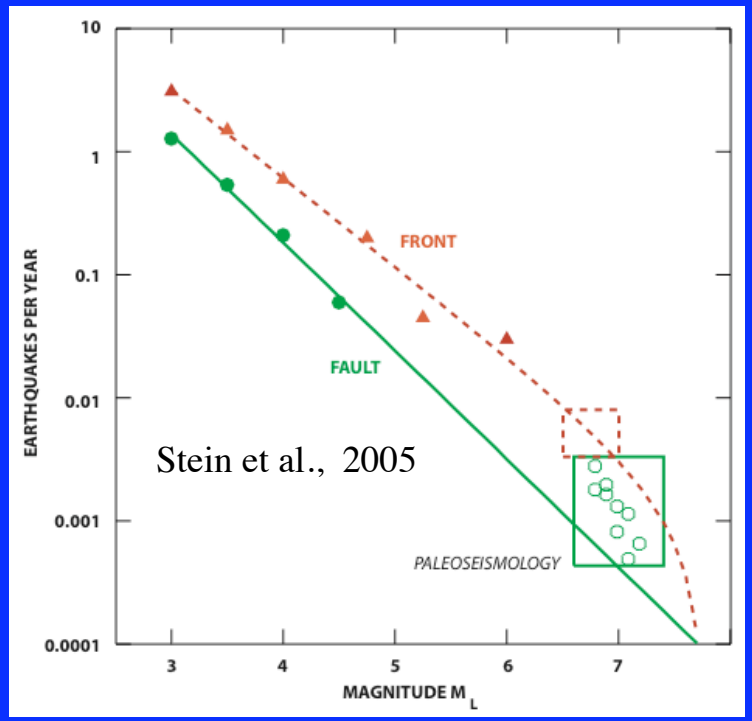


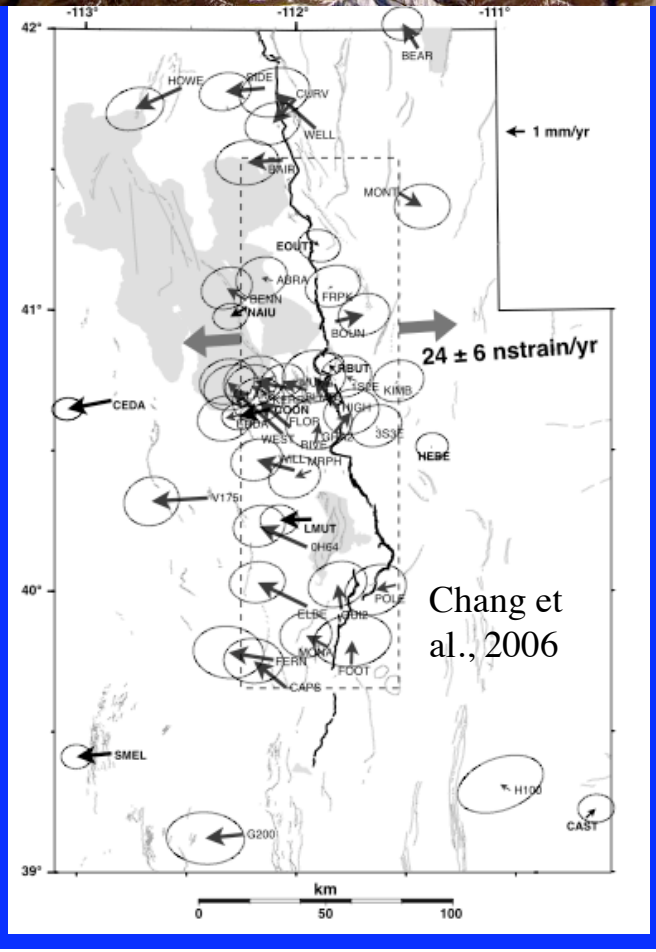
Hammond & Thatcher, 2007

Wasatch: GPS site motions show 1-2 mm/yr deformation accumulating that will be released in future large earthquakes

Consistent with M 7 expected ~ 1000 yr from seismicity & paleoseismology

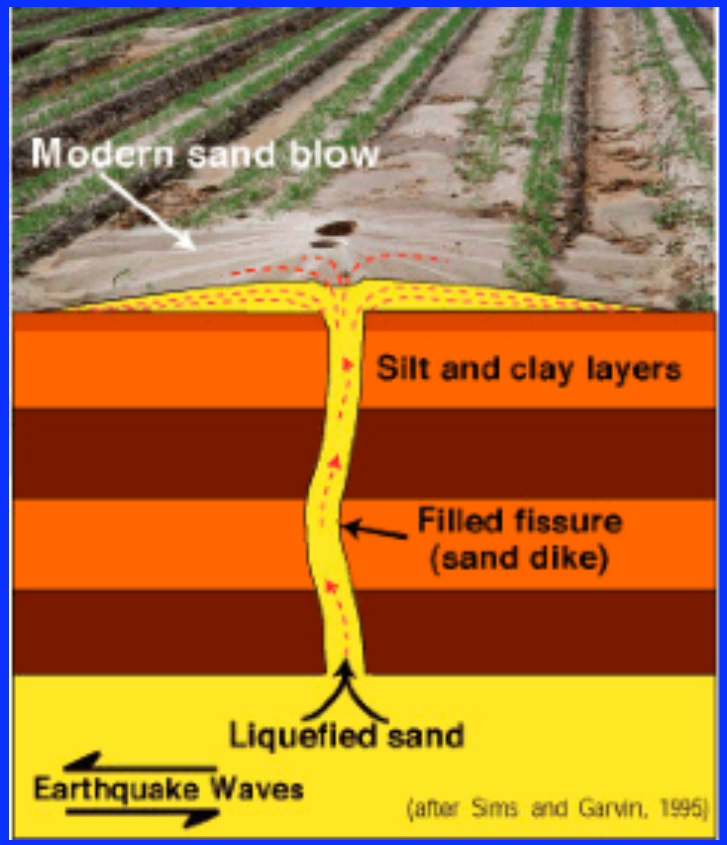






NEW MADRID EARTHQUAKE HISTORY

Paleoseismology - primarily paleoliquefaction - shows events ~ 1450 and 900 AD



Sand blows in New Madrid area (USGS)

Thus we started GPS at New Madrid expecting to find deformation accumulating, consistent with M7 events ~500 years apart

November 1991

After 8 years, 3 campaigns, 70 people from 9 institutions …

1999 surprise: no motion: 0 +/- 2 mm/yr

2 Centuries Later, Good News for Quake Area, Maybe

The New York Times Science, Tuesday, April 27, 1999. By Sandra Blakeslee

Midwesterners who worry about earthquakes got some good news last week: their risk of catastrophe may have been vastly overstated.

New measurements taken around New Madrid, MO - the epicenter of devastating earthquakes in 1811 and 1812 - show that the ground there is scarcely moving. According to many scientists, this means that it will take 2,500 to 10,000 years before another very large earthquake could occur in the region, although smaller, less damaging earthquakes are possible.

"The motions are small to zero," said Dr. Seth Stein, a professor of geological sciences at Northwestern University in Evanston, Ill., who made the new measurements. Earlier evidence showing rapid regional ground motion, a geologic sign that large quakes are probable, "was based on honest scientific errors," Dr. Stein said.

April 1999

Slow Deformation and Lower Seismic Hazard at the New Madrid Seismic Zone

Andrew Newman,[1] Seth Stein,[1*] John Weber,[2] Joseph Engeln,[3] Ailin Mao,[4] Timothy Dixon[4]

Global Positioning System (GPS) measurements across the New Madrid seismic zone (NMSZ) in the central United States show little, if any, motion. These data are consistent with platewide continuous GPS data away from the NMSZ, which show no motion within uncertainties. Both these data and the frequency-magnitude relation for seismicity imply that had the largest shocks in the series of earthquakes that occurred in 1811 and 1812 been magnitude 8, their recurrence interval should well exceed 2500 years, longer than has been assumed. Alternatively, the largest 1811 and 1812 earthquakes and those in the paleoseismic record may have been much smaller than typically assumed. Hence, the hazard posed by great earthquakes in the NMSZ appears to be overestimated.

No motion

Seismicity migrates

Recent cluster likely ended

Hazard overestimated

It is also possible that 1811–1812–style earthquakes may never recur. If more accurate future surveys continue to find essentially no interseismic slip, we may be near the end of a seismic sequence. It has been suggested that because topography in the New Madrid region is quite subdued, the NMSZ is a feature no older than a few million years and perhaps as young as several thousand years (*21*). Therefore, New Madrid seismicity might be a transient feature, the present locus of intraplate strain release that migrates with time between fossil weak zones.

Although much remains to be learned about this intriguing example of intraplate tectonics, the present GPS data imply that 1811–1812–size earthquakes are either much smaller or far less frequent than previously assumed. In either case, it seems that the hazard from great earthquakes in the New Madrid zone has been significantly overestimated. Hence, predicted ground motions used in building design there, such as the National Seismic Hazard Maps (*22*) that presently show the seismic hazard there exceeding that in California, should be reduced.

MAXIMUM MOTION STEADILY CONVERGES TO ZERO

Rate v of motion of a monument that started at x_1 and reaches x_2 in time T

$$v = (x_1 - x_2)/T$$

If position uncertainty is given by standard deviation σ

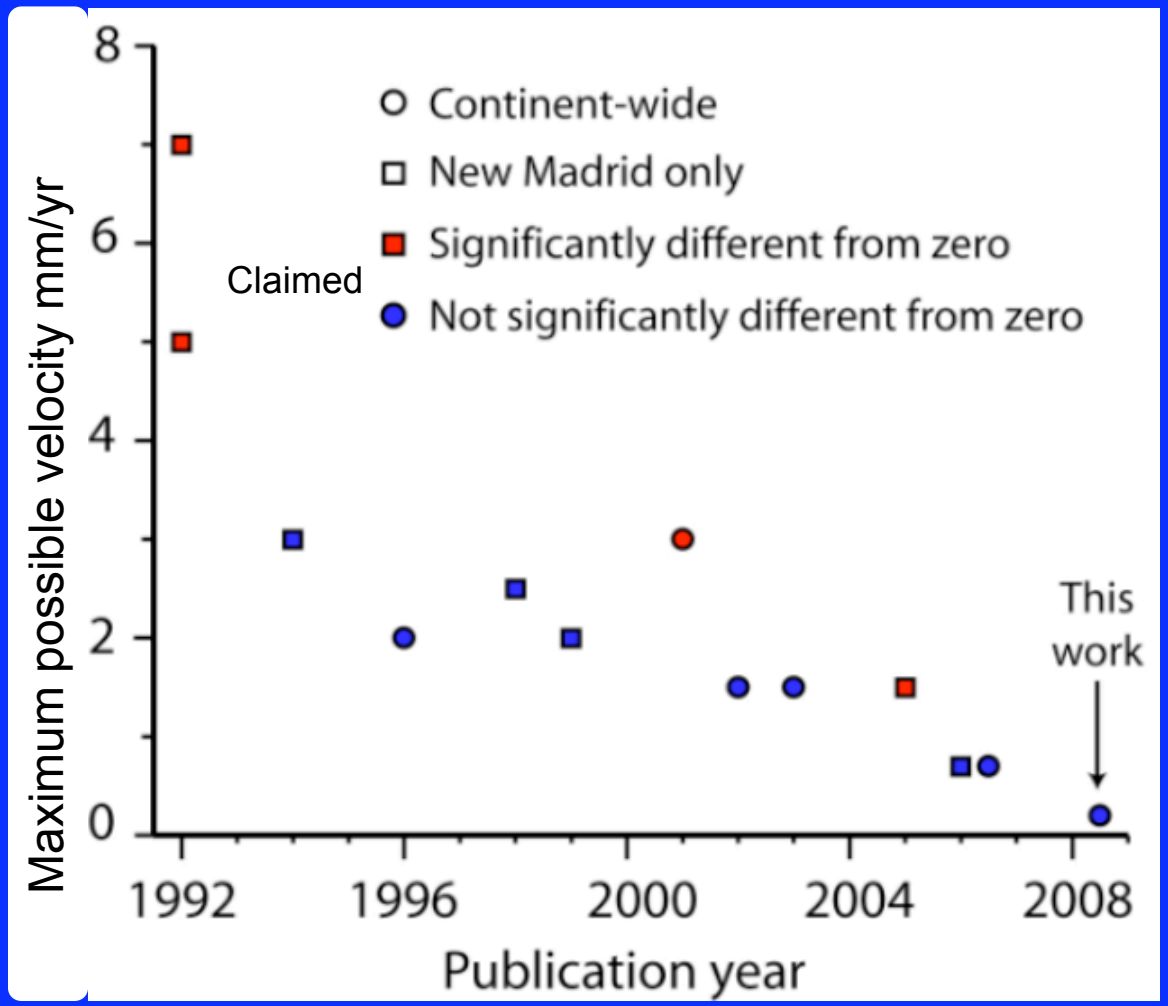
Rate uncertainty is

$\sigma_v = 2^{1/2} \sigma / T$

Rate precision improves with longer observations

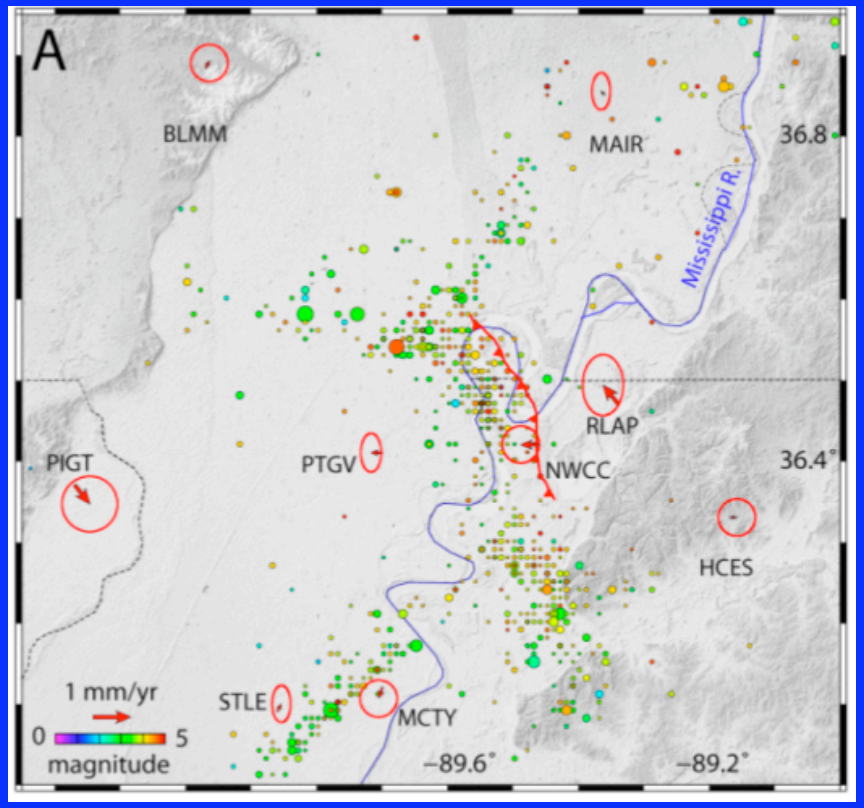
Rates < 0.2 mm/yr, will continue to converge on zero unless ground motion starts

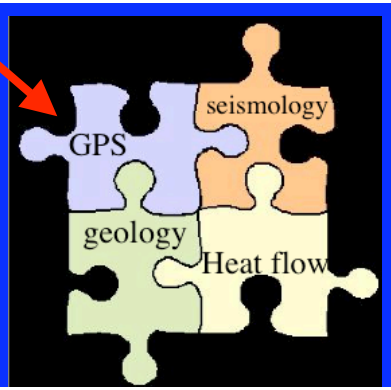
Strain rate does the same: $< 2 \times 10^{-9}$ /yr and shrinking



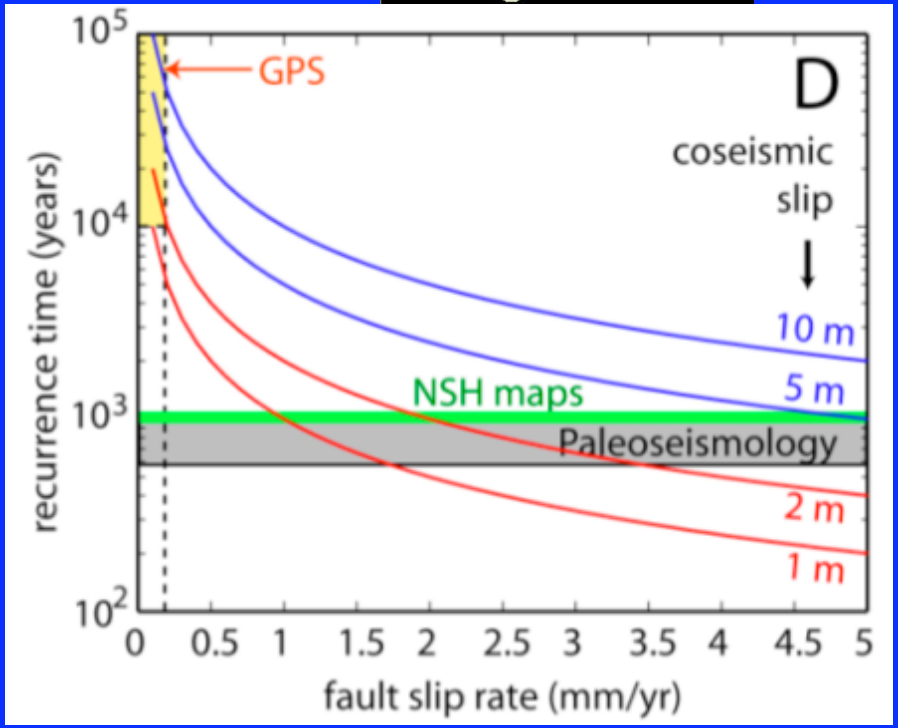
Calais & Stein, 2009

GPS SHOWS LITTLE OR NO MOTION





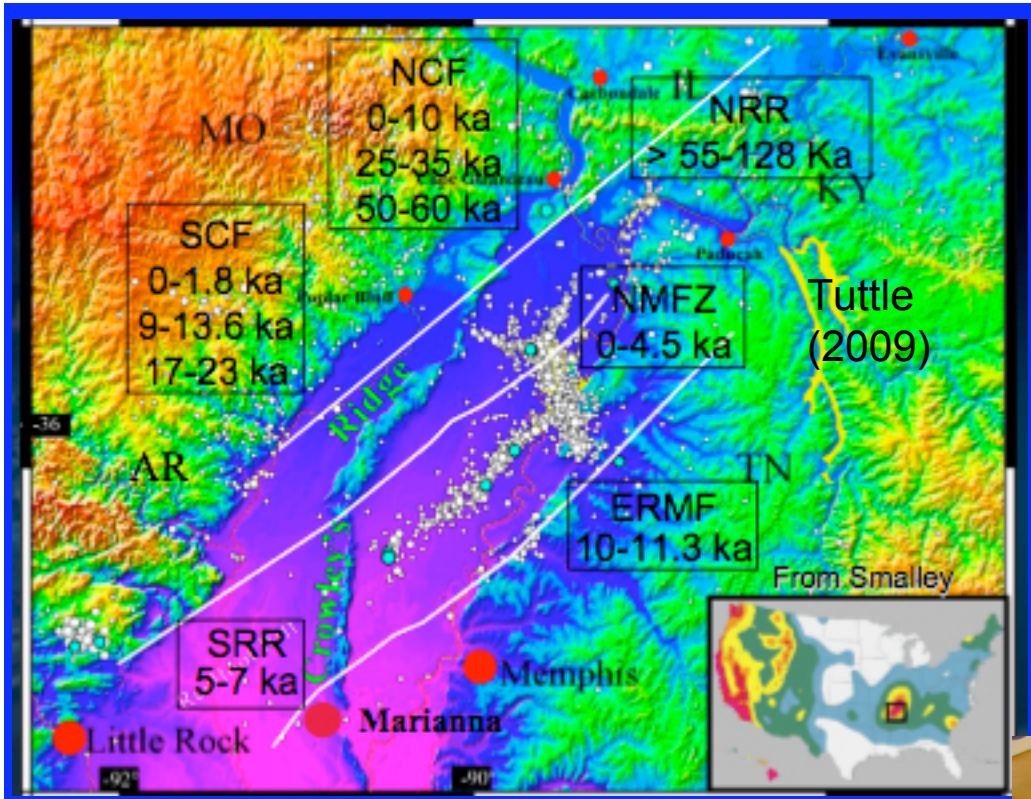
Calais & Stein, 2009



Motions with respect to the rigid North American plate are < 0.2 mm/yr , and within their error ellipses. Data do not require motion, and restrict any motion to being very slow.

Very long time would be needed to store up the slip needed for a future large earthquake

For steady motion, M 7 is at least 10,000 years away: M 8 100,000



Large earthquake cluster in past 2000 years isn't representative of long term NMSZ behavior

Recent large earthquake cluster likely ended

Seismicity migrates among faults due to fault interactions (stress transfer)

Many faults active in past show little present seismicity

OLD VIEW:

Intraplate zone acts like slow (< 2 mm/yr) plate boundary

Steady focused deformation: *past* shown by geology & earthquake record consistent with *present* shown by geodesy, and predicts future seismicity

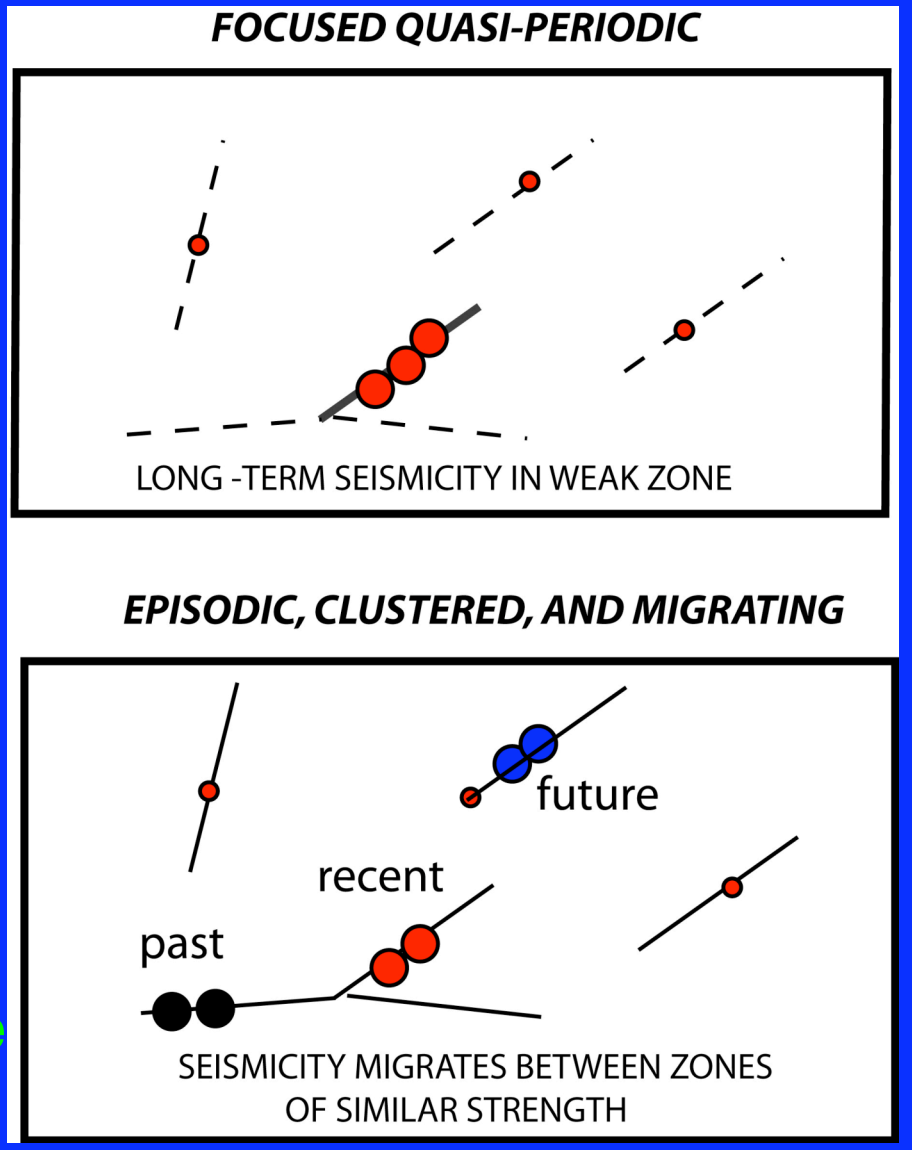
NEW VIEW:

Complex regional system of interacting faults

Deformation varies in space and time

Deformation can be steady for a while then shift

Past can be poor predictor



McKenna, Stein & Stein, 2007

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

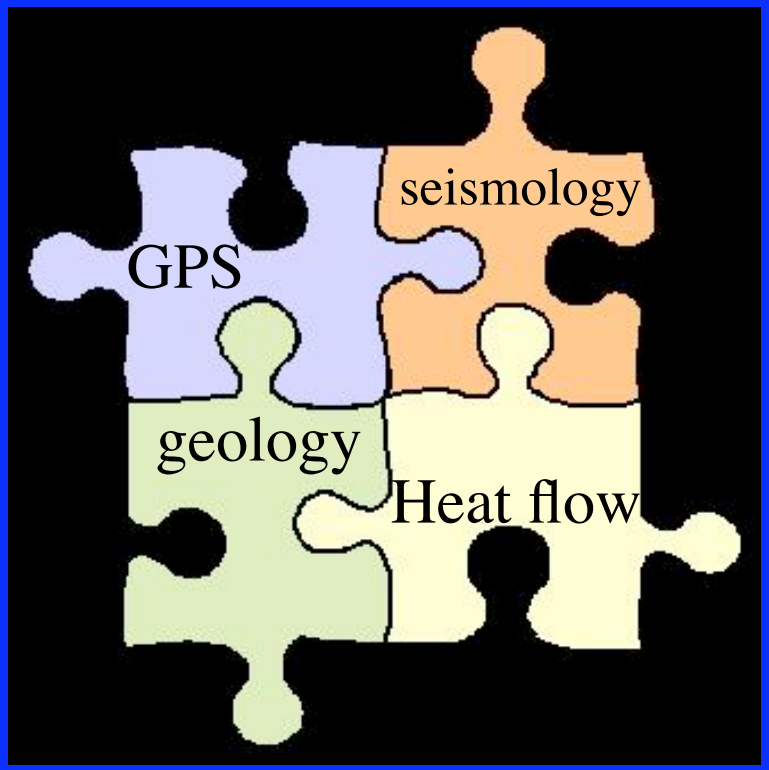
In complex systems, the whole behaves in ways more complicated than can be understood from analysis of its component parts.

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.

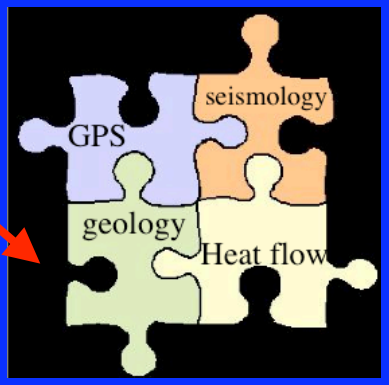
Studying such systems requires moving beyond the traditional reductionist approach, which focuses on the system's simplest component, understands it in detail, and generalizes it for the entire system. The system is viewed as a totality, so local effects in space and time result from the system as a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

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

Combining data types for New Madrid illustrates general aspects of continental intraplate earthquakes

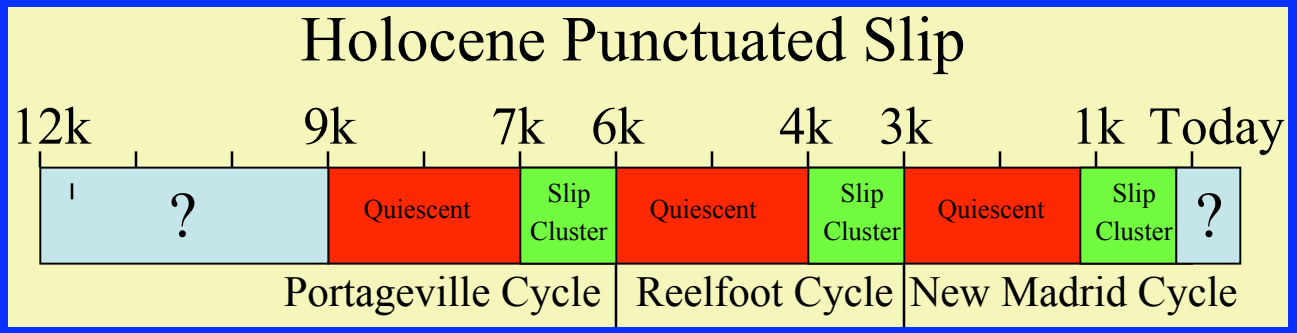


GEOLOGY ALSO IMPLIES NEW MADRID EARTHQUAKES ARE EPISODIC & CLUSTERED



Lack of significant fault topography, jagged fault, and other geological data, imply that recent pulse of activity is only a few thousand years old.

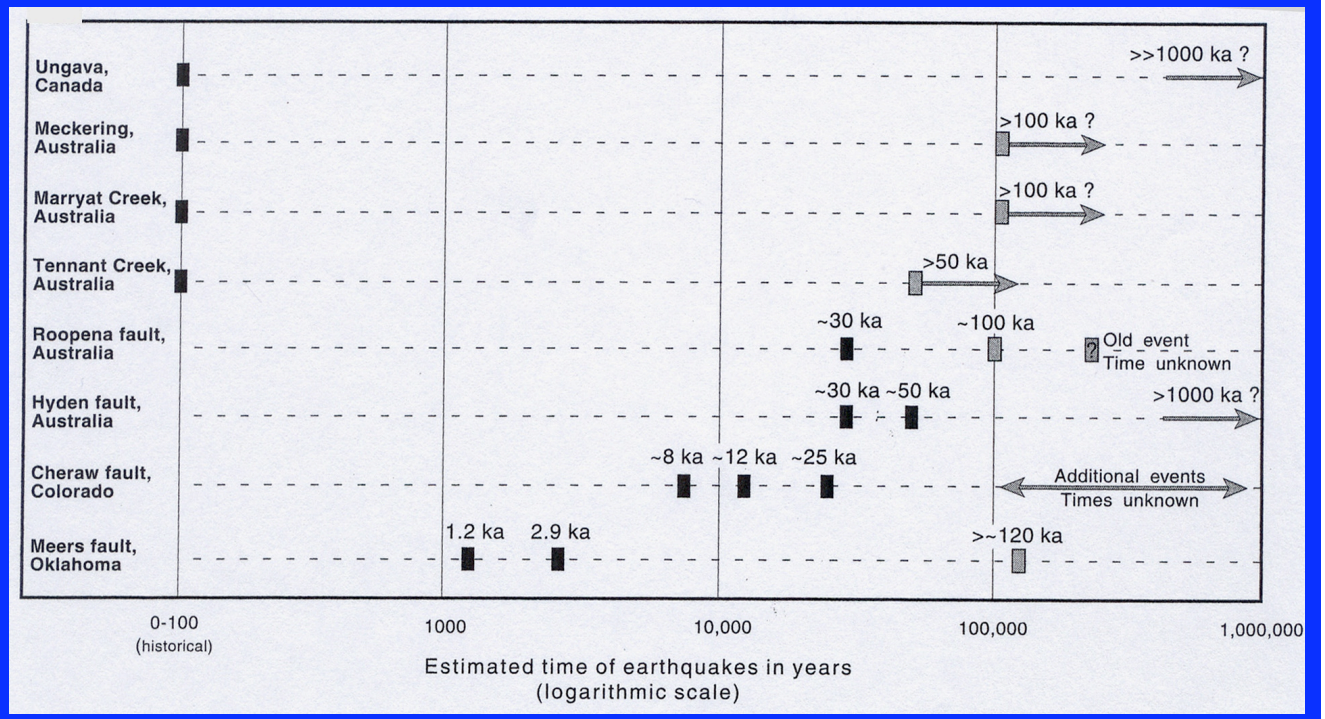
New Madrid earthquake history inferred from Mississippi river channels



Holbrook et al., 2006

CONTINENTAL INTRAPLATE EARTHQUAKES ARE OFTEN EPISODIC, CLUSTERED & MIGRATING

"Large continental interior earthquakes reactivate ancient faults … geological studies indicate that earthquakes on these faults tend to be temporally clustered and that recurrence intervals are on the order of tens of thousands of years or more." (Crone et al., 2003)

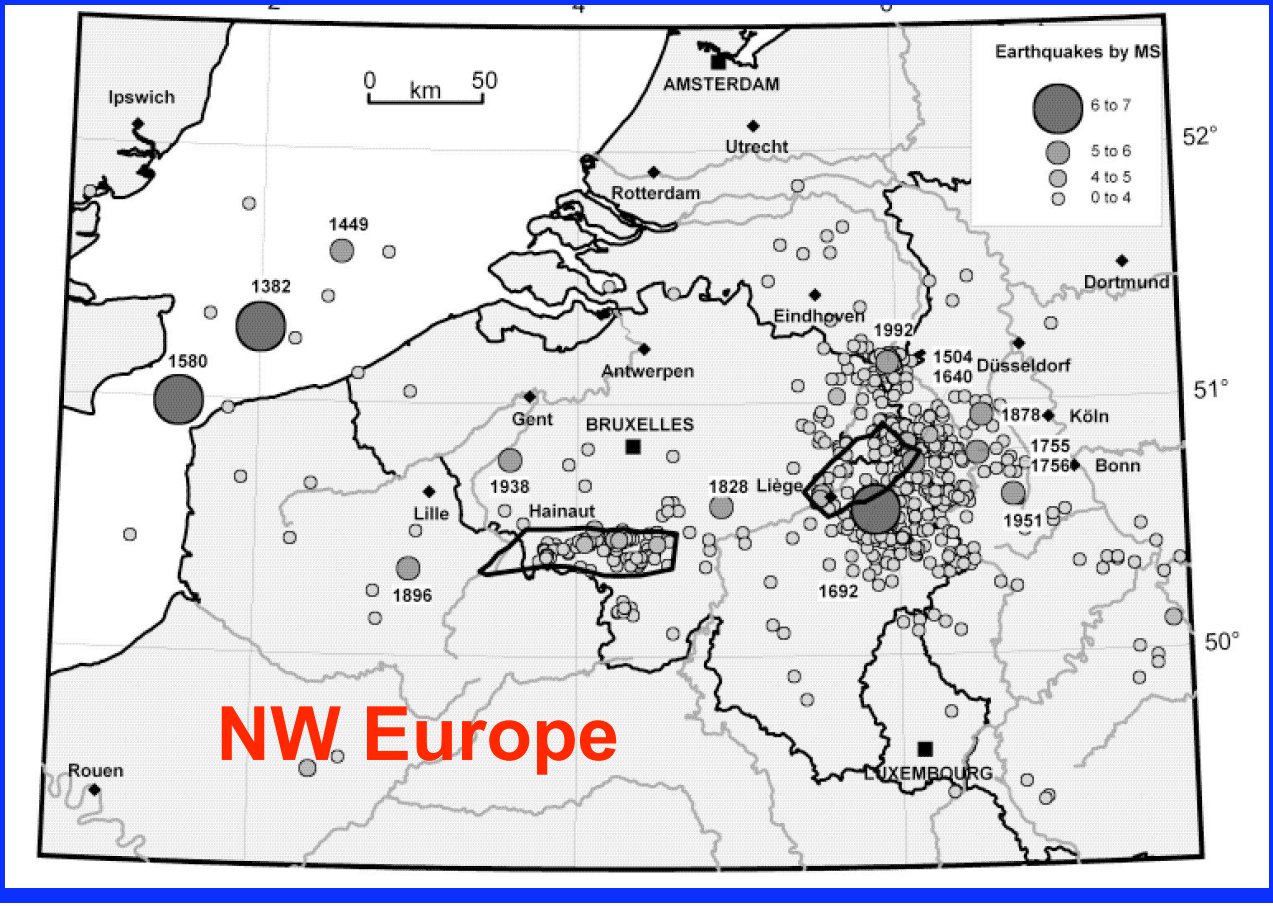


Meers fault, Oklahoma
Active 1000 years ago, dead now

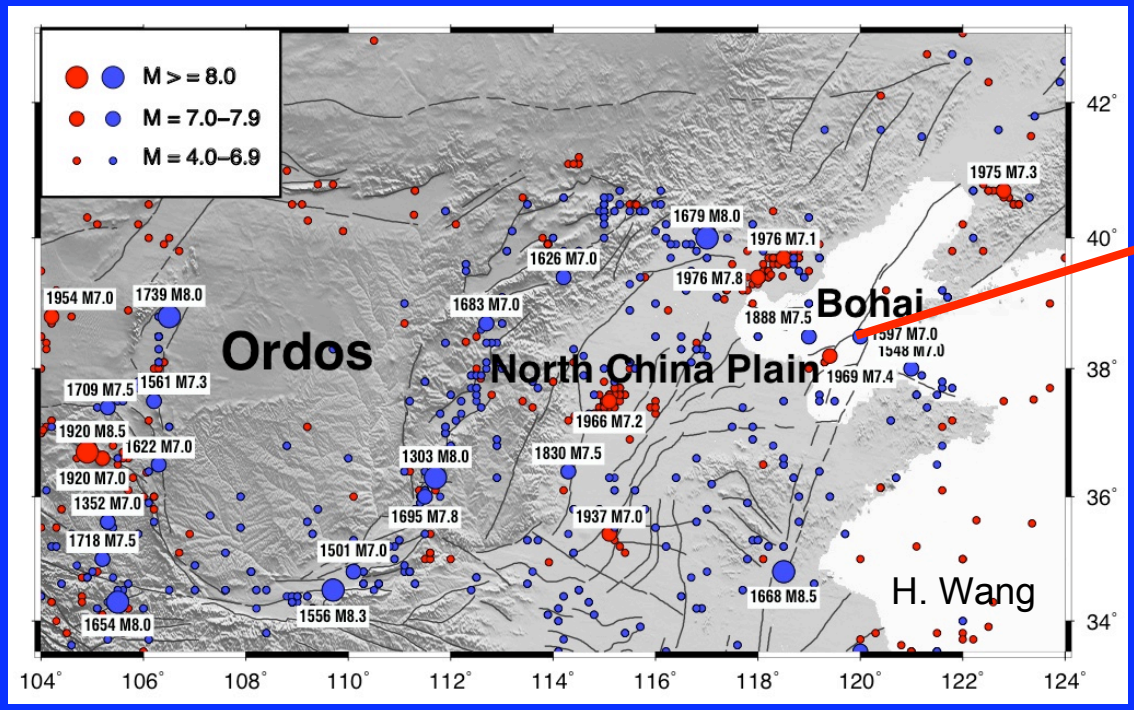
MIGRATING SEISMICITY

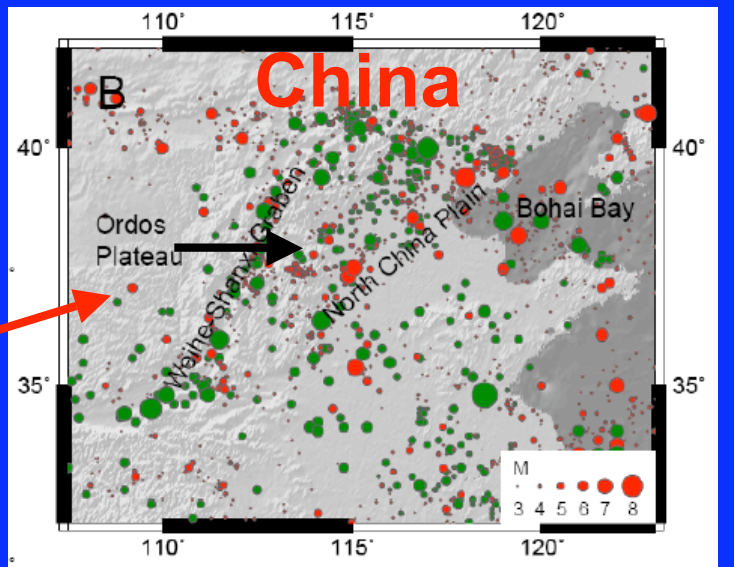
"During the past 700 years, destructive earthquakes generally occurred in different locations, indicating a migration of seismicity with time."

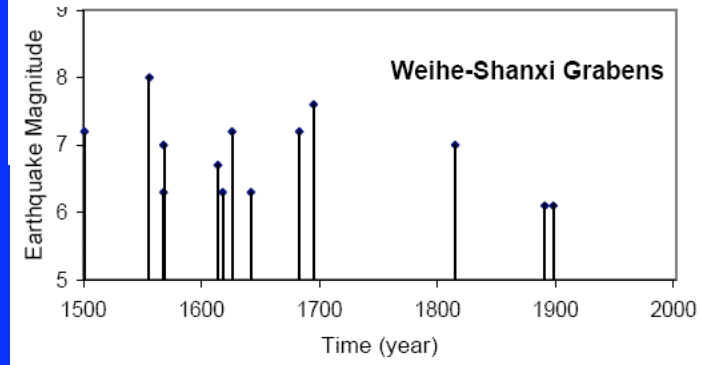
(Camelbeeck et al., 2007)

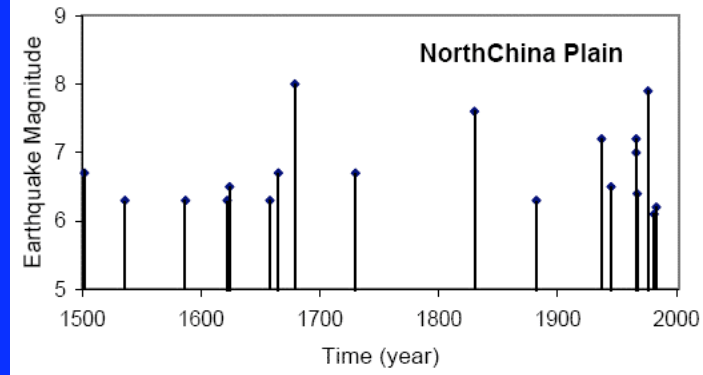


MIGRATING SEISMICITY









In North China, not one M>7 earthquake repeated in the same place since 1300 AD.

Since 1700 seismicity has been migrating from Shanxi Grabens to North China plain

Li, Liu & Stein, 2009

Rupture process in plate boundary & intraplate earthquakes are essentially the same

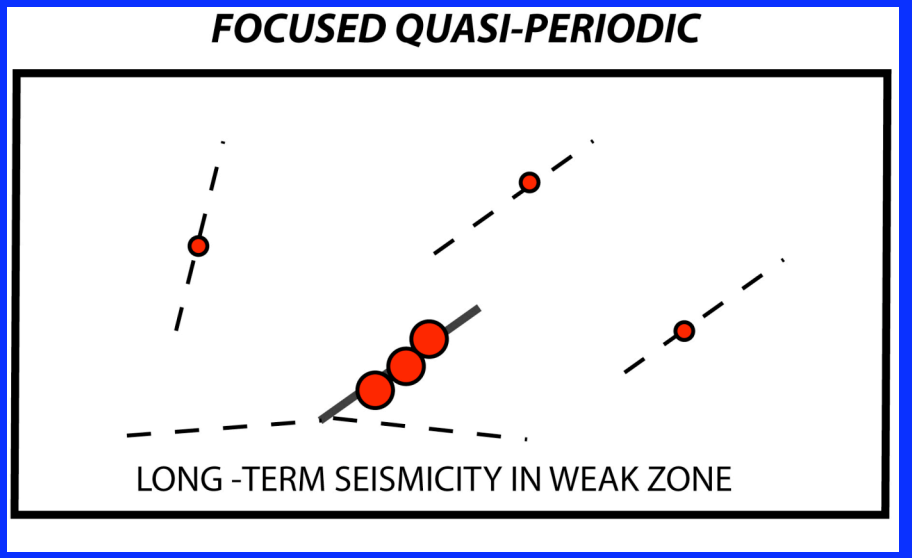
Different spatio-temporal patterns of seismicity result from

- geometry of faults on which earthquakes occur

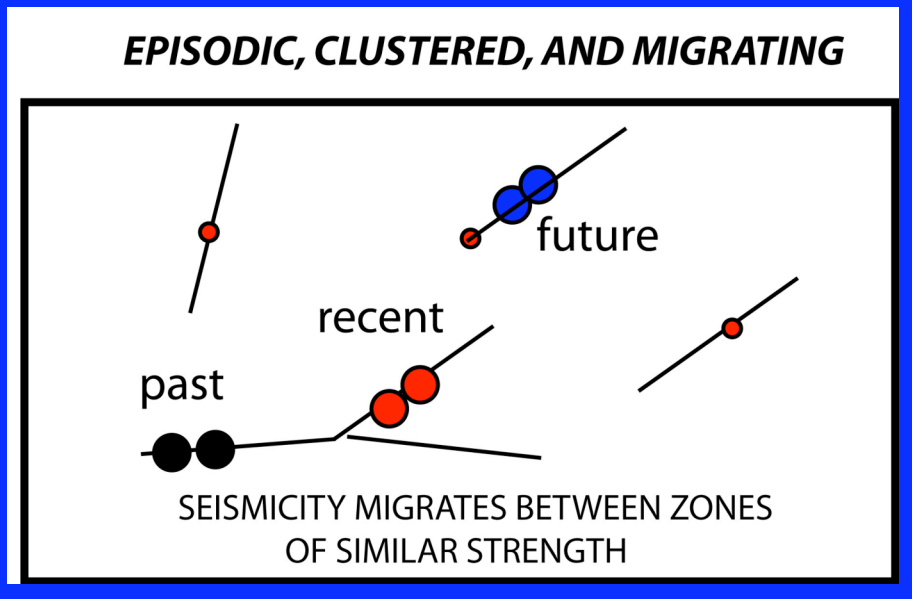
- stresses that cause rupture on them

McKenna, Stein & Stein, 2007

PLATE BOUNDARY



CONTINENTAL INTERIOR

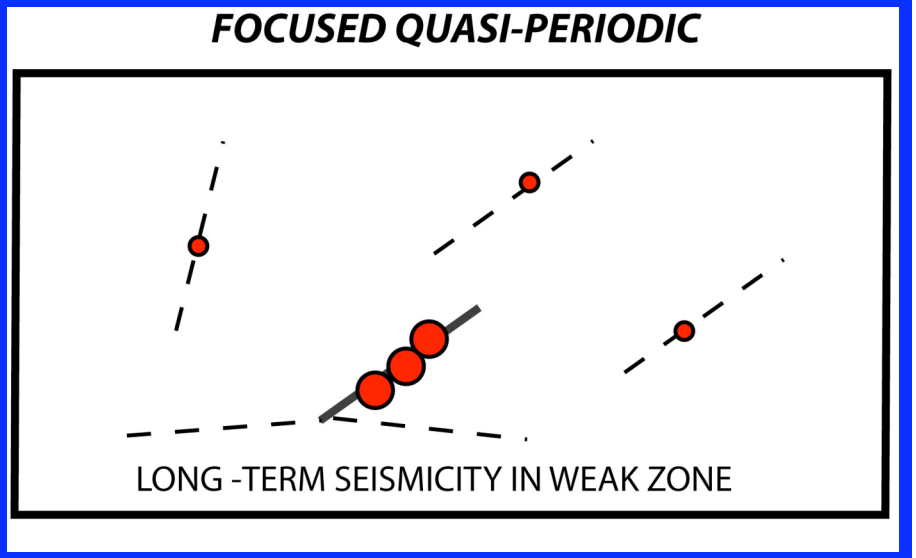


Major fault *loaded rapidly*, primarily by steady plate motion reflecting regional stress field that usually changes slowly

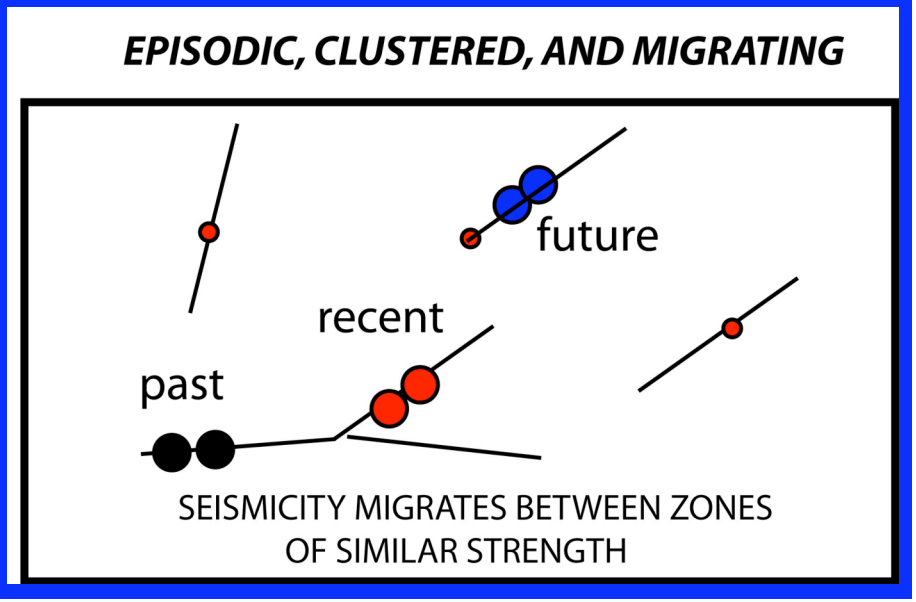
Network of faults *loaded slowly* by sources of stress localized in space and time including fault interactions

McKenna, Stein & Stein, 2007

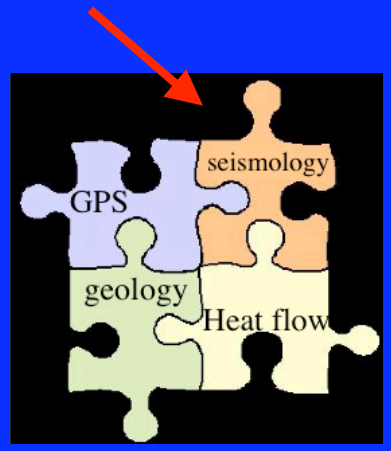
PLATE BOUNDARY

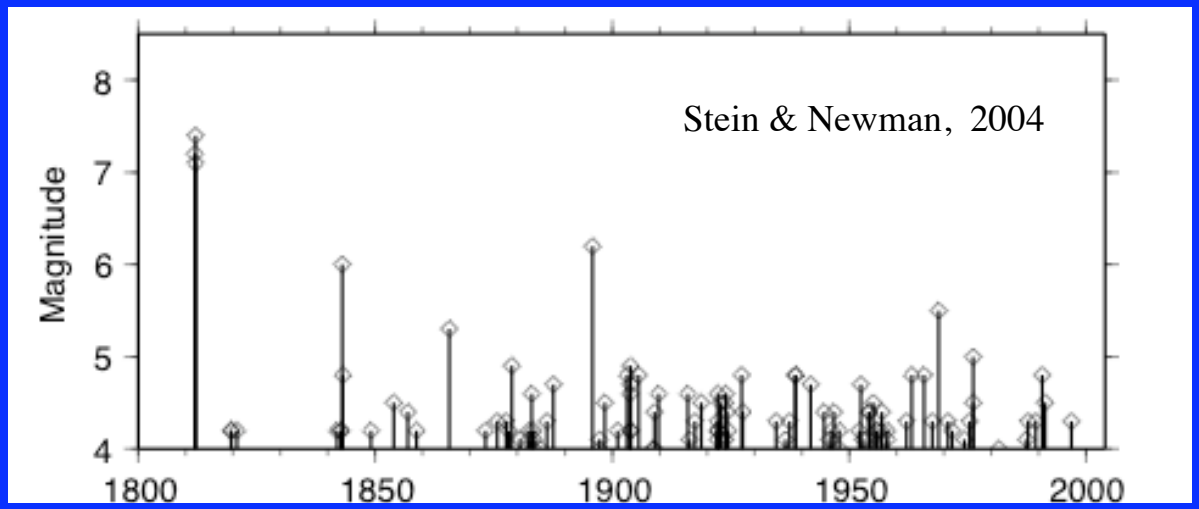


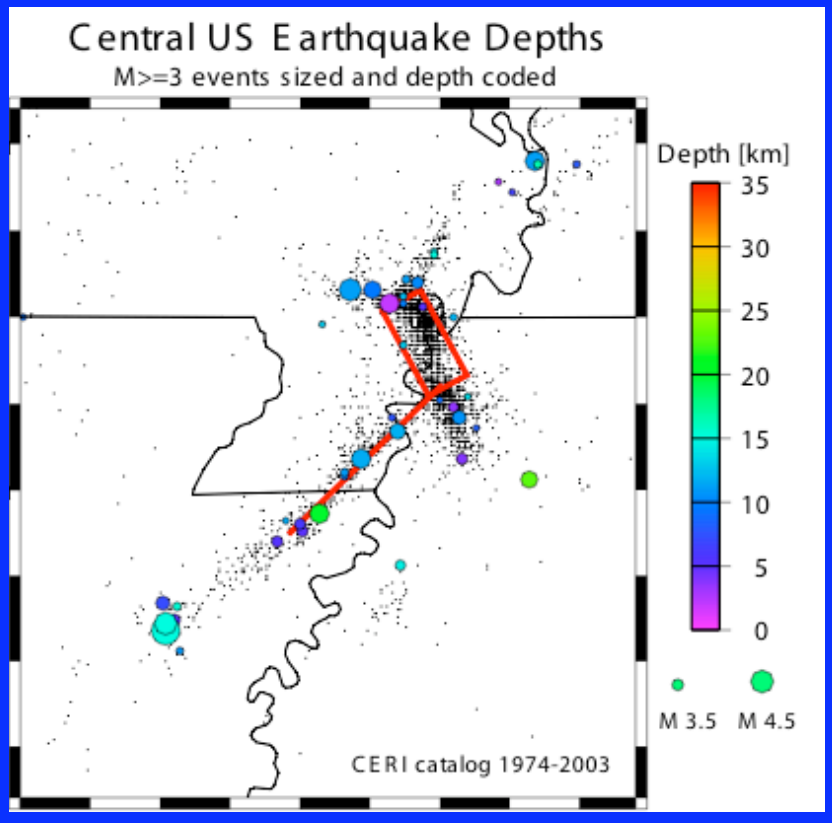
CONTINENTAL INTERIOR



NEW MADRID SEISMICITY: 1811-12 AFTERSHOCKS?







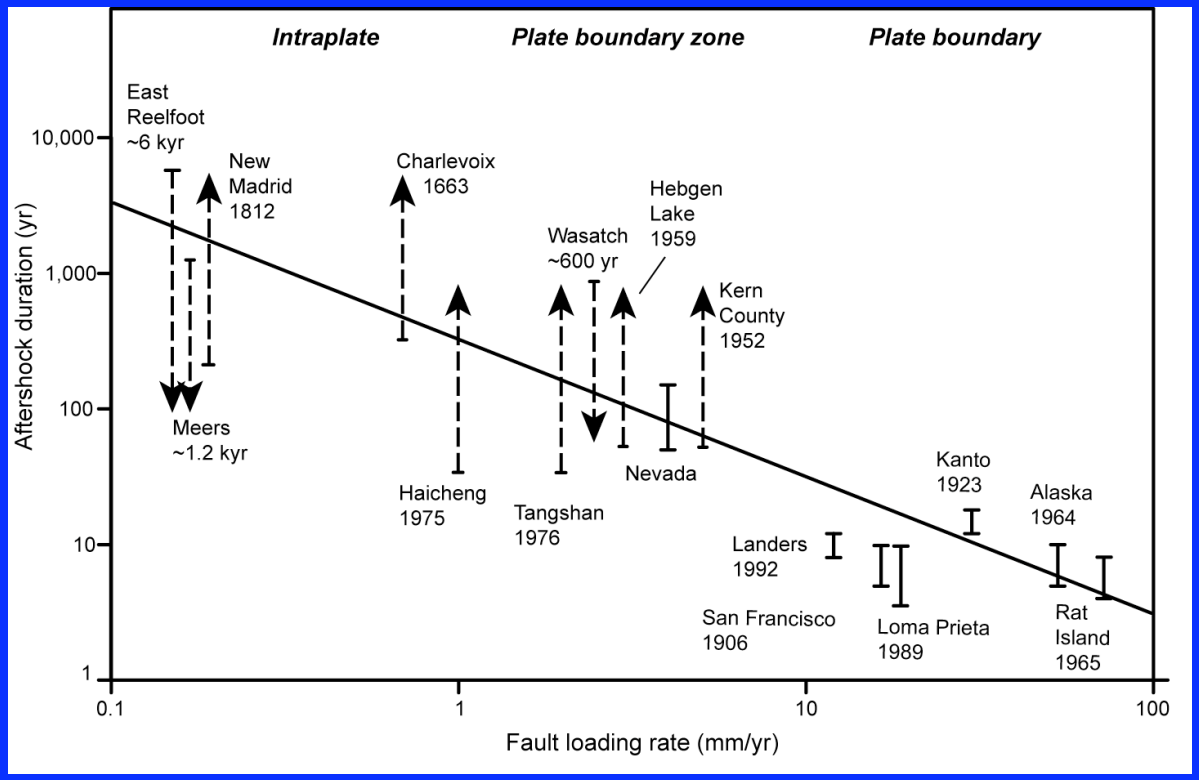
Instead of indicating locus of future large earthquakes, ongoing seismicity looks like aftershocks of 1811-12

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

LONG - 100+ YEAR - INTRAPLATE AFTERSHOCK SEQUENCES IN SLOWLY DEFORMING CONTINENTAL INTERIORS

Faults at plate boundaries are quickly reloaded by steady plate motion after a large earthquake that overwhelms the effects of the main shock.

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



Stein & Liu, 2009

LONGER AFTERSHOCK SEQUENCES ON SLOWLY LOADED FAULTS

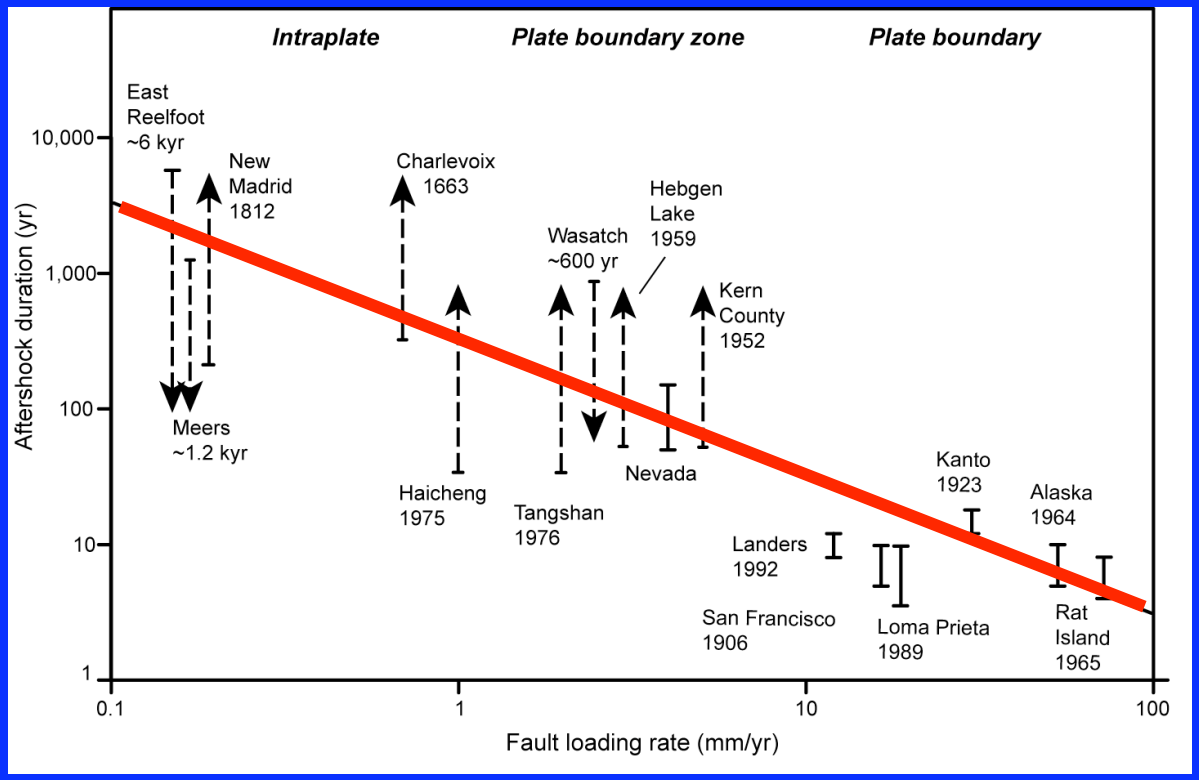
In Dieterich (1994) friction model aftershock duration $t_a \alpha$ 1/loading rate

For simple geometry

$$t_a = A\sigma\pi w/\mu v$$

A fault friction parameter
σ normal stress
w fault vertical extent
μ rigidity
v velocity across fault

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



Stein & Liu, 2009

IMPLICATIONS FOR SEISMIC HAZARD ESTIMATION IN CONTINENTS

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

Complex spatiotemporal patterns of large earthquakes, and the long durations of their aftershocks, make assessing hazards difficult.

In short term much of the hazard results from aftershocks, which shouldn't be removed in attempts to infer earthquake recurrence and hazards.

In long term, relying unduly on recent seismicity to predict the locations of future large earthquakes *will overestimate the hazard in some places and lead to surprises elsewhere*.

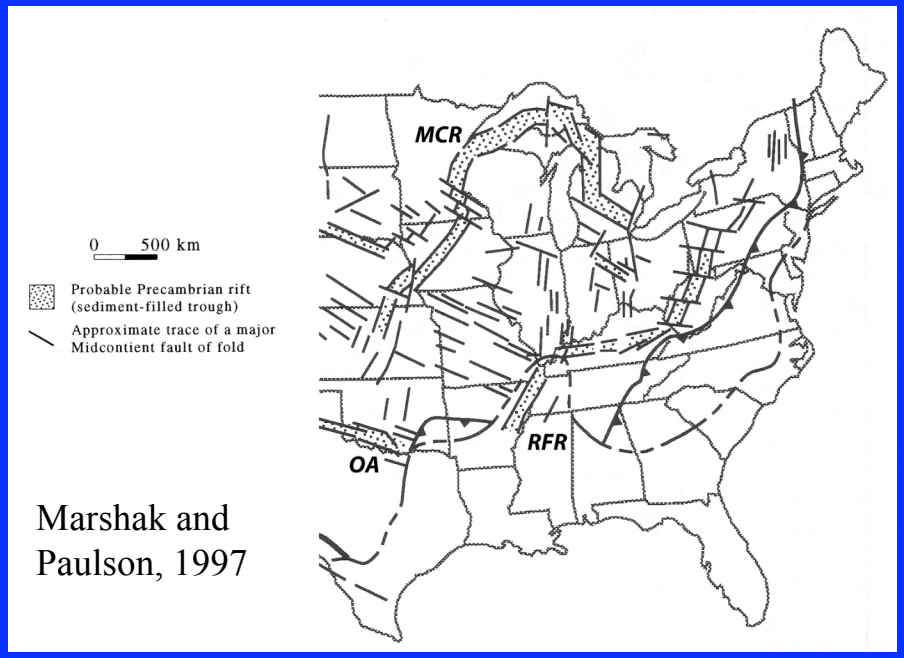
Need geodetic & seismological data to identify where strain accumulates, geologic data to define history, & models of the migration process to understand what observations mean

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 directly reflect platewide tectonic stresses, which change slowly in space and over millions of years

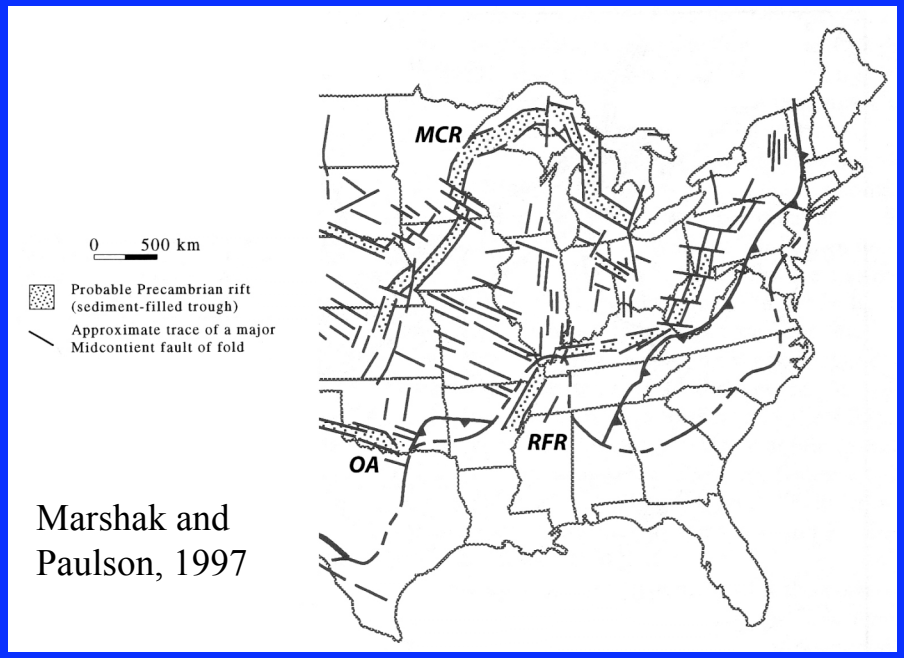
CAUSES OF INTRAPLATE EARTHQUAKES



Marshak and Paulson, 1997

Earthquakes probably reflect localized stress sources & fault interactions

CAUSES OF NEW MADRID EARTHQUAKES



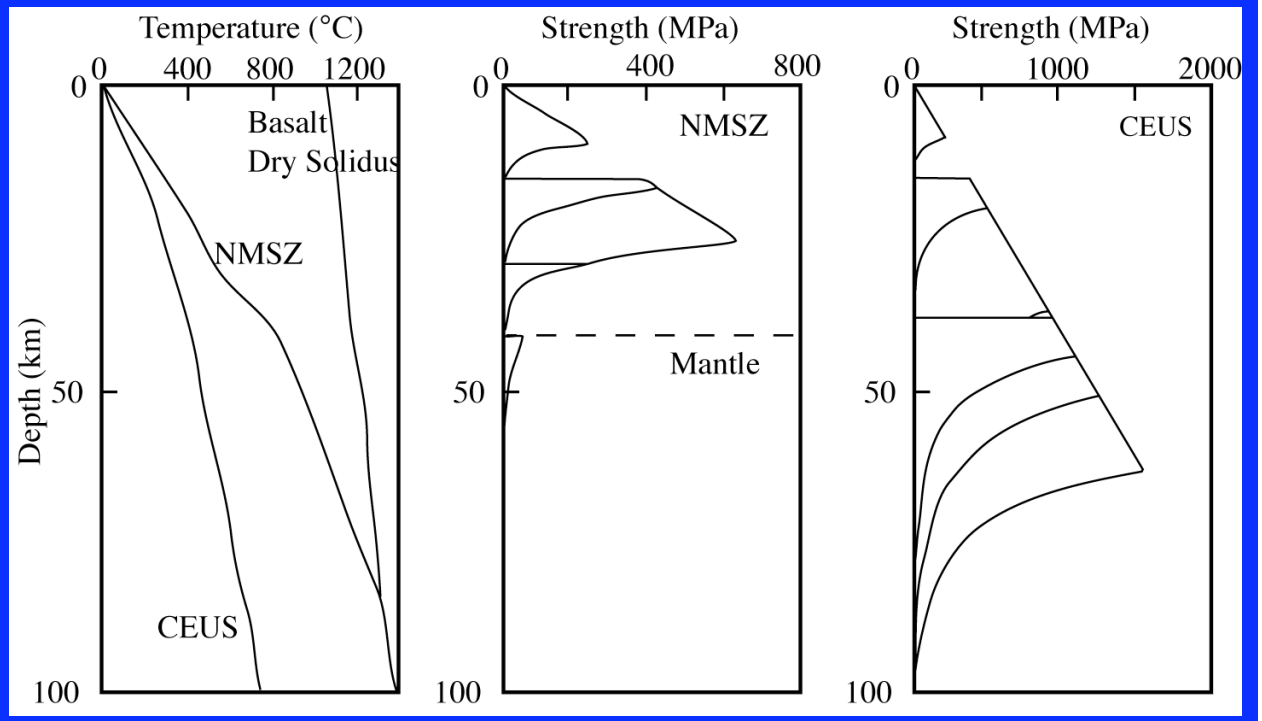
Marshak and Paulson, 1997

Although New Madrid earthquakes probably occur by reactivation of faults associated with Paleozoic rifting, a localized stress source must have recently triggerred these particular faults. Although slowly varying plate-wide or regional forces (Forte et al., 2007) may have a role in New Madrid seismicity, *the primary triggers must be localized in space and time.*

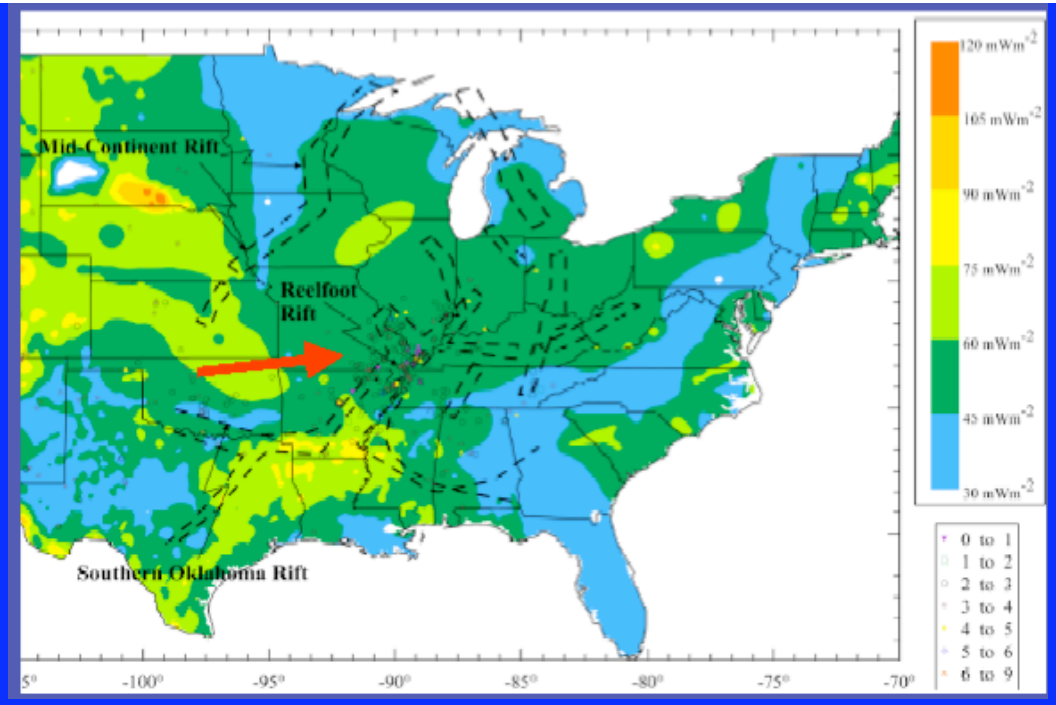
LOCAL EFFECT: IS NMSZ HOTTER & WEAKER THAN SURROUNDINGS?

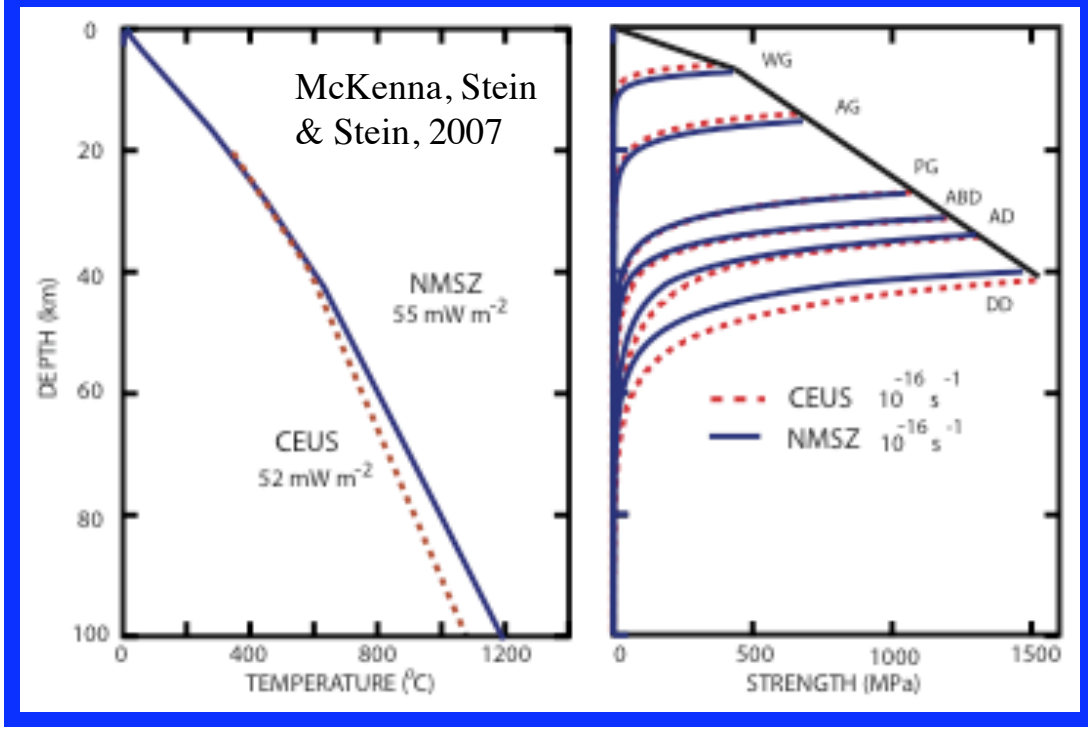
Liu & Zoback (1997) find NMSZ heat flow ~ 15 mW/m^2 higher than in surrounding area, so crust and upper mantle are significantly hotter and thus weaker than surroundings.

Weak lower crust and mantle concentrate platewide stress & cause seismicity



Liu & Zoback, 1997





NMSZ NOT HOT, WEAK, OR SPECIAL

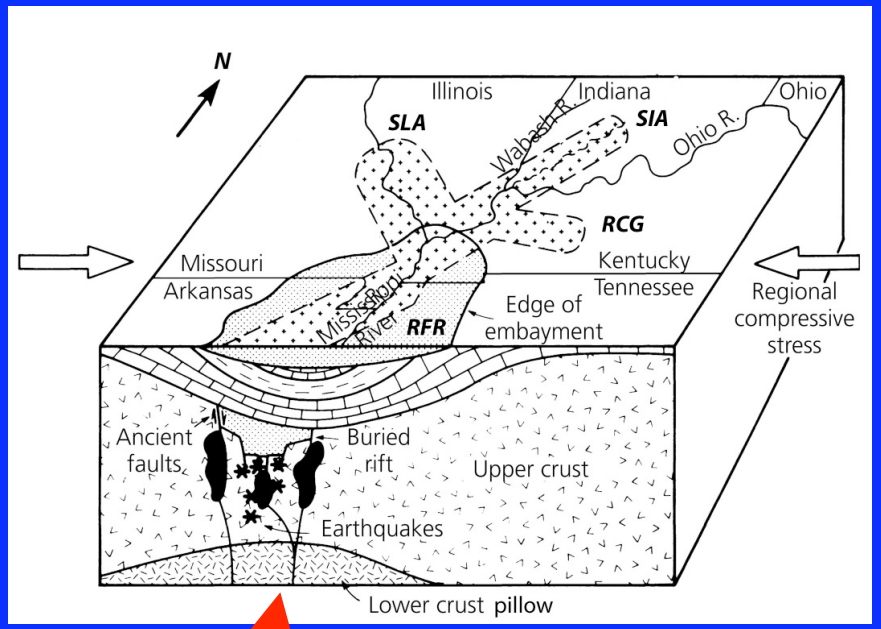
Reanalysis finds the anomaly is either zero or much smaller (3+/-23 mW/m^2), so the NMSZ and CEUS *have essentially the same temperature & thermally-controlled strength.*

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

McKenna, Stein & Stein, 2007

POSSIBLE LOCAL STRESS SOURCE FOR SEISMICITY: RIFT PILLOW SINKING

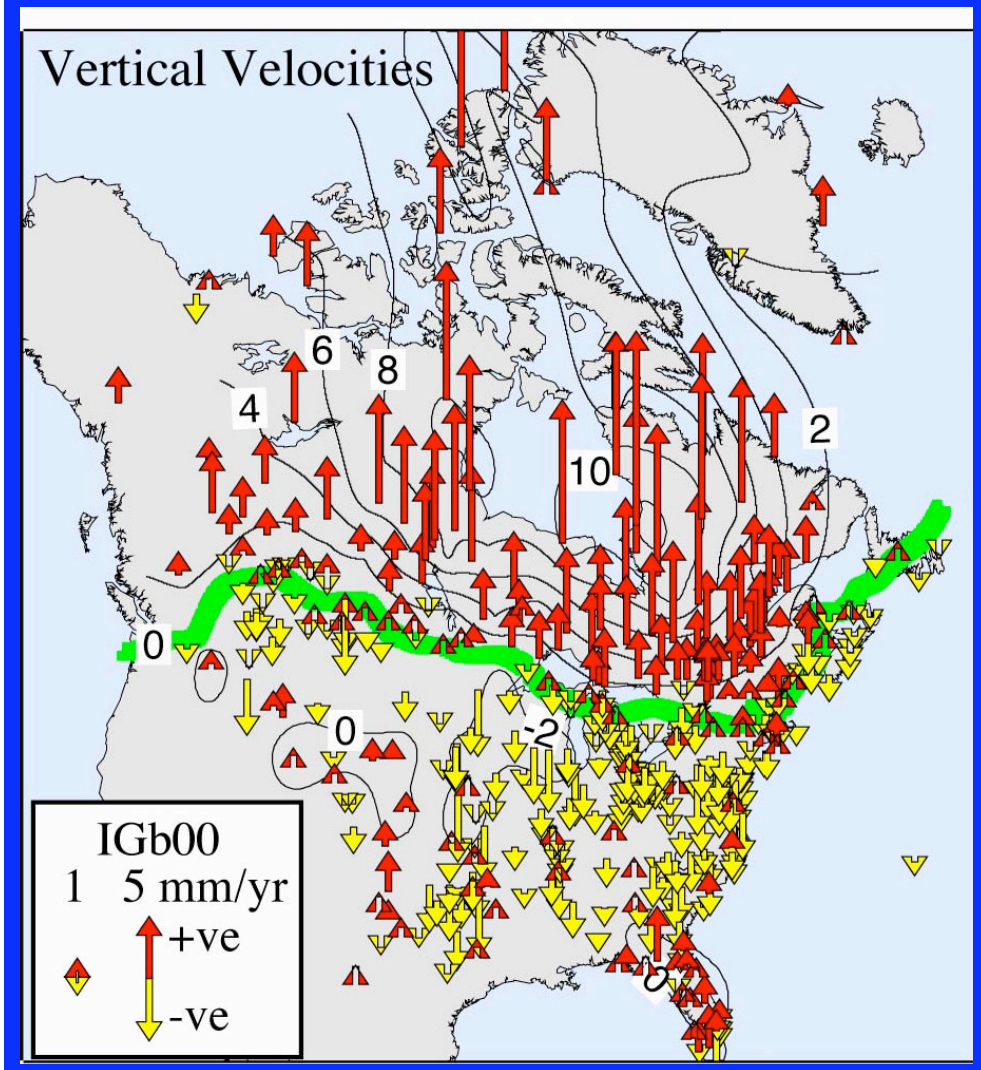
Sinking of "rift pillow" - ancient high density mafic body (Grana and Richardson, 1996; Stuart et al., 1997) - due to recent weakening of the lower crust in past 9 kyr (Pollitz et al., 2001)

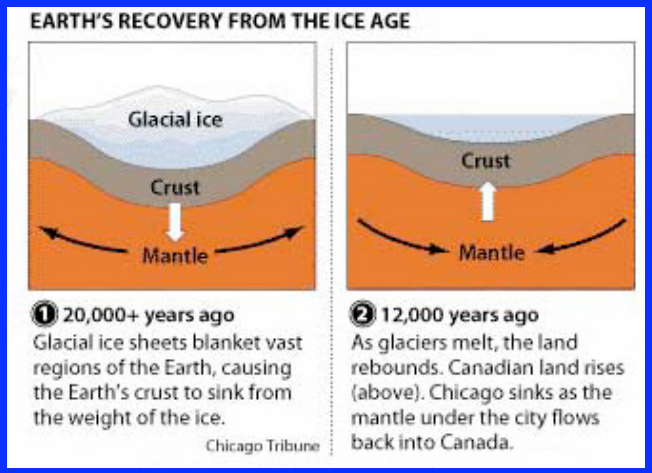


Braile et al., 1986

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

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





Most visible GPS motion in Eastern North America

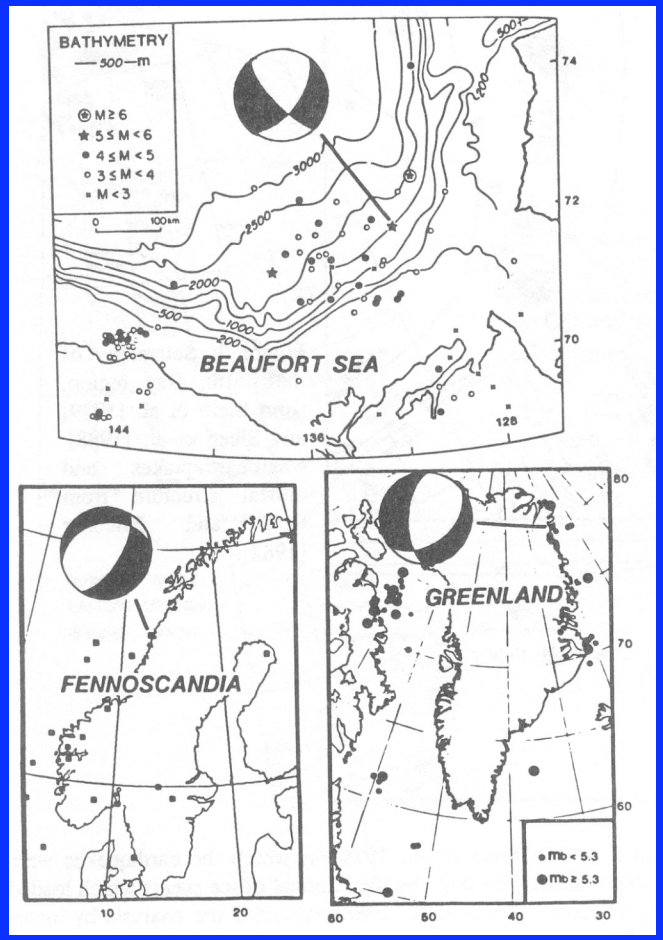
Sella et al., 2007

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

GIA invoked to explain seismicity along former ice sheet margin in Eastern Canada & elsewhere (Stein et al., 1979; 1989; Mazzotti et al., 2005)

Because flexural stresses decay rapidly away from the ice margin, GIA can't explain fault activation in the NMSZ (Wu and Johnson, 2000) unless its upper mantle and lower crust are two orders of magnitude weaker than the surroundings (Grollimund and Zoback, 2001)

No evidence for such weakening



Stein et al., 1989

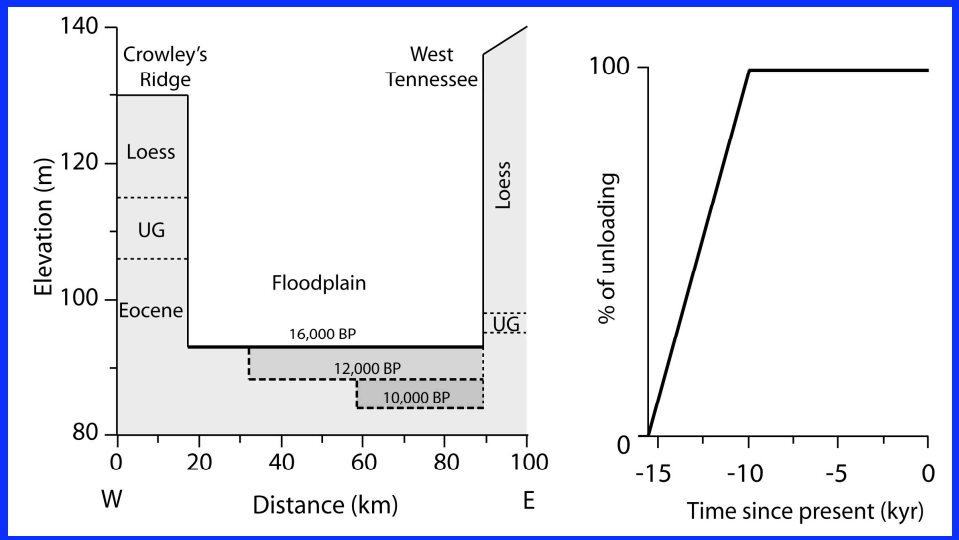
POSSIBLE LOCAL STRESS SOURCE FOR SEISMICITY:
POSTGLACIAL EROSION IN MISSISSIPPI EMBAYMENT

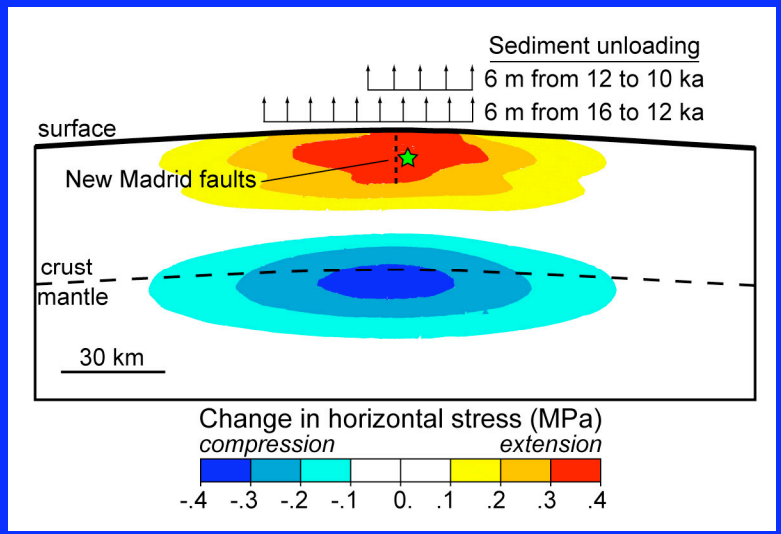
Flexure caused by unloading from river incision 16 - 10 ka reduces normal stresses sufficiently to unclamp pre-existing faults close to failure equilibrium

Fits timing of recent seismicity

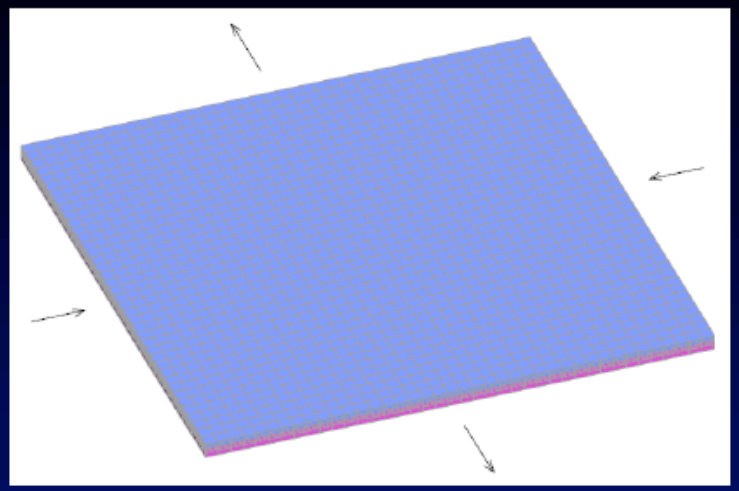
Doesn't require weak zone

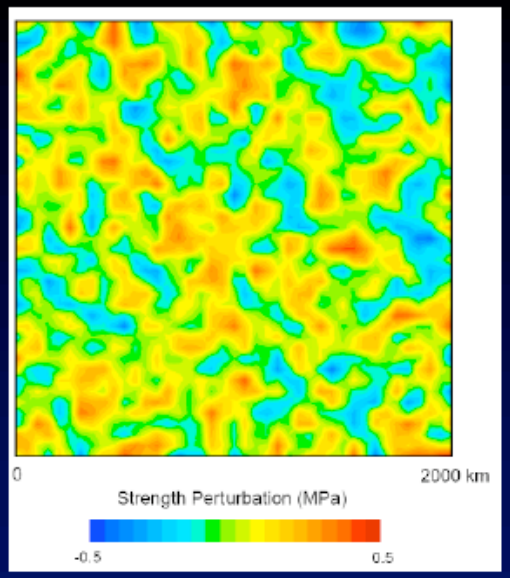
Fault segments that have already ruptured unlikely to fail again





Calais, Freed, Van Arsdale & Stein, 2009



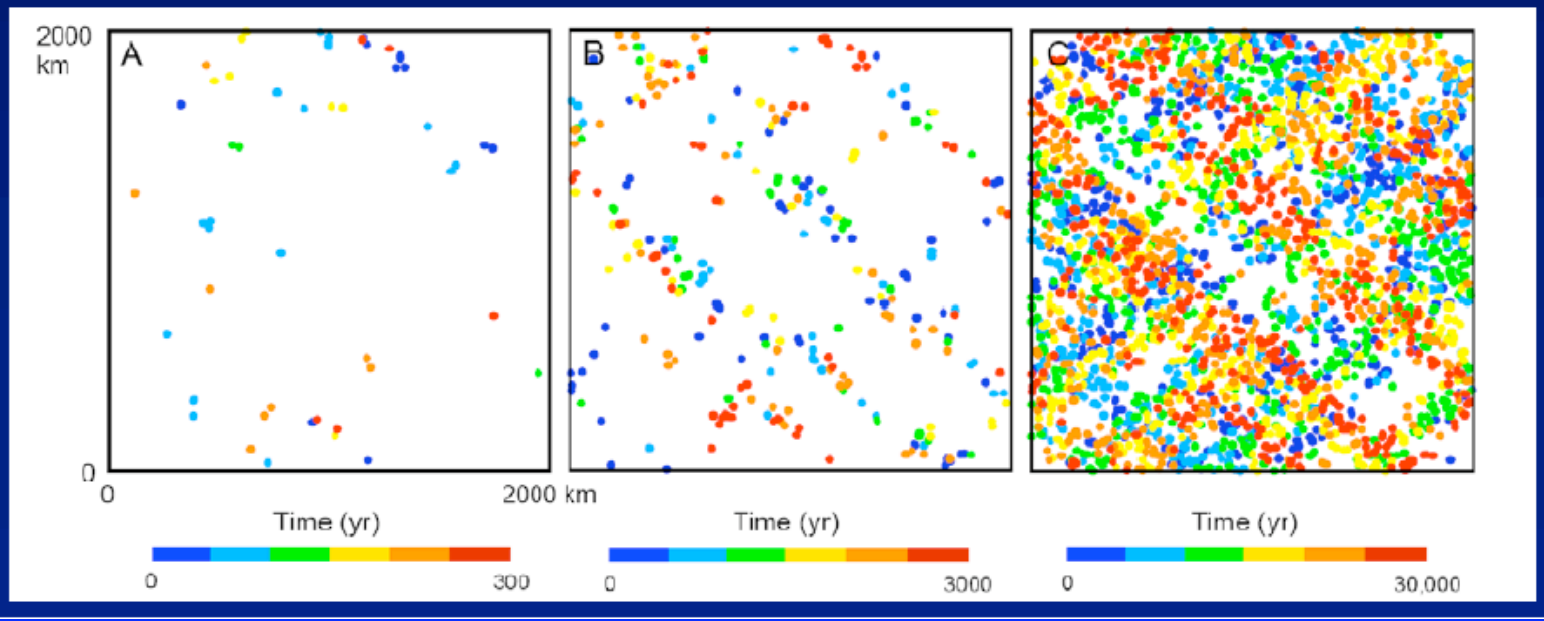


NUMERICAL MODEL

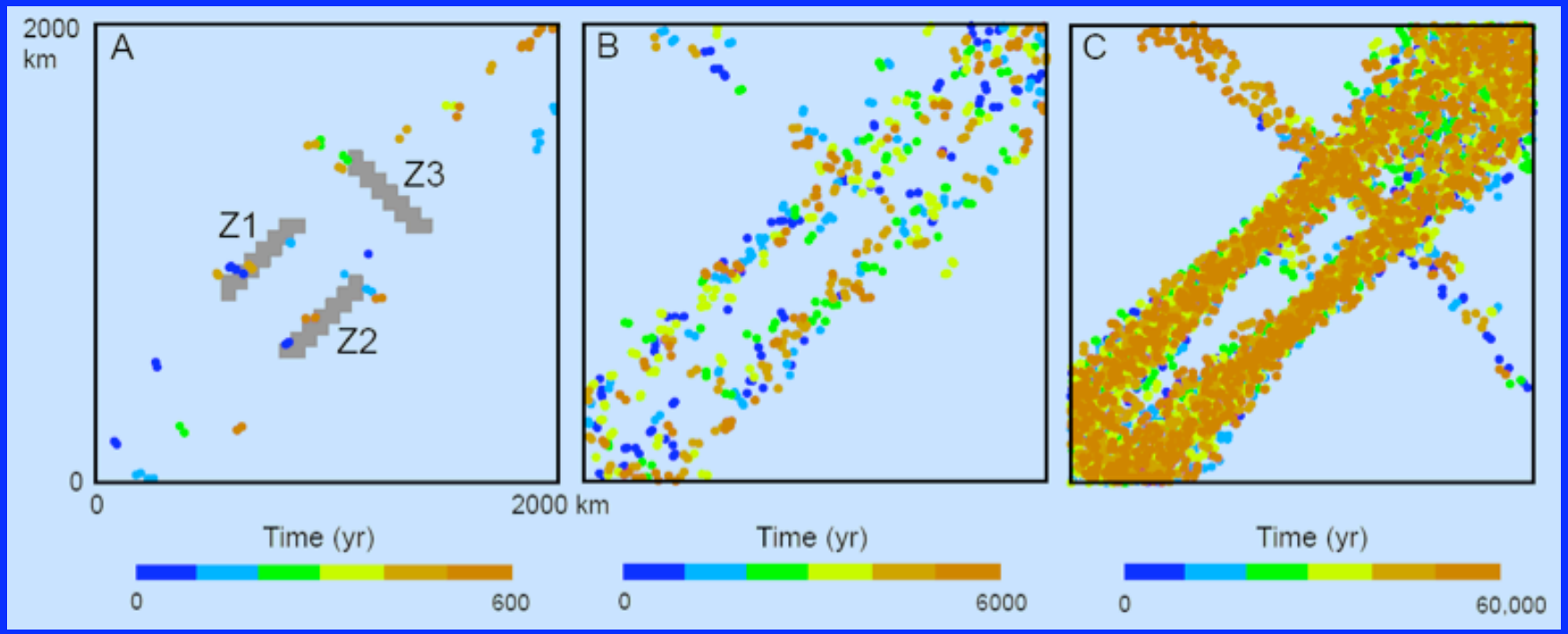
FOR INTRAPLATE EARTHQUAKES

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.



Effect of major (5 MPa) weak zones



Complex space-time variability due to fault interactions

Seismicity extends beyond weak zones

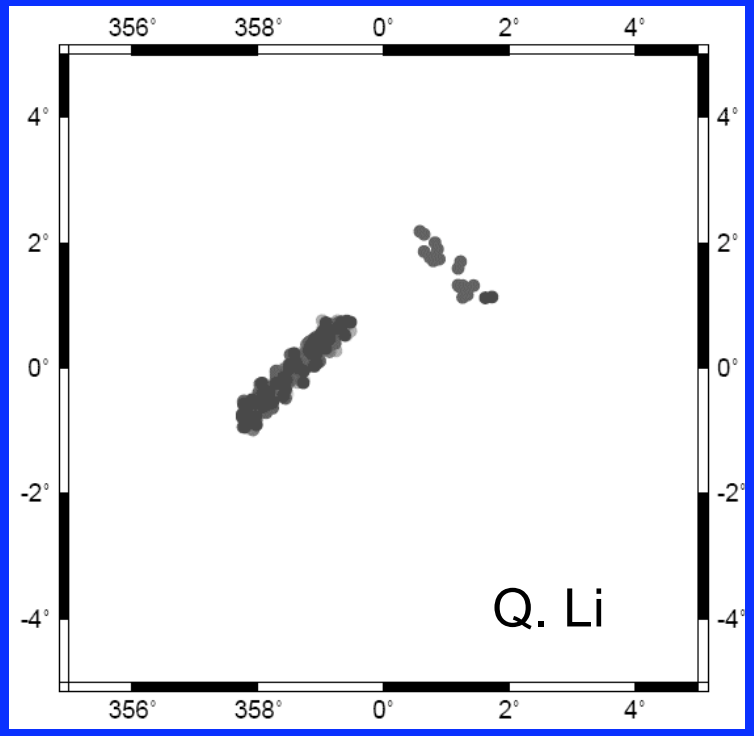
Short-term seismicity does not fully reflect long-term

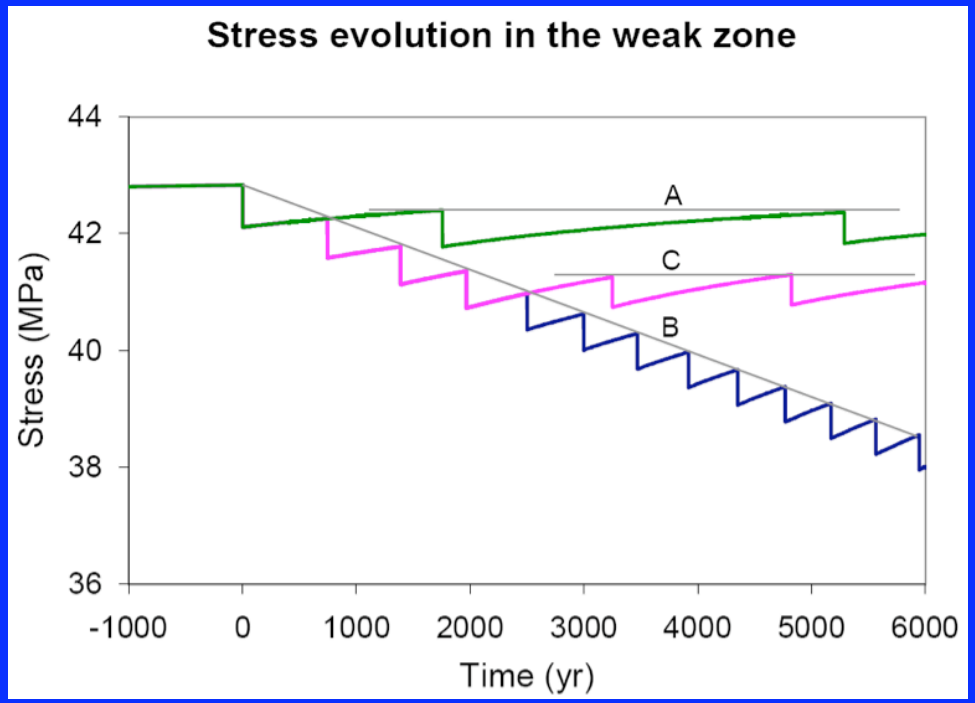
Variability results from steady platewide loading without local or time-variable loading

Li, Liu & Stein, 2009

HOW TO GET TEMPORAL CLUSTERS

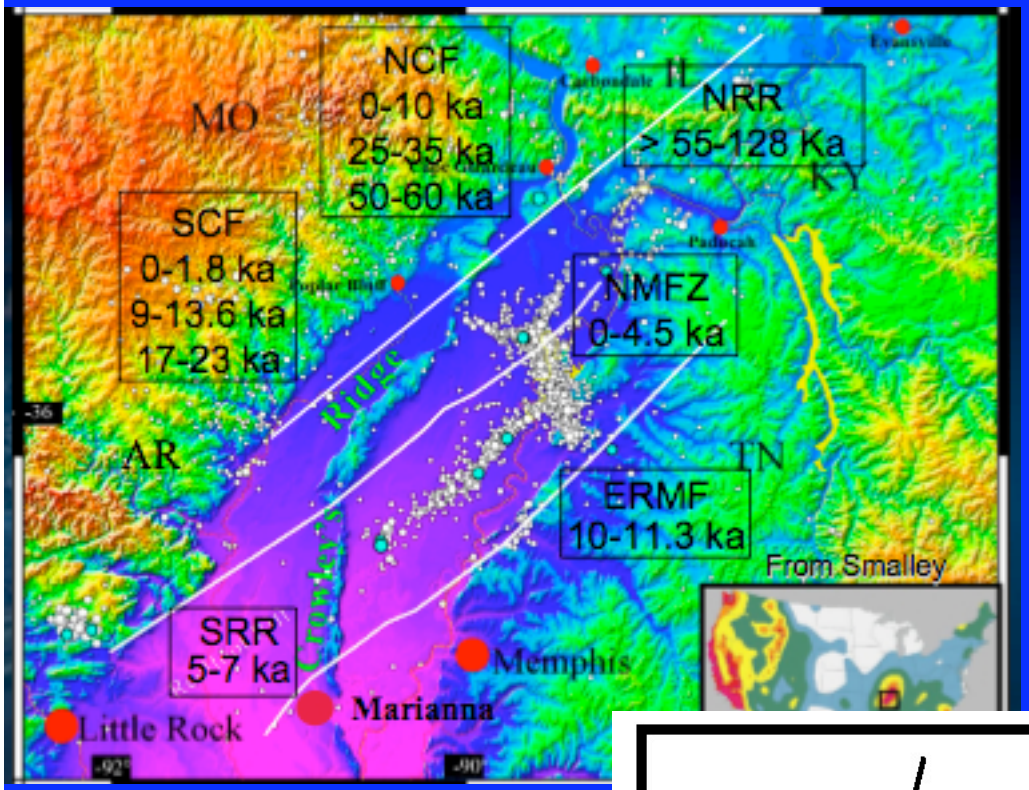
1 - Because of slow loading, repeated earthquakes (clusters) occur if fault strength decreases (for unknown reasons).





Earthquakes (1MPa stress drop) repeatedly occur in a 500-700 year period if there is a continuous strength decline (0.5 MPa /500 years). Without a decline no repeated earthquakes occur.

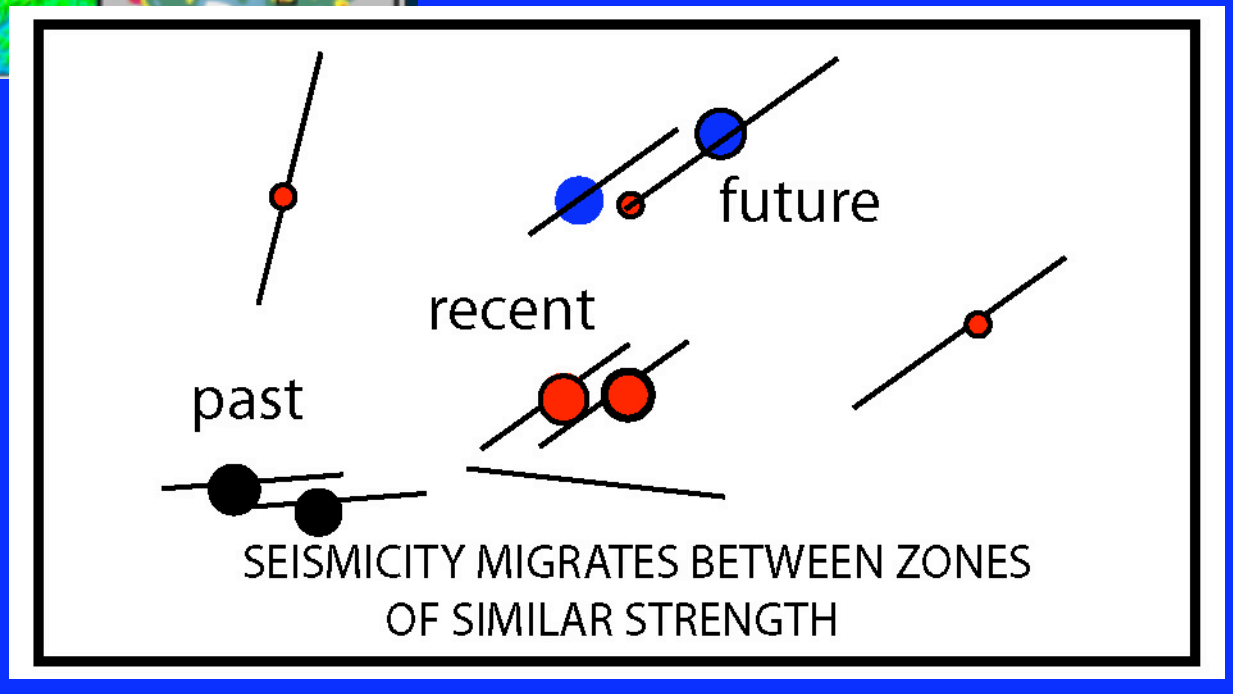
Li, Liu & Stein, 2009



Tuttle (2009)

HOW TO GET TEMPORAL CLUSTERS

2 - Nearby faults fail by stress transfer, causing apparent cluster possibly hard to resolve with geologic data



NEW MADRID MORE DANGEROUS THAN CALIFORNIA?

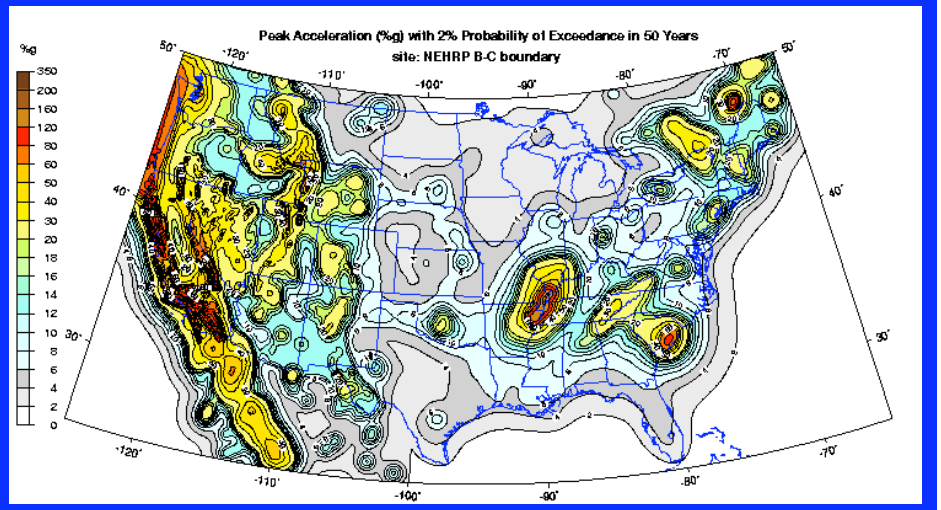
Quantify as maximum shaking (acceleration) predicted in some time period

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)

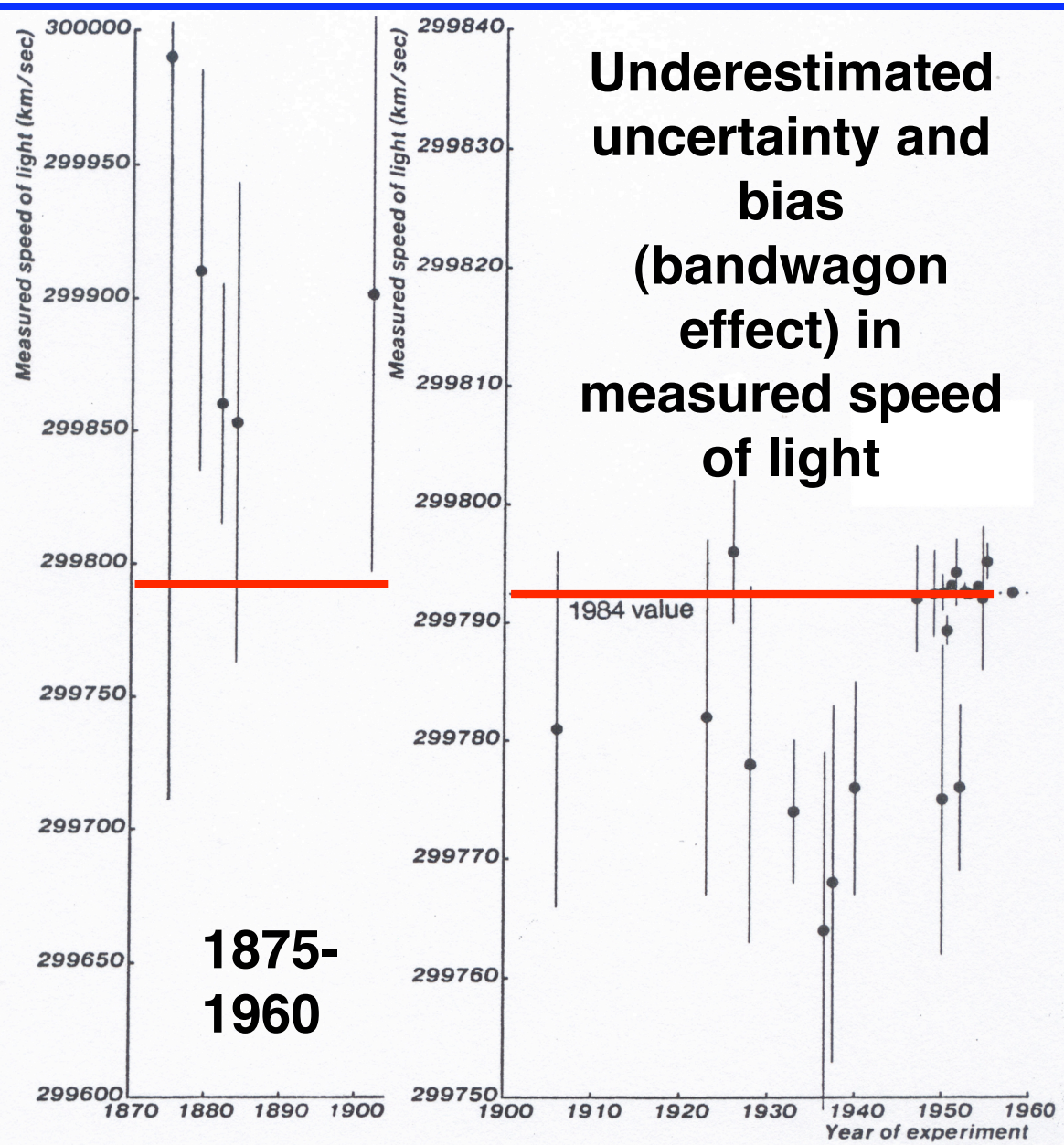
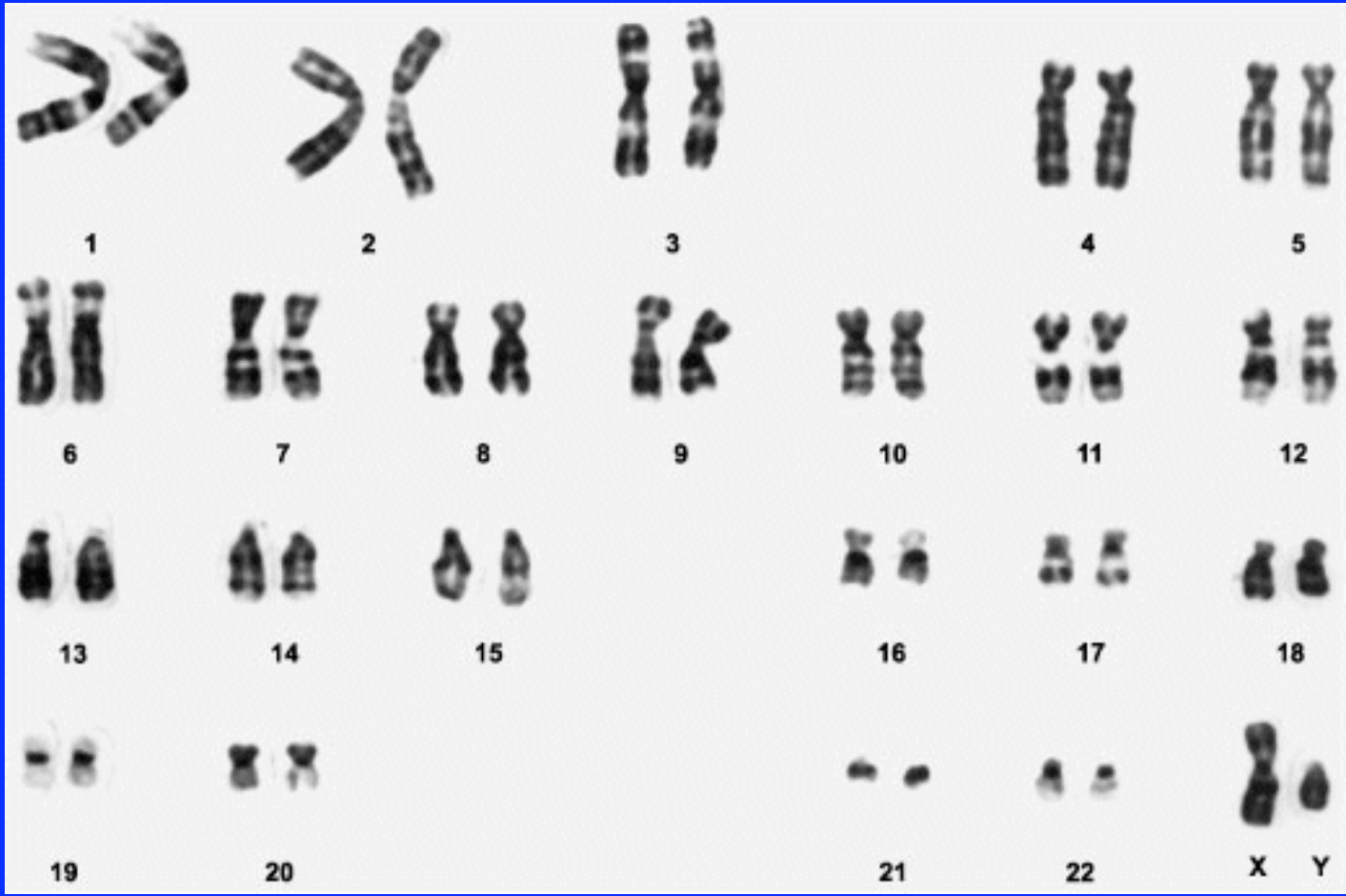


Figure 4.1. Experimental measurements of the speed of light between 1875 and 1960. Vertical bars show reported uncertainty as standard error. Horizontal dashed line represents currently accepted value. Less than 50% of the error bars enclose the accepted value, instead of the expected 70%. From Henrion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

Systematic

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

Doesn't consider space-time clustering & migration

- 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

Measurement

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

Uncertainty in interpreting intensity data

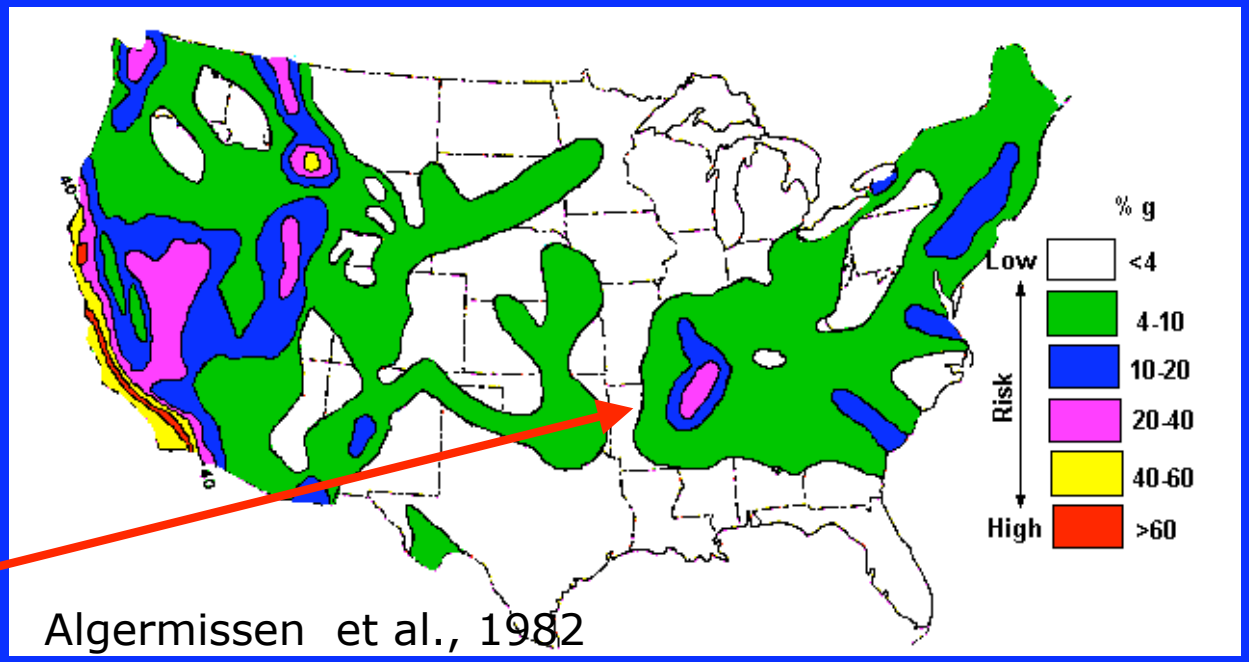
- High ground motion in large events

Lack of data

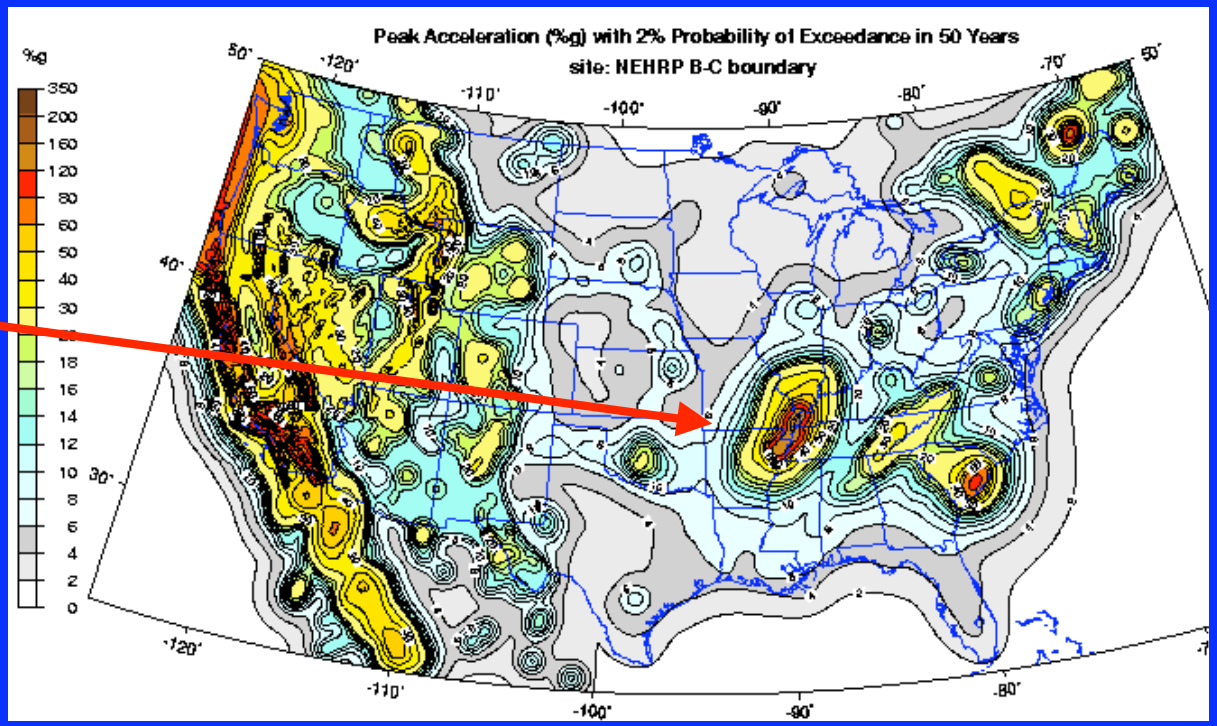
Hazard redefined

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

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

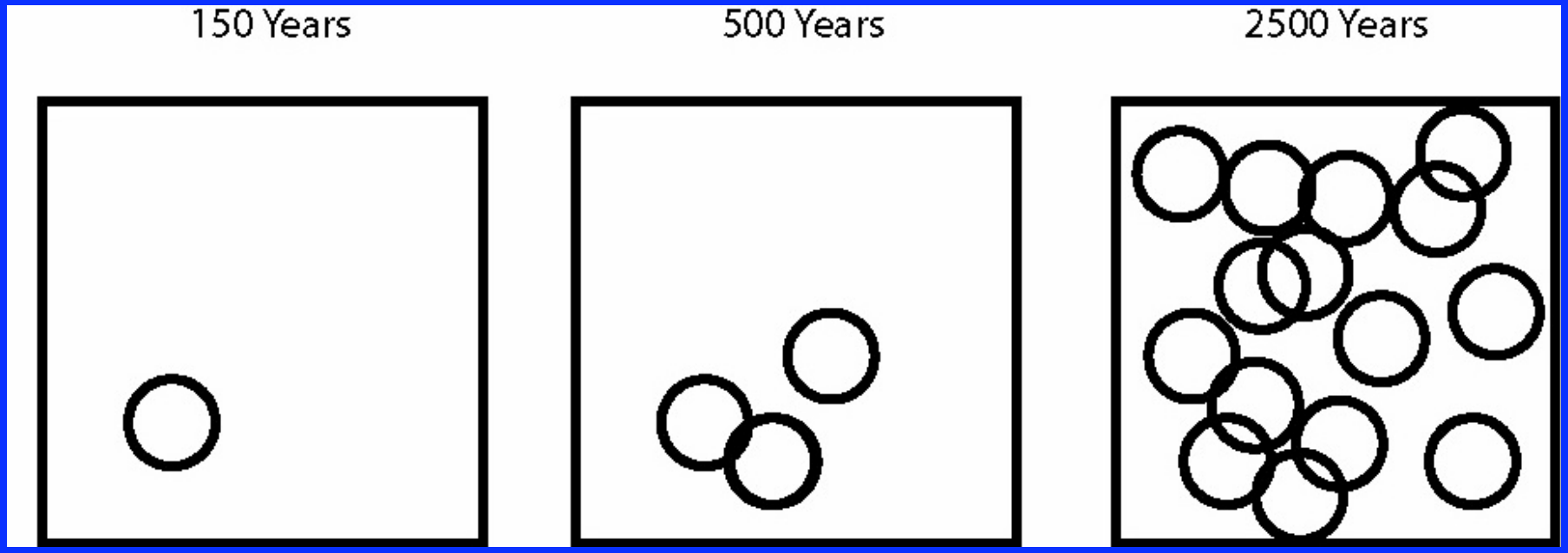


Algermissen et al., 1982



Frankel et al., 1996

ASSUMED HAZARD DEPENDS ON DEFINITION TIME WINDOW



Strongly shaken areas MMI > VII for M 6

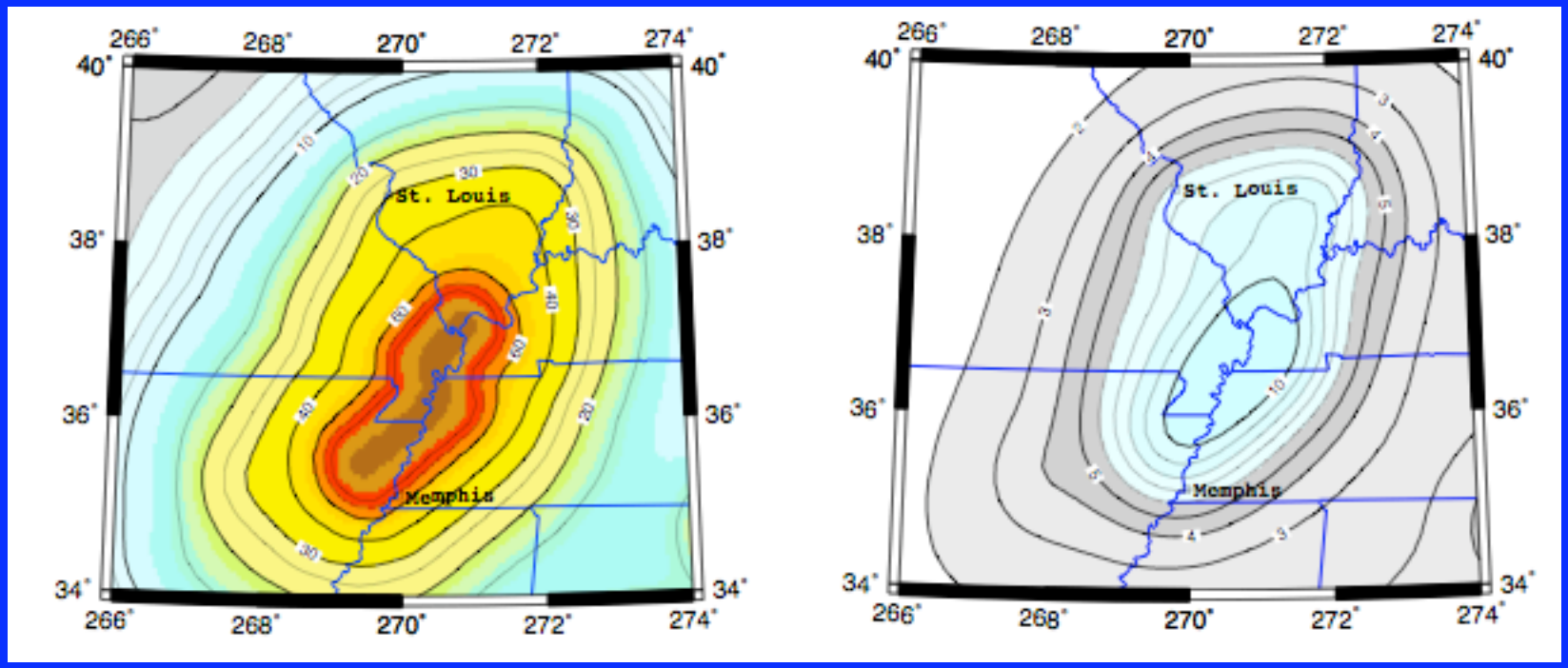
Over time, more earthquakes hit and a larger portion of the area gets shaken at least once. Some places get shaken a few times. *The longer a time the map covers, the scarier it looks.*

A typical building's life ~ 50 years, so almost all in NMSZ will be replaced before they're strongly shaken, much less damaged.

Assume from GPS data no M7 on the way

Some hazard remains from earthquakes up to M ~ 6.7

Hazard ~ 1/10 that of USGS prediction



USGS, 2500 yr, assumes M 7 coming

GPS, 500 yr, assumes no M 7 coming

Hard to assess possible hazard of M7 on other faults

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

Summary

GPS data show no strain accumulation in NMSZ

Recent cluster of large magnitude 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 still unclear

New Madrid earthquake hazard overestimated

Need careful study to develop cost-effective mitigation policy

Major science issues remain unresolved

More science needed for sensible hazard policy