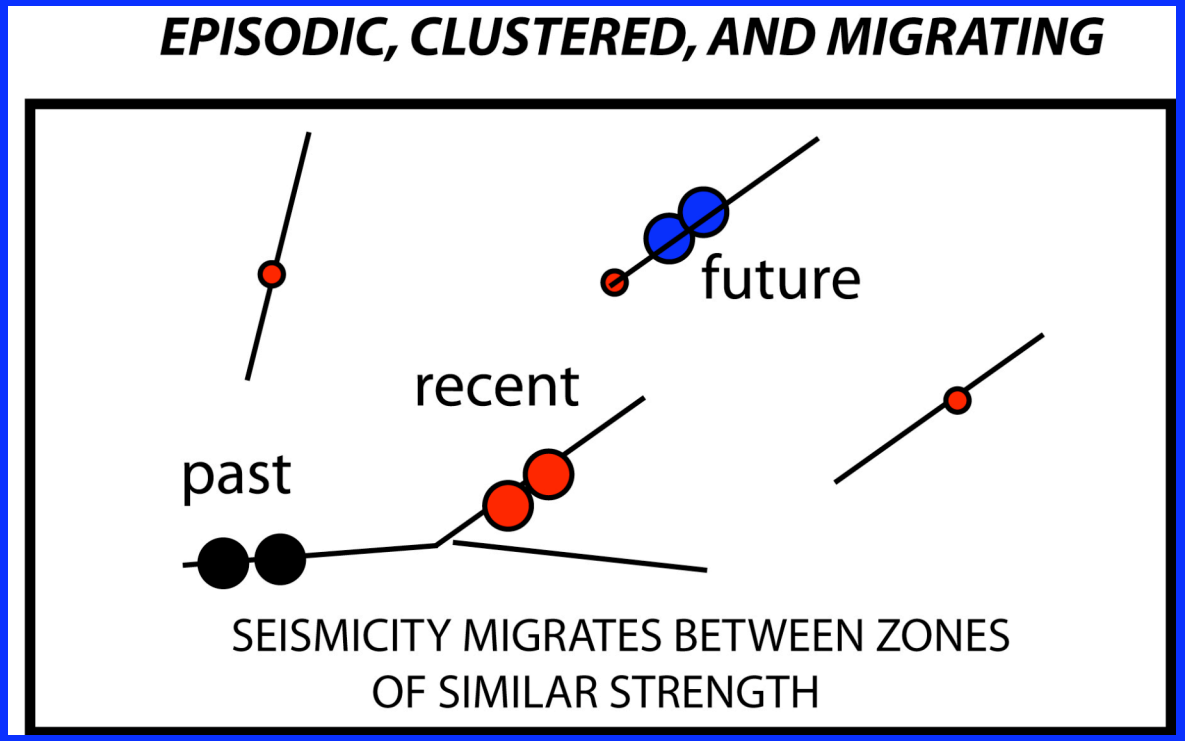
Migrating earthquakes and faults switching on and off: a complex system view of intracontinental earthquakes

Seth Stein

Northwestern University



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

PARADOXES

Intraplate earthquake rupture processes are no different from interplate quakes, but they are much less regular in space and time

Short term and long term intraplate deformation rates can be very different

Plate Boundary Earthquakes

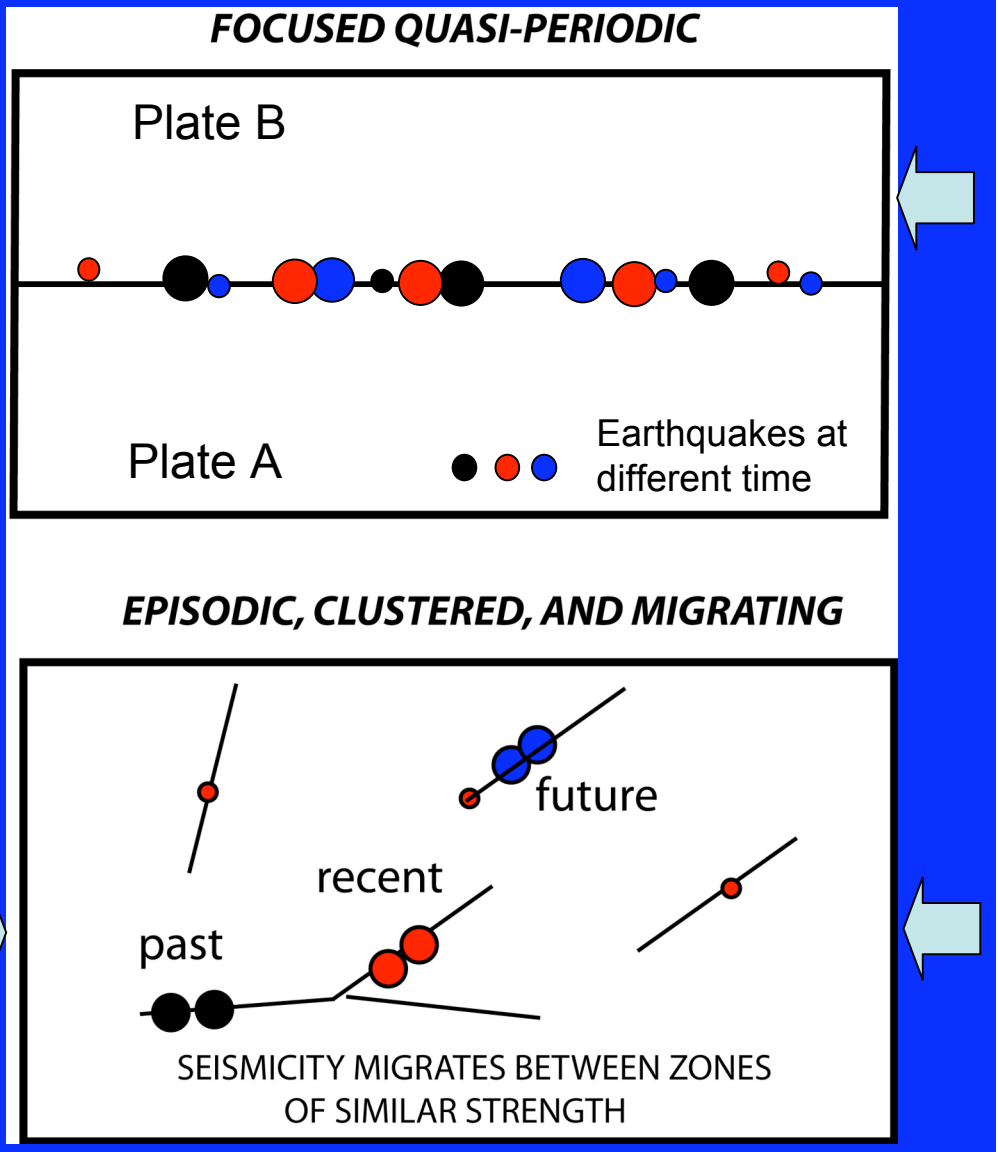
- Major fault loaded rapidly at constant rate
- Earthquakes spatially focused & temporally quasi-periodic

Past is good predictor

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



Stein, Liu & Wang 2009

You must unlearn what you have learned.

Alan Kafka

Collaborators

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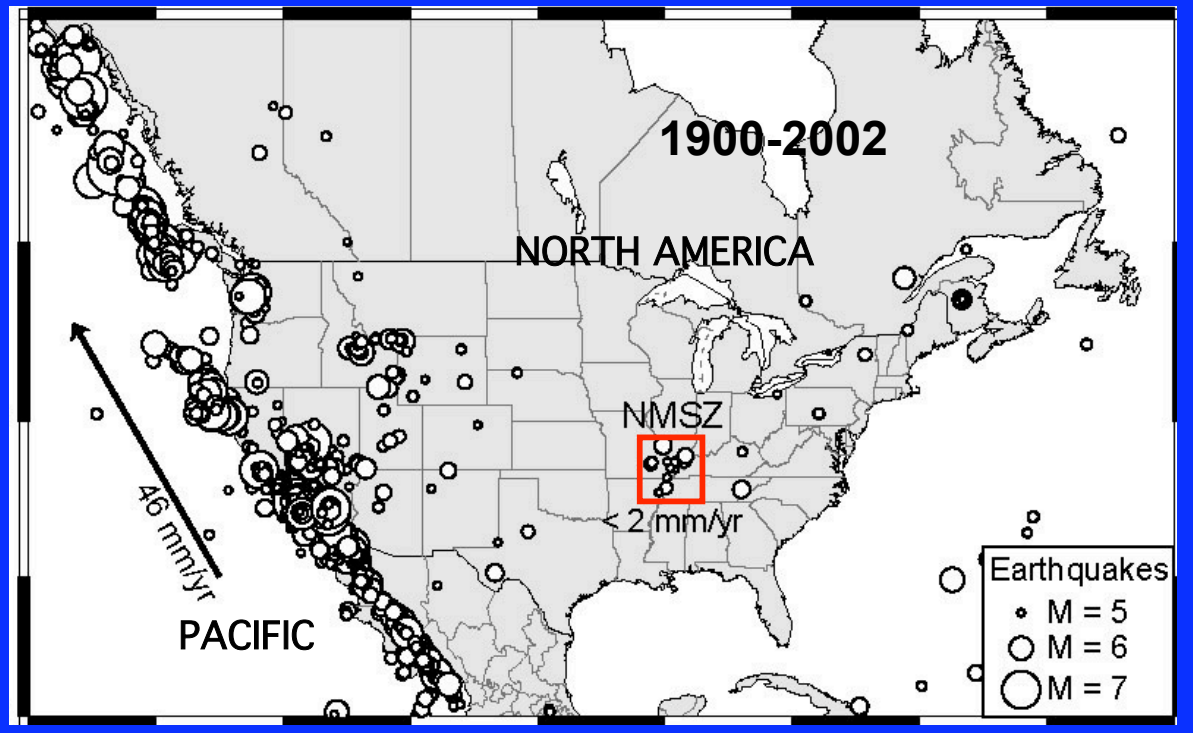
New Madrid seismic zone

M 7 earthquakes in 1811-12

Small quakes continue (M>6 about every 175 years) with little damage

Big ones might happen again

Don't know why, when, how dangerous



Somehow

1811-12 events acquired image as almost mythical cataclysms

Hazard said comparable to or greater than California

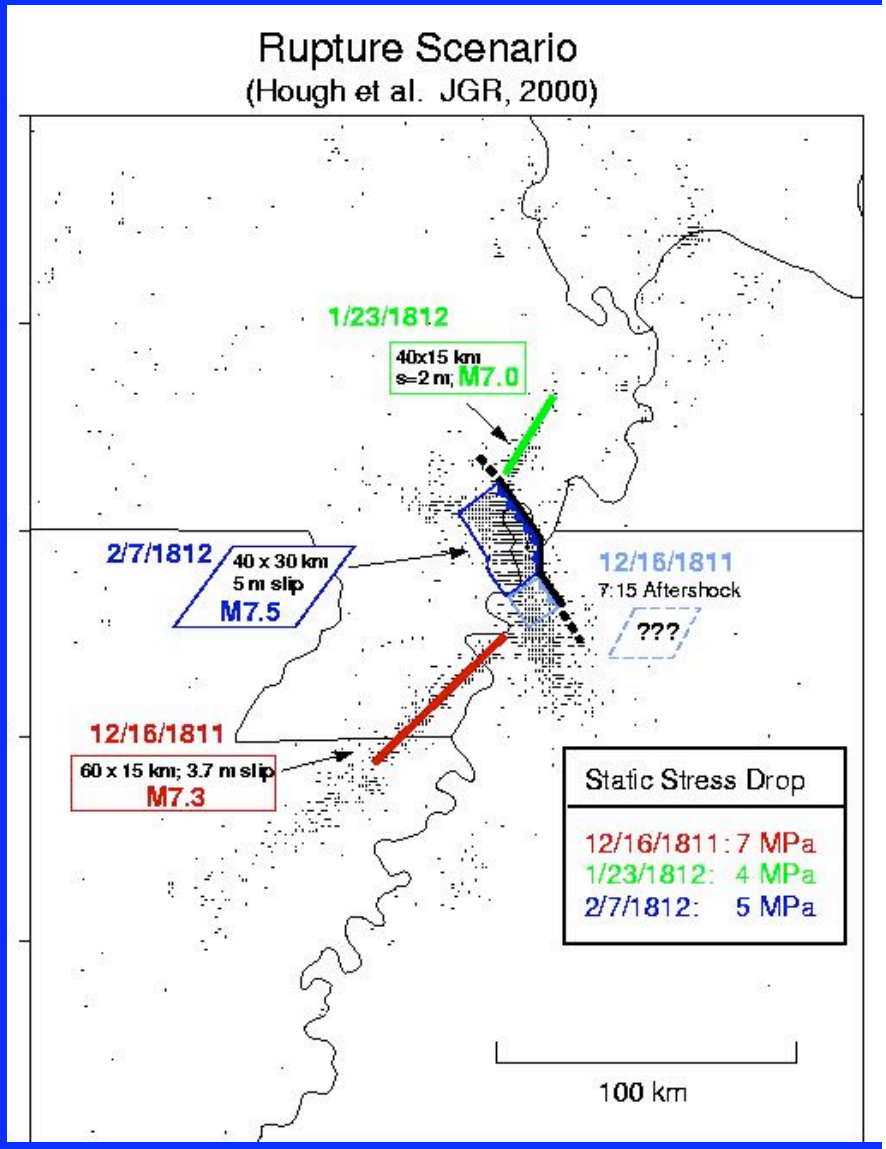
New Madrid:

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 over months, with three major shocks

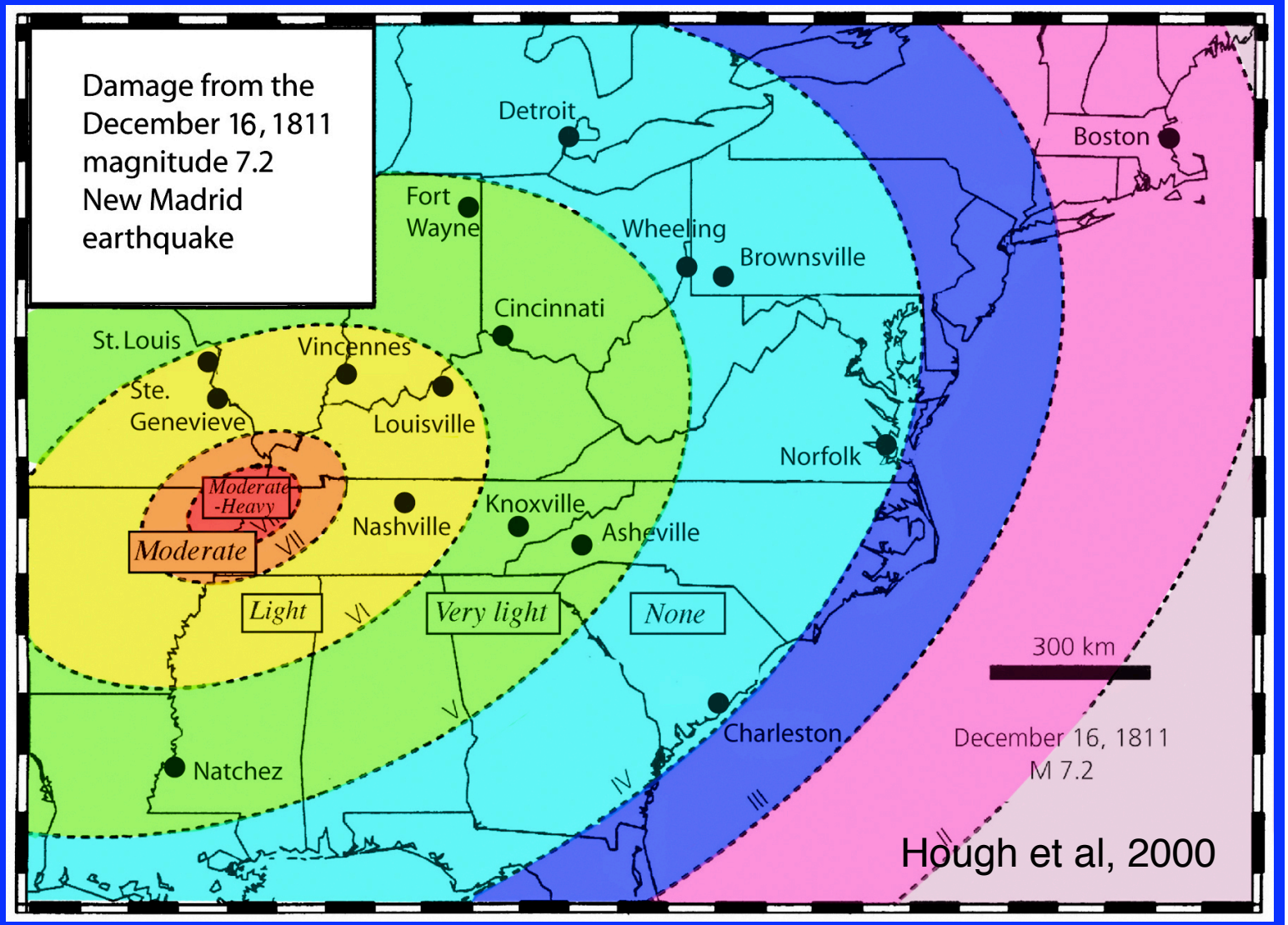


Shaking intensity (Hough et al., 2000) yields low magnitude 7 first inferred (Nuttli, 1973), not subsequently quoted 8 (Johnston, 1996)

Log cabin damage at New Madrid

Minor damage in St Louis, Nashville, Louisville, etc.

Not felt in Boston, no church bells ring



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News

Quake analysis rewrites history books

Magnitude keeps shrinking

New Madrid quakes were smaller than originally thought.

Richard A. Lovett

A series of earthquakes that hit the North American heartland nearly 200 years ago were considerably smaller than reported in the history books, according to research presented at a meeting this week.

The New Madrid earthquakes may have been considerably smaller than scientists had estimated.

The quakes struck the New Madrid fault zone 200 kilometres south of St Louis, Missouri, in 1811 and 1812, long before modern seismometers allowed accurate measurements of their intensity. In the 1980s, however, some scientists estimated that the magnitudes of these quakes were over 8.0, says Susan Hough, a seismologist at the US Geological Survey's Pasadena office in California.

"You'll still find claims that these were the largest earthquakes ever in the contiguous United States," says Hough, who presented her findings on 23 April at a meeting of the Seismological Society of America, in Portland, Oregon.

Previously, Hough had stated[1] that the earthquake magnitudes were only about 7.5. Now, she has reduced her estimates by another half point, to "right around magnitude 7.

These were big earthquakes

Hidden Fury

The New Madrid Earthquake Zone

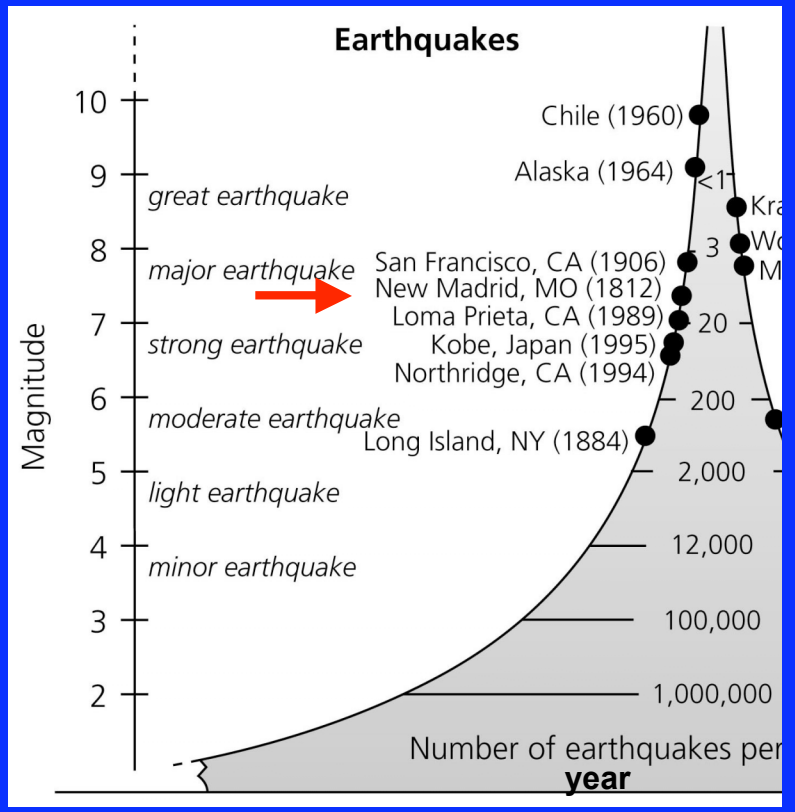
The danger posed by the New Madrid earthquake zone along the Mississippi River.

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.



Stein & Wysession (2003) after IRIS

But a lot smaller & more common than often stated

~15 earthquakes of this size occur each year

Did the Mississippi run backwards after February shock?

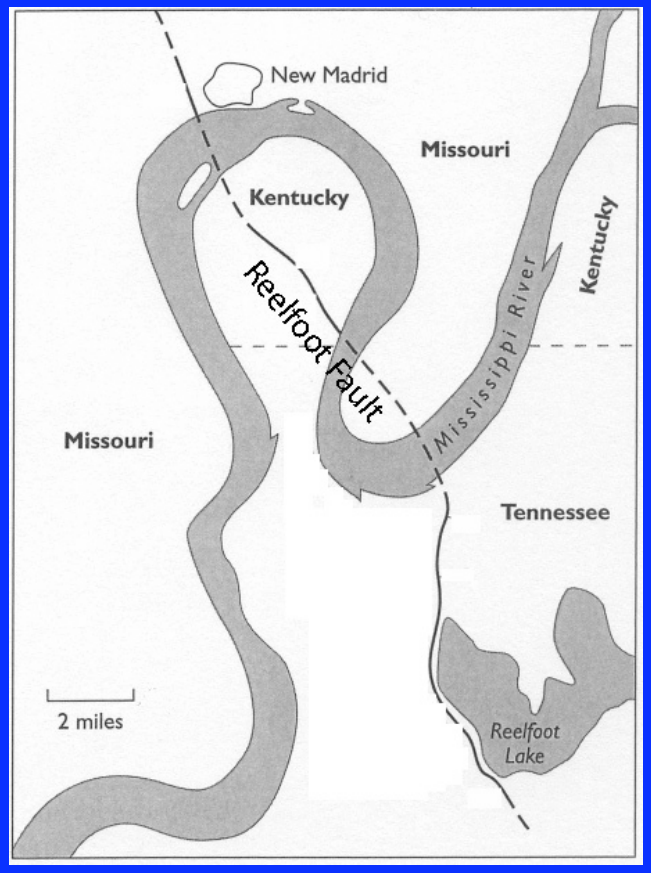
Historical Society of Missouri

"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."

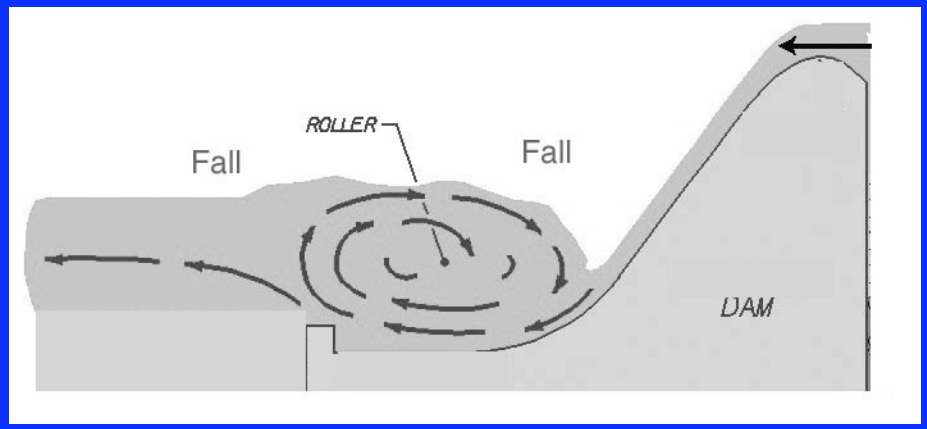
Reverse current lasted a few hours.

Real or legend?

Vertical motion on Reelfoot fault 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 natural dams and slower current upriver

AFTERMATH

"Loss and suffering were brought to the attention of Congress, but in the light of subsequent events *it is not certain to what extent assistance was the real object of the agitation or to what extent it was a pretext for land grabbing on the part of certain unscrupulous persons*." (M. Fuller, 1912)

People whose lands had been destroyed could get certificates to replace them. Most stayed and sold their certificates for a few cents per acre. Of 516 certificates issued, original claimants used only 20. Speculators in St. Louis acquired most of the others, and *"perjury and forgery became so common that for a time a New Madrid claim was regarded as a synonym for fraud."*

The earthquake legend grew…

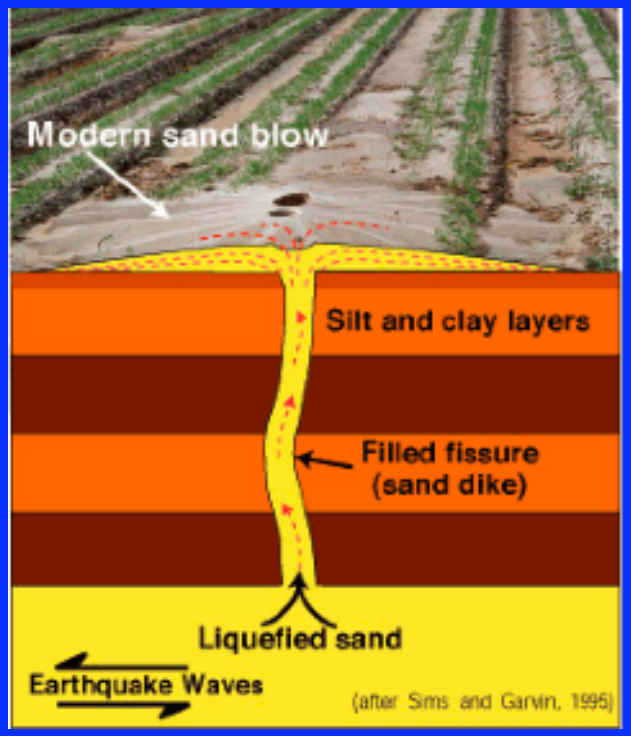
Public fear 1811-12 recurrence

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

Because paleoseismology shows large events in 900 & 1450 AD, we started GPS in 1991 expecting to find deformation accumulating, consistent with M7-8 events ~500 years apart



After 8 years, 3 campaigns, 70 people from 9 institutions … 0 +/- 2 mm/yr!

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

Recent cluster likely ended

Seismicity migrates

Hazard overestimated

April 1999

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 site 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

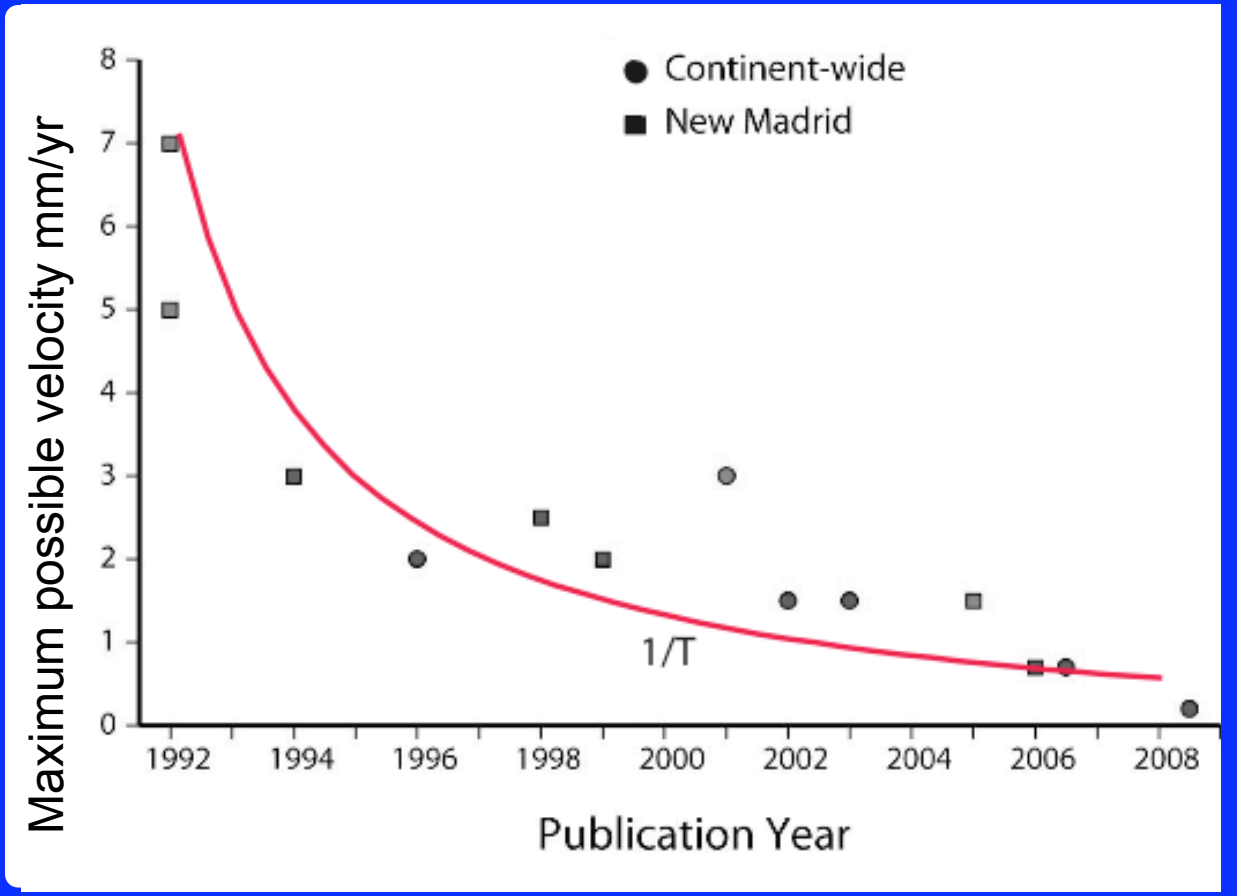
Rate uncertainty is

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

Rate precision improves with longer observations

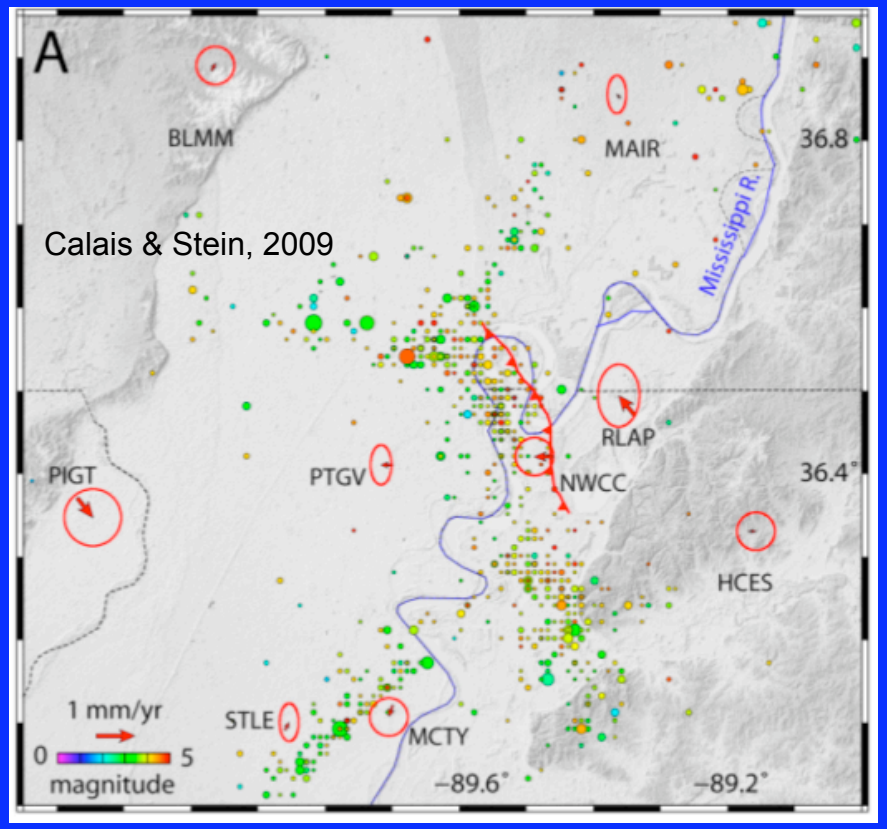
Rates < 0.2 mm/yr, will continue to converge on zero unless ground motion starts

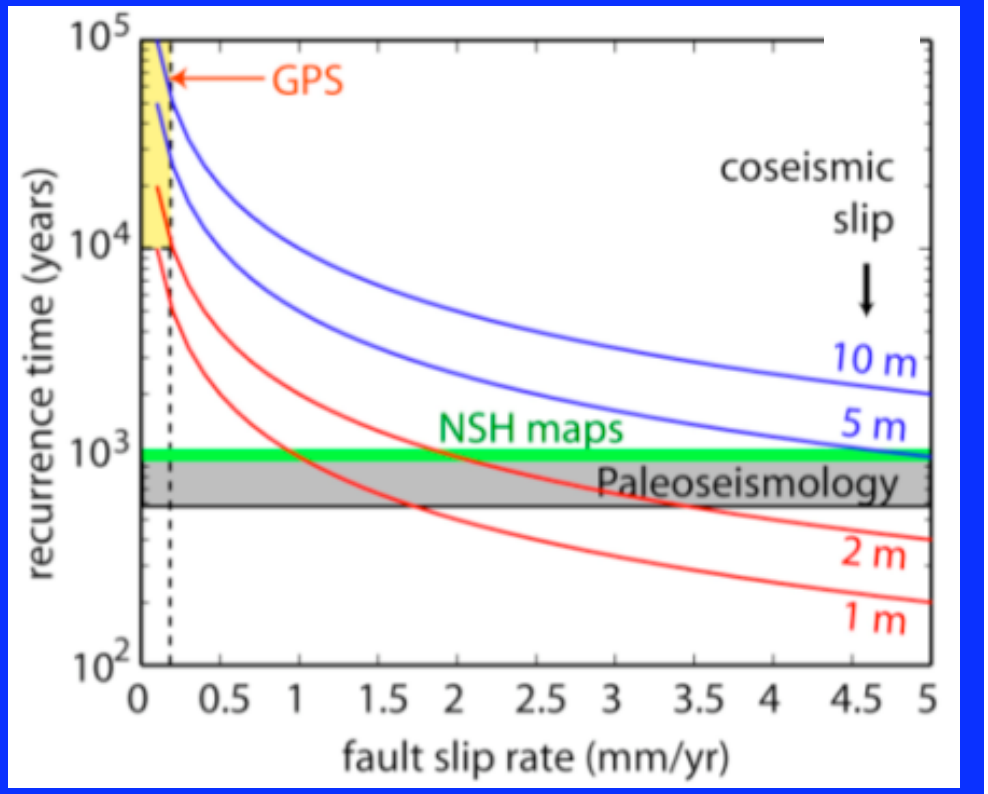
Strain rate does the same: < 2 x 10^{-9} /yr and shrinking



Calais & Stein, 2009

GPS INCONSISTENT WITH STEADY-STATE SEISMICITY





Motions with respect to rigid North America < 0.2 mm/yr & within error ellipses. Data do not require motion, and restrict any motion to being very slow.

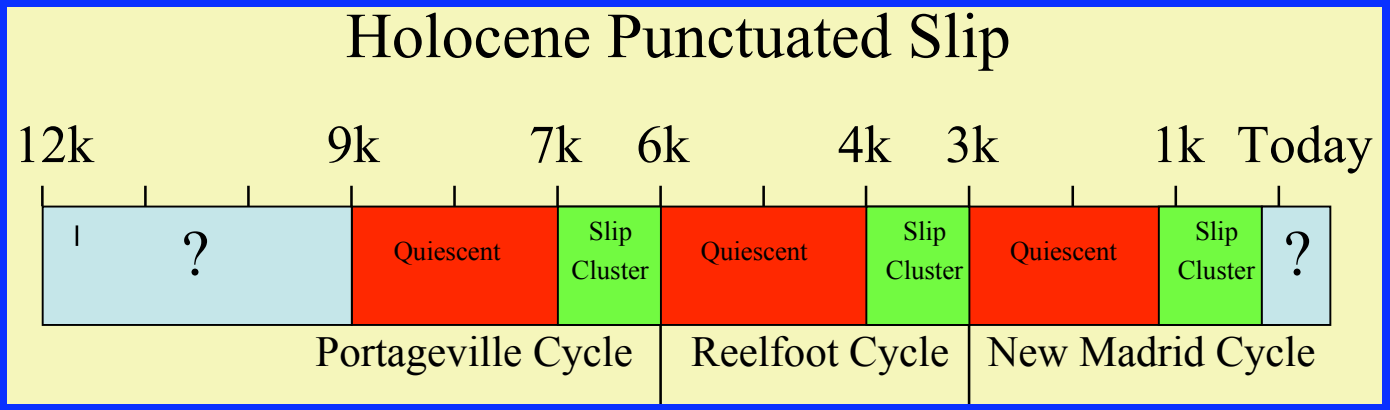
Very long time needed to store up slip needed for a future large earthquake

For steady motion, M 7 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

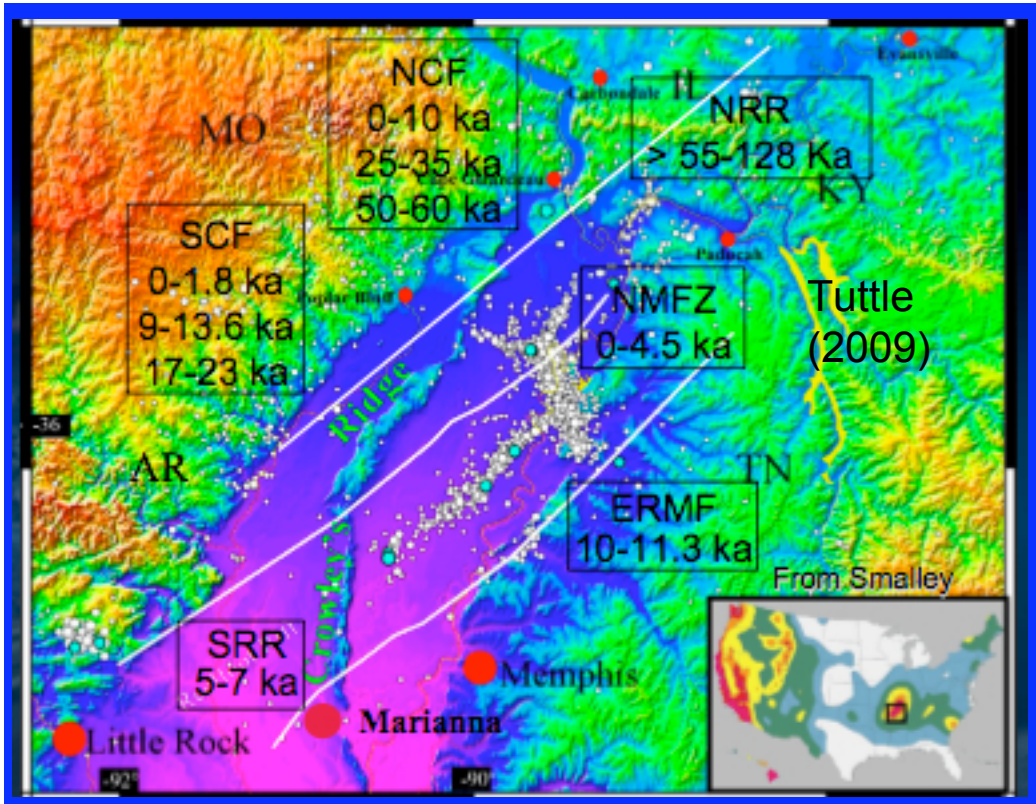
Lack of significant fault topography, jagged fault, seismic reflection, and other geological data also imply that recent pulse of activity is only a few thousand years old

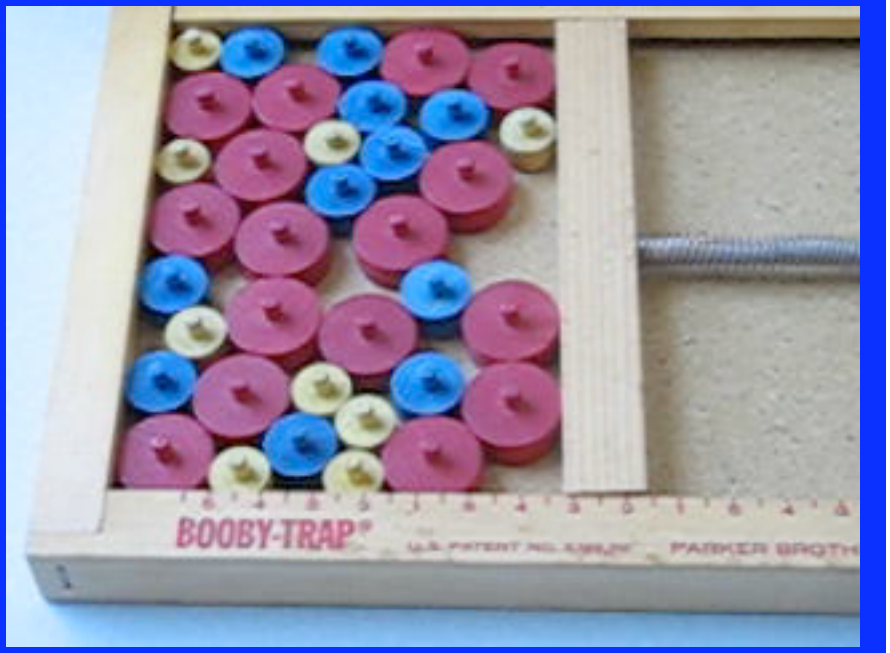
Recent cluster likely ended



New Madrid earthquake history inferred from Mississippi river channels

Holbrook et al., 2006



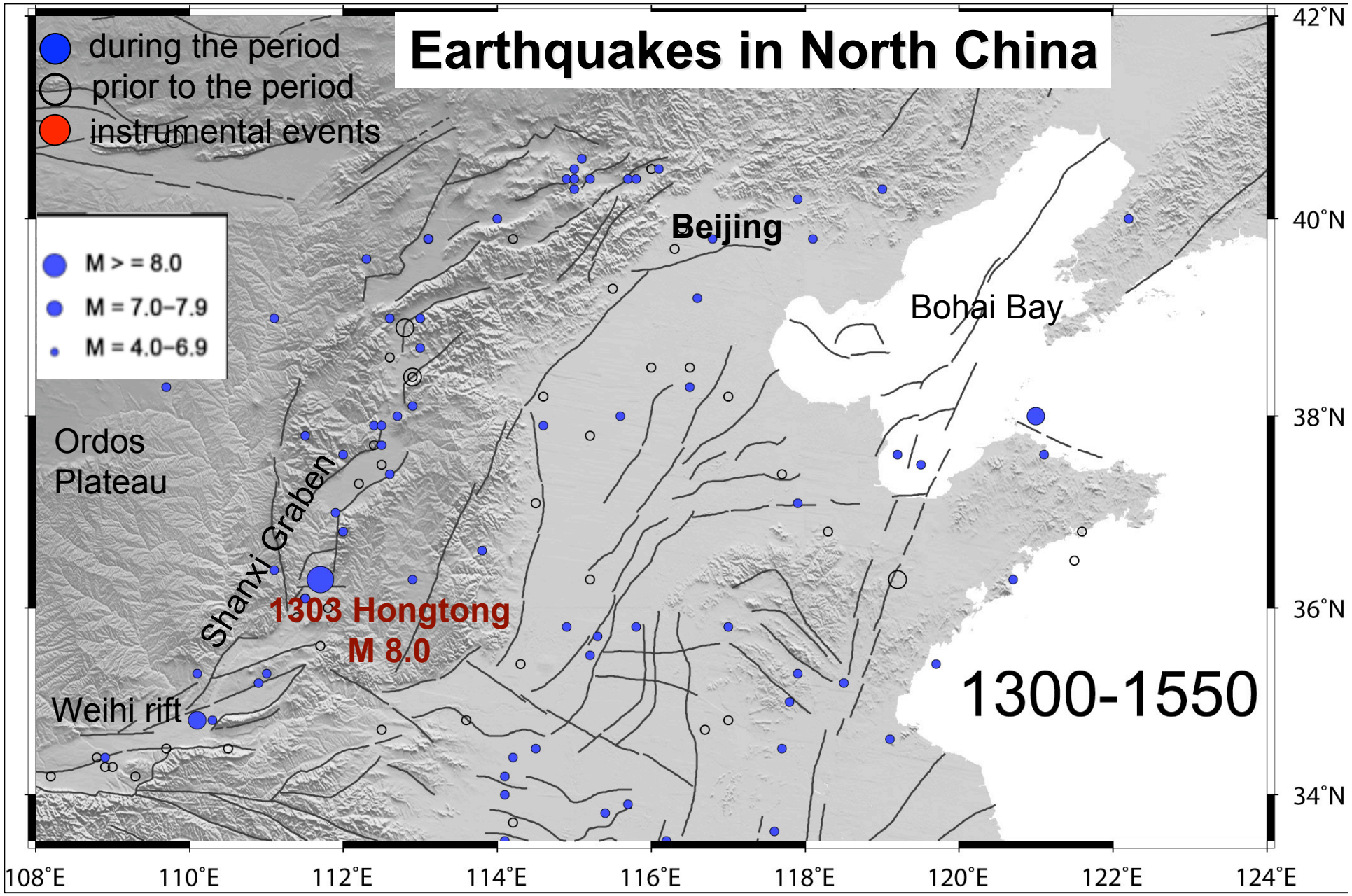


Faults active in past show little present seismicity

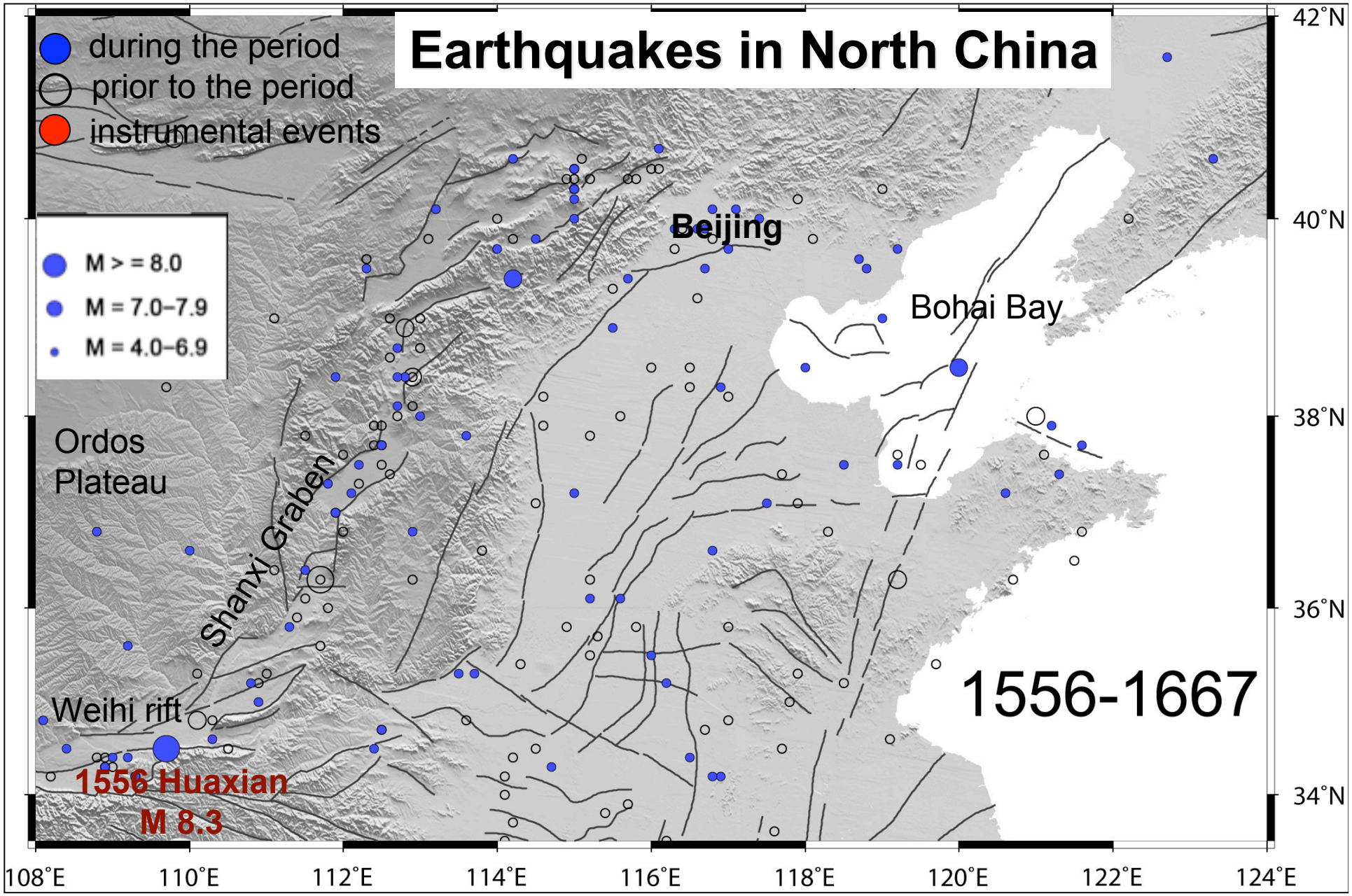
Seismicity migrates among faults due to fault interactions (stress transfer)

Meers fault, Oklahoma
Active 1000 years ago, dead now

Liu, Stein & Wang 2010



Large events often pop up where there was little seismicity!



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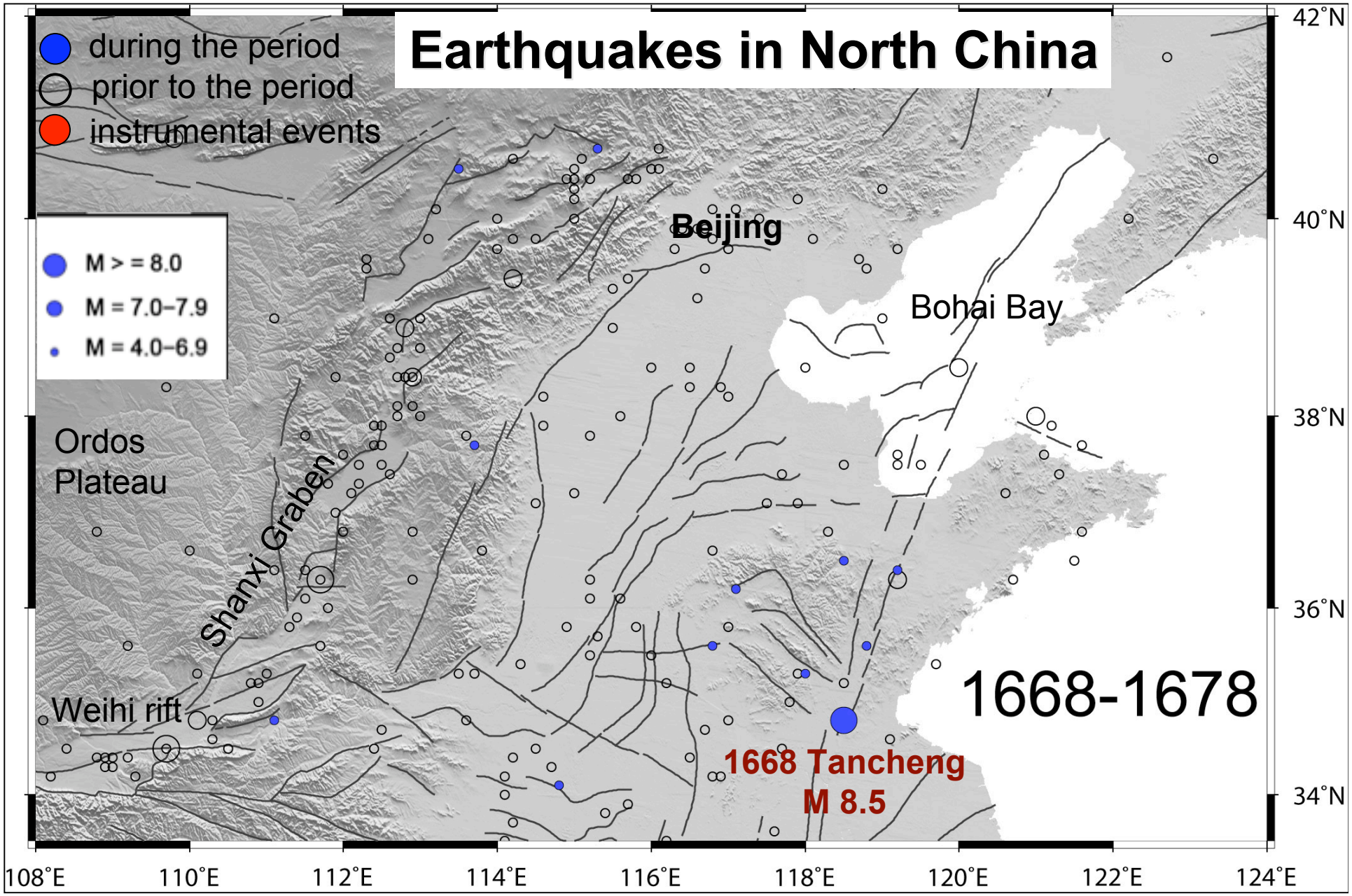

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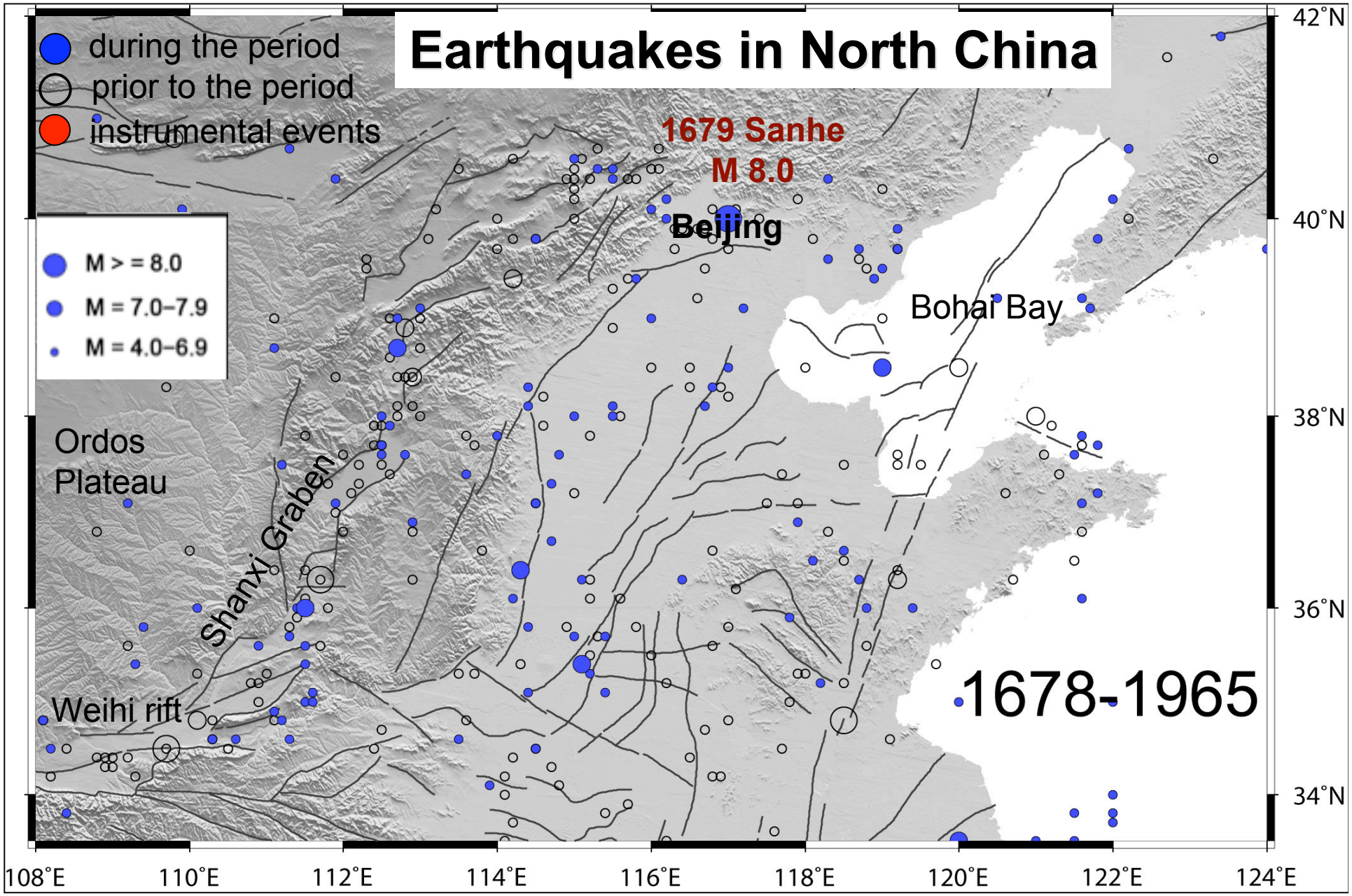

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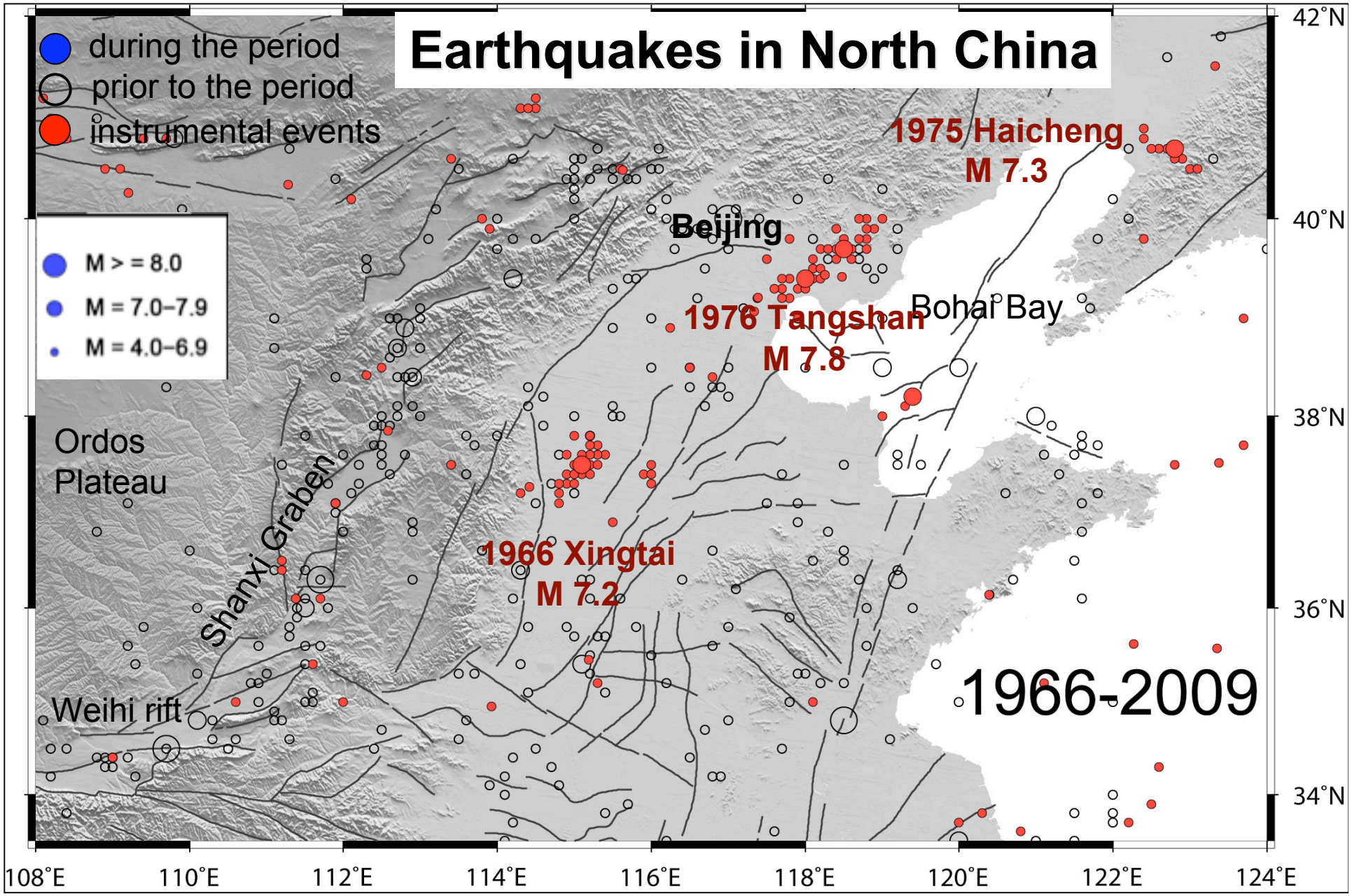
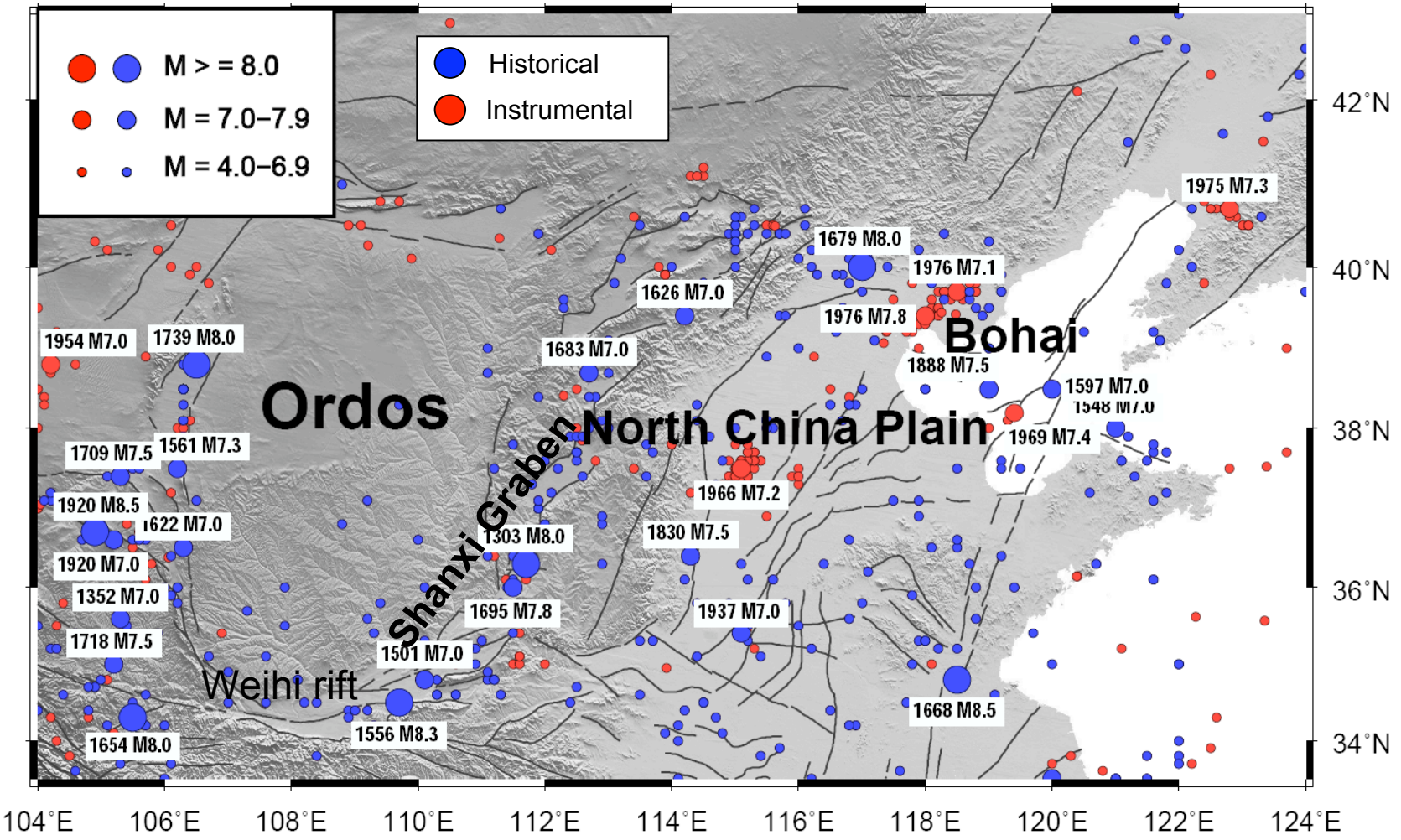


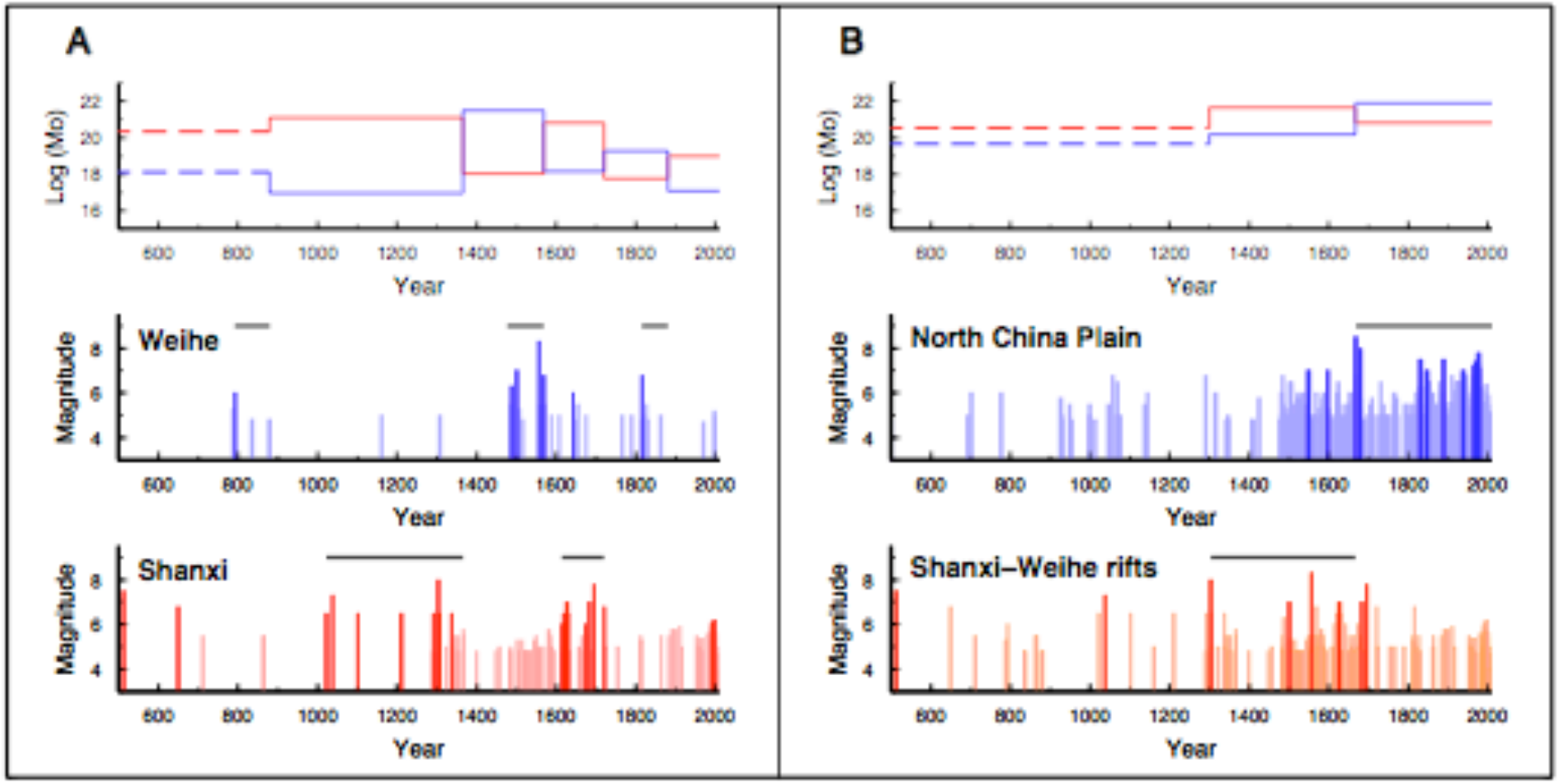
Large events often pop up where there was little seismicity!

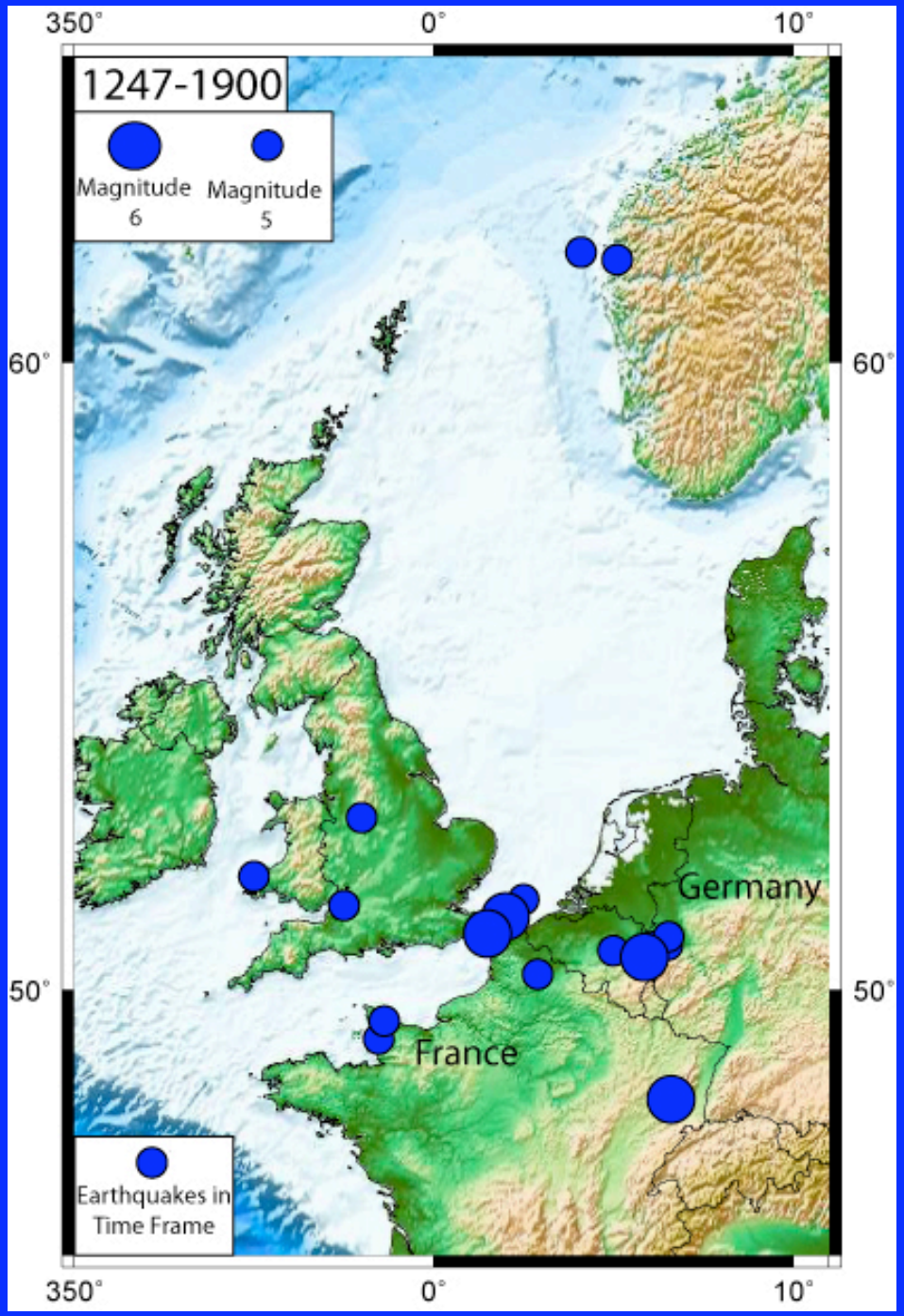
No large (M>7) events ruptured the same fault segment twice in N. China since 1303



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

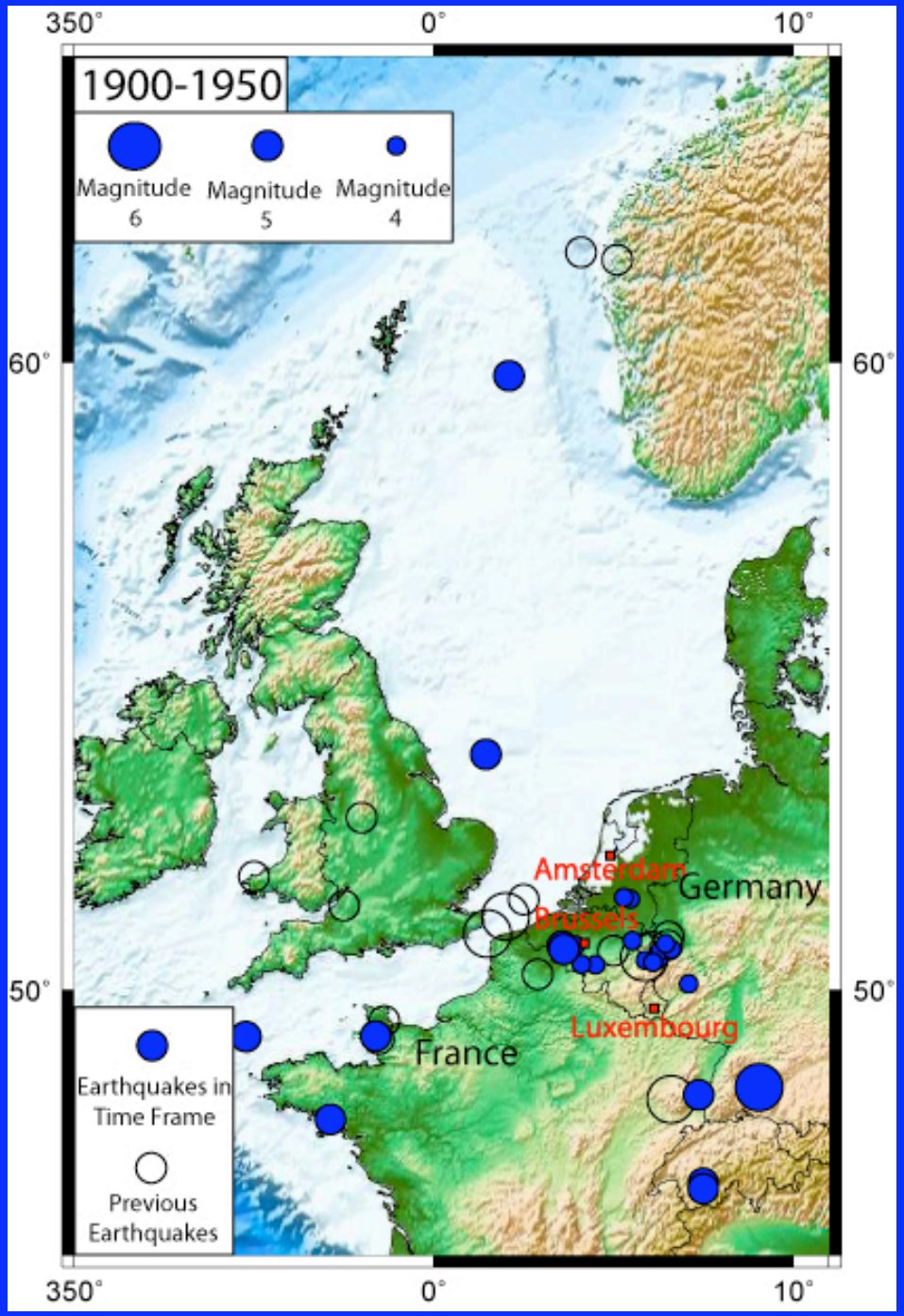
Seismic moment release shows coupled fault systems

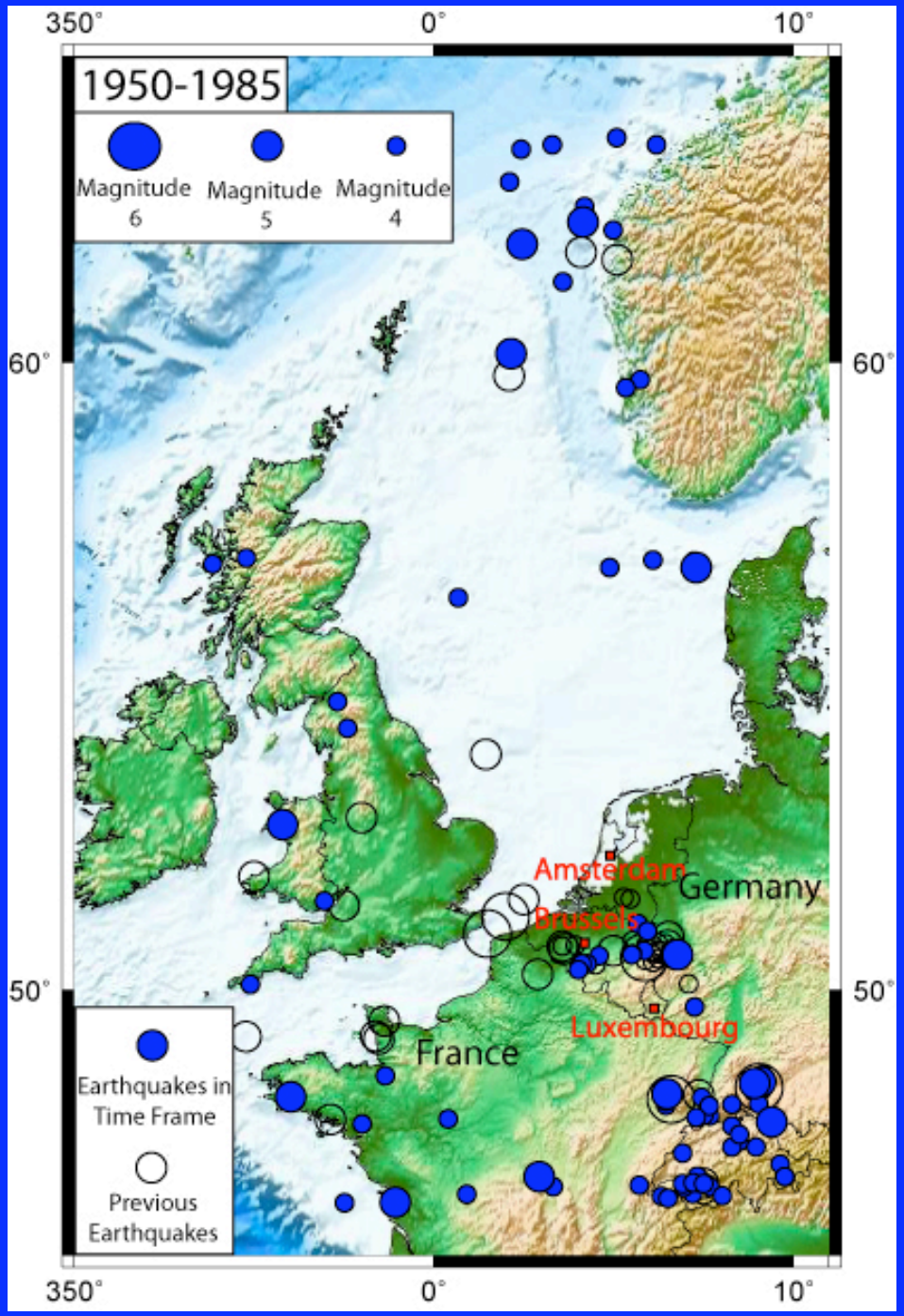


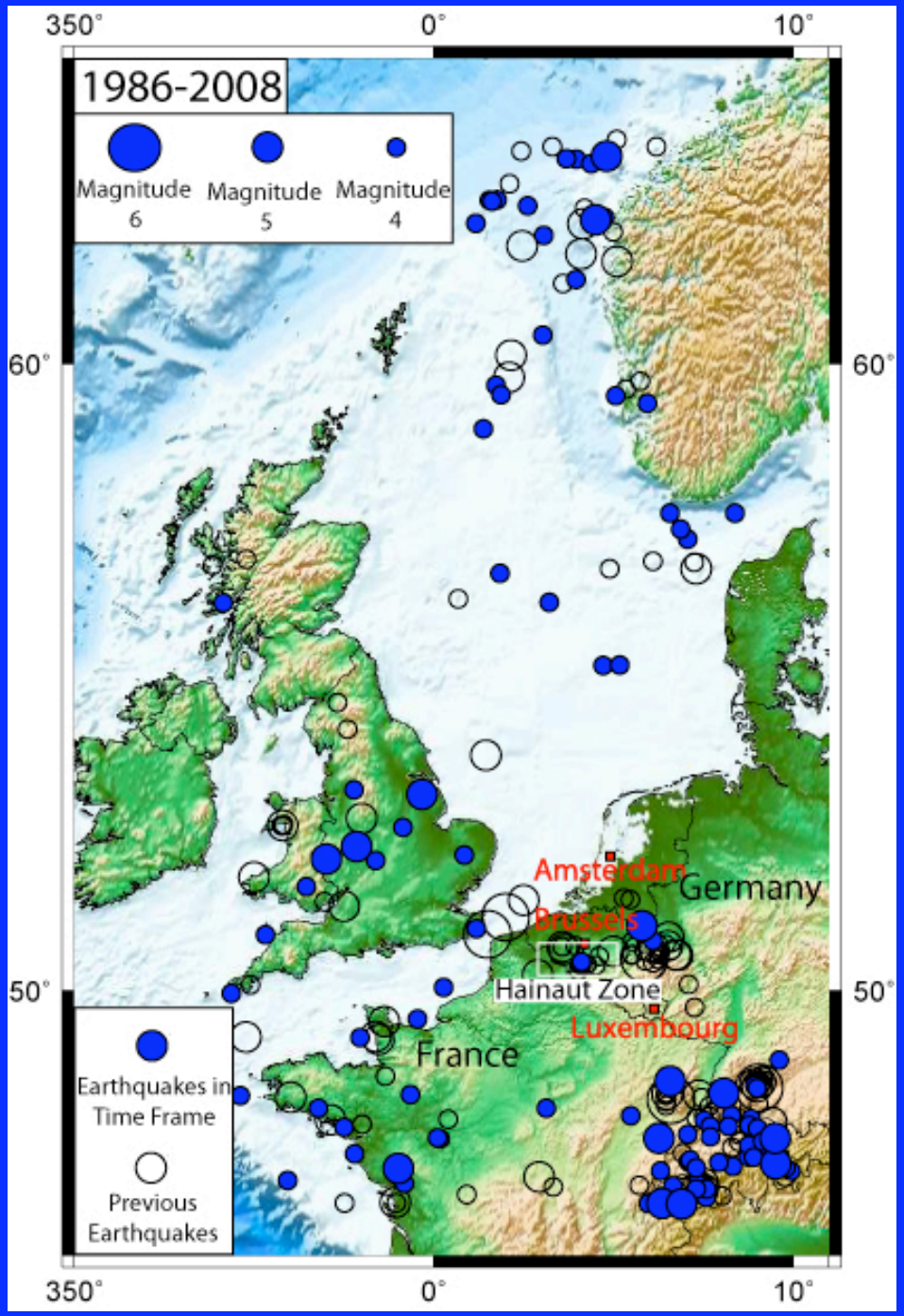


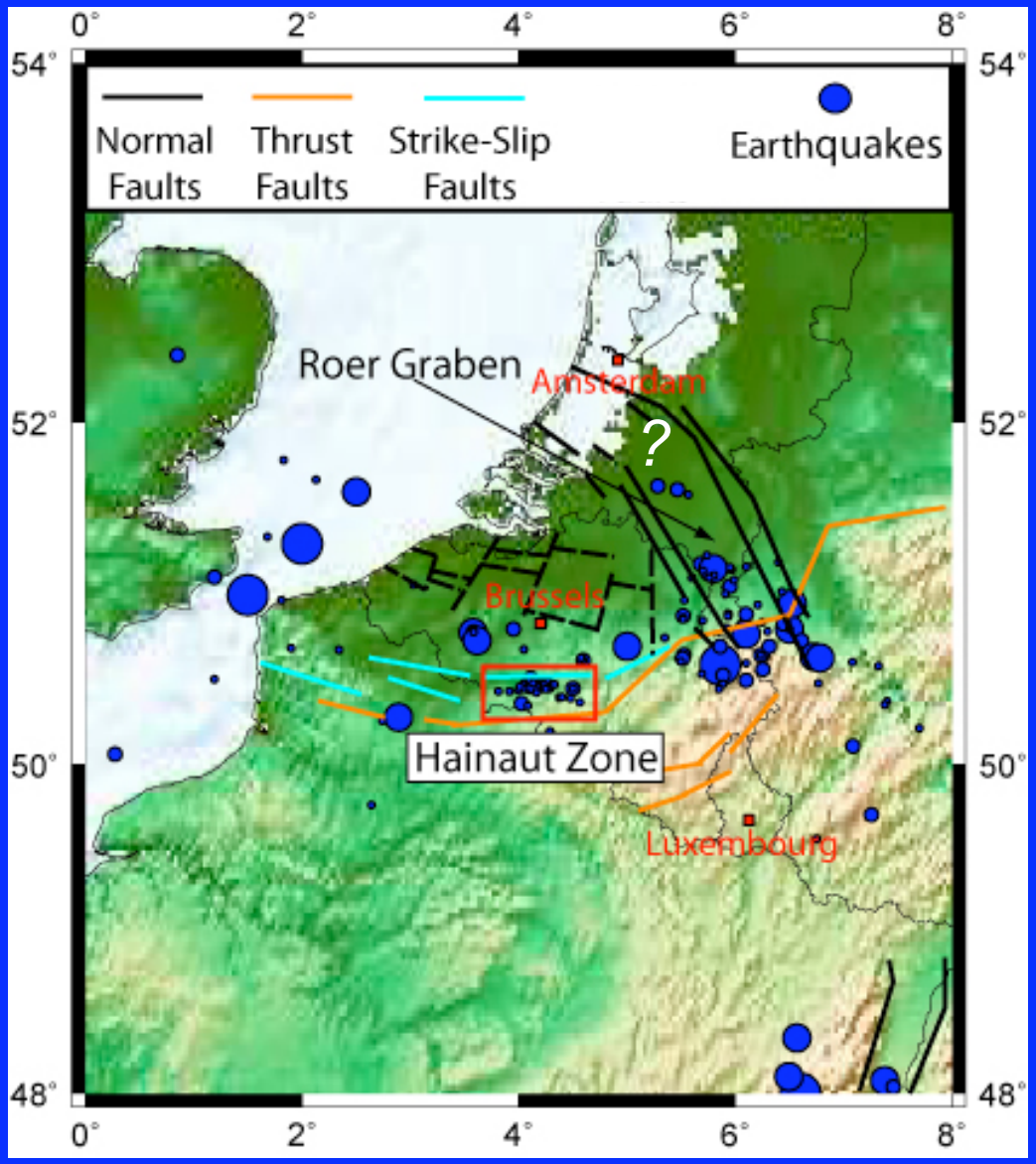
"During the past 700 years, destructive earthquakes generally occurred in different locations, indicating a migration of seismicity with time."

(Camelbeeck et al., 2007)

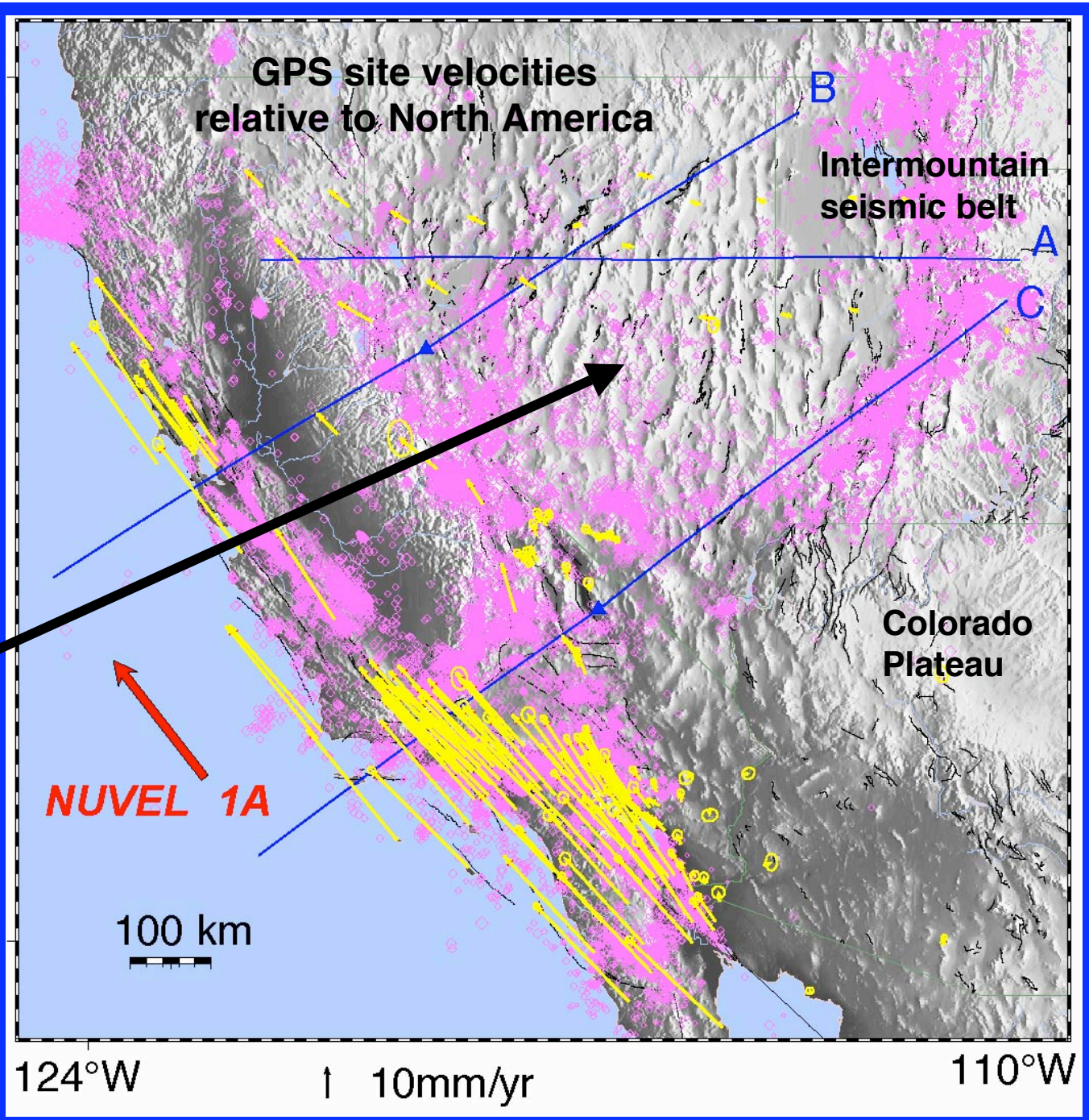

350°
0°
10°
1900-1950
Magnitude 6
Magnitude 5
Magnitude 4
60°
50°
Amsterdam
Brussels
Germany
Luxembourg
France
Earthquakes in Time Frame
Previous Earthquakes


350°
0°
10°
1950-1985
Magnitude 6
Magnitude 5
Magnitude 4
60°
50°
Amsterdam
Germany
Brussels
Luxembourg
France
Earthquakes in Time Frame
Previous Earthquakes


350°
0°
10°
1986-2008
Magnitude 6
Magnitude 5
Magnitude 4
60°
50°
Amsterdam
Germany
Brussels
Hainaut Zone
Luxembourg
France
Earthquakes in Time Frame
Previous Earthquakes

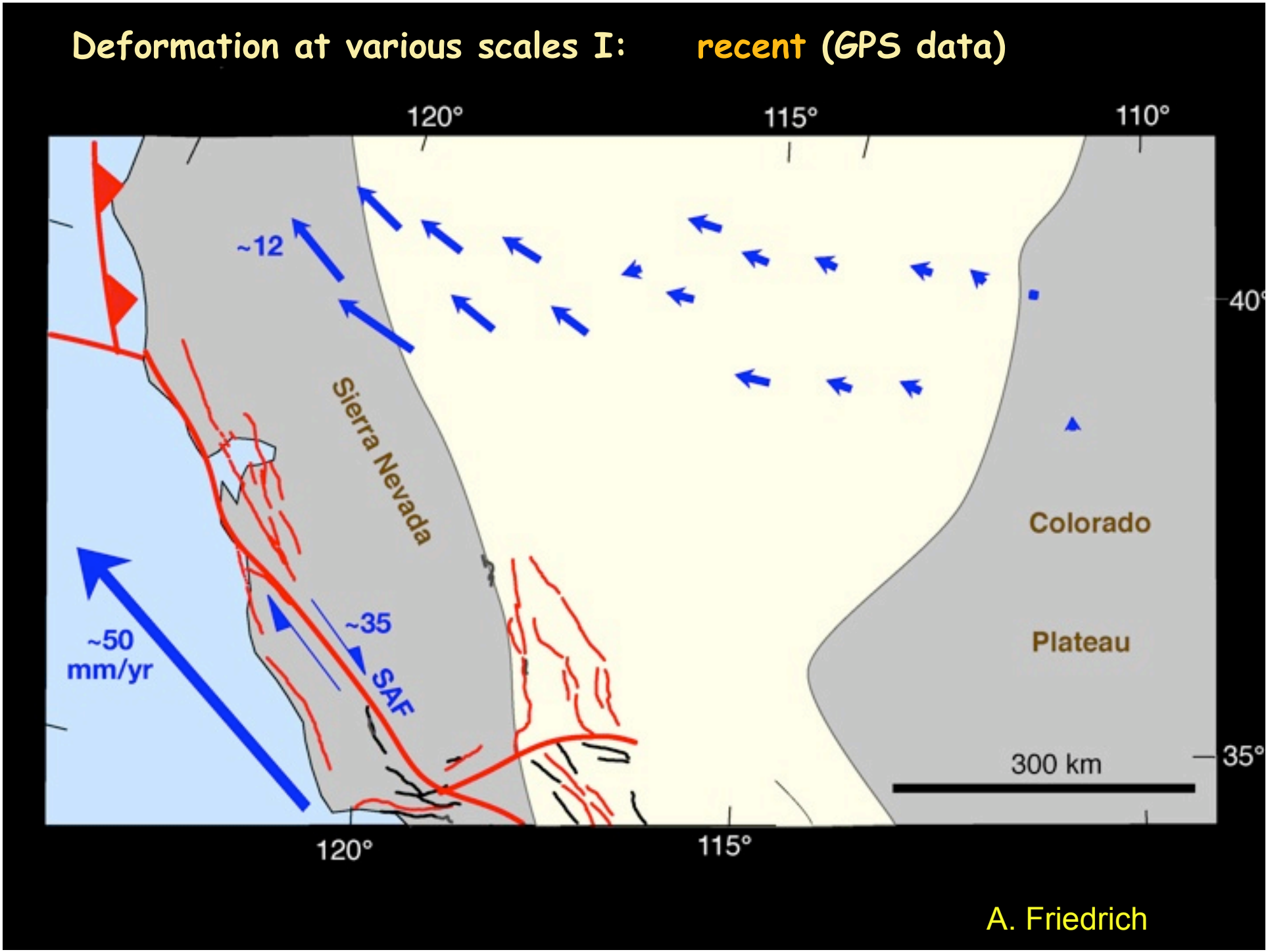

0°
2°
4°
6°
8°
54°
52°
50°
48°
Normal Faults
Thrust Faults
Strike-Slip Faults
Earthquakes
Roer Graben
Amsterdam
?
Brussels
Hainaut Zone
Luxembourg

Deformation migrates between faults within boundary zone



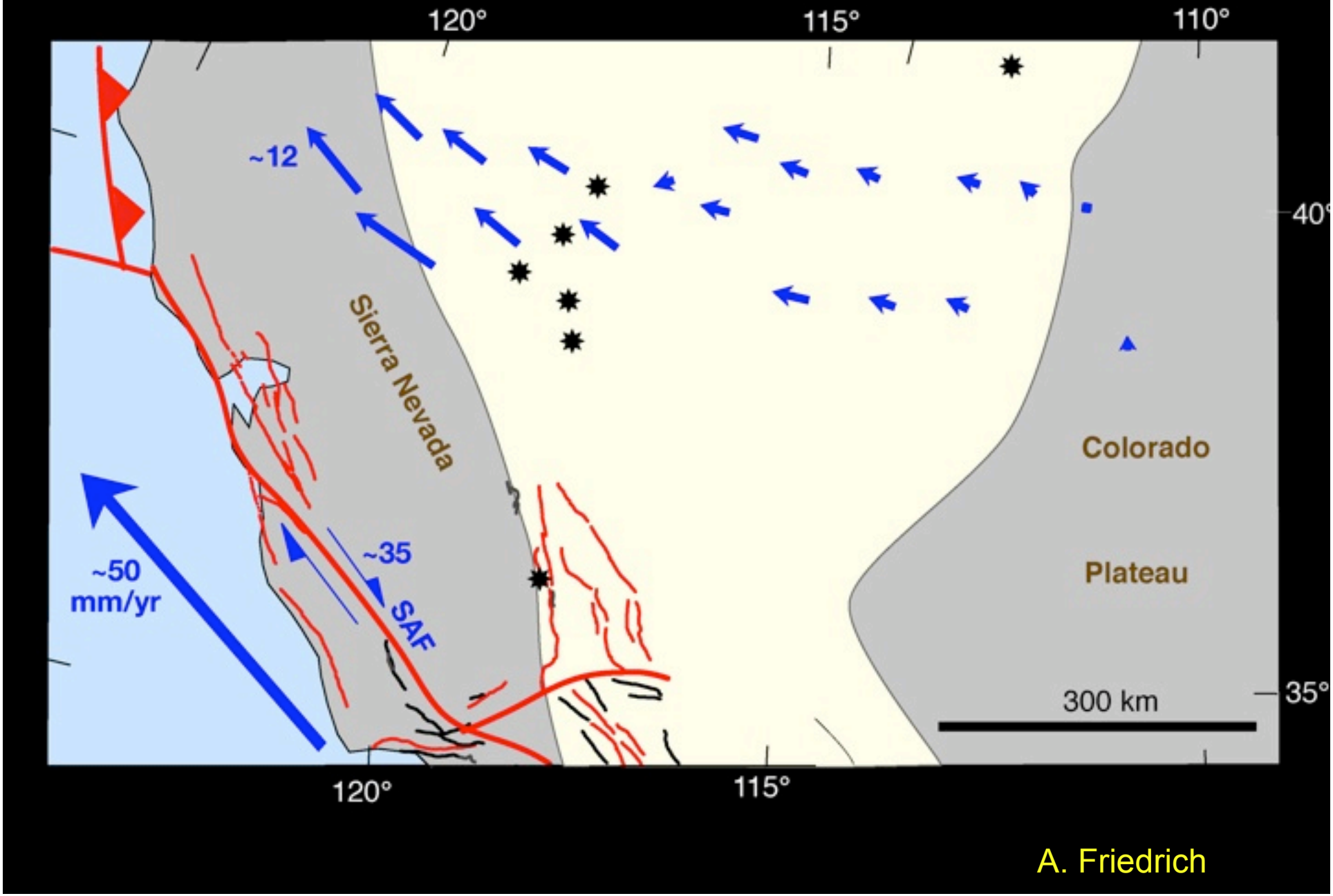
Bennett et al., 1999

Deformation at various scales I: recent (GPS data)



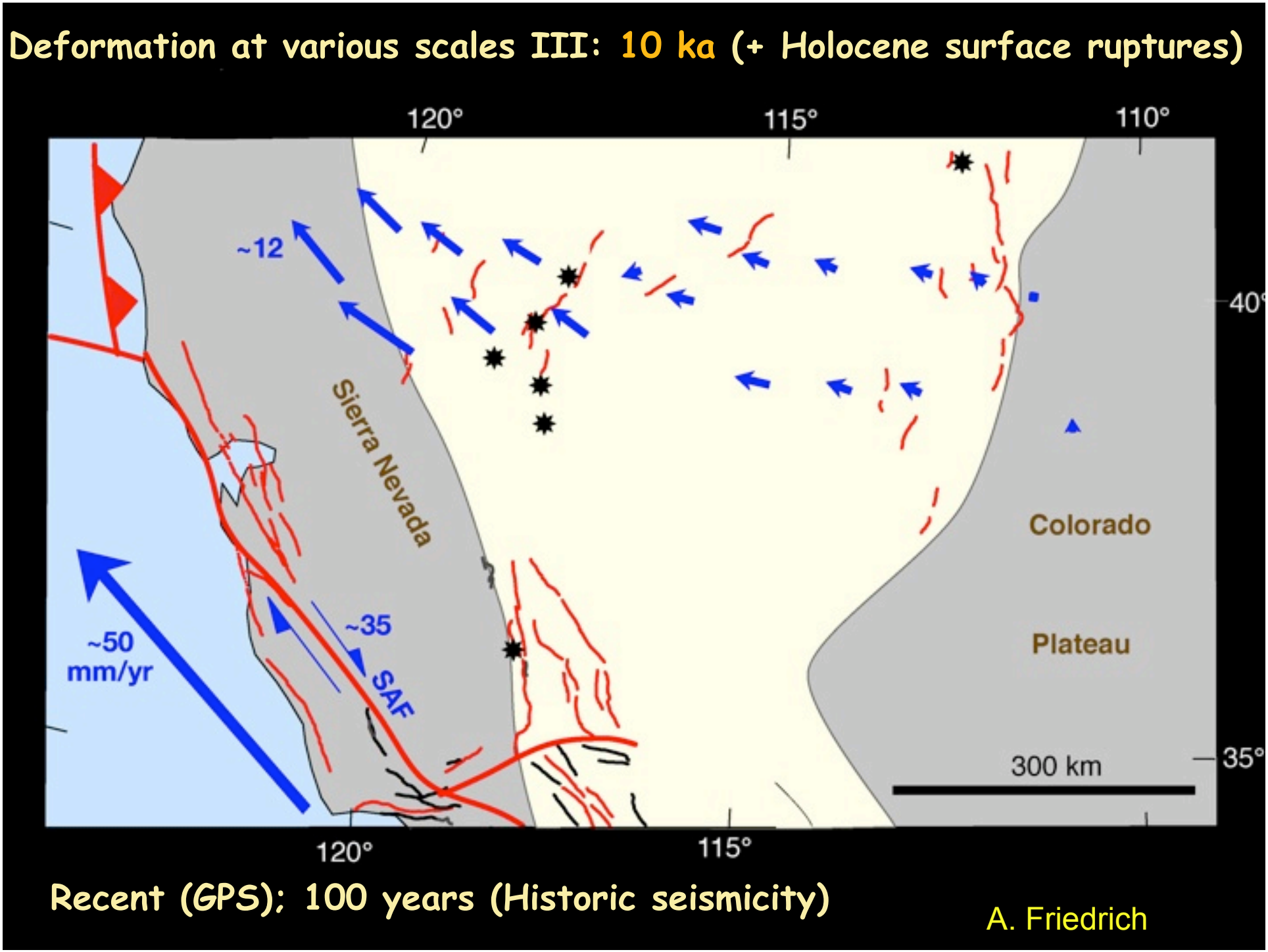
A. Friedrich

Deformation at various scales II: 100 years (GPS + Historic seismicity)



A. Friedrich

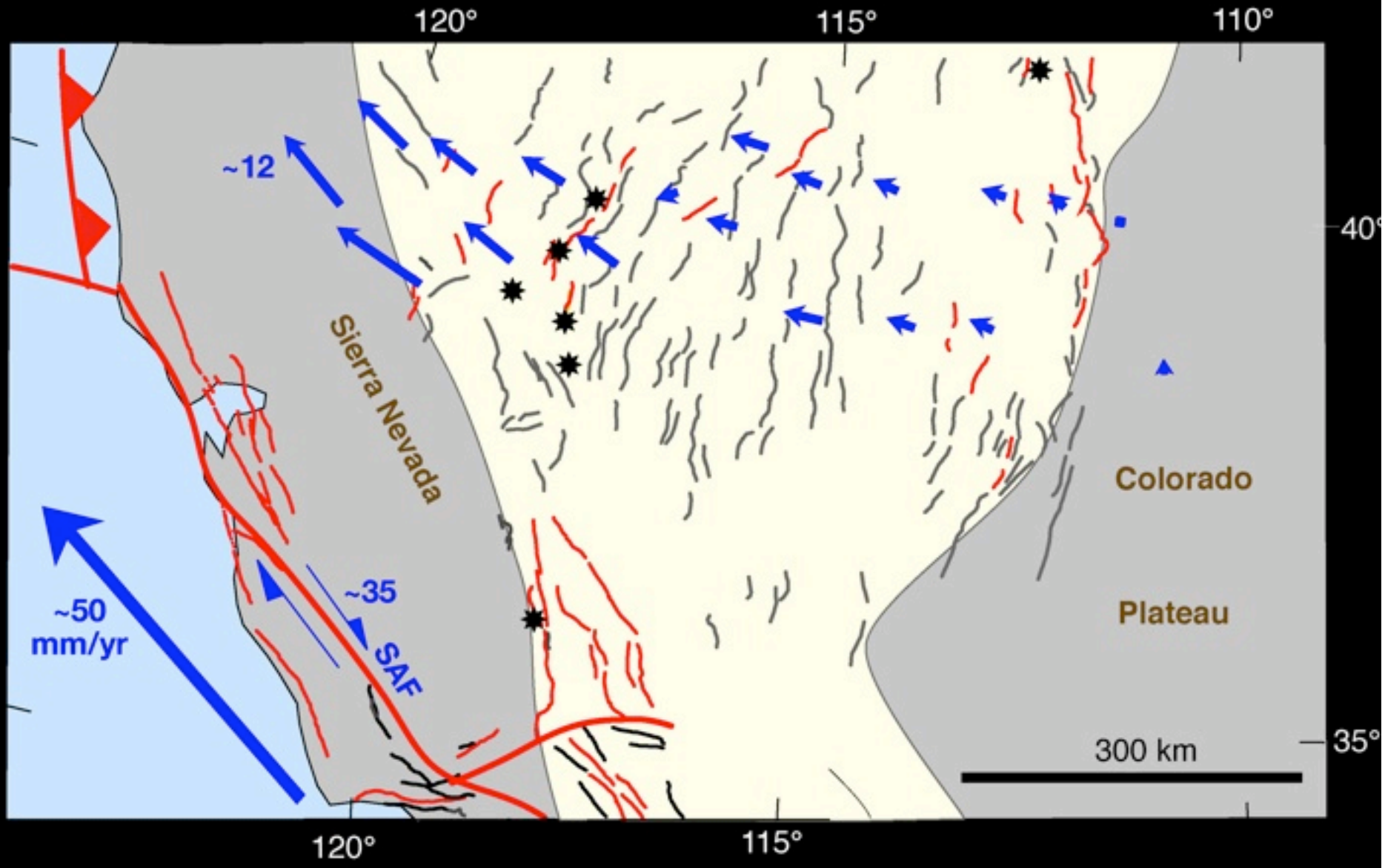
Deformation at various scales III: 10 ka (+ Holocene surface ruptures)



Recent (GPS); 100 years (Historic seismicity)

A. Friedrich

Deformation at various scales IV: 1 Ma (Quaternary fault traces)



Recent (GPS); 100 years (Historic seismicity); 10 ka (Holocene surface ruptures)

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

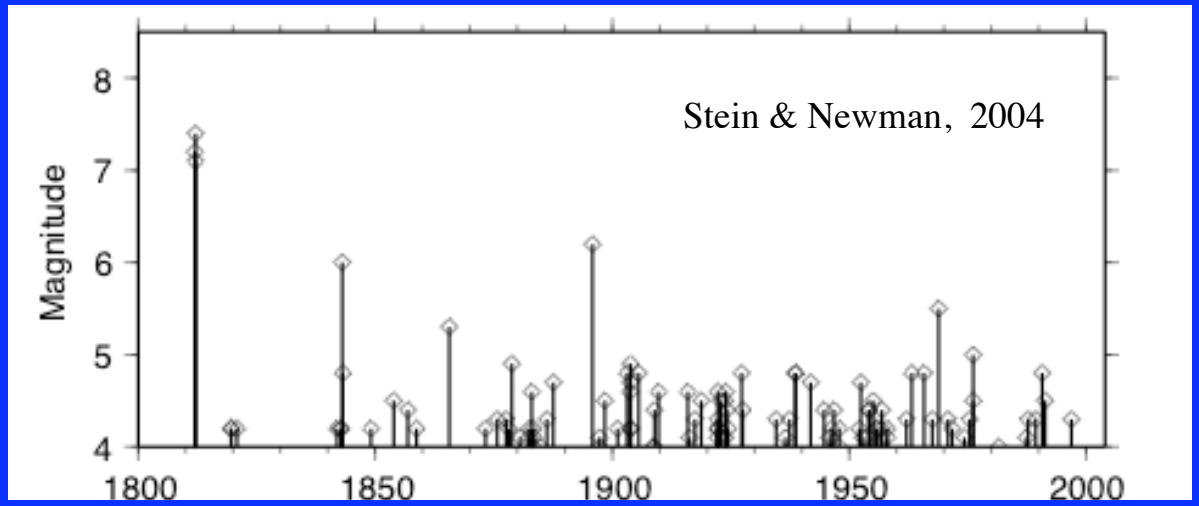
In complex systems, the whole behaves in ways more complicated than can be understood from analysis of its component parts.

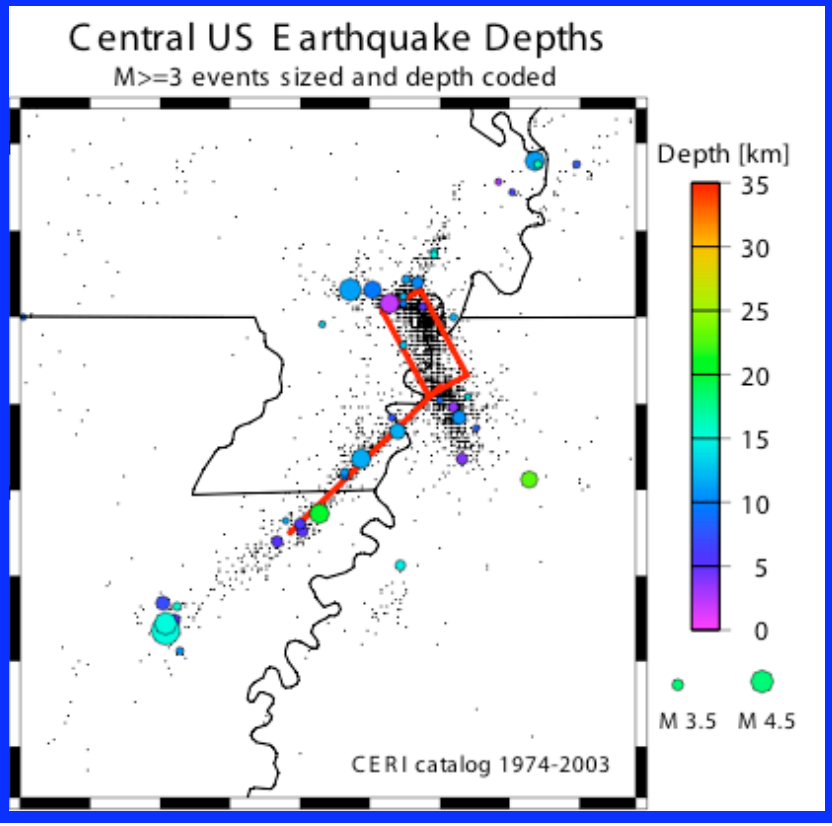
A human body is more complicated than we can understand by studying individual cells, the economy is more complicated than explained by individual business transactions, and studying one ant doesn't tell how a colony behaves.

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

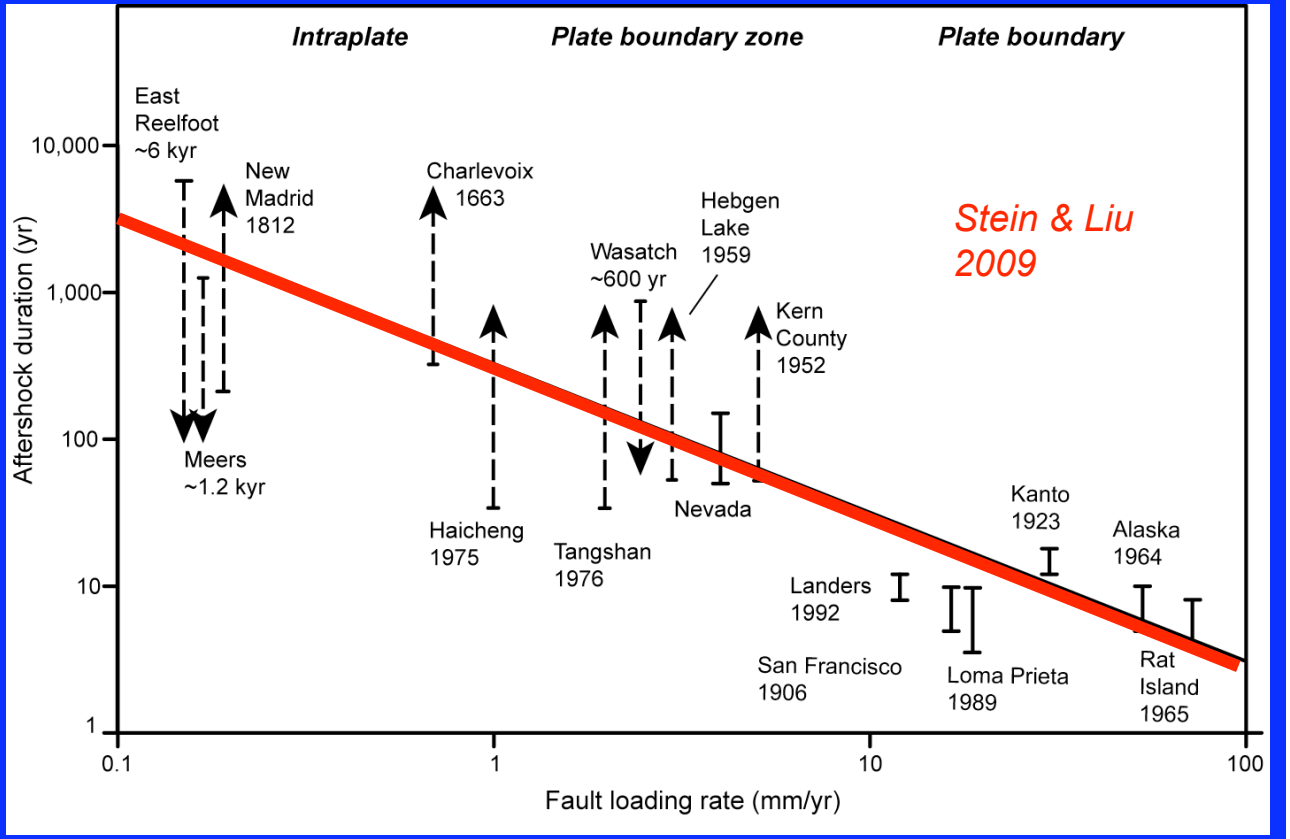
- used to delineate 1811-12 ruptures
- rate & size decreasing
- largest at the ends of presumed 1811-12 ruptures

LONG AFTERSHOCK SEQUENCES IN SLOWLY DEFORMING CONTINENTAL INTERIORS

Plate boundary faults quickly reloaded by steady plate motion after large earthquake

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

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



Aftershock duration α 1/loading rate