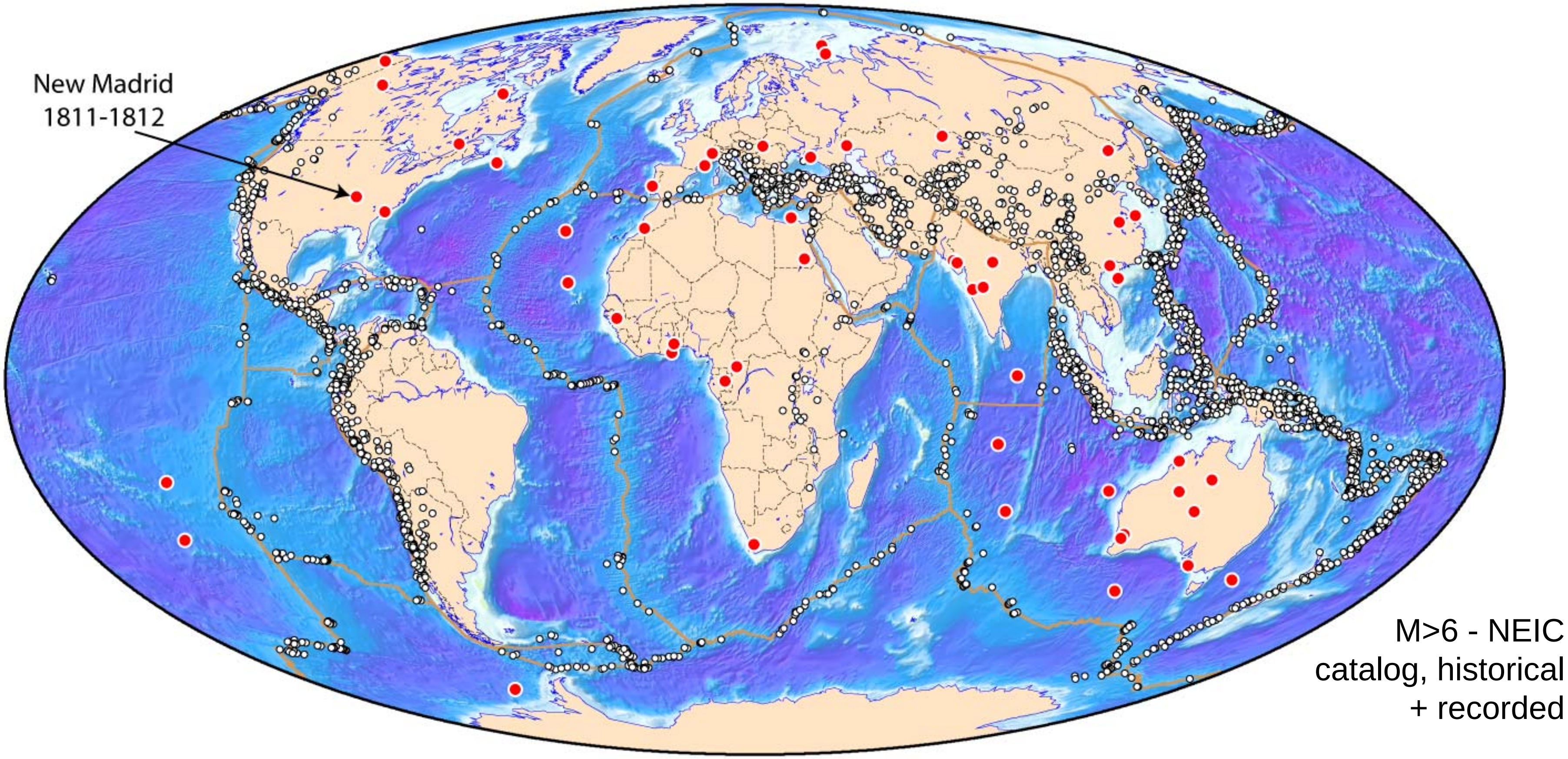
What next?

- Why would seismogenic strain localize in a continent?
  - No reason for strain to localize in an elastic plate -- the whole plate deforms (= stores elastic strain) uniformly (“strain reservoir”)
  - Strain localizes at PBZ because there is flow in viscous layers
  - No reason to happen in a continent unless there has been local weakening:
    - Thermal -- unclear for NMSZ
    - Previous earthquake -- could keep earthquakes going for a while, but reloading of fault from below is not efficient
  - It is possible that strain accumulation before large earthquake sequences is not detectable at local scale inside continents
- Earthquakes are the result of stress changes rather than strain accumulation
  - Continental faults are near failure (cf. Zoback et al.)
  - If so, small (~1 MPa) perturbations may be sufficient to trigger earthquakes (if fast enough w.r.t. Maxwell time of relaxing layers)
  - Example follows



M>6 - NEIC
catalog, historical
+ recorded

- Steady-state model: strain accumulation rate = rate of seismic strain release
  - Geodesy and paleoseismology should agree
  - Works well at plate boundaries
  - Present-day strain accumulation has predictive power
- In addition to steady-state assumption:
  - = Fault strength constant
  - = Surface representative of the whole crust
  - = Constant tectonic loading

RETHINKING MIDCONTINENTAL SEISMICITY AND HAZARDS

Seth Stein
Northwestern University

What is the relationship between geodetic deformation and earthquake occurrence?

Is the absence of evidence for geodetic deformation a definitive indicator of future earthquake potential?

What weight would you give geodetic data versus observed seismicity in establishing rates of earthquake occurrence?

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

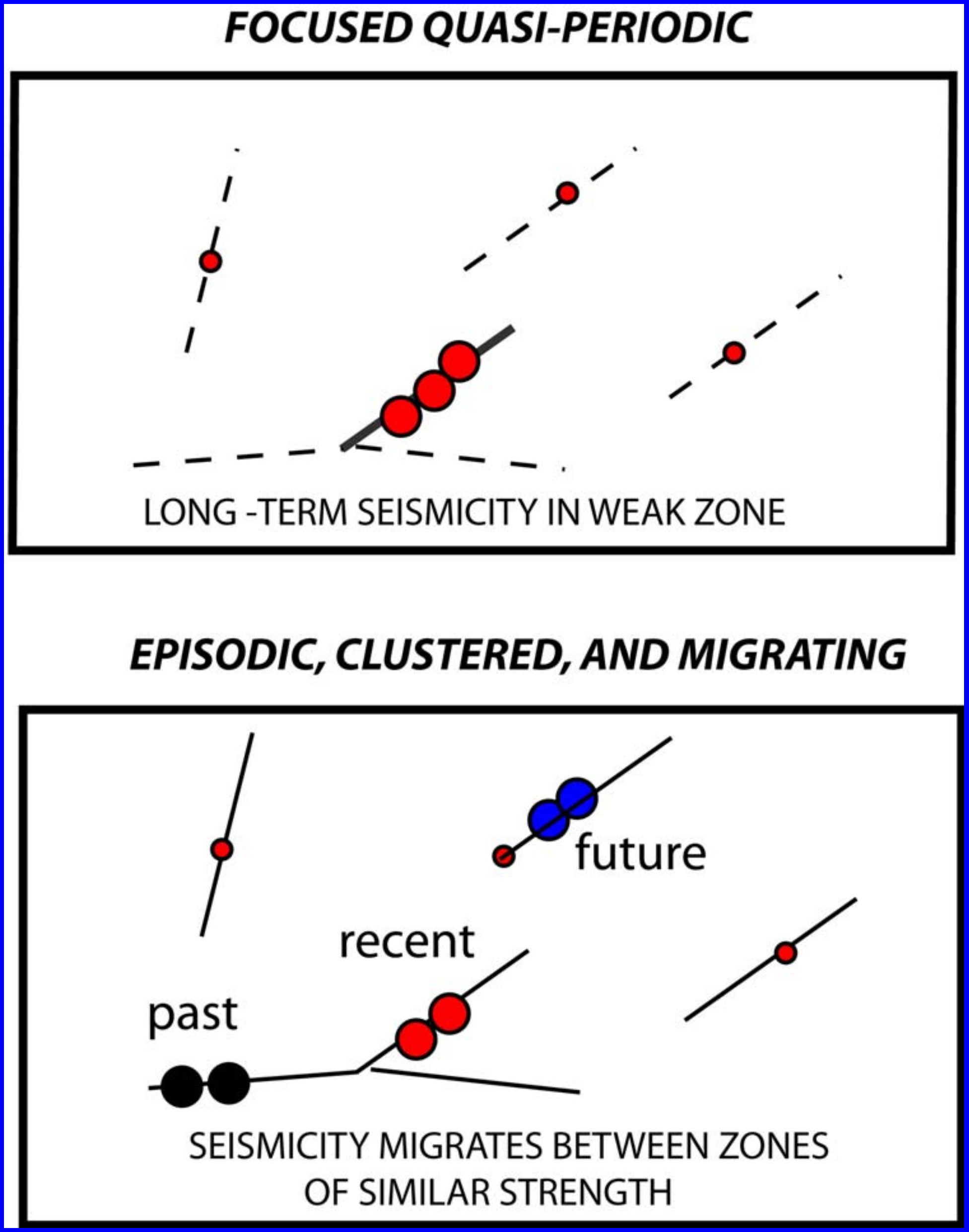
Steady focused deformation: *past* shown by geology & earthquake record consistent with *present* shown by geodesy, and predicts future seismicity

Complex regional system of interacting faults

Deformation varies in space and time

Deformation can be steady for a while - as in FQP model - then shift

Past can be poor predictor



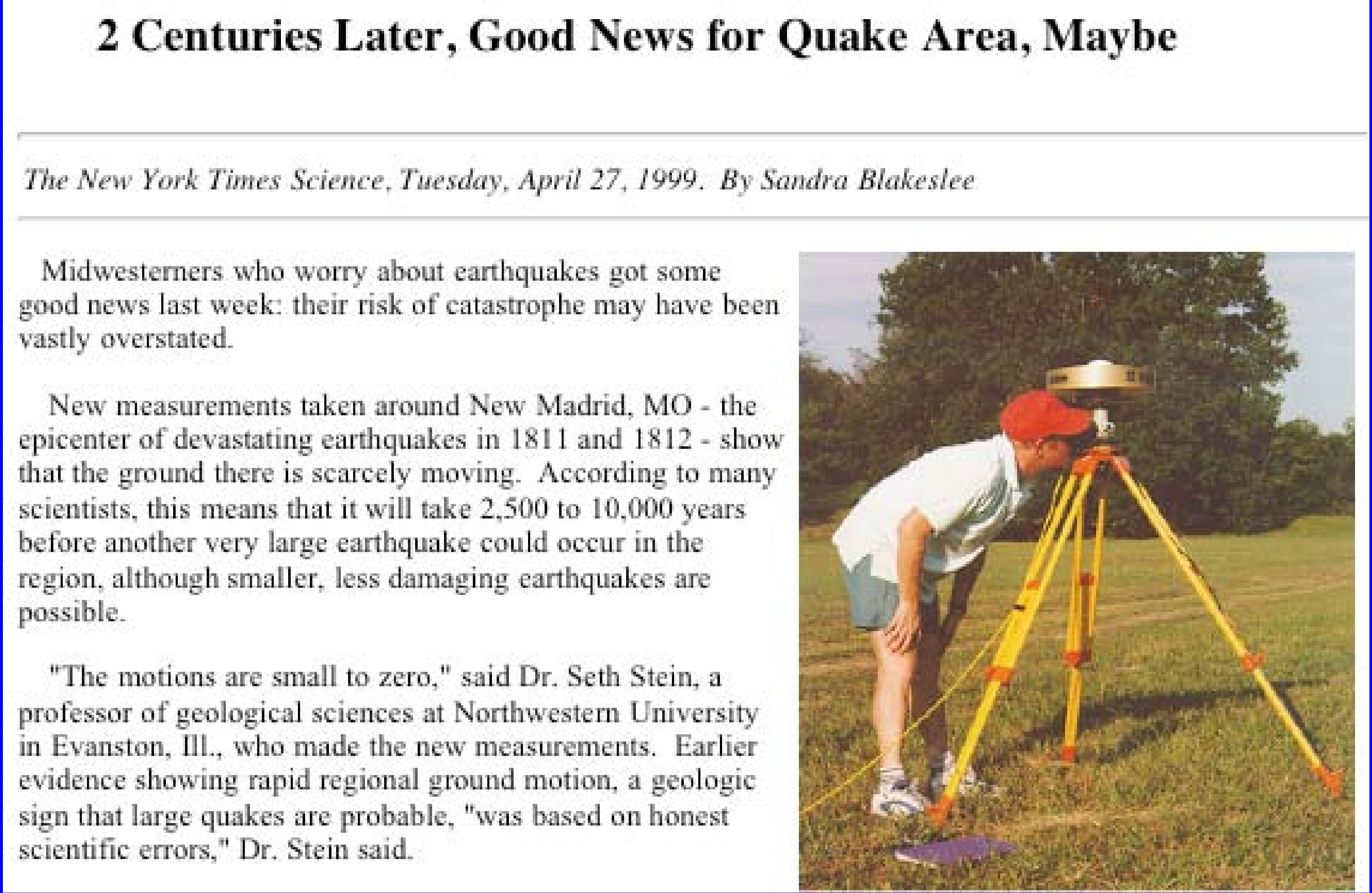
McKenna, Stein & Stein, 2007

We started GPS at New Madrid expecting to find strain 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



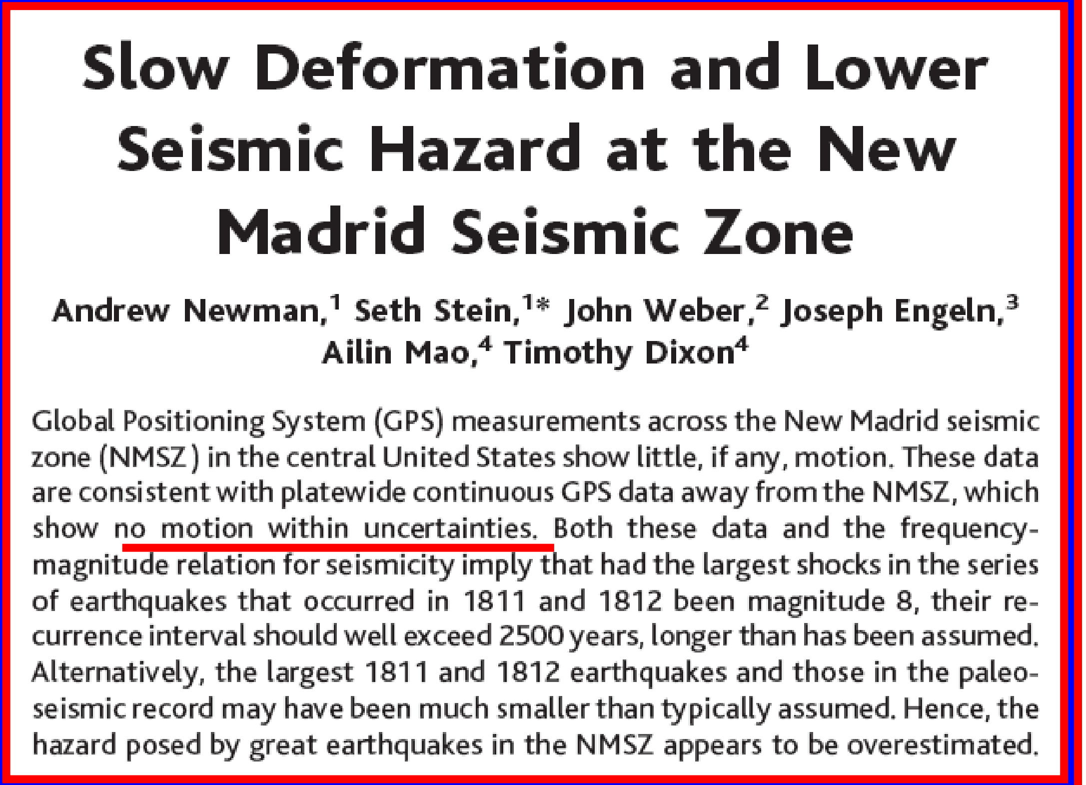
2 Centuries Later, Good News for Quake Area, Maybe

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.

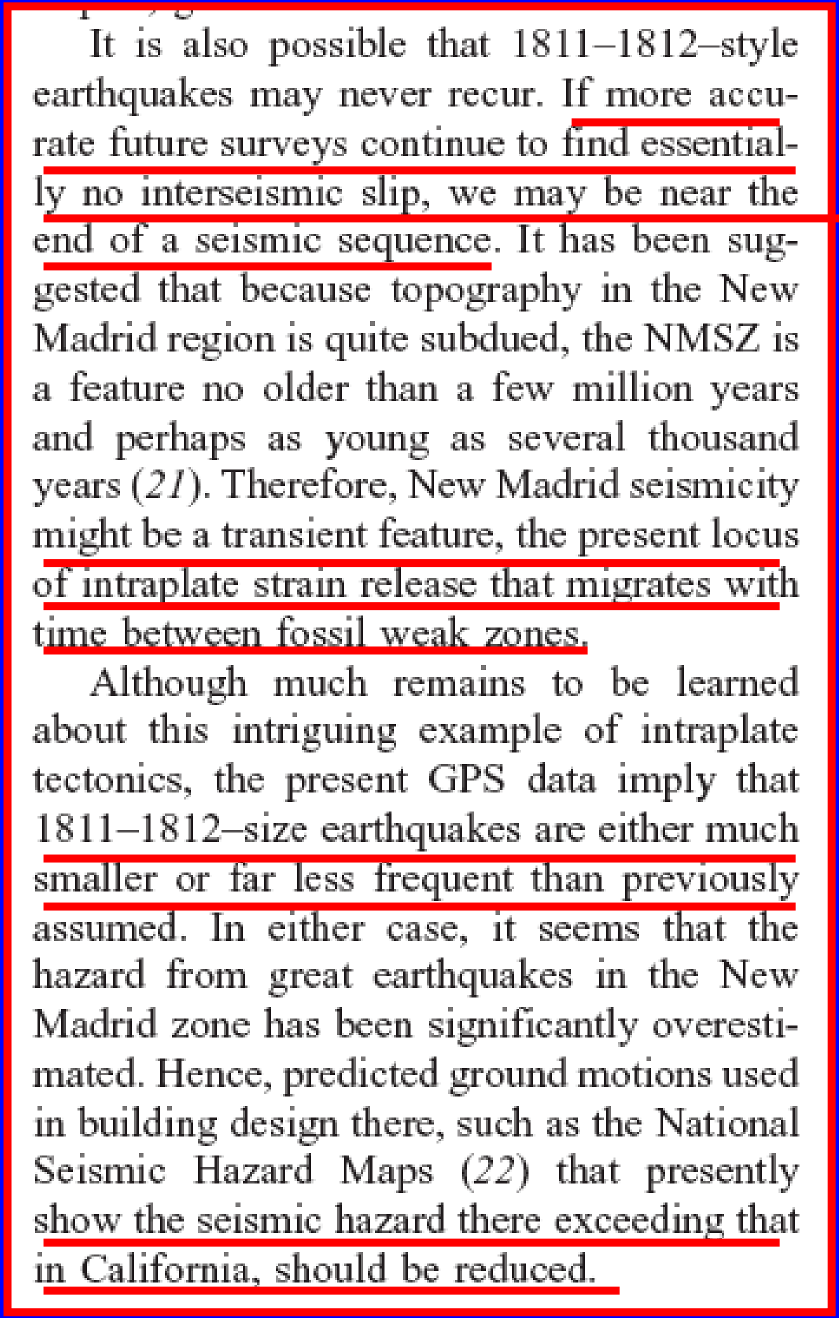
"The motions are small to zero," said Dr. Seth Stein, a professor of geological sciences at Northwestern University in Evanston, Ill., who made the new measurements. Earlier evidence showing rapid regional ground motion, a geologic sign that large quakes are probable, "was based on honest scientific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



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.



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.

April 1999

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

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

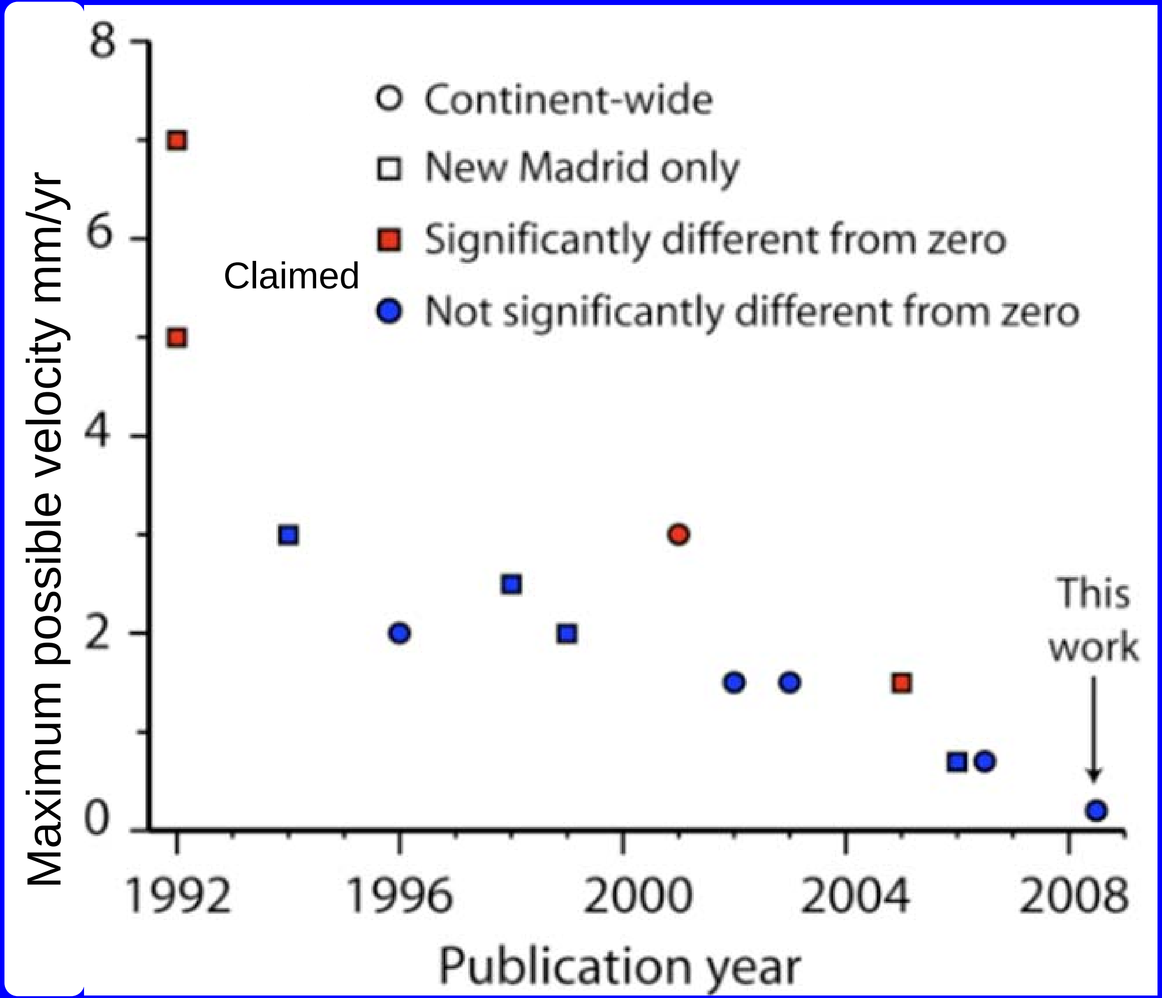
If position uncertainty is given by standard deviation σ

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

Rate precision improves
with longer observations

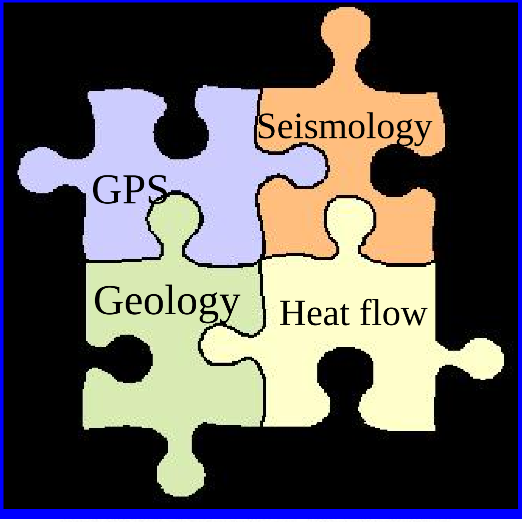
Rates < 0.2 mm/yr,
will continue to
converge on zero unless
ground motion starts

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



Calais & Stein, 2009

DATA TAKEN JOINTLY FAVOR NEW VIEW

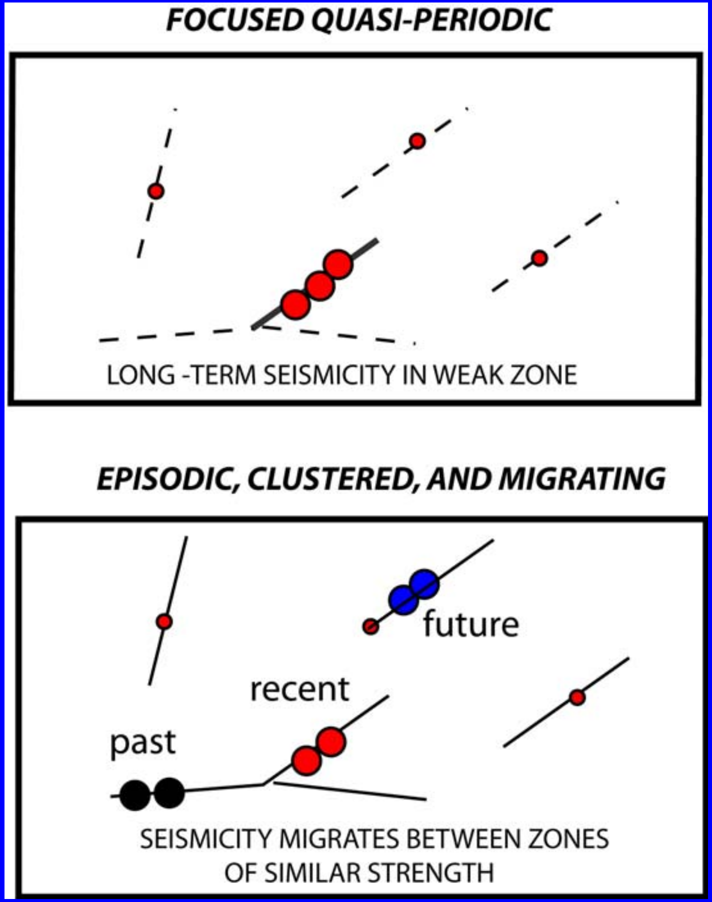


Past 2000 years aren't representative of long term NMSZ behavior

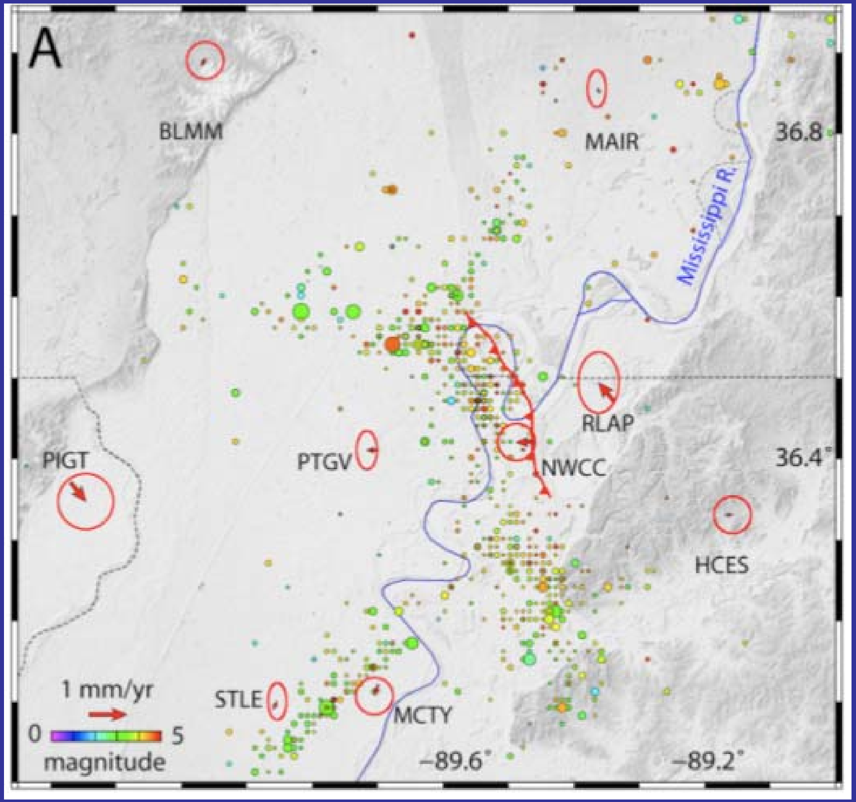
NMSZ isn't special - don't need to invoke site-specific processes

Seismicity migrates among equivalent faults

Recent large earthquake cluster may be ending

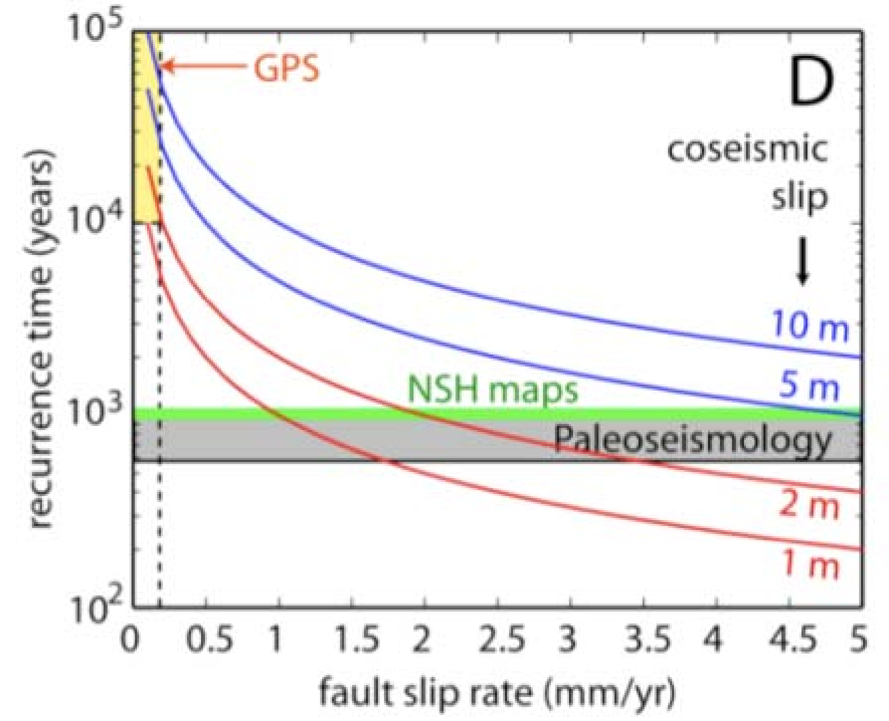


GPS SHOWS LITTLE OR NO MOTION



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.

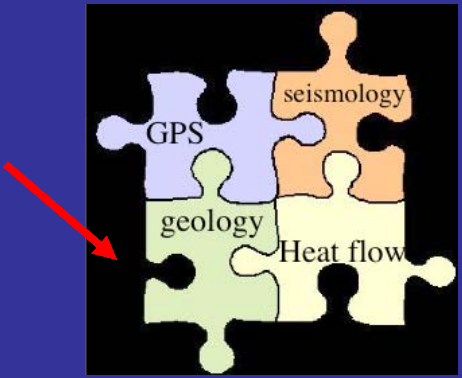
Calais & Stein, 2009



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

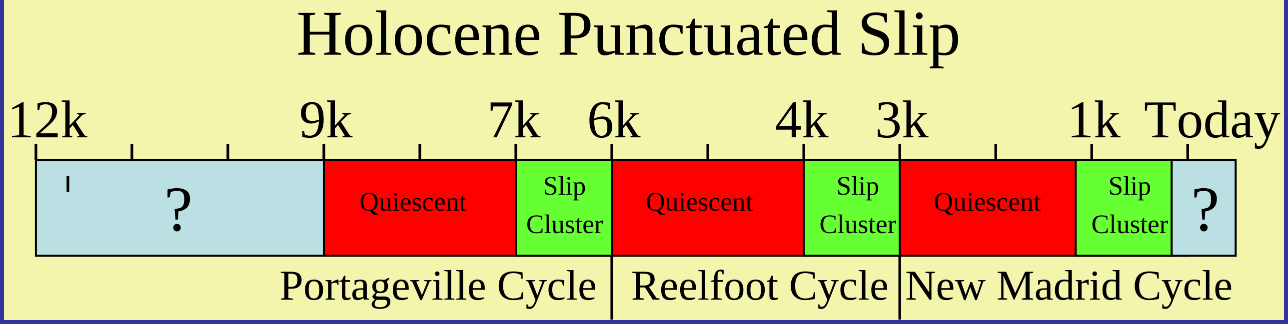
GEOLOGY IMPLIES NEW MADRID EARTHQUAKES ARE EPISODIC & CLUSTERED



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

This is consistent with results from other continental interiors

New Madrid earthquake history inferred from Mississippi river channels



Holocene Punctuated Slip

12k 9k 7k 6k 4k 3k 1k Today

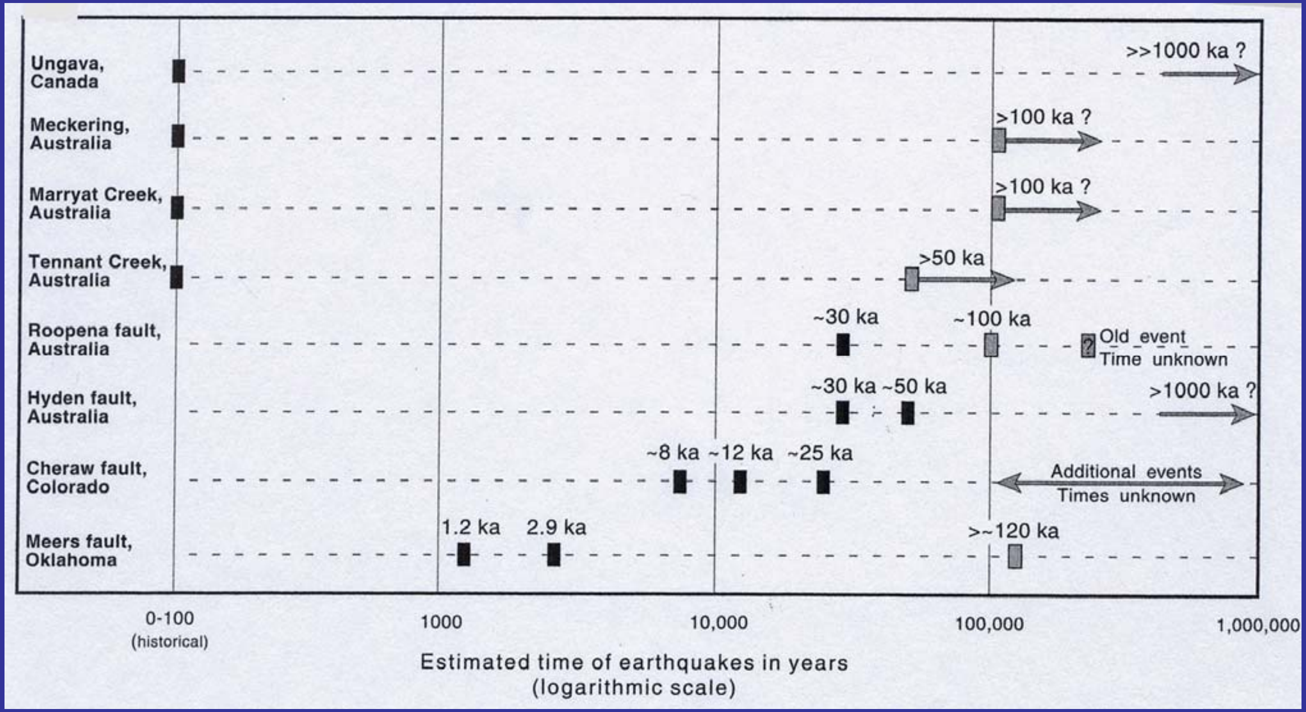
? | Quiescent | Slip Cluster | Quiescent | Slip Cluster | Quiescent | Slip Cluster | ?

Portageville Cycle | Reelfoot Cycle | New Madrid Cycle

Holbrook et al., 2006

CONTINENTAL INTRAPLATE EARTHQUAKES ARE OFTEN EPISODIC, CLUSTERED & MIGRATING

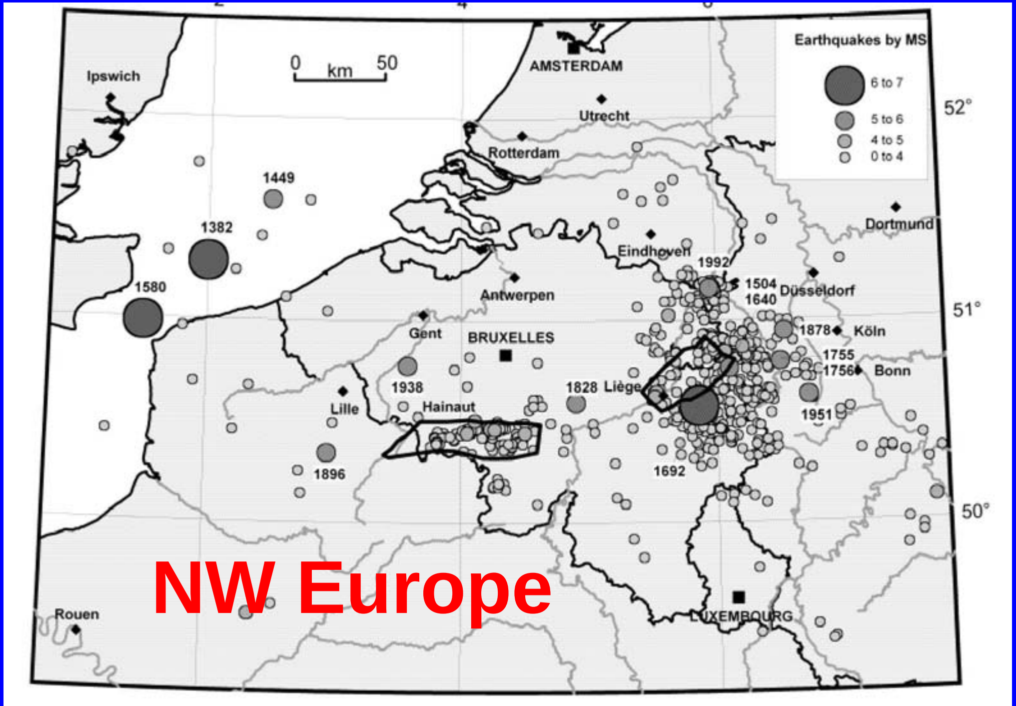
"Large continental interior earthquakes reactivate ancient faults … geological studies indicate that earthquakes on these faults tend to be temporally clustered and that recurrence intervals are on the order of tens of thousands of years or more." (Crone et al., 2003)

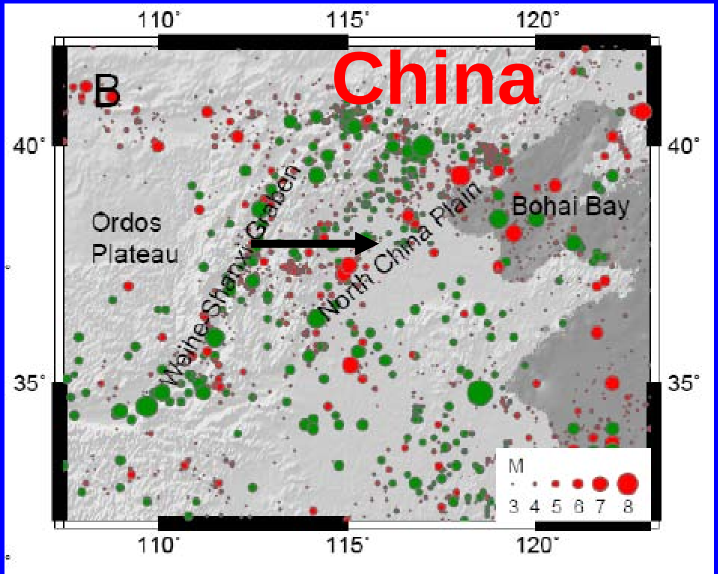


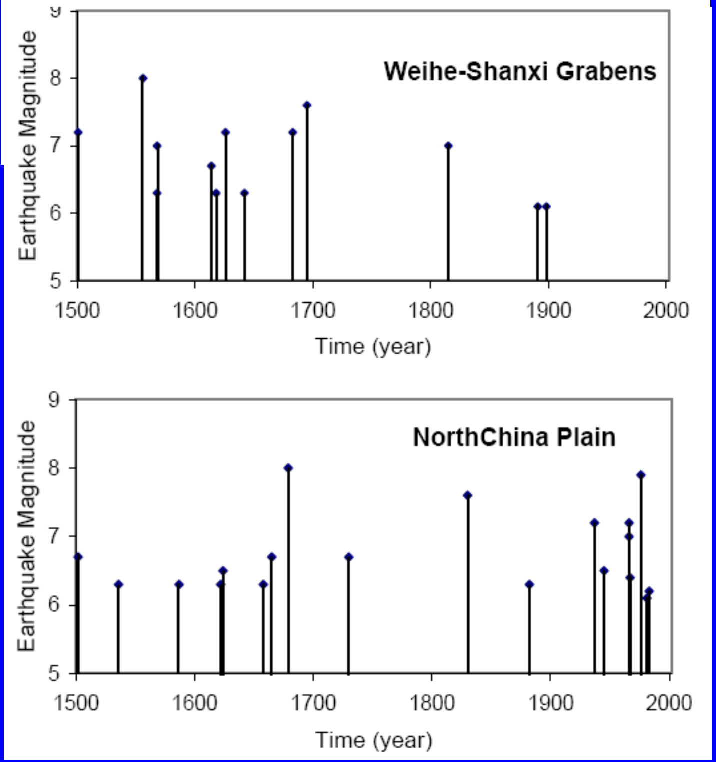
Meers fault, Oklahoma
Active 1000 years ago, dead now

MIGRATING SEISMICITY

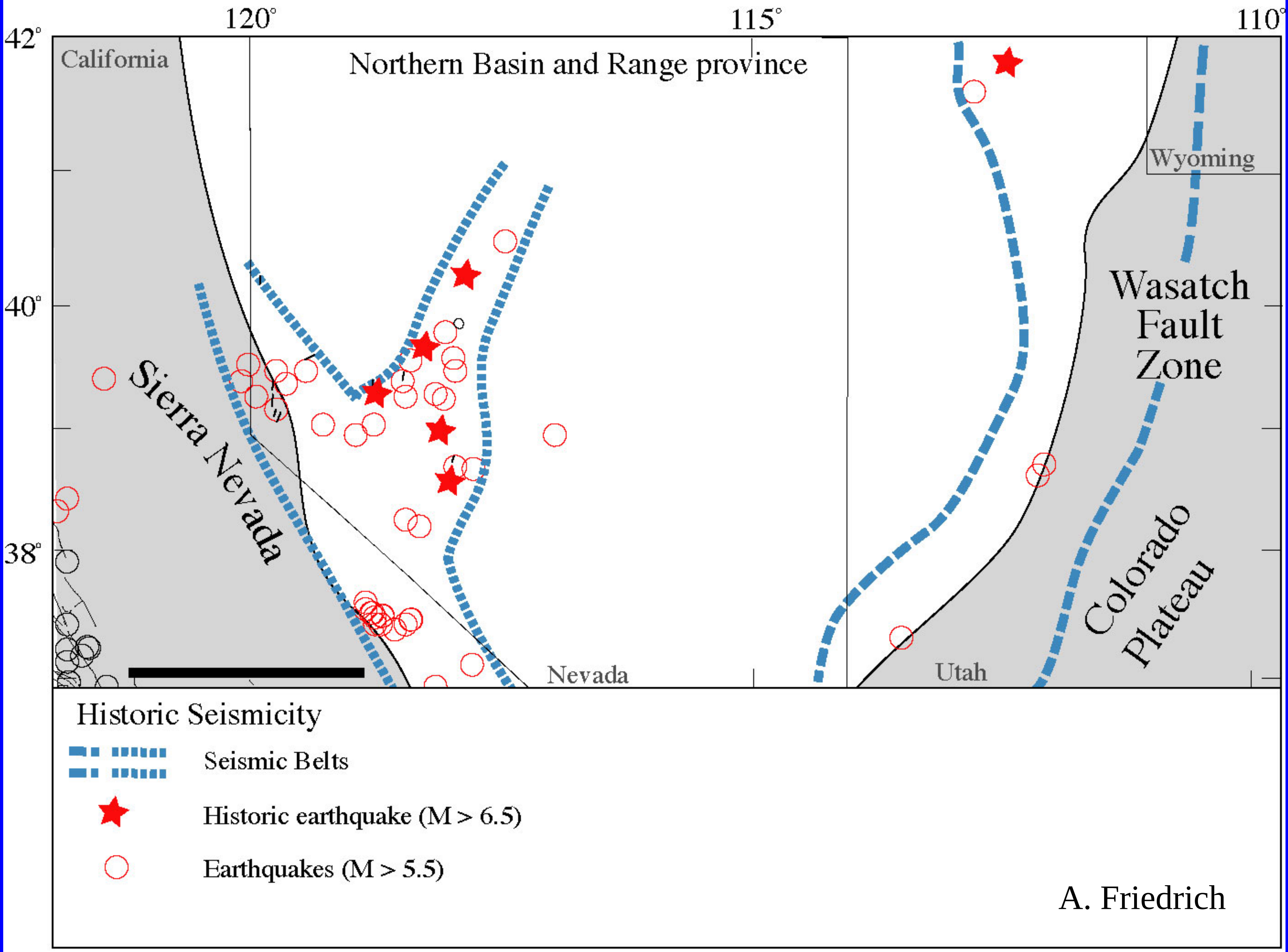
"During the past 700 years, destructive earthquakes generally occurred in different locations, indicating a migration of seismicity with time." (Camelbeeck et al., 2007)



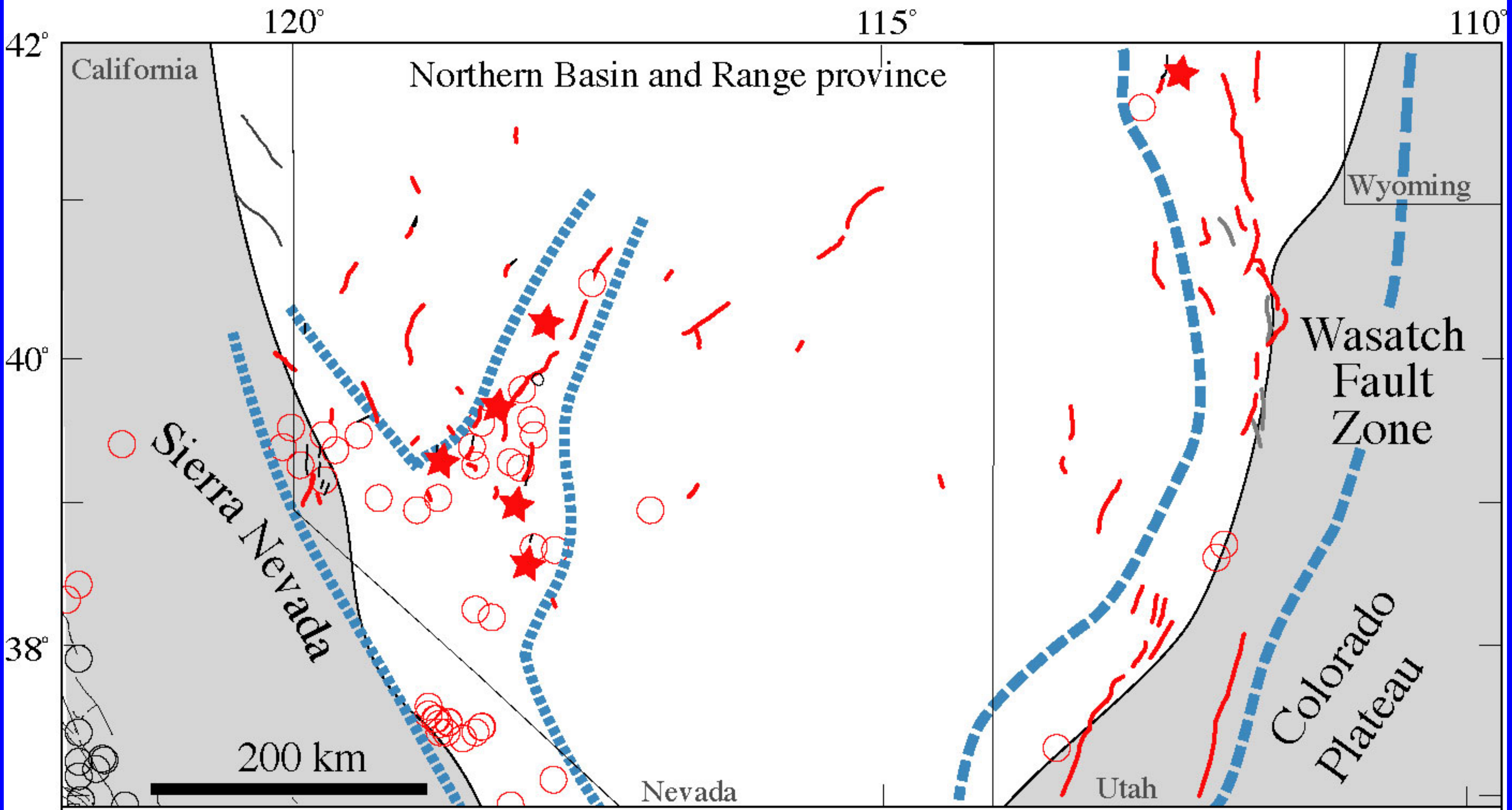




Li, Liu & Stein, 2009


120°
115°
110°
42°
40°
38°
California
Northern Basin and Range province
Wyoming
Wasatch Fault Zone
Sierra Nevada
Colorado Plateau
Nevada
Utah
Historic Seismicity
Seismic Belts
Historic earthquake (M > 6.5)
Earthquakes (M > 5.5)

A. Friedrich



Historic Seismicity

▬ ▪▪▪ Seismic Belts

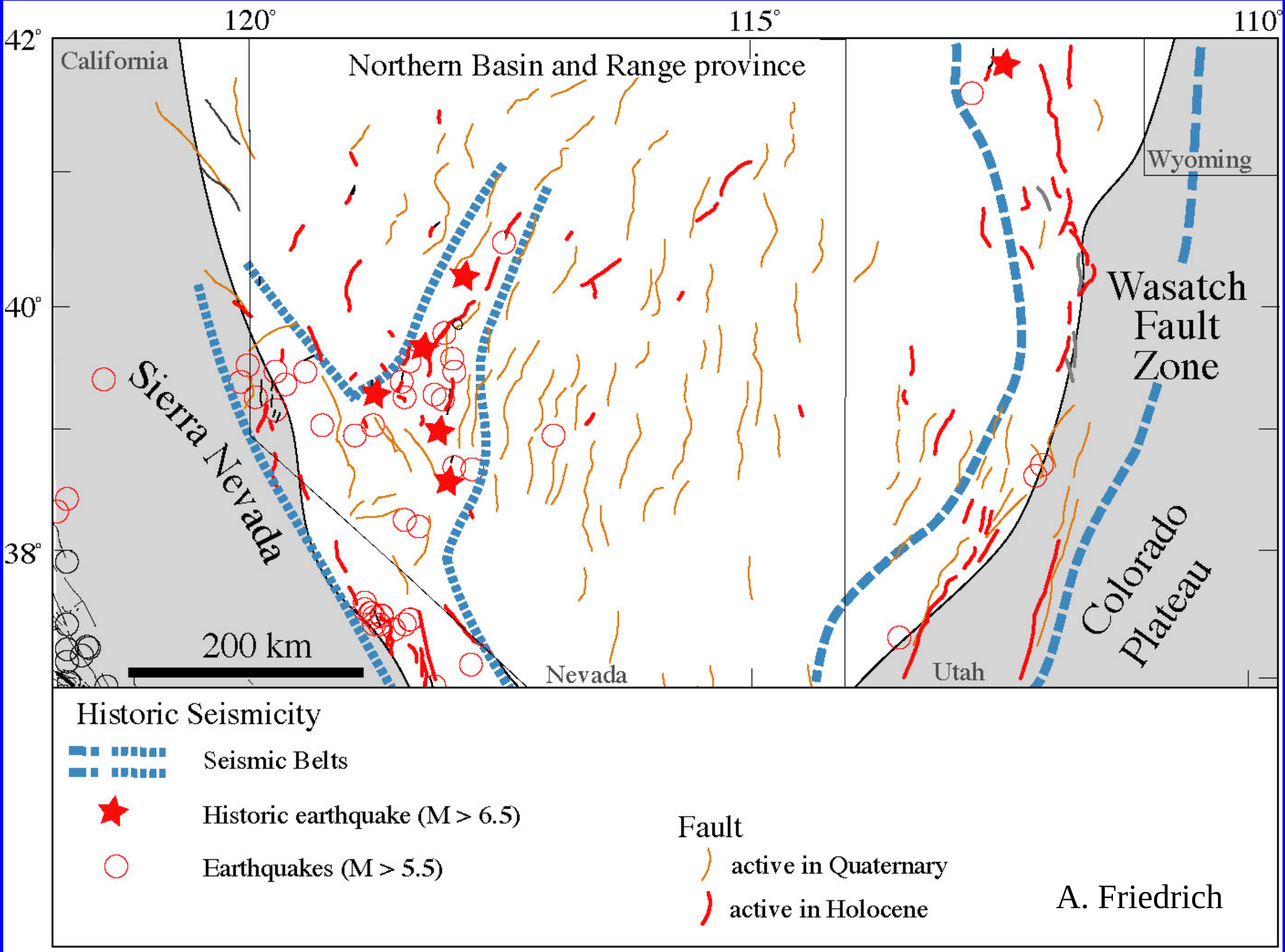
★ Historic earthquake (M > 6.5)

○ Earthquakes (M > 5.5)

Fault

) active in Holocene

A. Friedrich


120°
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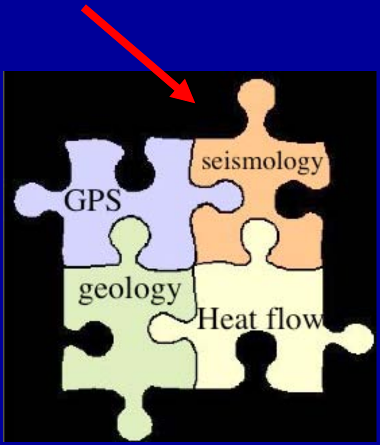
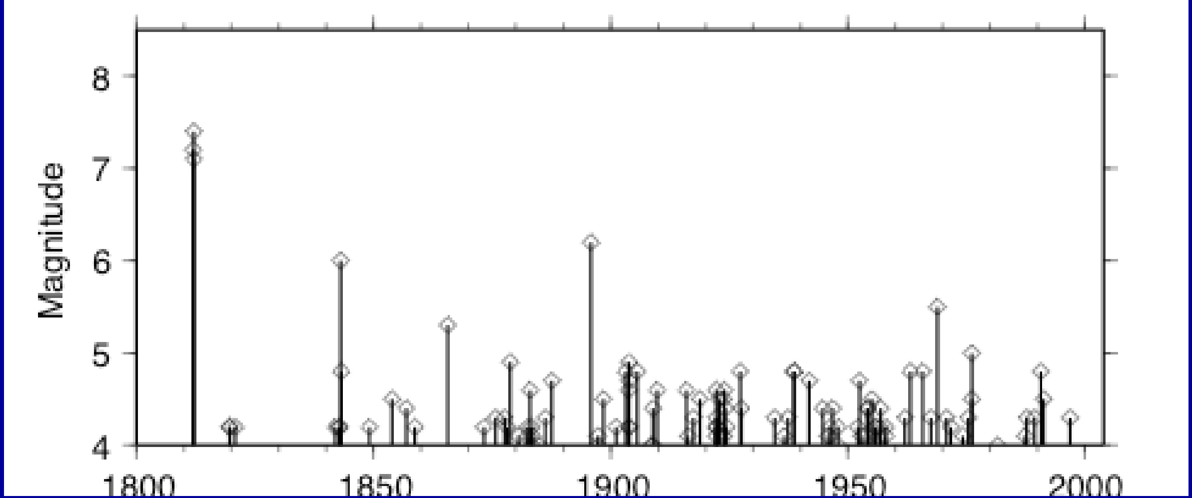
California
Northern Basin and Range province
Wyoming
Wasatch
Fault
Zone
Sierra Nevada
Colorado
Plateau
200 km
Nevada
Utah
Historic Seismicity
Seismic Belts
Historic earthquake (M > 6.5)
Earthquakes (M > 5.5)
Fault
active in Quaternary
active in Holocene

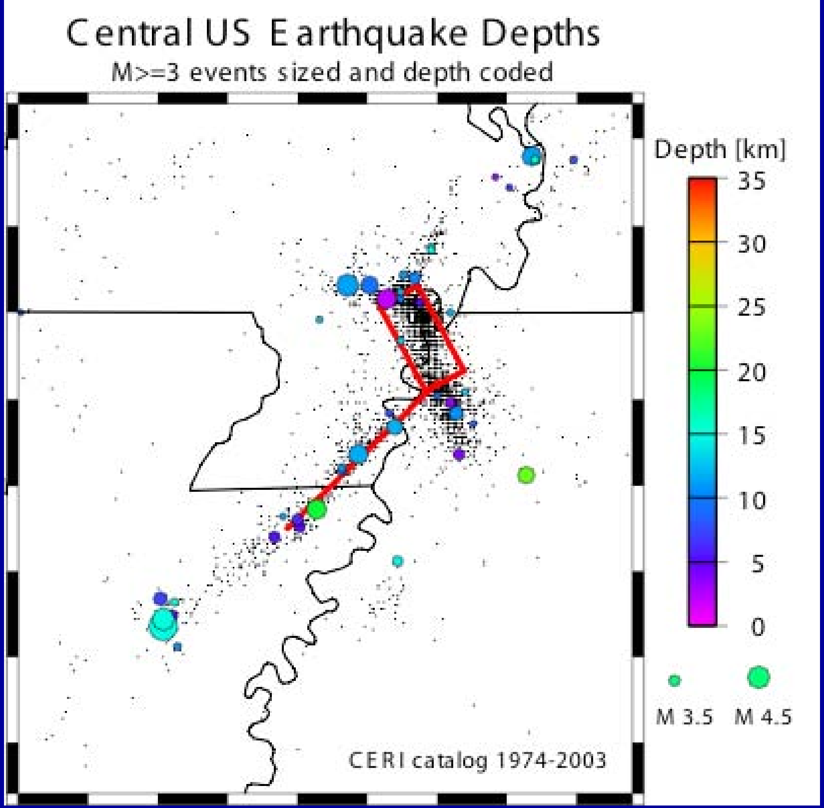
A. Friedrich

NEW MADRID SEISMICITY: 1811-12 AFTERSHOCKS?





Stein & Newman, 2004



Ongoing seismicity looks like aftershocks of 1811-12, as suggested by the fact that the rate & size are decreasing. Moreover, the largest are at the ends of the presumed 1811-12 ruptures

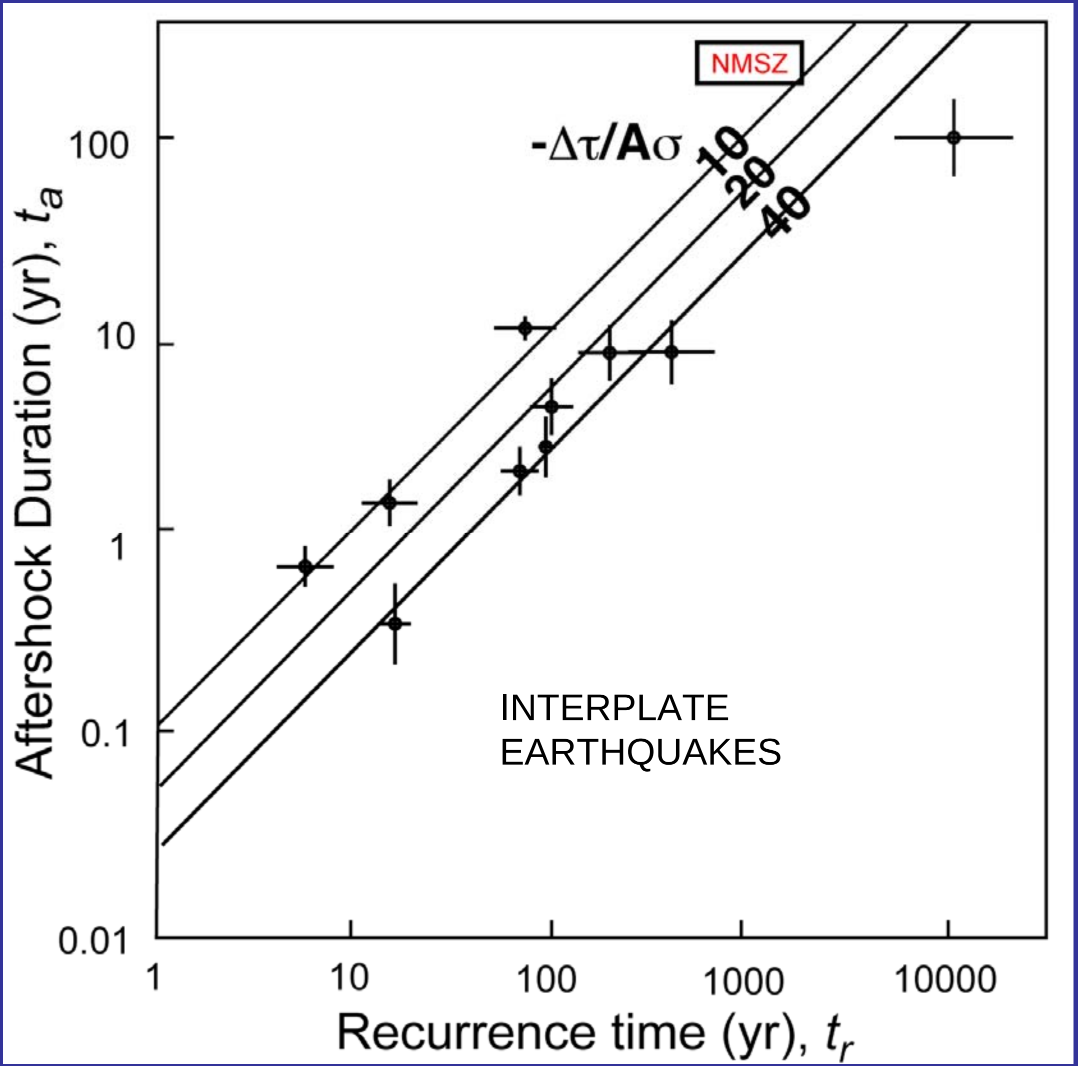
LONG INTRAPLATE AFTERSHOCK SEQUENCES CONSISTENT WITH ROCK MECHANICS

Dieterich (1994) model relates ratio of aftershock length to main shock recurrence

t_a / t_r α 1/stressing rate

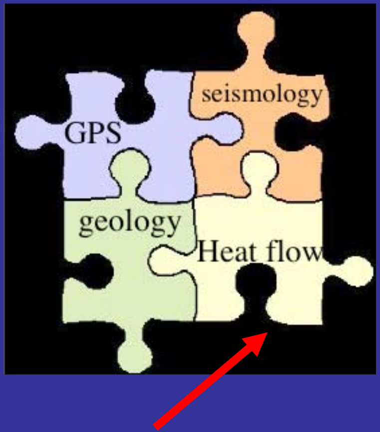
For low intraplate stressing rate, could have 200 year aftershocks for 500 yr recurrence

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



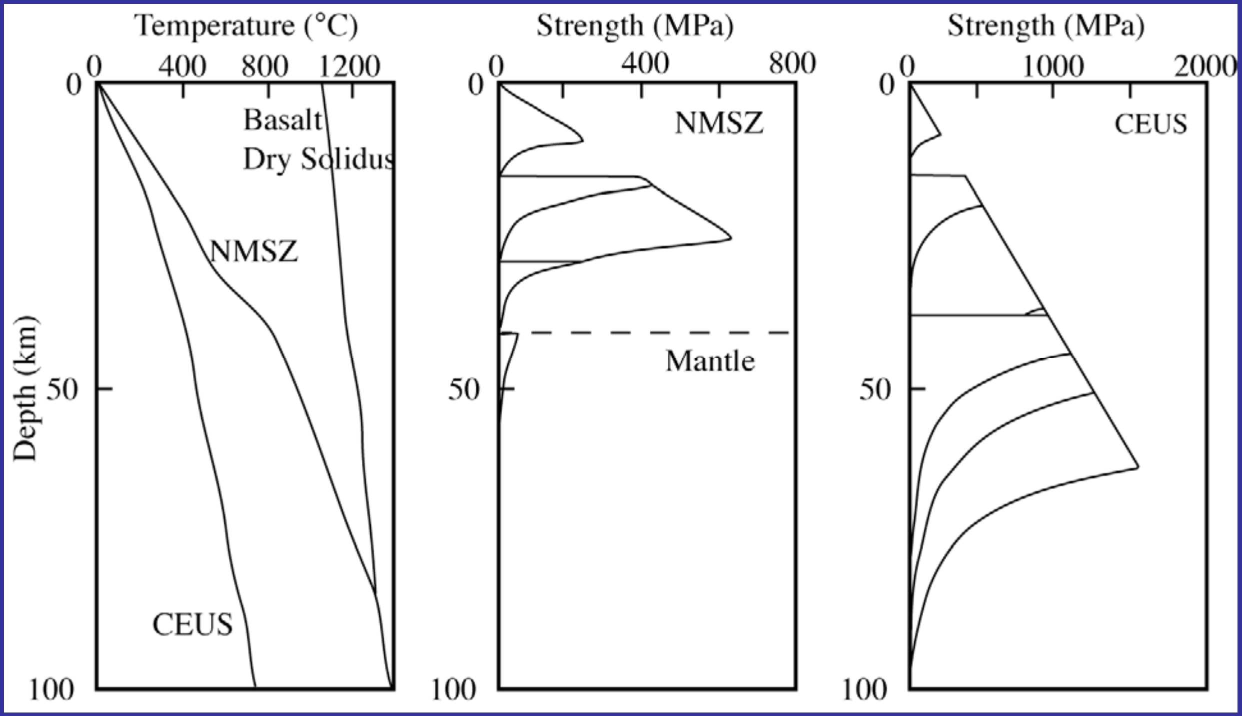
Stein & Newman, 2004

IS NMSZ SPECIAL - HOTTER & WEAKER THAN SURROUNDINGS?



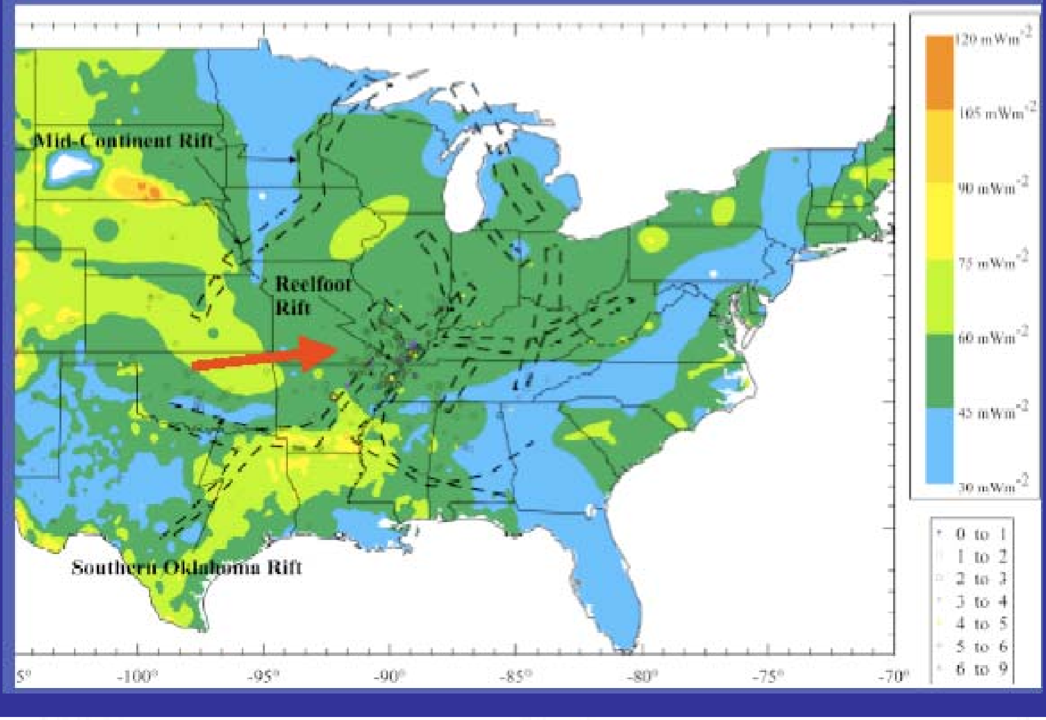
Liu & Zoback (1997) find NMSZ heat flow ~ 15 mW/m^2 higher than in surrounding area, so crust and upper mantle are significantly hotter and thus weaker than surroundings.

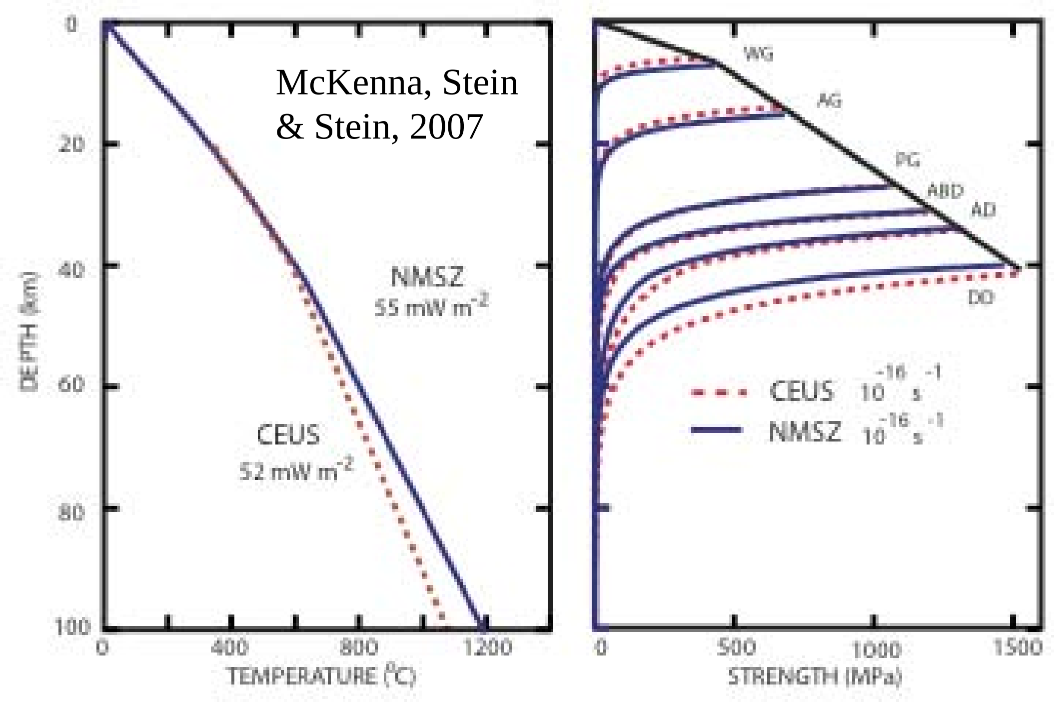
Weak lower crust and mantle concentrate stress & seismicity in NMSZ upper crust



Liu & Zoback, 1997

NMSZ NOT HOT, WEAK, OR SPECIAL





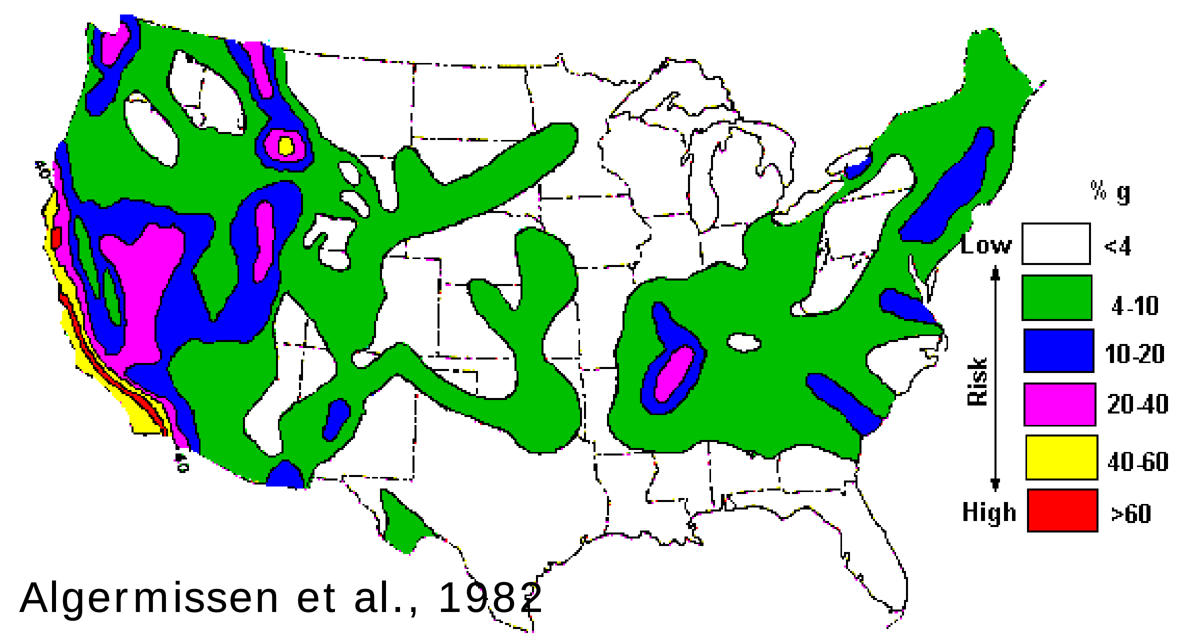
Reanalysis finds the anomaly is either zero or much smaller (3+/-23 mW/m^2), so the NMSZ and CEUS have essentially the same temperature & thermally-controlled strength.

Hence there is no need for upper crustal stresses to concentrate in the NMSZ rather than other faults

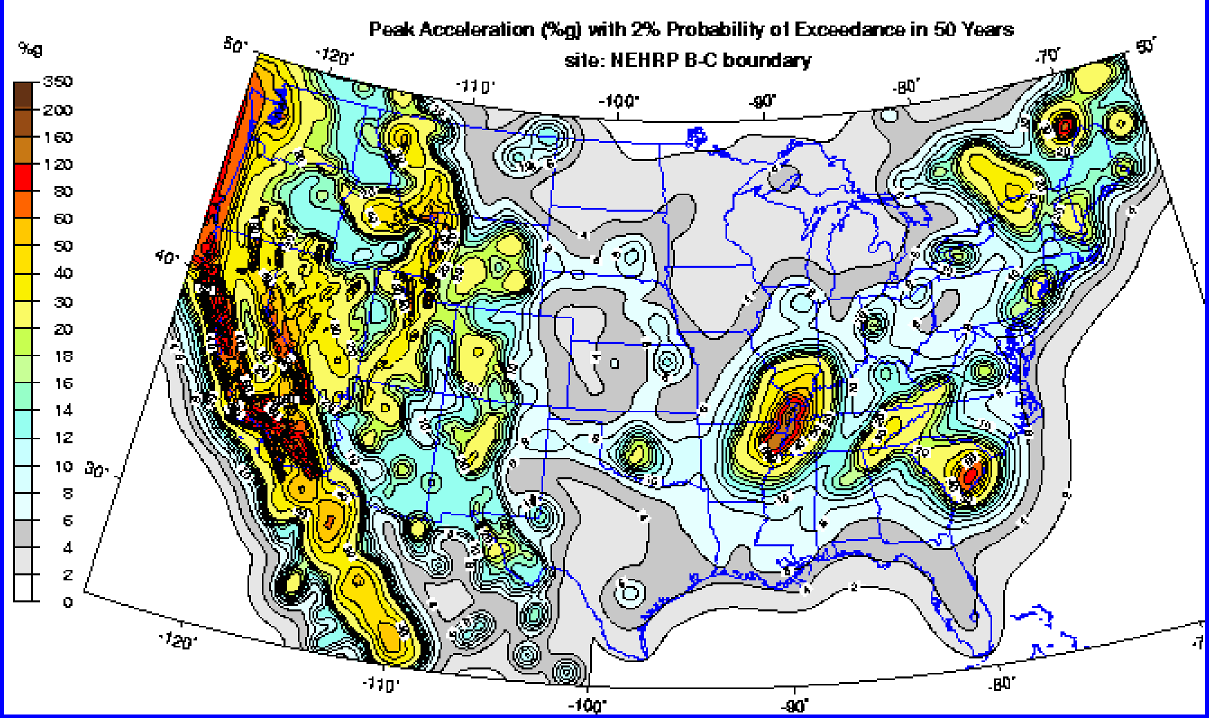
In 1990s

Estimated NMSZ hazard increased to as high as California

As the maximum motion permitted by the GPS data decreased steadily toward zero



Algermissen et al., 1982



Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years

site: NEHRP B-C boundary

Frankel et al., 1996

HIGH MODELED NEW MADRID HAZARD RESULTS FROM ASSUMPTIONS

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

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

-High ground motion in large events

-*Time-independent recurrence of large events*

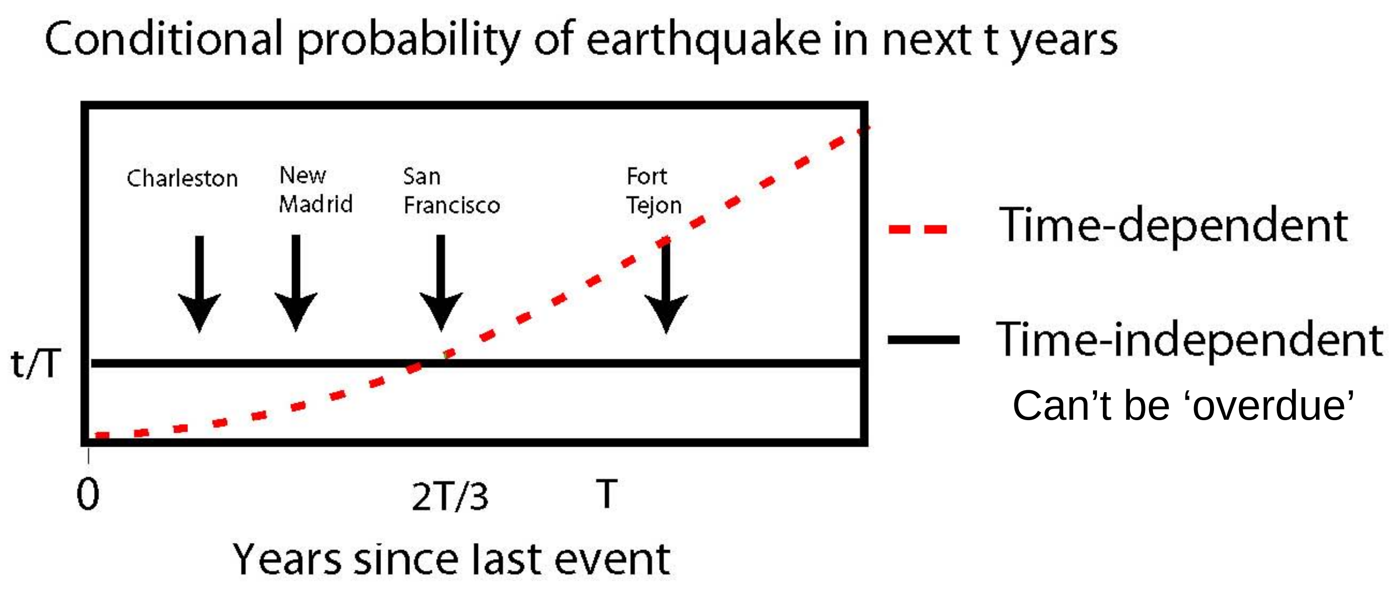
- *Earthquakes continue as in past 2000 years*

LAST TWO ARE CRUCIAL - describe whether large earthquakes will happen, whereas others describe effects if they do - AND INCONSISTENT WITH GPS DATA

PREDICTED HAZARD DEPENDS ON POSITION IN EARTHQUAKE CYCLE

Time dependent lower until ~2/3 mean recurrence

Charleston & New Madrid early in their cycles so time dependent predicts lower hazard

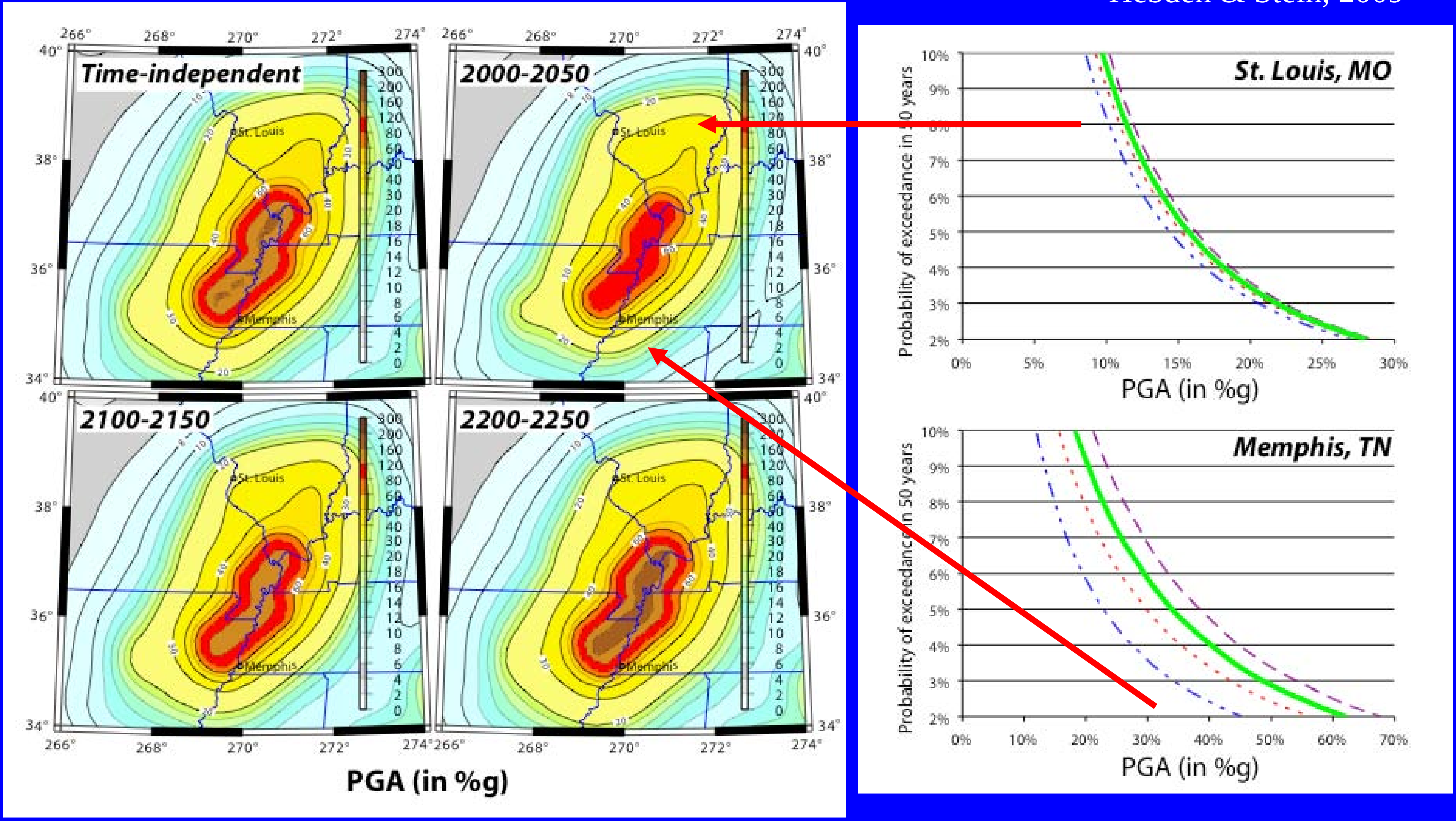


Can’t be ‘overdue’

Hebden & Stein, 2009

NEW MADRID

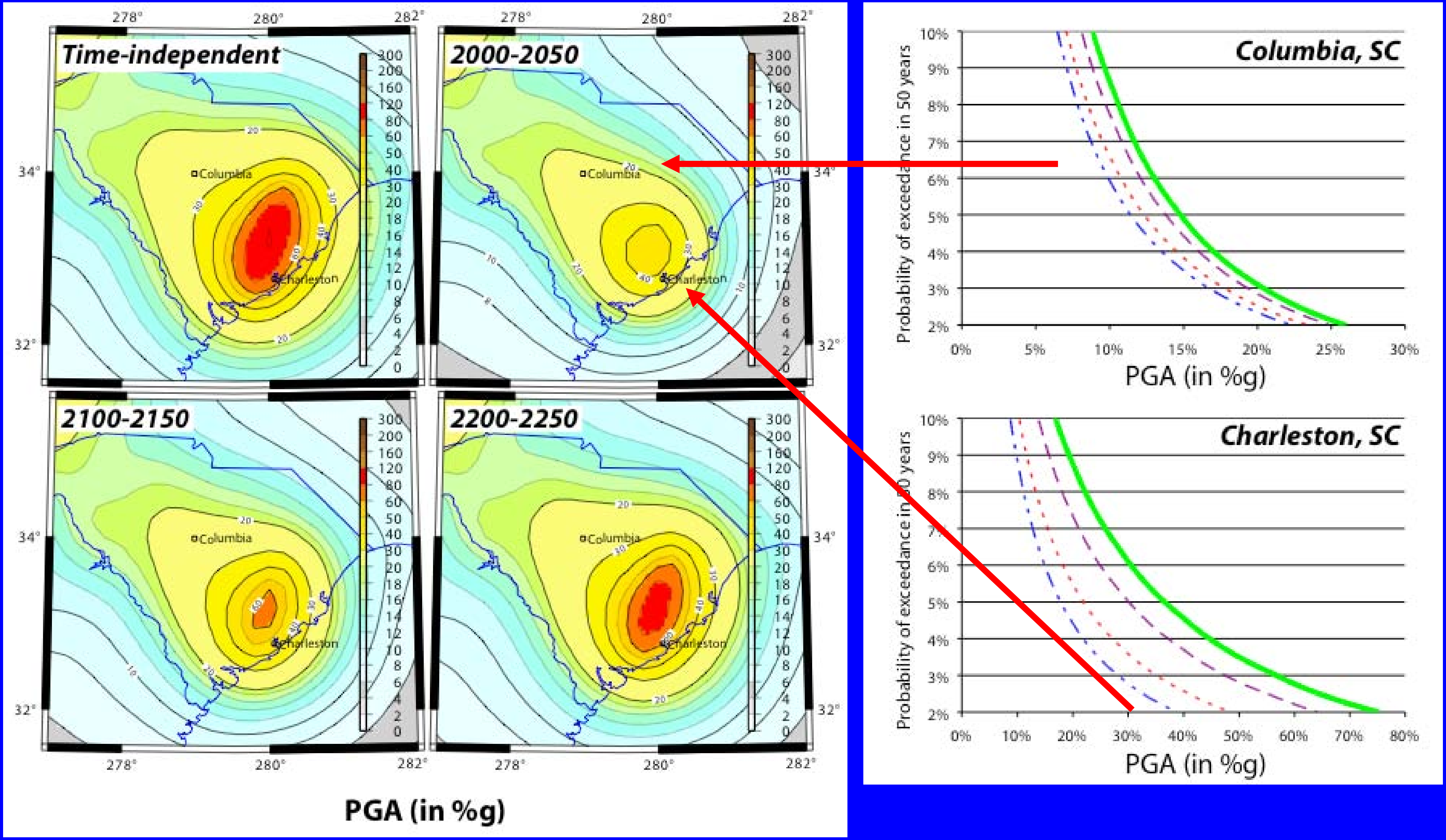
Hebden & Stein, 2009



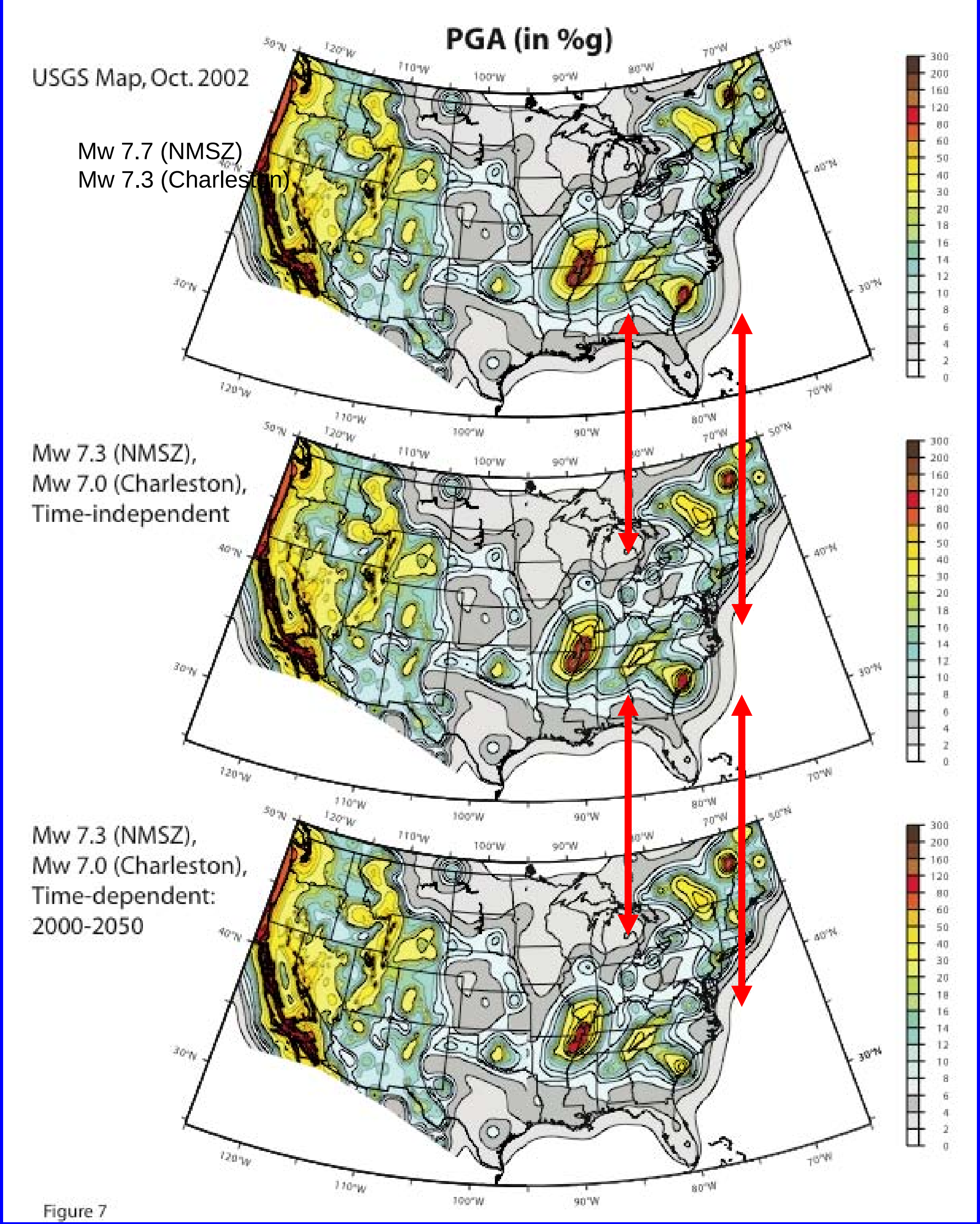
2% in 50 yr (1/2500 yr)

CHARLESTON

Hebden & Stein, 2009



2% in 50 yr (1/2500 yr)



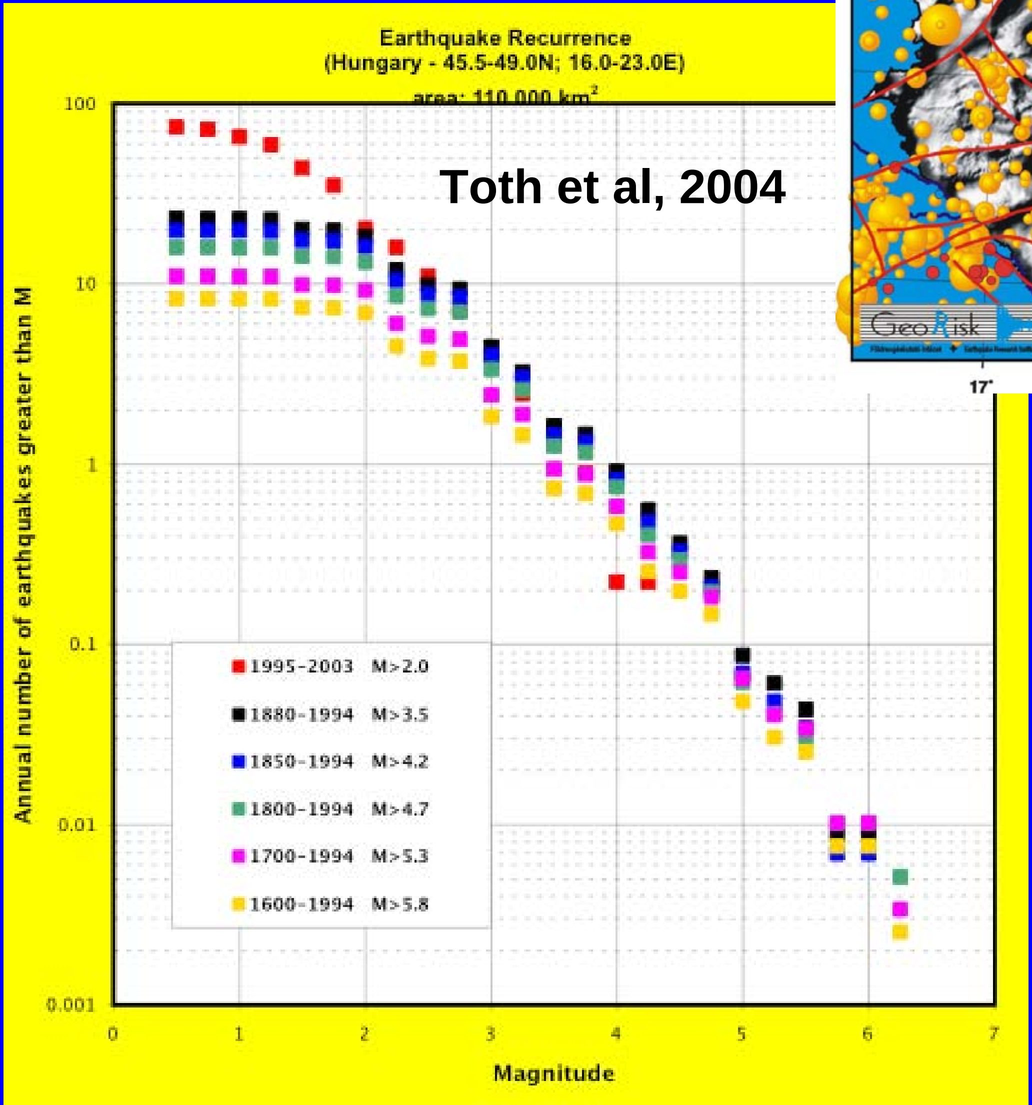
Time dependent model for eastern US predicts lower New Madrid & Charleston hazard

Effect can be larger than M_{max} and ground motion model

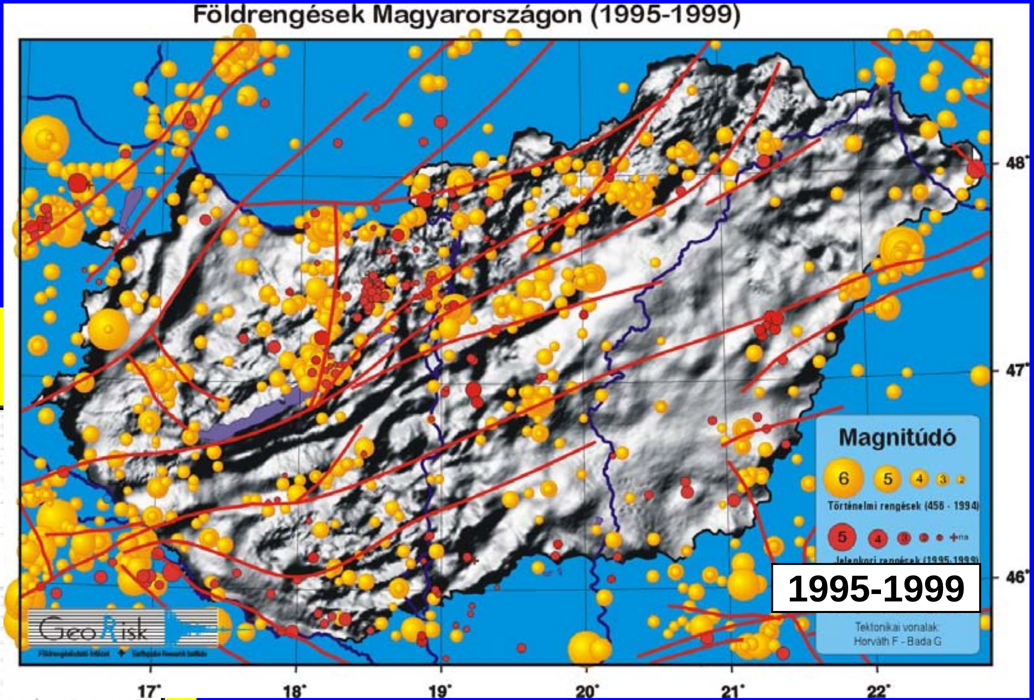
NM cluster ending would have even greater effect

Hebden & Stein, 2008

HUNGARY - PANNONIAN BASIN (INTRACONTINENTAL EURASIA)



Toth et al, 2004



1995-1999

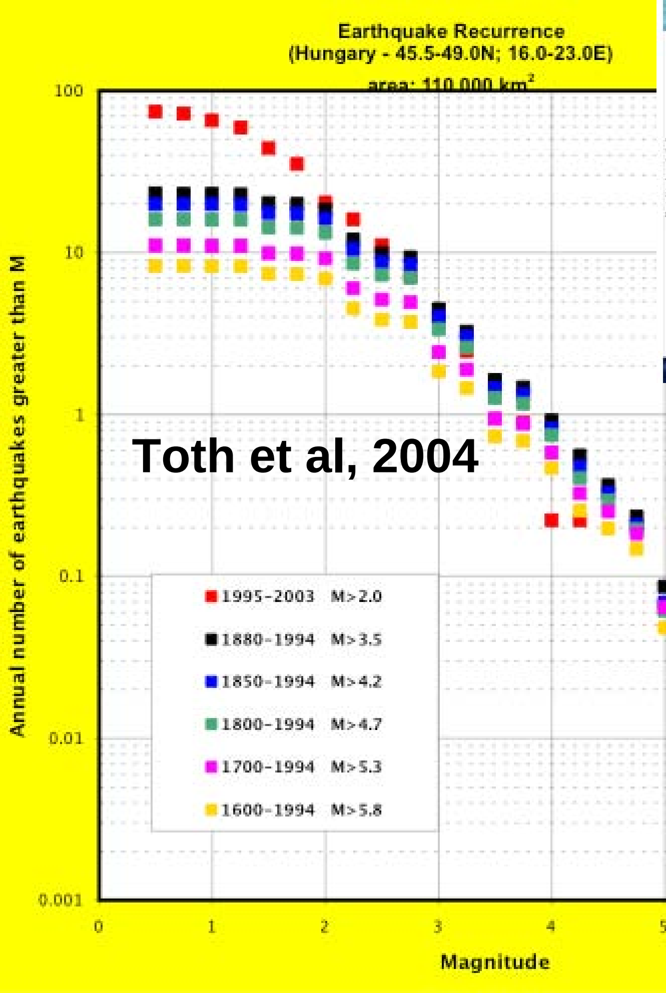
Diffuse seismicity, migrates

M_{max} observed = 6.2

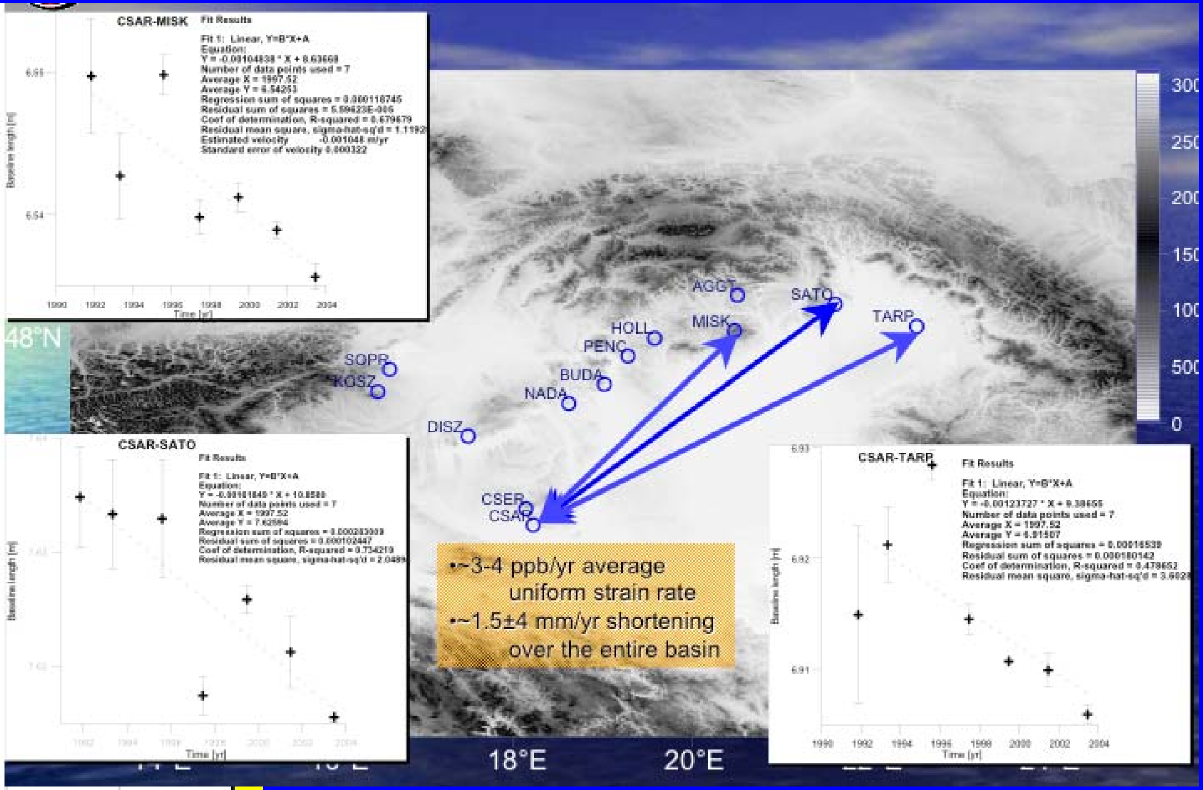
M 7 expected ~ 1000 yr from seismicity

Hungary

Pannonian Basin Intracontinental Eurasia



Toth et al, 2004



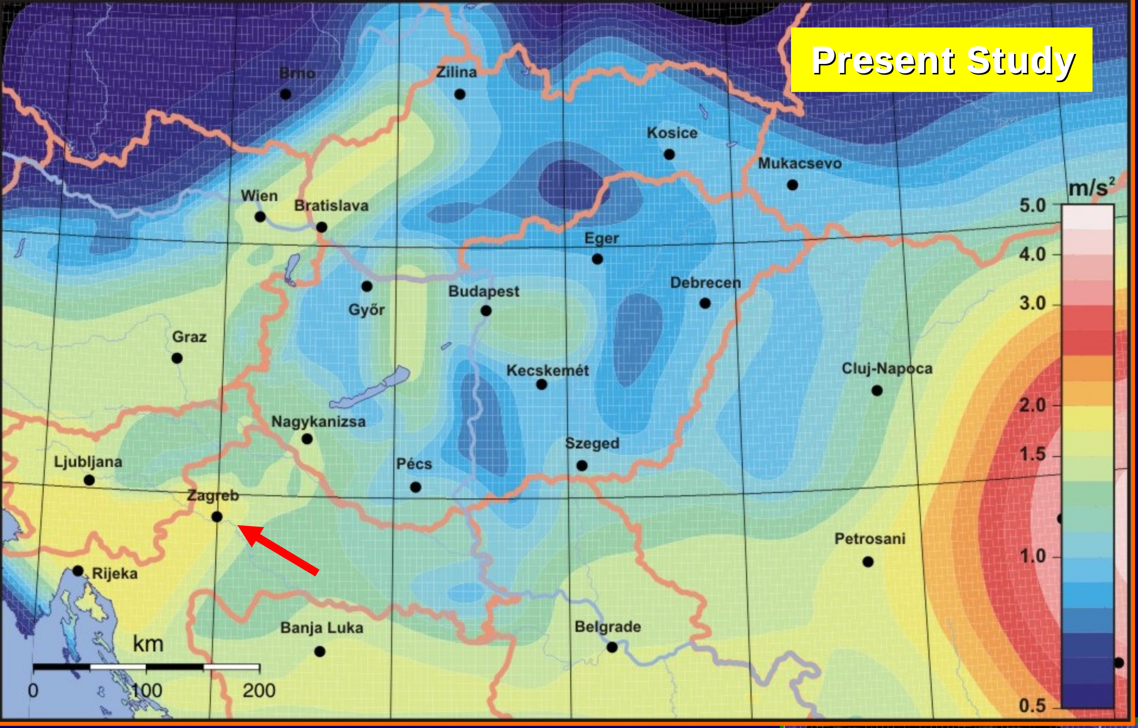
- ~3-4 ppb/yr average uniform strain rate
- ~1.5±4 mm/yr shortening over the entire basin

M 7 expected ~ 1000 yr from seismicity

GPS consistent - shows ~1-2 mm/yr shortening (Grenerczy et al., 2000)

GPS shows motion at least 50x New Madrid & CEUS

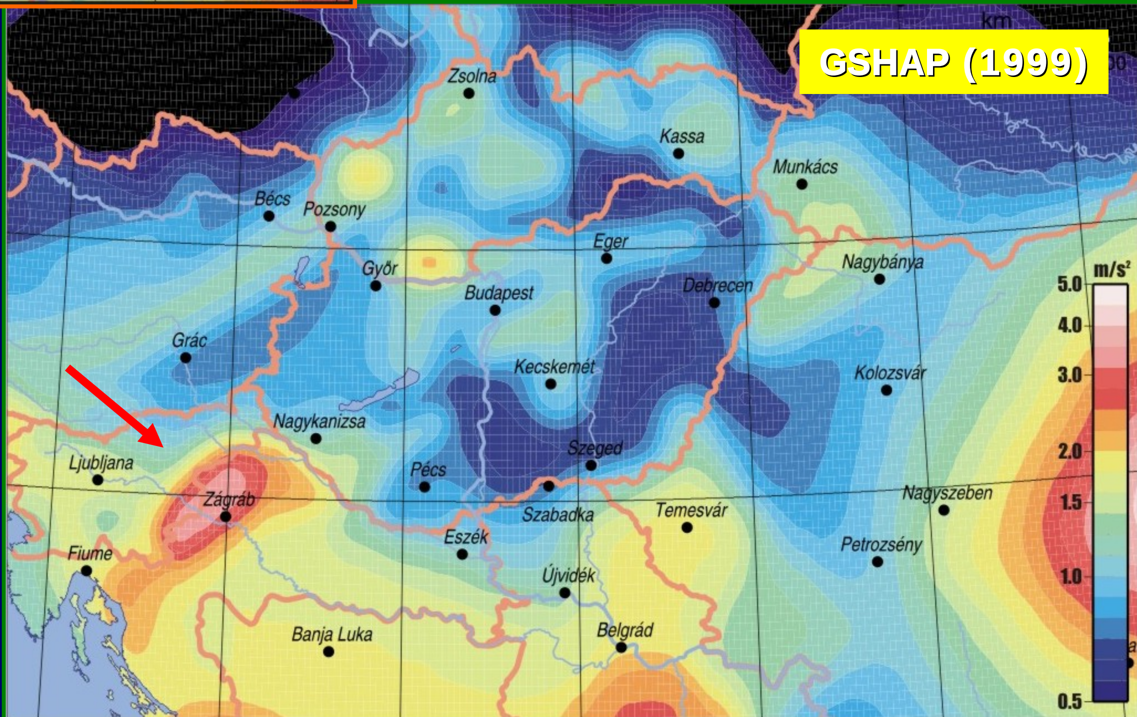
HUNGARY: ALTERNATIVE HAZARD MAPS



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

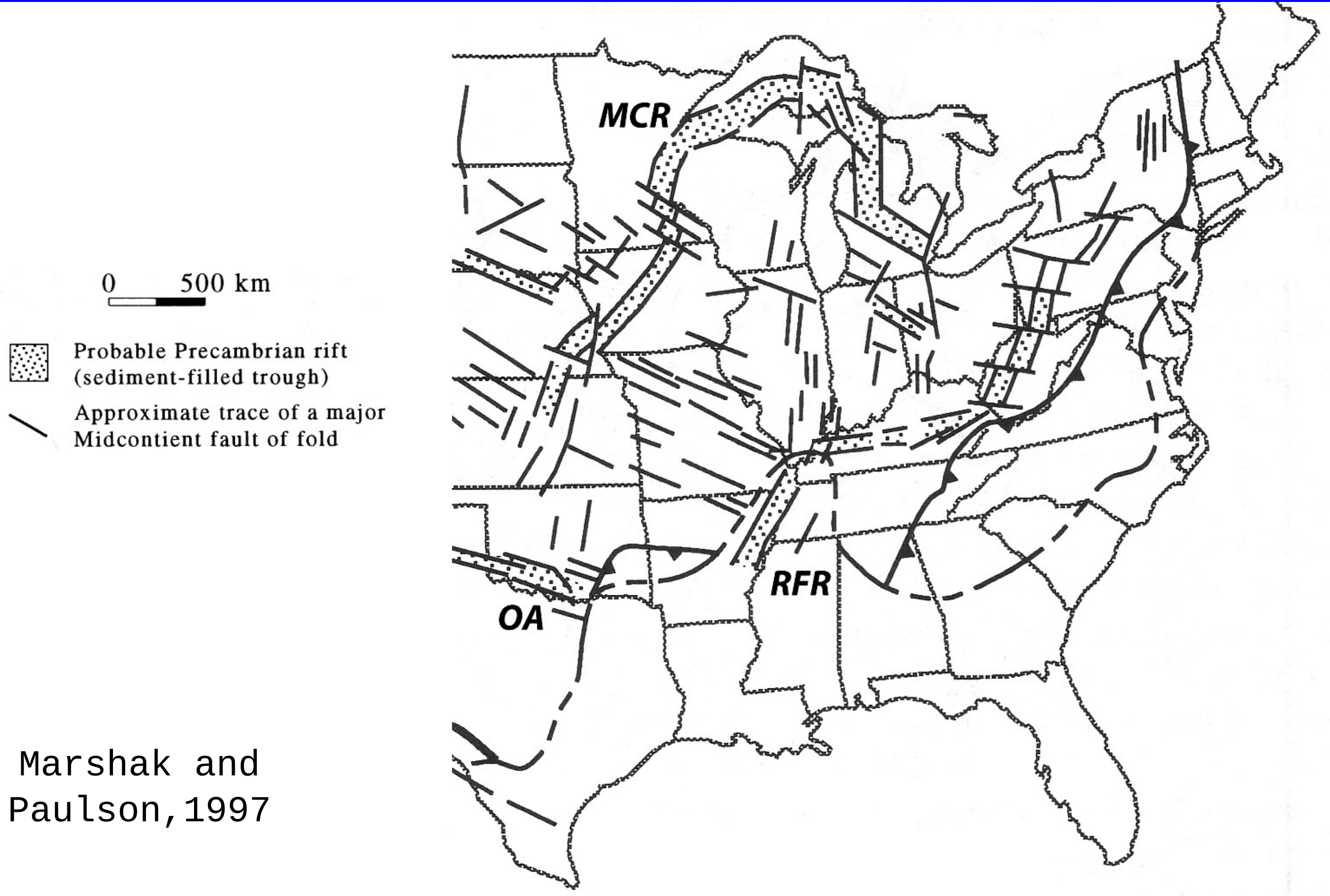


Toth et al., 2004

HOW TO MAKE PROGRESS?

More & better data

Explore dynamics of forces, faulting & fault interactions in plate interior



Marshak and Paulson,1997

GPS is giving constraints on effects like post-glacial rebound

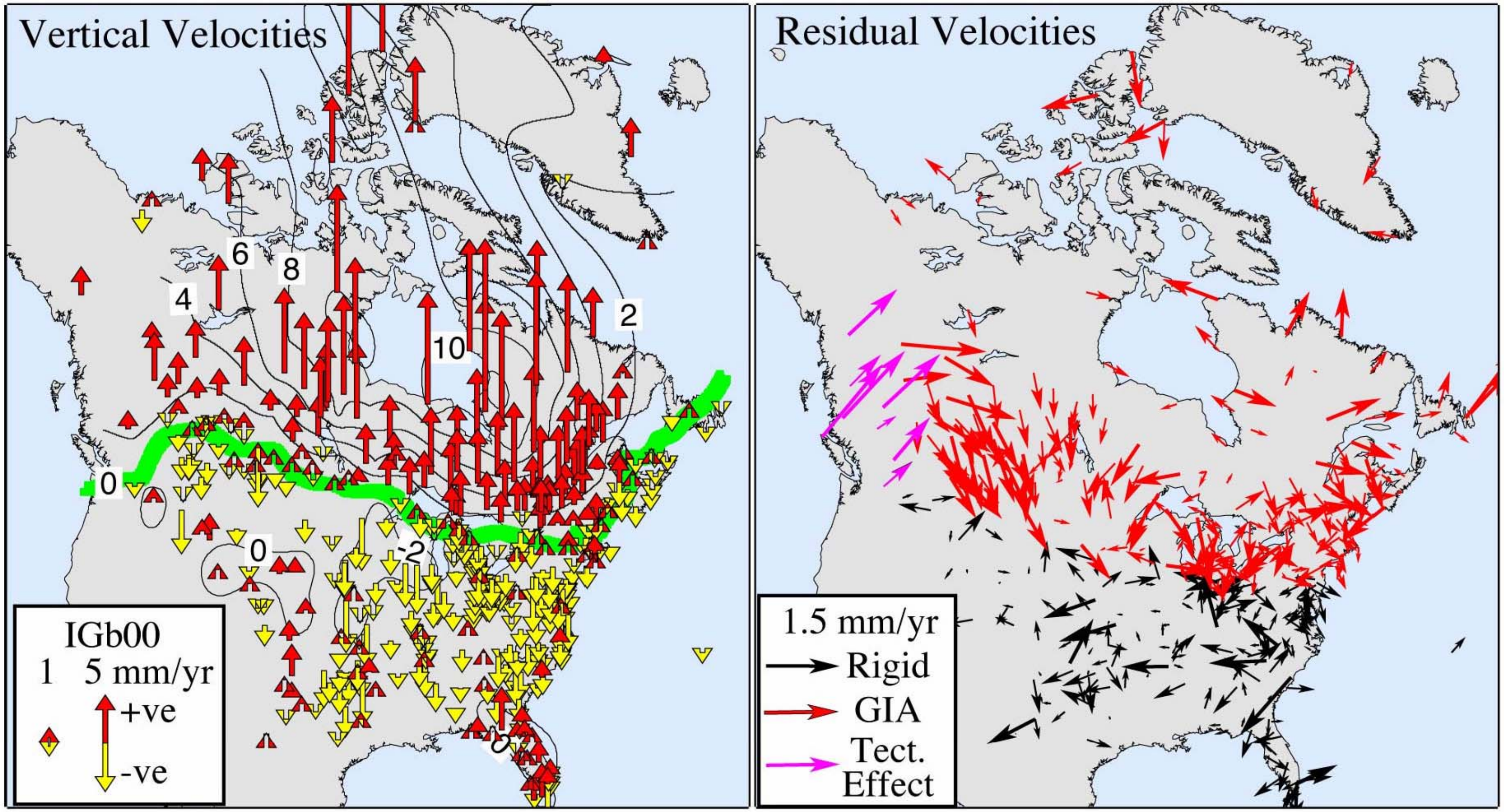
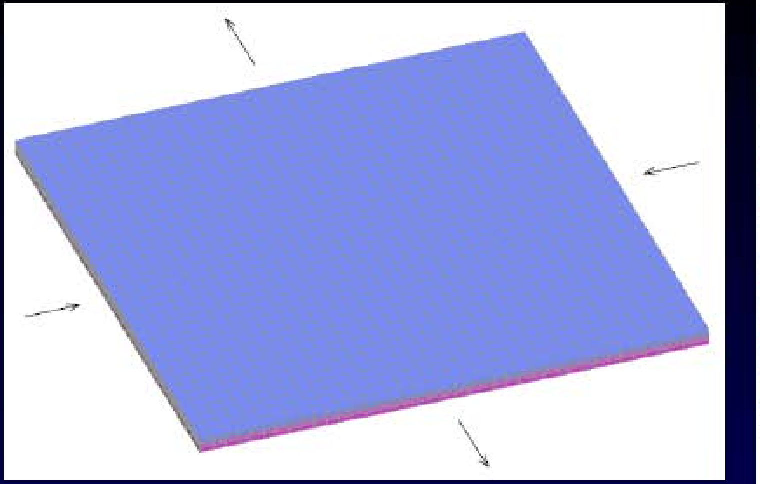
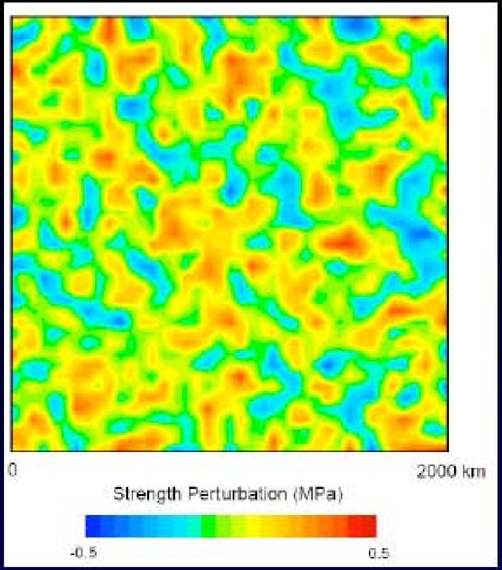


Figure 1. Left: Vertical GPS site motions. Note large uplift rates around Hudson Bay, and subsidence to the south. Green line shows observed "hinge line" separating uplift from subsidence. Right: Horizontal motion site residuals after subtracting best fit rigid plate rotation

Sella et al., 2007



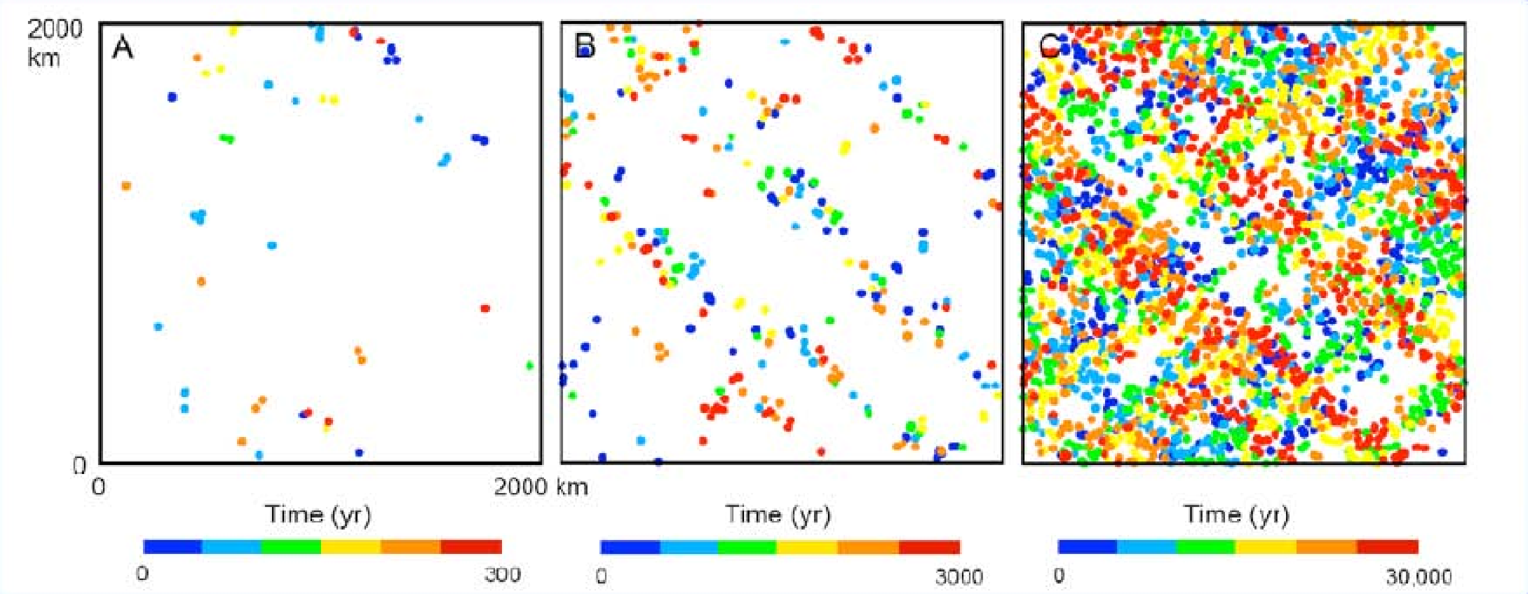


NUMERICAL MODEL

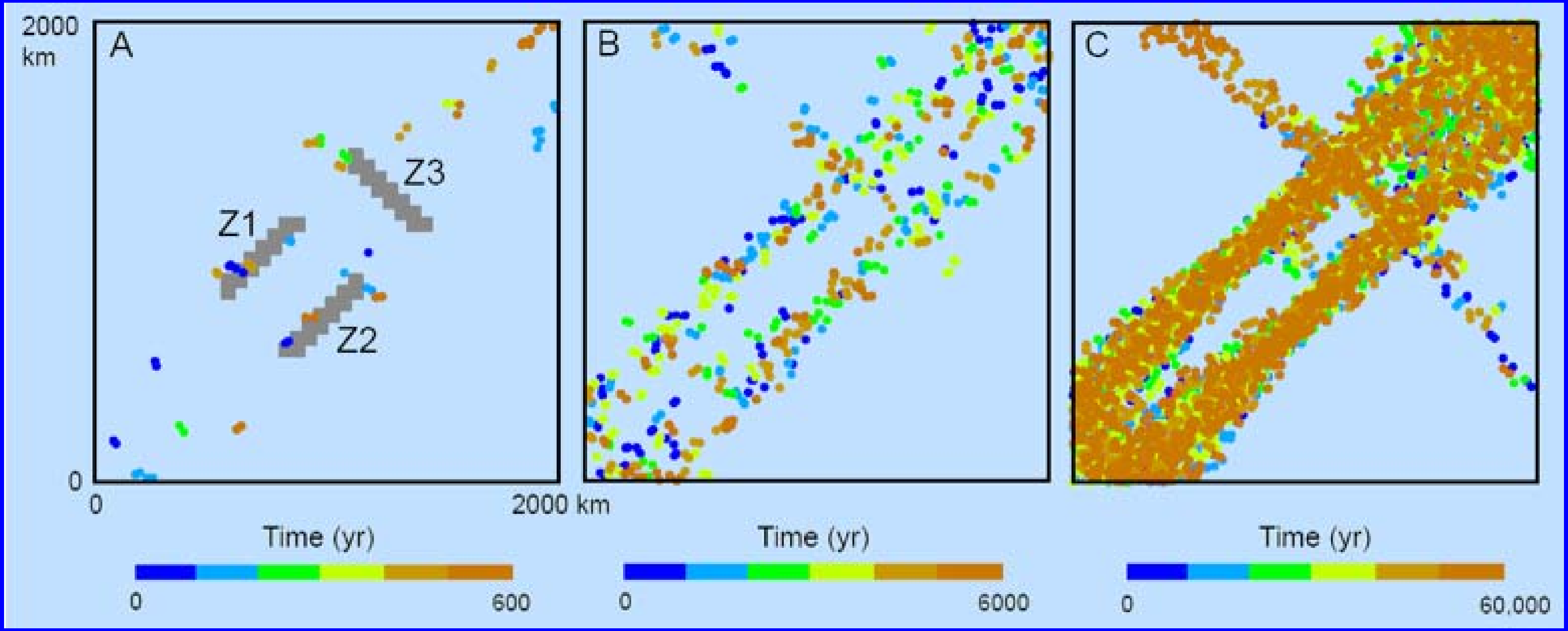
FOR INTRAPLATE EARTHQUAKES

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

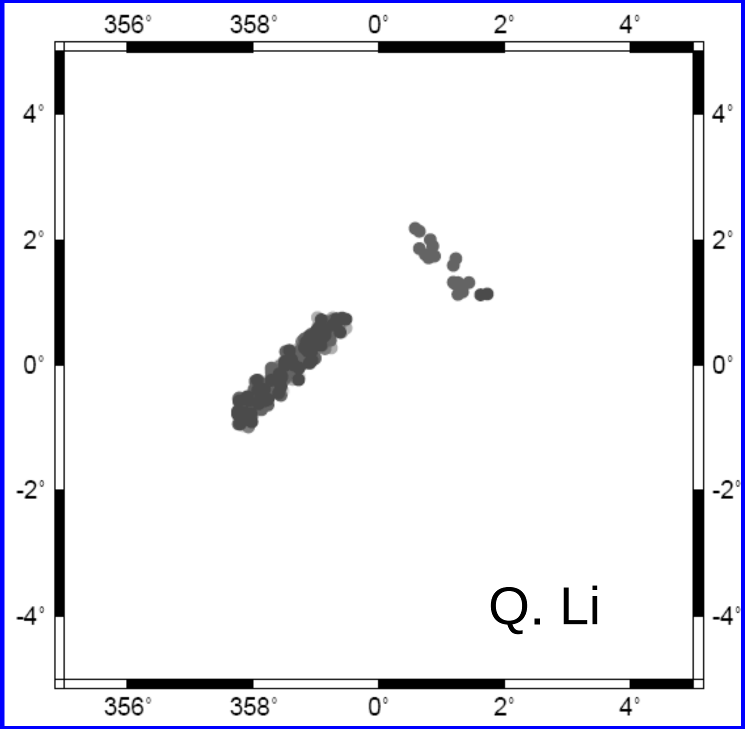
Short-term seismicity does not fully reflect long-term

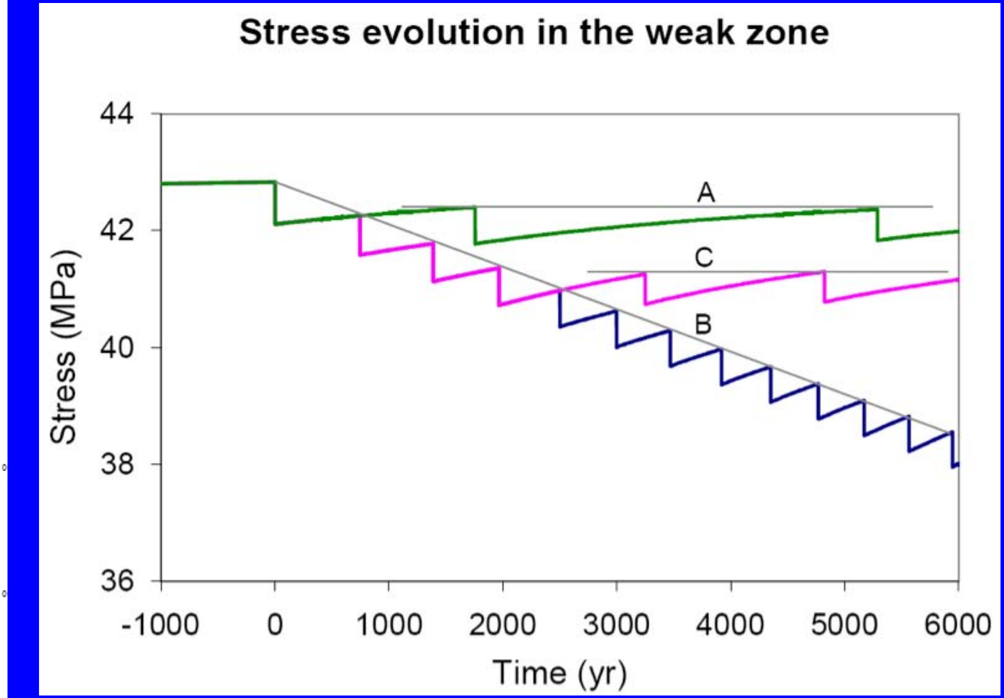
Variability results from steady platewide loading
without local or time-variable loading

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).



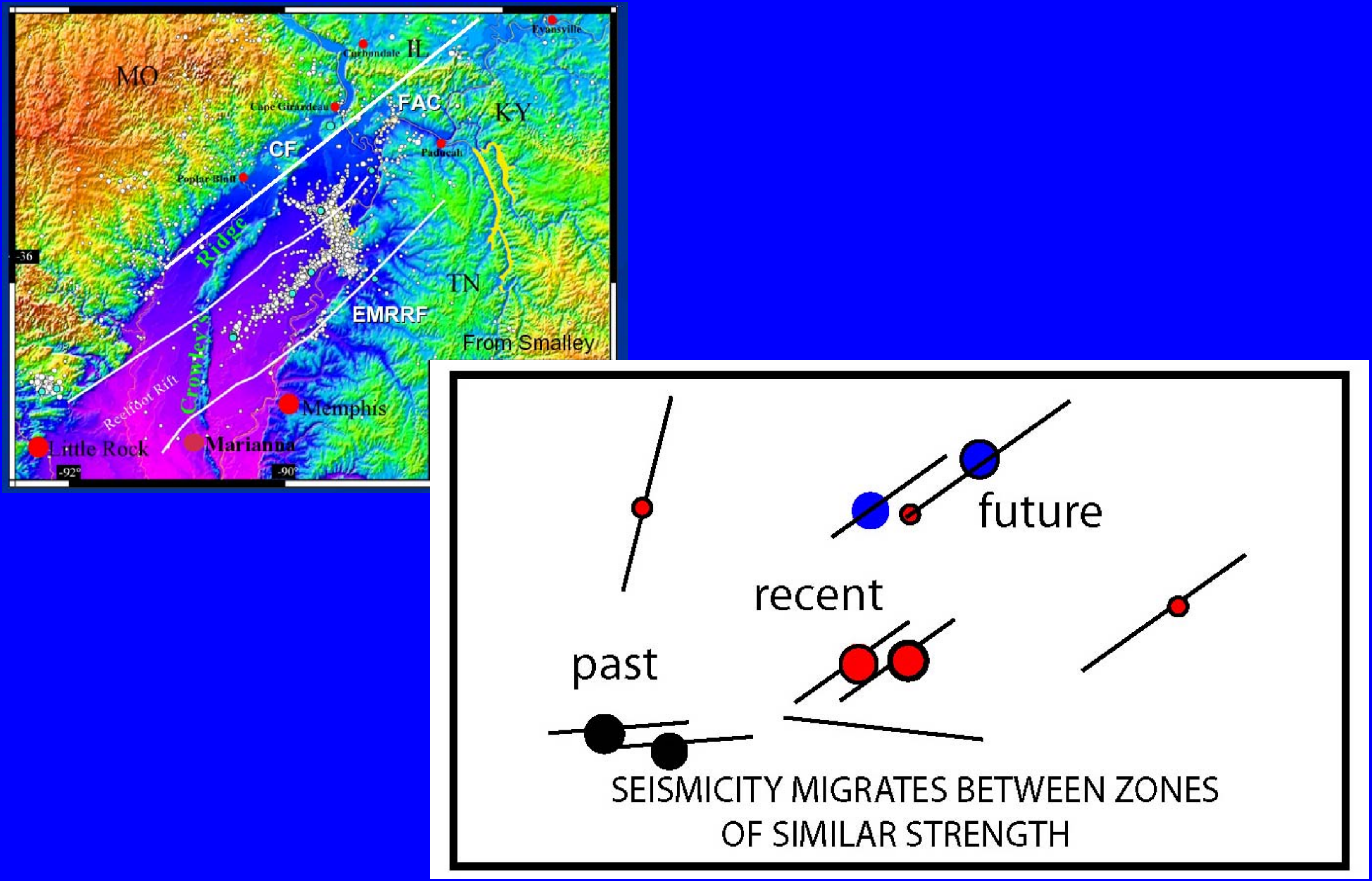


Earthquakes (1MPa stress drop) repeatedly occur in a 500-700 year period if there is a continuous strength decline (0.5 MPa /500 years). Without this decline no repeated earthquakes occur.

Li, Liu & Stein, 2009

HOW TO GET TEMPORAL CLUSTERS

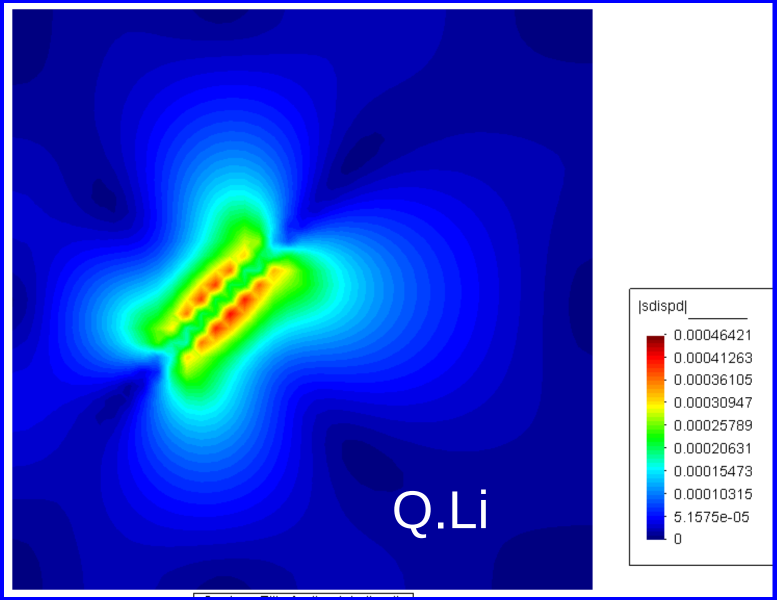
2 - Nearby faults fail by stress transfer, causing apparent cluster possibly hard to resolve with geologic data



From Smalley

Predicted velocities easily detectable with GPS, so GPS can constrain & test models

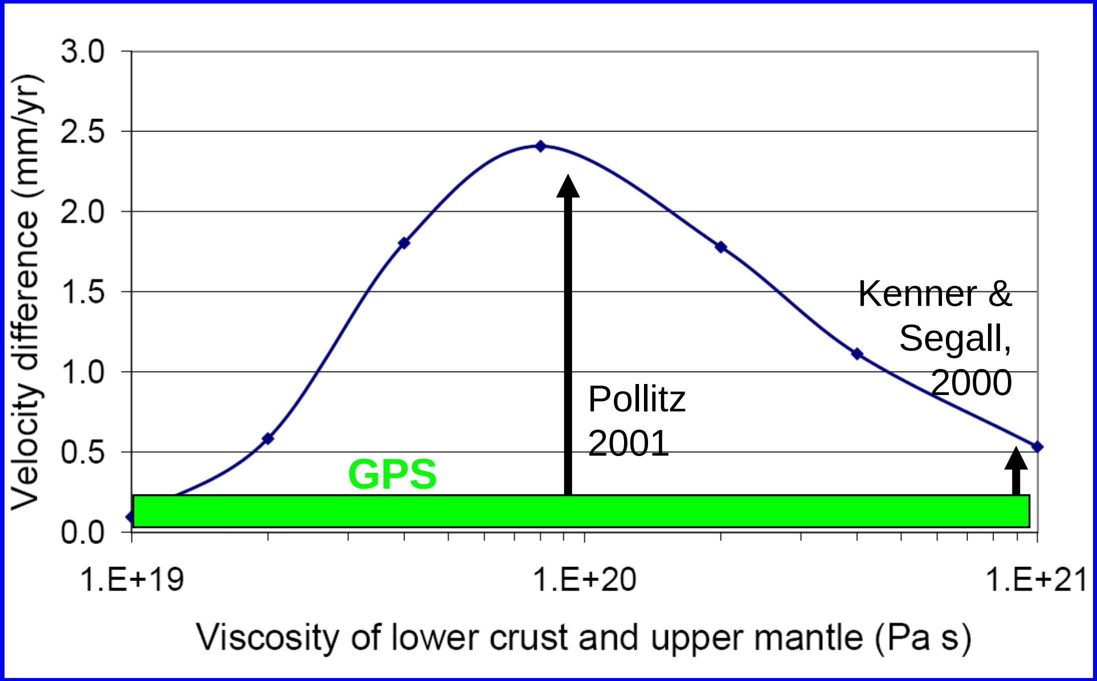
Resolution will continue to improve as velocity estimates improve



Q.Li

Predicted surface velocity 232 years after an earthquake

Maximum predicted velocity across the fault ~ 1 mm/yr



PRESENT STATUS

GPS, seismological, geologic, & geothermal data are consistent with NMSZ - and midcontinental seismicity in general - being episodic, clustered & migrating.

For NMSZ, past 2000 years don't represent long term

The longer GPS data show essentially no motion, the more likely it seems that the recent cluster of large NMSZ events is ending

Seismicity may migrate to somewhere else

Hazard from 1811-12 style large events may be

- small for tens of thousands of years

- lower and diffuse rather than high and concentrated near 1811-12 rupture

CRUCIAL QUESTIONS

- How would we expect seismicity patterns to evolve in space and time?
- How do these compare to what we know about the earthquake and faulting history?
- How well can we discriminate between models of fault behavior?
- How do the predicted deformations near and between faults compare to what GPS data show?
- Does the absence of deformation observed in the GPS data show that the recent New Madrid earthquake cluster has ended?
- Where might we expect future large earthquakes?
- How could we use GPS data to test these predictions?
- How can we use these insights to develop a new generation of more realistic earthquake hazard models?

What is the relationship between geodetic deformation and earthquake occurrence?

Is the absence of evidence for geodetic deformation a definitive indicator of future earthquake potential?

What weight would you give geodetic data versus observed seismicity in establishing rates of earthquake occurrence?

Tentative answers, based on what we know & suspect, pending future study:

Geodetic deformation is probably required for large earthquakes, so its absence argues against large earthquakes any time soon

Our challenges aren’t unique

“As science turns to complexity, one must realize that 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.

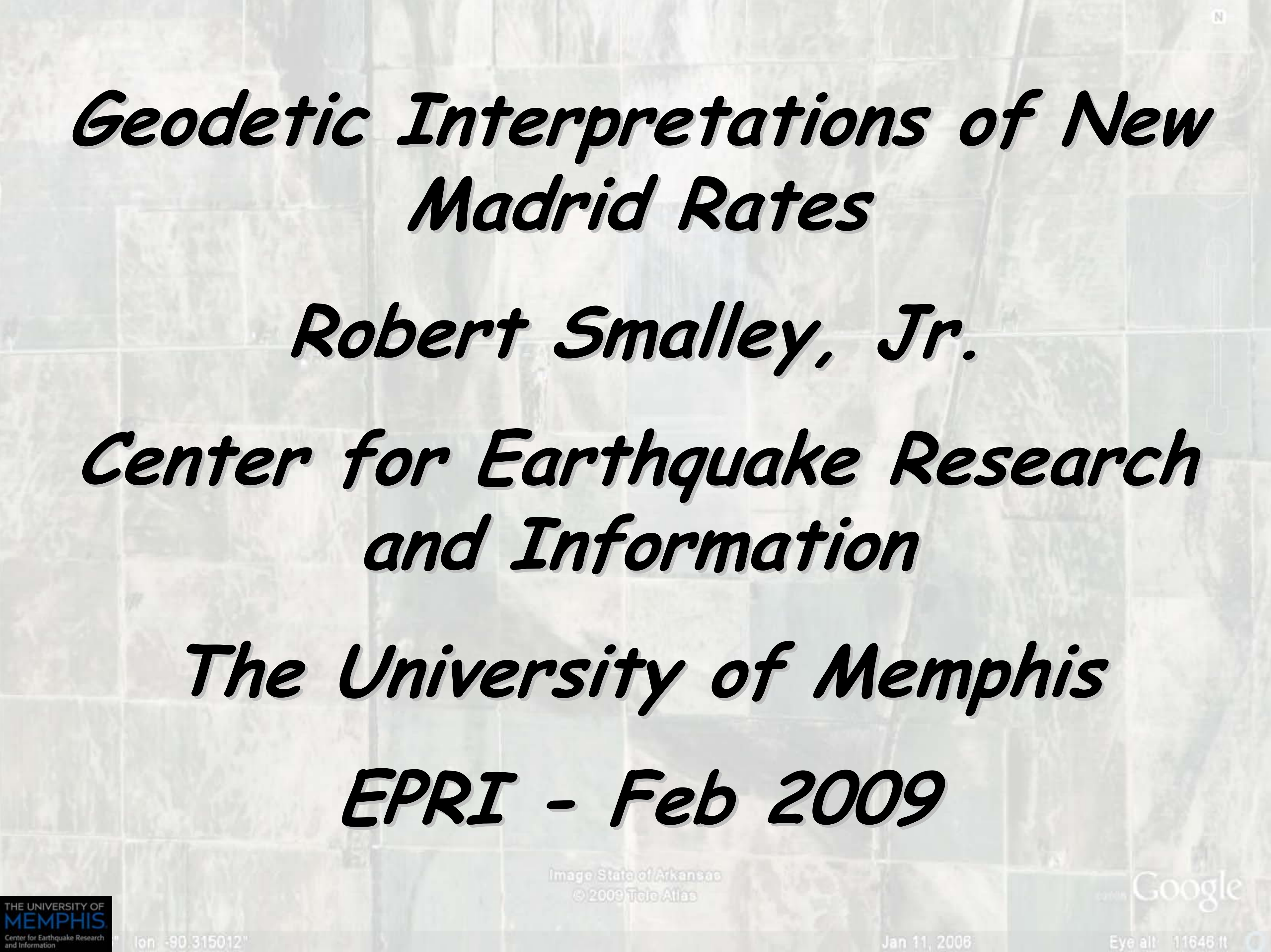
Geodetic Interpretations of New Madrid Rates

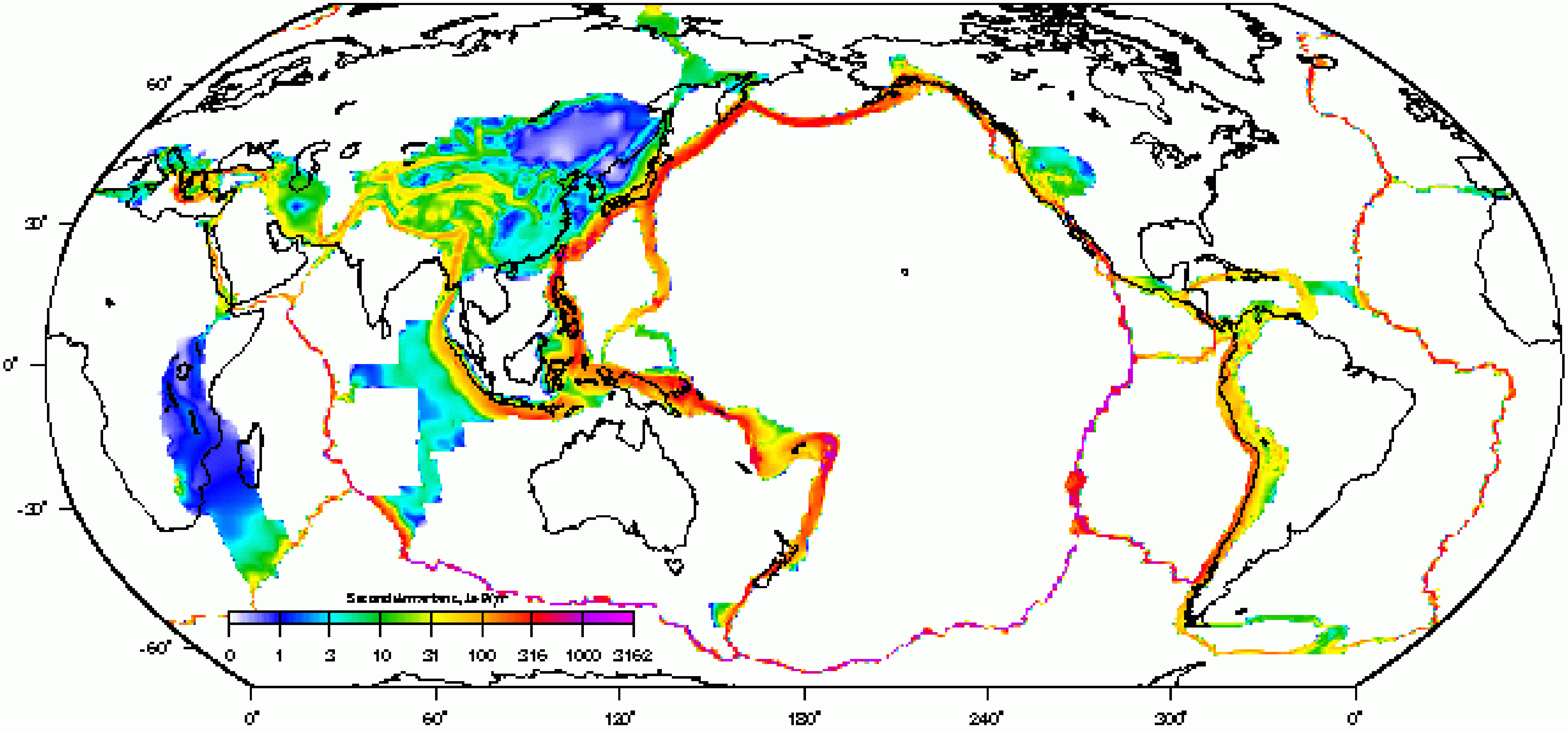
Robert Smalley, Jr.

Center for Earthquake Research and Information

The University of Memphis

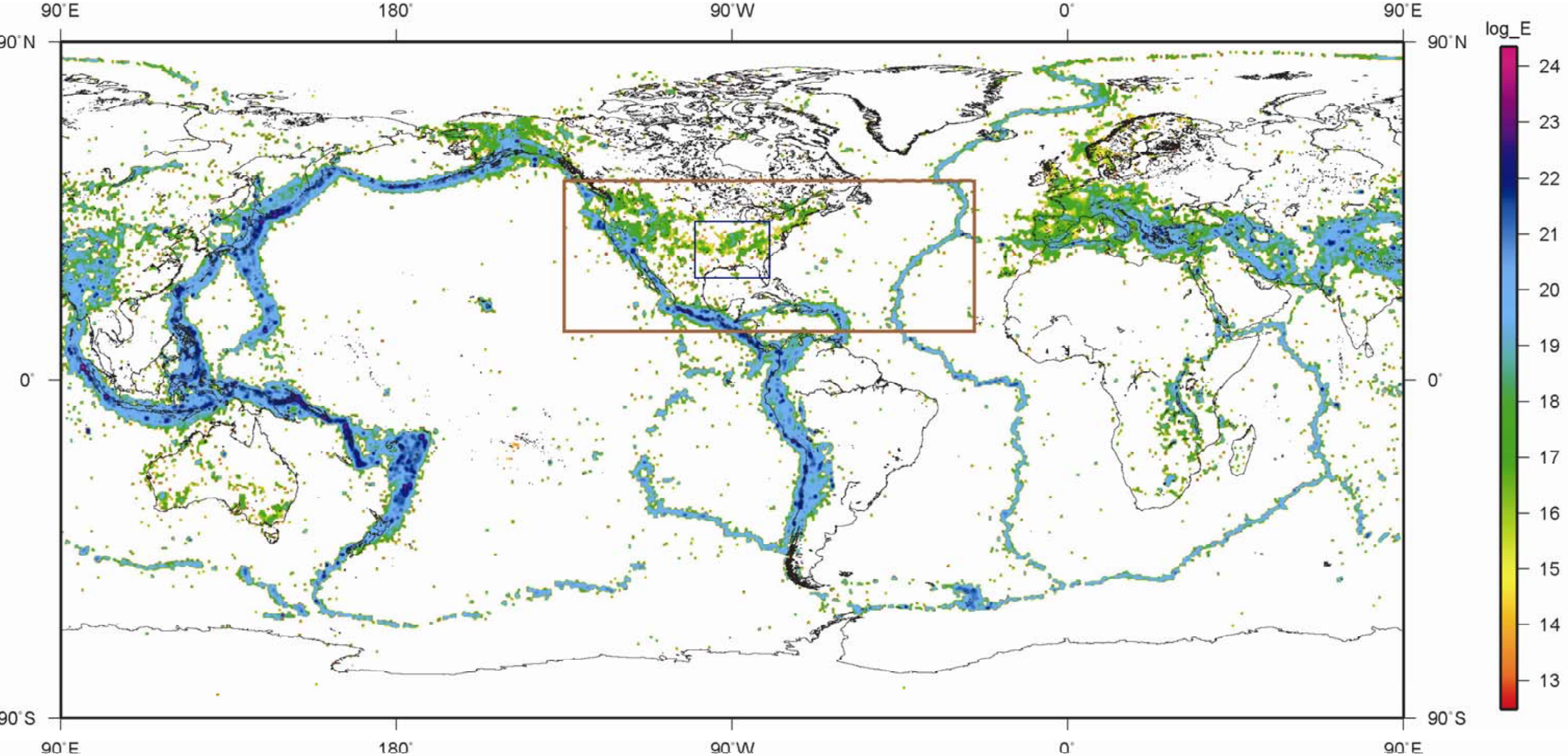
EPRI - Feb 2009





Second invariant of the strain rate tensor.
Based mostly on GPS data.
Excellent agreement with Plate Tectonics.

Kreemer, et al., On the determination of a global strain rate model, Earth Planets Space, 52, 765-770, 2000.



Logarithm Earthquake Energy Release Rate. Based on seismic data. Excellent agreement w/ Plate Tectonics - BUT.

Miao, Q., and C. A. Langston, Spatial Distribution of Earthquake Energy Release in the Central United States from a Global Point of View, Seismological Research Letters ***79****, 33-40, 2008*

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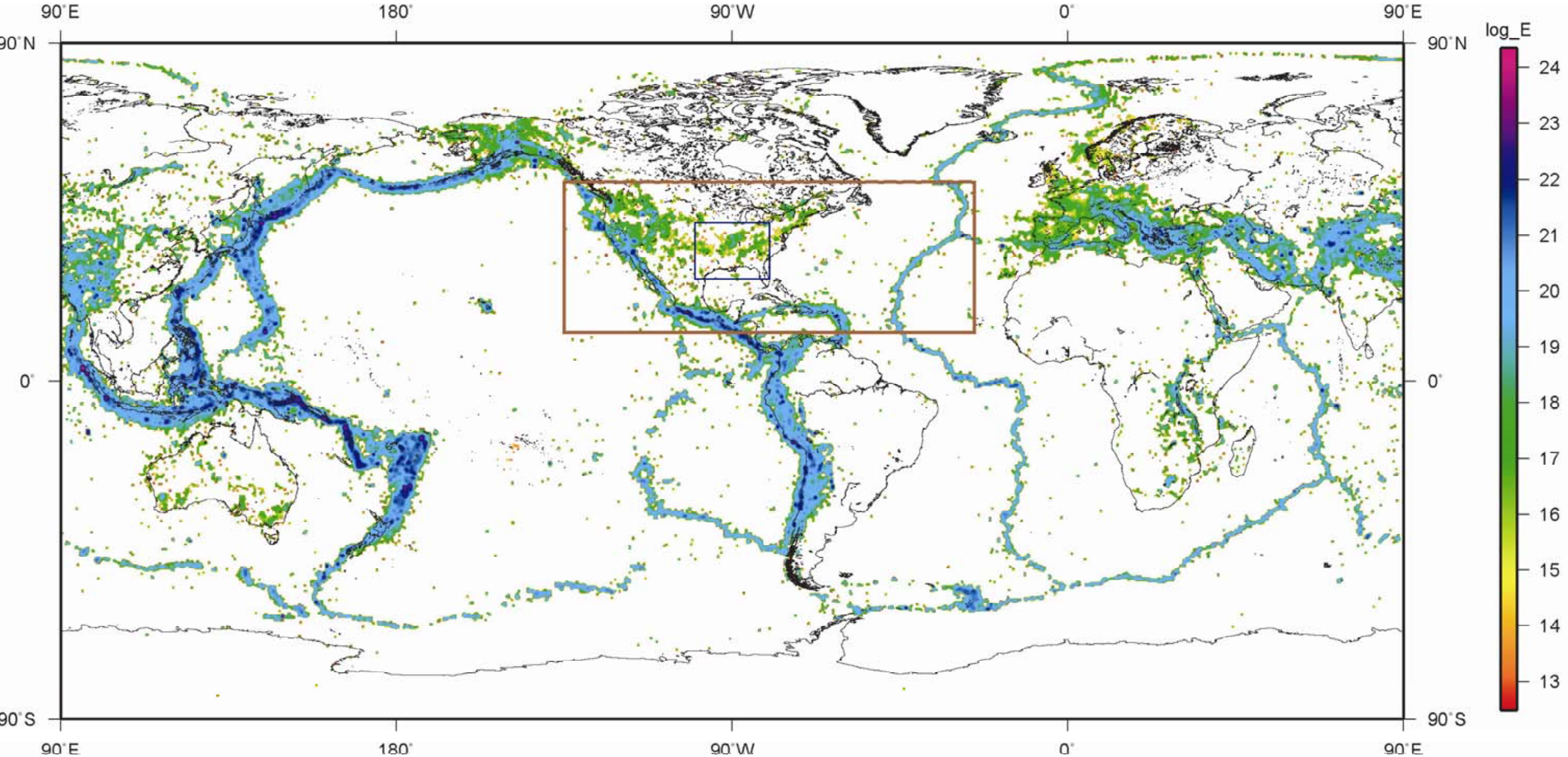

(Organized?) pattern of energy release in some plate interiors that was missed in the strain rate figure.

Miao, Q., and C. A. Langston, Spatial Distribution of Earthquake Energy Release in the Central United States from a Global Point of View, Seismological Research Letters 79, 33-40, 2008

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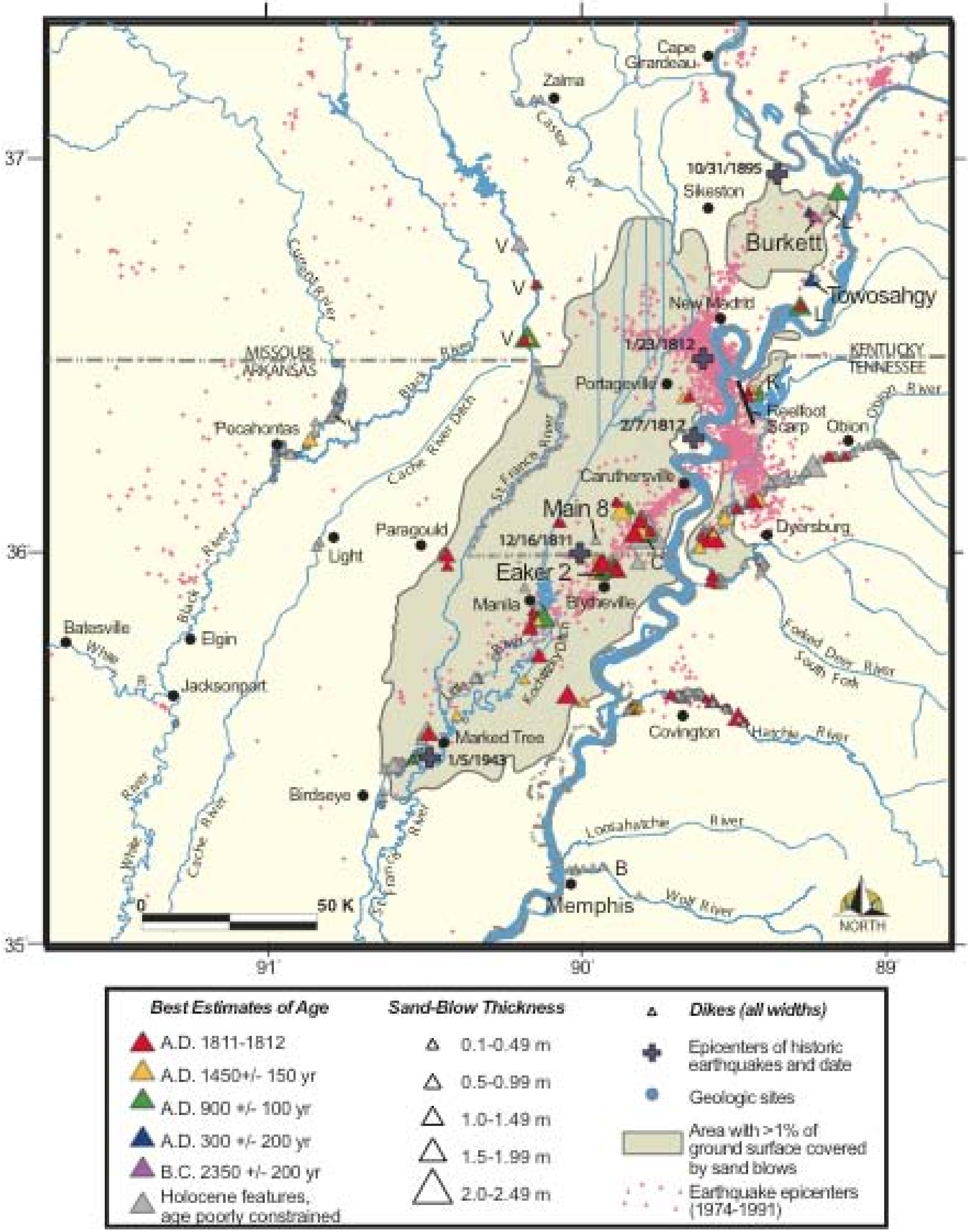
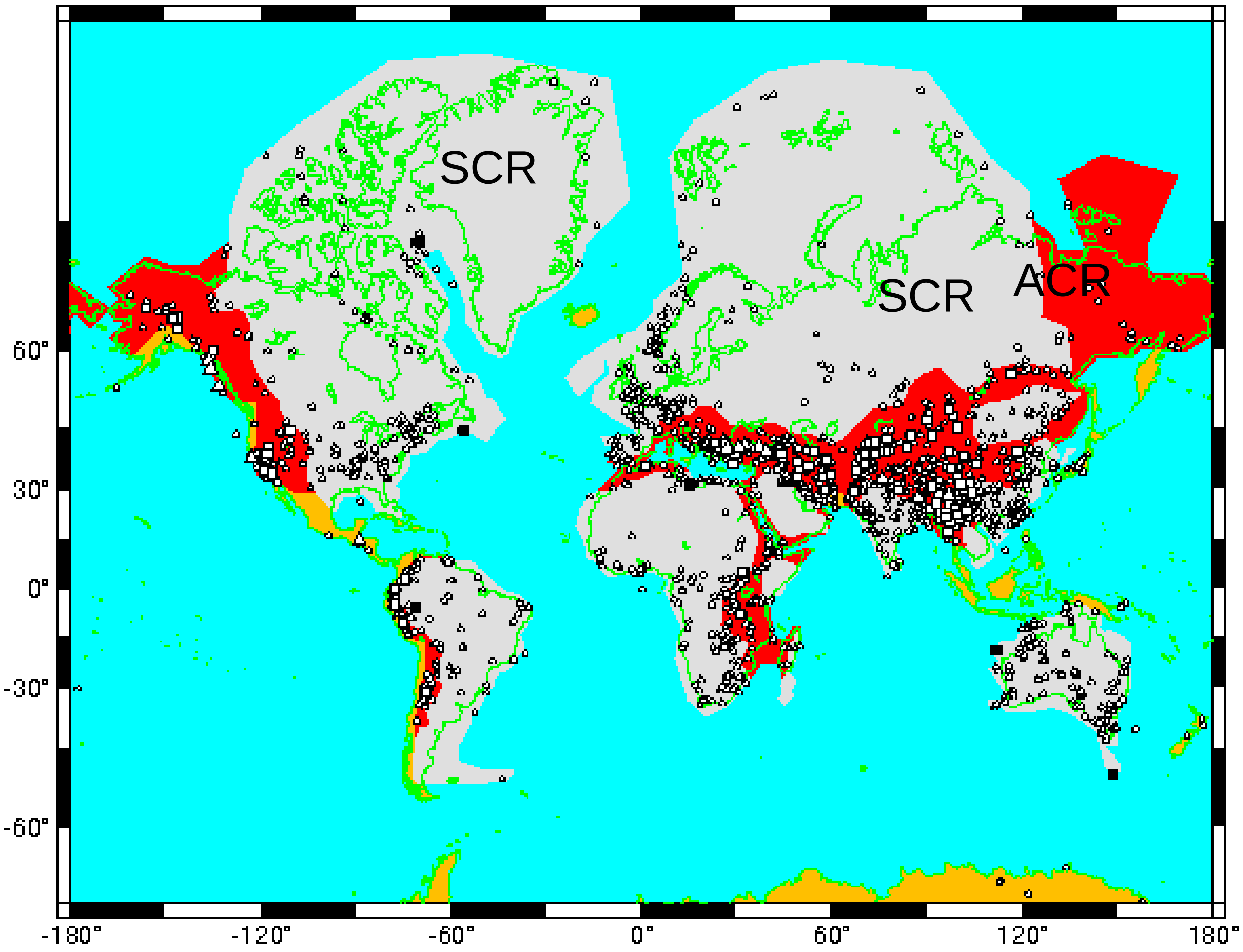


Enigma: Multiple occurrences large earthquakes over past few thousand years.

Not explained by
-Plate Tectonic paradigm
-Elastic rebound paradigm



Shallow Intracontinental Earthquakes 1900 – 1994

Circles: Mw≥ 5.0. Squares: Mw >= 7.0, solid 7 events in SCR.

Catalog of Shallow Intracontinental Earthquakes, 1996, Triep & Sykes http://www.ldeo.columbia.edu/seismology/triep/intra.expl.html

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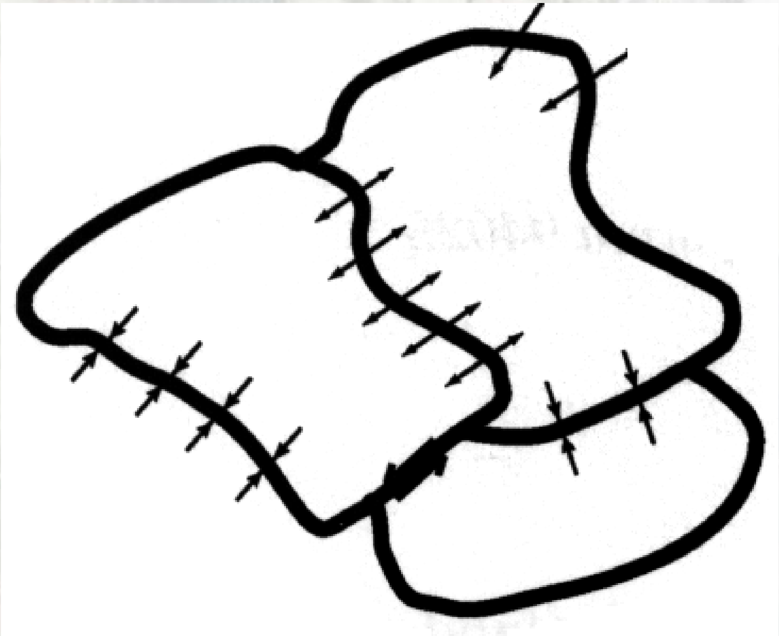
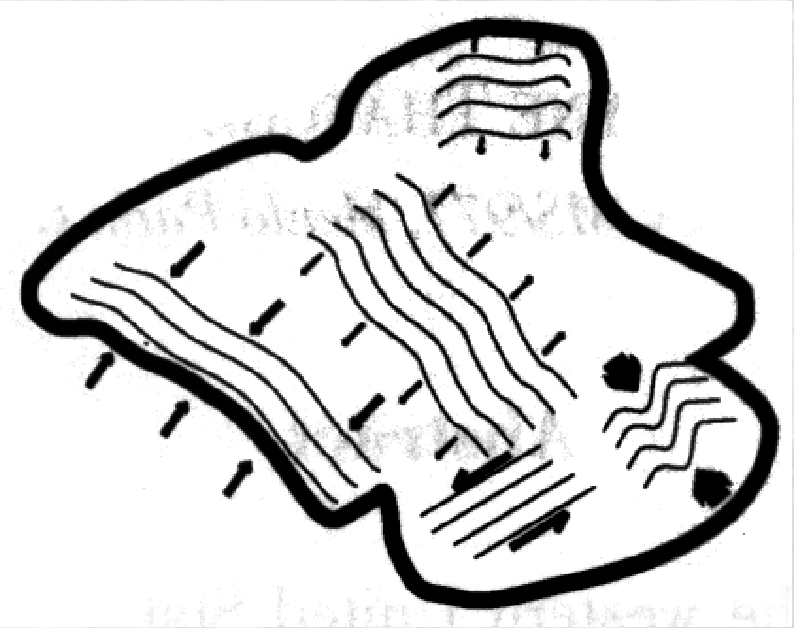
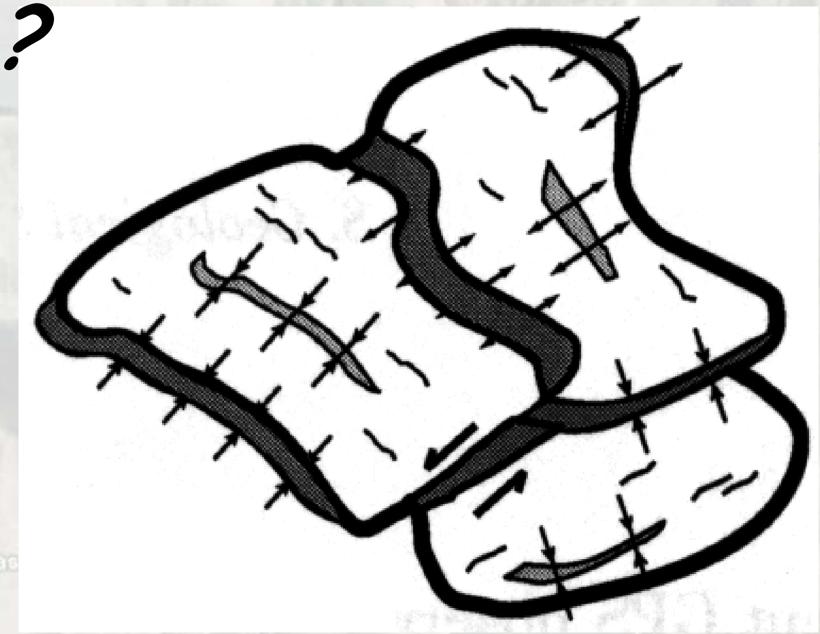




How might plates deform?



Thacher, 2003

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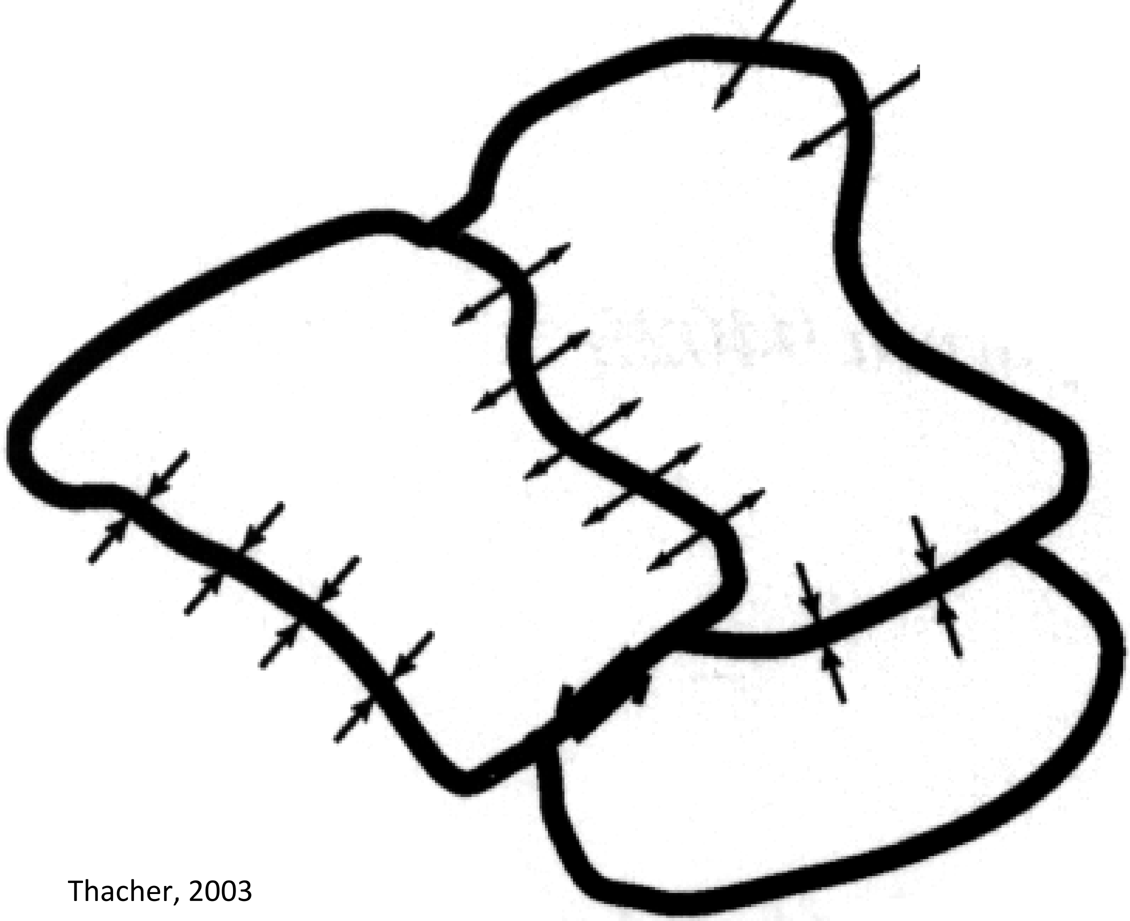
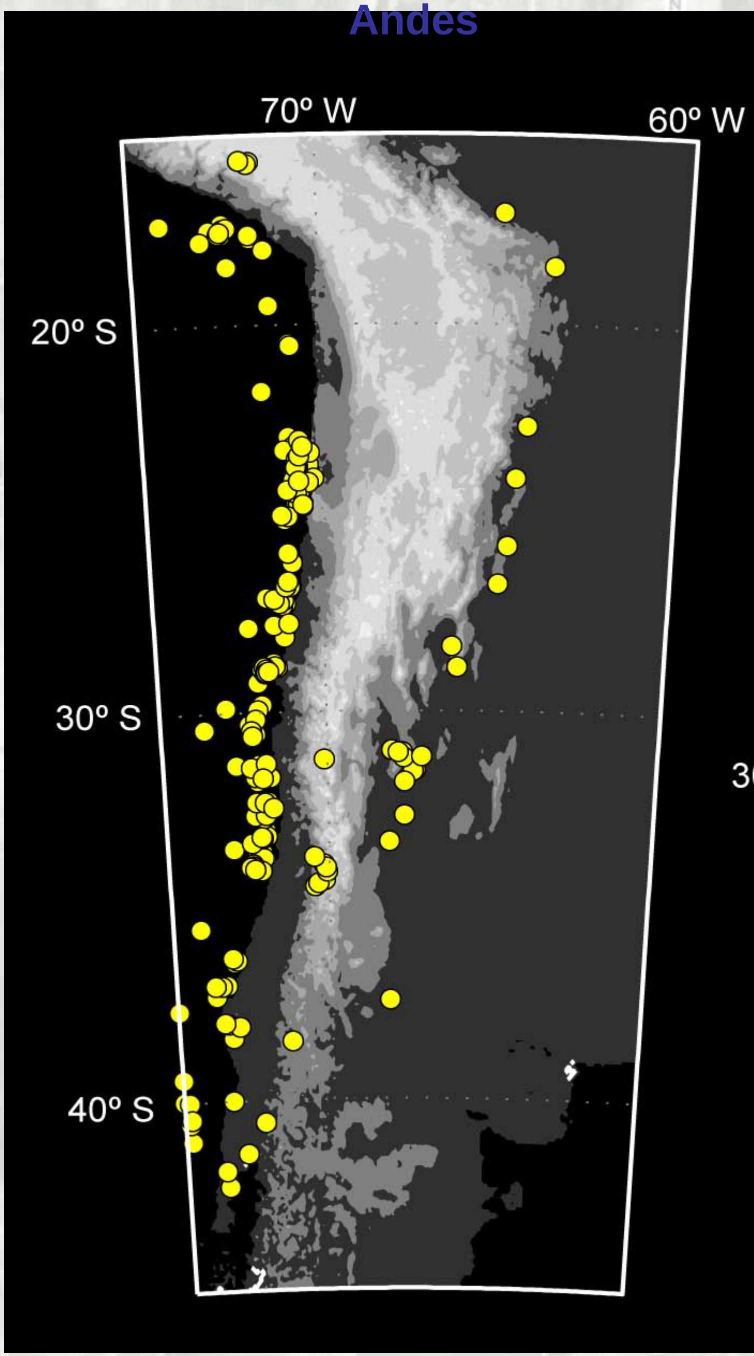
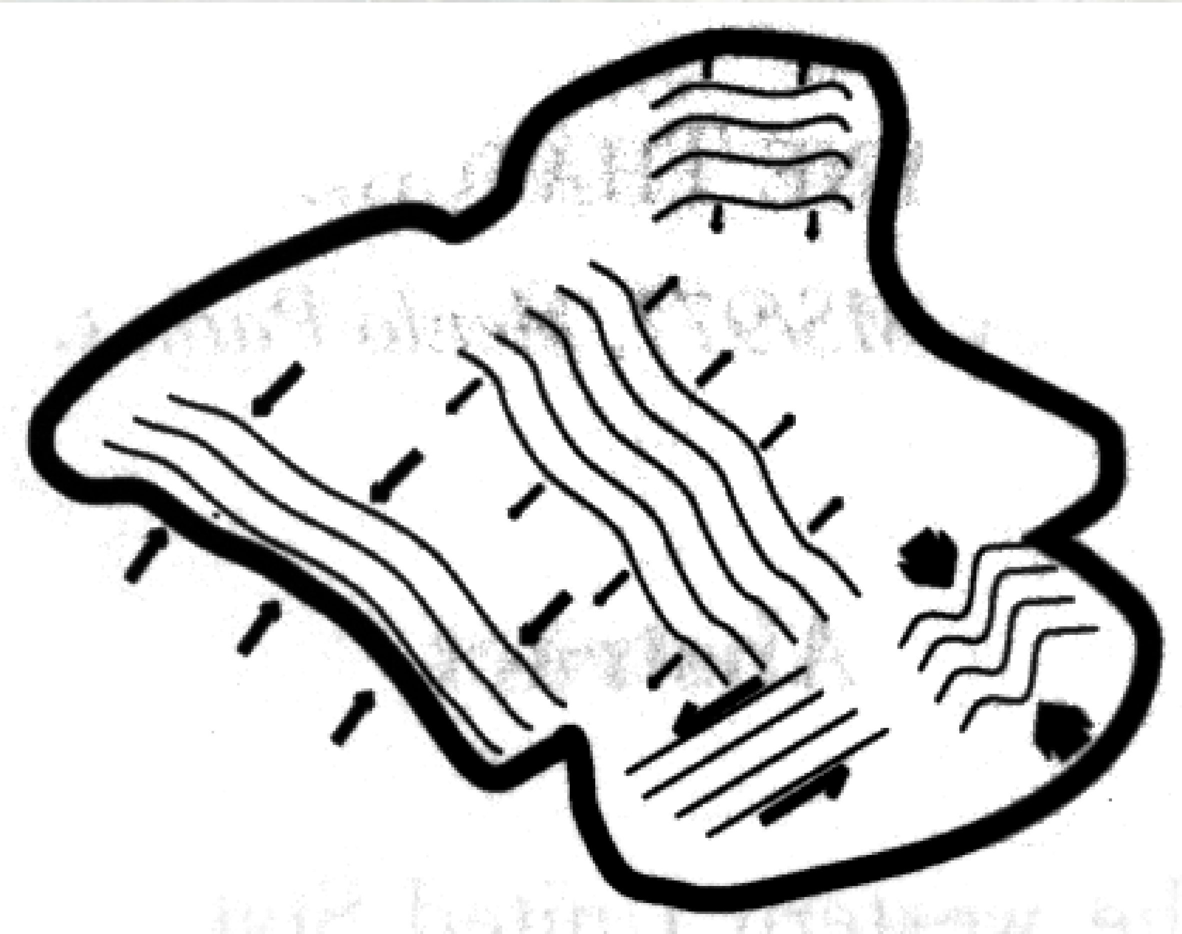
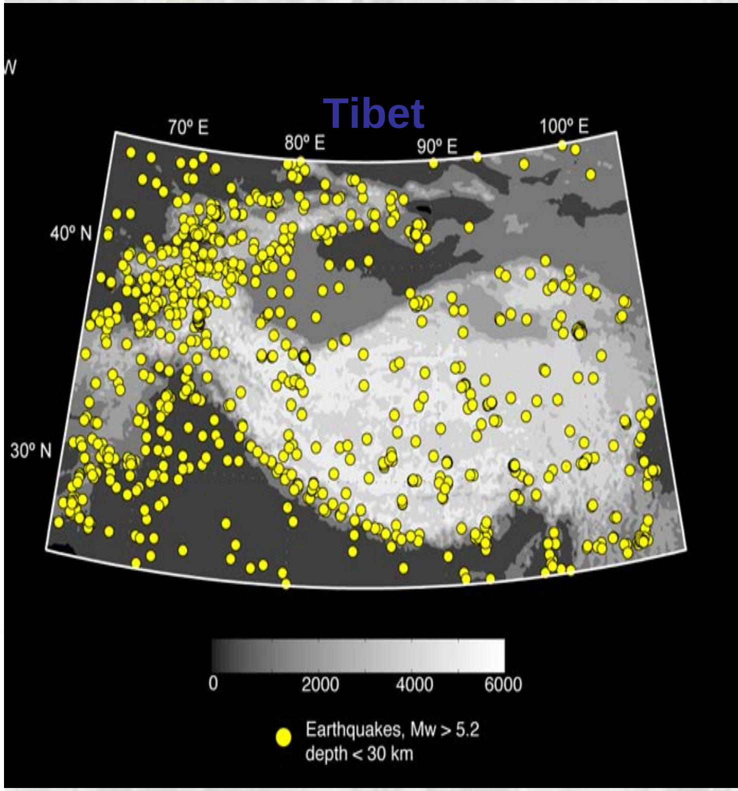

Thacher, 2003

Andes



Rigid blocks.
Sort of mini-version of plate tectonics.
"Easy" to see with GPS.



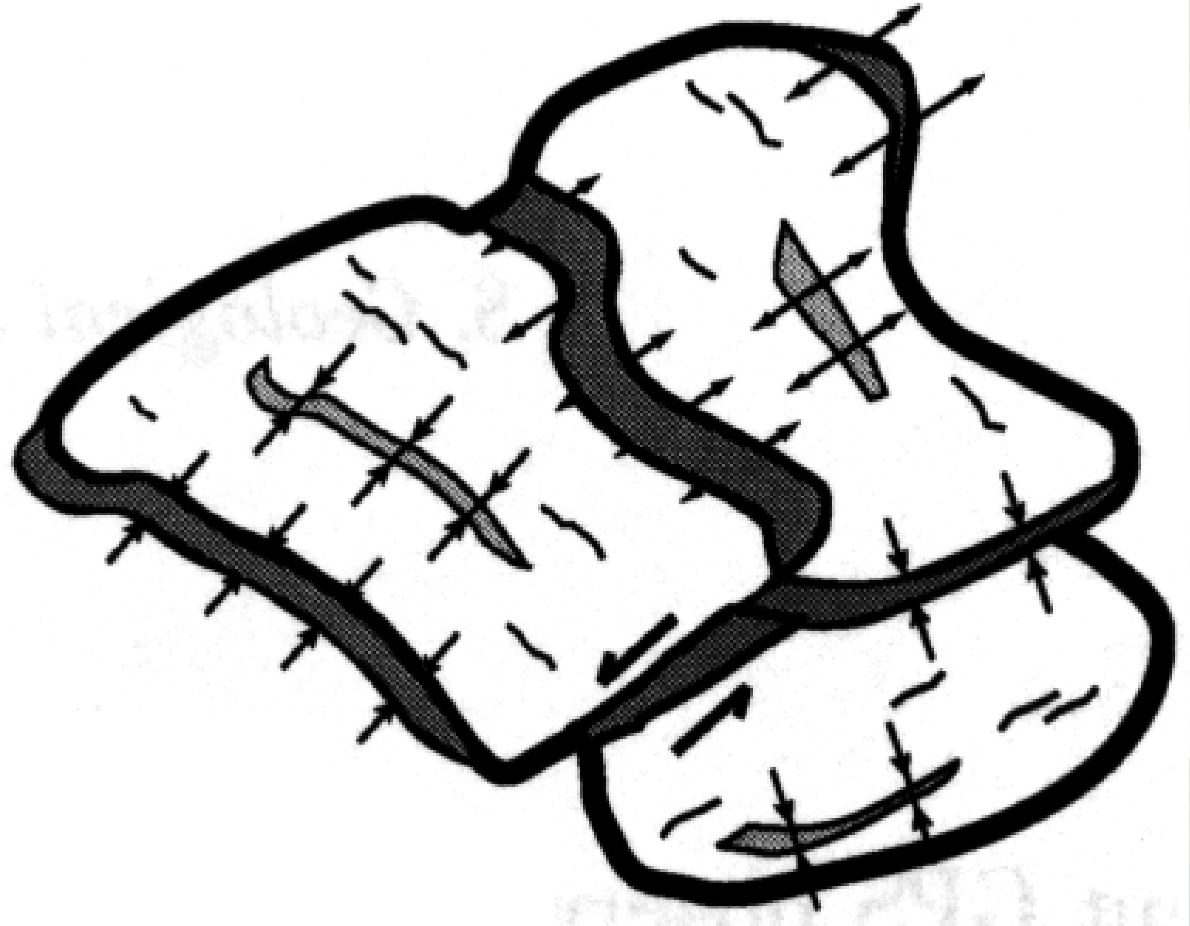


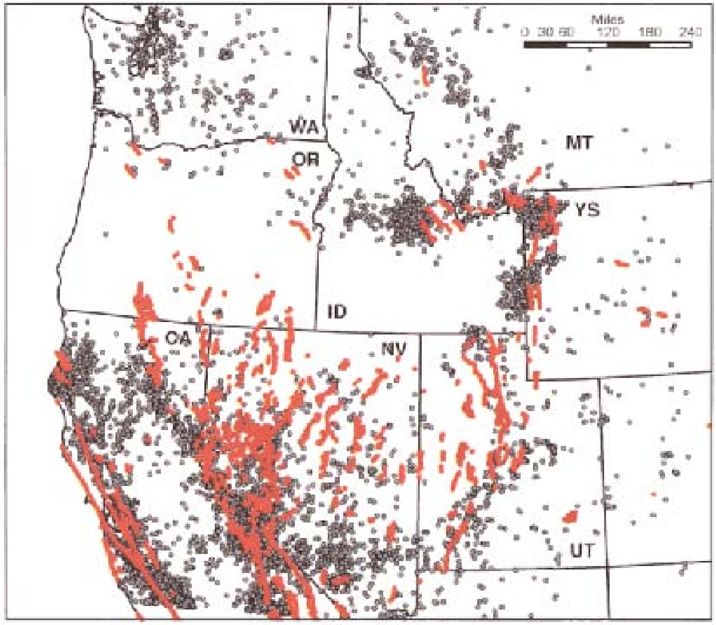
Quasi-continuous deformation. Pervasive internal deformation** (but not fast enough to invalidate plate tectonics)**.

Continuum sea.

"Hard" to see with GPS.

Thacher, 2003





Narrow deformation zones.
Concentrated zones of deformation within inactive regions.
"Challenging" to see with GPS.

Thacher, 2003

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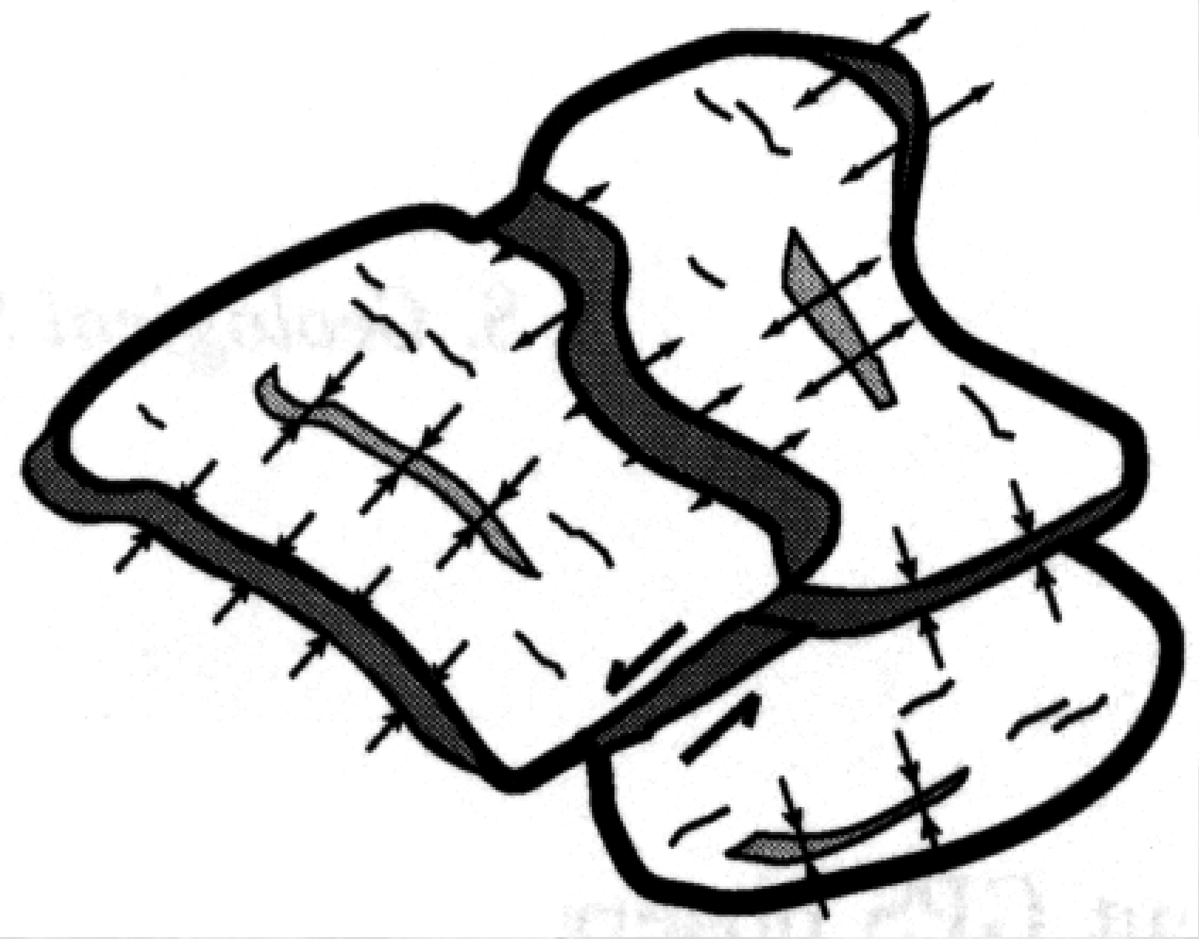
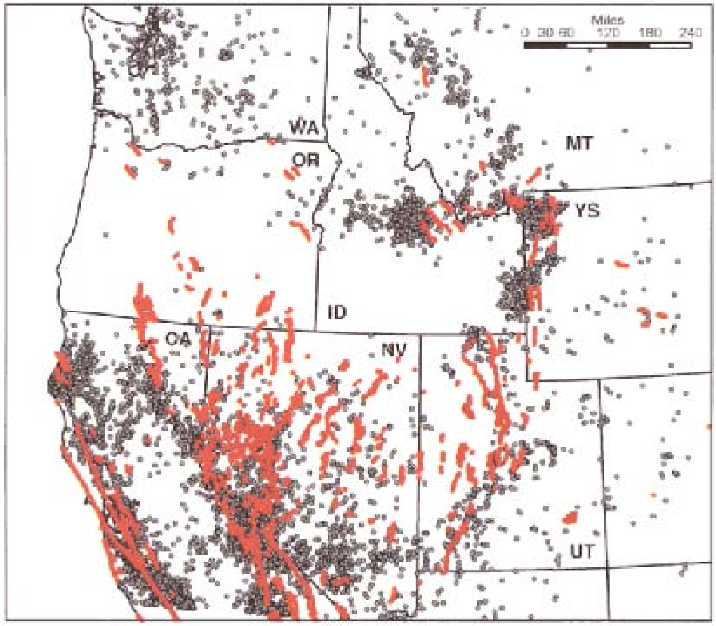


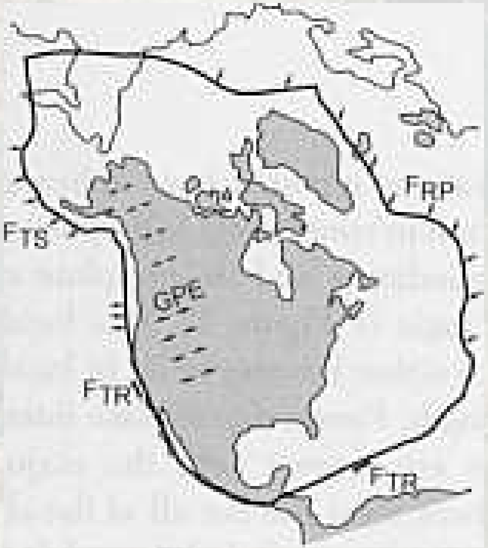


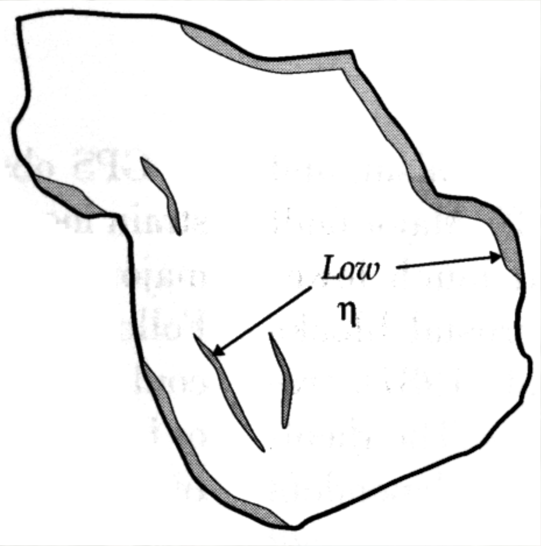
More faults with evidence of active deformation than actively deforming zones.

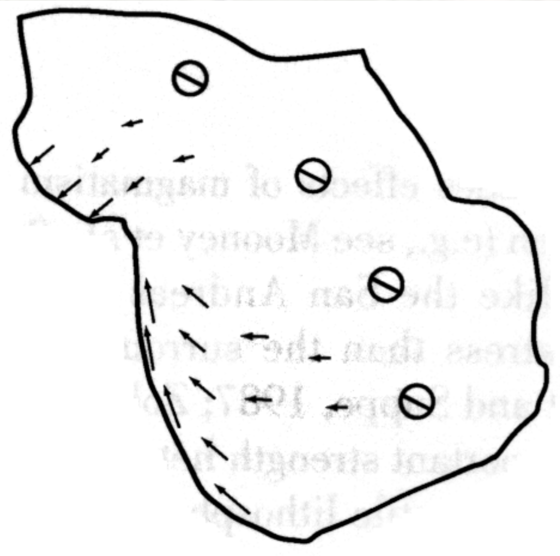
May jump around** (on human or geologic scale)**.

"Challenging" to see with GPS.

Thacher, 2003





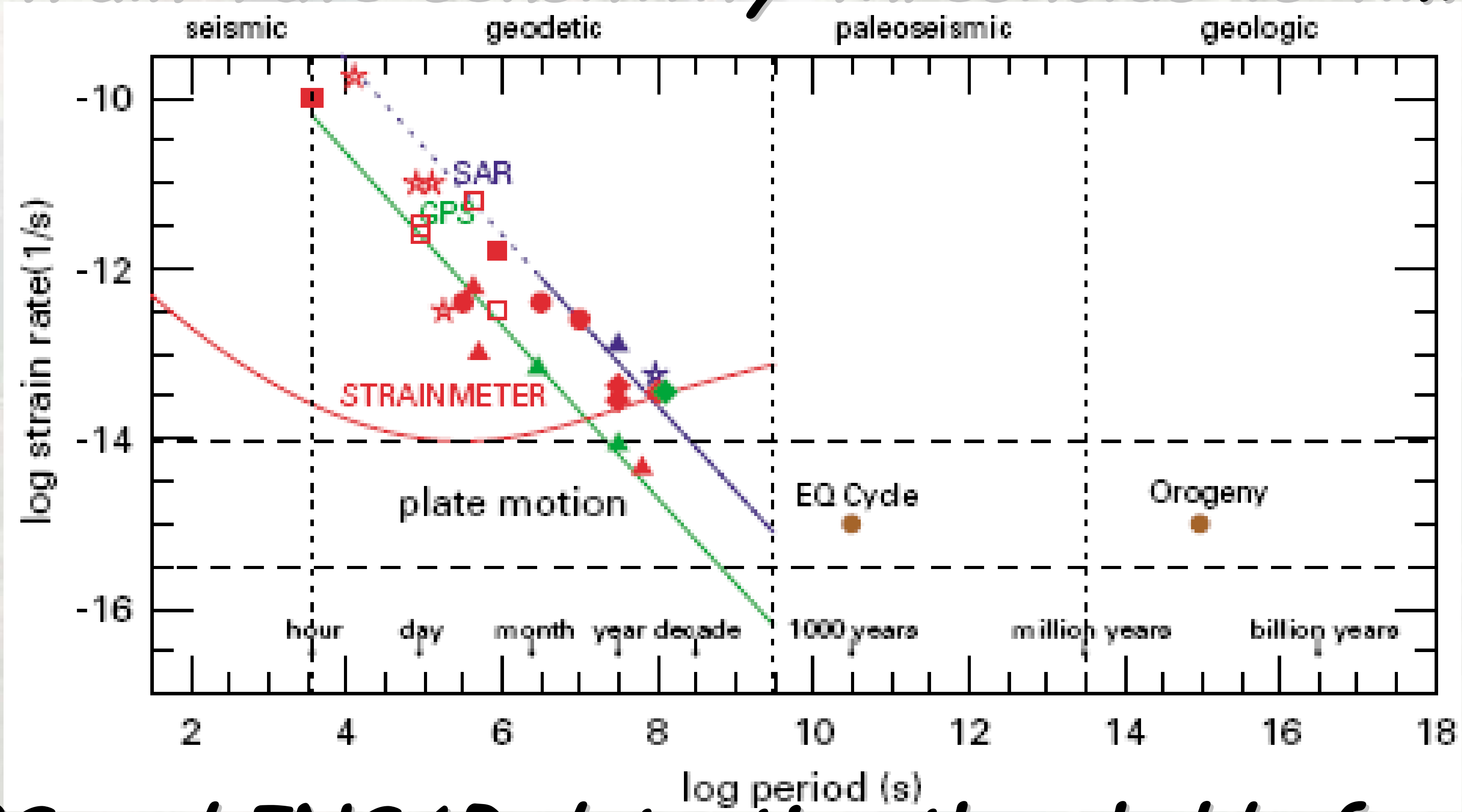


Forces (boundary) + Rheology = (continental) Deformation

Plate tectonic dynamics (lithosphere horizontal stress guide) responds to boundary conditions.

Thacher, 2003

Strain-rate sensitivity thresholds vs time



GPS and INSAR detection thresholds for 10 km baselines, assuming 2 mm and 2 cm displacement resolution for GPS and INSAR, respectively (horizontal).

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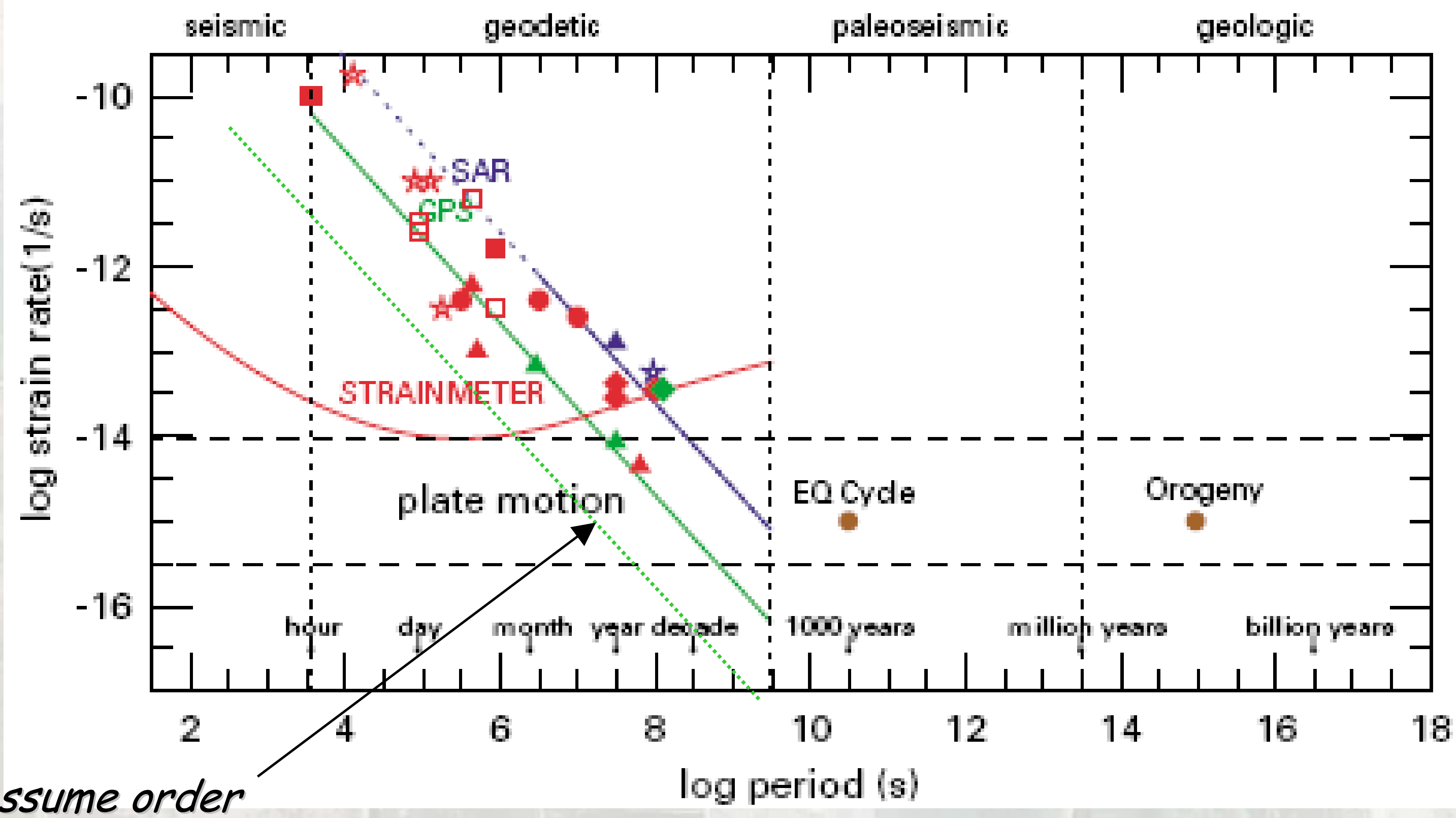
http://www.iris.iris.edu/USArray/EllenMaterial/assets/es_proj_plan_lo.pdf,

Strain rates in stable plate interiors



Assume order magnitude improvement in GPS

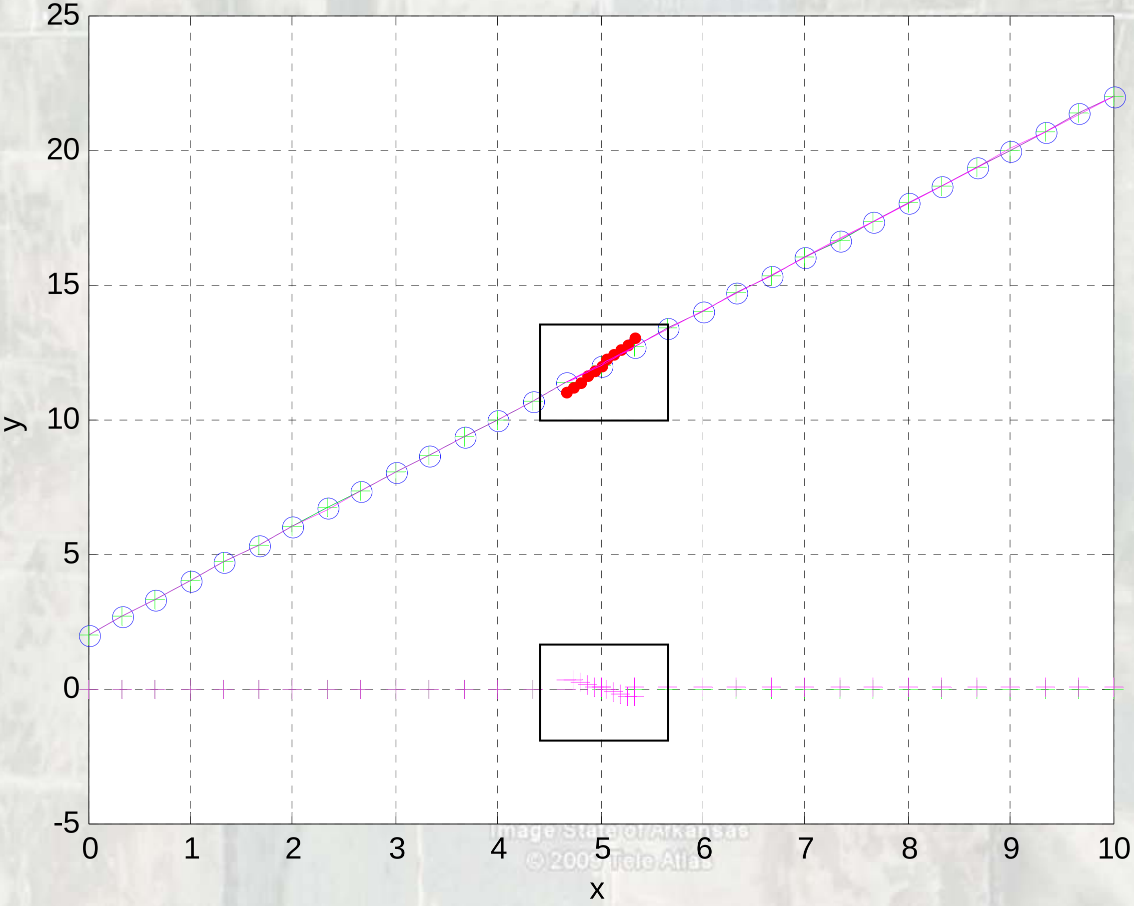
bounded between

$3\ \times 10^{-20}$ - 10^{-19} /sec and 10^{-17} /sec.

Gordon (1998)

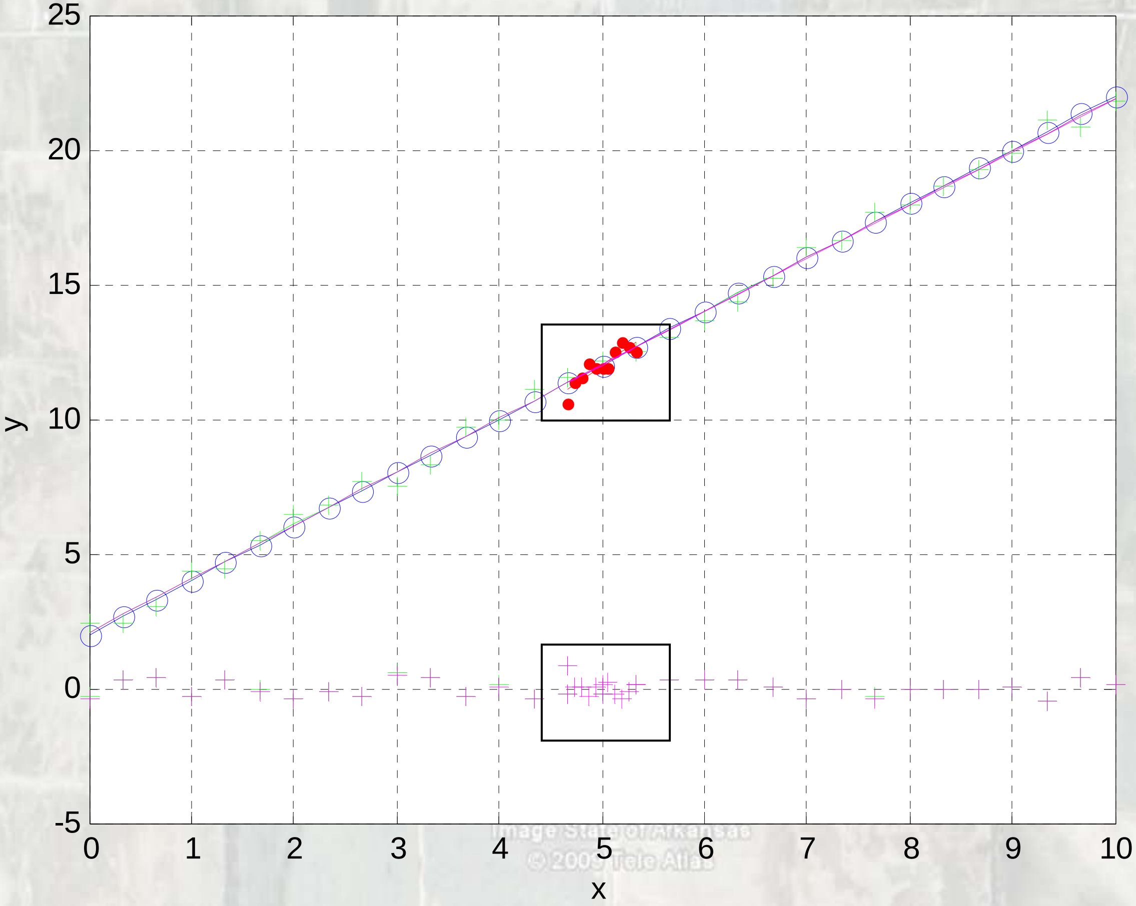
Challenge - detecting small signal buried in larger signal.

No noise.



Bigger challenge - detecting small signal buried in larger signal.

With noise.



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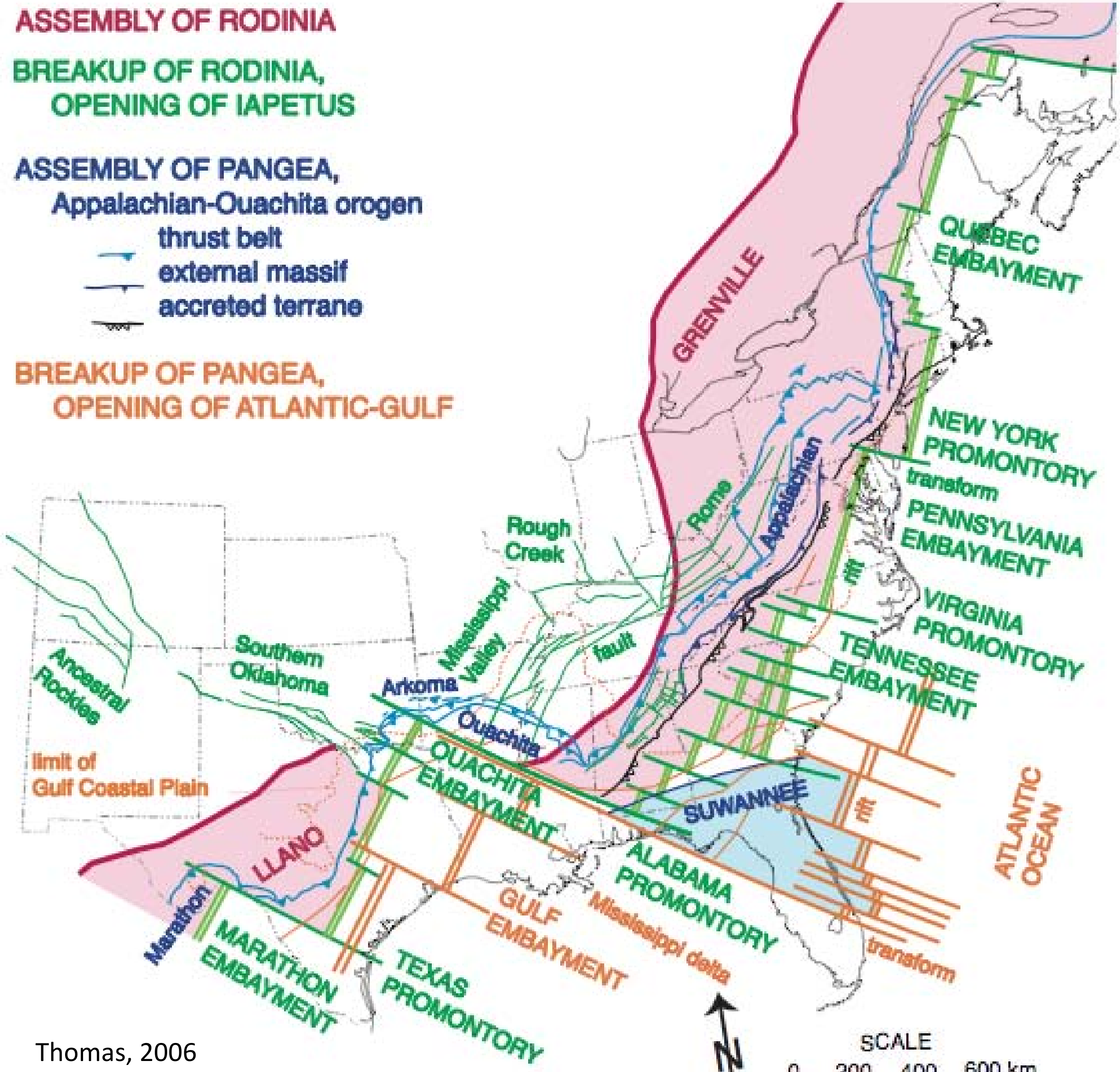
Number of explanations for SCR earthquakes

(1) reactivation of zones of weakness
(2) localization of stress by physical stress concentrators
(3) crustal weakening by fluids
(4) anomalous high temperatures

(5) Foundering of subducted plates
(6) stress changes due to deglaciation or sediment loading (vertical)
(7) Anthropogenic (dams, injection, withdrawal)

Paleozoic-Mesozoic structural framework ENA provides lots structures for New Madrid, Wabash Valley, Charleston, eastern Canadian seismic zones.



Thomas, 2006

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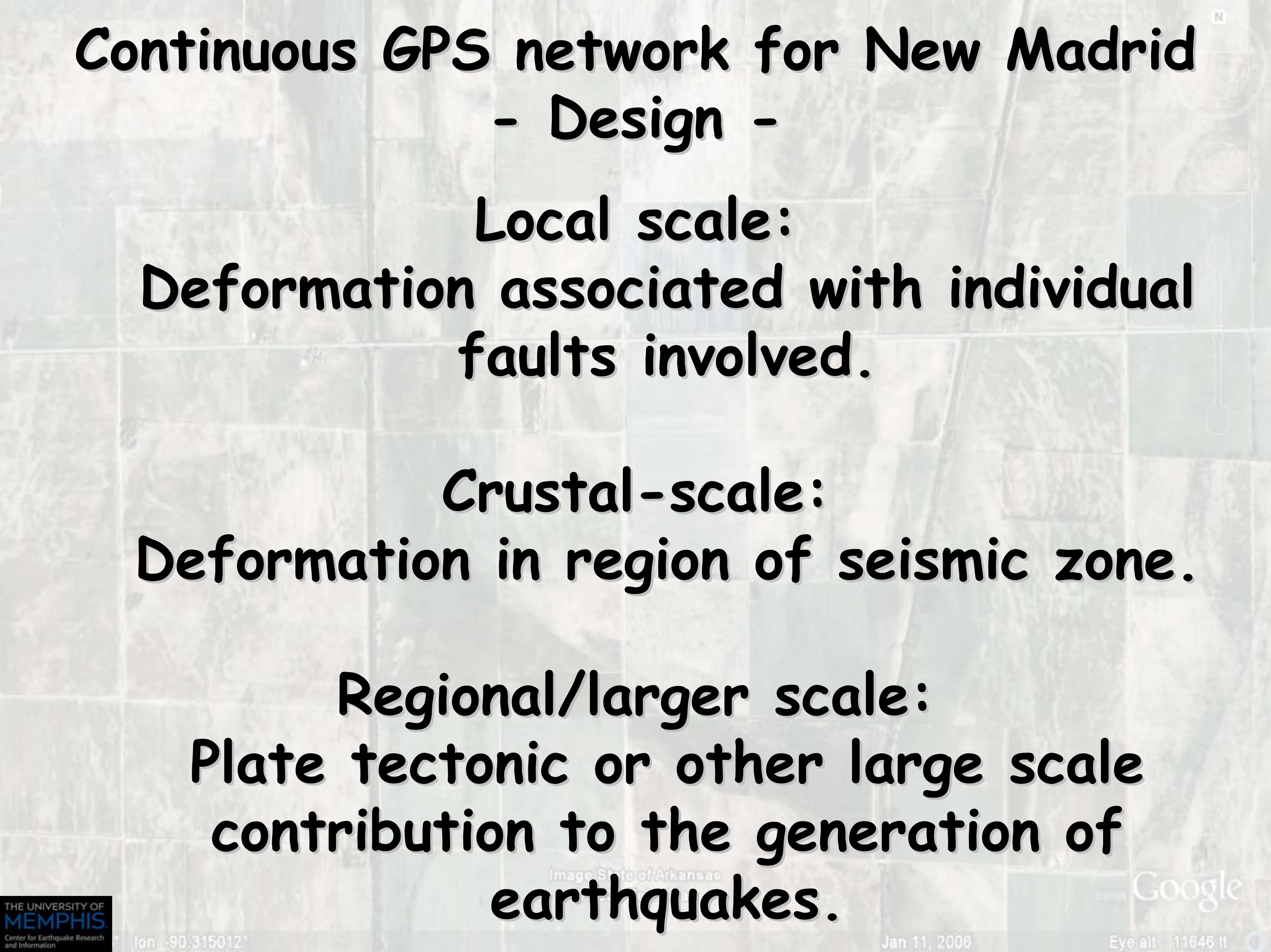
Continuous GPS network for New Madrid
- Design -



Local scale:
Deformation associated with individual faults involved.

Crustal-scale:
Deformation in region of seismic zone.

Regional/larger scale:
Plate tectonic or other large scale contribution to the generation of earthquakes.

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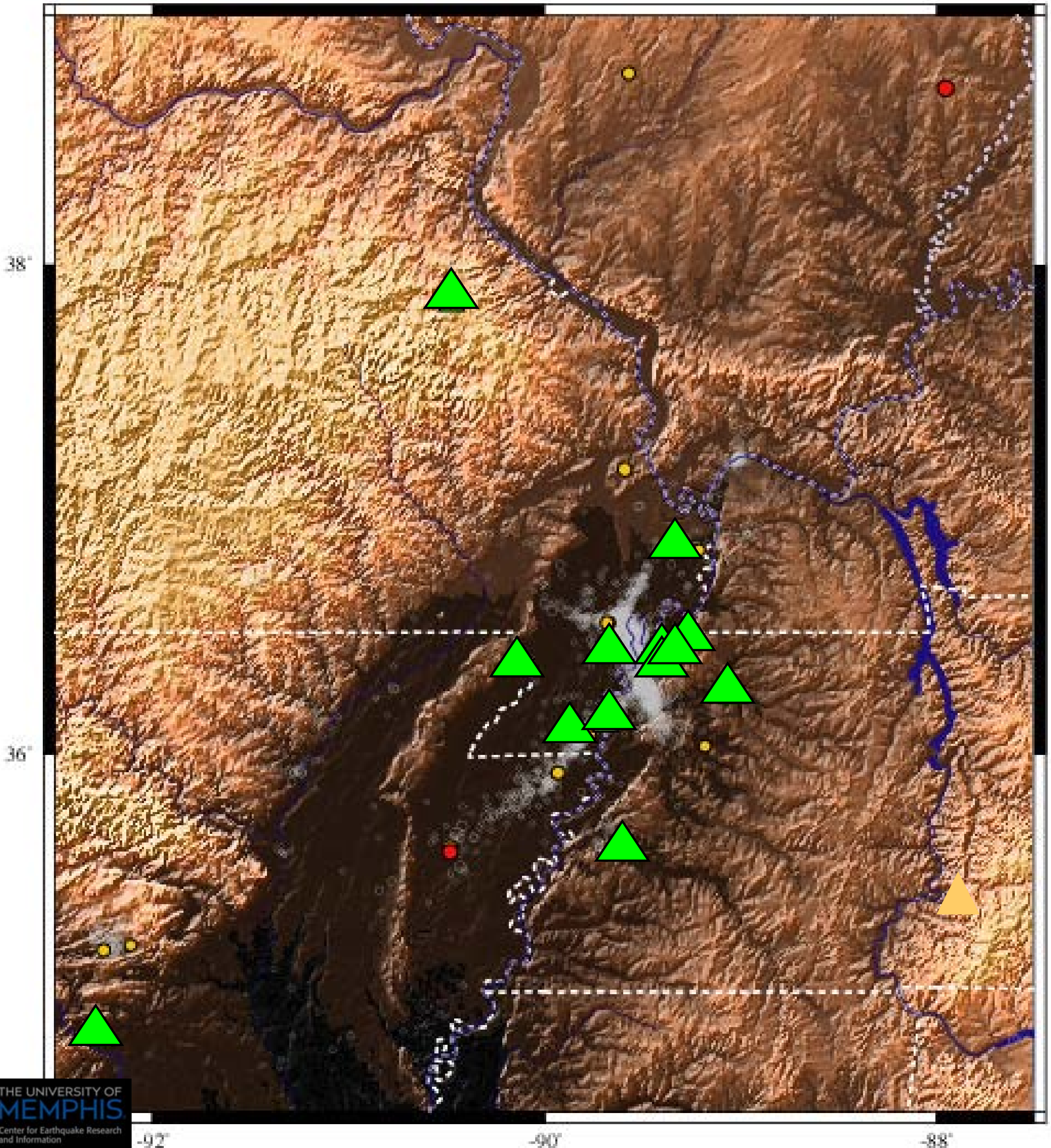

Continuous GPS network for New Madrid Design

Local scale

Mid-scale

Regional scale

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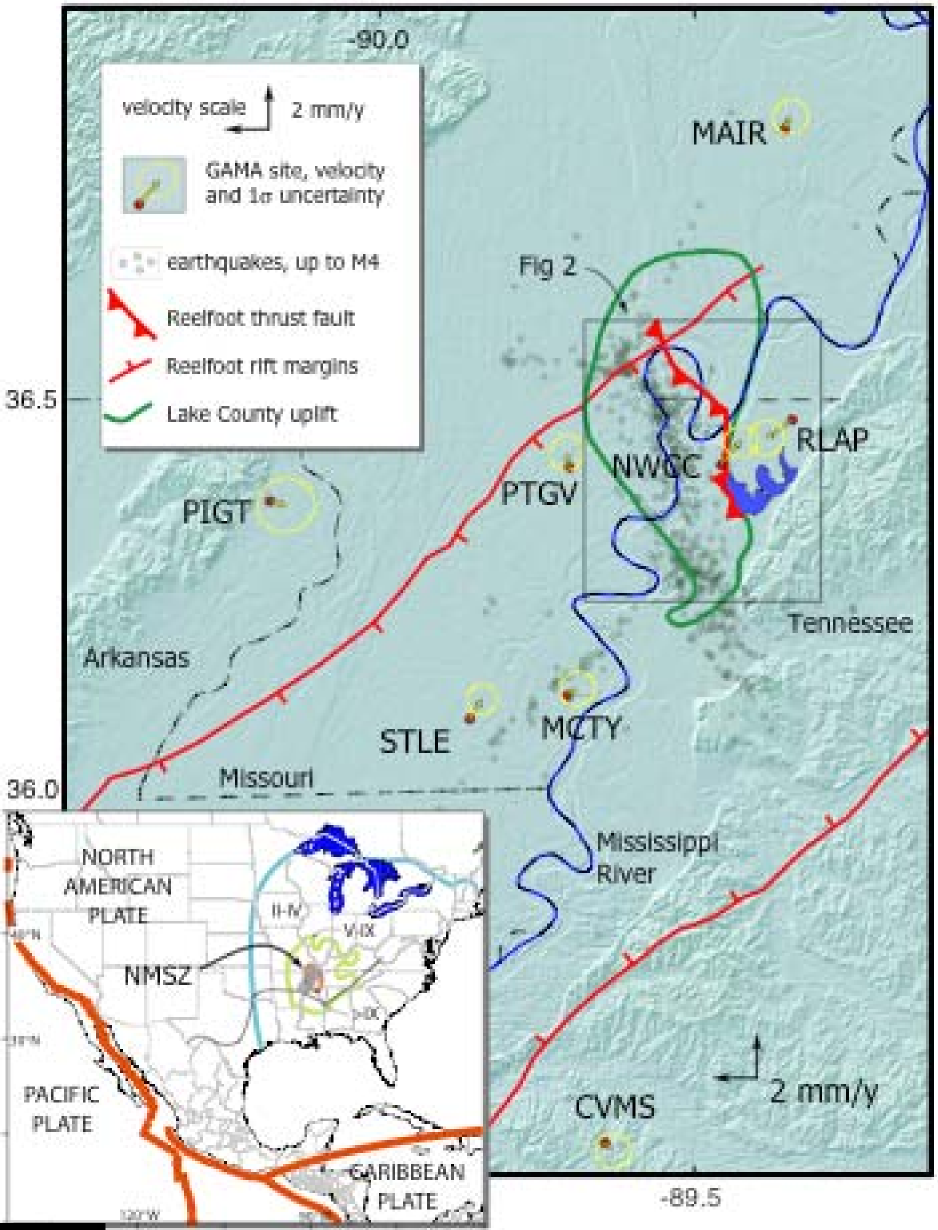
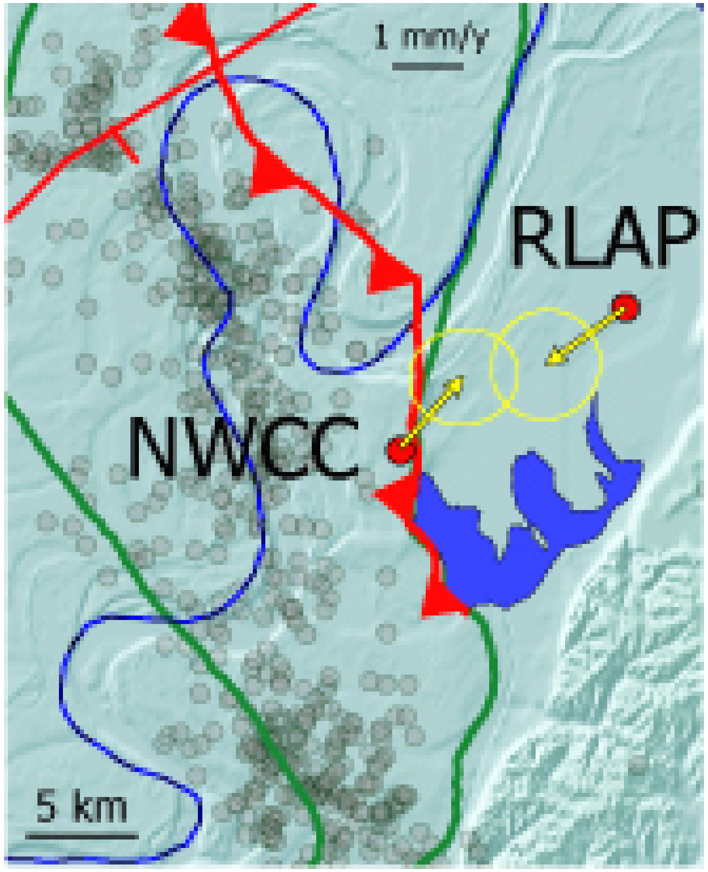
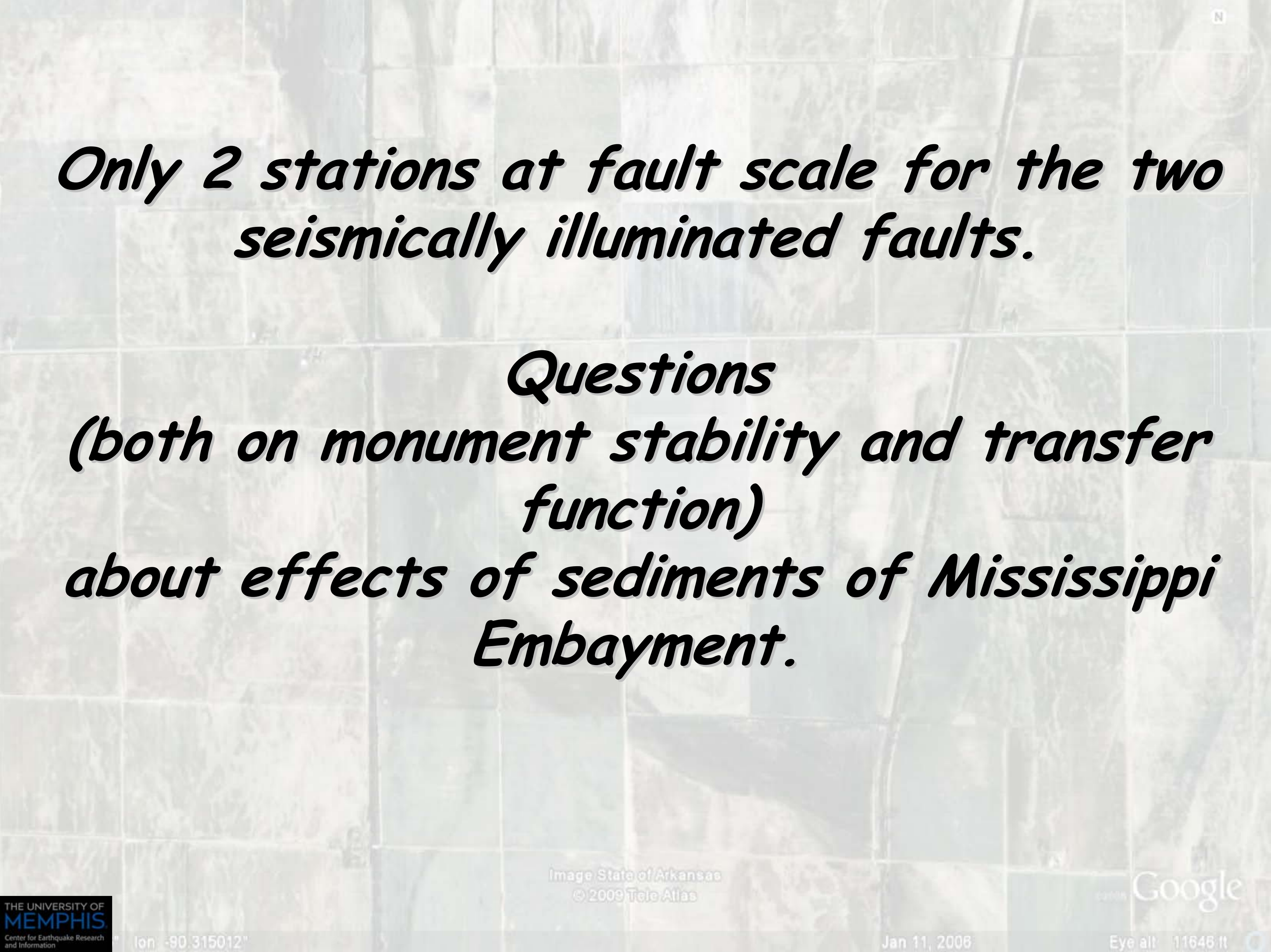


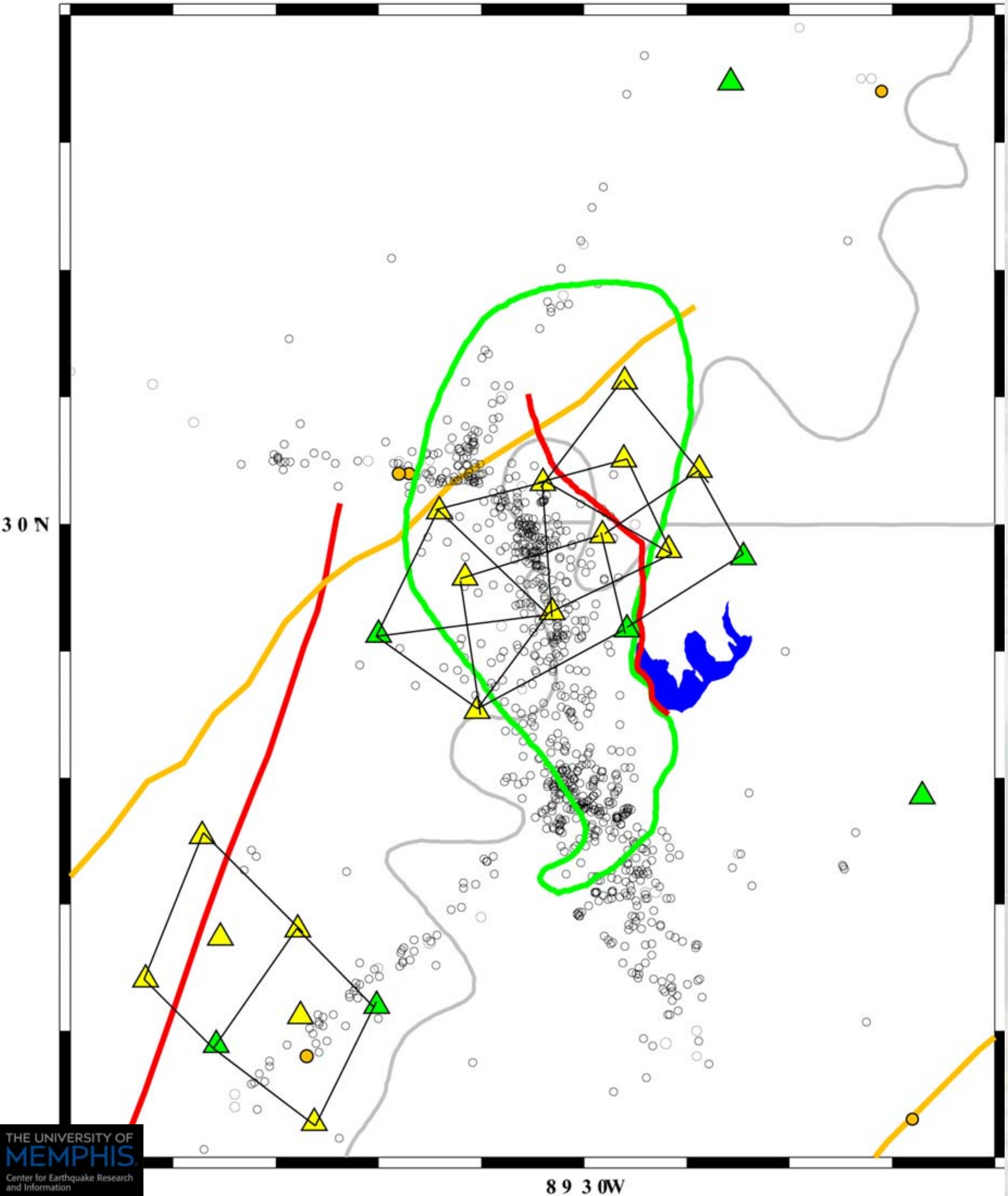


Initial results from first 5 years of data.

Only 2 stations at fault scale for the two seismically illuminated faults.

Questions
(both on monument stability and transfer function)
about effects of sediments of Mississippi Embayment.





What we need ----

- Longer time series providing more accurate velocities
- Larger number stations providing higher density and redundancy

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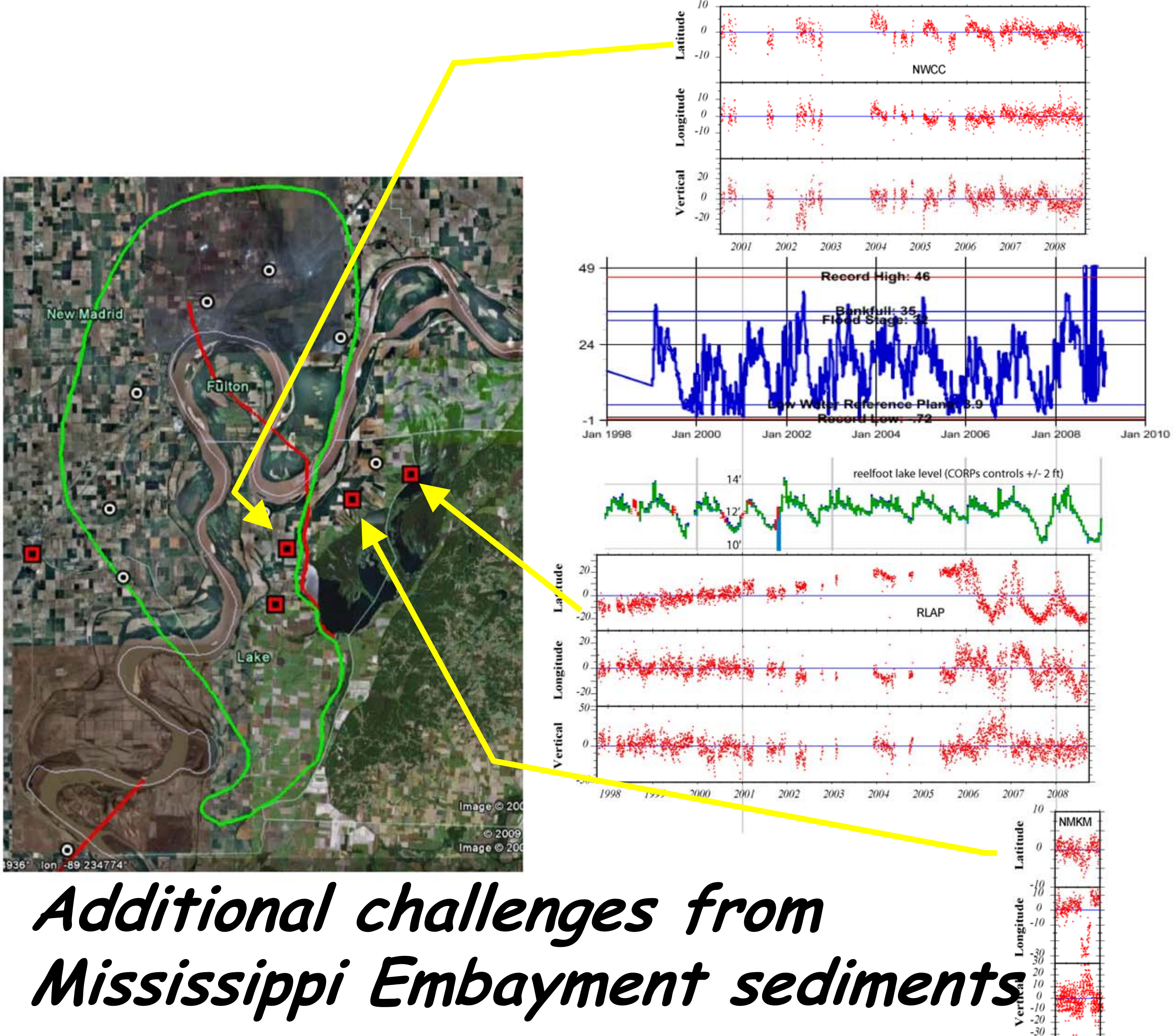
Continuous GPS

- Stable monuments -



Additional challenges from Mississippi Embayment sediments

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Geodetic results from other SCR regions

In ENA: Mostly campaign –

-Wabash Valley - marginally significant 0.5-0.7 mm/yr wrt SNAM (Hamburger et al., 2008, abstract).

-Charleston, SC. – marginally significant strain rates 10^{-7} yr $^{-1}$ (Trencamp and Talwani, 2005, abstract)

E. Canada

ESE-WNW regional shortening ~2×10^{-9} yr $^{-1}$

(Mazzotti et al. 2004)

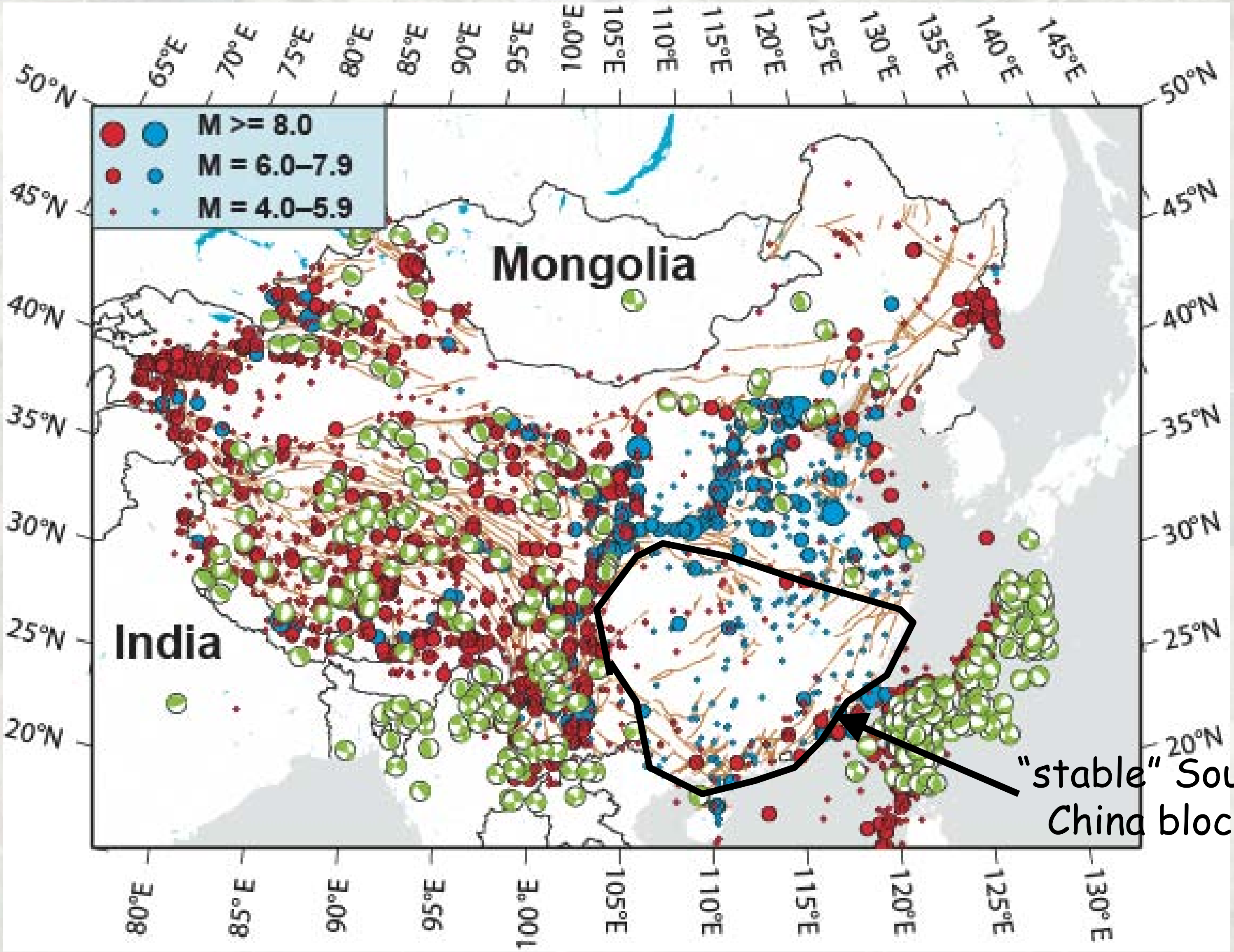
Geodetic results from other SCR regions

In Europe -

Western Europe moving as block 1-2 mm/yr with respect to Eastern Europe across Rhine Graben (Nocquet et al., 2001).

India –

Indian plate stable to $7\times10^{-9}yr^{-1}$ (Paul et al., 2001).



"stable" South China block

Earthquakes and active faults in China

Liu et al, 2007, Active tectonics and intercontinental earthquakes in China: the kinematics and geodynamics

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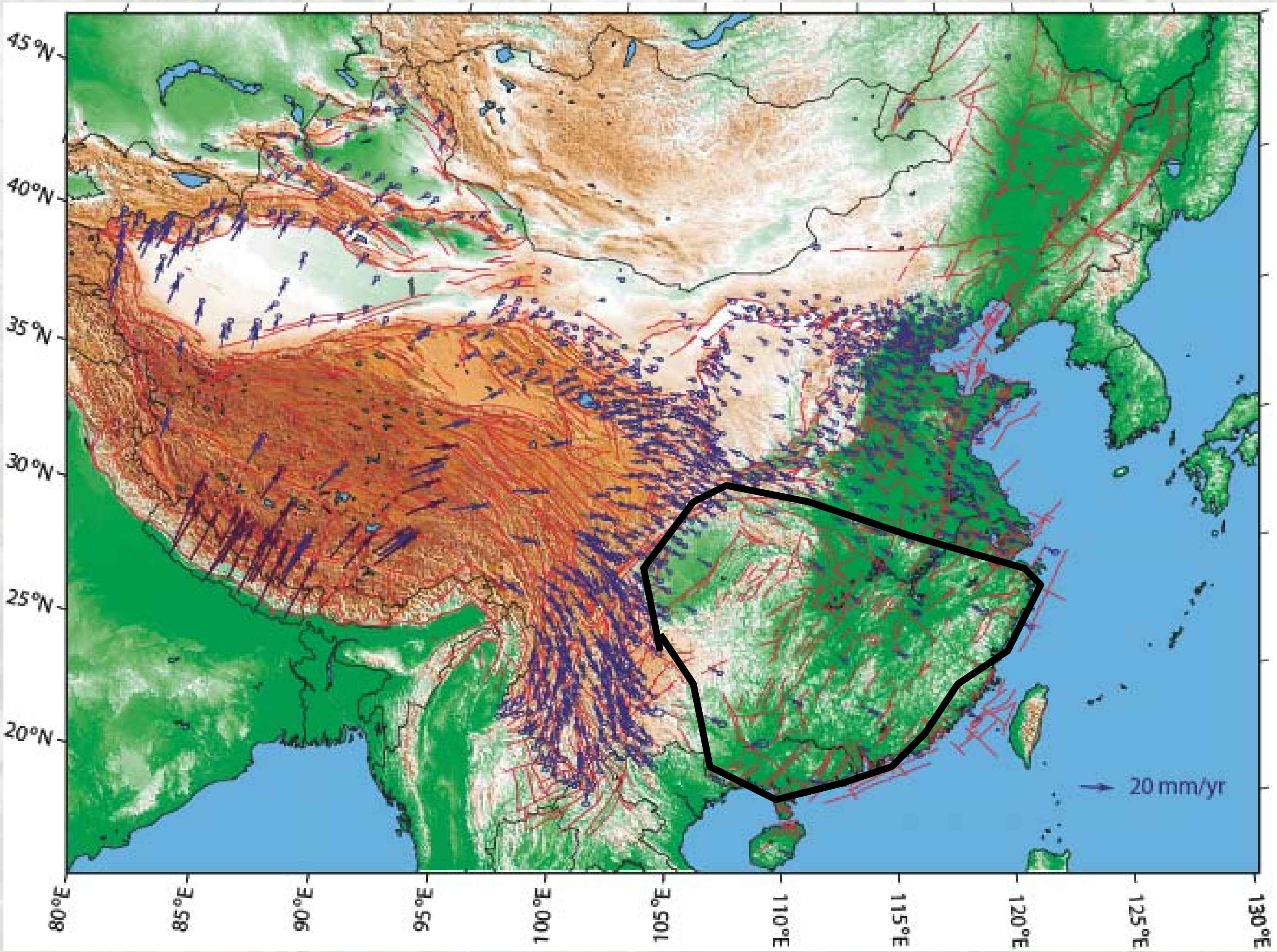

Horizontal crustal velocity field wrt stable Eurasia. Few GPS stations in stable SCB.

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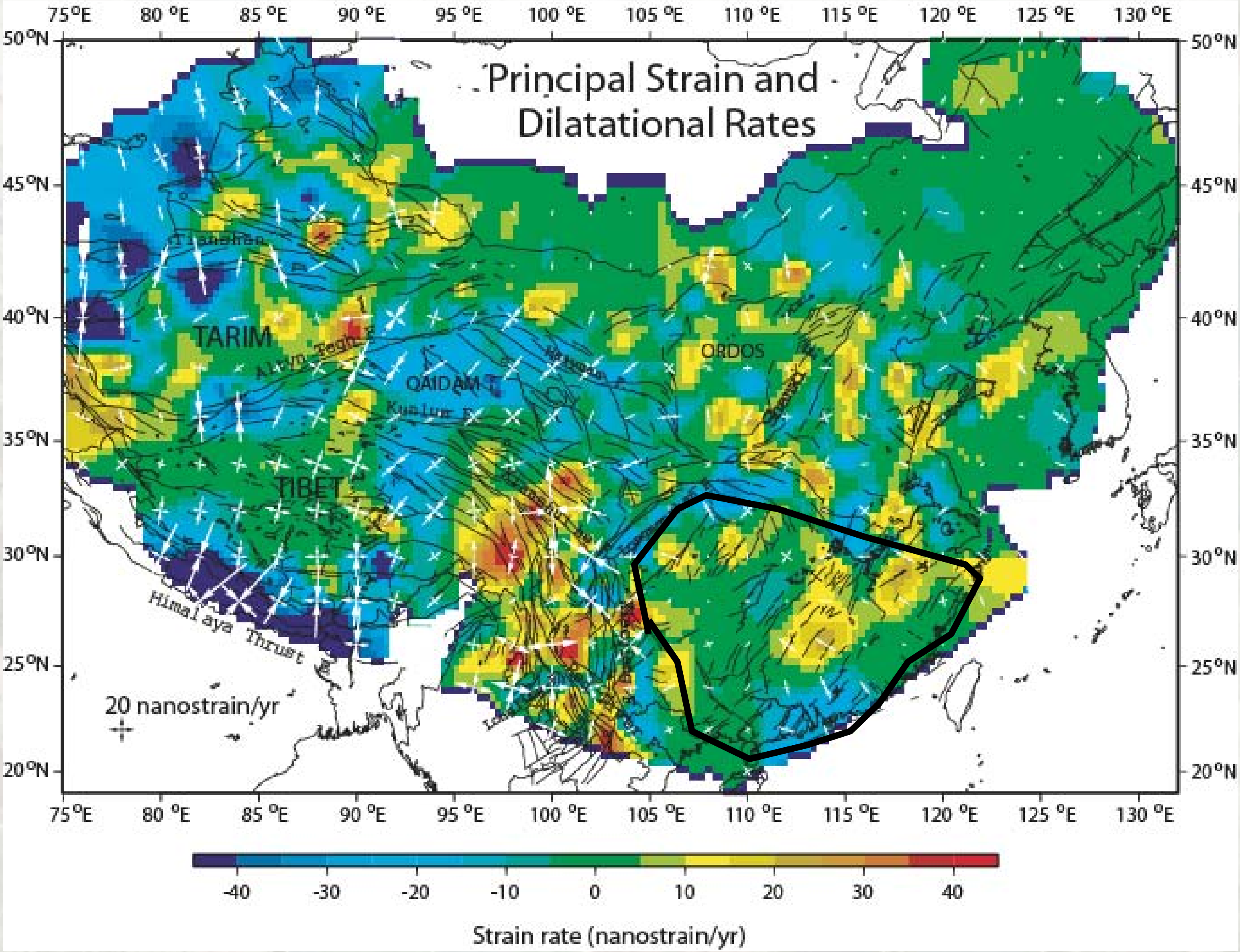
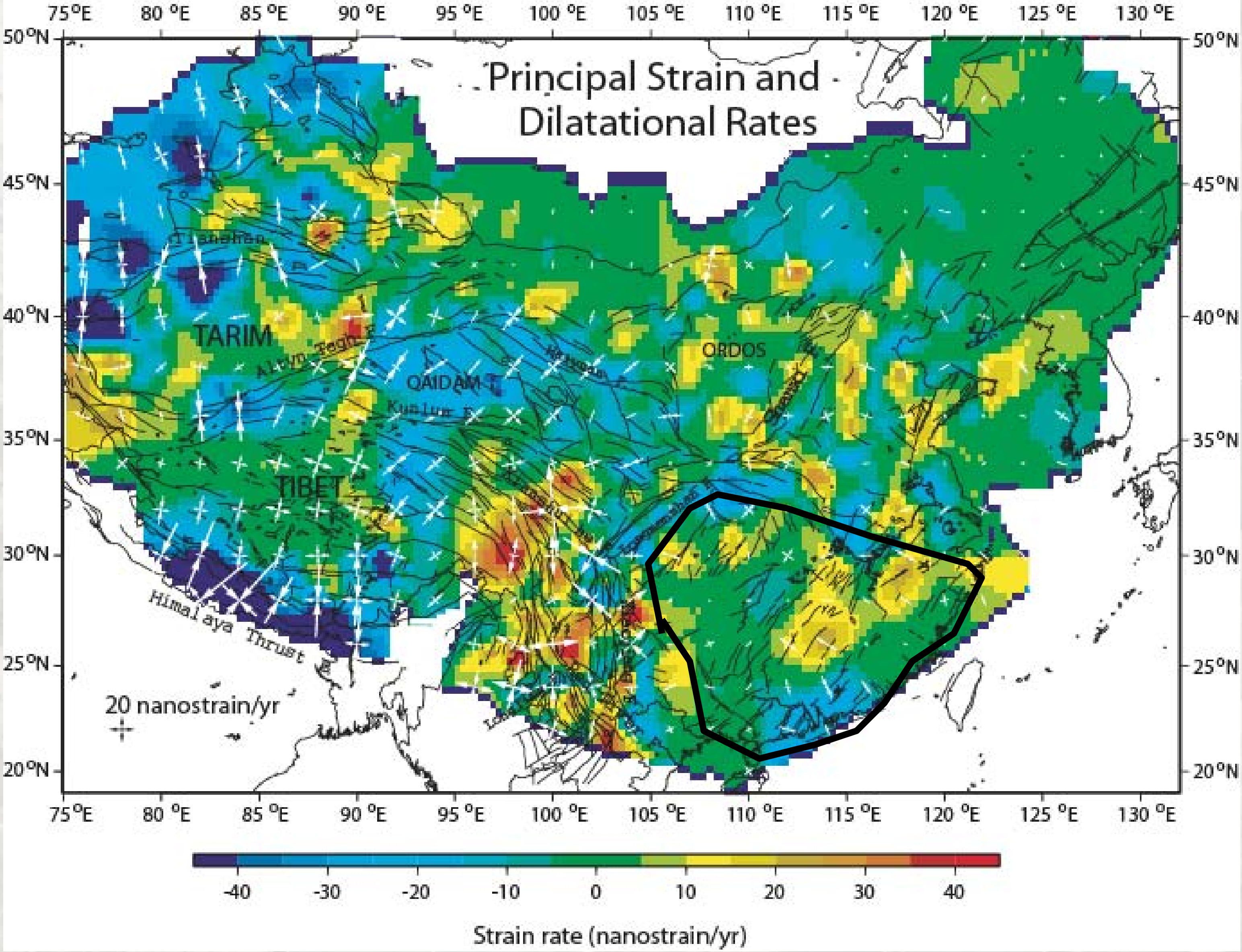
Blue vectors - Crustal Motion Observation Network of China (CMONOC) and black vectors - non-CMONOC networks, respectively.

Liu et al, 2007, Active tectonics and intercontinental earthquakes in China: the kinematics and geodynamics



Little to no strain in stable SCB.

Liu et al, 2007, Active tectonics and intercontinental earthquakes in China: the kinematics and geodynamics



But little to no sampling in SCB.

Liu et al, 2007, Active tectonics and intercontinental earthquakes in China: the kinematics and geodynamics

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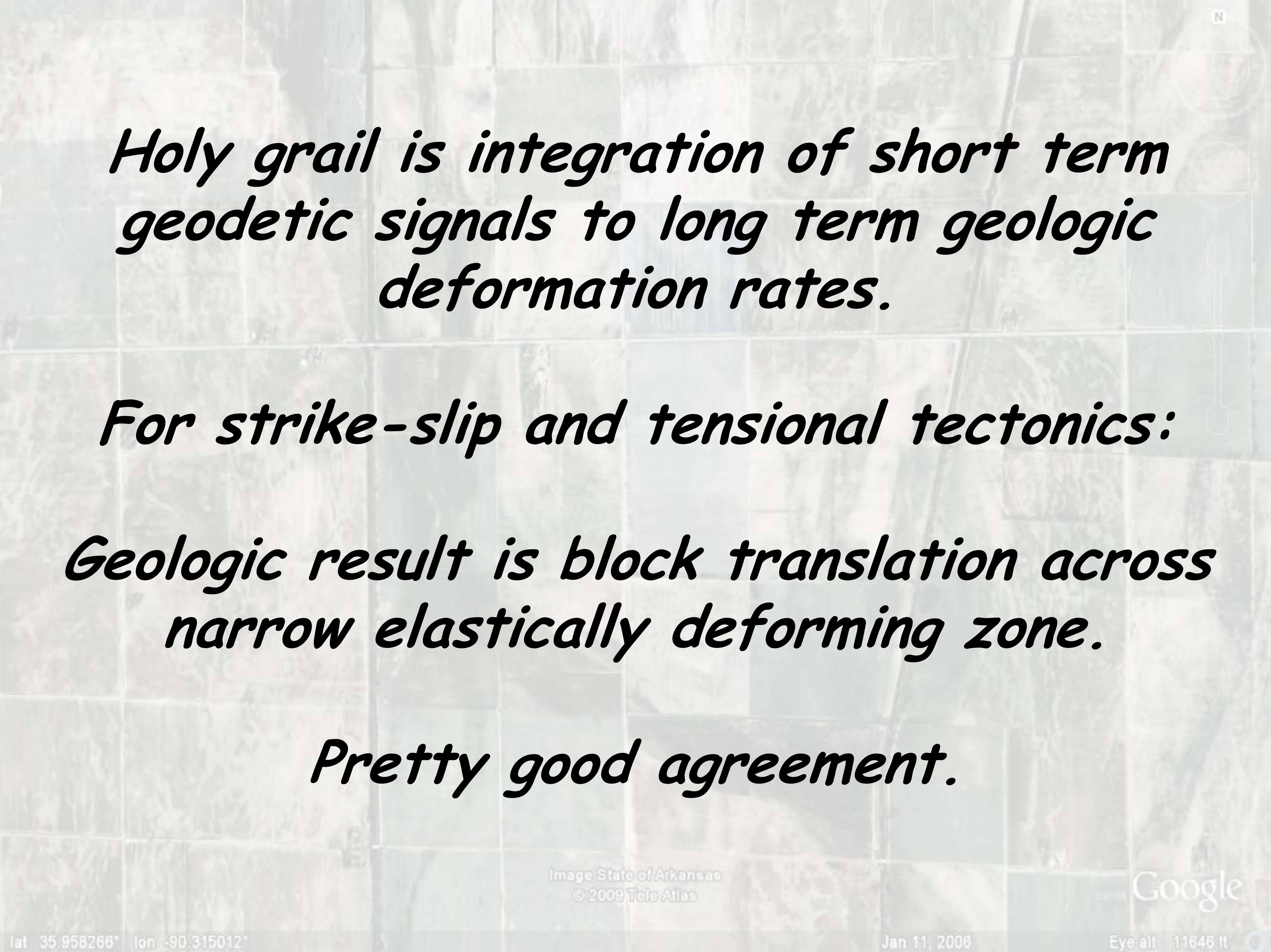
Low strain rates suggest long repeat times *(using same relationship between deformation and rock strength as for plate boundaries)*.

Geologic evidence suggests repeat time is more rapid.

Geologic evidence also suggests activity not constant over geologically significant time periods.

Geologic evidence *(additional sand blow fields S of New Madrid seismic zone, active deformation in young sediments in ME from seismic reflection)* **suggests larger regional zone of seismic sources.**

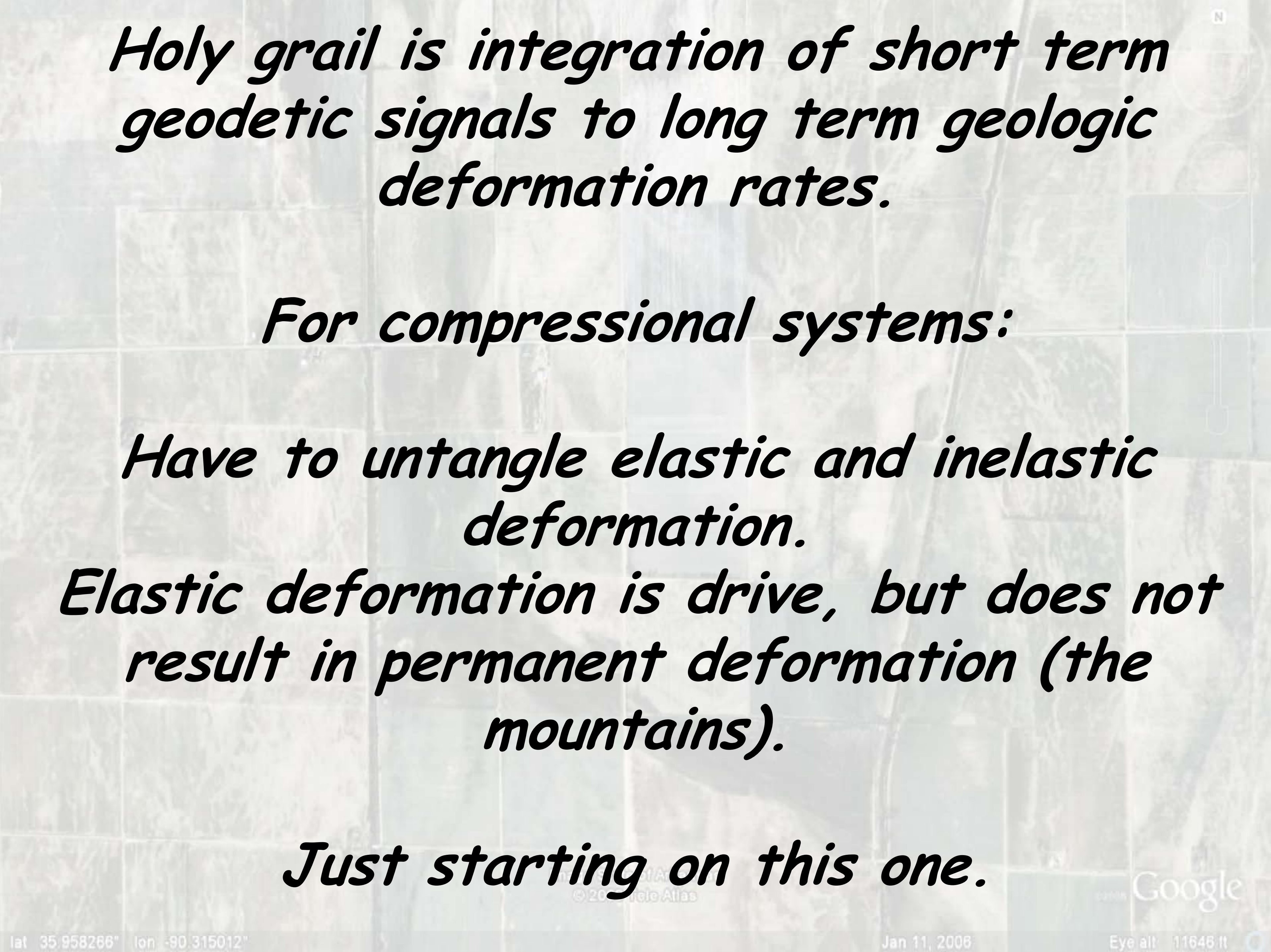


Holy grail is integration of short term geodetic signals to long term geologic deformation rates.

For strike-slip and tensional tectonics:

Geologic result is block translation across narrow elastically deforming zone.

Pretty good agreement.



Holy grail is integration of short term geodetic signals to long term geologic deformation rates.

For compressional systems:

Have to untangle elastic and inelastic deformation.
Elastic deformation is drive, but does not result in permanent deformation (the mountains).

Just starting on this one.

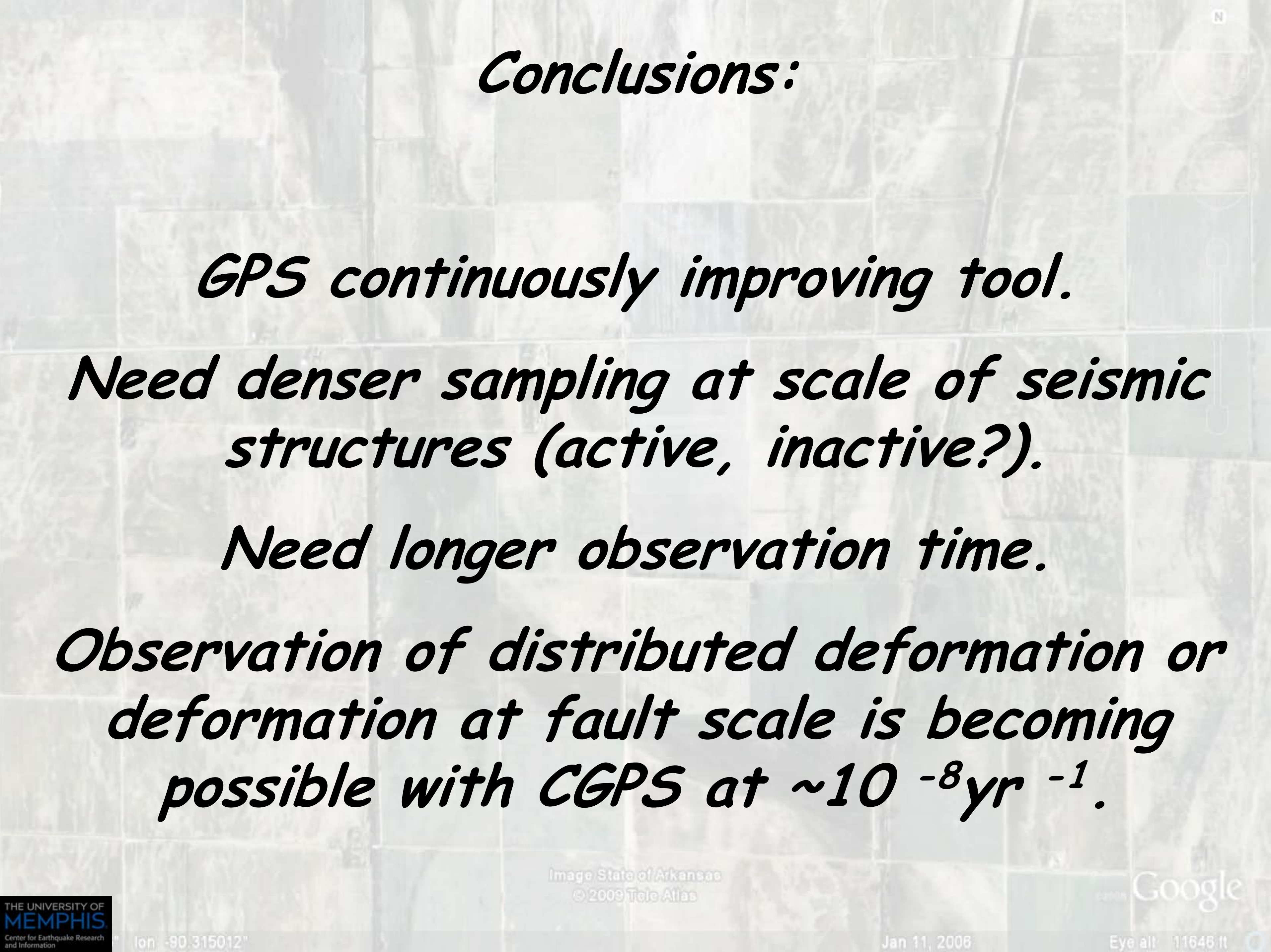
Conclusions:

GPS continuously improving tool.

Need denser sampling at scale of seismic structures (active, inactive?).

Need longer observation time.

Observation of distributed deformation or deformation at fault scale is becoming possible with CGPS at $\sim 10^{-8} yr^{-1}$.



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Intraplate Stress and Strain in The Central and Eastern United States and Their Relation to Intraplate Seismicity

Mark D. Zoback
Department of Geophysics
Stanford University

CEUS Seismic Source Characterization Project
EPRI – February 19, 2009

Key Questions*

- Do available stress and strain data provide sufficient resolution to aid in defining seismic source zones?

- Given far-field (i.e., ridge-push) sources of stress in the CEUS, are there local sources of stress that modify the regional stress field? If so, are these important for purposes of identifying seismic sources?

- What are mechanisms to localize stress? Is stress localization an important consideration for identifying seismic sources?

- Are observed rates of historical and prehistorical seismicity (in those places where we have evidence) consistent with observed strain rates?

*As posed by Kevin Coppersmith

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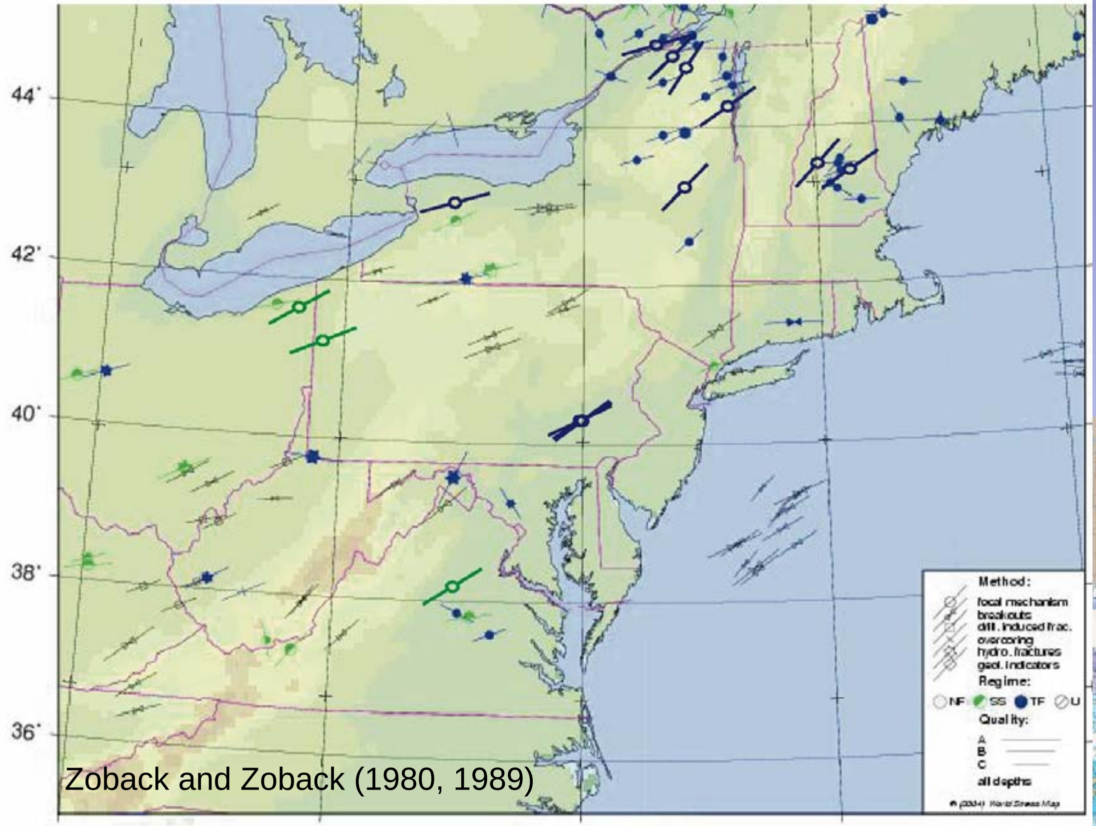
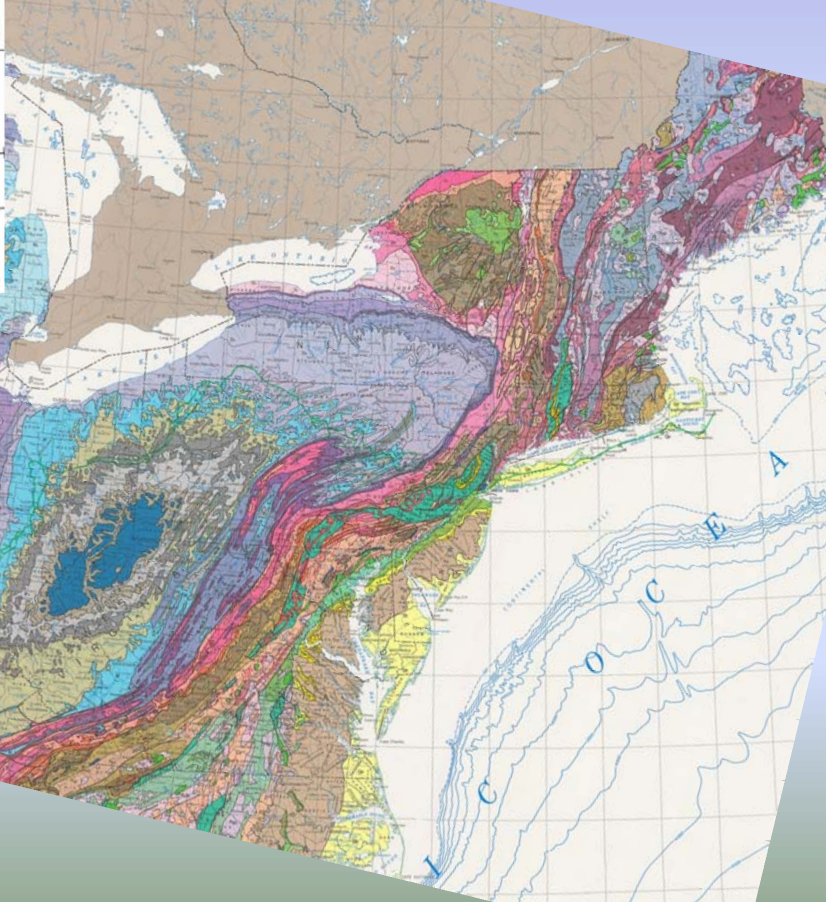
*As posed by Kevin Coppersmith

Relatively Uniform Stress Orientations Across Complex Geologic Boundaries

Intraplate Earthquakes Result from Contemporary Stress Field Acting on Pre-Existing Faults

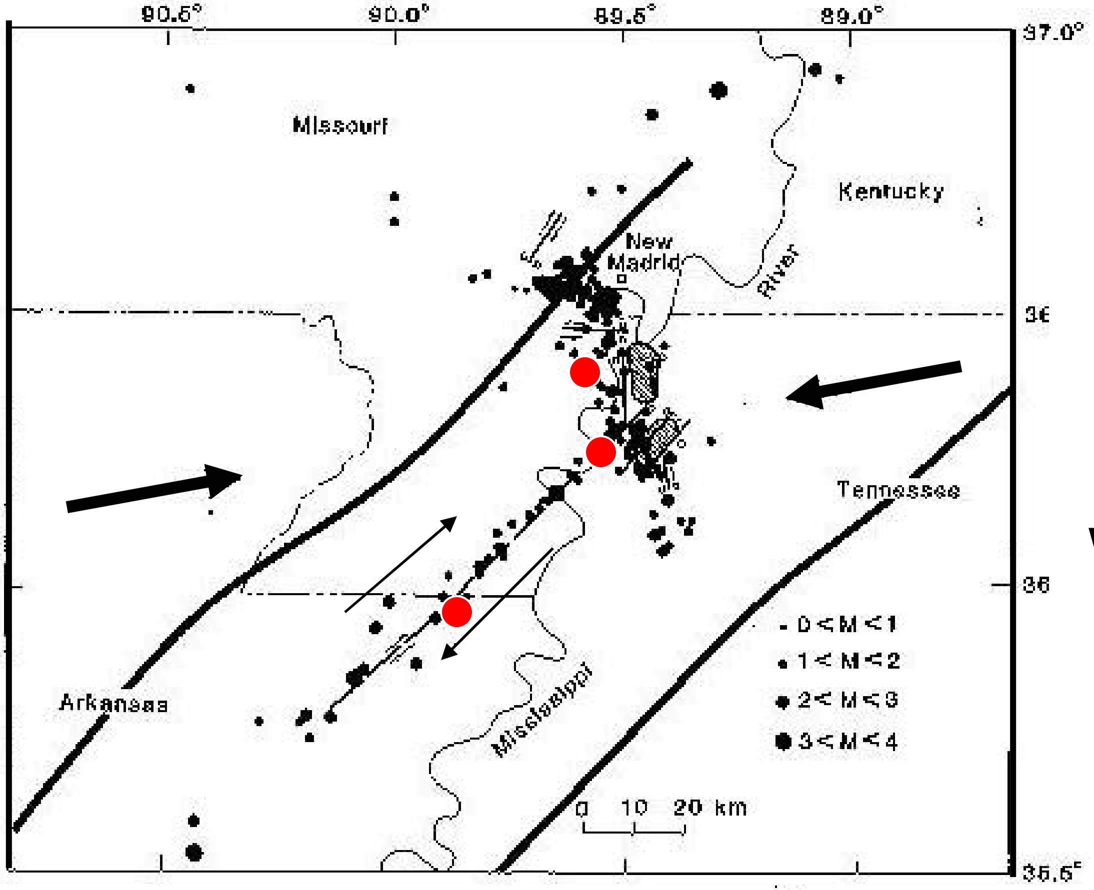


Zoback and Zoback (1980, 1989)



Reprint Series
3 July 1981, Volume 213, pp. 96–104

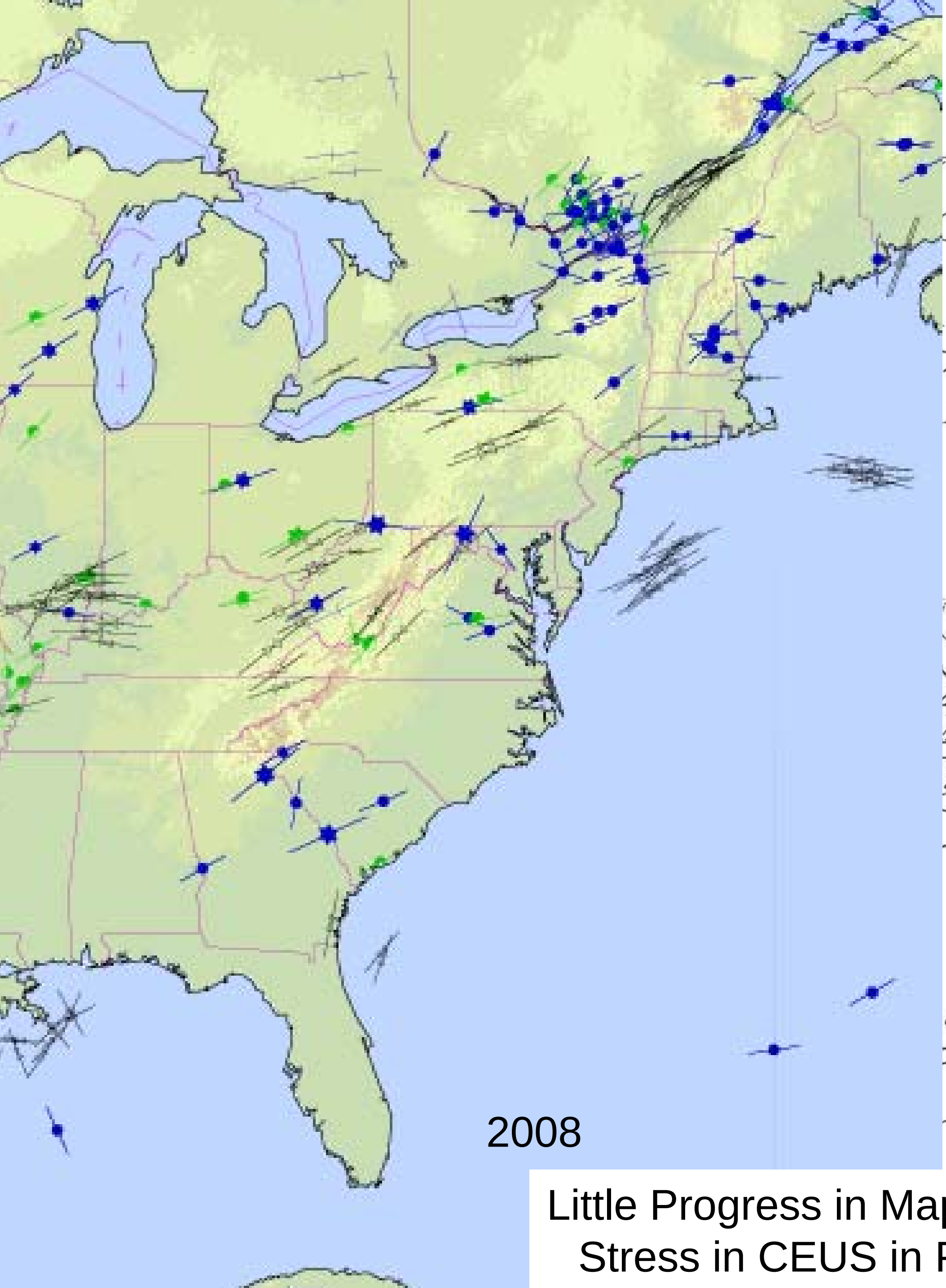
SCIENCE



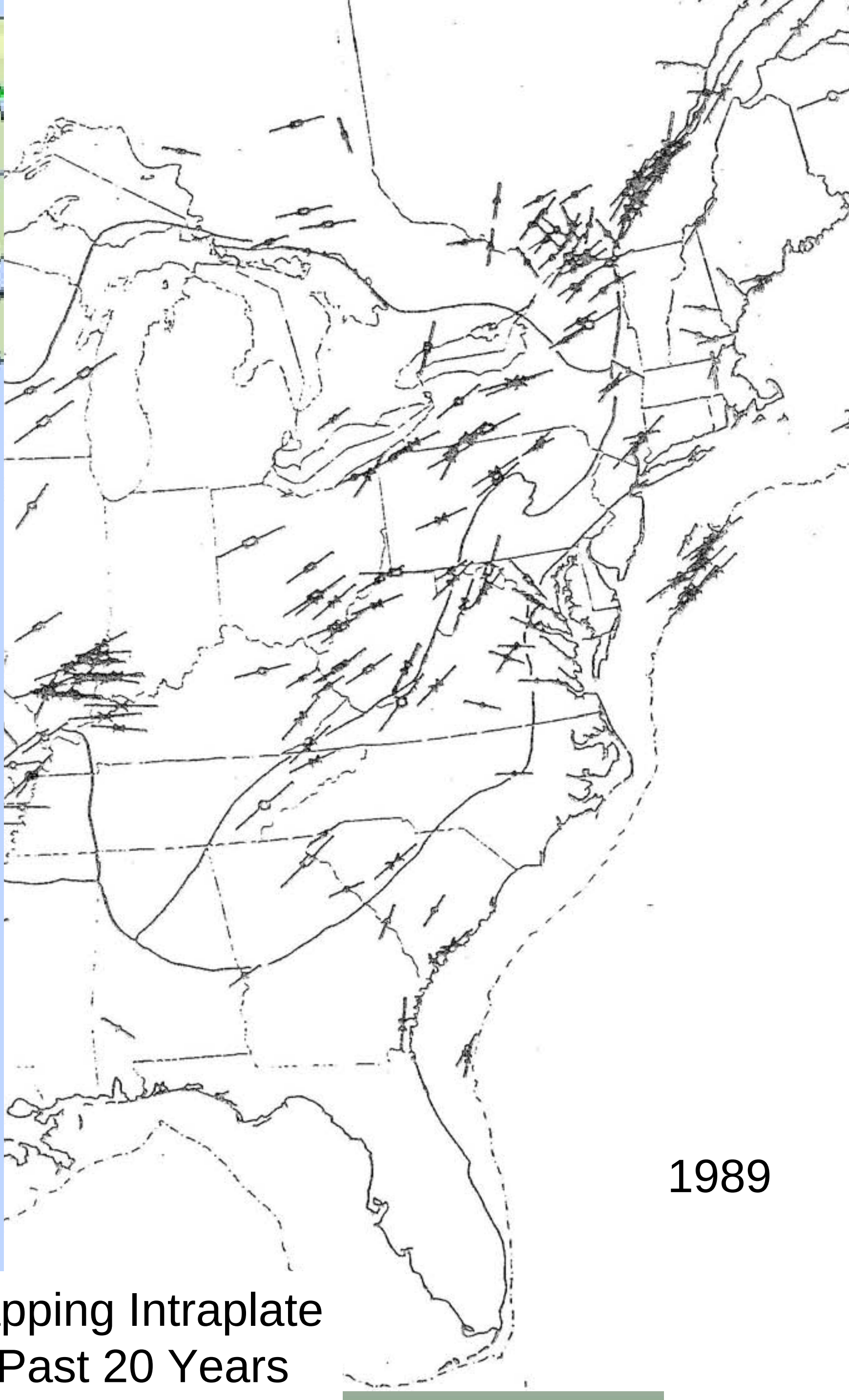
State of Stress and Intraplate Earthquakes in the United States

Mark D. Zoback and Mary Lou Zoback

Fault Slip in New Madrid Consistent with Regional ENE-WSW Compression

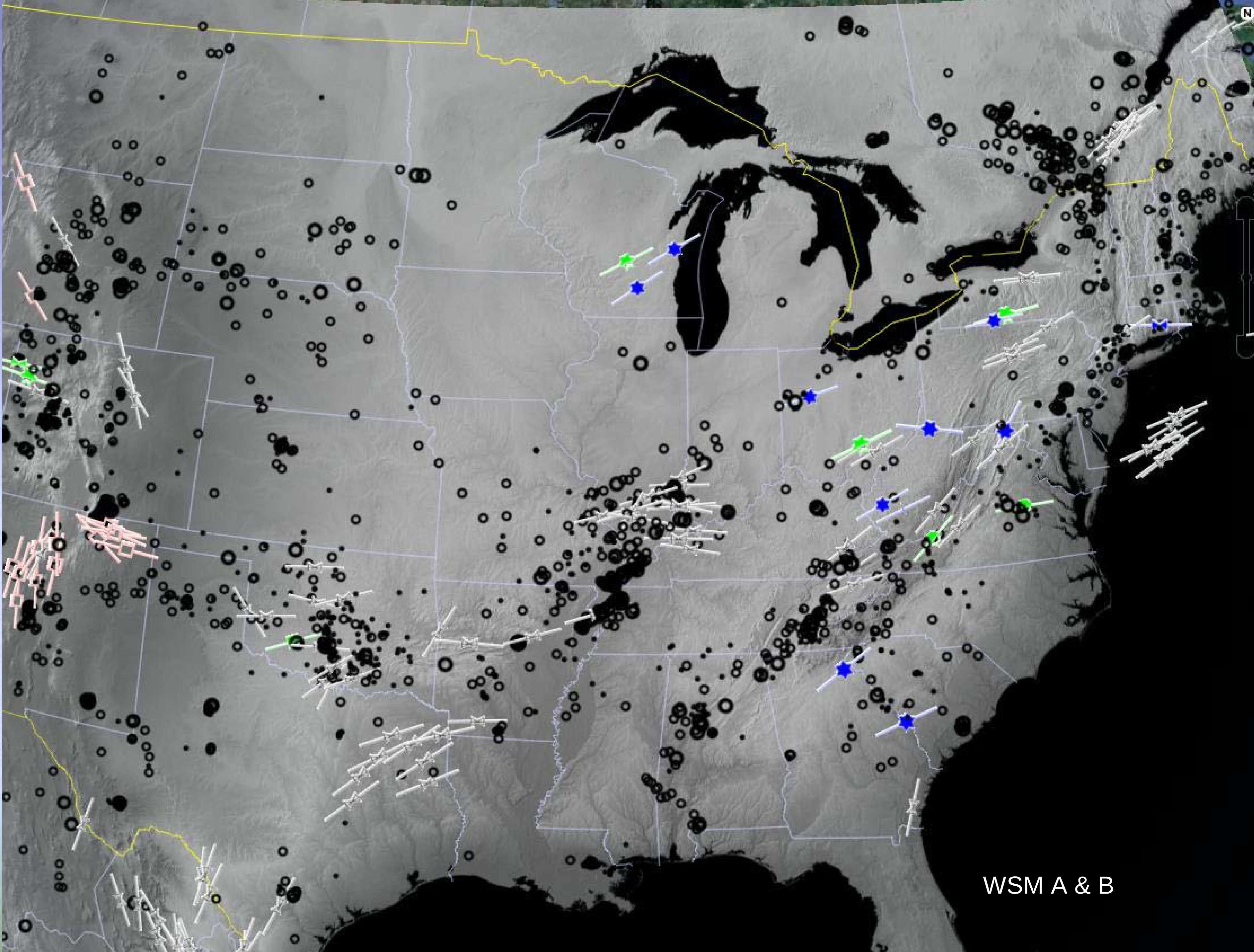


2008

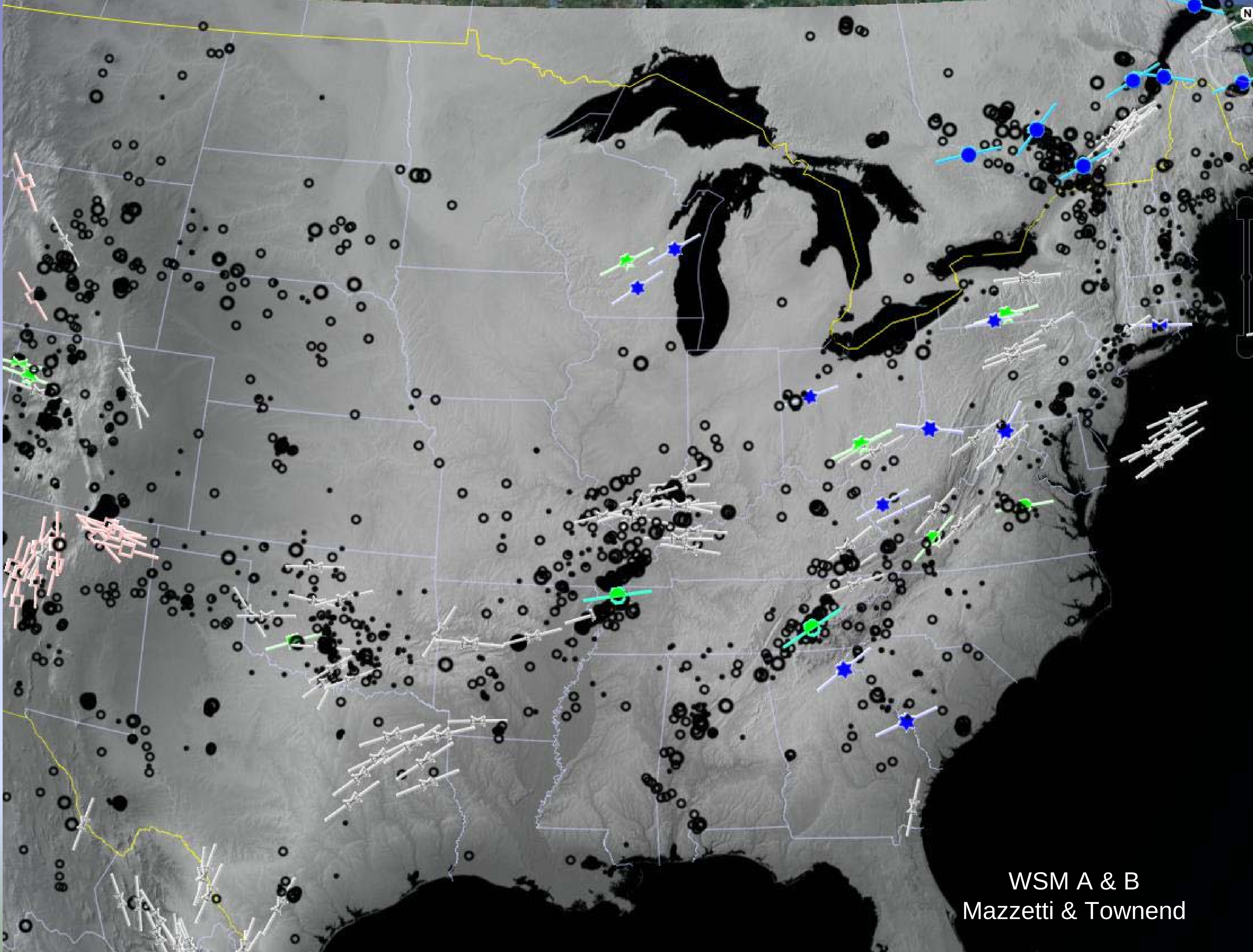


1989

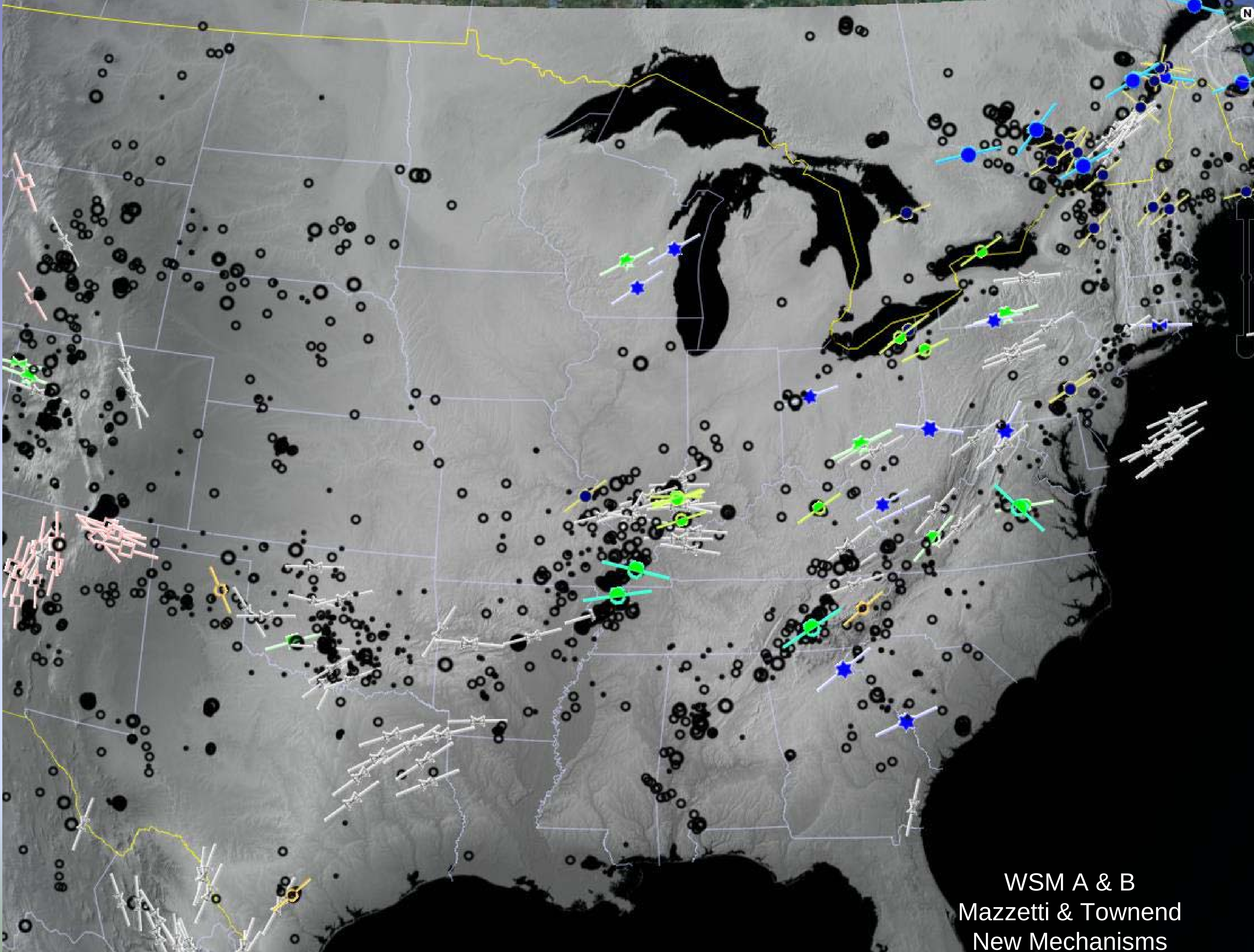
Little Progress in Mapping Intraplate Stress in CEUS in Past 20 Years



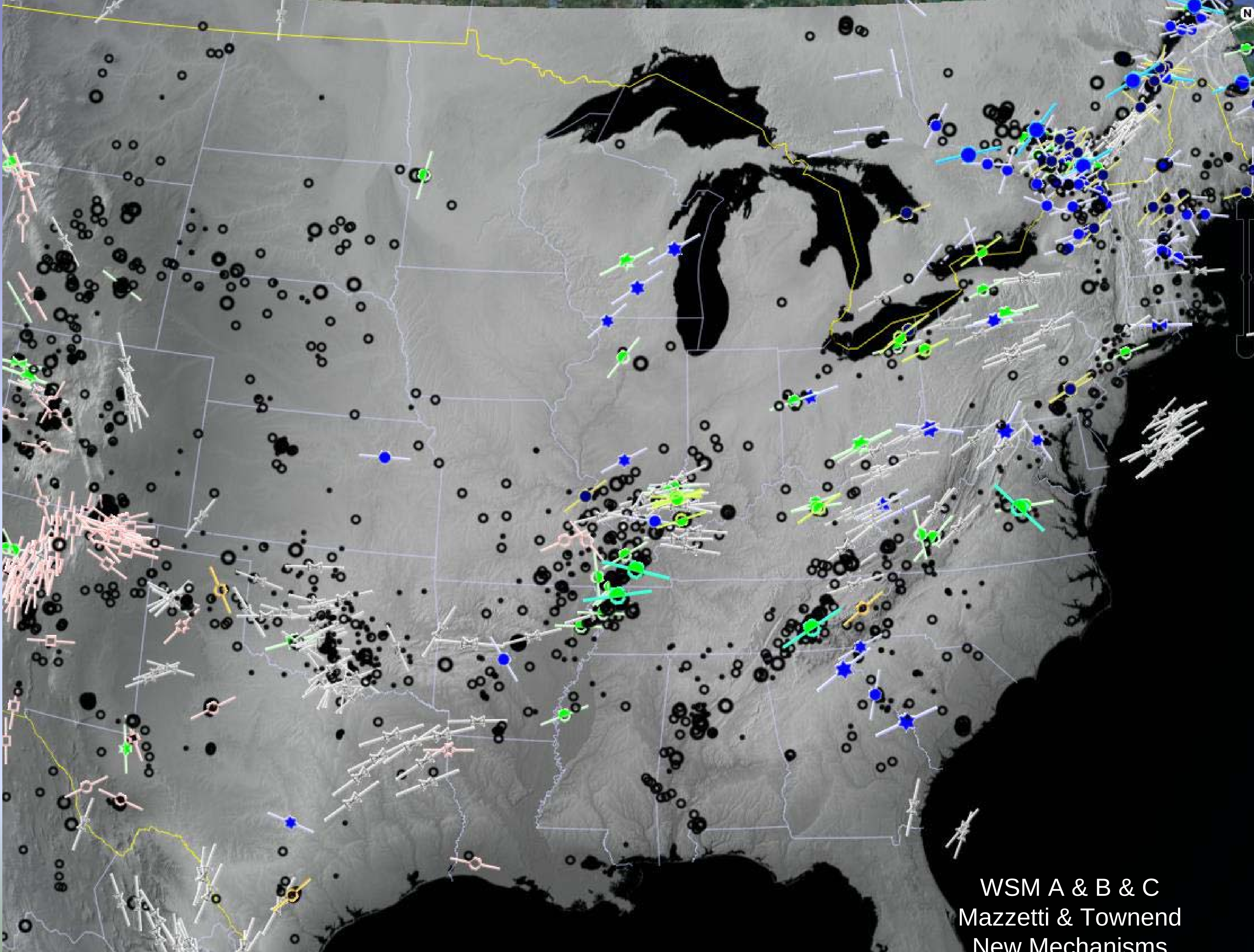
WSM A & B



WSM A & B
Mazzetti & Townend



WSM A & B
Mazzetti & Townend
New Mechanisms



WSM A & B & C
Mazzetti & Townend
New Mechanisms

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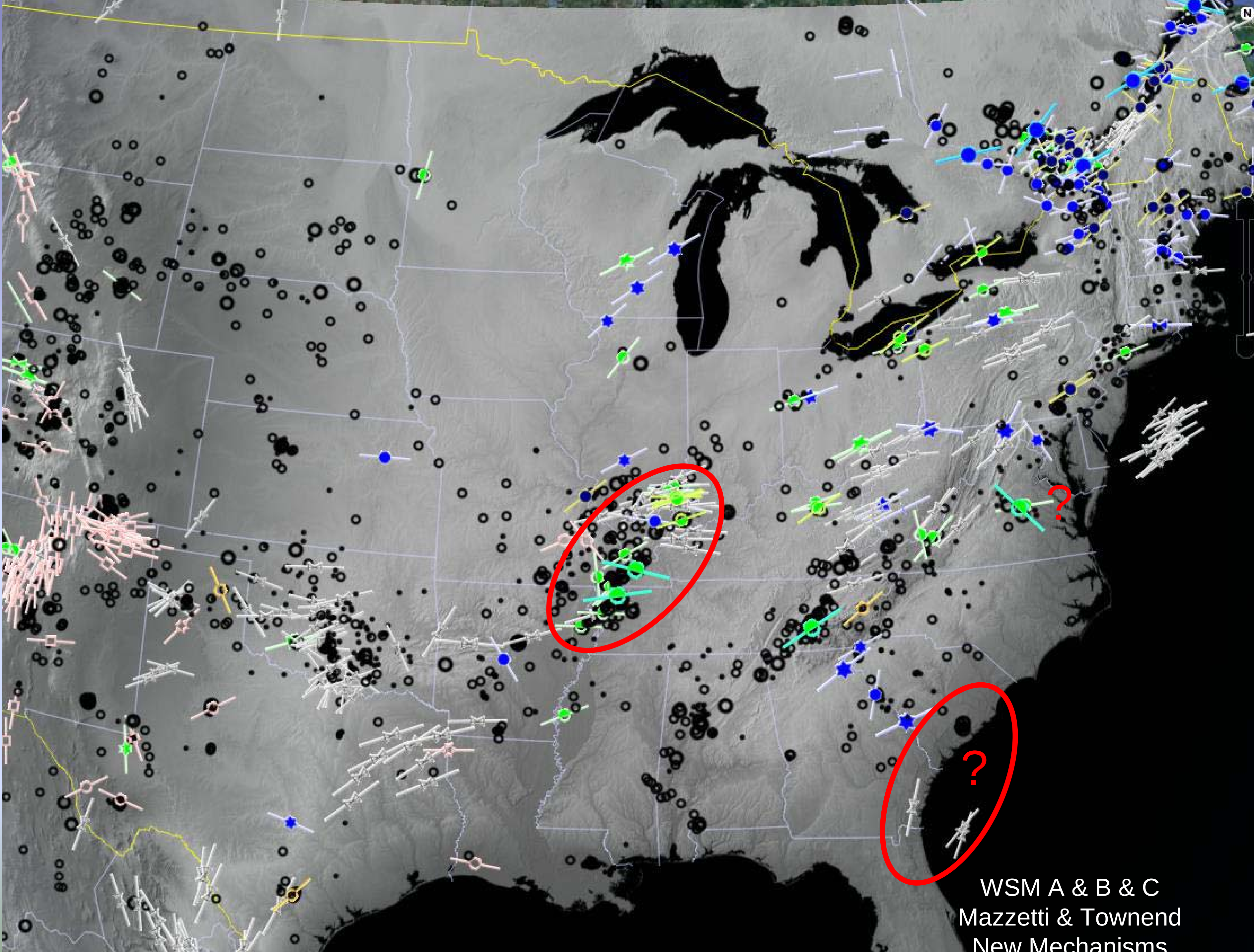
*As posed by Kevin Coppersmith



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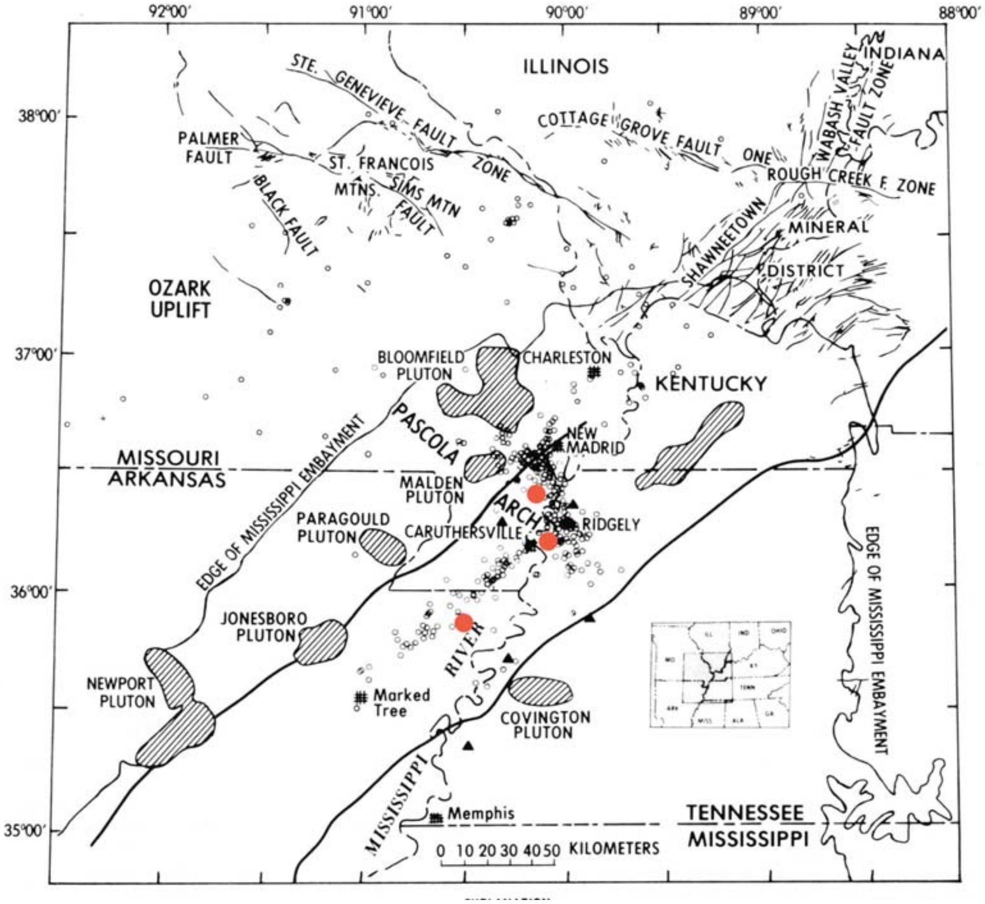
Reprint Series
29 August 1980, Volume 209, pp. 971–976

SCIENCE

1811/1812
Events and
Modern
Seismicity Occur
Within a
Failed Rift of Late
PreCambrian/
Early Paleozoic
Age

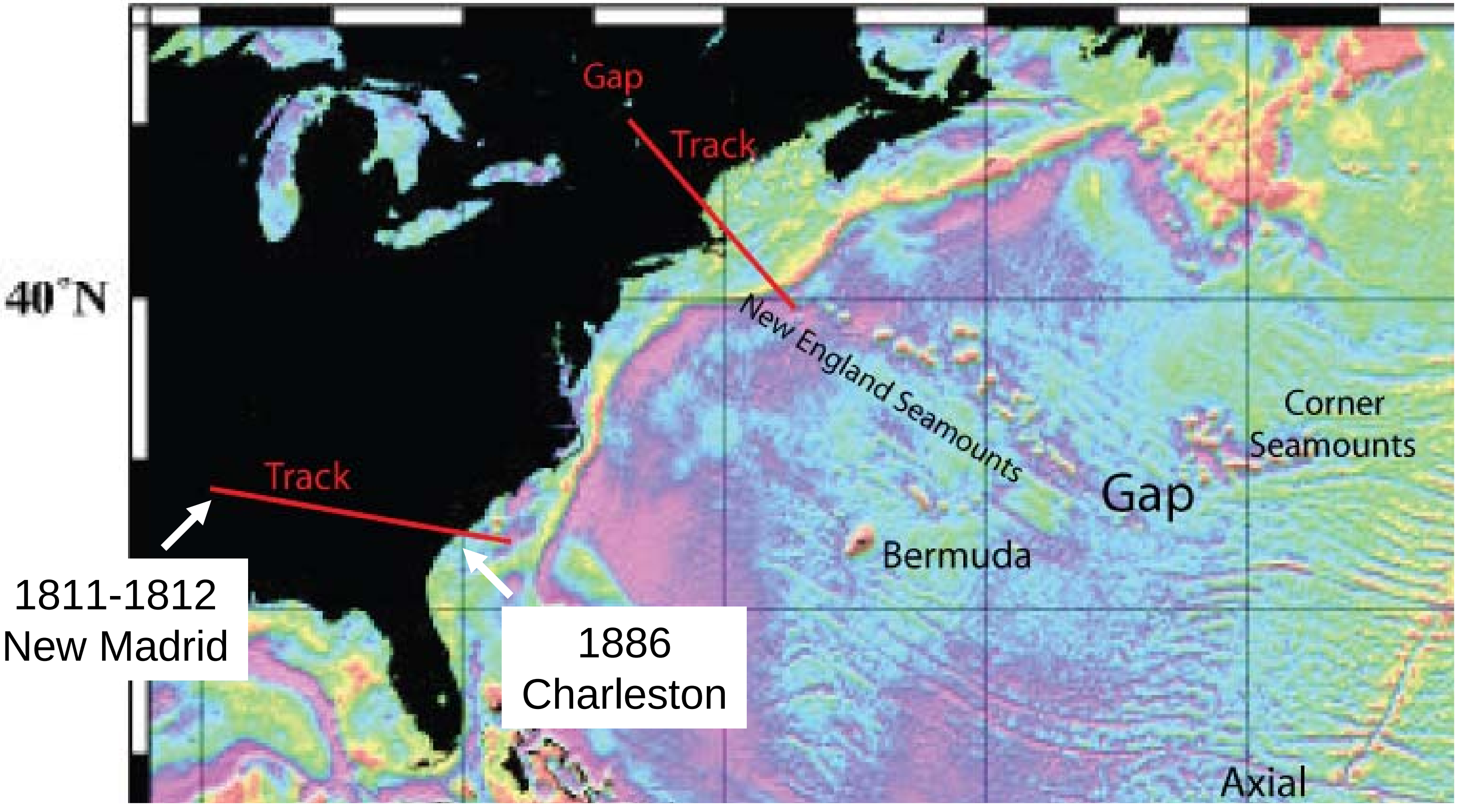


Following Rifting
Late Cretaceous
Volcanism and
Faulting

Recurrent Intraplate Tectonism in the New Madrid Seismic Zone

M. D. Zoback, R. M. Hamilton, A. J. Crone,
D. P. Russ, F. A. McKeown, and S. R. Brockman

Bermuda Hot Spot Track
(in New Madrid Area in Late Cretaceous Time)

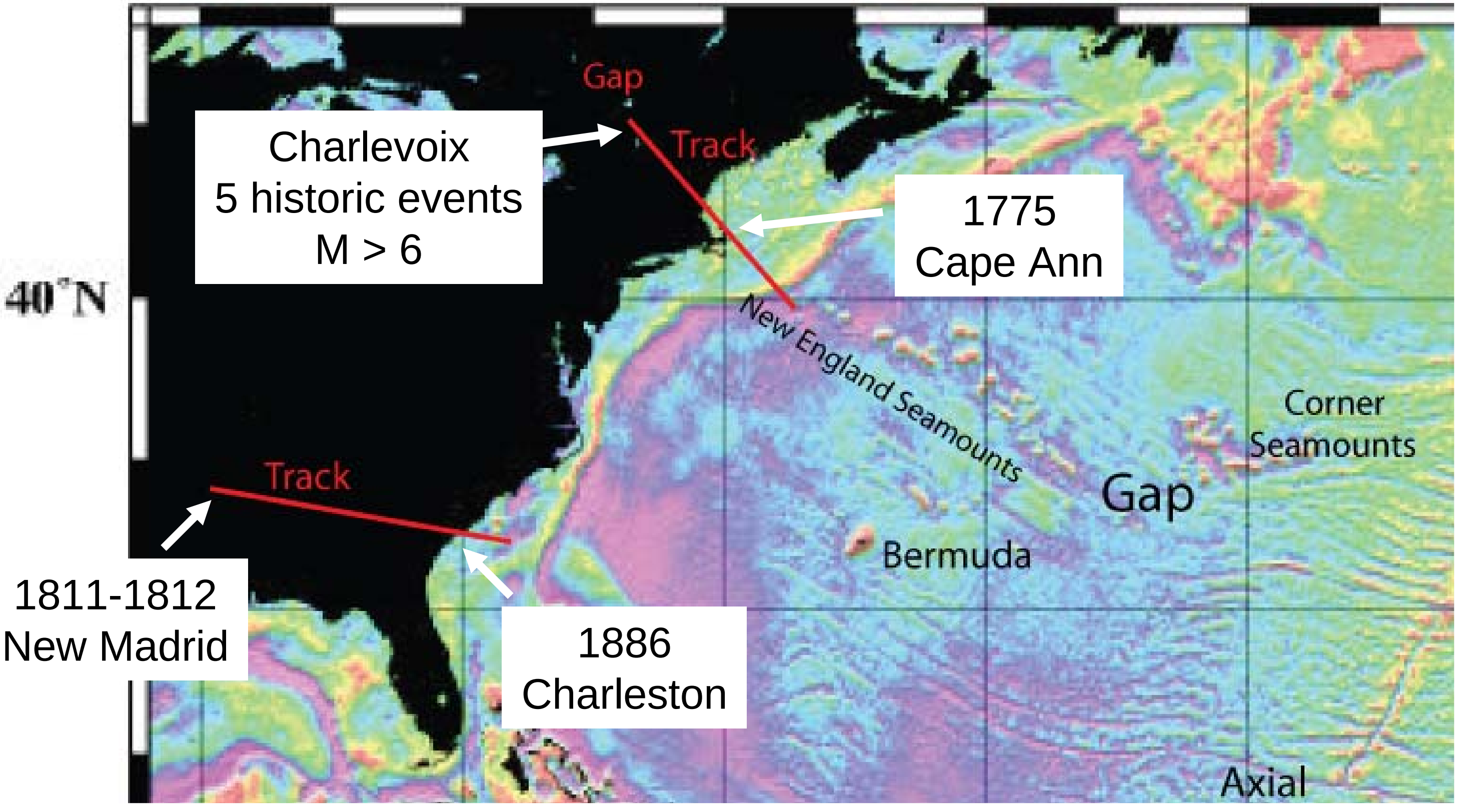


1811-1812
New Madrid

1886
Charleston

Sleep (2002)

Bermuda Hot Spot Track
(in New Madrid Area in Late Cretaceous Time)



Charlevoix
5 historic events
M > 6

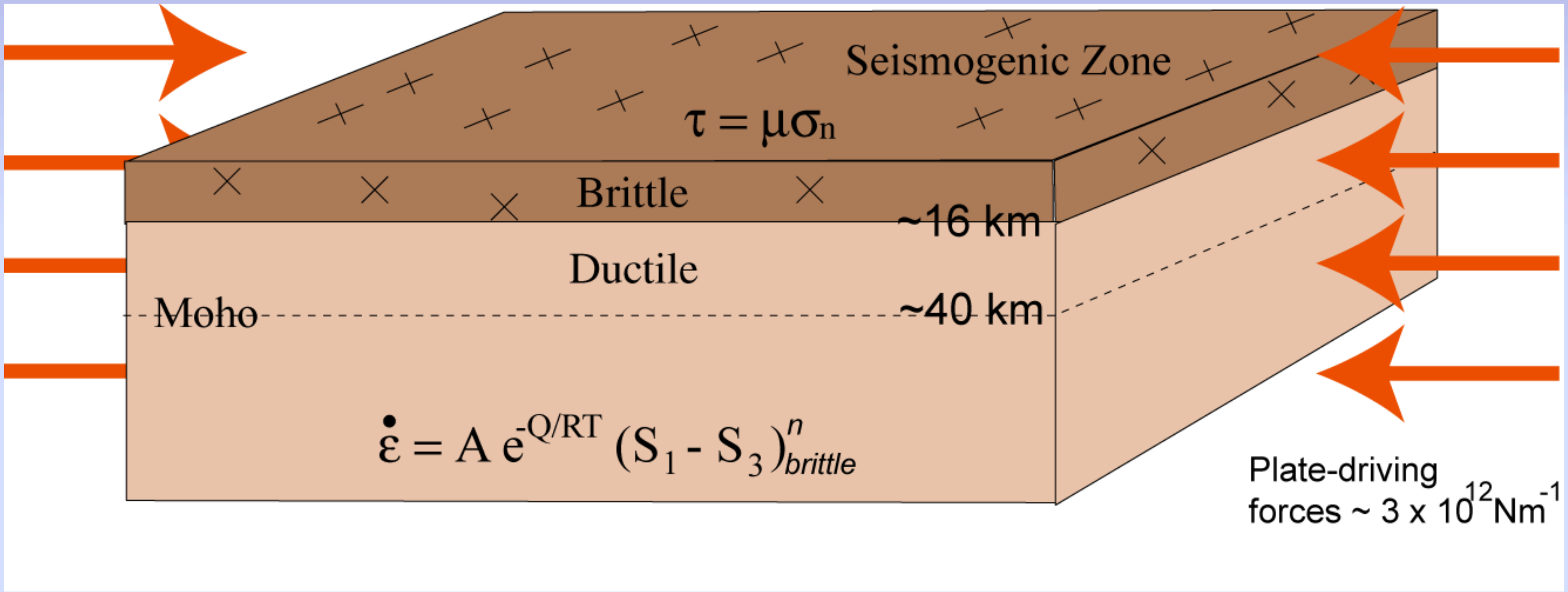
1775
Cape Ann

1811-1812
New Madrid

1886
Charleston

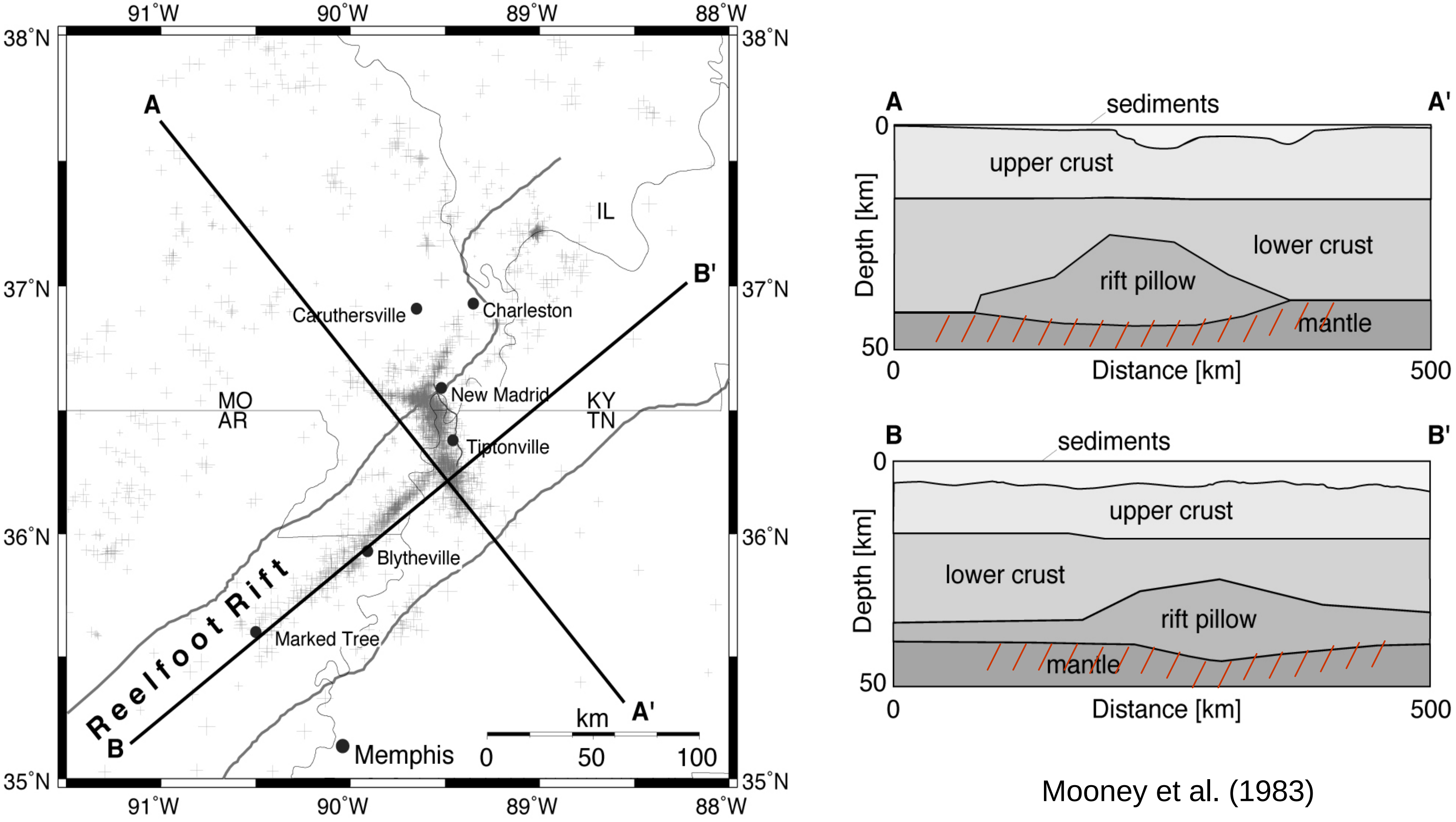
Geologic History and Inheritance of Potential Seismogenic Structures is Important

Brittle Failure in Critically-Stressed Crust Results From Creep in Lower Crust and Upper Mantle

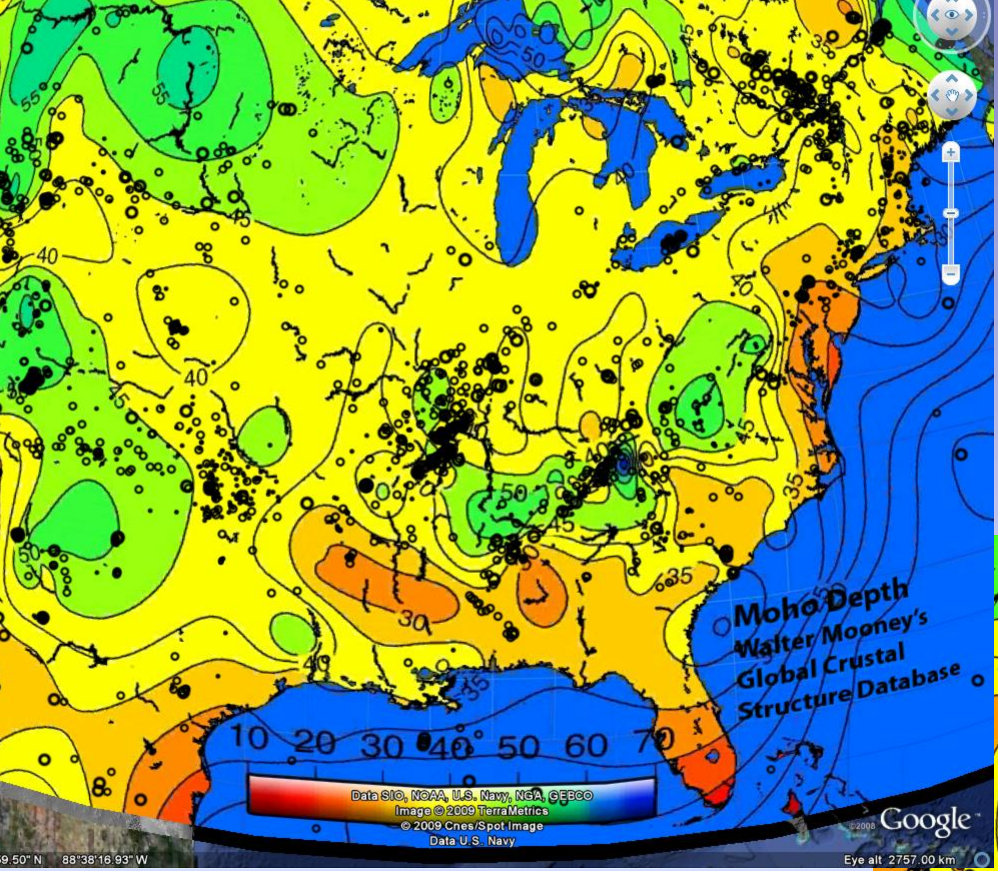


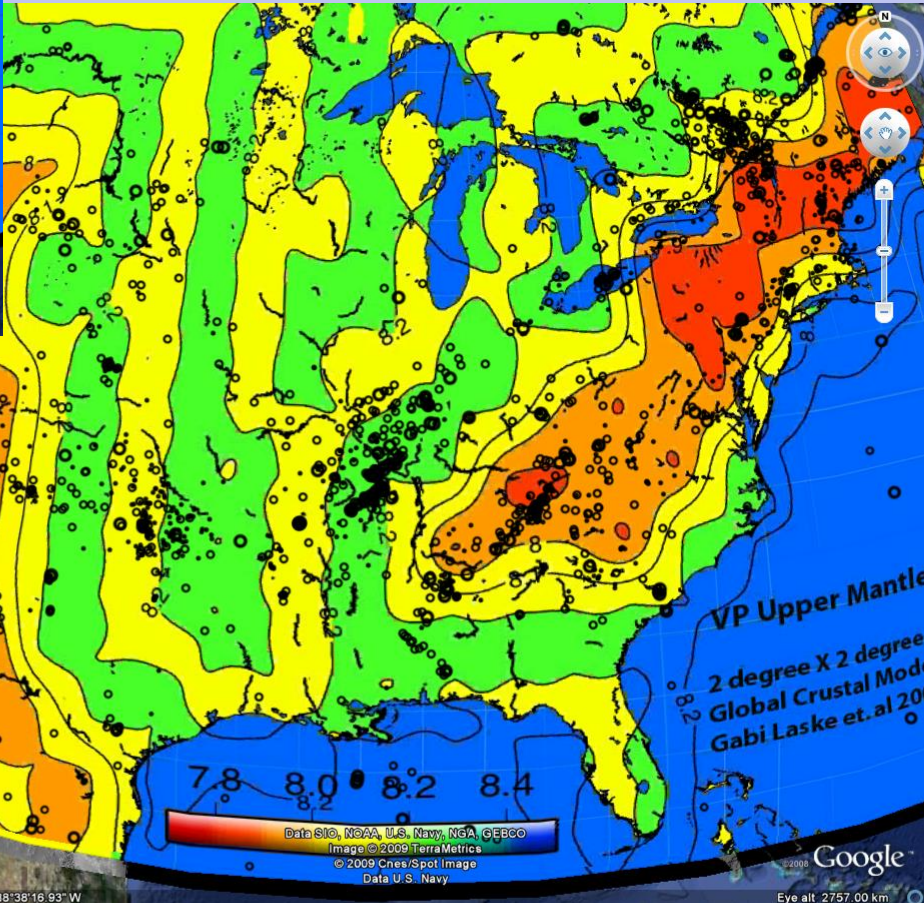
Zoback, Townend and Grollimund (2002)

Anomalous Crust/Upper Mantle Structure in the New Madrid Seismic Zone



Mooney et al. (1983)


Moho Depth
Walter Mooney's
Global Crustal
Structure Database
10 20 30 40 50 60 70
55
50
45
40
35
30
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2009 TerraMetrics
© 2009 Cnes/Spot Image
Data U.S. Navy
Google
9.50" N 88°38'16.93" W
Eye alt 2757.00 km


VP Upper Mantle
2 degree X 2 degree
Global Crustal Mod
Gabi Laske et. al 20
7.8 8.0 8.2 8.4
8.2
8
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2009 TerraMetrics
© 2009 Cnes/Spot Image
Data U.S. Navy
Google
37°08'59.50" N 88°38'16.93" W
Eye alt 2757.00 km

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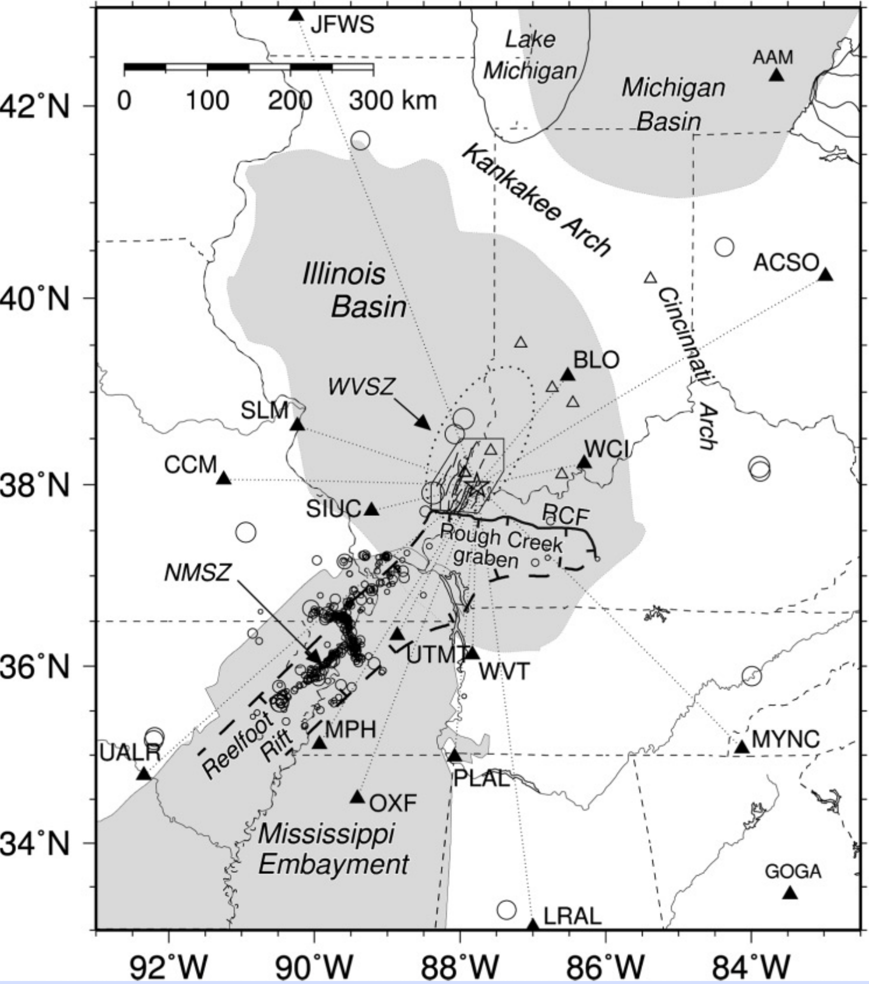
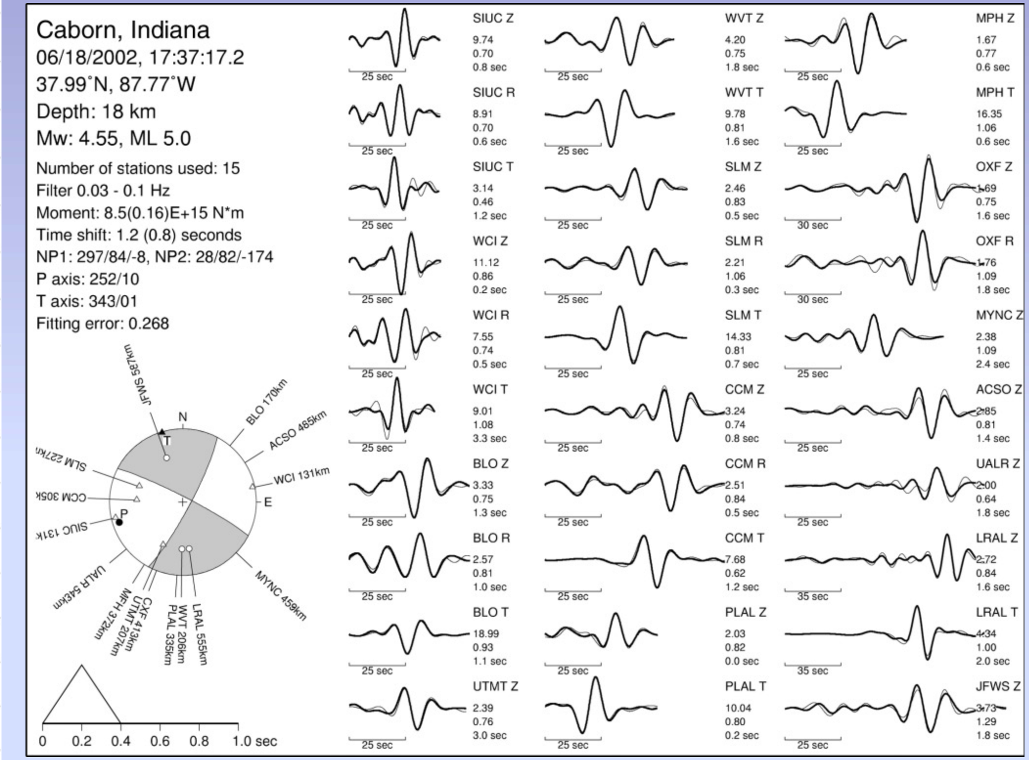
*As posed by Kevin Coppersmith

Caborn, IN Mw 4.6 – June 18. 2002



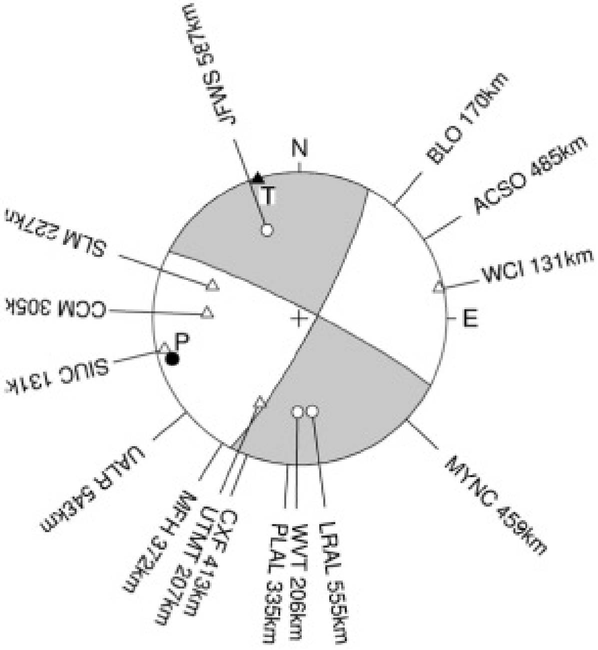


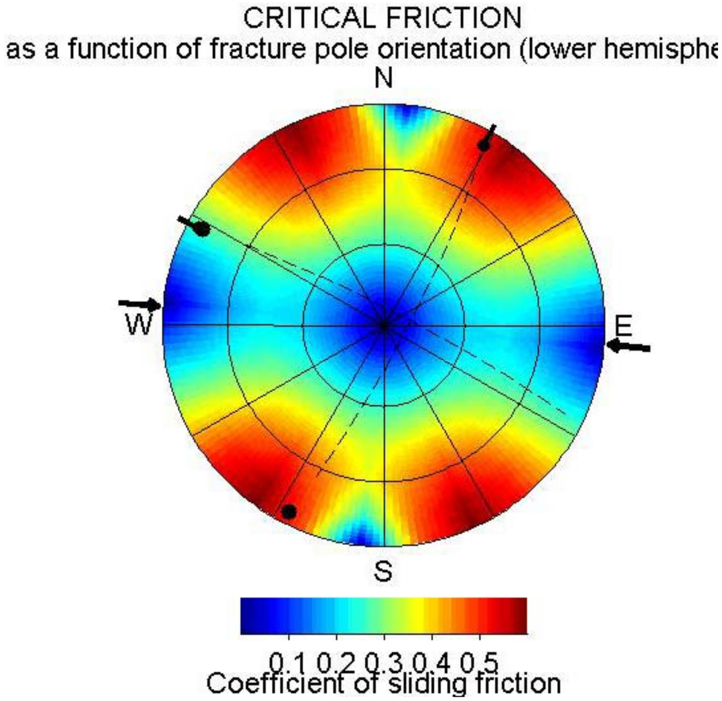
Bulletin of the Seismological Society of America, Vol. 93, No. 5, pp. 2201–2211, October 2003

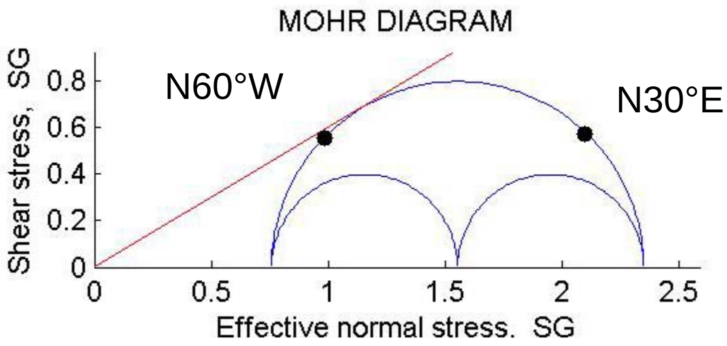
The 18 June 2002 Caborn, Indiana, Earthquake: Reactivation of Ancient Rift in the Wabash Valley Seismic Zone?

by Won-Young Kim

Slip on WNW Plane Consistent with ~E-W Stress and Conventional Fault Mechanics



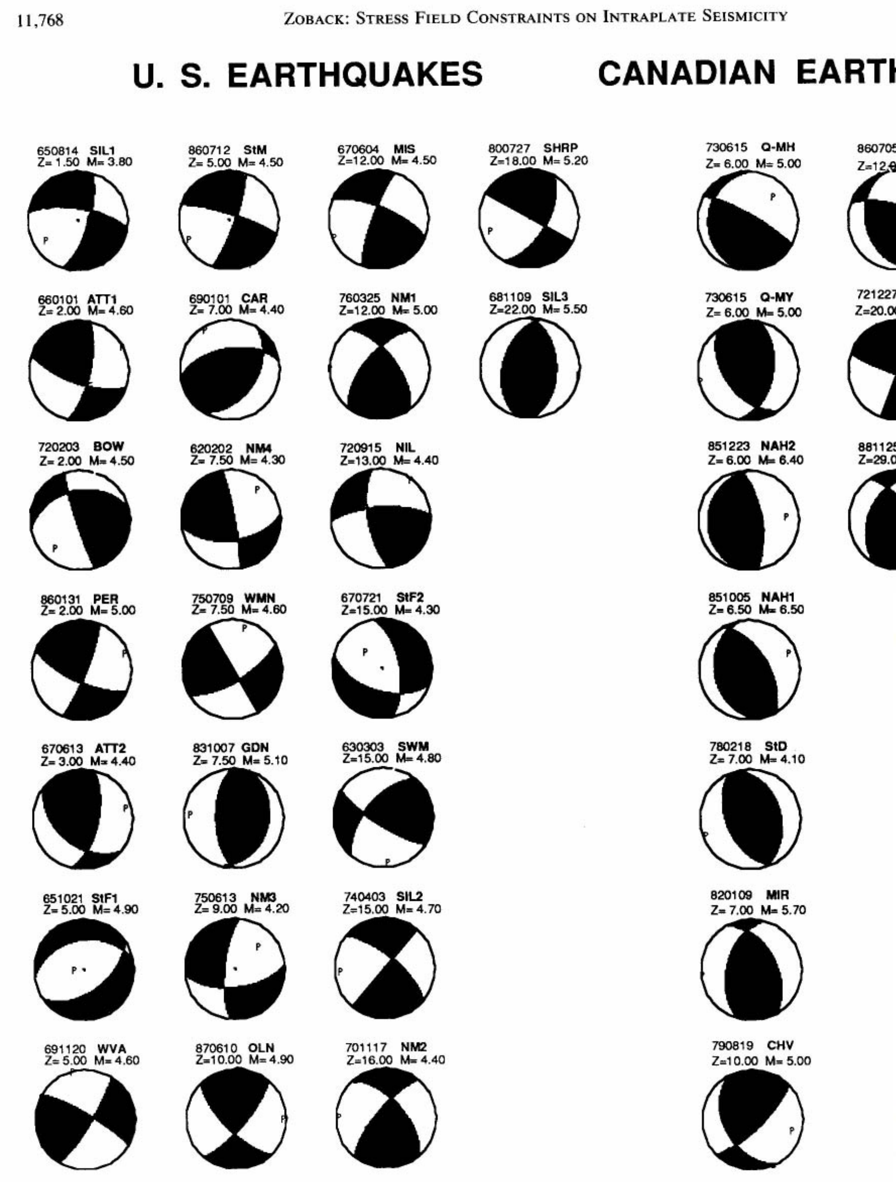


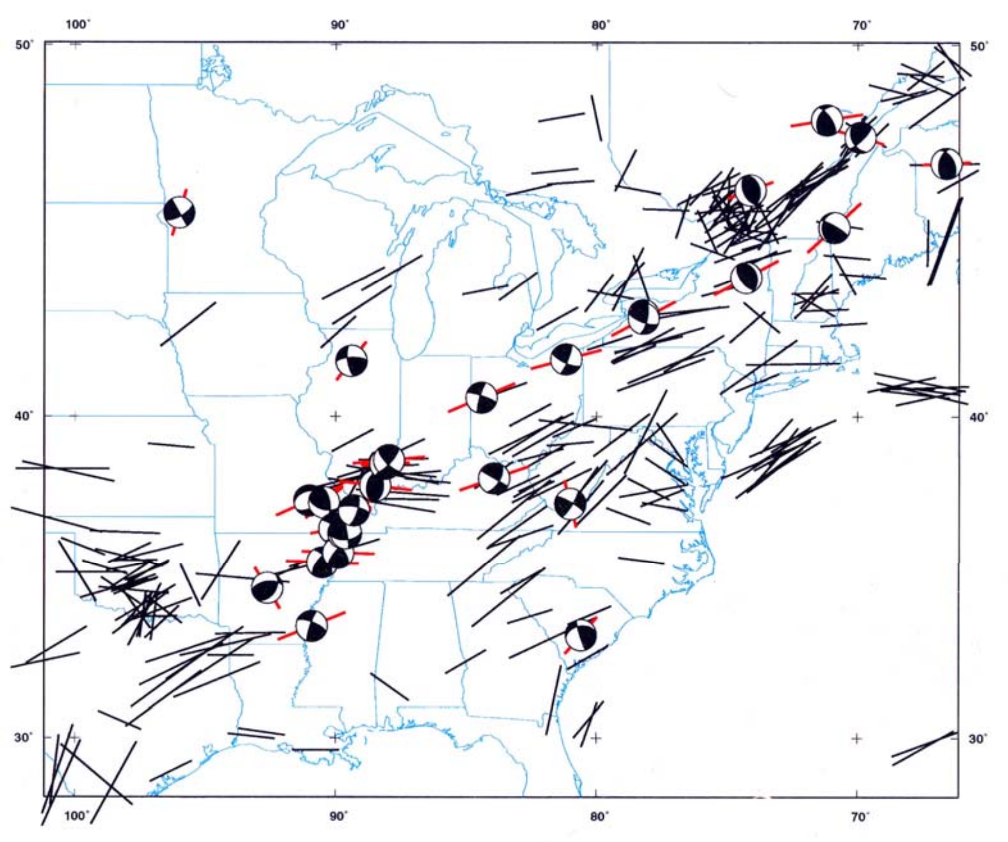


N60°W

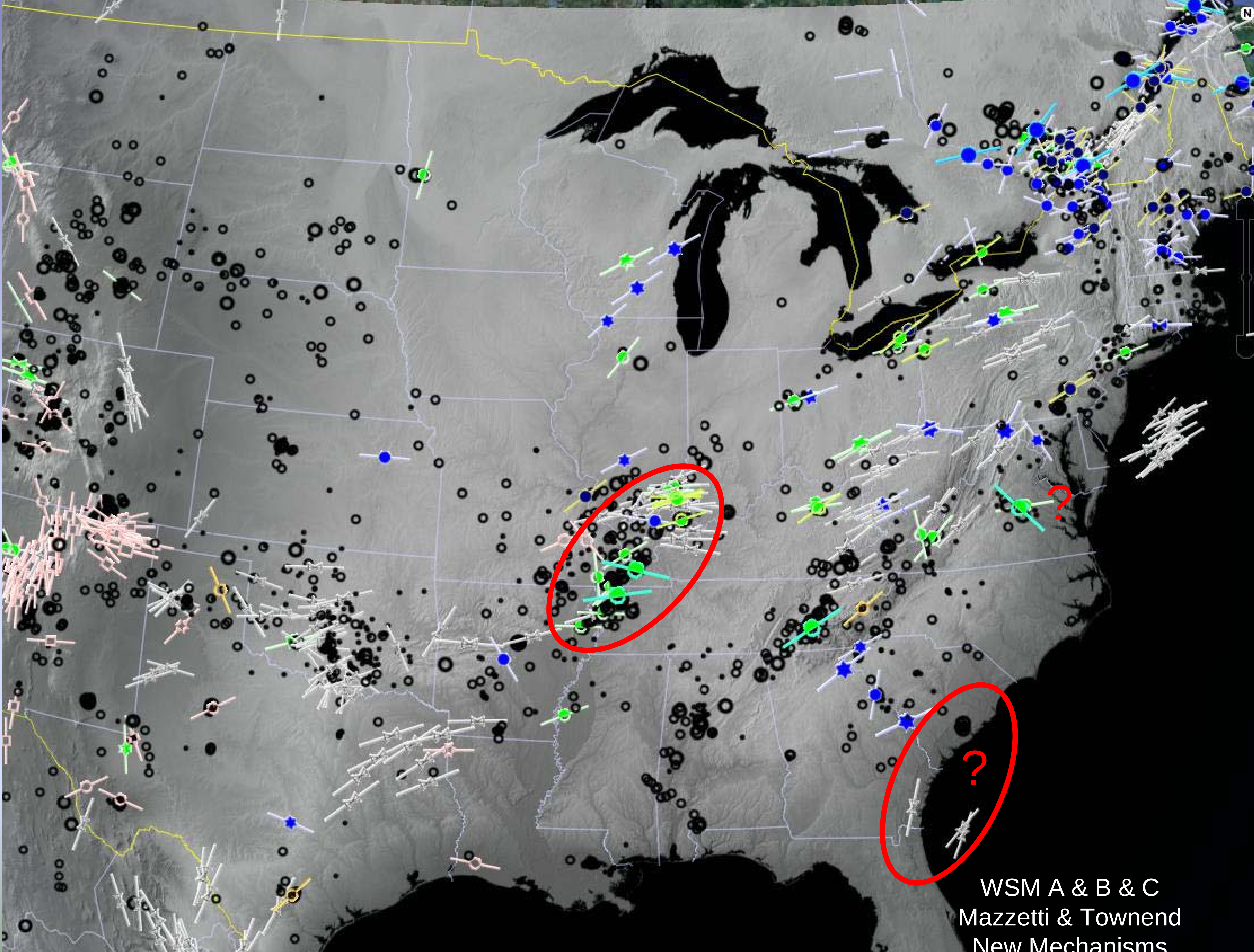
N30°E

Slip in Earthquakes Consistent with Regional Stress Field

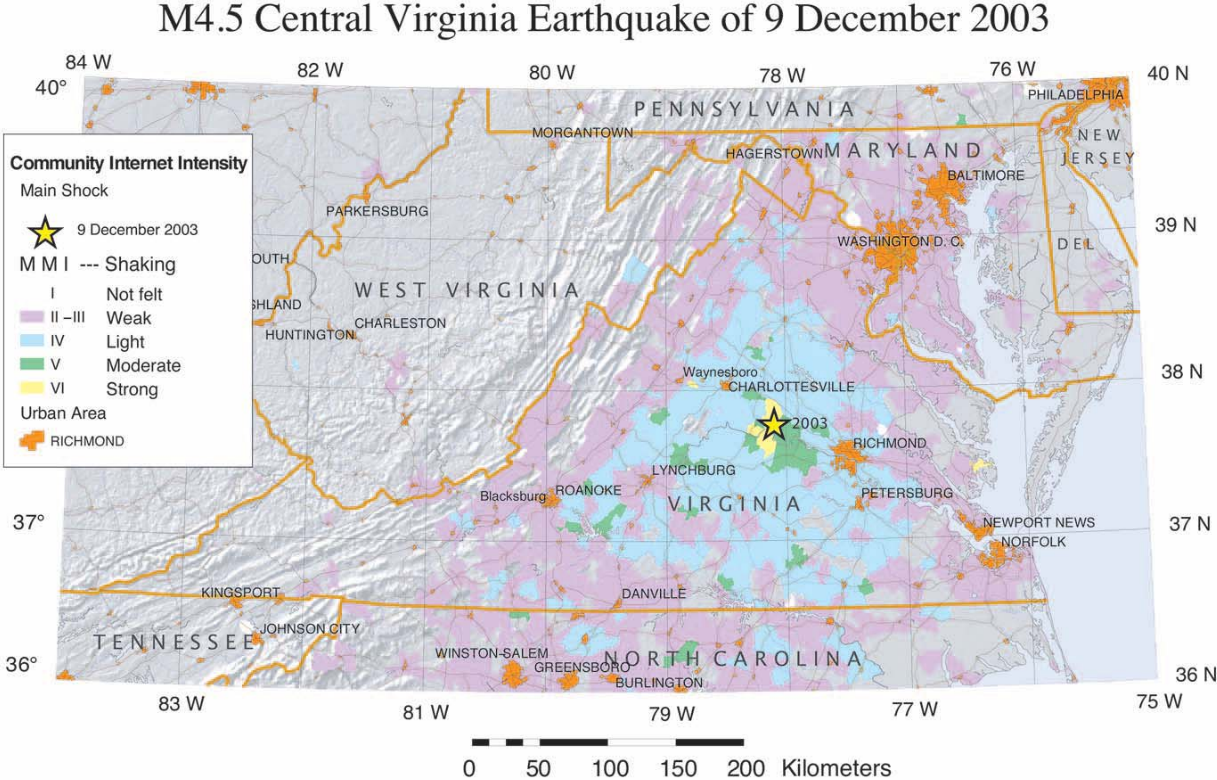




ML Zoback, 1992, JGR



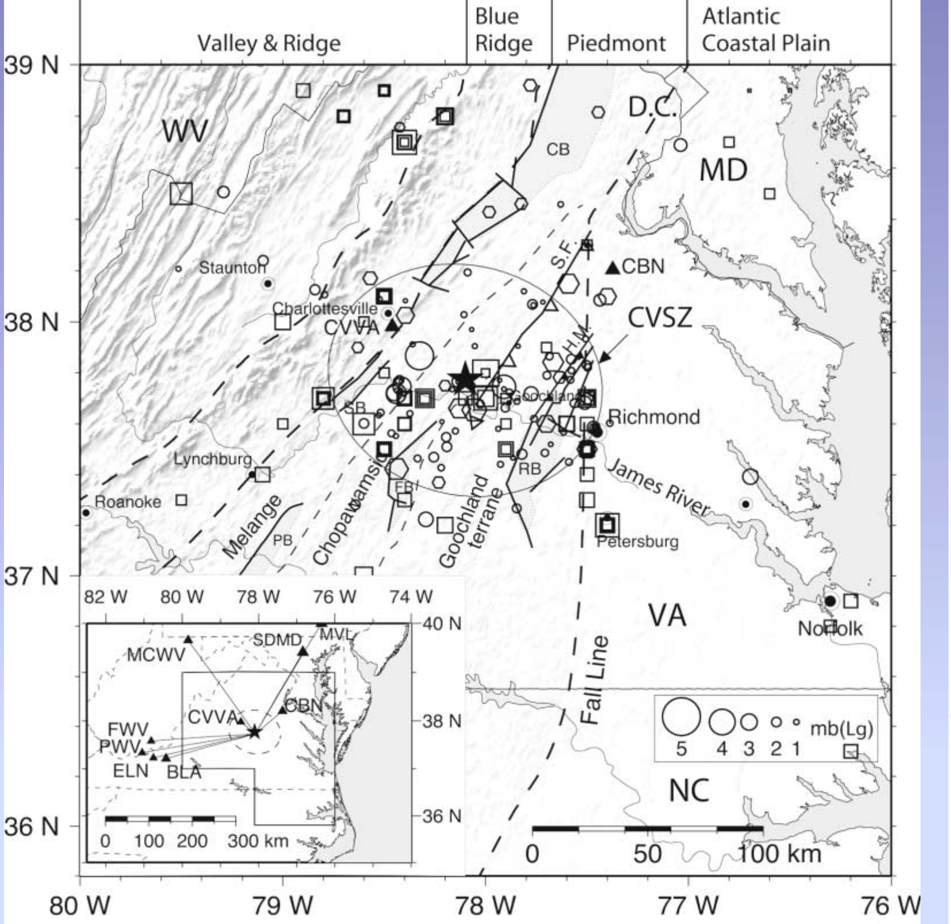
WSM A & B & C
Mazzetti & Townend
New Mechanisms

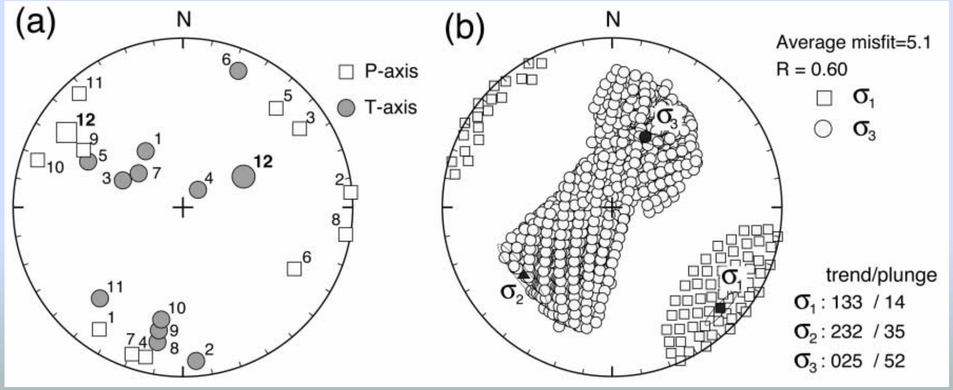


Bulletin of the Seismological Society of America, 2003, v. 95

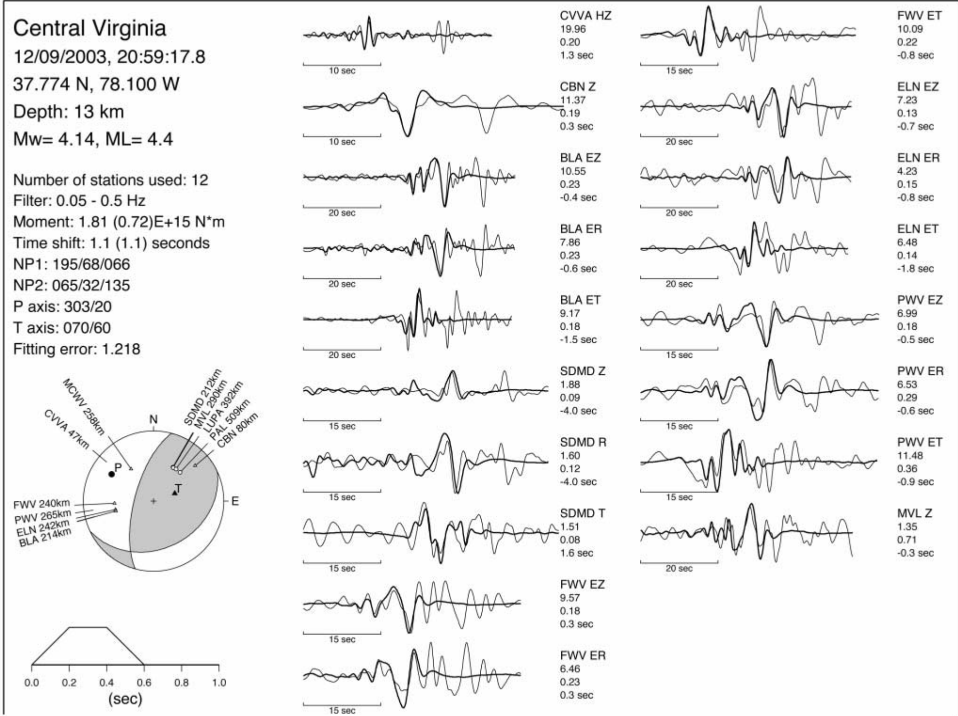
The 9 December 2003 Central Virginia Earthquake Sequence: A Compound Earthquake in the Central Virginia Seismic Zone

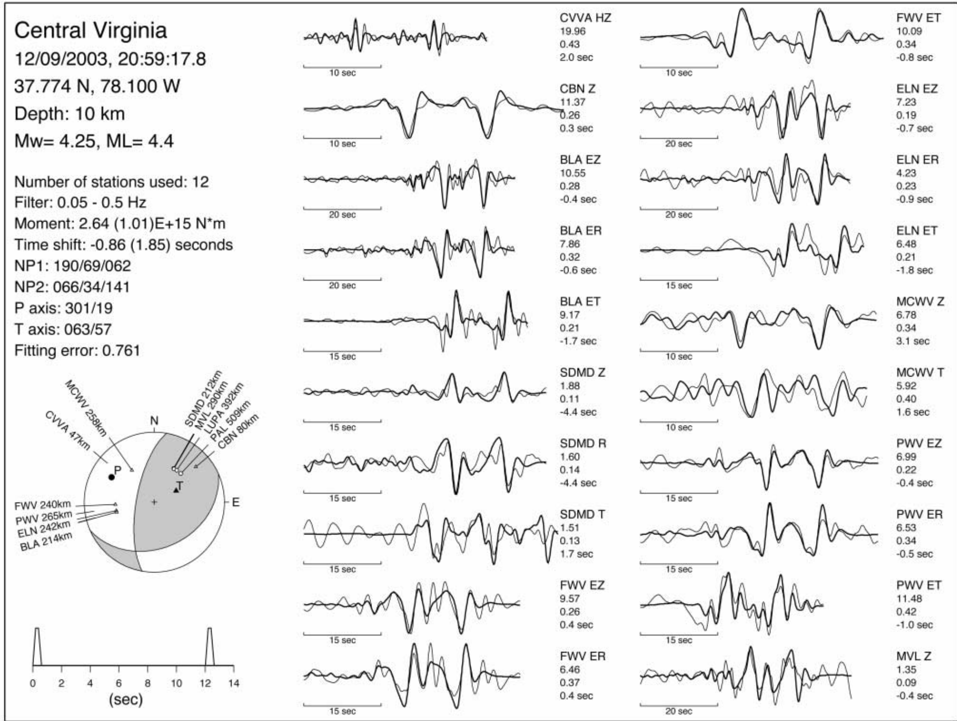
by Won-Young Kim and Martin Chapman





12 events in CVSZ





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*As posed by Kevin Coppersmith

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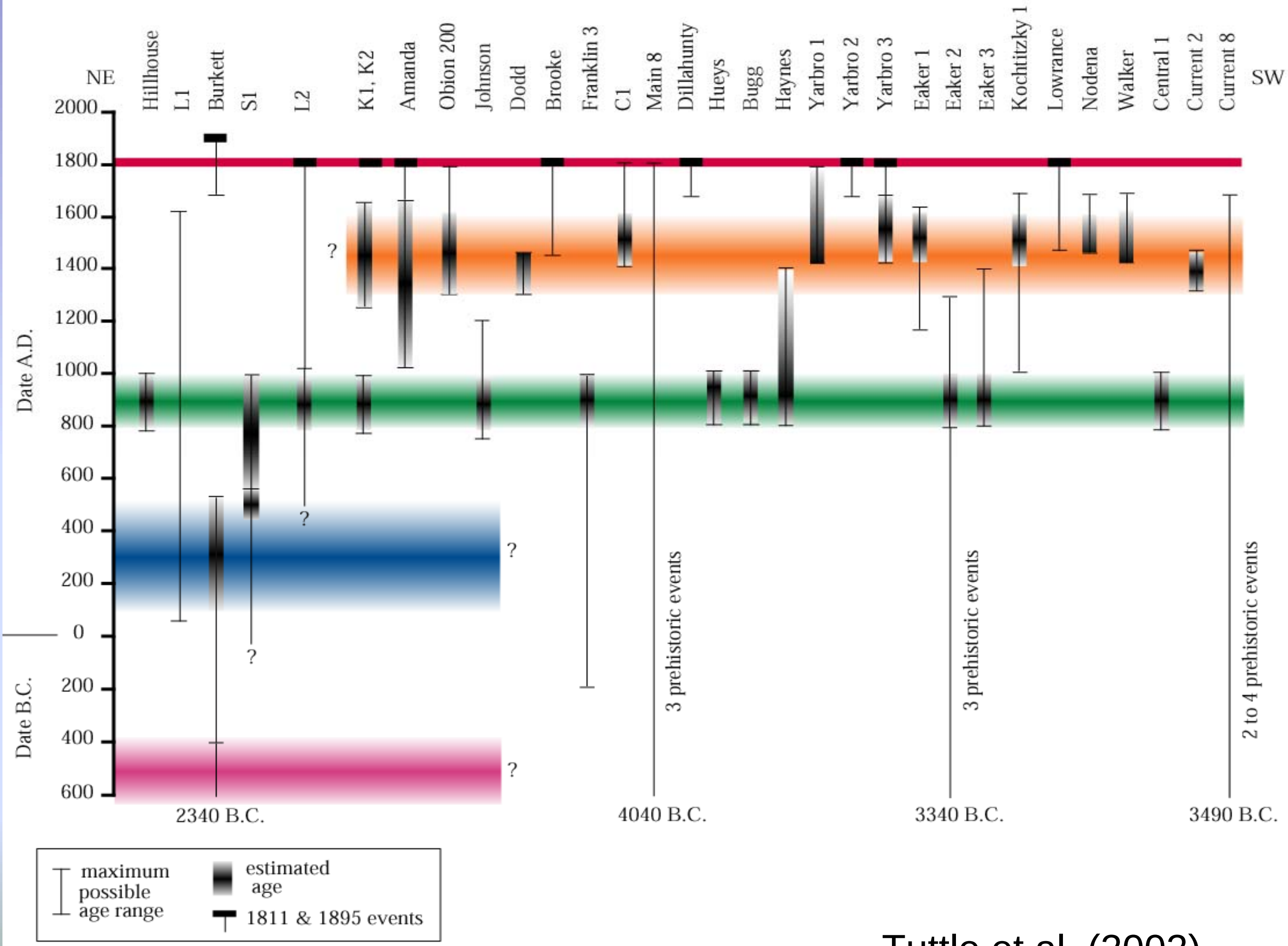
- Are observed rates of historical and prehistorical seismicity (in those places where we have evidence) consistent with observed strain rates? YES, BUT THIS CONCLUSION IS MODEL DEPENDENT

*As posed by Kevin Coppersmith

New Madrid Seismicity

- Three Very Large Earthquakes in 1811-1812 (and Ongoing Seismicity) in Region of Failed Pre-Cambrian/Early Pz Rift That was Apparently Later Reactivated in Late Cretaceous
- Earthquakes are Occurring on Faults in Response to Regional Stress Field
- Extraordinarily High Rate of Holocene Activity
- Seismic Reflection Profiles Show Small Cumulative Fault Offset in Post-Late Cretaceous Mississippi Embayment Sediments
- Very Low Strain Rate

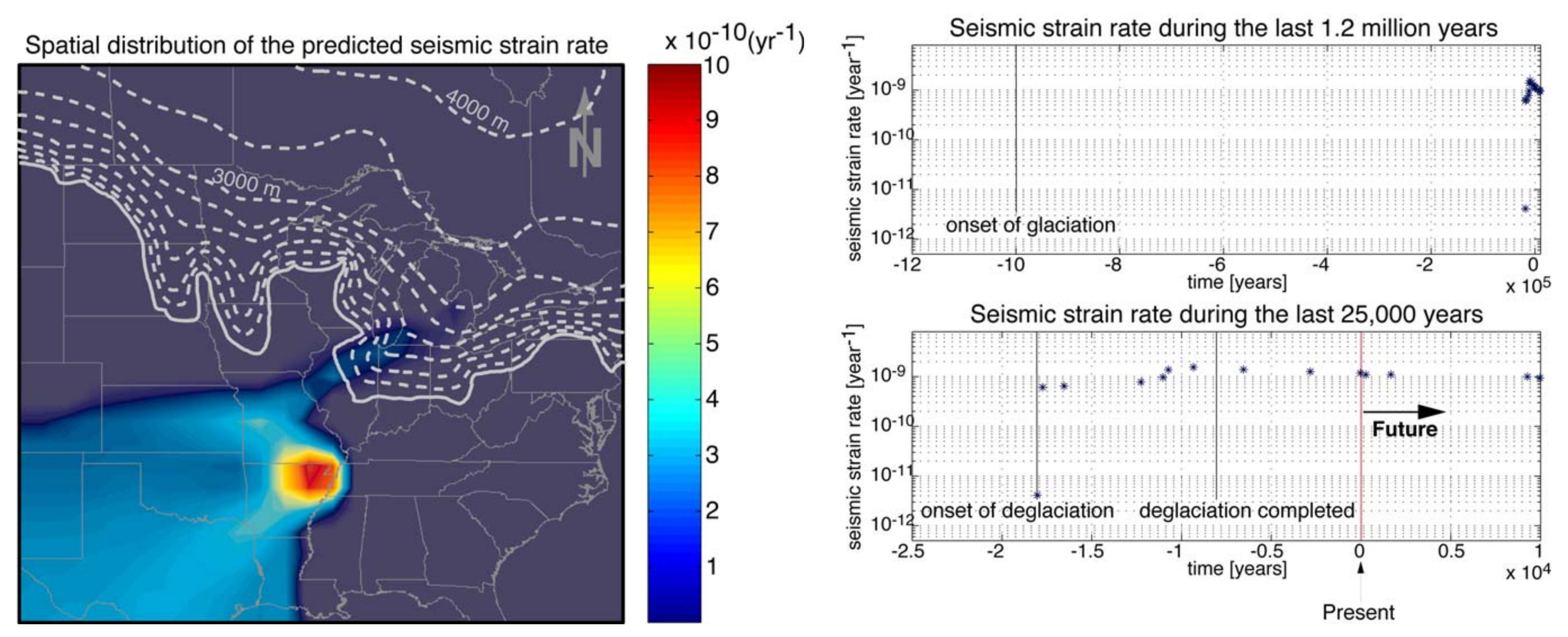
Paleoseismic Data Indicates 2 to 4 Large Earthquakes Prior to 1811-1812



Tuttle et al. (2002)

Hypothesis - Did Retreat of the Laurentide Ice Sheet Trigger Rapid Holocene Seismicity in a Region of Anomalous Crust/Upper Mantle Properties?

Concentrated Deformation in Area of Localized Weak Mantle Model

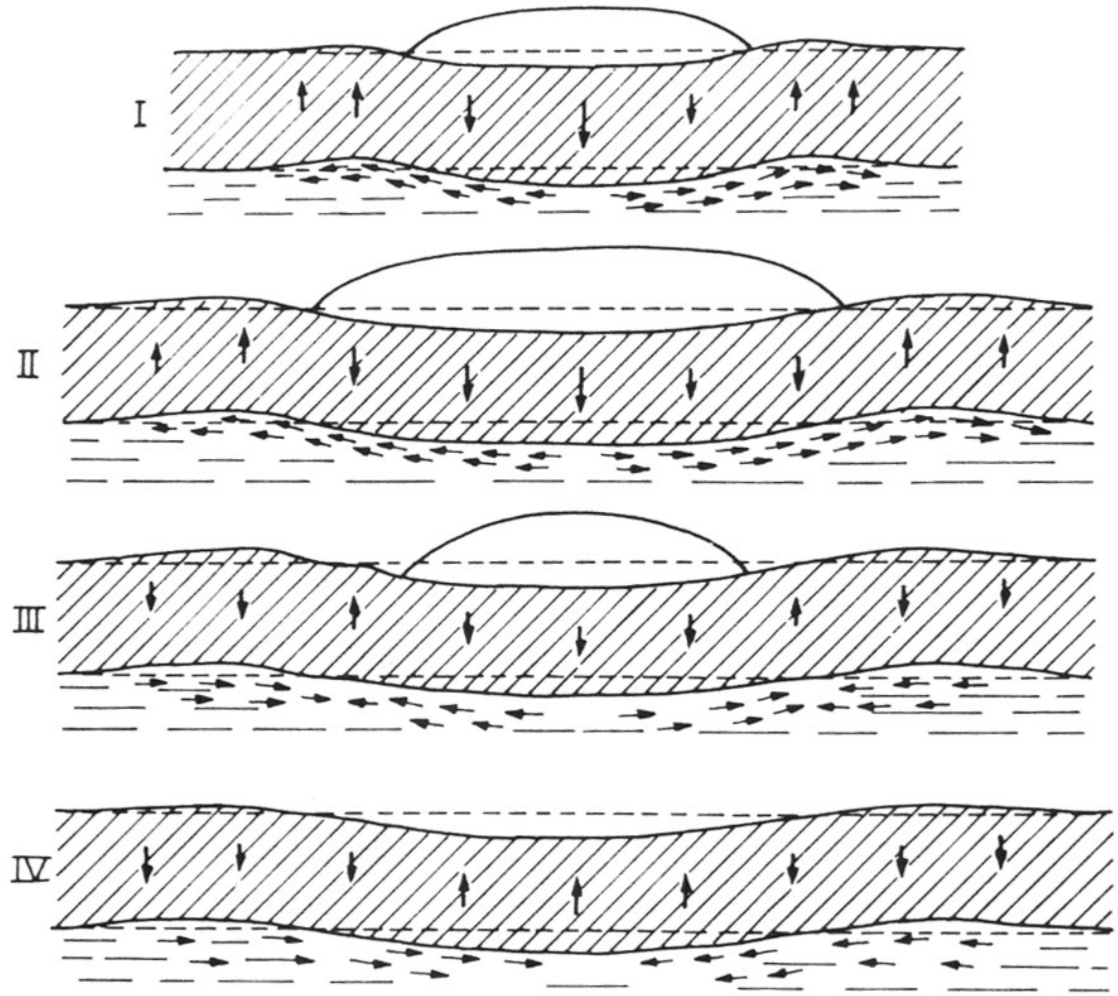


Grollimund and Zoback (2001)

Deglaciation Model

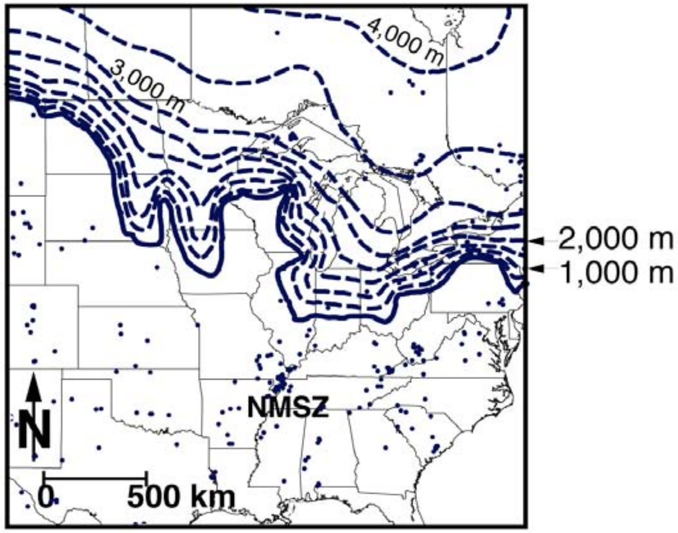
- Helps explain rapid Holocene seismicity/low long term rate
- The modeled seismicity is concentrated in the NMSZ due to the anomalous crust/upper mantle structure.
- A weak upper mantle model appears to work best by matching the following observations.
  - High seismic strain rate in the NMSZ.
  - Onset of rapid deformation in Holocene time.
  - Localization of seismicity, *i.e*. low present-day seismic strain rates in surrounding areas.
- With all models tested, seismicity rate remains high for 10,000’s of years into the future.

Lithospheric Flexure and Deglaciations
Nansen (1921)

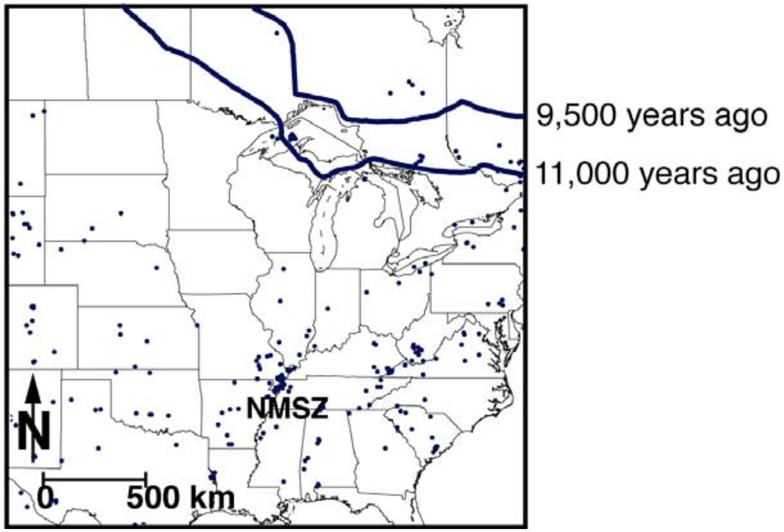


Shape of the Ice Sheet

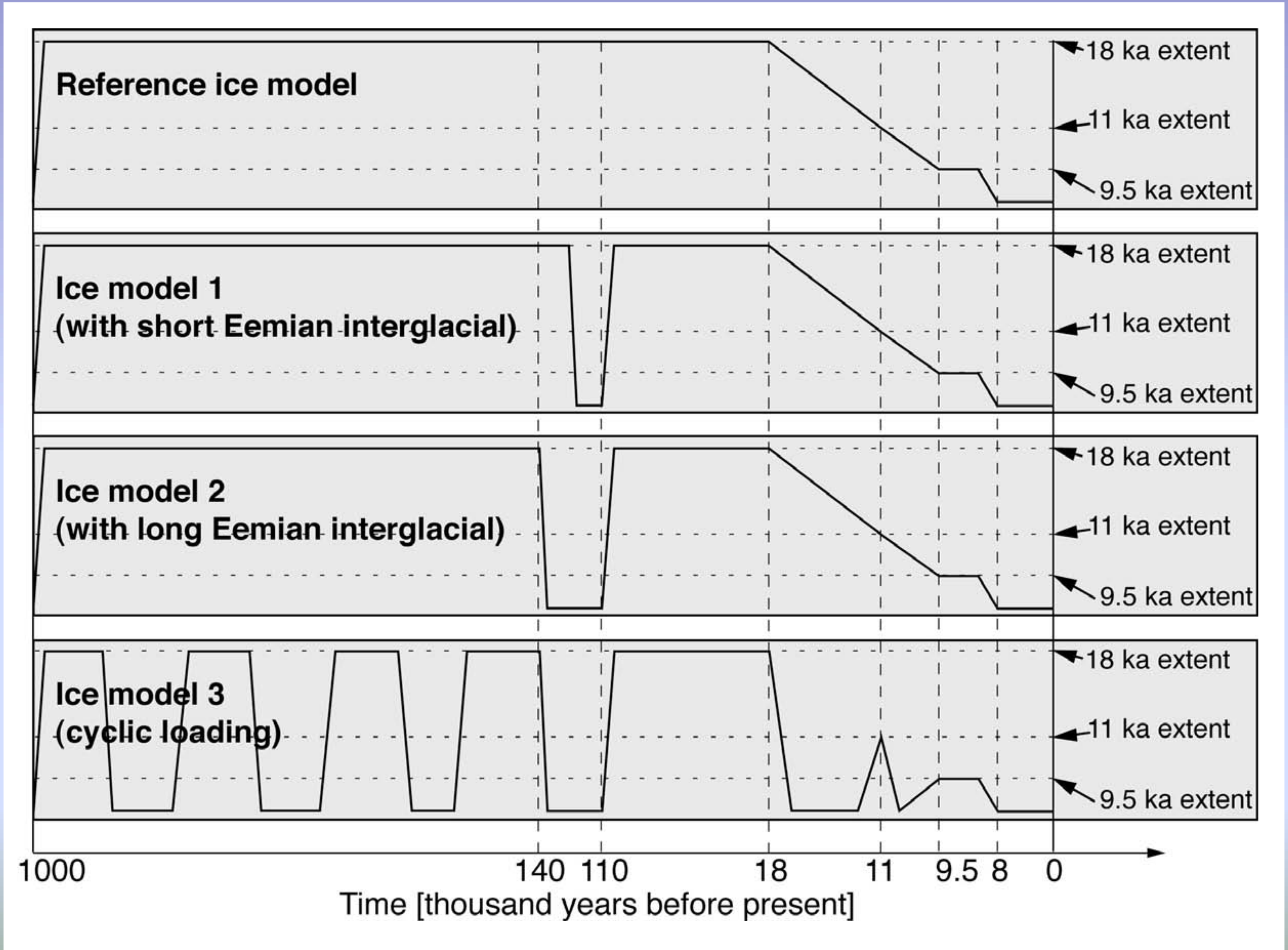
18,000 years ago



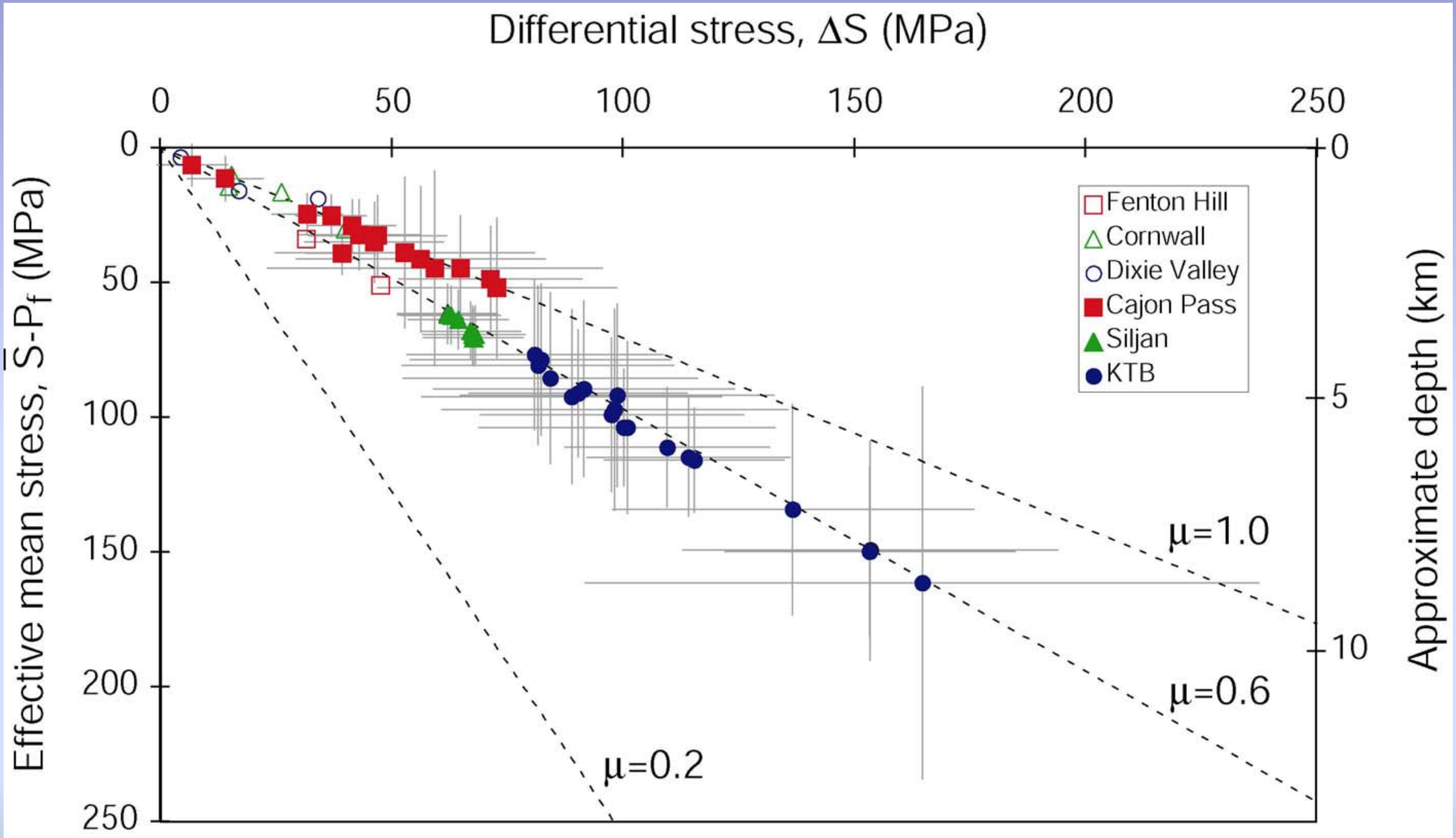
Ice front during melt back and recent seismicity



Tested Ice Histories

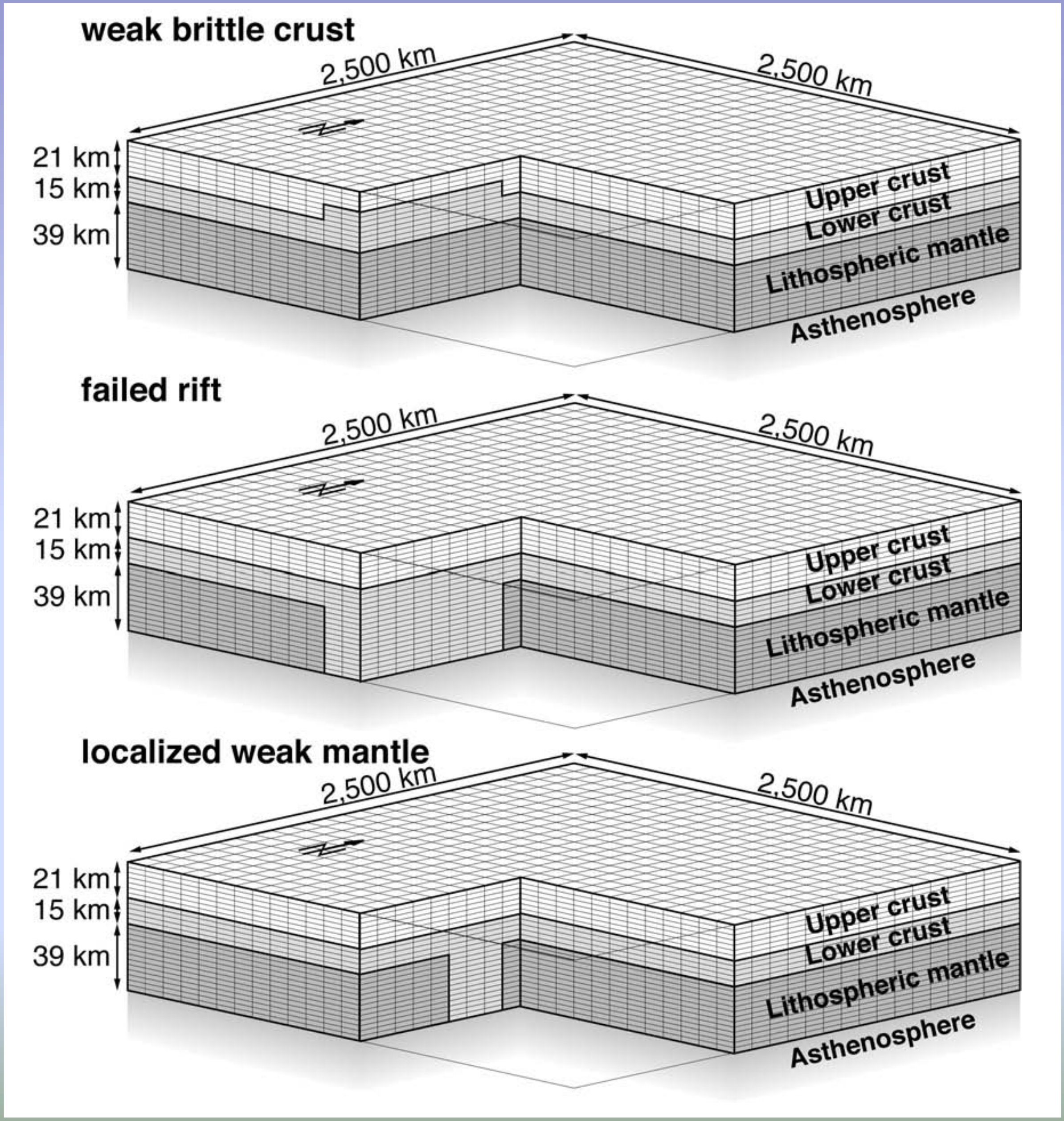


Crust Failure Equilibrium in Intraplate Areas

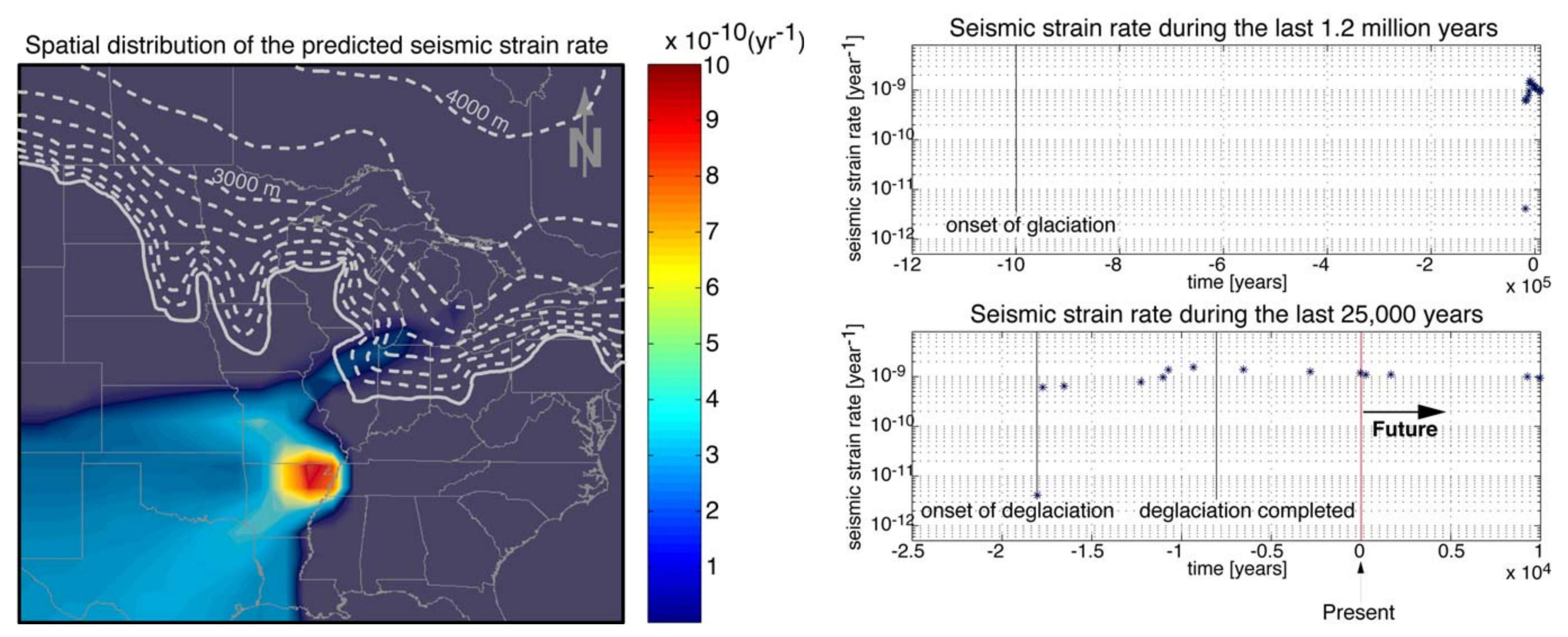


Townend and Zoback (2001)

Modeled Heterogeneities

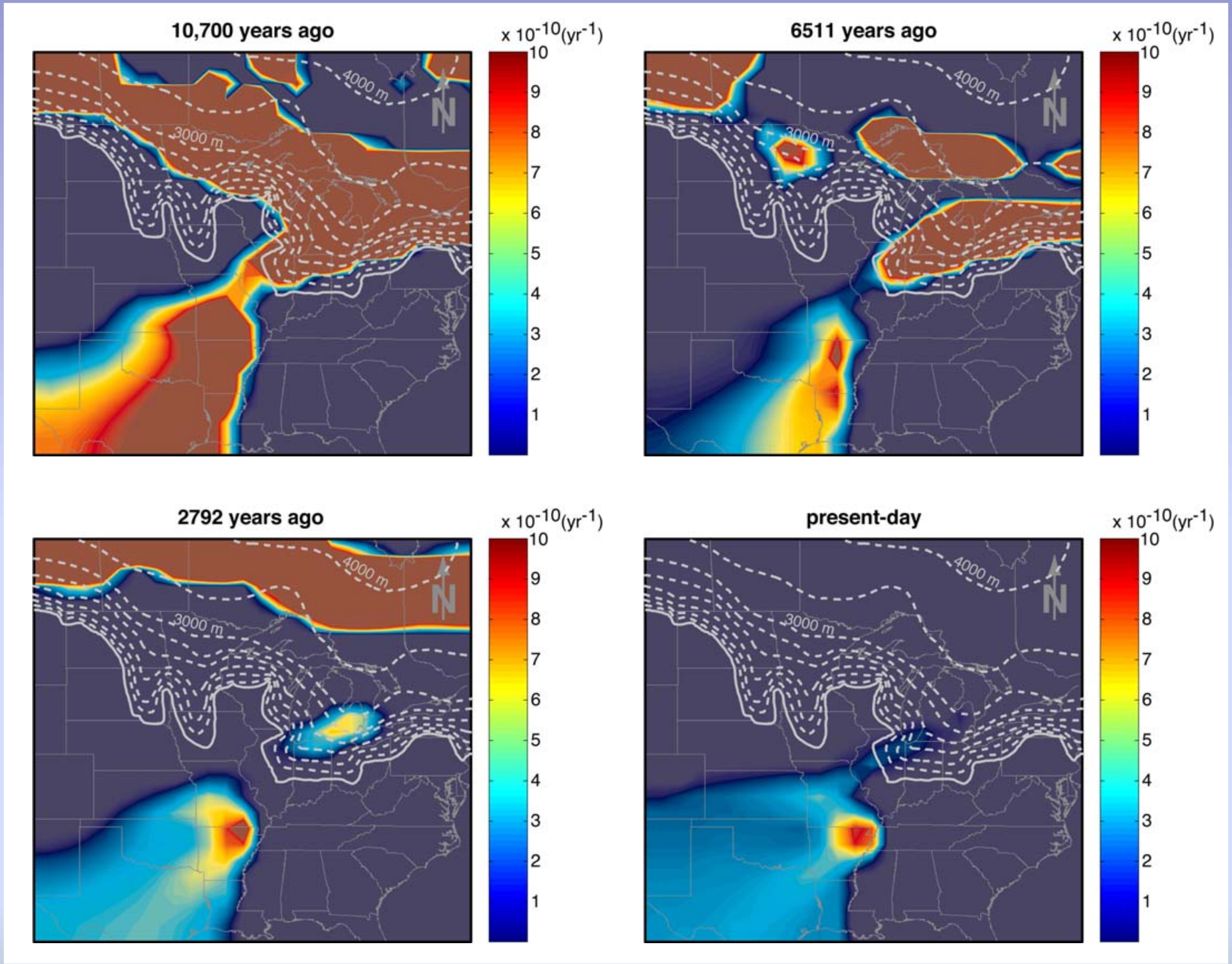


Concentrated Deformation in Area of Localized Weak Mantle Model



Grollimund and Zoback (2001)

Predicted of Change of Seismicity with Time



Offers the Possibility to Test Hypothesis

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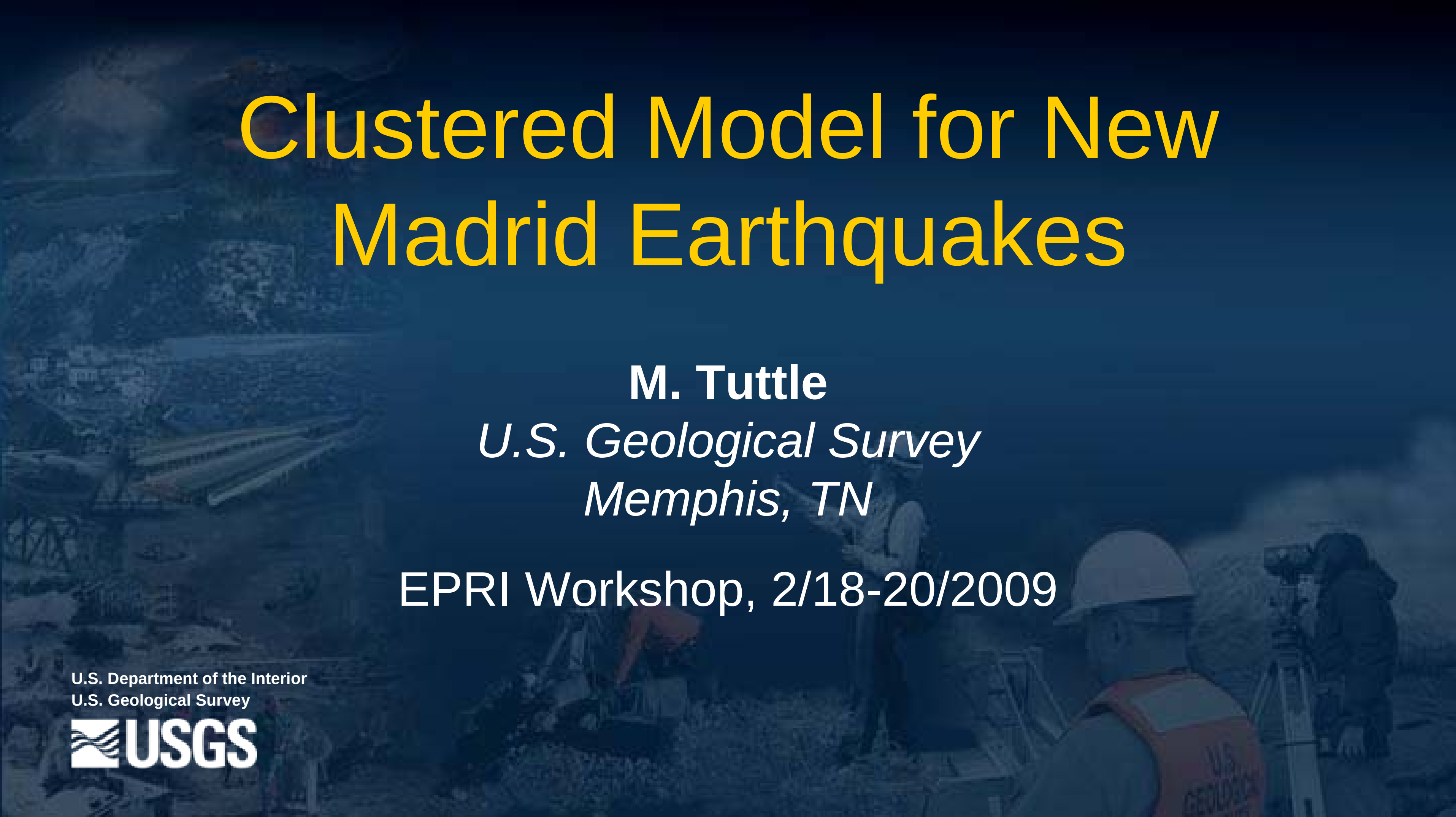
- Given far-field (i.e., ridge-push) sources of stress in the CEUS, are there local sources of stress that modify the regional stress field? MAYBE If so, are these important for purposes of identifying seismic sources? MAYBE

- Do large intraplate earthquakes occur on anomalously weak faults? APPARENTLY NOT

- What are mechanisms to localize stress? STRAIN LOCALIZATION IN LOWER CRUST/UPPER MANTLE Is stress localization an important consideration for identifying seismic sources? MAYBE

- Are observed rates of historical and prehistorical seismicity (in those places where we have evidence) consistent with observed strain rates? YES, BUT THIS IS MODEL DEPENDENT

*As posed by Kevin Coppersmith



Clustered Model for New Madrid Earthquakes

M. Tuttle
U.S. Geological Survey
Memphis, TN

EPRI Workshop, 2/18-20/2009

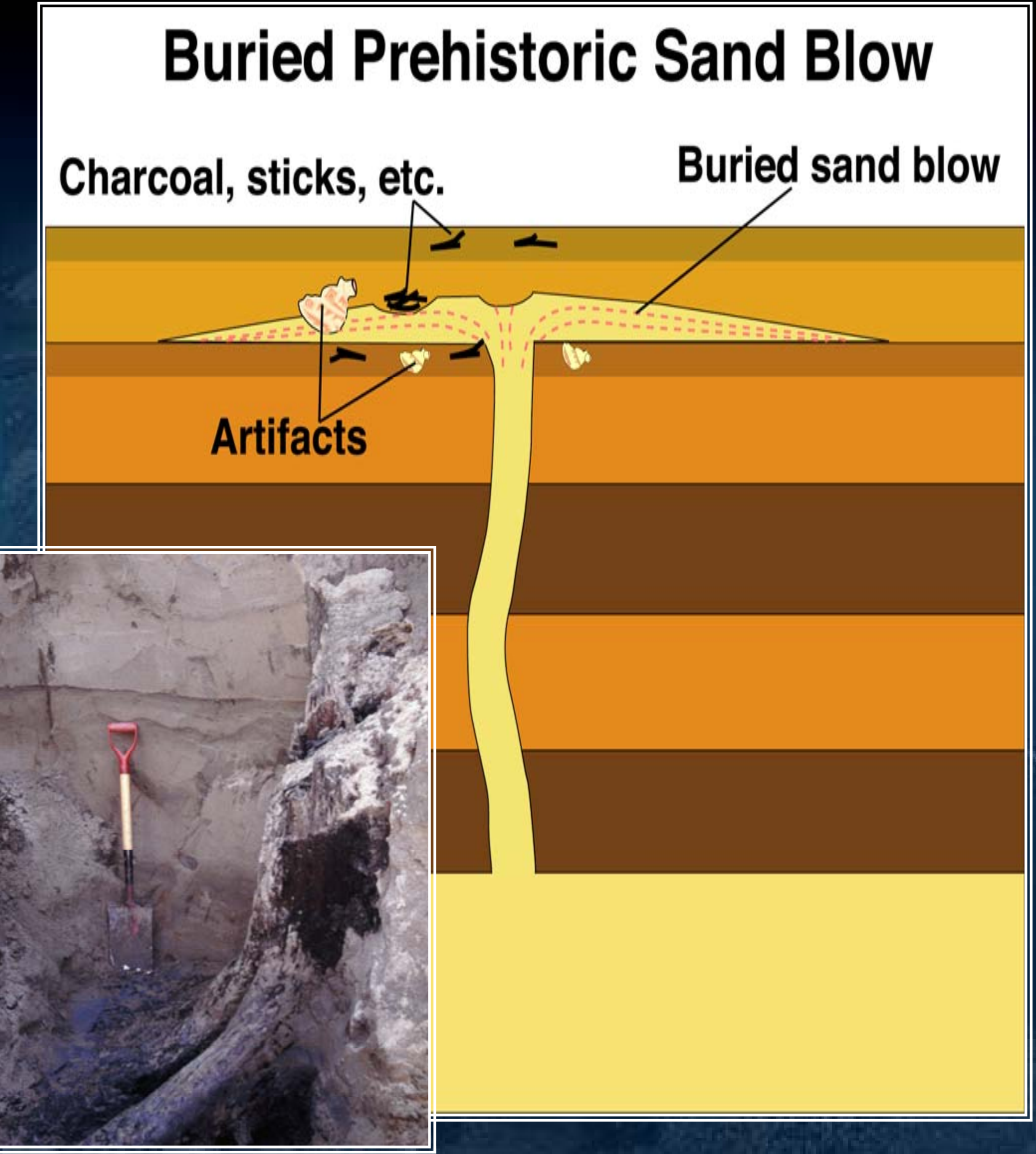
Questions

- What are the resolution issues for identifying individual events and estimating the size of such events?
- What are the constraints and uncertainties associated with the earthquake cluster model & what are the eq interarrival times within a cluster and the cluster-to-cluster intervals?
- What is your confidence that the regional absence of liquefaction in susceptible deposits reflects an absence of large magnitude (> 6) earthquakes?

Outline

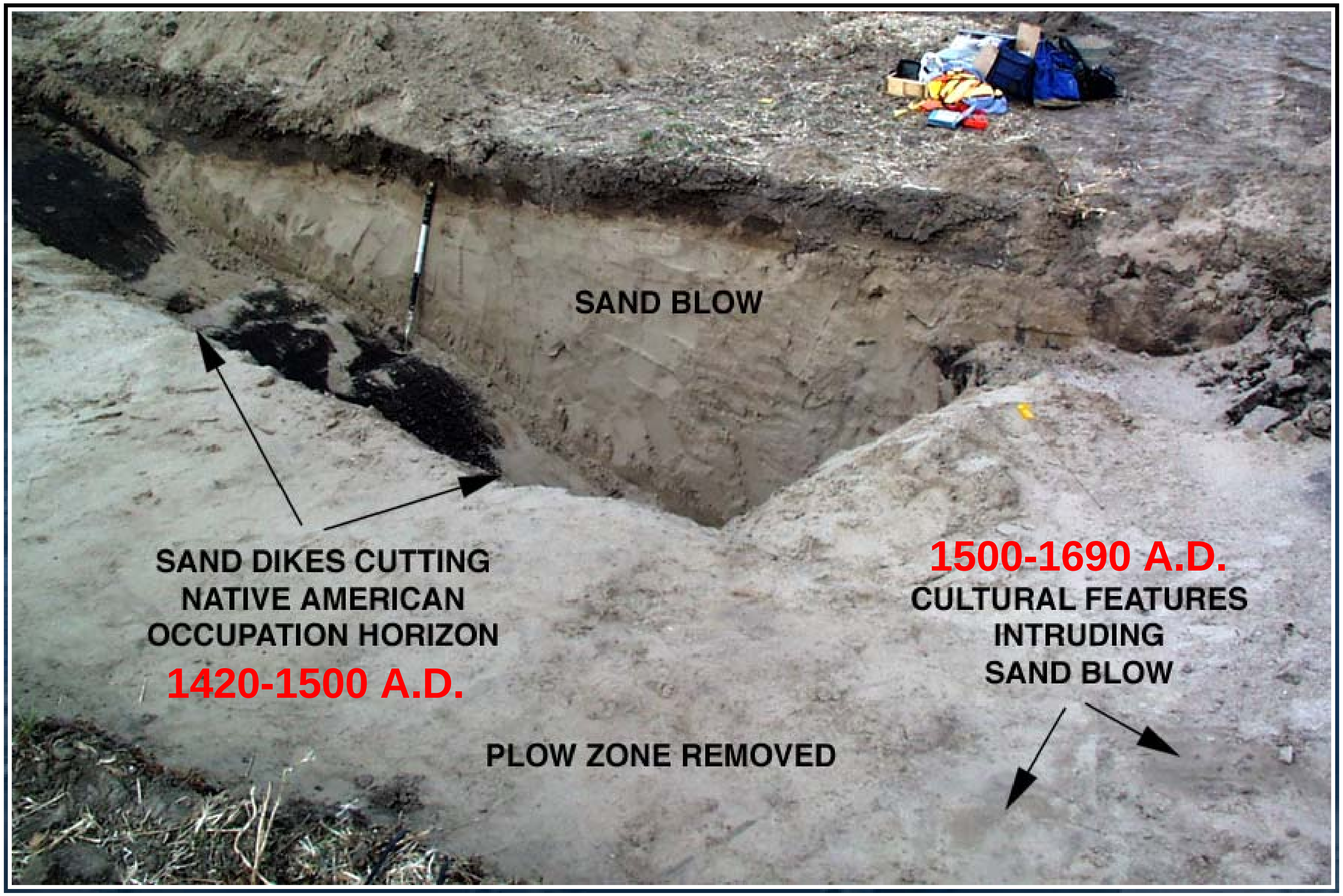
- Review - timing, location, magnitude, and recurrence times estimated for New Madrid paleoeqs; uncertainties and completeness of paleoseismic record
- Evidence for clustered earthquakes; intra- and intercluster times; migration of seismicity within Reelfoot Rift
- Negative evidence of earthquake-induced liquefaction; example - St. Lawrence Lowlands

Dating Sand Blows



- Sand blows provide best opportunity to date paleoearthquakes
- In situ material in soils provide close max, min, contemporary ages; correlation; reworked material in sediment give max ages
- Dendrochronology, radiocarbon and OSL dating, artifact analysis, stratigraphic correlation, soil development; uncertainties (+/- 1 to 1000^+ yr)

Age Estimates

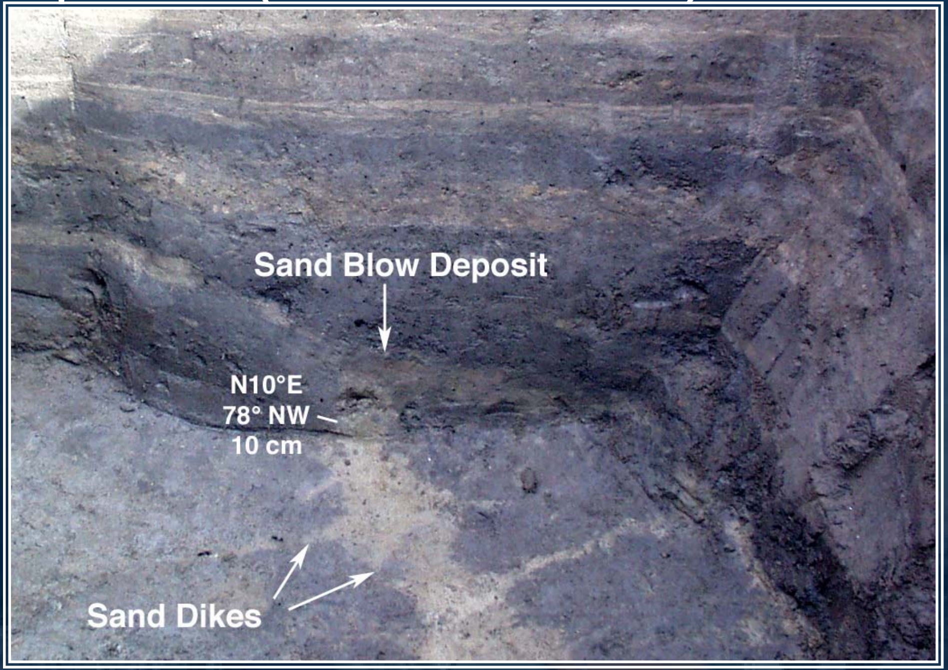


Sand blows overlies cultural horizon w/artifacts (1400-1650 A.D.) and organic material & is intruded by post molds; 2 sigma calibrated dates; bracketed age 1420 - 1690 AD

USGS

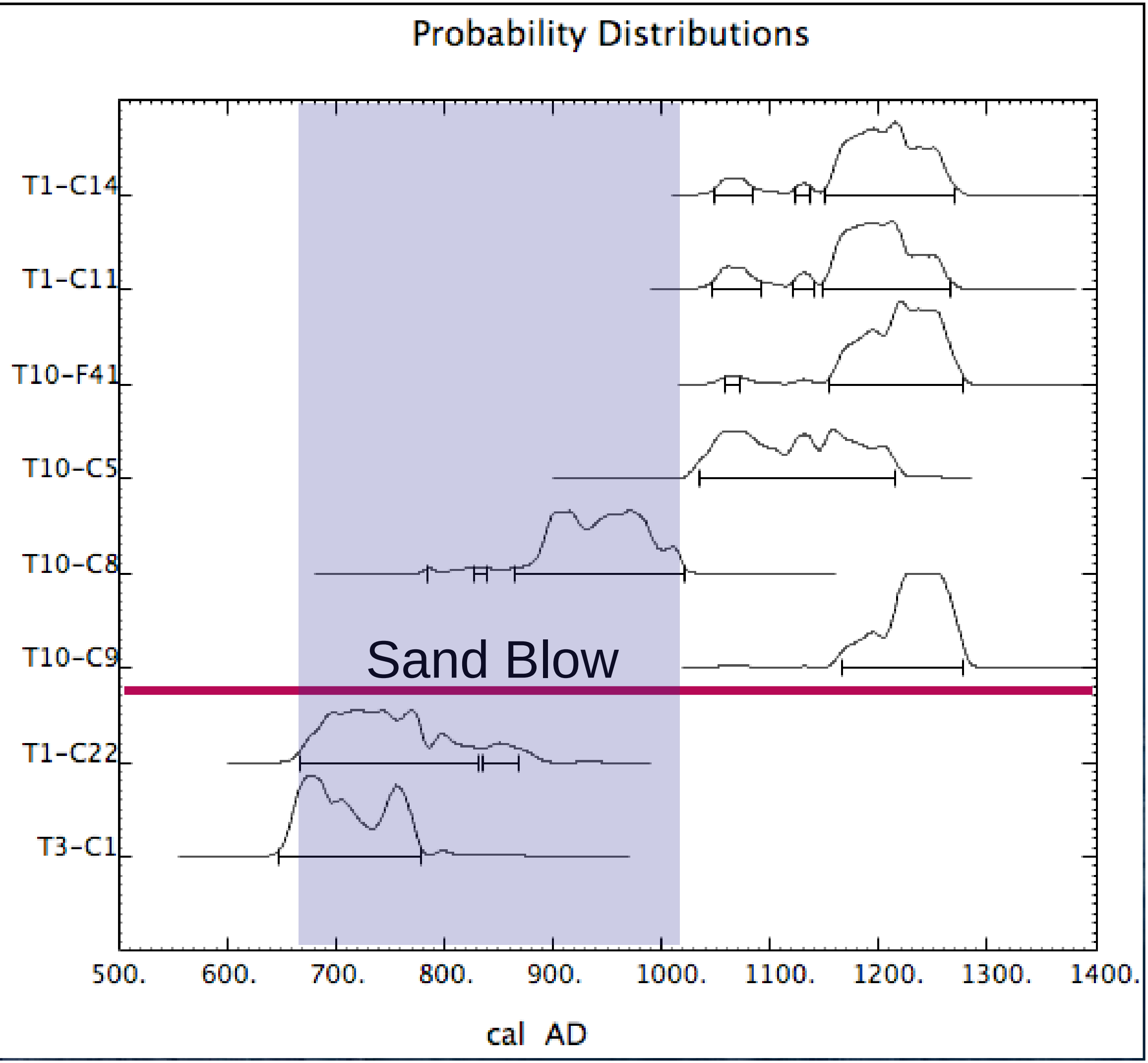
Age Estimates

Towosahgy Revisited (Saucier, 1991): Artifacts above and below sand blow indicate that it formed during L Woodland - E Mississippian transitional period (700-1000 A.D.)



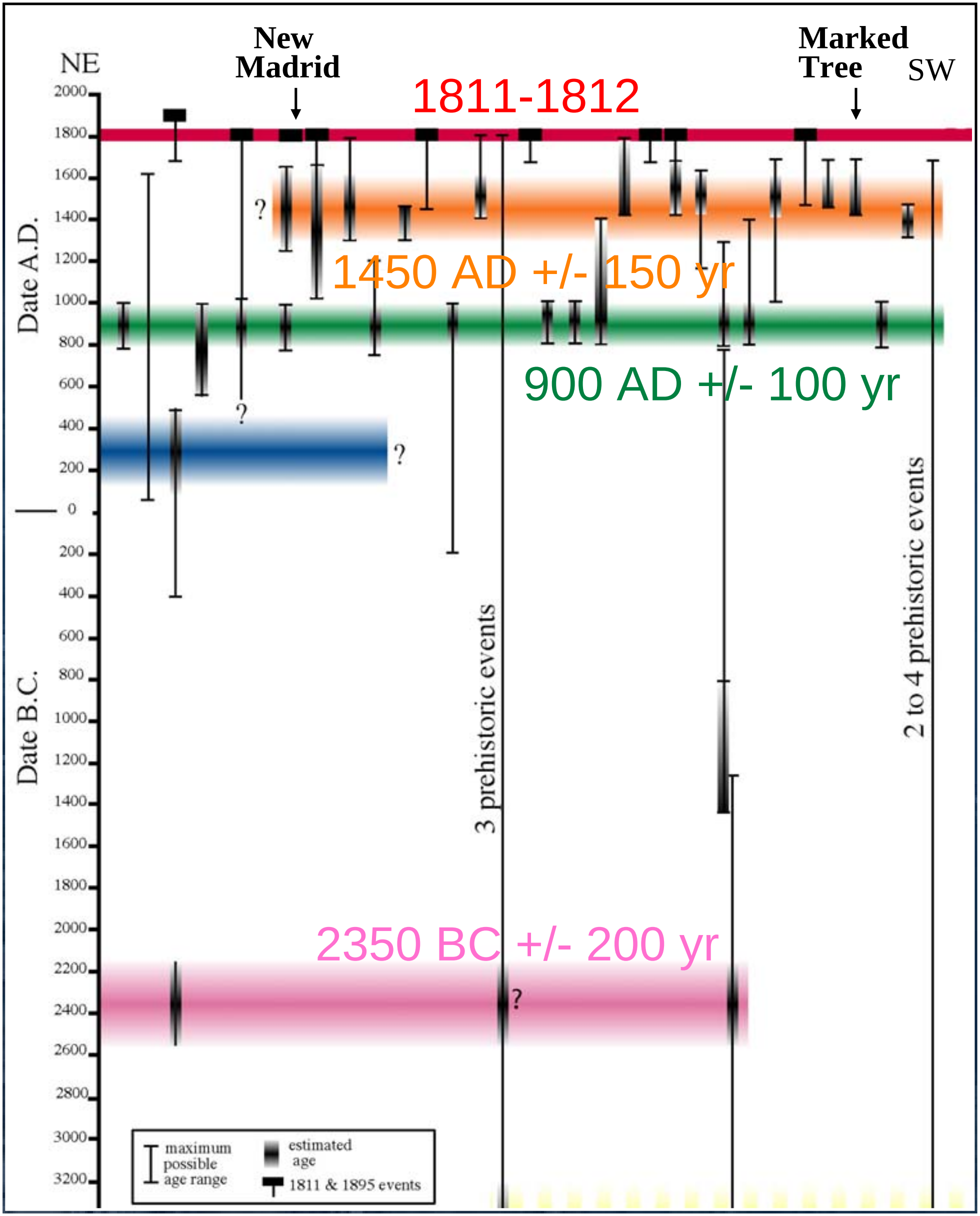
Tuttle, Schweig, Sims, Lafferty, Price, in prep.

Age Estimates



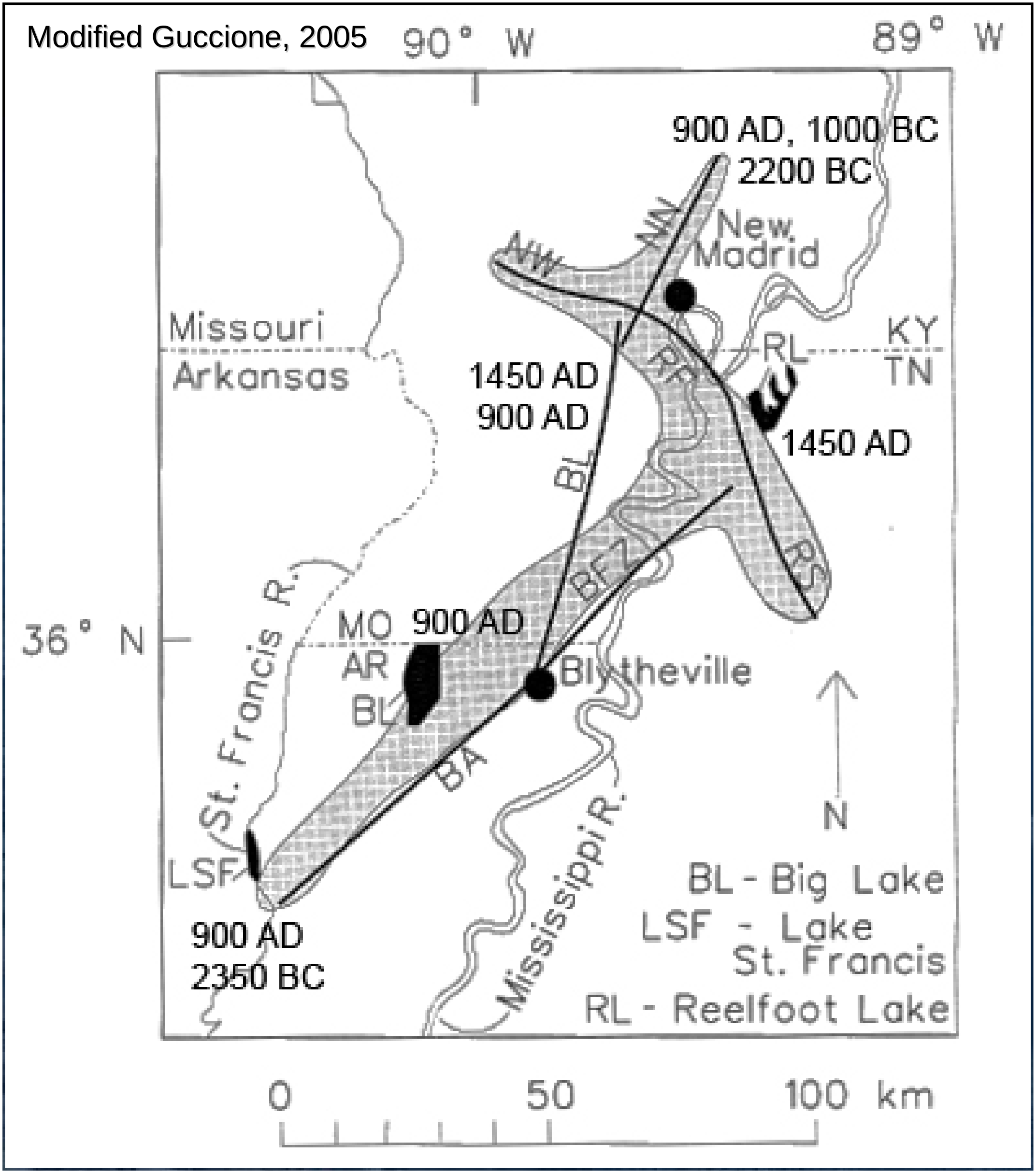
- Radiocarbon dating indicates sand blow formed between 670-1010 A.D.
- Sample T10-C8 provides close minimum age constraint of 880-1010 A.D.
- Sand blow formed between 670-1010 A.D. probably closer to upper end

NM Paleoearthquake Chronology



- Estimated ages for numerous sand blows
- Age estimates cluster at 1450 & 900 A.D. and 2350 B.C. - timing of past events; sand blows of other ages; data gap
- Prehistoric sand blows are *large, compound, and broadly* distributed like historic features
- Prehistoric sand blows formed during very large New Madrid-type events, not multiple smaller eqs (e.g., Charleston, MO)

NM Paleoearthquake Chronology



Modified Guccione, 2005

Independent paleoseismic studies; event ages from liquefaction studies supported by

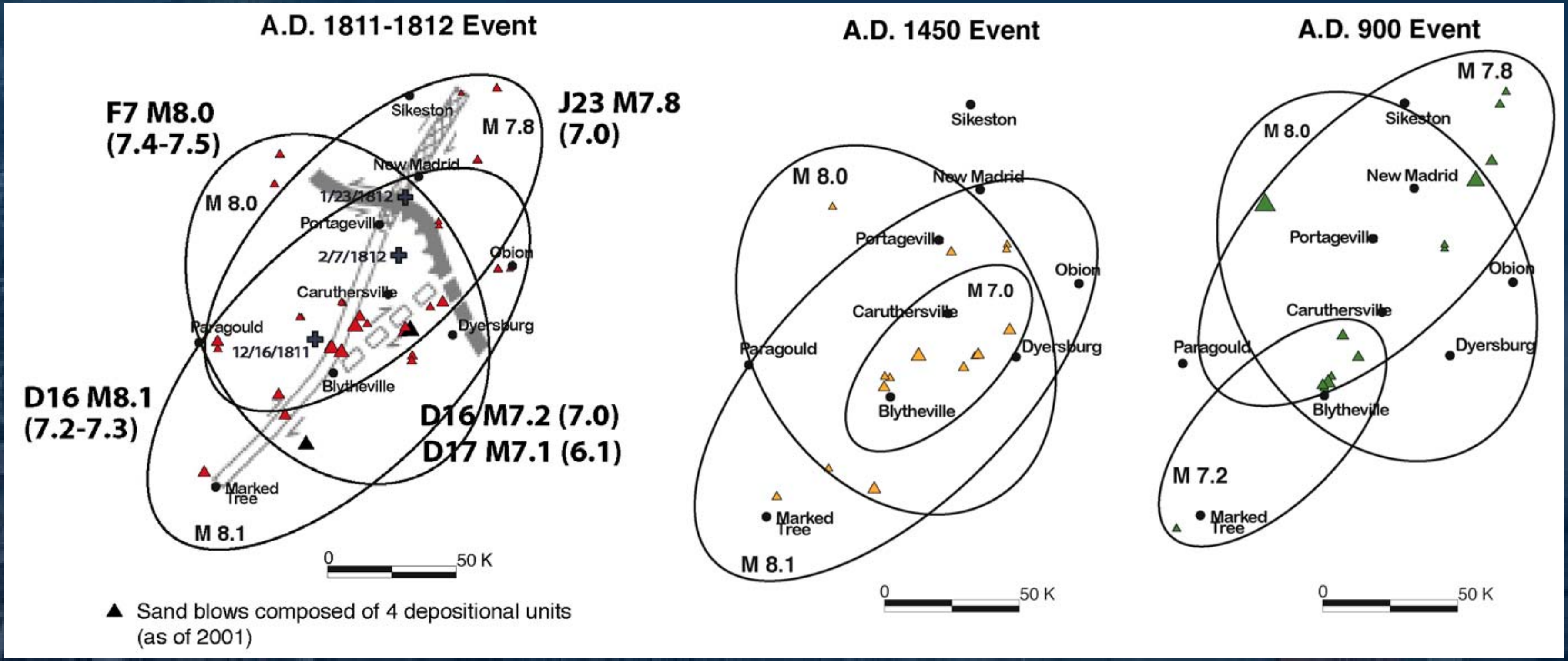
a) deformation along Reelfoot & Bootheel faults, at Reelfoot & Big Lakes (Kelson et al., 1996; Guccione et al., 2002, 2005), and by

b) channel straightening events of Mississippi River northeast of Reelfoot fault (Holbrooke et al., 2006)

NM Paleoearthquake Magnitudes

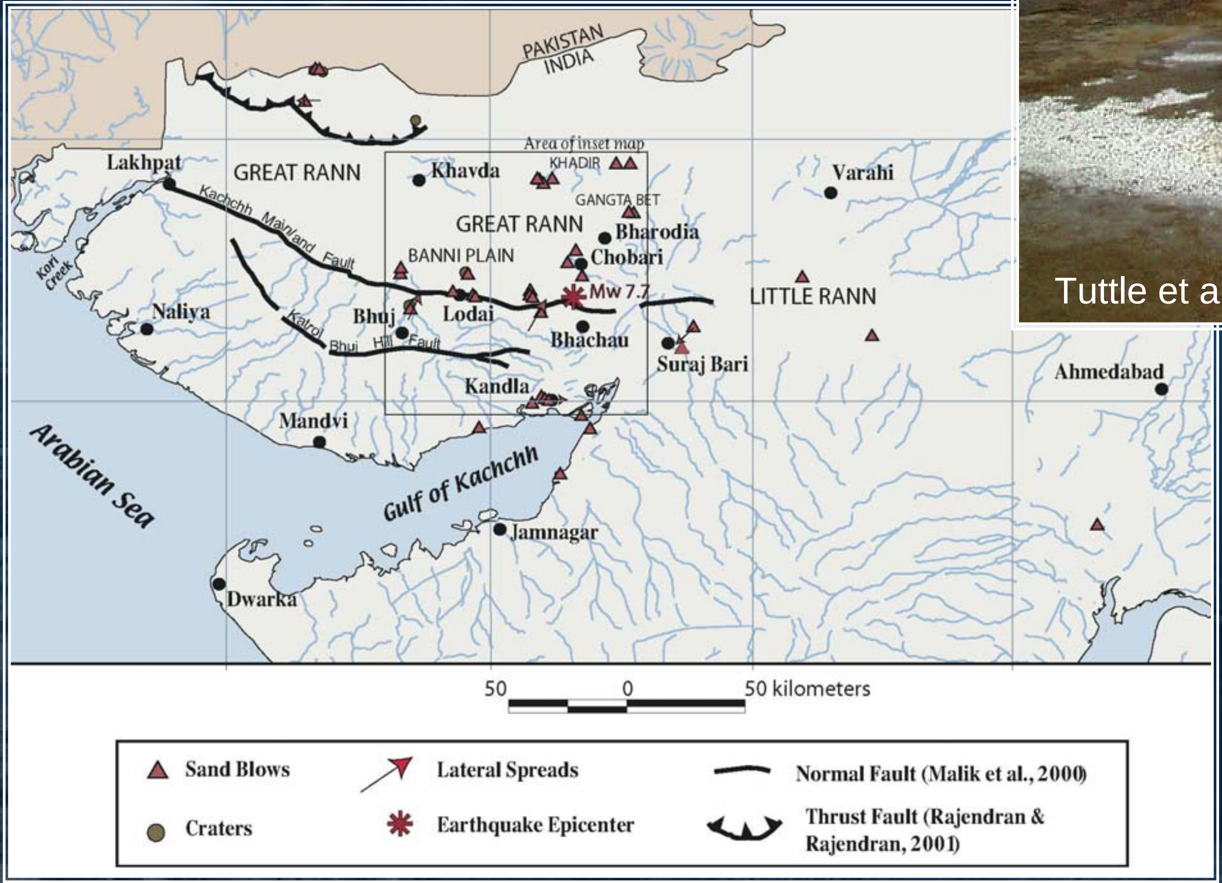
- 1811-1812 earthquakes serves as an historic analogue; however, interpretations of magnitudes of paleoeqs are at least as uncertain as those for historic earthquakes (0.5-1 magnitude unit)

Johnston and Schweig, 1996; Revised magnitudes (#) from Hough et al., 2000; Hough and Martin, 2002



2001 M 7.6-7.7 Bhuj, India Earthquake

- Analogue of NM-like event
- Liquefaction >15,000 km^2 and ~ 240 km from epicenter



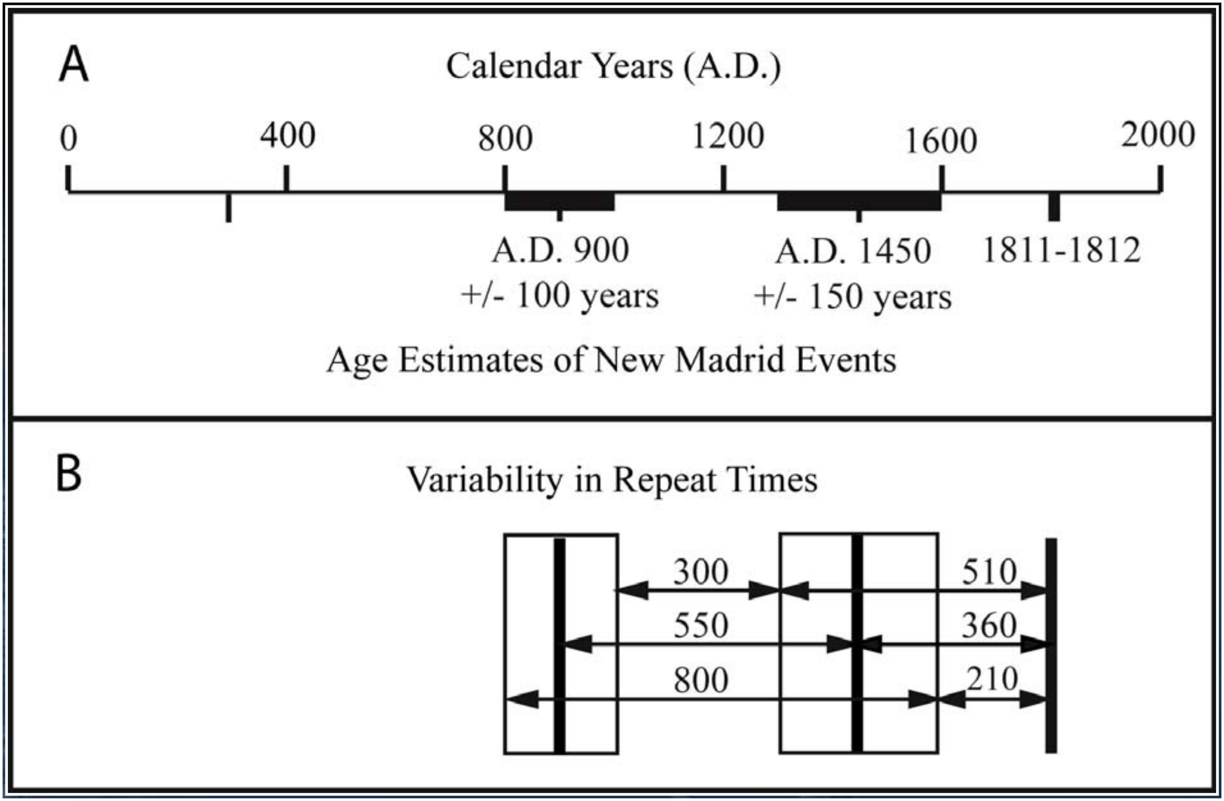

Tuttle et al., 2002

- 1811-1812 New Madrid event: liquefaction >10,000 km^2 and ~ 240 km; NM historic & prehistoric eqs M > 7.5

NM Paleoearthquake Magnitudes

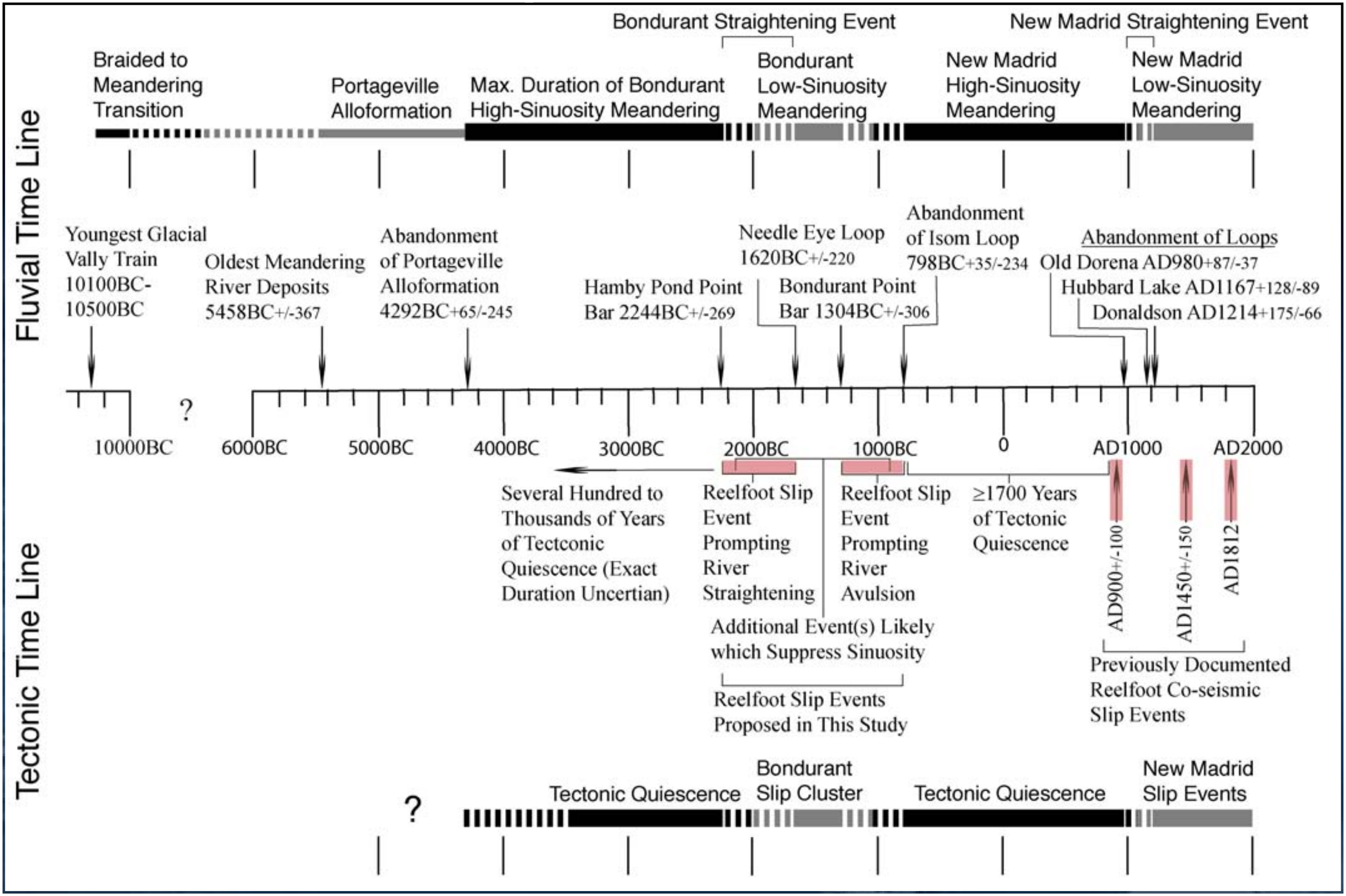
- Limited application of geotechnical approach of back-calculating magnitude; several studies in different areas derived similar estimates in M 7.2-8.0 range (Schneider et al., 1999; Stark, 2002; Tuttle, Schweig, Dyer-Williams; 2003)
- Very useful guide for constraining magnitudes; uncertainties in method related to identification of layer that liquefied, density of layer at time of event, characteristics of earthquake itself, site amplification, and ground motion attenuation used in analysis

NM Earthquake Recurrence



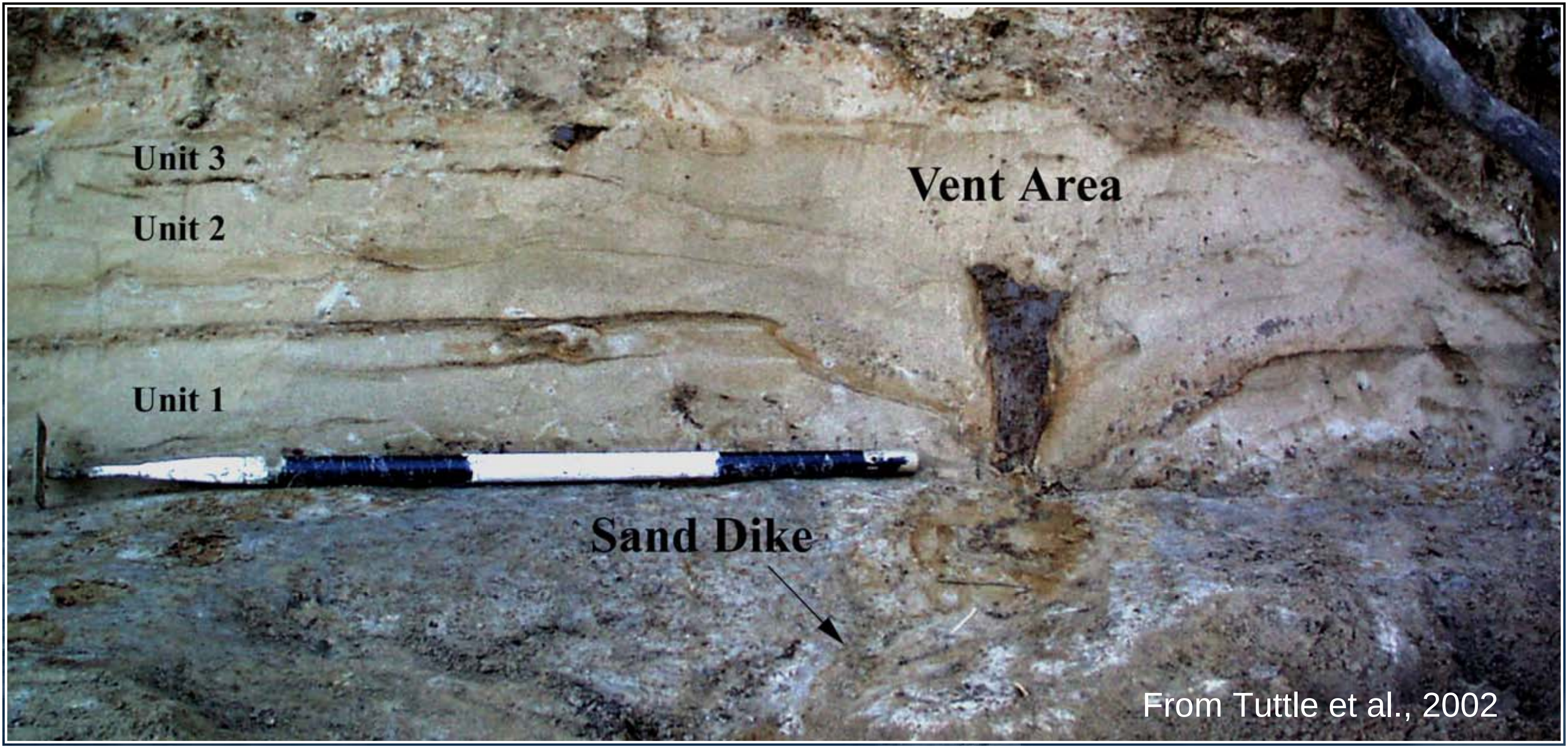
- Liquefaction record suggests NM events in 1450 & 900 A.D.; average repeat time 500 yr in past 1200 yr (Tuttle et al., 2002); Cramer (2001) estimated RI 160-1200 yr; mean of ~500 yr
- Similar repeat times estimated for Reelfoot and Bootheel faults (Kelson et al., 1996; Guccione et al., 2005)

NM Earthquake Recurrence



Mississippi channel straightening events indicate rupture of Reelfoot fault 2000 & 1000 B.C. and 900 A.D.; groups events into two active periods separated by ~1700 yr of quiescence (Holbrooke et al., 2006)

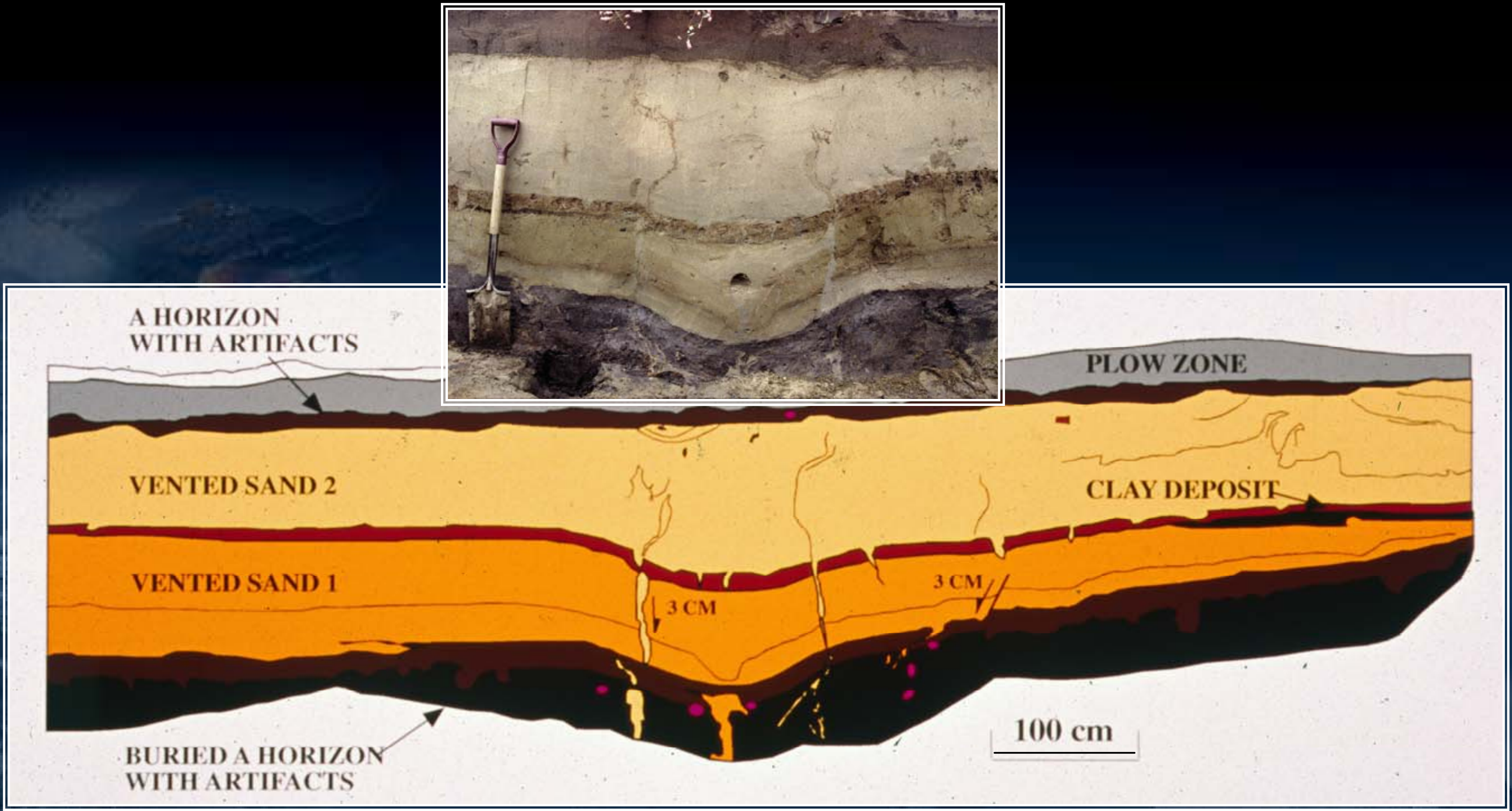
Evidence for Clustered Earthquakes



From Tuttle et al., 2002

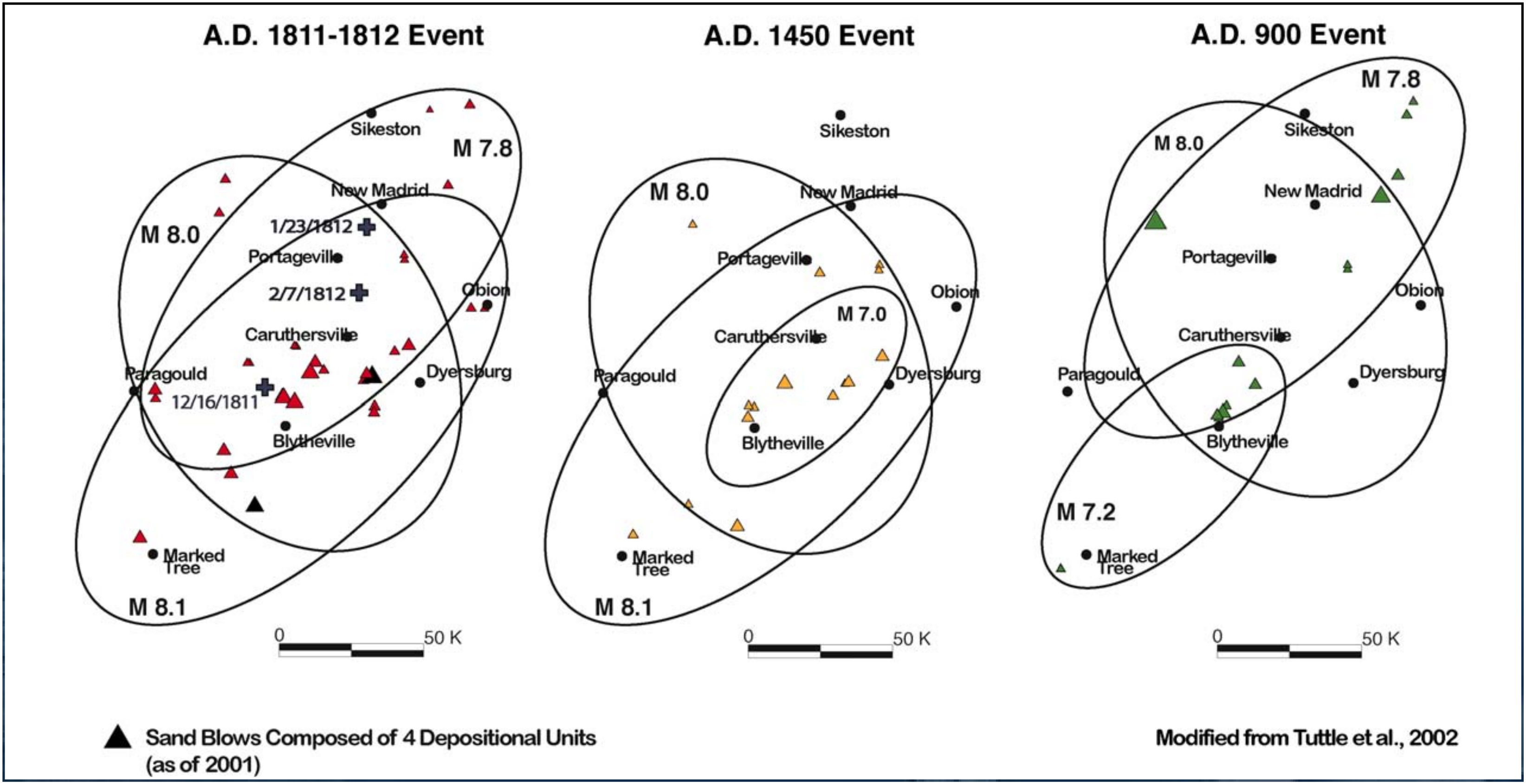
Saucier (1989) observed historic sand blows composed of several depositional units related to 3 largest eqs in 1811-1812 sequence; compound sand blow in W TN composed of 3 sandy units separated by clayey silt - short periods of quiescence between eqs

Evidence for Clustered Earthquakes



Prehistoric (~900 A.D.) compound sand blow in NE AR composed of 2 sandy units separated by clay; formed as result of separate but closely timed eqs (days- mos)

Clustered Earthquakes

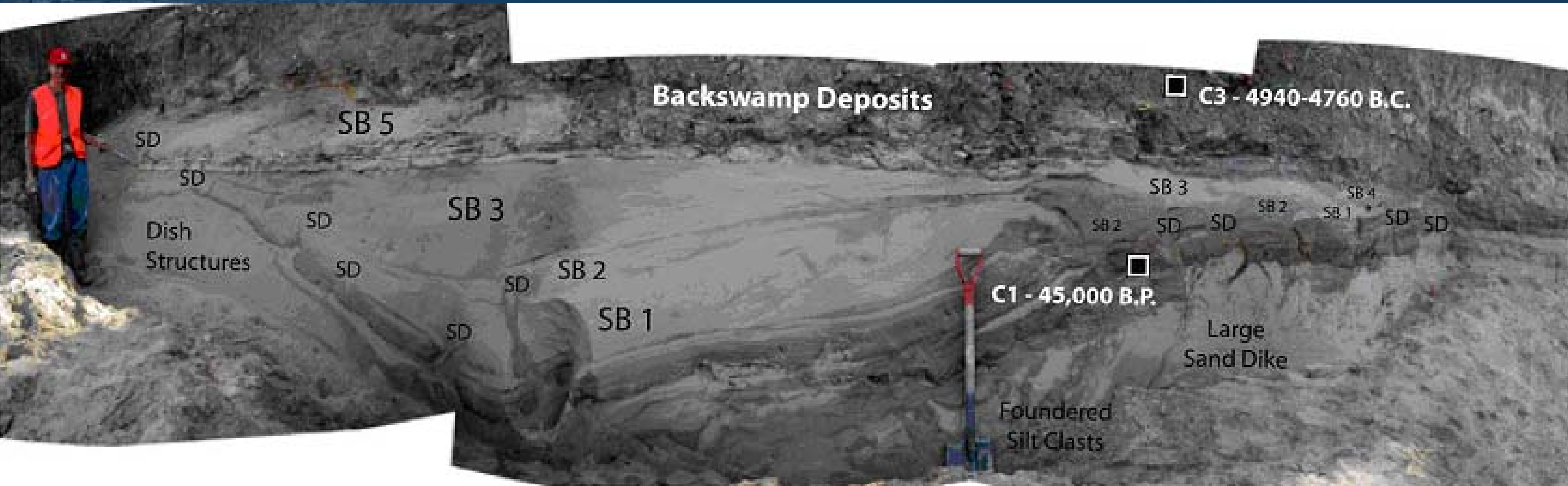


▲ Sand Blows Composed of 4 Depositional Units (as of 2001)

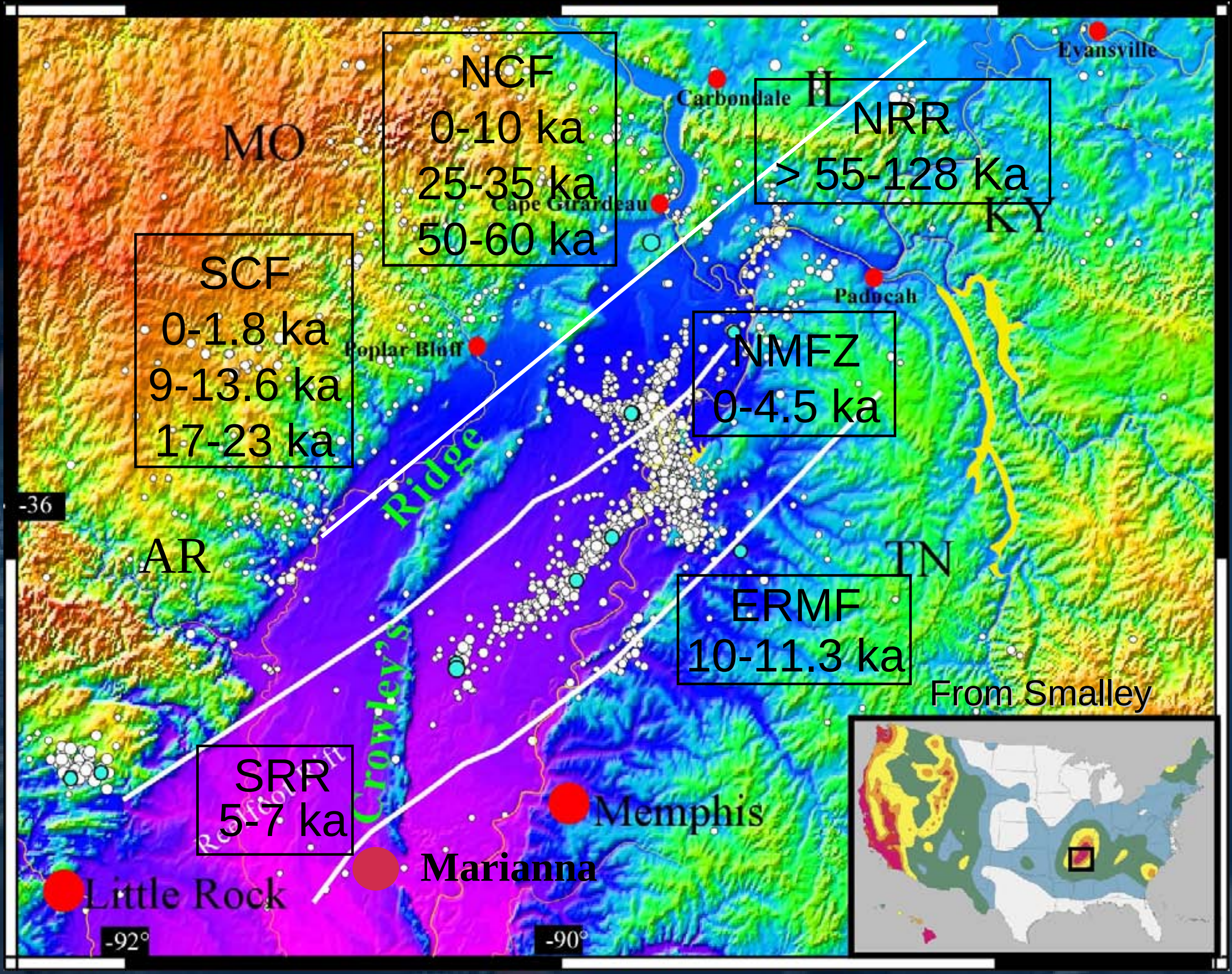
Modified from Tuttle et al., 2002

Bi-modal clustering; intracluster times - days to months; intercluster times - 300 to 800 yr (1700 yr); temporal clustering may result from contagion and complex interaction between faults

Clustered Earthquakes



Paleoseismology of Reelfoot Rift



From Smalley

Seismicity migrates (5-15 ky) within rift most recently to NMSZ (McBride et al., 2002); NMFS, ERMF - E Reelfoot Margin Flt, CF Commerce Flt, RR - Reelfoot Rift

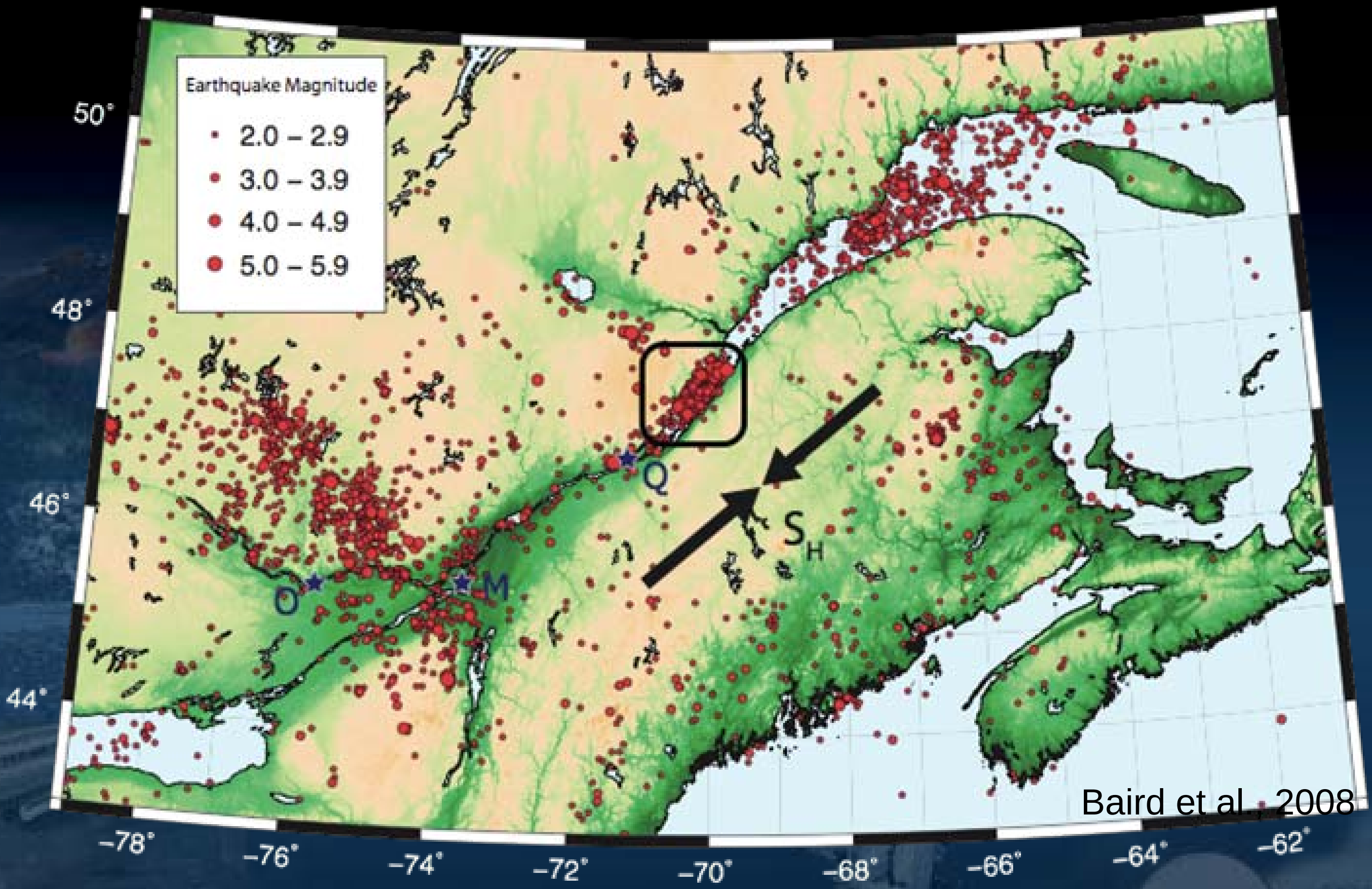
Negative Evidence

- Certain *conditions* must be met for negative evidence to be meaningful
  a) presence of *loose, sandy sediments* overlain by fine-grained sediments (surficial geology maps and borehole data)
  b) *water-saturated* conditions during the time period under consideration; fluctuating water table seasonally, annually, during past tens of thousands of yr could lead to incomplete record of events
  c) good *exposure* of sediments provided by low river levels and actively eroding banks; search adequate length of exposure (depends on quality)
- Even when these conditions are met and no liquefaction features are found, large earthquake *cannot be ruled out*

Negative Evidence

- Local *case histories* of eq-induced liquefaction and *liquefaction potential analysis* can be used to help constrain level of ground shaking
    a) Local events can help to establish liquefaction threshold (e.g., M 5.1-6.2)
    b) Liquefaction potential analysis can help to establish the magnitude and distance of eqs that are likely to induce liquefaction (e.g., M 5.5-6.2)
    c) If no liquefaction features found, *unlikely* that earthquakes of certain magnitudes (e.g., M > 6.2) occurred in area during time period evaluated

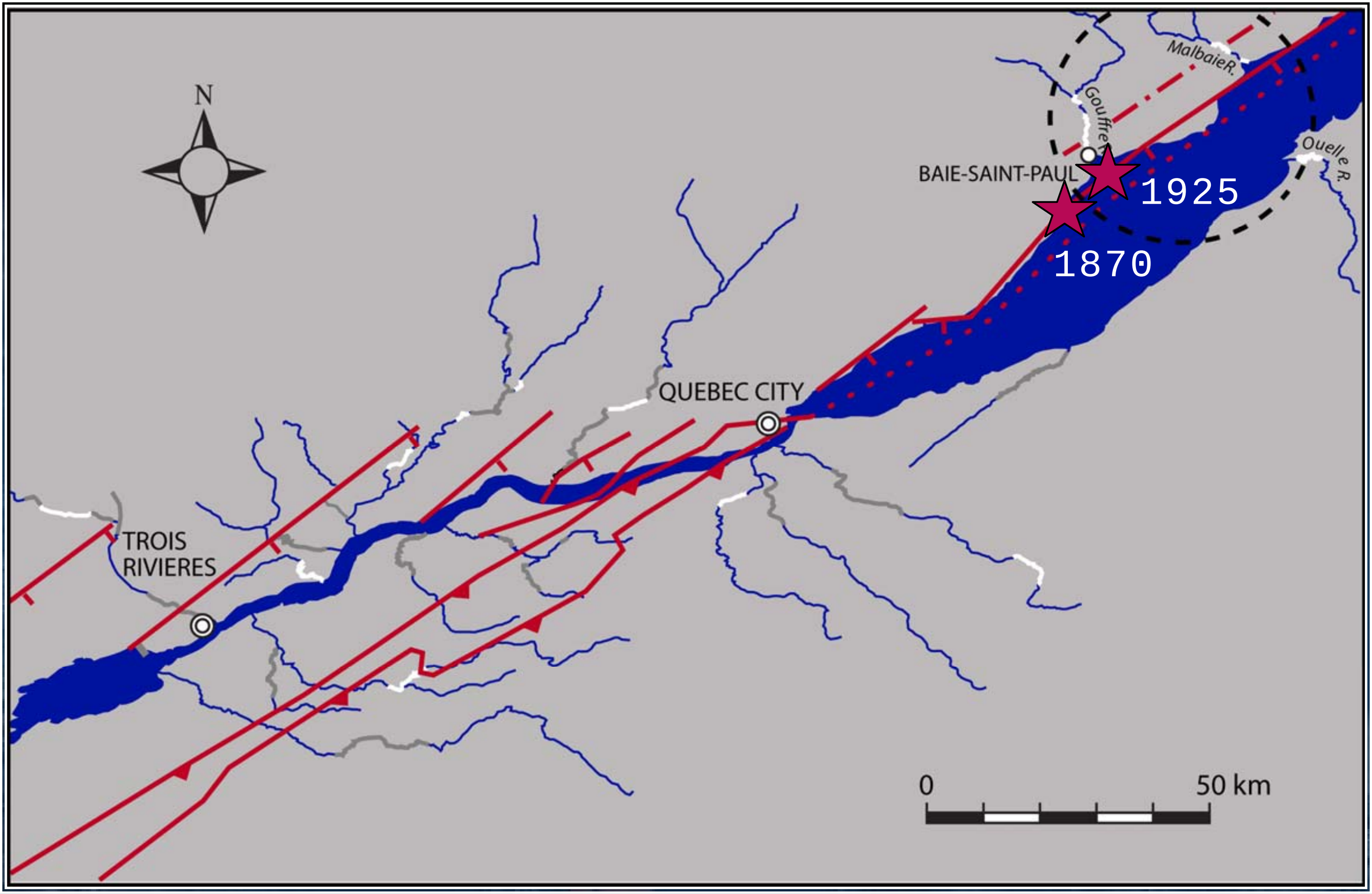
Charlevoix Seismic Zone



Baird et al., 2008

Historically, larger and more frequent eqs than surrounding region. Purpose of study was to determine if historically high rate typical of longer-term (Tuttle, Atkinson, Dyer-Williams)

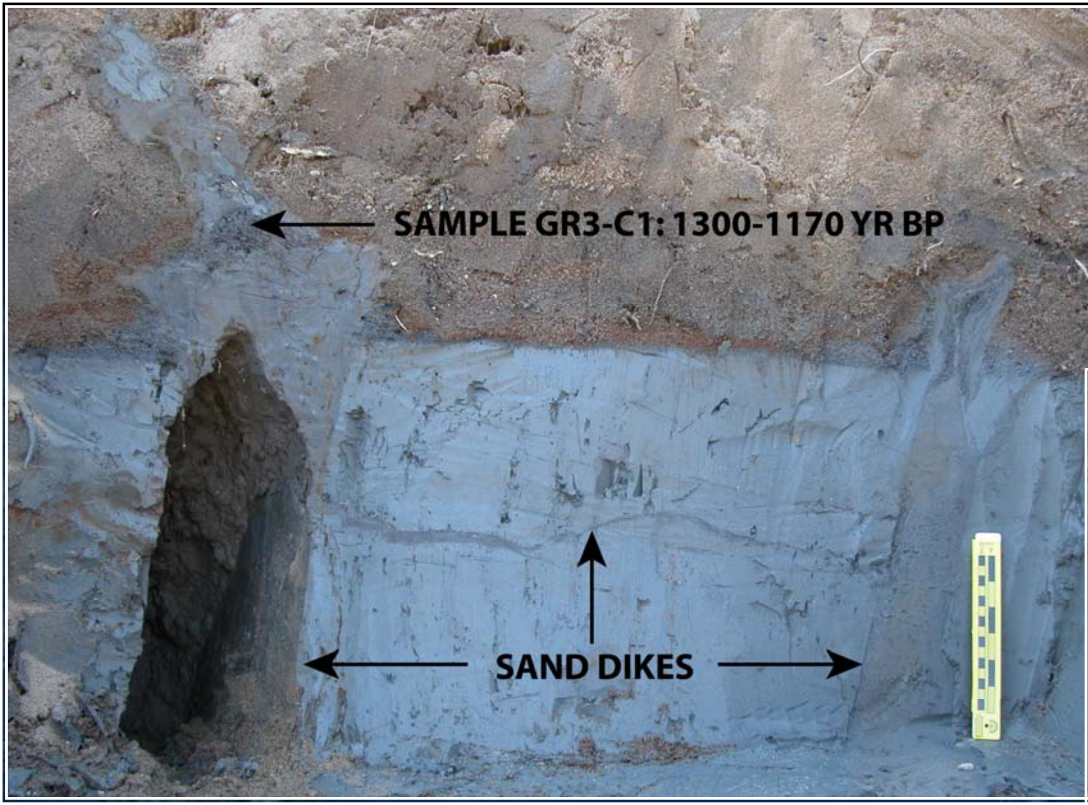
Search for Paleoliquefaction Features



- Surveyed 40 km of 3 rivers in Charlevoix region and 100 km of 8 rivers in Quebec City-Trois Rivieres region

Charlevoix Region

- Three generations of liquefaction features in 10 ky along all 3 rivers in CSZ



- Sand dikes intrude layered marine deposit and terminate in base of sandy fluvial deposits (poorly constrained 1-9 ka)

Quebec City-Trois Rivieres Region

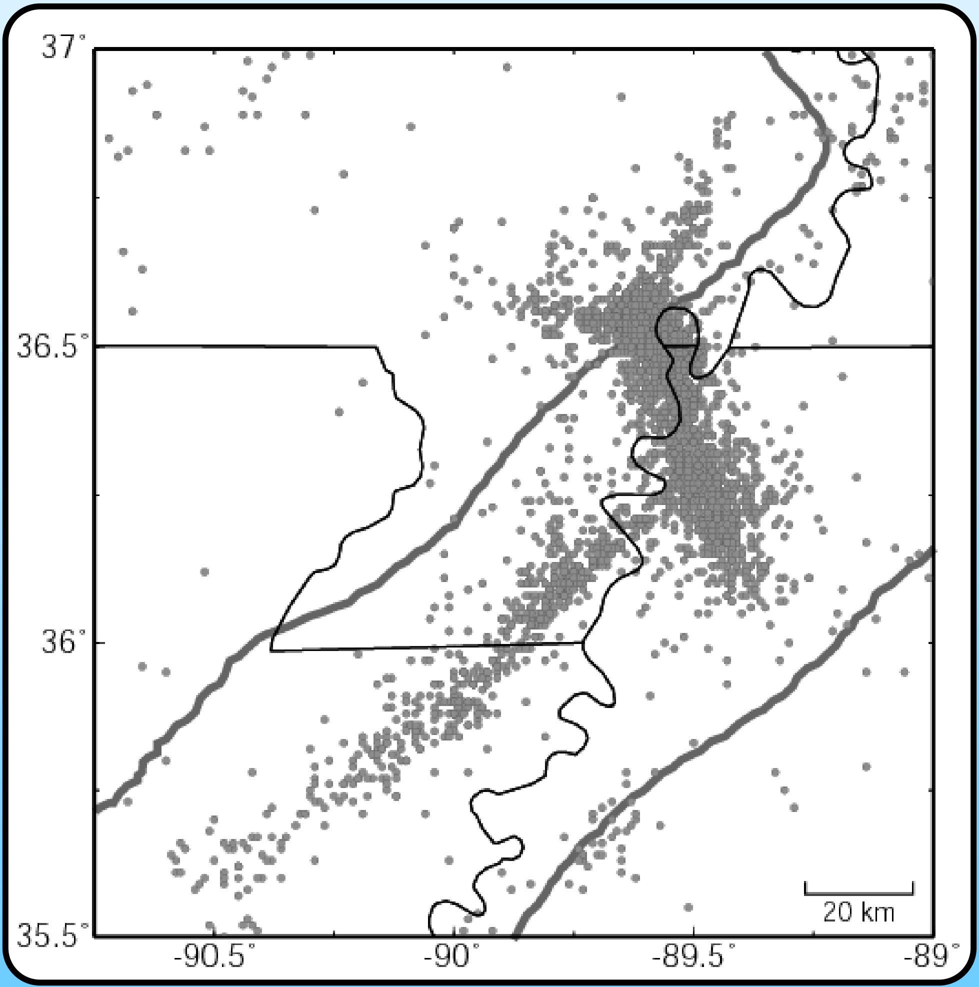
- No sand dikes or other liquefaction features found despite examining exposure of similar deposits for 100 km

Summary of Findings

- Sand dikes and other deformation structures related to liquefaction found *only in Charlevoix* region
- Stratigraphic position and radiocarbon dating suggest at least *3 events during past 10,000 yrs*; other events possible that would not induce liquefaction during low sea-level stands
- M ≥ 6.2 eq in CVSZ likely produced observed liquefaction features; M 5.5-6.2 eq in Quebec City-Trois Rivieres region could induce liquefaction locally but no features found
- *More frequent* large earthquakes in Charlevoix than in QC-TR area during past 10,000 yr

La Fin

New Madrid Model for Repeated Events; Geodetic Signature Along the Southeast Margin and Elsewhere



S.J. Kenner

Acknowledgements: P. Segall, Stanford University

Understanding Intraplate Seismicity

To properly evaluate observations and asses seismic hazard in the NMSZ and other intraplate regions

- Require a conceptual framework appropriate to the tectonic regime being considered
- If an appropriate framework is not used, data will be ambiguous

Unfortunately, the majority of our knowledge regarding earthquake physics has been derived from studies of plate boundary faults

Localized Intraplate Faulting vs. Plate Boundary Tectonic Regimes

Key Differences

Kinematics

- Far-field relative velocities
- Spatial distribution and magnitude of interseismic deformation rate
- Continuity with adjoining faults (i.e., do fault end effects constrain cumulative offsets)

Temporal

- Regular vs. systematically varying earthquake recurrence intervals*
- Geologically long-lived vs. transient seismicity

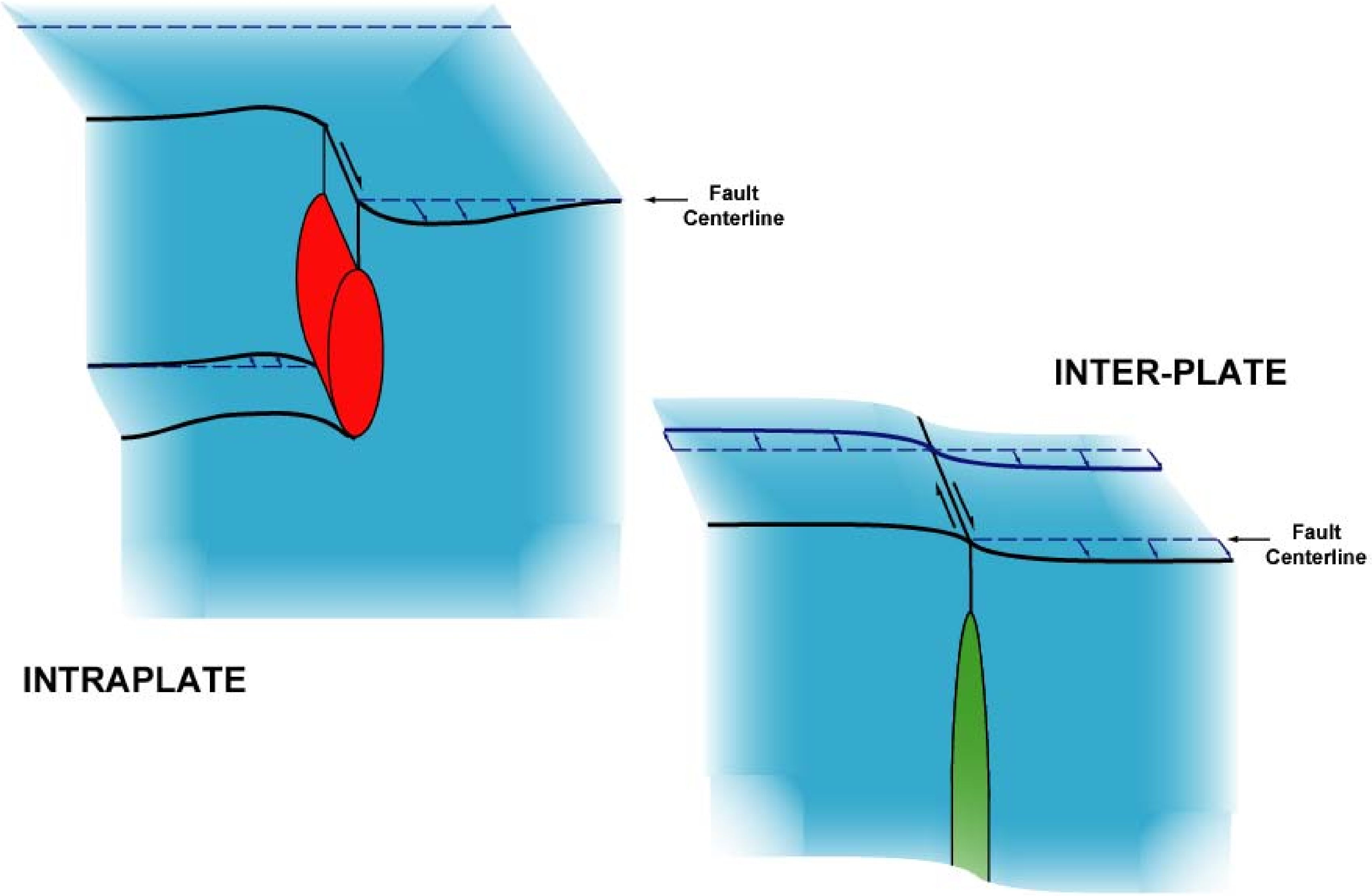
Reason for stress localization

- Plate boundary vs. rheological heterogeneity

Source of stress that drives seismicity

- Far-field plate tectonic forces vs. local or regional perturbations to the stress field

* After accounting for natural variability in earthquake recurrence intervals

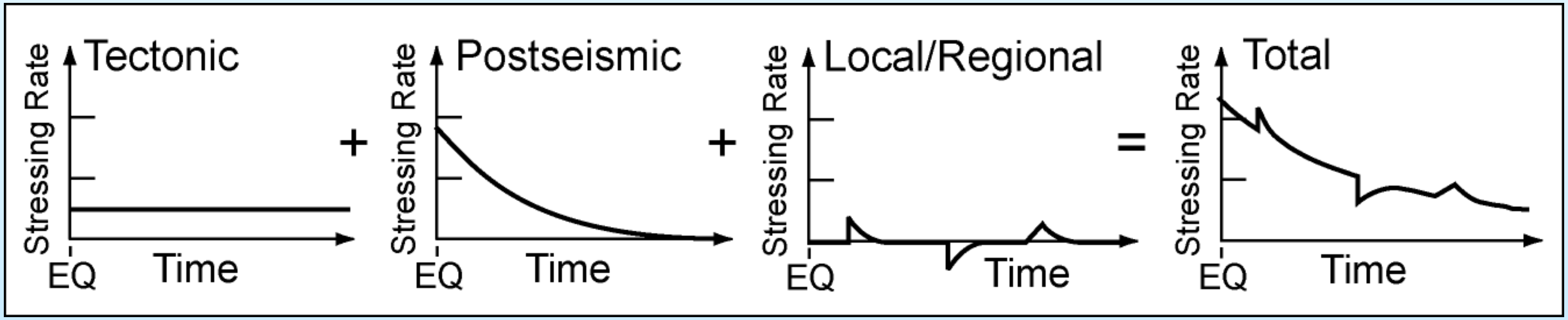


🟩 Aseismic Slip

🟦 Standard

🟥 Weak

Stress Accumulation Along Faults



Stresses, which accumulate as a function of time and ultimately produce earthquakes, derive from a number of potential sources.

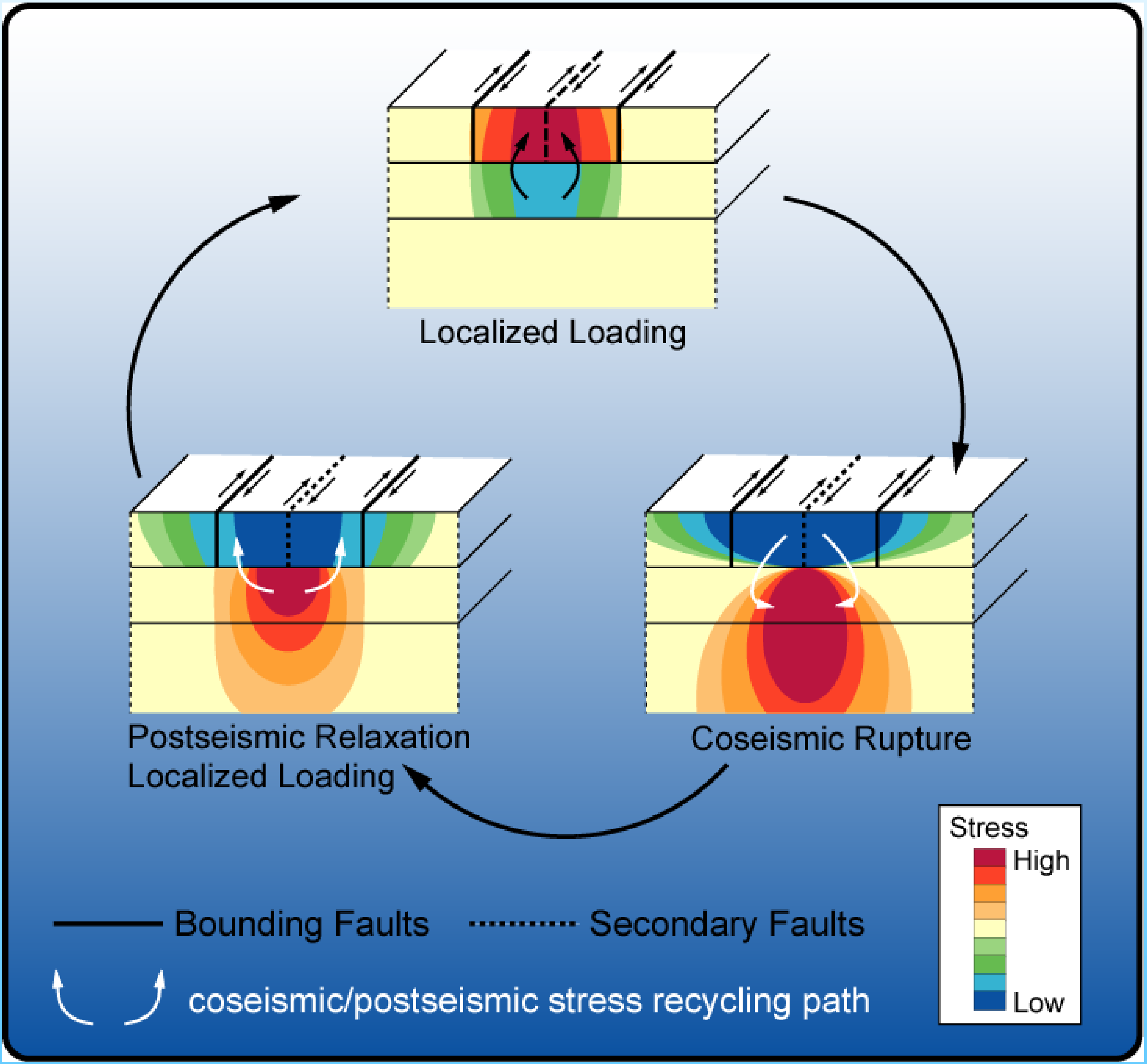
Tectonic: Due to large scale, far-field plate motions. Probably constant over time-scales < a few million of years.

Postseismic: Result from postseismic stress recycling from prior coseismic events on the fault.

Local/Regional Sources: Due to a) postseismic transients from neighboring faults, b) fluid effects, c) thermal effects, d) changes in local or regional scale gravitational forces due to buoyancy, topographic, or other surface loads, and/or e) concentration of stress due to rheological or structural heterogeneities of all length scales, etc.

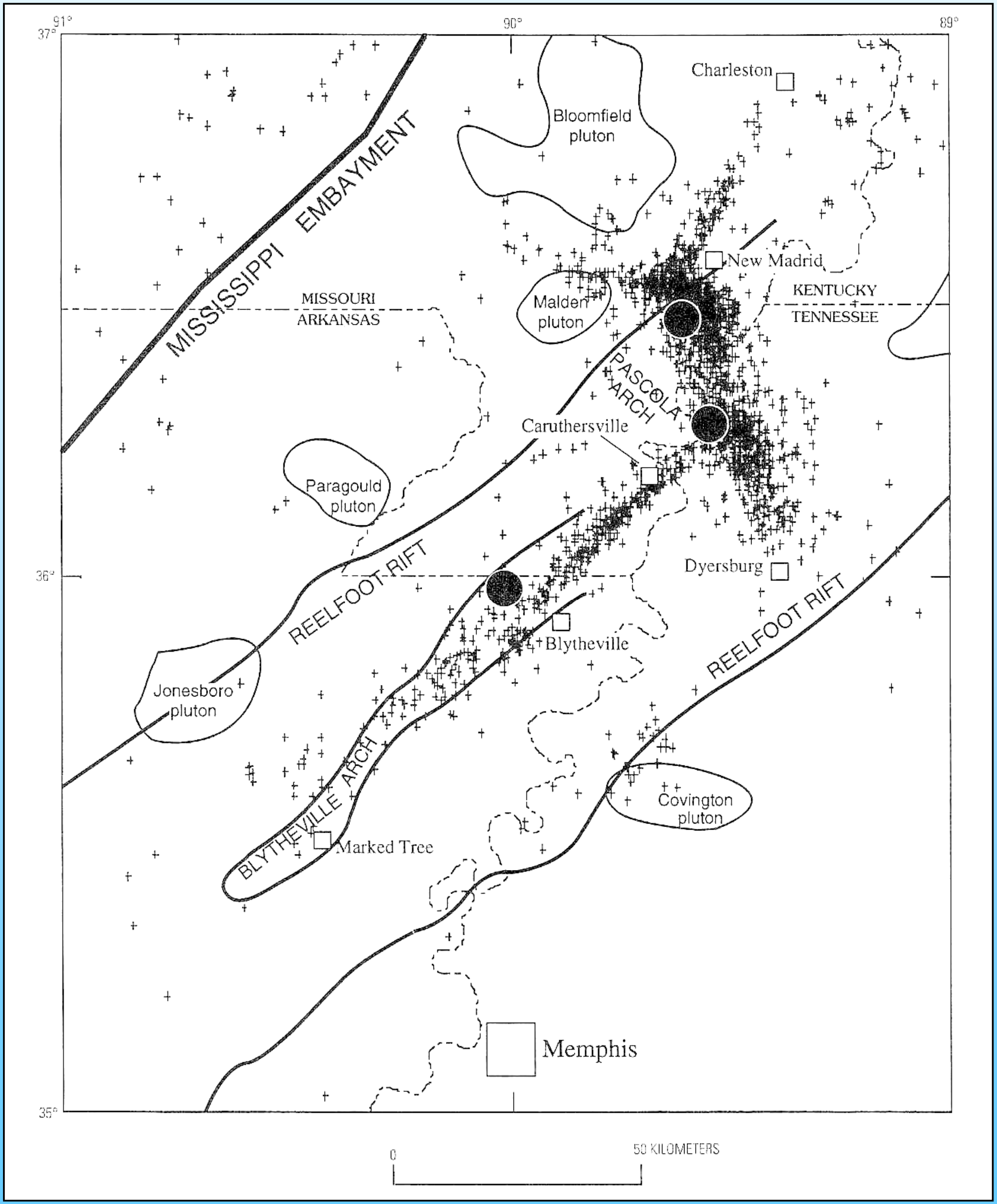
Crustal Stress Cycle

Localized Loading Source



New Madrid Seismic Zone

- Located above failed rift zone
- A complex structure repeatedly reactivated throughout geological time
- Must re-equilibrate to changes in the tectonic stress field in the N. American plate



Sheldock and Johnston (1994)

Pertinent Observations from the New Madrid Seismic Zone

1. Large (M 7-8) earthquakes spaced every ~500 years

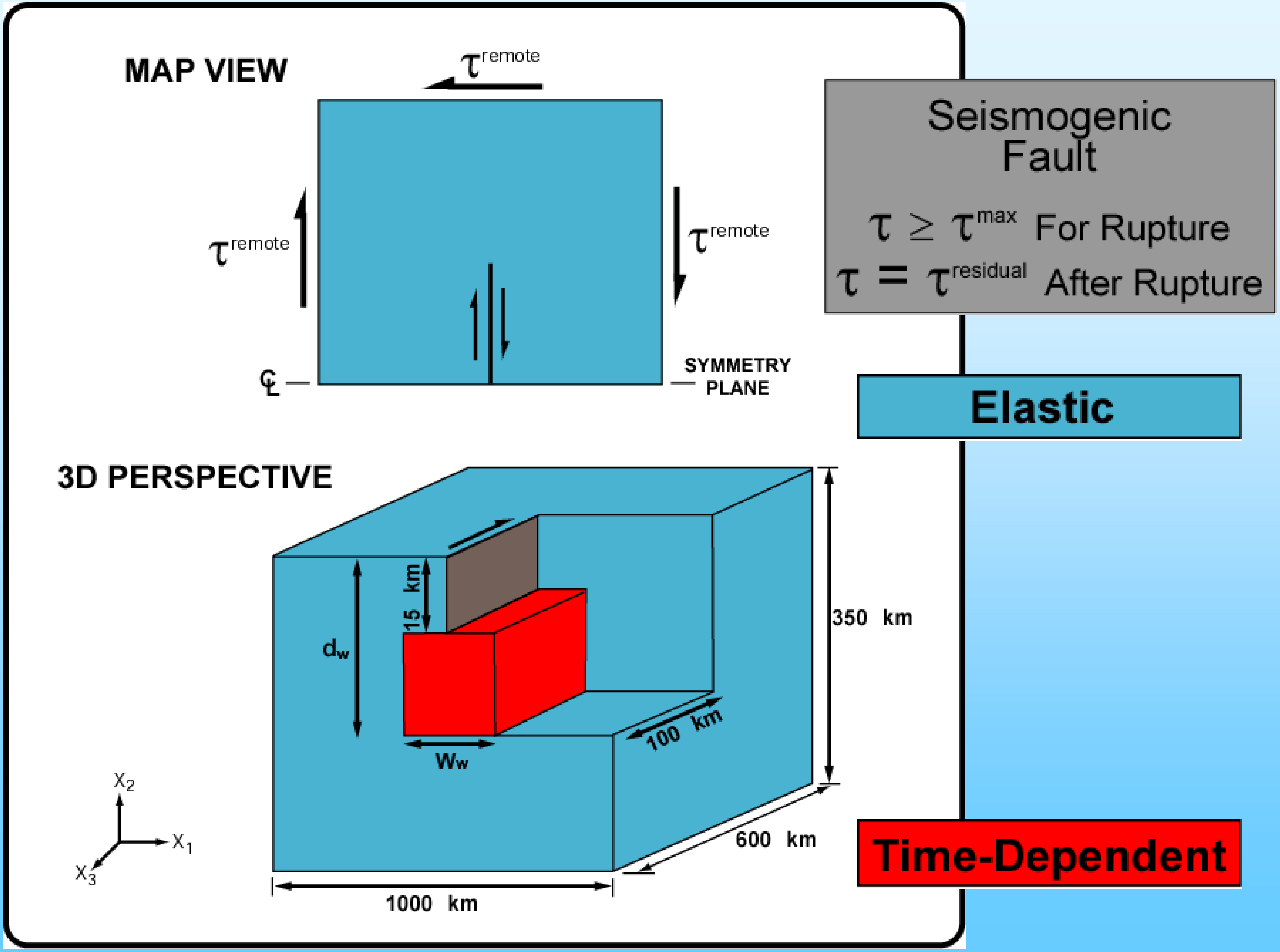
2. Cumulative fault offset < 100 m

3. Recent earthquakes confined to late Holocene (last 10,000 yrs). At very least, rate of earthquakes has increased during the Holocene

4. Zone of current seismicity ~200 km long

5. No far-field relative velocities (intraplate)

6. Strain-rates may be very low ~200 yrs after the 1811-1812 earthquakes.



Seismogenic Fault

$\tau \geq \tau^{max}$ For Rupture

$\tau = \tau^{residual}$ After Rupture

Elastic

Time-Dependent

Fault Constitutive Relation

- Maximum shear stress criteria

$$\tau \geq \tau^{\text{max}} \text{ for rupture}$$
$$\tau = \tau^{\text{residual}} \text{ after rupture}$$

- Defined using contact surfaces
- Evaluated independently at each node on fault plane

Material Rheologies

- **Elastic material**

Shear Modulus = $3.5\text{x}10^4$ MPa; Poisson's Ratio = 0.25

- **Weak Zone** (Maxwell viscoelastic)

Shear Modulus = $3.5\text{x}10^4$ MPa; Poisson's Ratio = 0.25
Viscosity (η) = 10^{21} Pa-s
Relaxation Time ($2\eta/\mu$) ~ 1800 yrs

Model Behavior

Because the weak zone is finite and constant stress boundary conditions are applied ...

net fault offset is finite as $\tau \to \infty$
there are a finite number of large slip events

Numerical analyses investigate:

earthquake magnitude, recurrence intervals
deformation rates

Relaxation could be induced by:

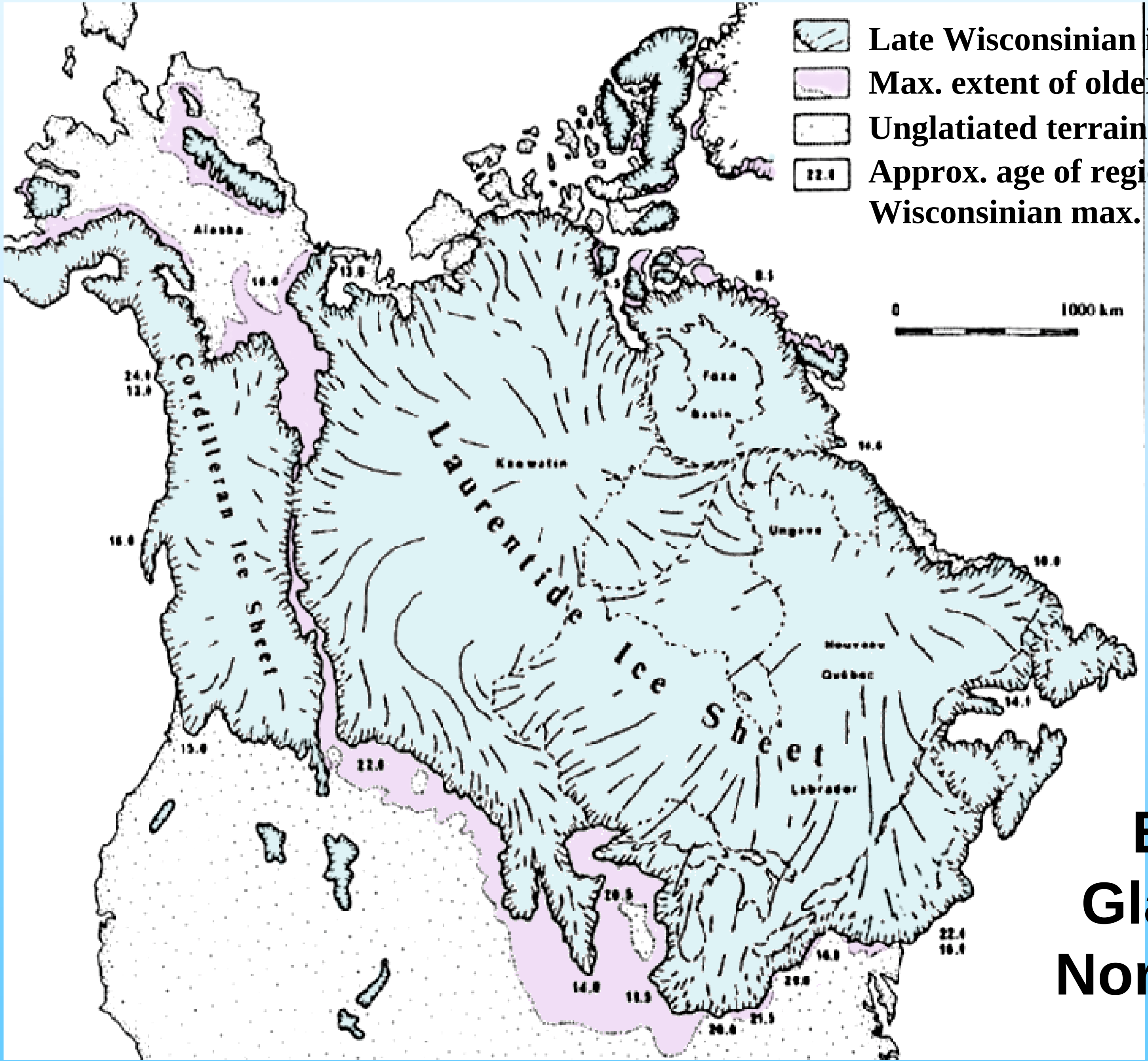
Variation in Strength (e.g. thermal or fluid perturbation)
or
Transients in local or regional stress

Major questions:
In regions of concentrated intraplate seismicity ...

- Is there a zone of weakness? If so, how/why did it form?

- What tectonic process could have triggered the seismicity transient?

Extent of Glaciation in North America



Late Wisconsinian ice sheets and glaciers

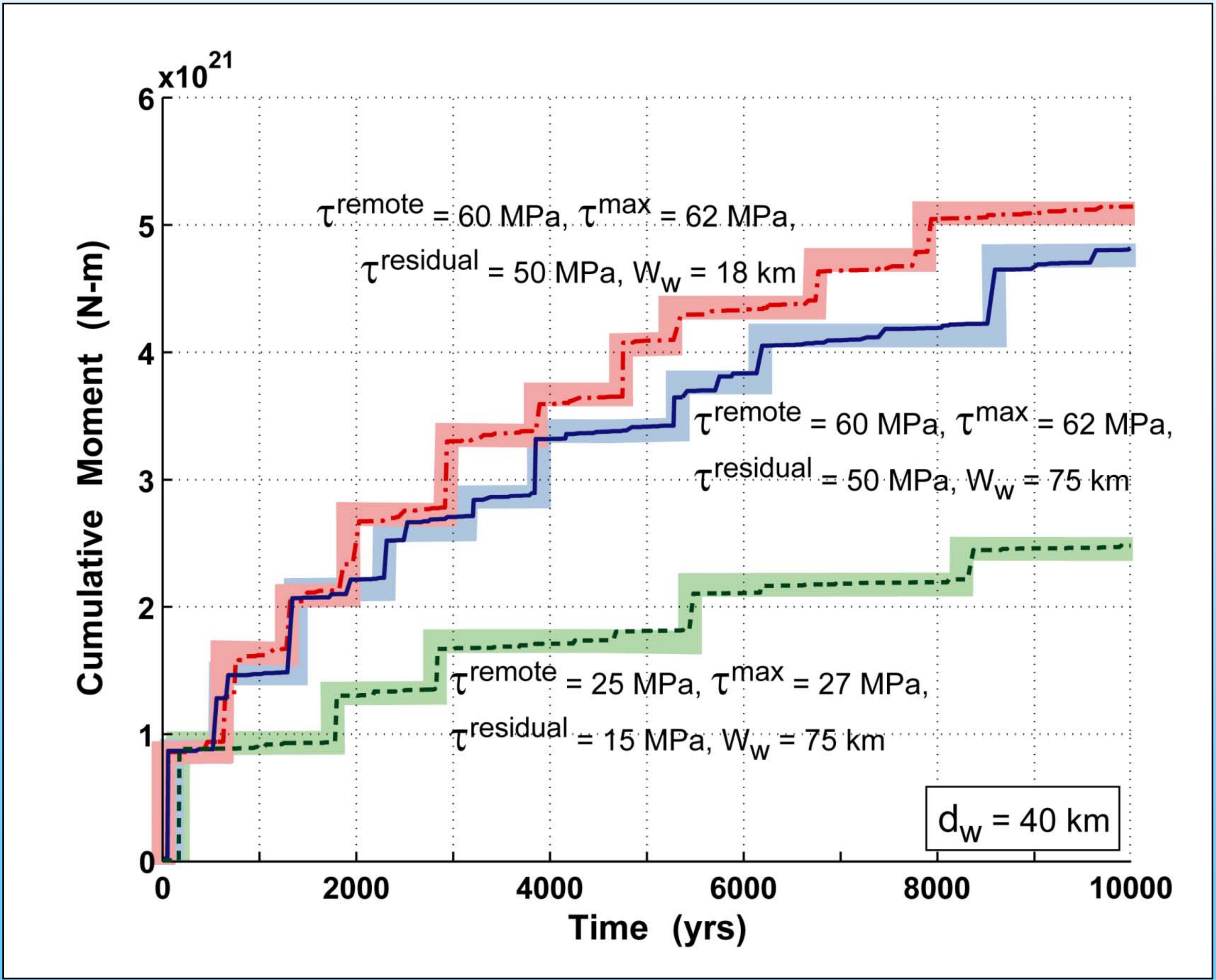
Max. extent of older Pleistocene glatiation

Unglatiated terrain

Approx. age of regional Late Wisconsinian max.

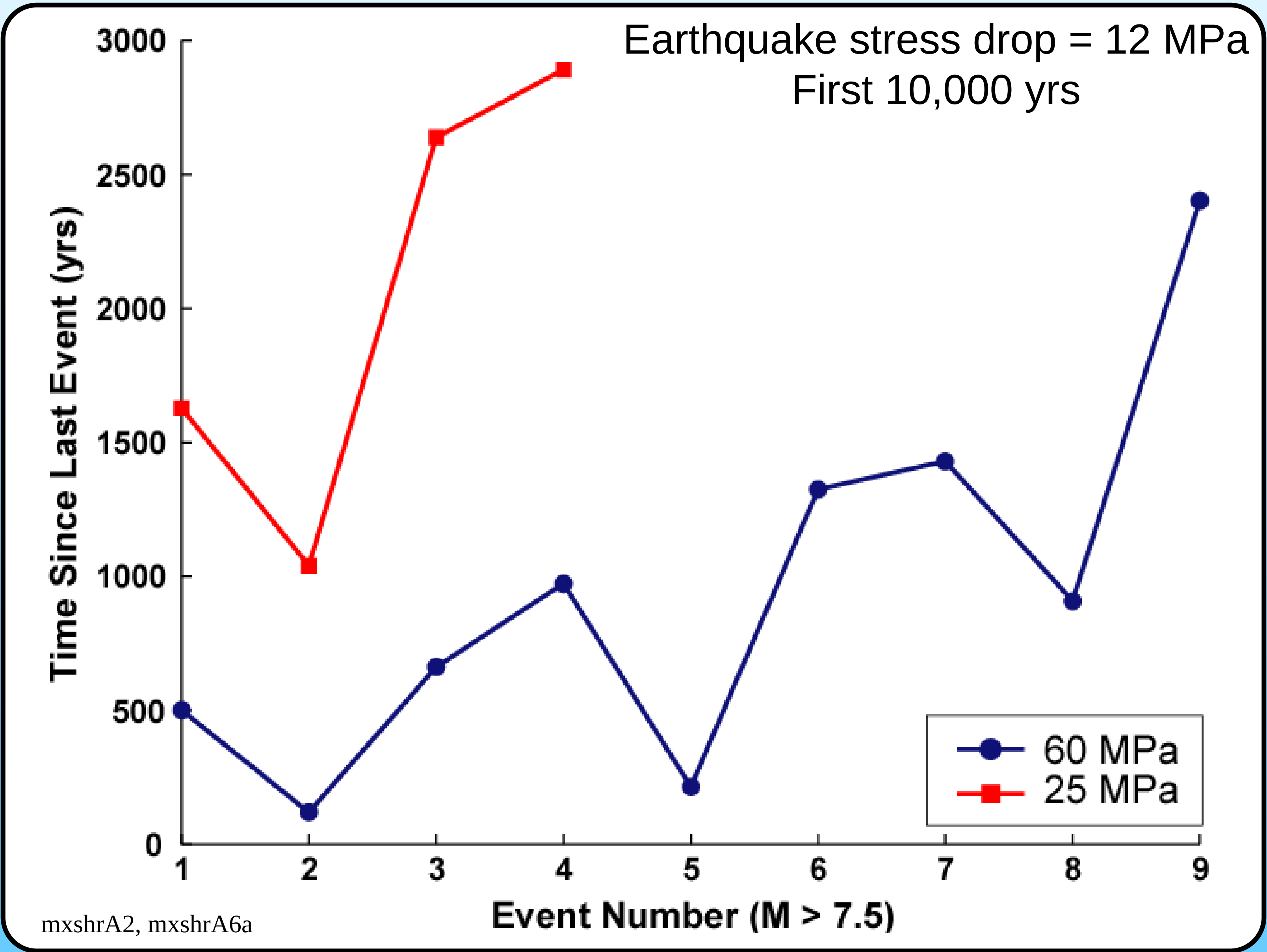
http://geology.isu.edu/Digital_Geology_Idaho/Module12/mod12.htm, from *Thackray et al., 2004, and Sherard, 2006*

Cumulative Moment vs. Time

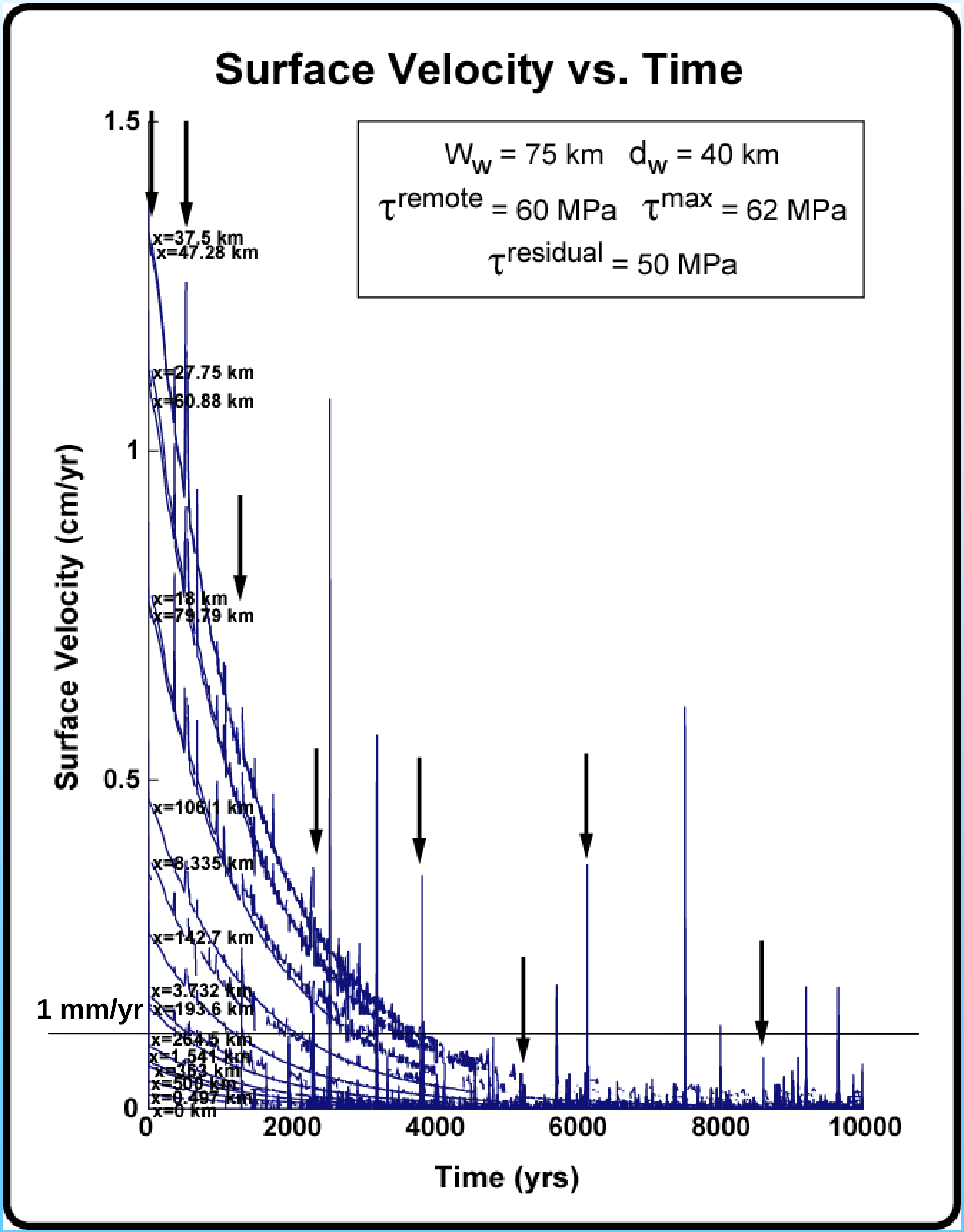


mxshrA2, mxshrA6a, mxshrA3c

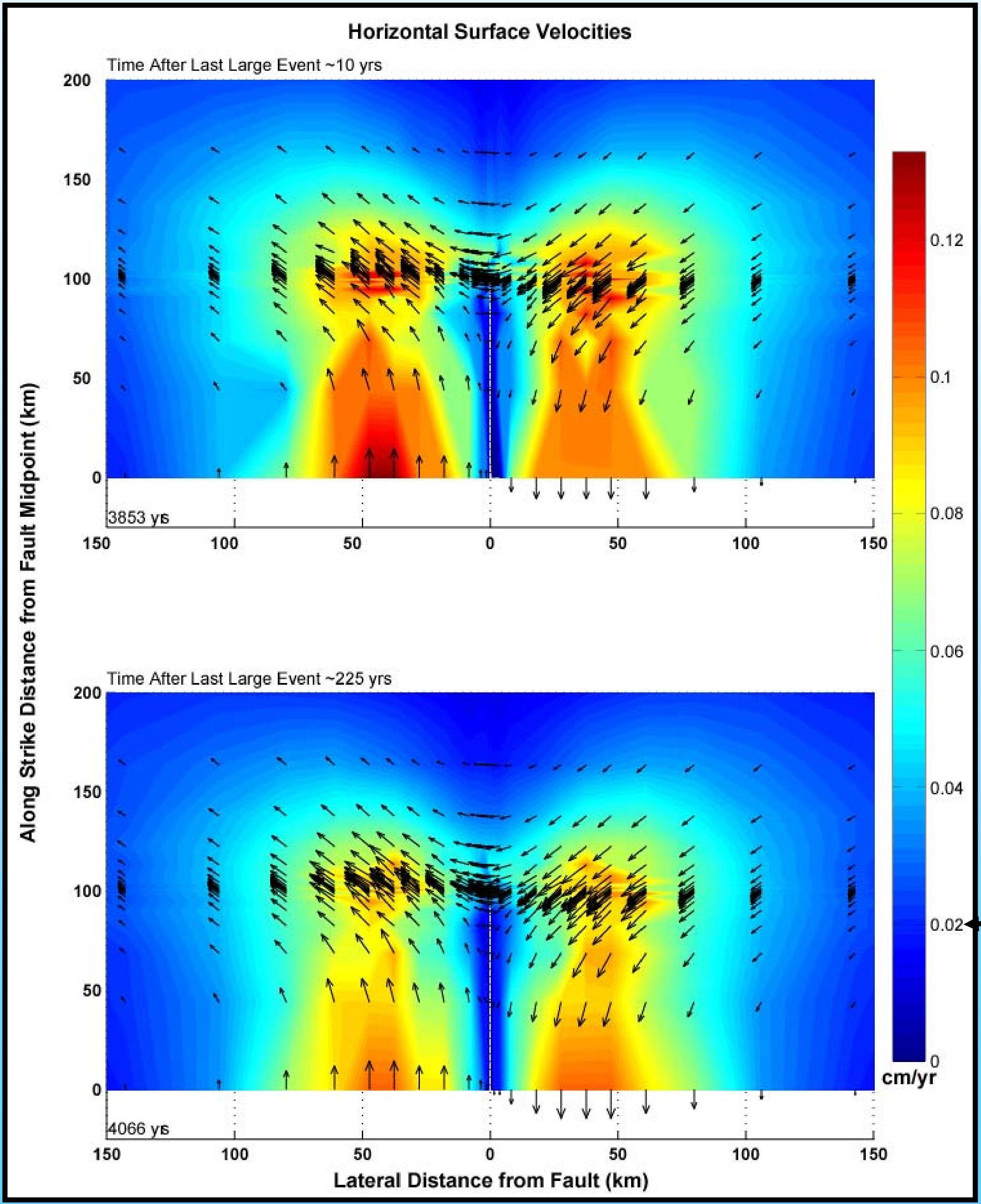
Dependence of Earthquake Recurrence Interval on Remote Stress



Surface Velocity vs. Time



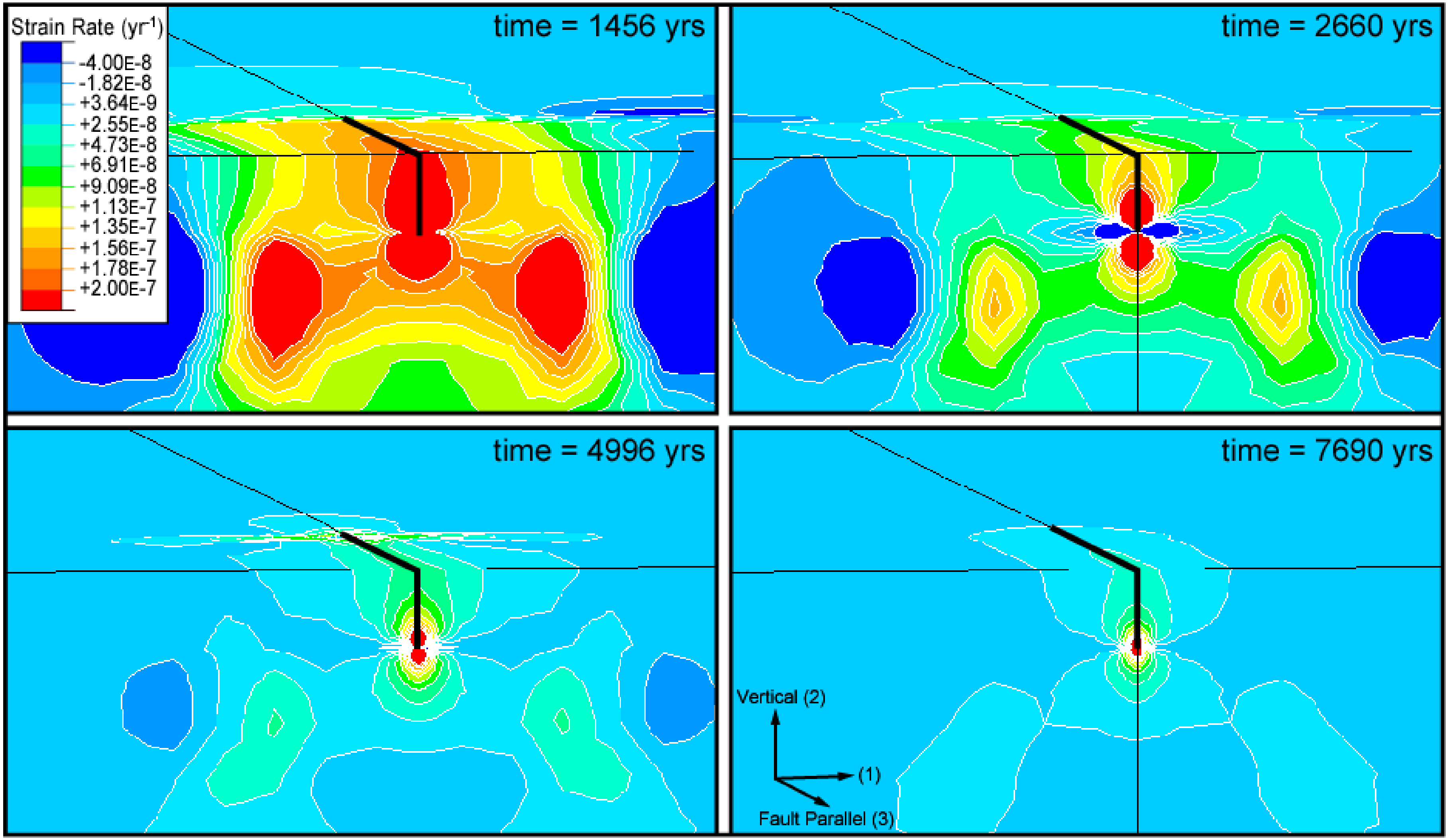
Surface Velocity Contours



0.2 mm/yr

Time 0: Uniform Stress (τ_{13} = 60 MPa, all other components = 0)

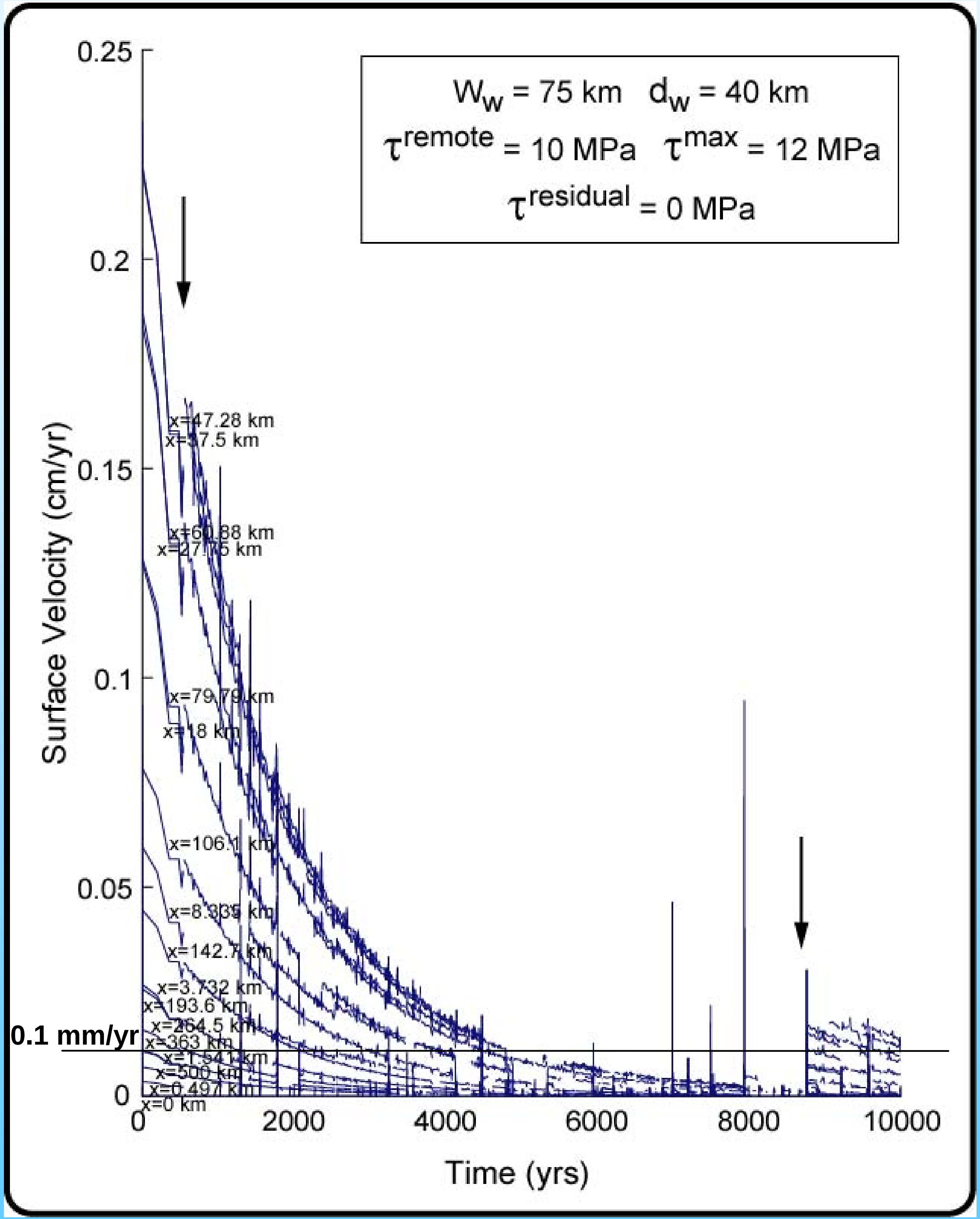
W_w = 75 km; d_w = 40 km; τ^{remote} = 60 MPa; τ^{max} = 62 MPa; $\tau^{residual}$ = 50 MPa; η_w = 10^{21} Pa-s



Fault Parallel Shear Strain Rate

mxshrA2

Surface Velocity vs. Time



mxshrA6b

Weak Zone Relaxation

Preliminary Estimates

Characteristic Time of Relaxation Process

(Voigt solid)

$$T_{tot} \propto \frac{\eta_w}{\mu}$$

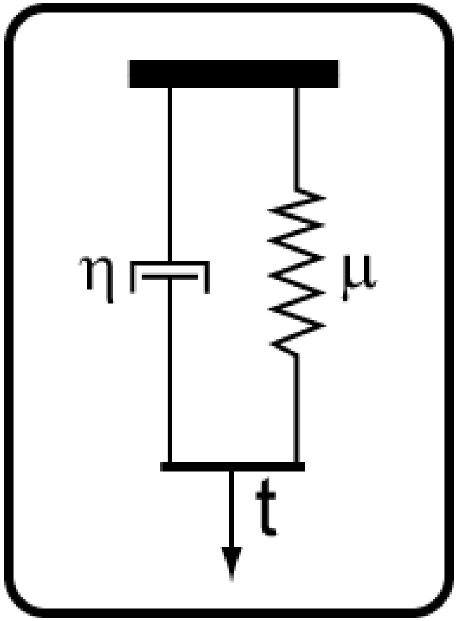
Recurrence Interval

(Voigt solid)

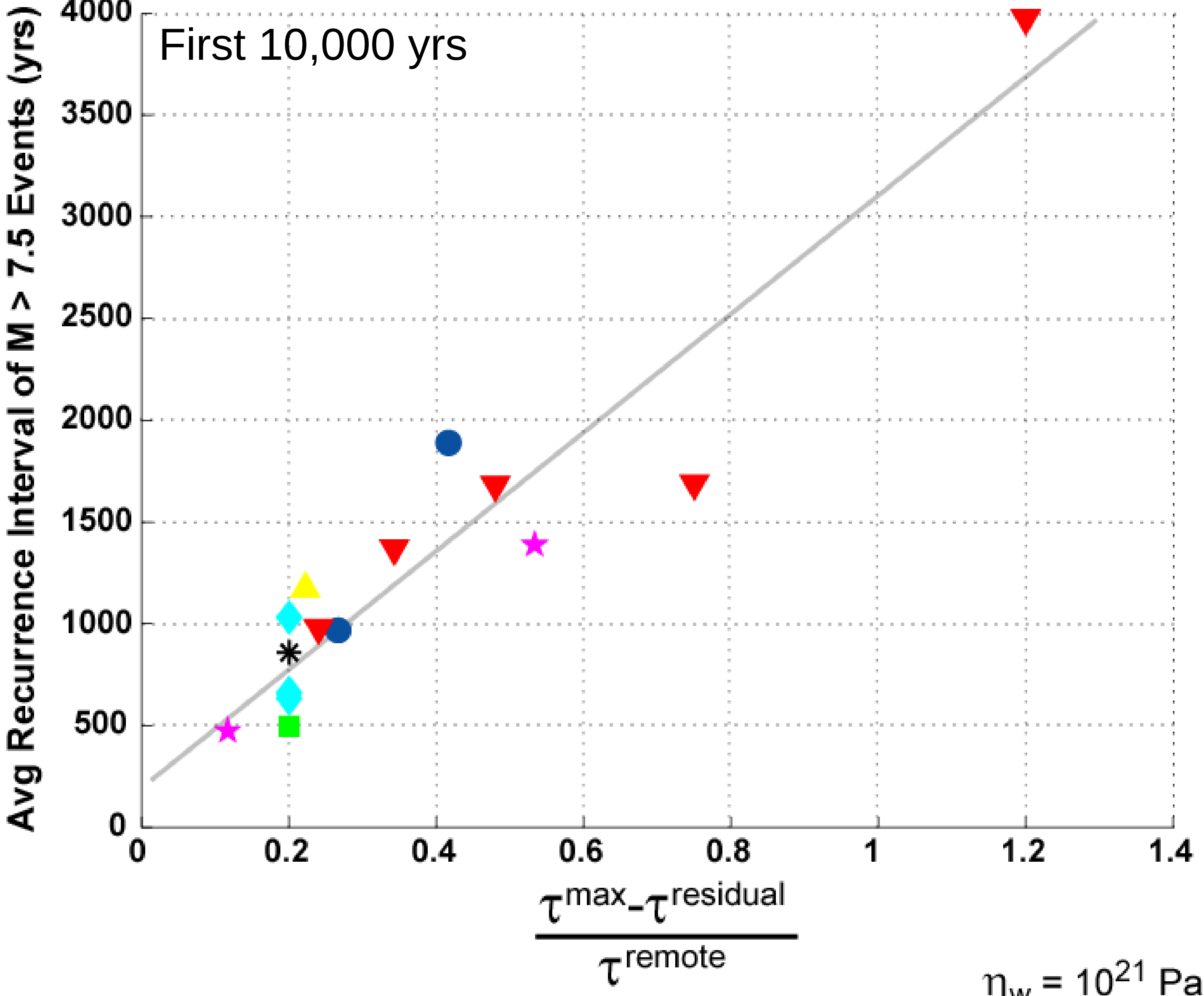
$$\Delta T = \frac{\tau^{max} - \tau^{residual}}{\dot{\tau}}$$

$$\dot{\tau} \approx \mu \dot{\varepsilon}$$

$$\Delta T = \frac{\eta_w}{\mu} \frac{\tau^{max} - \tau^{residual}}{\tau^{remote}} \exp\left(\frac{\mu}{\eta_w} t\right)$$

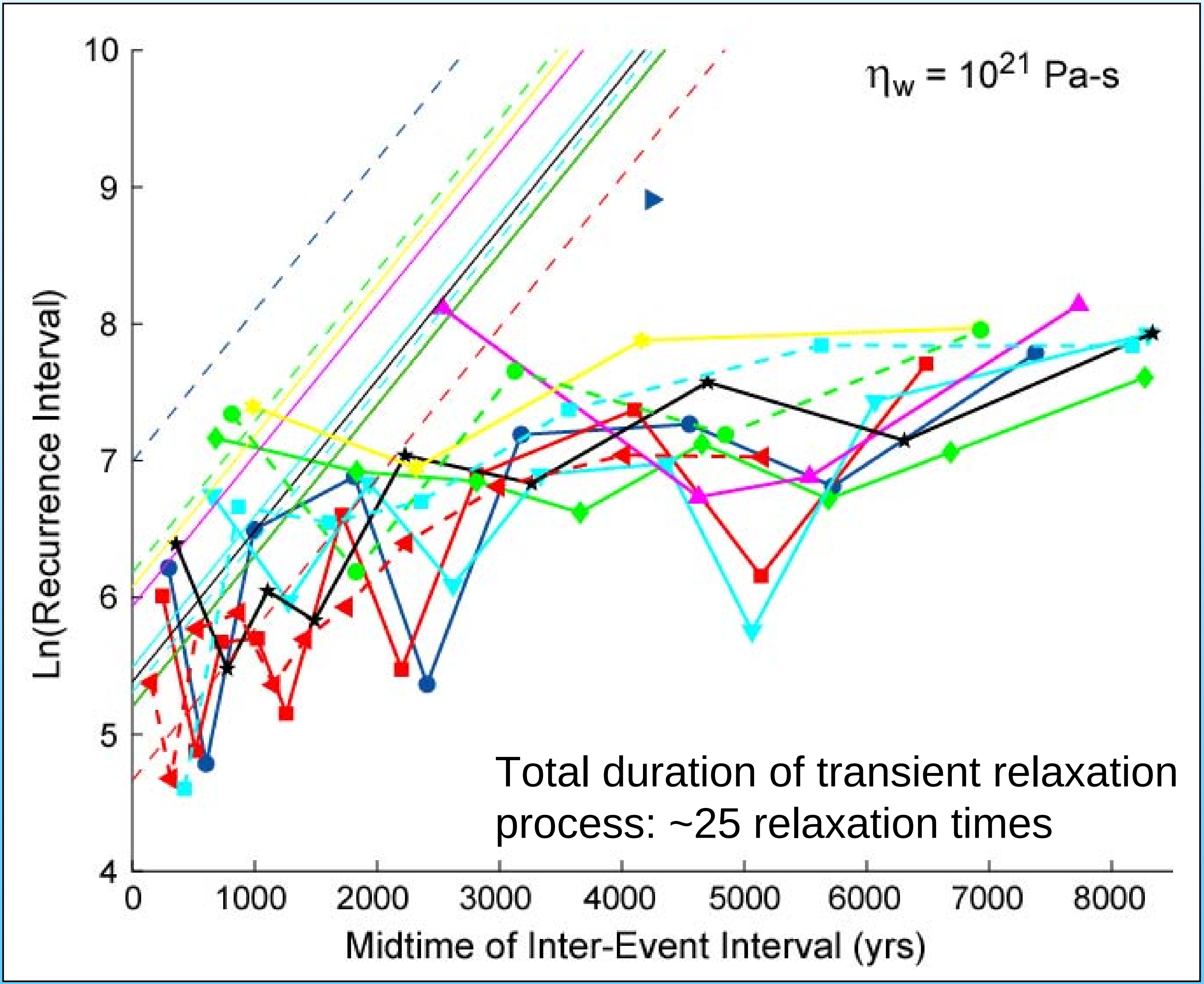


Average Recurrence Interval vs. $\frac{\tau^{max}-\tau^{residual}}{\tau^{remote}}$



$\eta_w = 10^{21}$ Pa-s

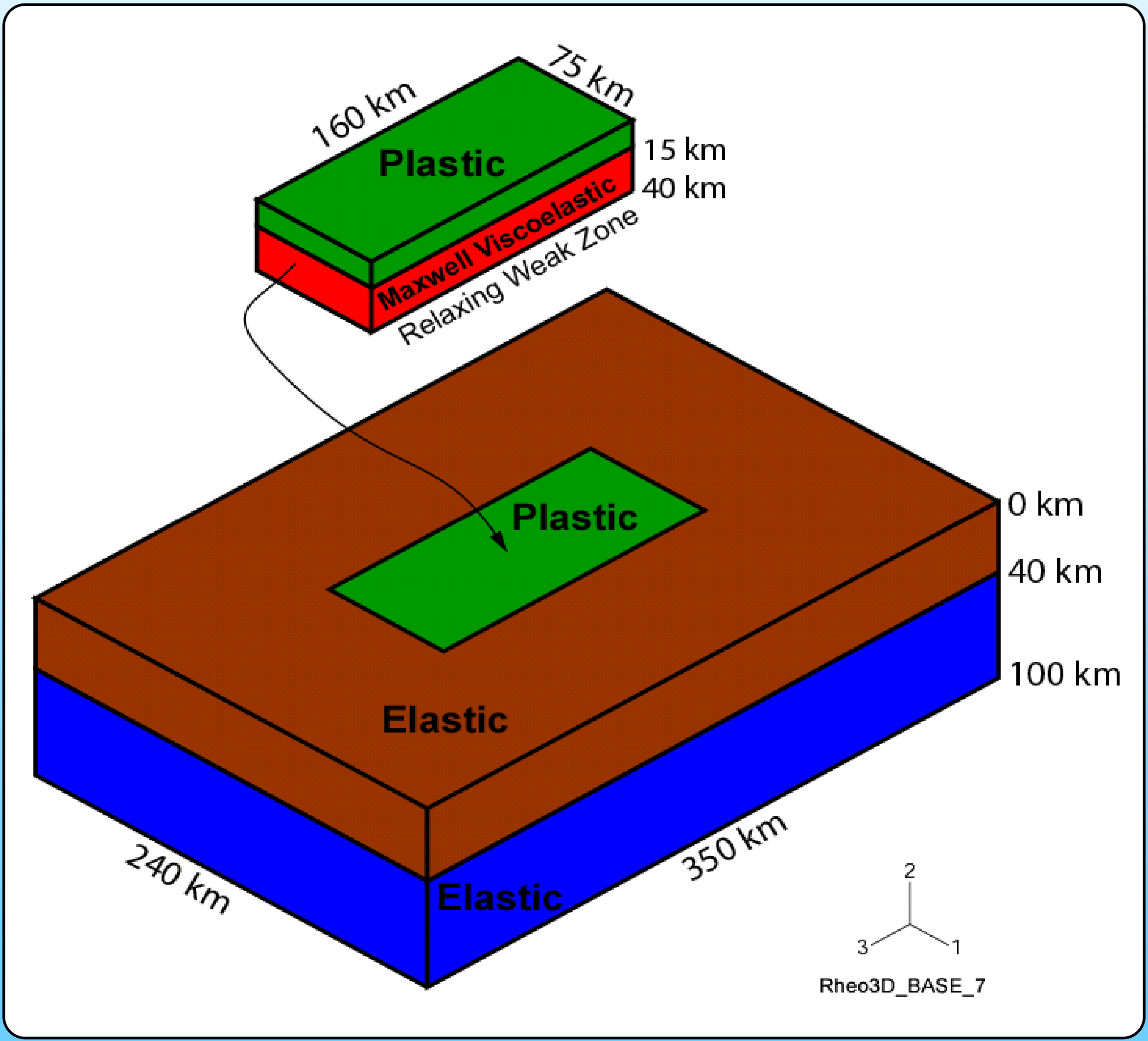
Recurrence Interval (M > 7.5) vs. Time



Total duration of transient relaxation process: ~25 relaxation times

3D Weak Zone Models

- Fixed far-field boundaries
- Prestress entire body uniformly
  - Initial stress field approximates stress directions in the NMSZ
- Allow weak zone to relax
- Observe resultant geometry and temporal evolution of plastic shear zones in overlying seismogenic crust
- Consider times qualitatively
  - Viscosities scaled for faster execution
- No gravity

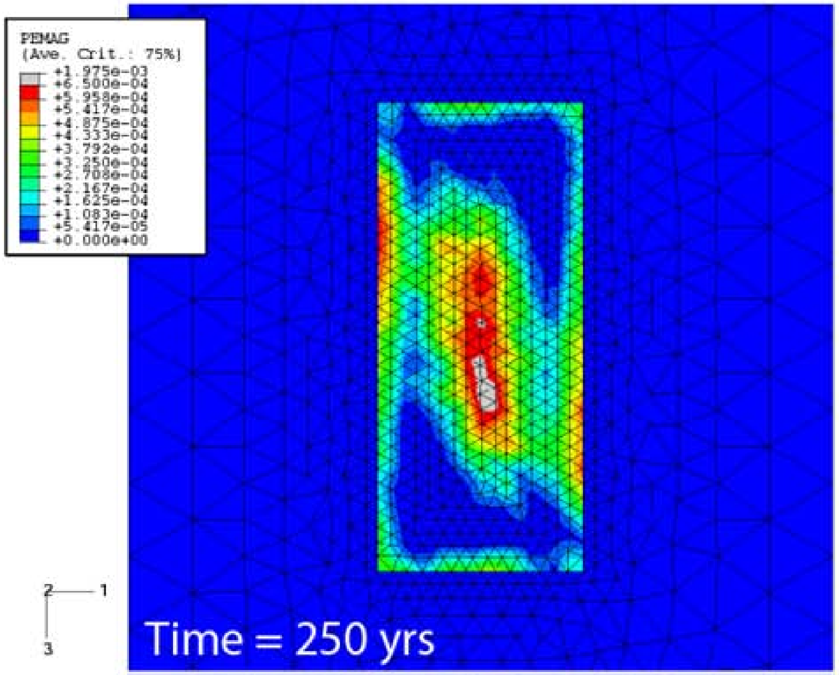


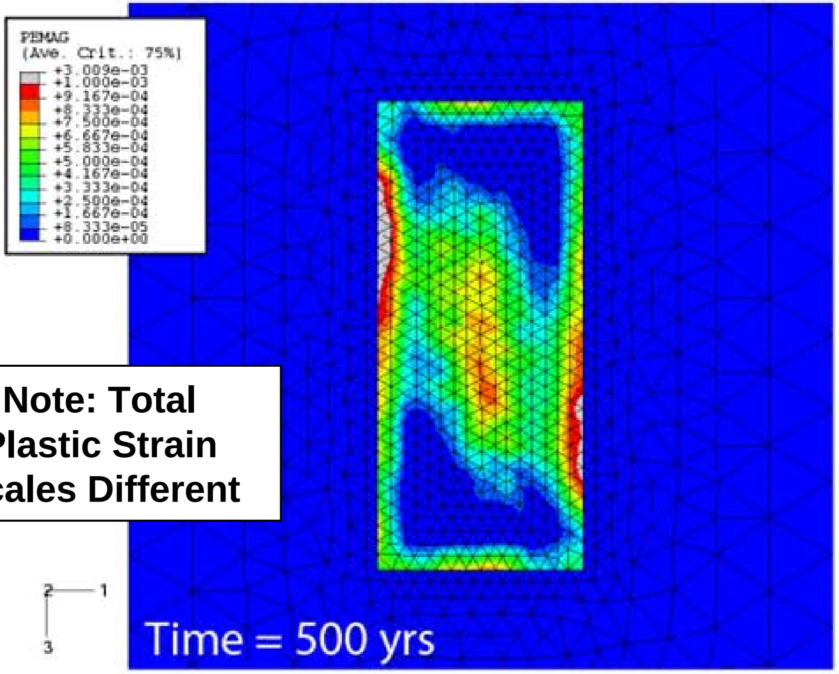
3D Models

Realistic Stress Directions

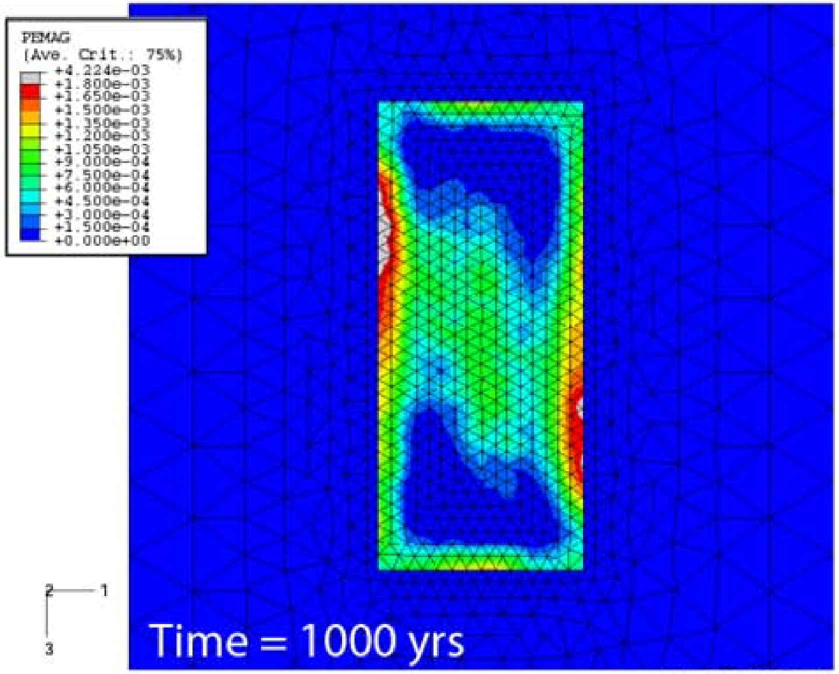
Total Plastic Strain

- Temporal variations in areas of plastic strain accumulation
- Initially shear zones develop diagonally across weak zone (similar to geometry seen in NMSZ)
- With increasing time shear zones move towards weak zone boundaries





Note: Total Plastic Strain Scales Different



Rheo3D_BASE_7rot2

Summary

- Stress loading from an underlying weak zone is a physically plausible mechanical mechanism for earthquakes in intraplate regions

---

- Model satisfies observational evidence from the New Madrid seismic zone

Earthquake Magnitude
Recurrence Interval
Cumulative Offset
Far-field Velocities
Local Deformation Rates

- Depending on parameters, model simultaneously predicts the occurrence of large earthquakes (sufficient to produce M > 7 EQ's every 500 yrs) and extremely low deformation rates
  - Estimated geodetic slip-rates may not equal inferred geologic slip-rates
  - Surface deformation rate may not be directly proportional to seismic hazard

Conclusions I

- Earthquake generation within intraplate seismic zones results from very different processes than earthquakes at plate boundaries
  - Local variations in rheology can influence/concentrate the temporal & spatial distribution of stress accumulation and seismic energy release
    - NMSZ repeatedly reactivated throughout geological time, an indication of weakness???
  - May be a transient (10,000’s years), temporally variable response to local/regional stress perturbations
    - Earthquake rates may not change significantly over time periods of only a few thousand years
- Sequences of earthquakes due to weak zone relaxation may be triggered by temporally variable localized stress transients
  - Due to a) postseismic transients from neighboring faults, b) fluid effects, c) thermal effects, d) changes in local or regional scale gravitational forces due to buoyancy, topographic, or other surface loads, and/or e) concentration of stress due to rheological or structural heterogeneities of all length scales, etc.
    - NMSZ: Deglatiation of North America beginning at the end of the Pleistocene???

Conclusions II

- Following a tectonic perturbation, the relaxation transient may last >20 times longer than the characteristic relaxation time of the weak zone material even though surface deformation rates are low

Due To
Geometric Effects
Postseismic Effects

- In low strain-rate environments, postseismic stress recycling has a significant effect on fault (re)loading rates and, therefore, the total duration of the relaxation process (duration of transient is rheology dependent)

- As the weak zone relaxes, the distribution of shear zones in the overlying seismogenic crust evolves with time
  - Shear zones initially develop diagonally across the weak zone as observed in NMSZ
  - Eventually (timing not modeled) deformation concentrates above the weak zone boundaries

Conclusions III

- Geodetic data MUST be interpreted with a tectonically reasonable model
  - Given small enough uncertainties in the geodetic data, a velocity distribution characteristic in intraplate faulting should emerge
- Methods for assessing seismic hazard should account for
  - The potentially unique behavior of intraplate seismic zones
  - The large uncertainties that still exist in proposed intraplate earthquake generation mechanisms

Physical processes occurring in the mantle under the Eastern US and their implications for surface stress and deformation

Alessandro Forte (*Université du Québec à Montréal*)

Robert Moucha (*U Québec à Montréal*), Jerry Mitrovica (*U Toronto*),
Nathan Simmons (*LLNL*), Stephen Grand (*U Texas Austin*)

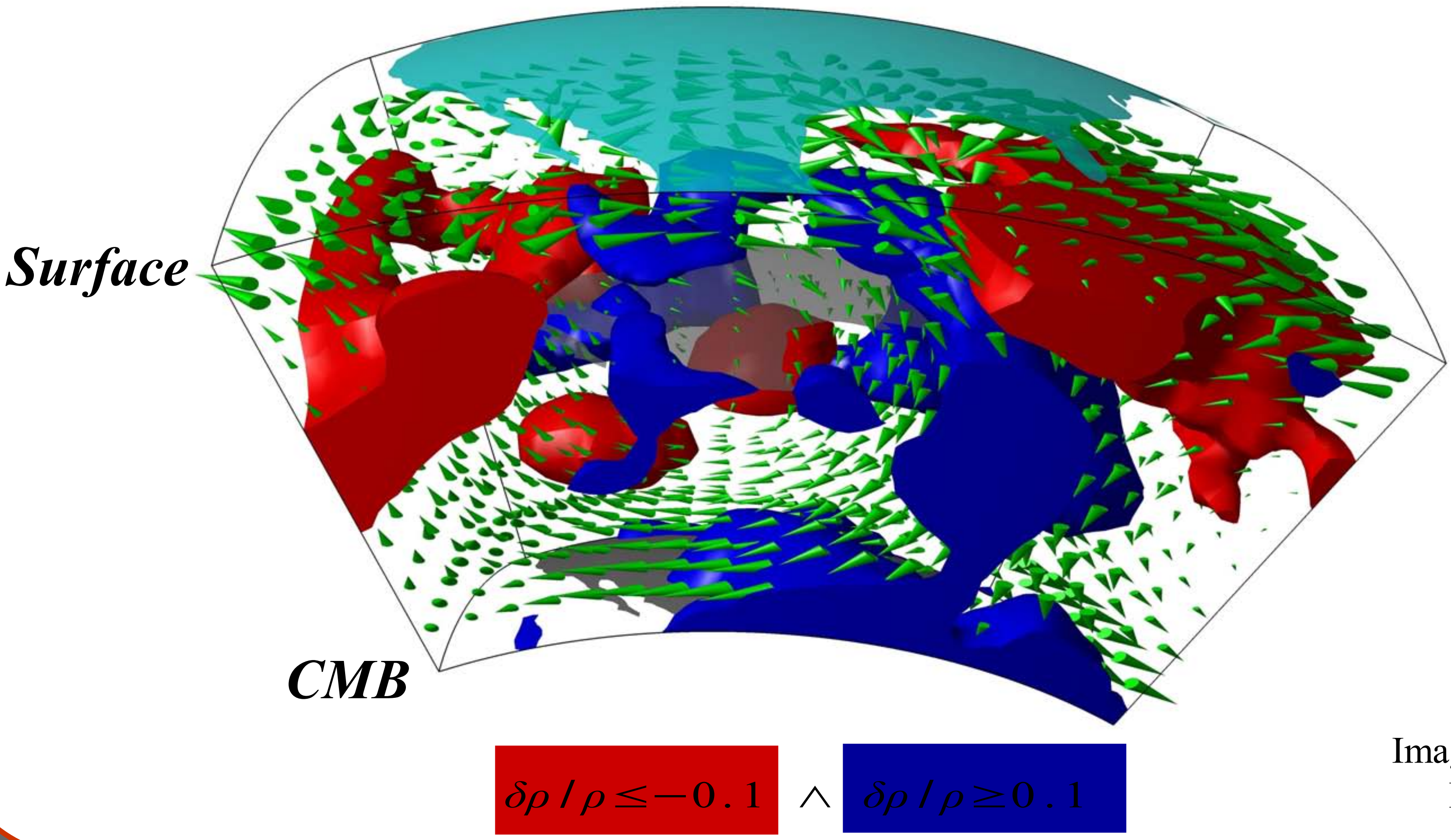
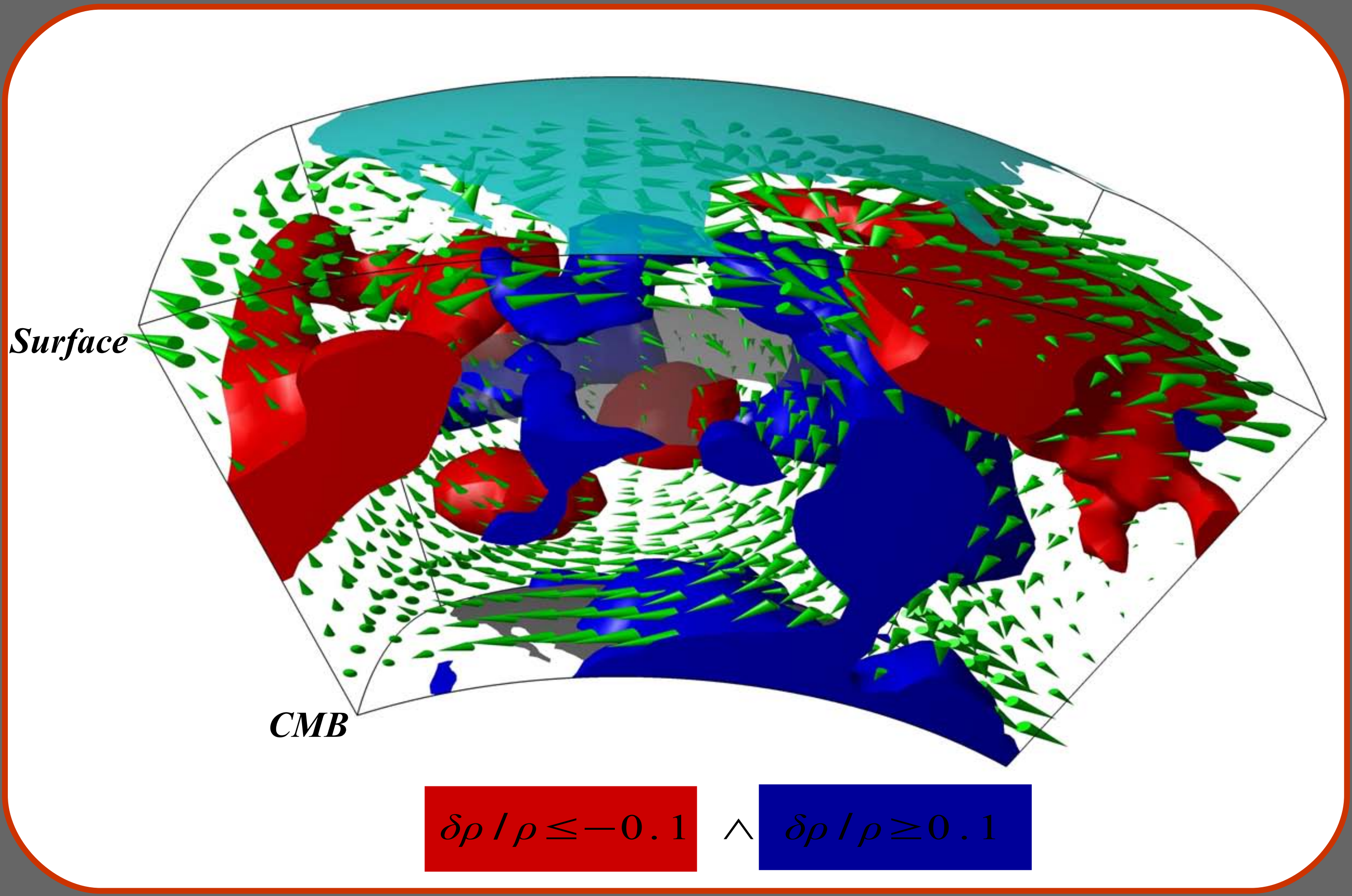


Image: courtesy of
R. Moucha

Fundamental Lessons Learned from Geodynamic Modelling Presented Here

- **Plate Tectonics is ultimately a 3-D process!** The deep-seated forces that drive the horizontal motions of the plates also drive substantial (km-scale) vertical displacements that contribute to crustal stresses. These time and spatially dependent vertical displacements of continental platforms are important to understanding the geological evolution of continents (rock uplift, erosion, sedimentation).



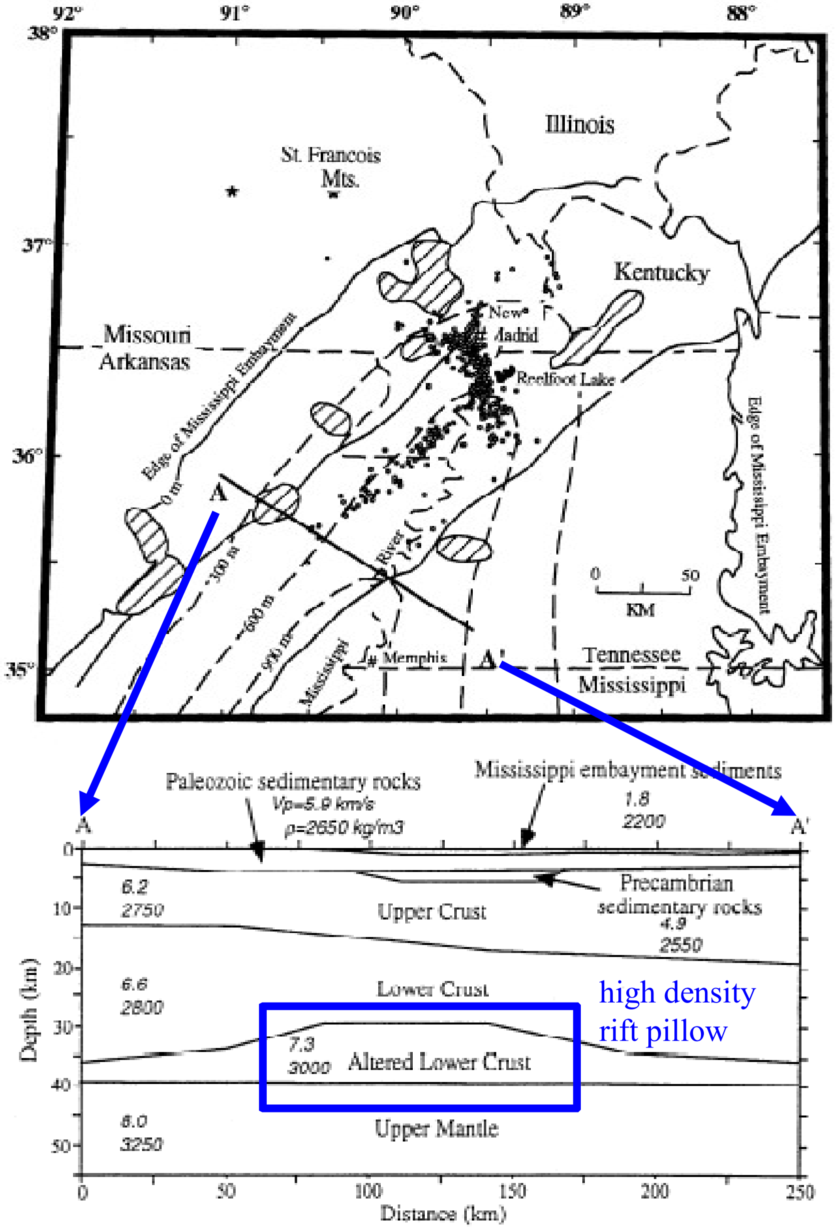
- **Can GPS detect this activity?** These geologically important vertical motions (e.g. 1 km vertical displacement in 5 Myrs = 0.2 mm/yr) are below the current resolution of space geodetic methods. Yet, the surface stresses (SHmax) associated with these motions are substantial (order 10 MPa).

Proposed Questions
(courtesy of K. Coppersmith)

- Do mantle processes influence current seismicity?
- Can these patterns be used as as a basis for defining seismic source zones?
- Do mantle processes occur at rates that should influence short term (tens of years) or long-term (thousands of years) seismicity?
- What is your confidence that available heat flow data can be used to detect mantle anomalies?

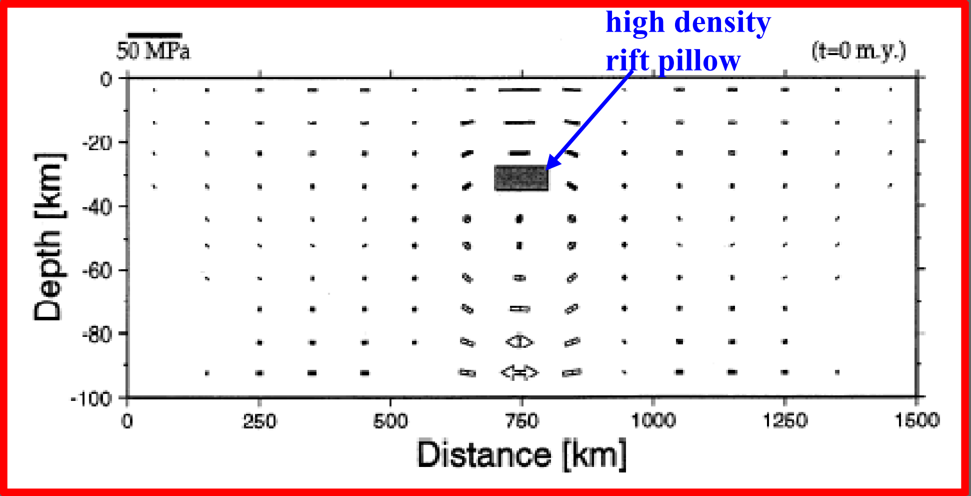
Previous Dynamical Models of the Origin of Stress and Seismicity in the NMSZ

Grana & Richardson (JGR, 1996)

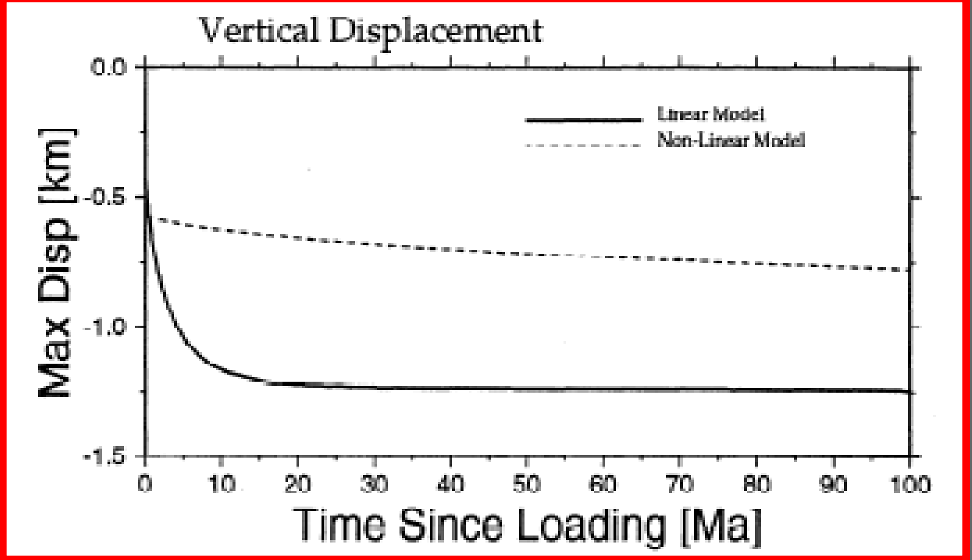


A cross section across the rift axis from a refraction survey by *Ginzburg et al.* [1983].

Viscous flow and stress generated by sinking rift pillow



Vertical surface displacement created by sinker. Note: 1 km agrees with sediment thickness in northern Mississippi Embayment



Pollitz, Kellogg& Burgmann (BSSA, 2001)

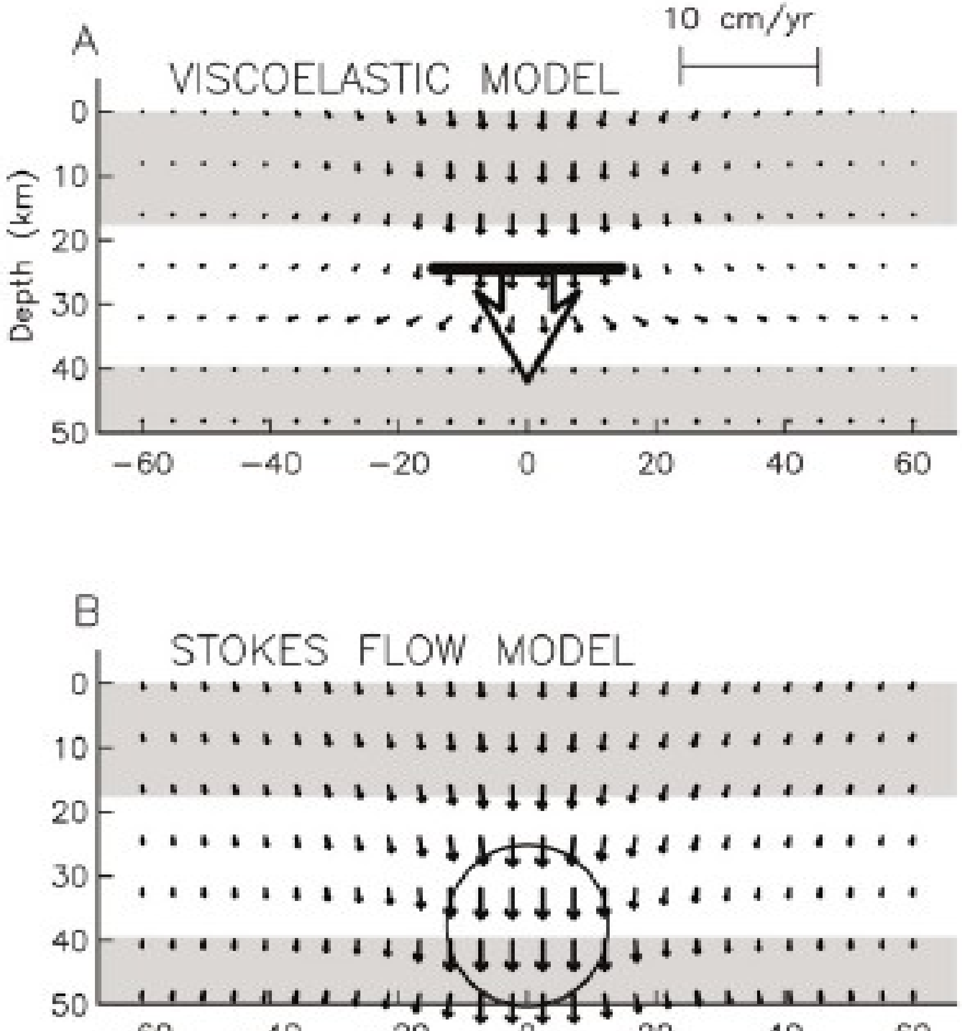


Figure 8. Flow fields associated with (A) distributed force on the viscoelastic model, averaged over the first 400-yr of a seismic cycle, and (B) Stokes' flow associated with a 25-km-diameter sphere sinking through a viscous fluid at a rate of 2 cm/yr. The flow fields in Figures 3A and 8A are identical.

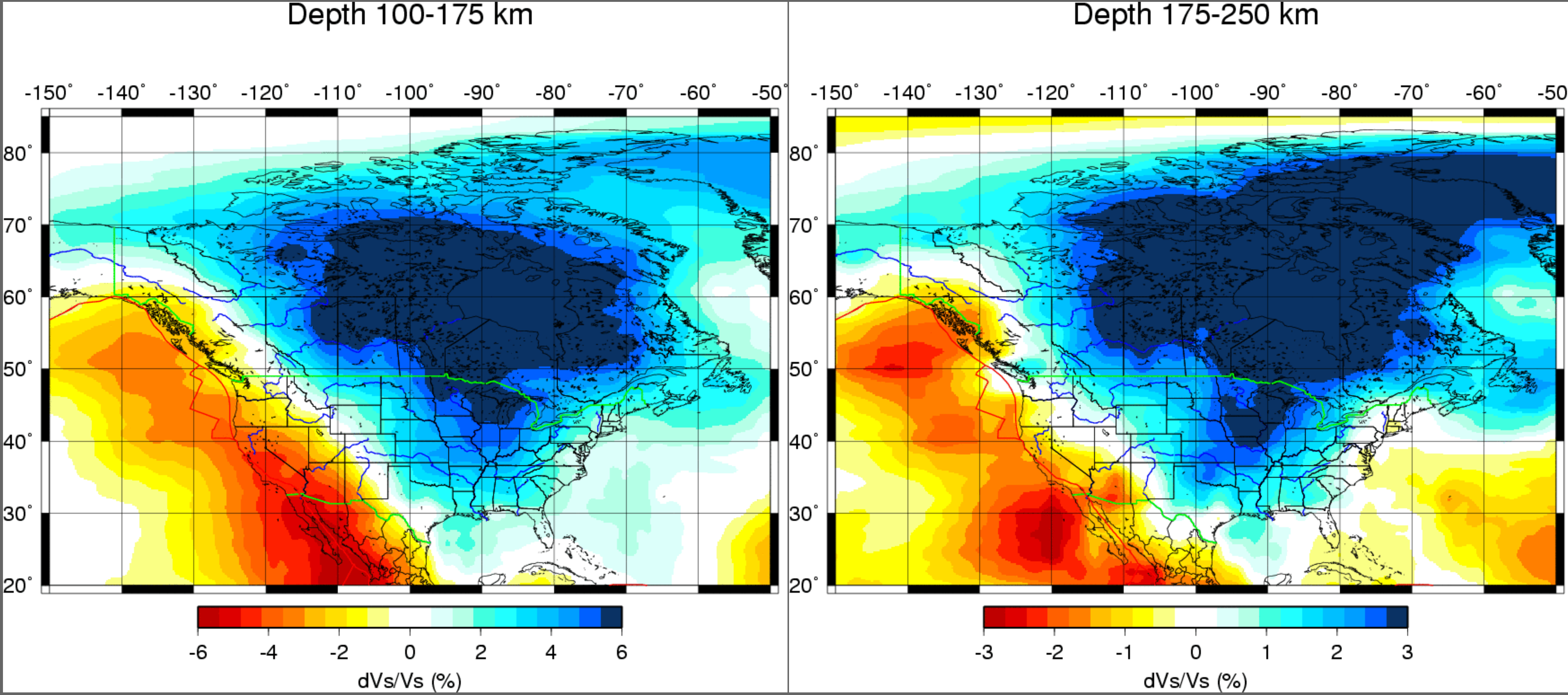
Assumptions:

- Prior weakening of the lower crust by passage of New Madrid region over the Bermuda hotspot (at ~100 Ma)?
- Laurentide, deglaciation induced pressure-release melting of hot patches of mantle material?

Difficulties:

- Low to average surface heat flow in this region (i.e. no evidence of unusual heating below the crust).
- No evidence from seismic tomographic imaging of hotspot induced changes in the thermal structure of the lithosphere below this region.

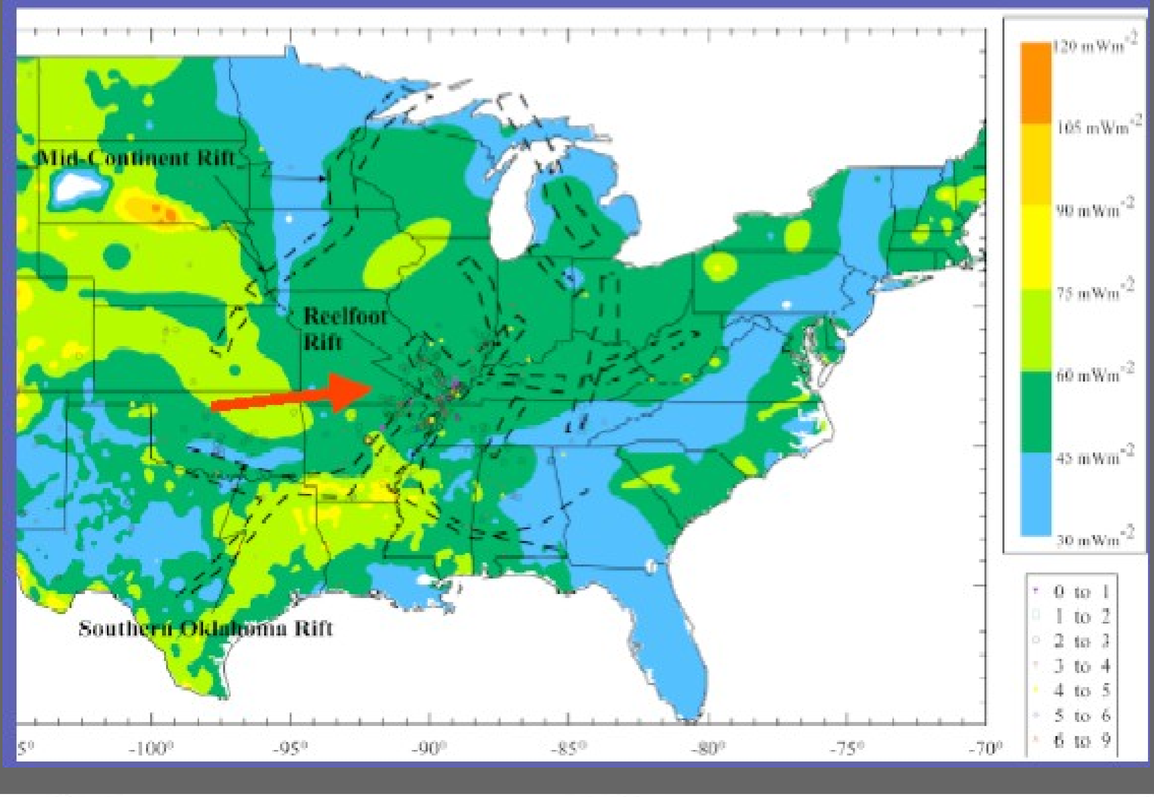
Tomographic imaging of shallow mantle structure below North America*

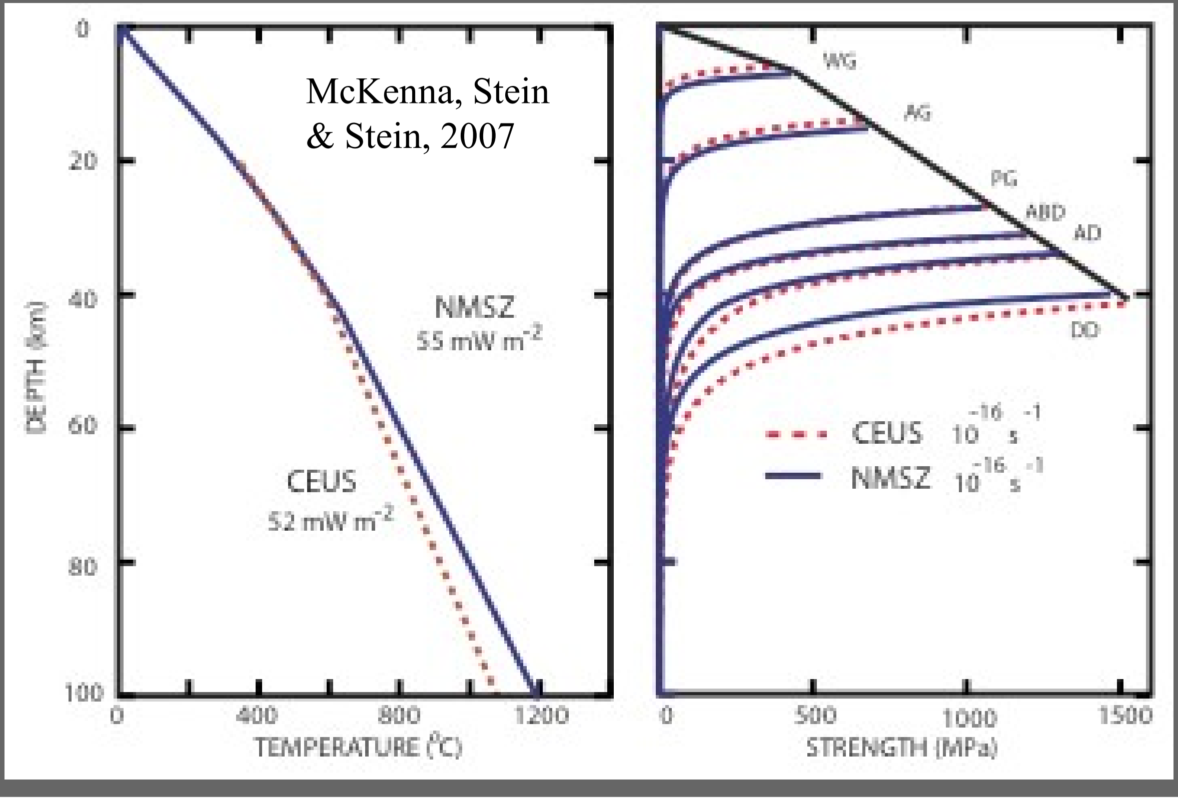


* From global tomography model of Simmons et al. (2007)

“NMSZ NOT HOT, WEAK, OR SPECIAL”

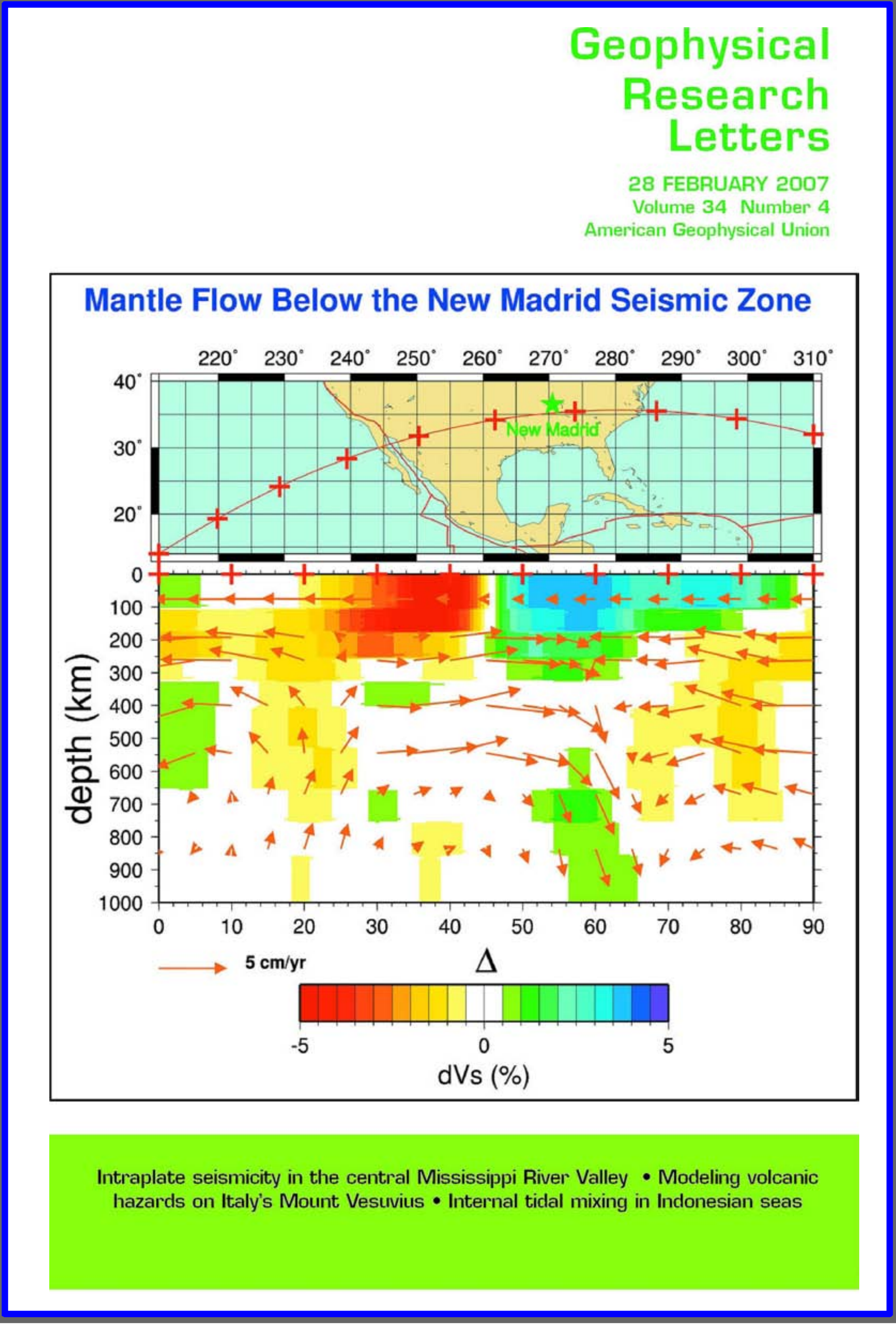
(Slide courtesy of S. Stein!)





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.

An alternative model to a localized mafic 'sinker' in the lower-crust is a similarly high-density load in the flowing mantle. (Both models can yield equivalent surface bending stresses.)



Geophysical
Research
Letters

28 FEBRUARY 2007
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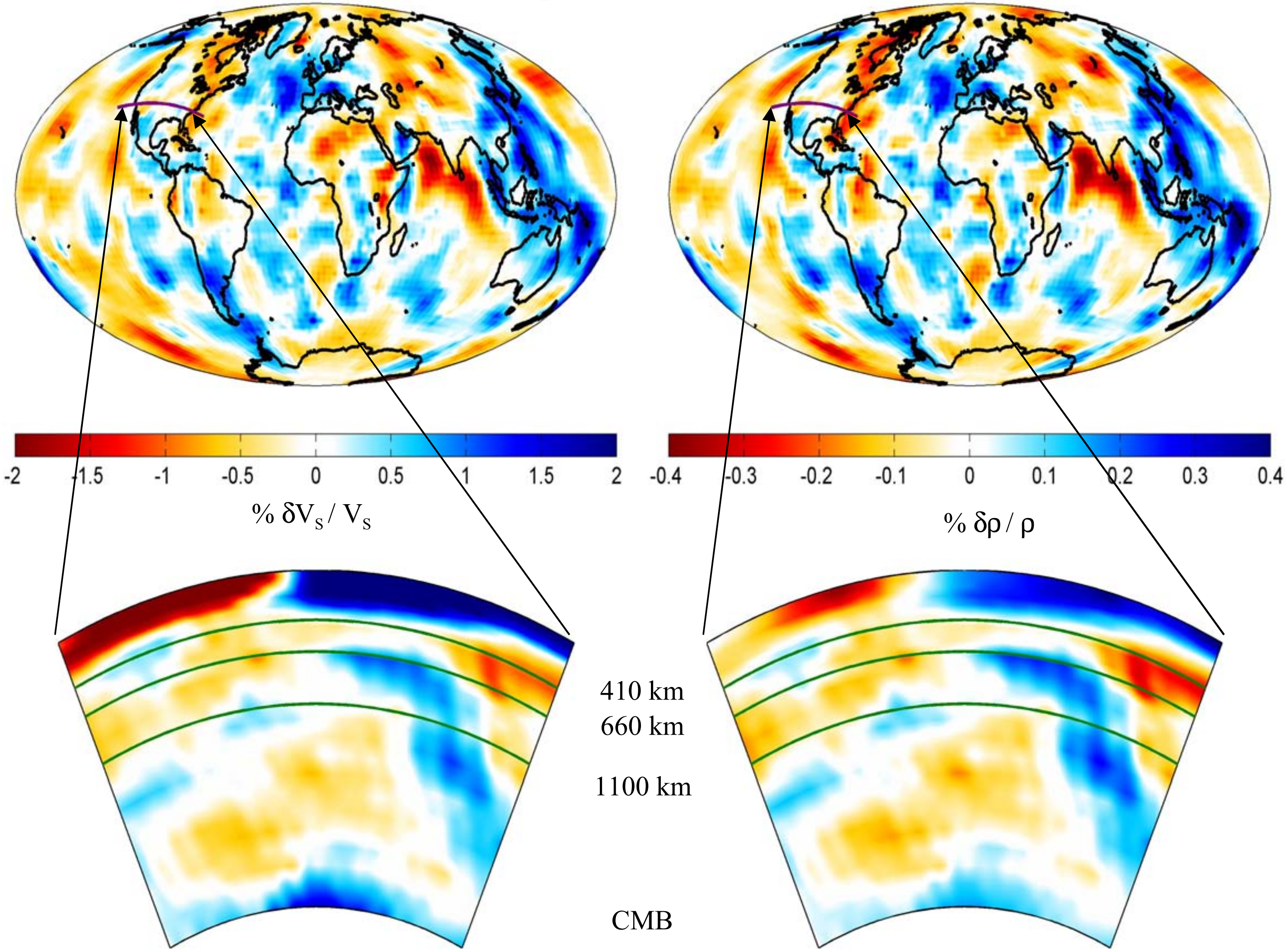
Mantle Flow Below the New Madrid Seismic Zone

Intraplate seismicity in the central Mississippi River Valley • Modeling volcanic hazards on Italy's Mount Vesuvius • Internal tidal mixing in Indonesian seas

3-D Mantle Structure from Joint Inversion of Global Seismic & Geodynamic Data



Depth 525 – 650 km

see Simmons et al. (GRL 2007, GJI 2009)

Modelling Present-day Mantle Flow Dynamics Below North America

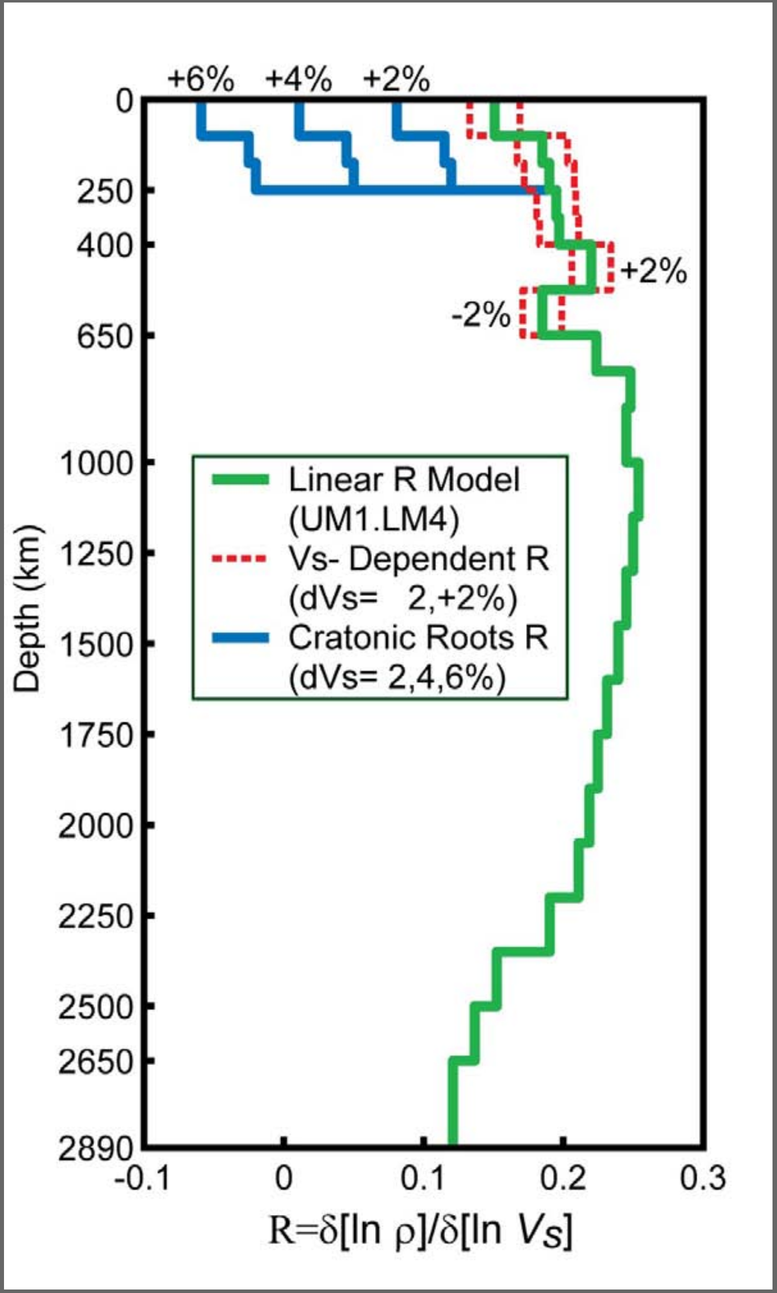
The two necessary inputs are :

1. a model of the rheological structure of the mantle, which we represent in terms of an effective mantle viscosity

2. a model of the 3-D distribution of mantle density perturbations that describe the buoyancy (Archimedes) forces that drive convection

Note: We carry out <u>fully global calculations of mantle flow</u> and we then zoom in on the dynamics below the North American plate

Joint tomography inversions for mantle density perturbations
(see Simmons et al., GJI 2009)



Scaling Corrections

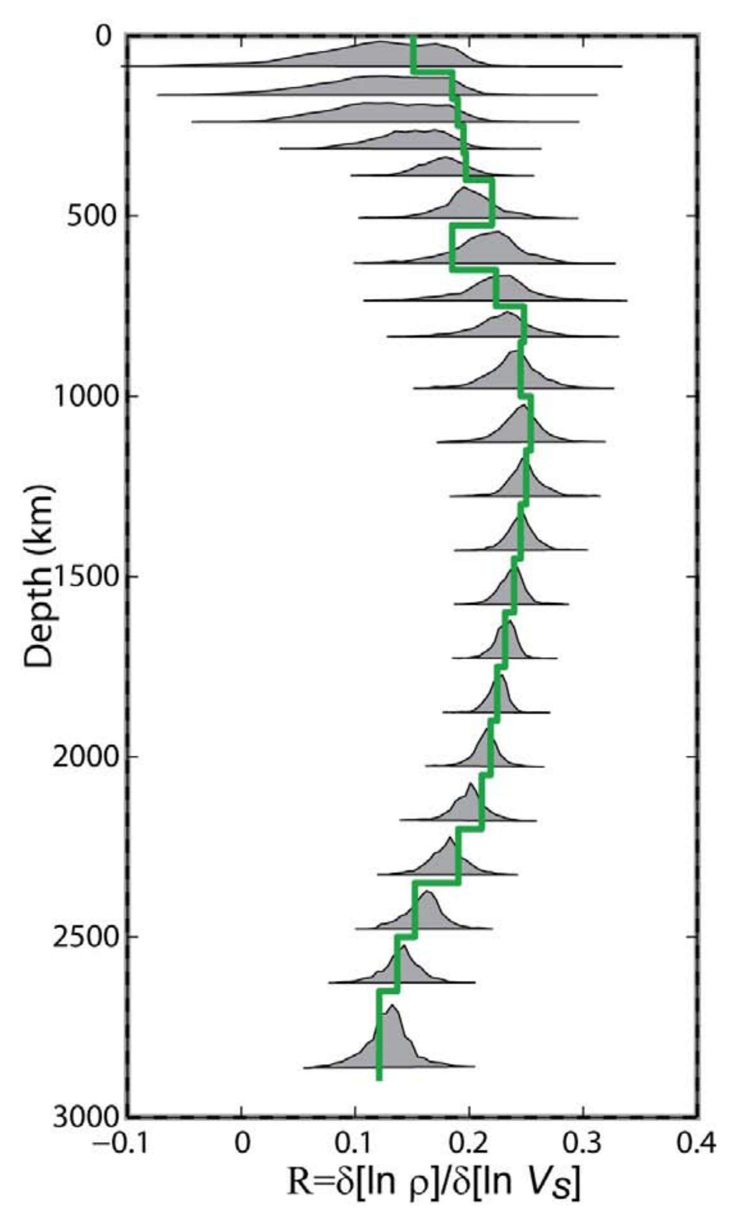
$$R_{\rho/S} = R_{\rho/S}^{1D} + \left(\frac{\partial R_{\rho/S}^{1D}}{\partial \ln V_S} \right) \delta \ln V_S$$

Systematically correct scaling model

- Cratonic mass depletion
- Non-linearity of thermal scaling in upper mantle
- Grid search for correction derivatives

Case	*Seismic*	*Gravity*	*Plates*	*Topography*
Seismic	93.5(%)	-46(%)	32(%)	-80(%)
Joint(1D)	93.2	71	96	-9
Joint(1D+)	93.2	75	98	41

Joint tomography inversions for mantle density perturbations (see Simmons et al., GJI 2009)



Fully 3-D Scaling between density and seismic shear velocity:

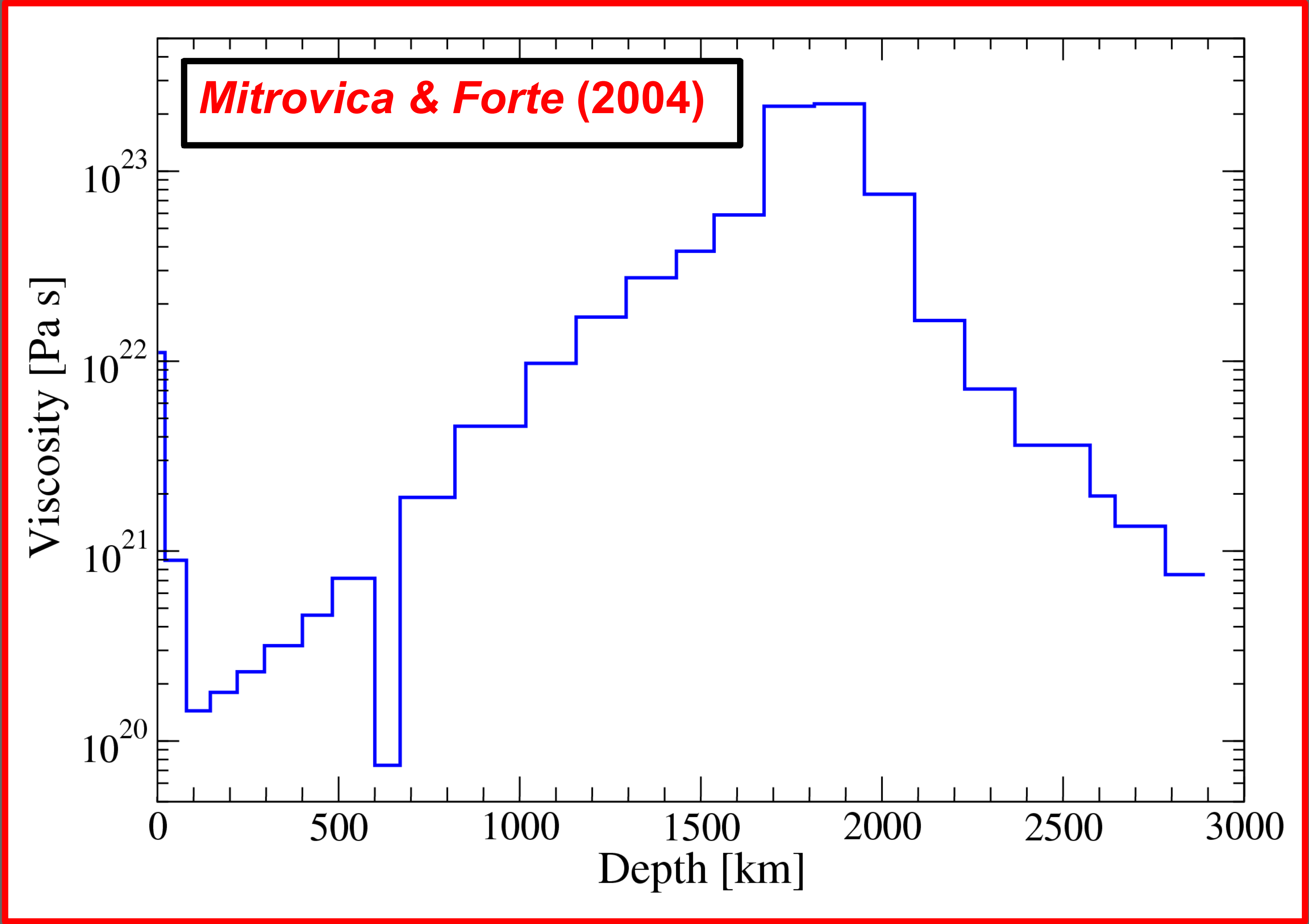
$$R_{\rho/S} = R^{3D}_{\rho/S} = \left[\mathbf{G}(\Delta\mathbf{m})\right]^{-1}\mathbf{s}$$

Invert for fully 3-D scaling factors

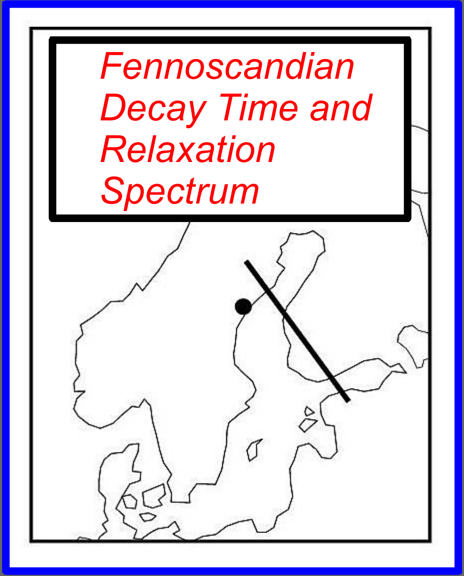
- **Use corrected scaling and seismic velocity from previous step as starting solutions**
- **Replace scaling with seismic model, invert**
- **Divergence from thermal = compositional**

Case	*Seismic*	*Gravity*	*Plates*	*Topography*
Seismic	93.5(%)	-46(%)	32(%)	-80(%)
Joint(1D)	93.2	71	96	-9
Joint(1D+)	93.2	75	98	41
Joint(3D)	93.2	92	99	82

Mantle Viscosity from Joint Inversions of Glacial Isostatic Adjustment (GIA) and Mantle Convection Data



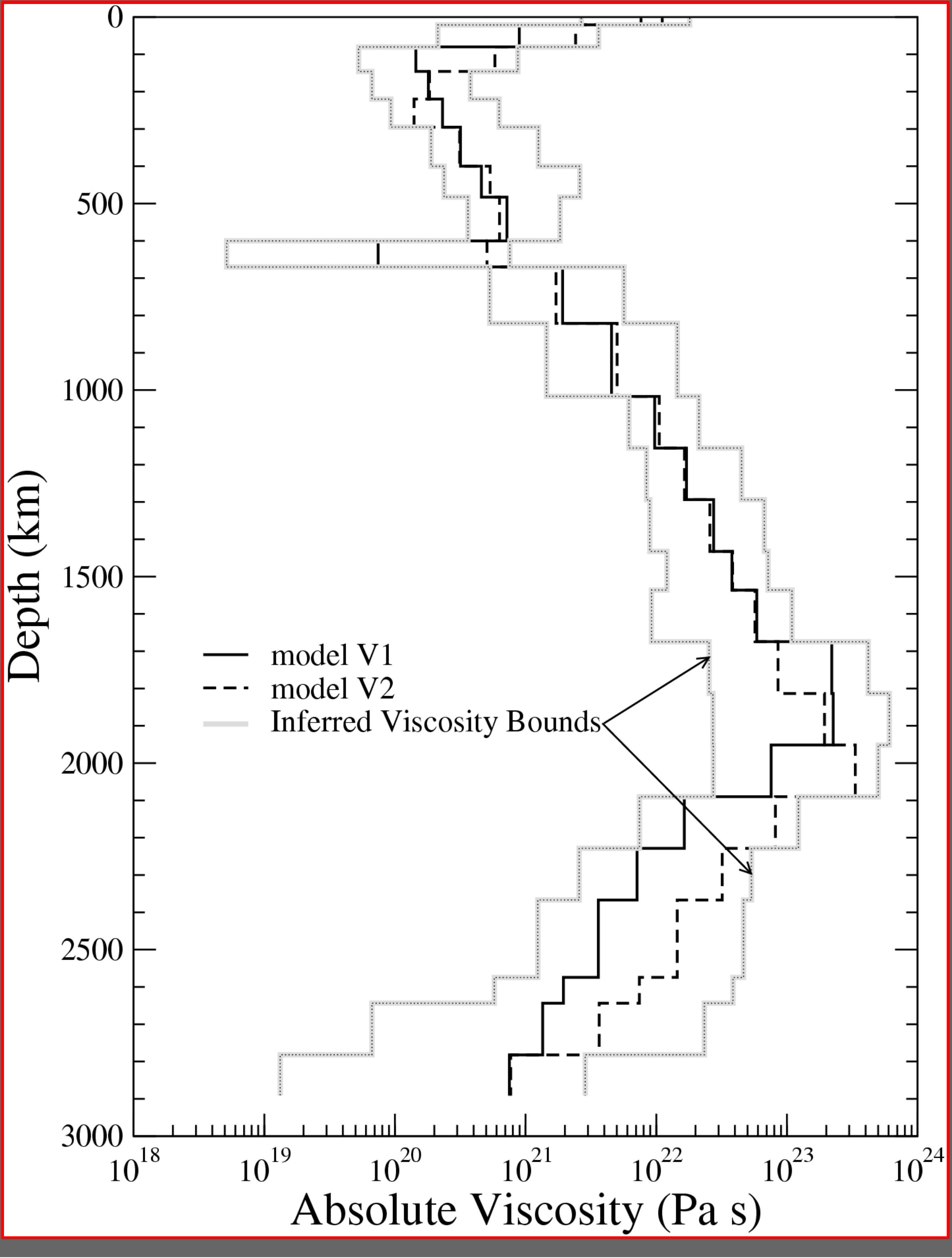
GIA Data Sets



Convection Data Sets: ***Free-Air Gravity Anomalies, Tectonic Plate Motions, Dynamic Surface Topography, CMB ellipticity***

Range of optimally smooth (Occam-inverted) viscosity profiles consistent with joint GIA-convection data sets

(a mapping of non-uniqueness)

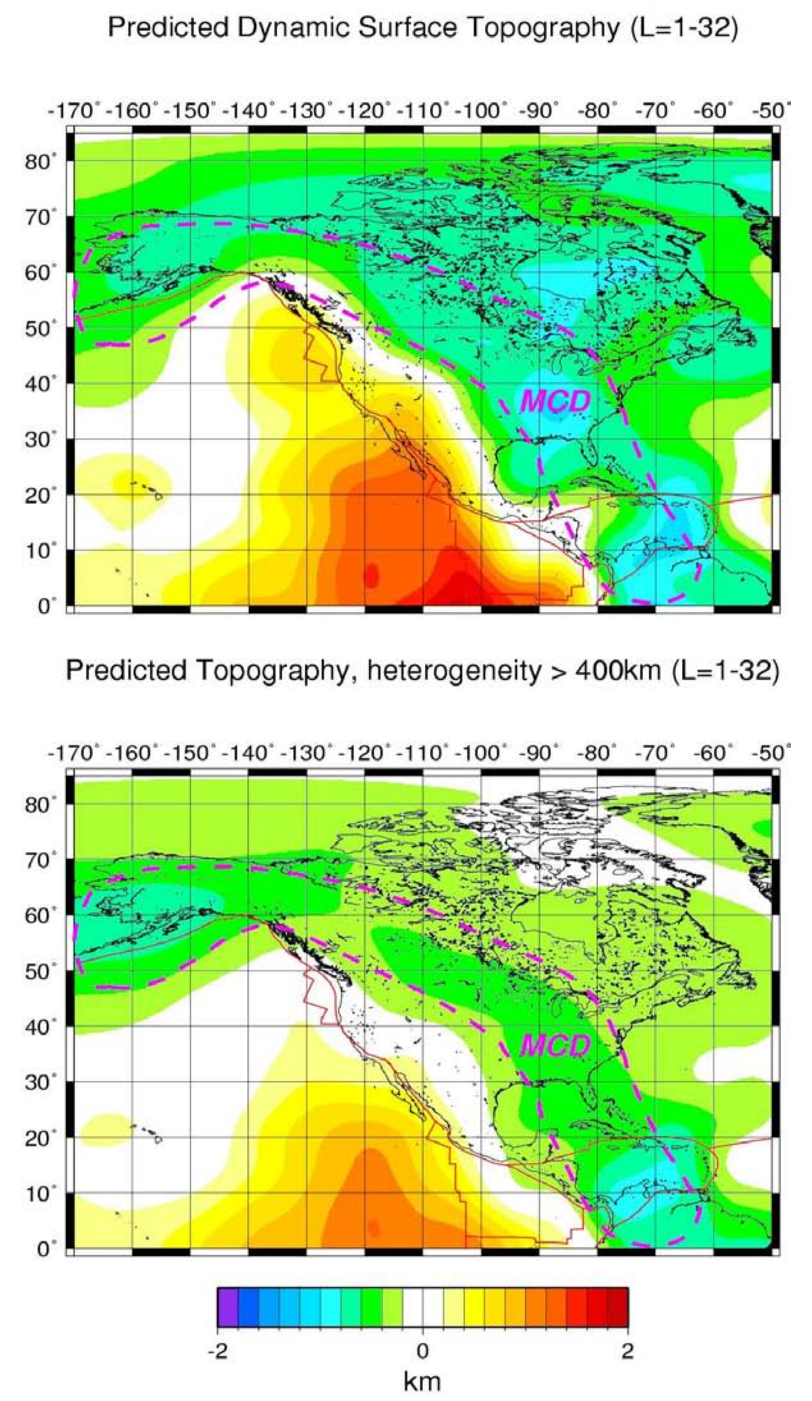


Deep-Mantle Contributions to North American Dynamics*

Kula-Farallon slab signal in surface observables

Variance Reductions:

Gravity:	**71%**
Topography:	**60%**
Plate Motion:	**96%**

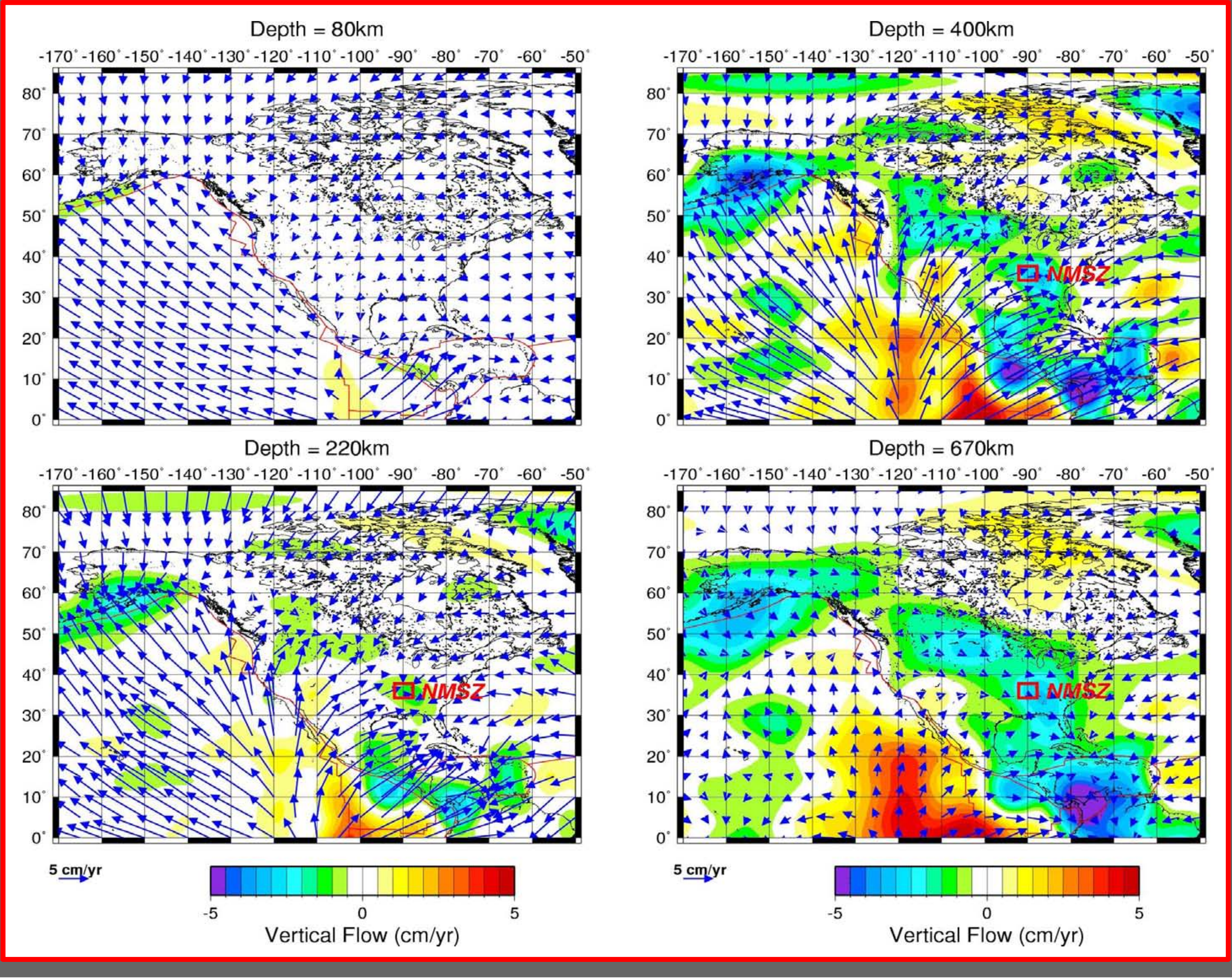


MCD depression = ~ 1000 m

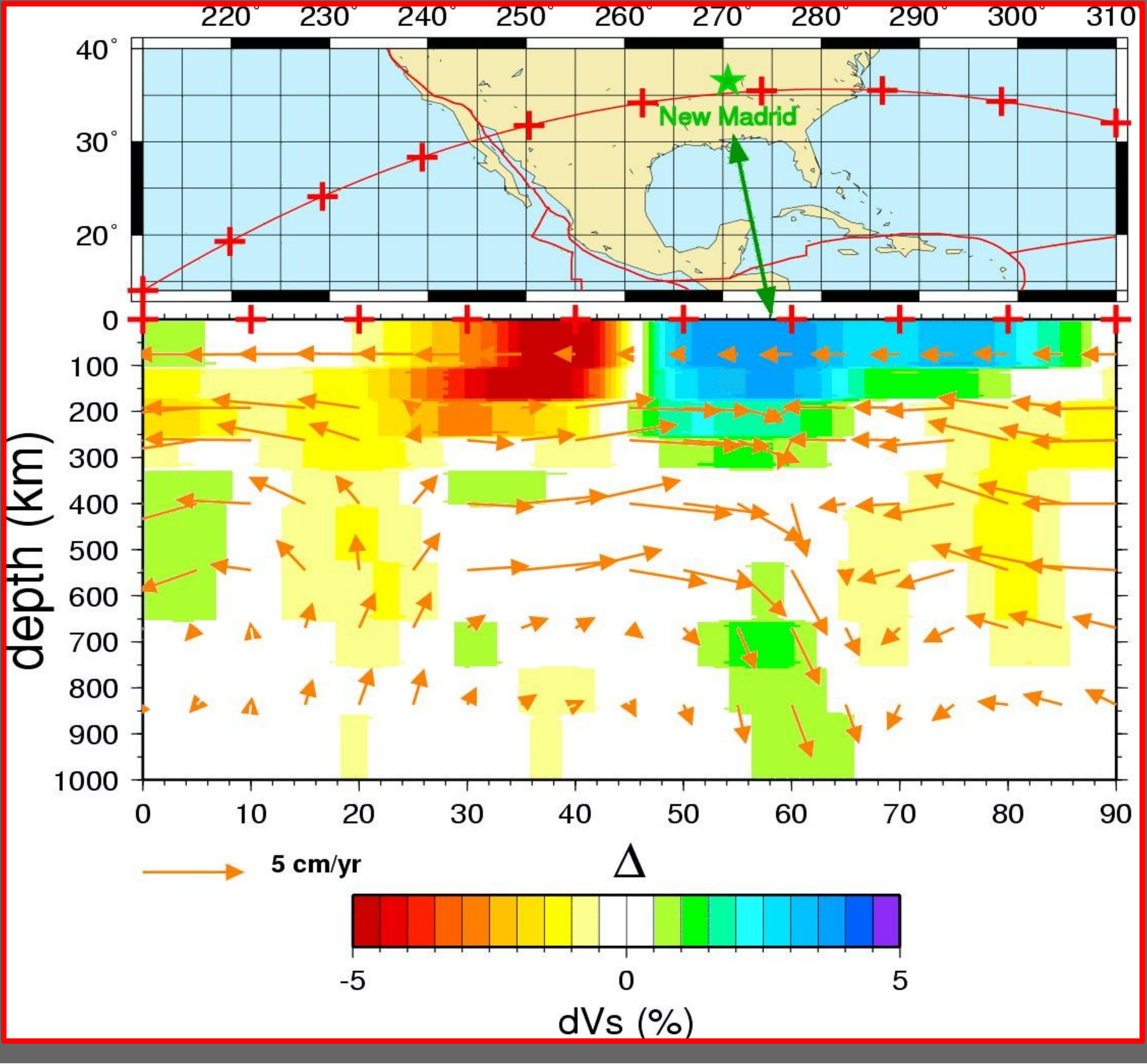
MCD depression = ~ 600 m

* Forte et al., *Tectonophysics*, 2009

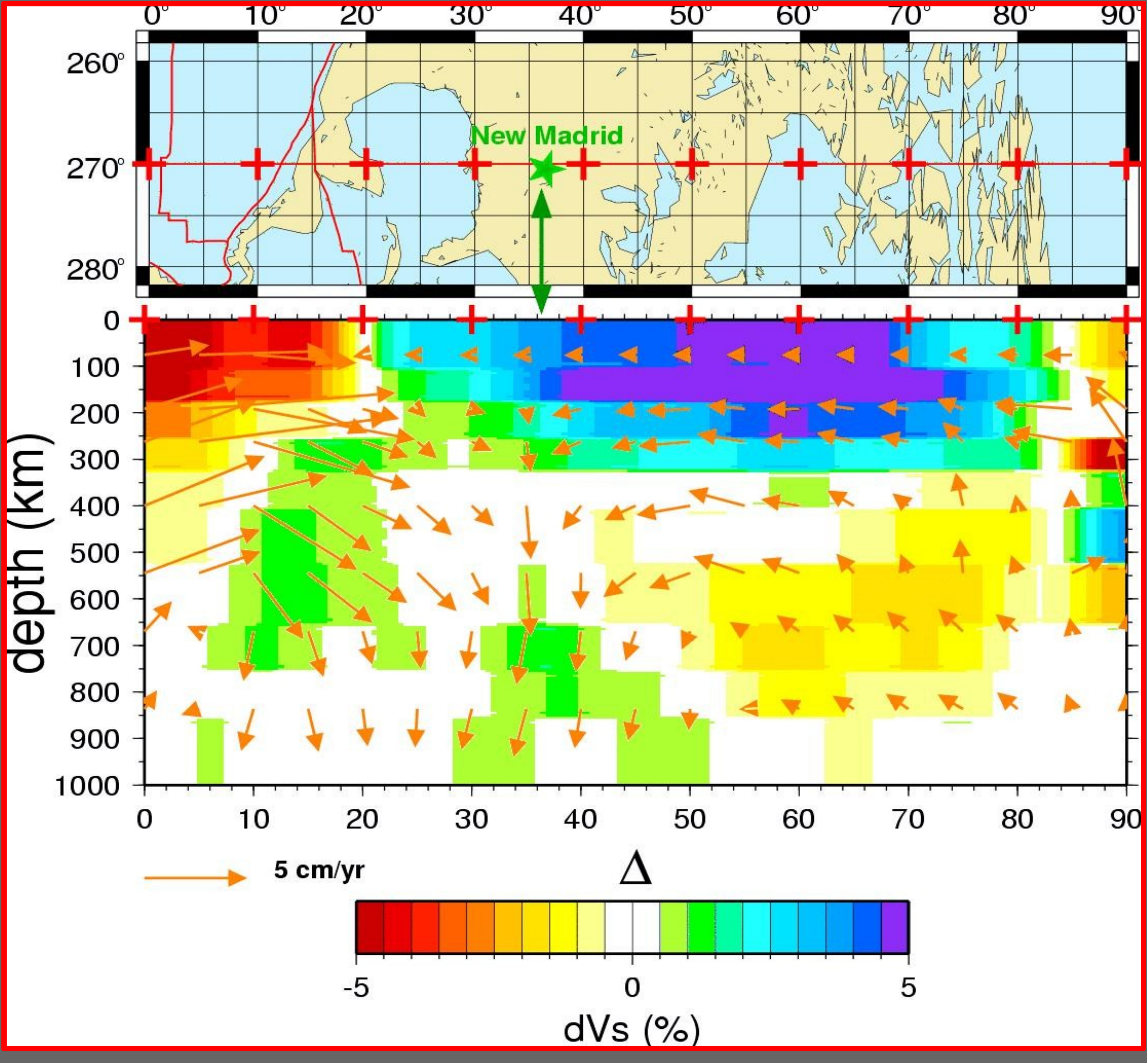
Implications for Subcontinental Mantle Flow



Mantle Flow Below Central US



Mantle Flow Below Central US



Do mantle processes influence current seismicity?

- Subduction zones are characterized by strong and sustained seismic activity due to the stresses generated by oceanic lithosphere descending under an overriding plate boundary.

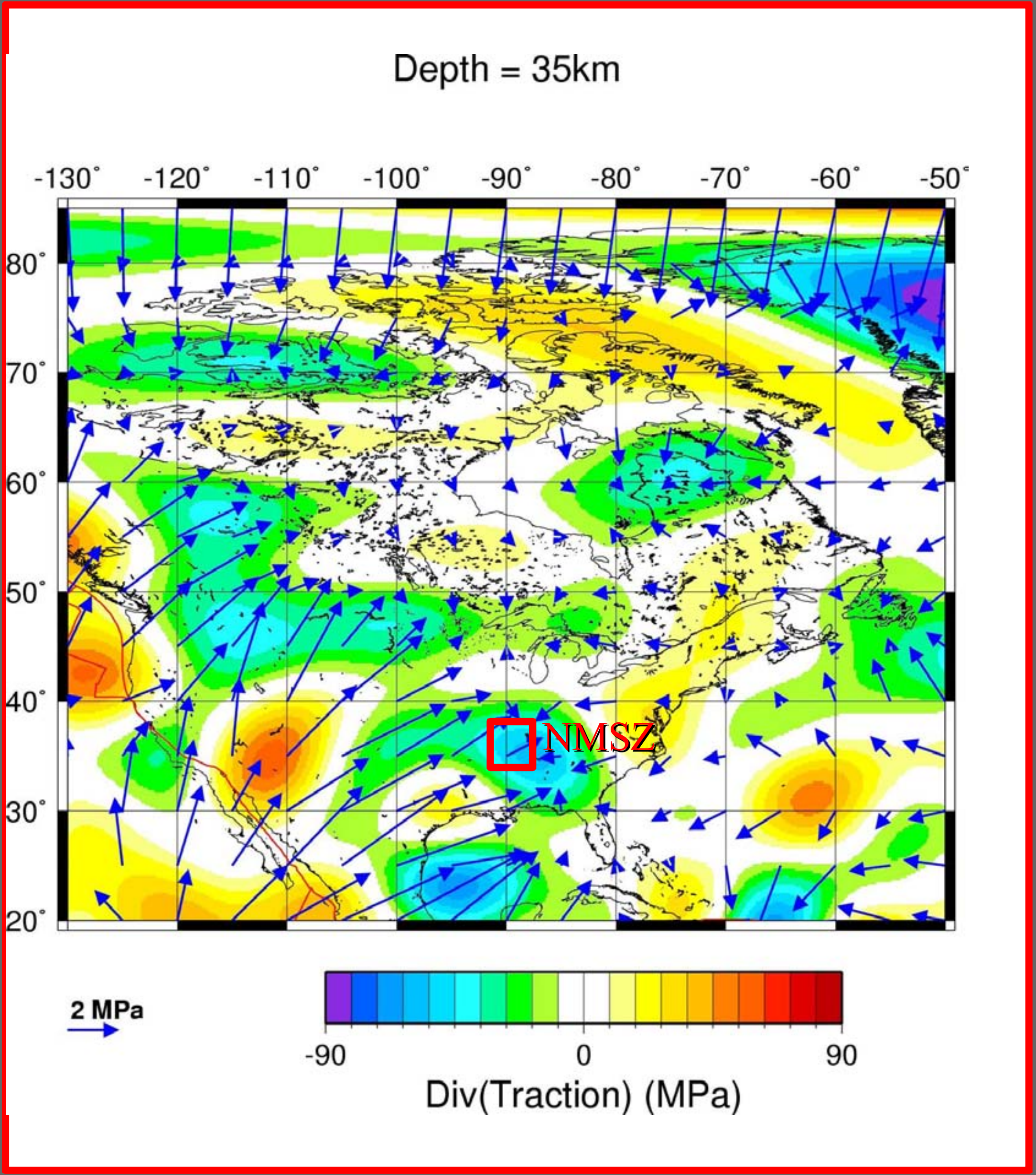
- Can similarly strong and long lived seismic activity be produced by the descent of ancient lithospheric slabs subducting below continental interiors?

- To address this question we should consider the magnitude of the surface stress generated by the subducting slabs and whether these stresses are favourably aligned with pre-existing 'susceptible' zones of crustal weakness (re-activated Mesozoic rift structures).

- We must therefore evaluate whether the descent of the ancient Kula-Farallon slab system under North America can yield sufficiently strong surface stresses with appropriate geometry relative to geologically mapped zones of weakness (e.g. the New Madrid and Wabash Valley seismic zones) or with respect to deep fault systems that are difficult to delineate from the surface geology.

Implications for Surface Stress*

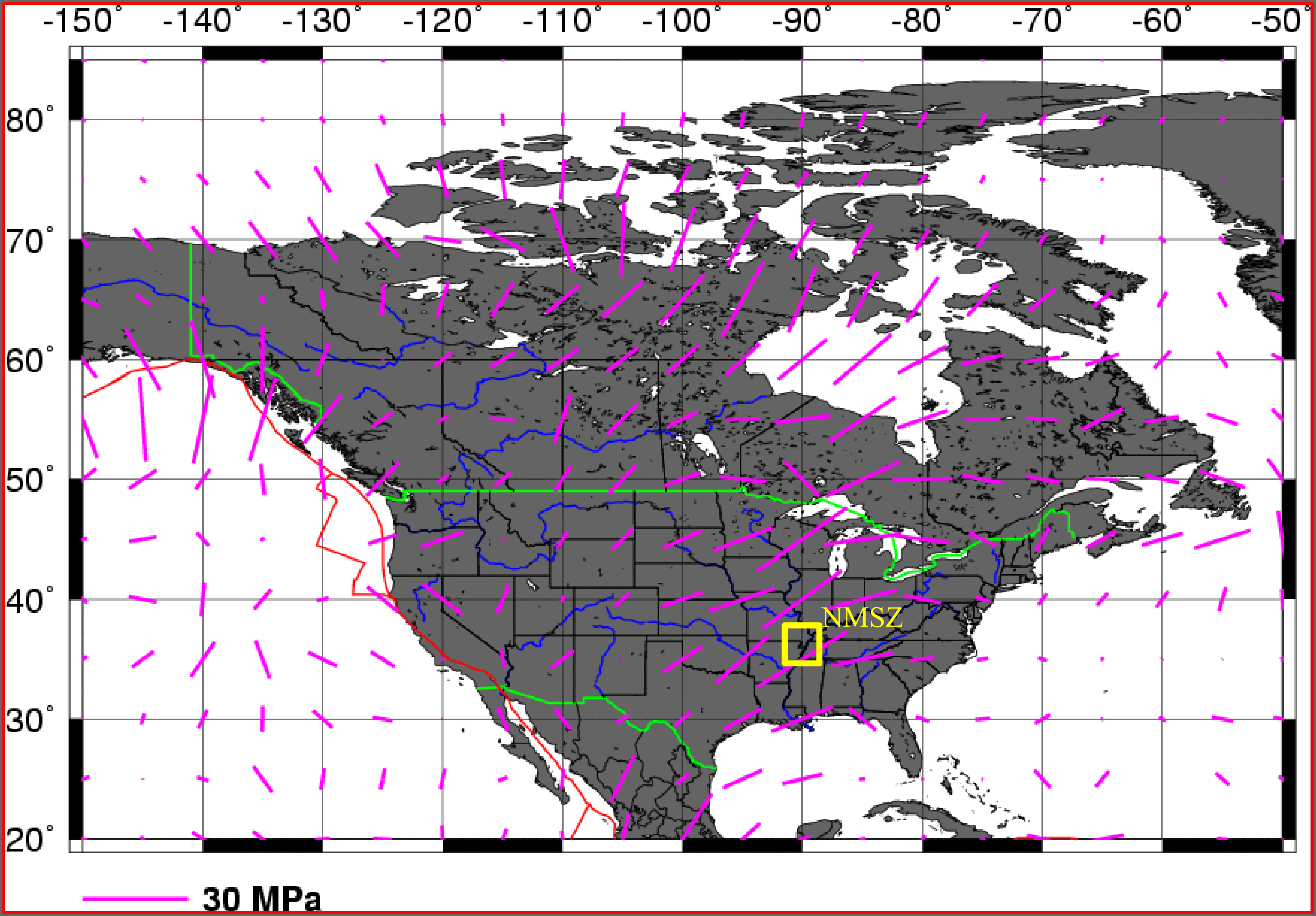
Mantle flow-induced horizontal tractions on crust.



* Forte et al., *GRL*, 2007

Mantle flow prediction of SHmax at depth of 30km

(based on TX2007, viscosity V2)

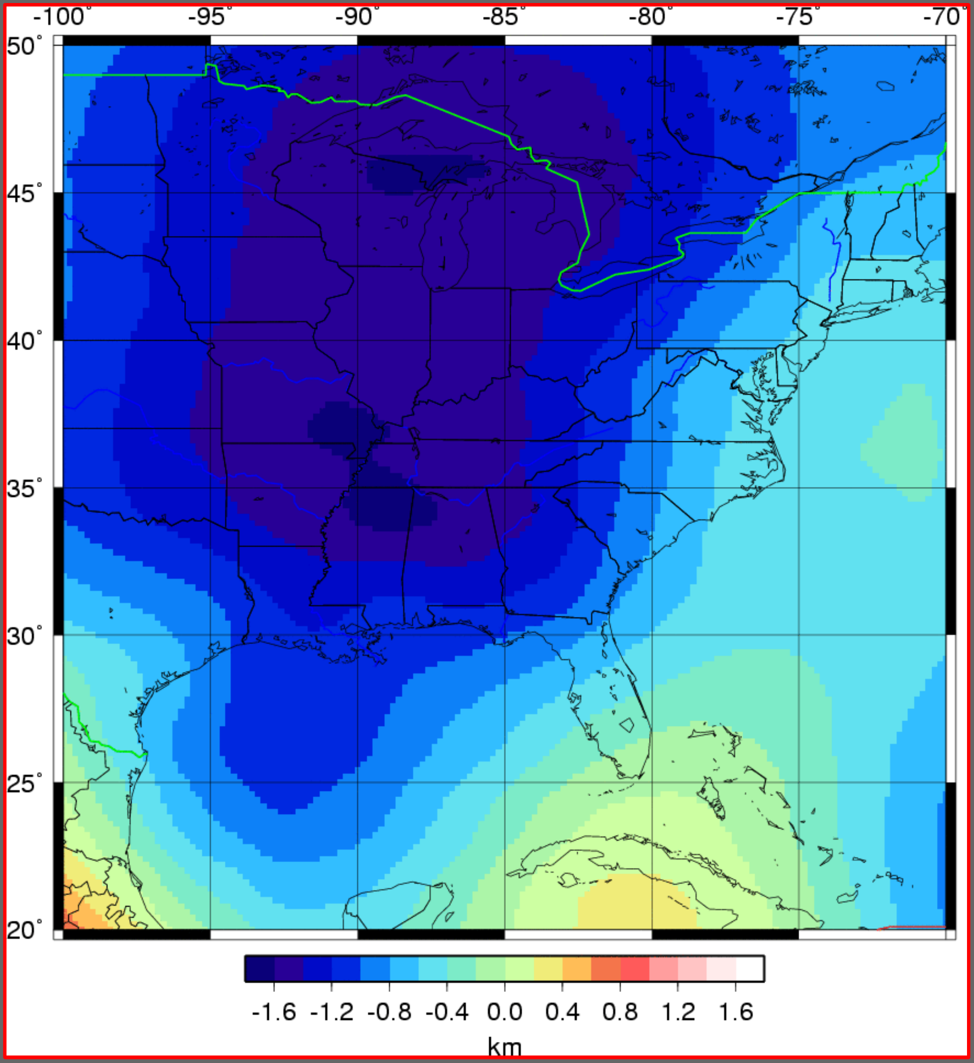


Predicted SHmax in New Madrid Seismic Zone (NMSZ) has amplitude of 30 MPa at 30 km depth and is aligned ~N55ºE. (Note: Rift-related fault is aligned N50ºE.)

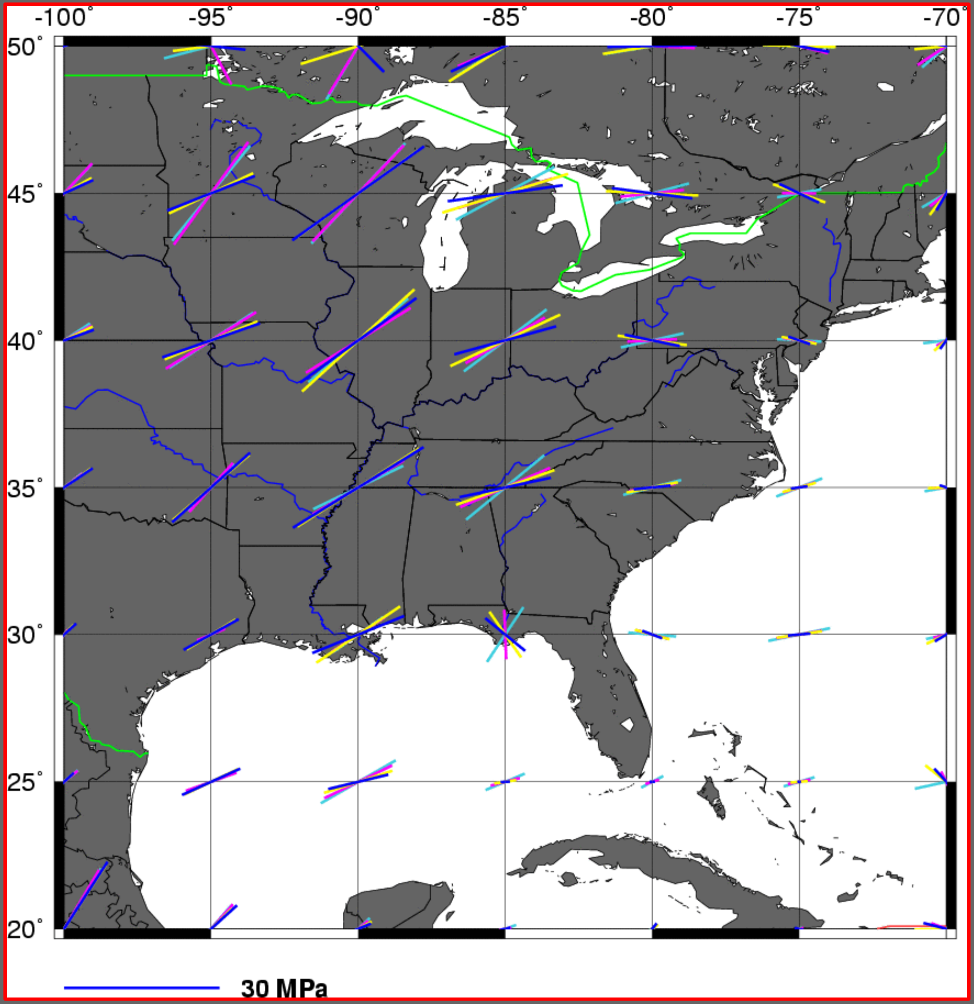
Relationship between flow-induced bending stress and predicted SHmax

Dynamic Surface Topography

Predicted SHmax at 30 km depth



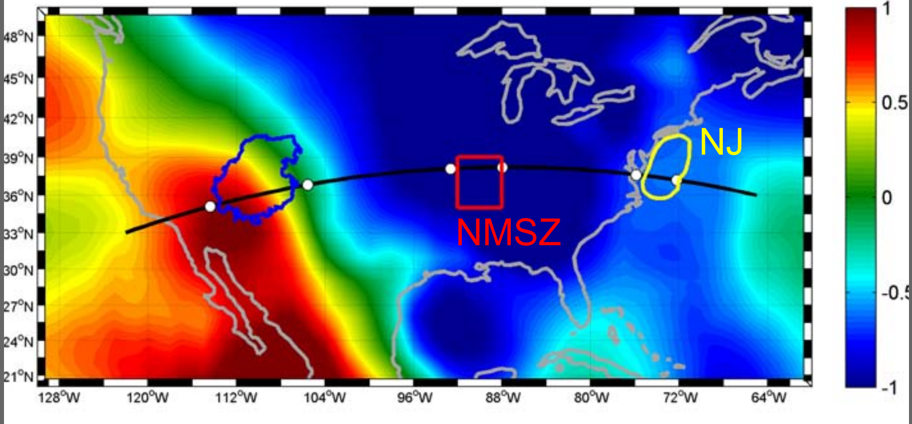
Prediction based on TX2009 (Viscosity model V2)



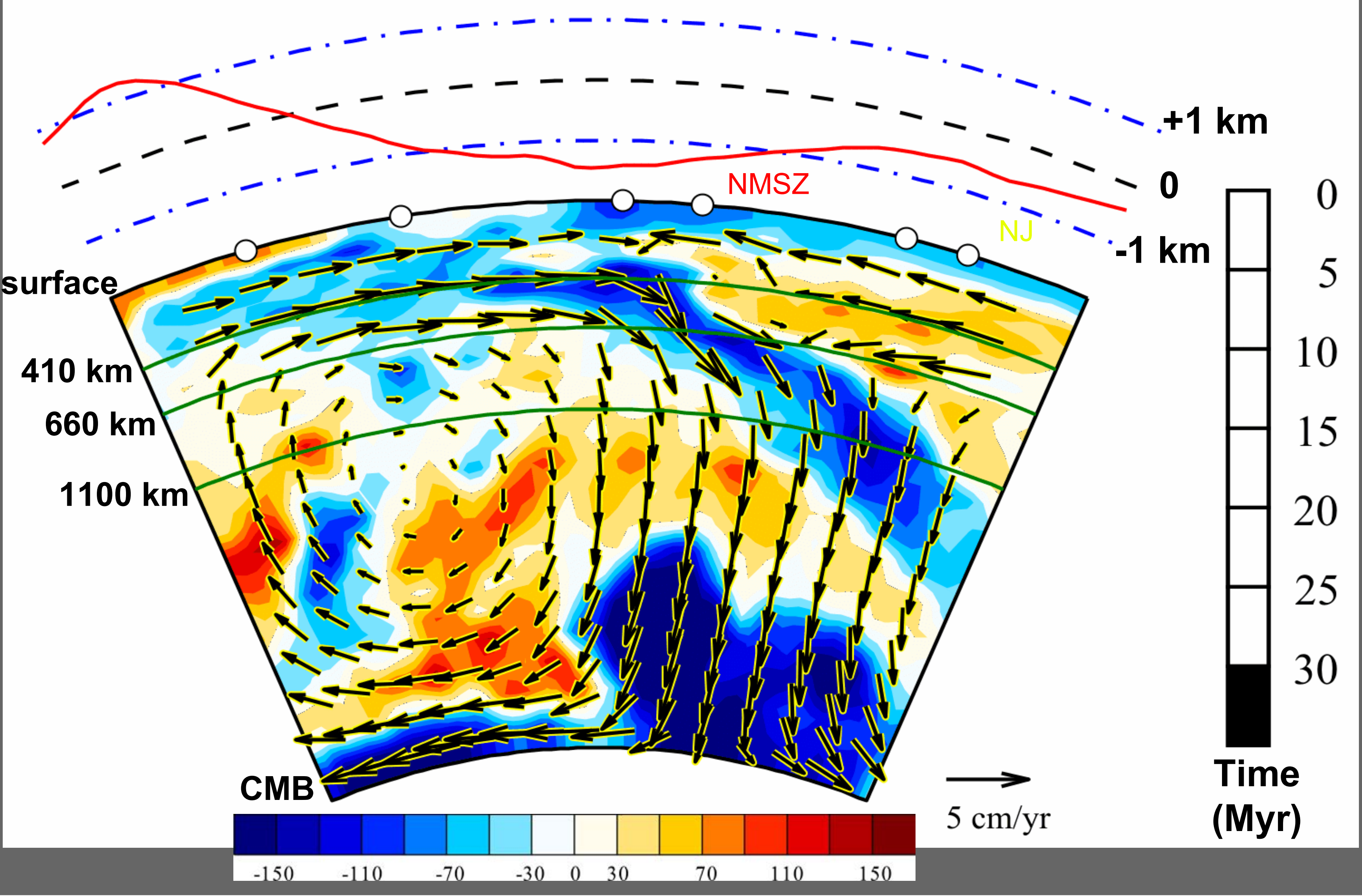
Predictions based on TX2007 and TX2009 (for both viscosity models V1 and V2)

These stresses are generated on mantle convection time scales (millions of years) and can therefore support long-lived seismicity (recurrence times?).

Time-dependent mantle dynamics and surface flexure over the past 30 Myrs



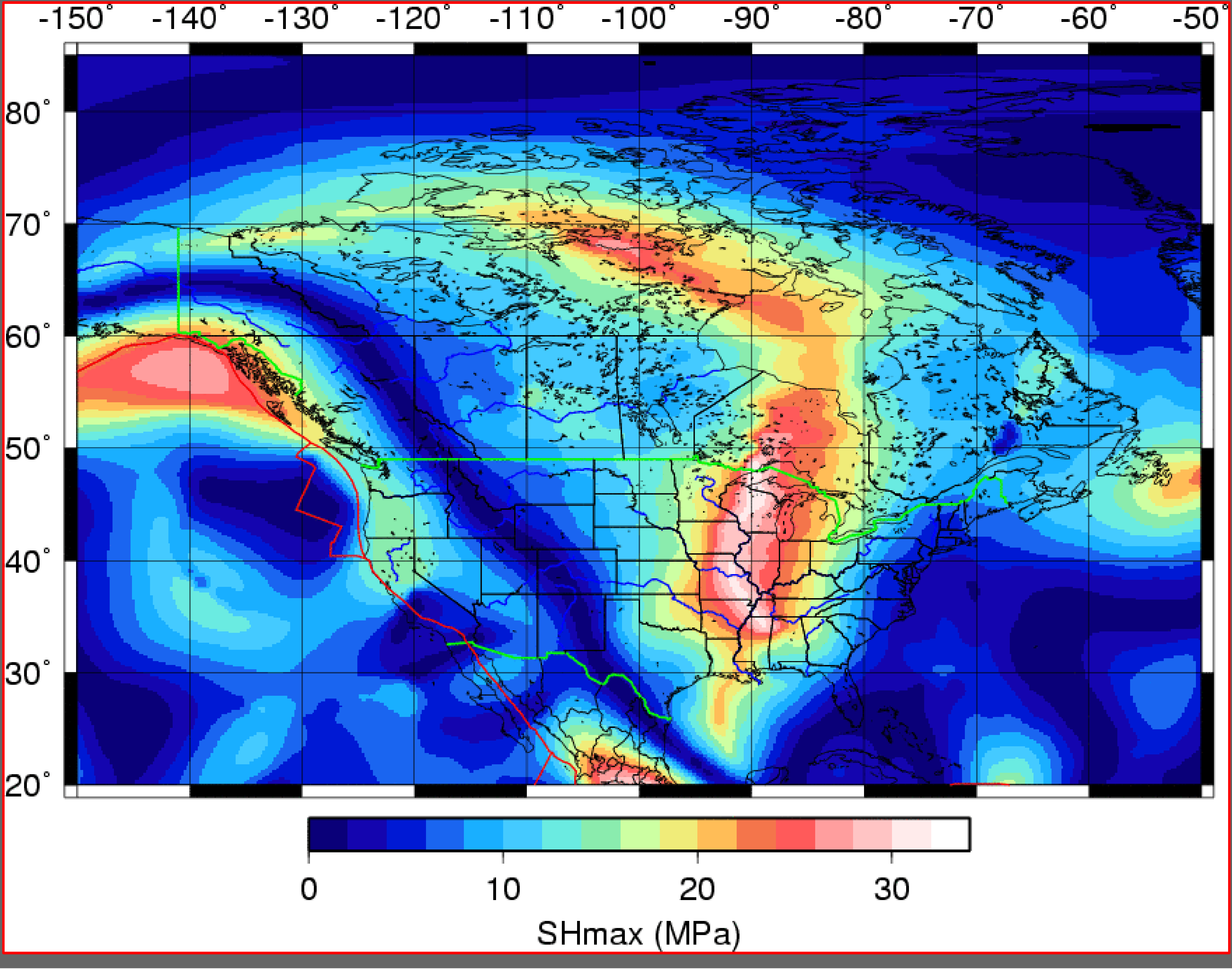
Dynamic Surface Topography



Moucha et al (submitted, 2009)

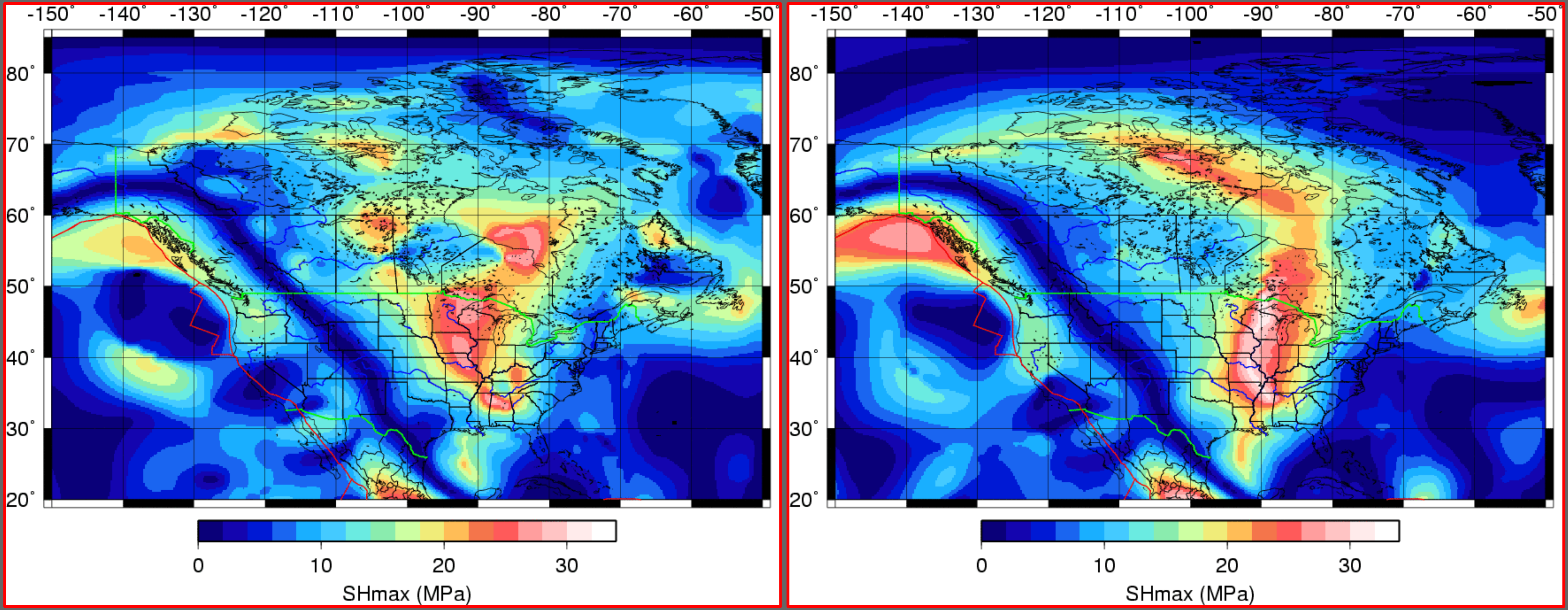
Can flow-induced stress patterns be used for defining seismic source zones?

Predicted SHmax amplitude at depth of 30km (based on model TX2009, viscosity V2)



Uncertainties in predicted stress from non-unique mantle viscosity inferences

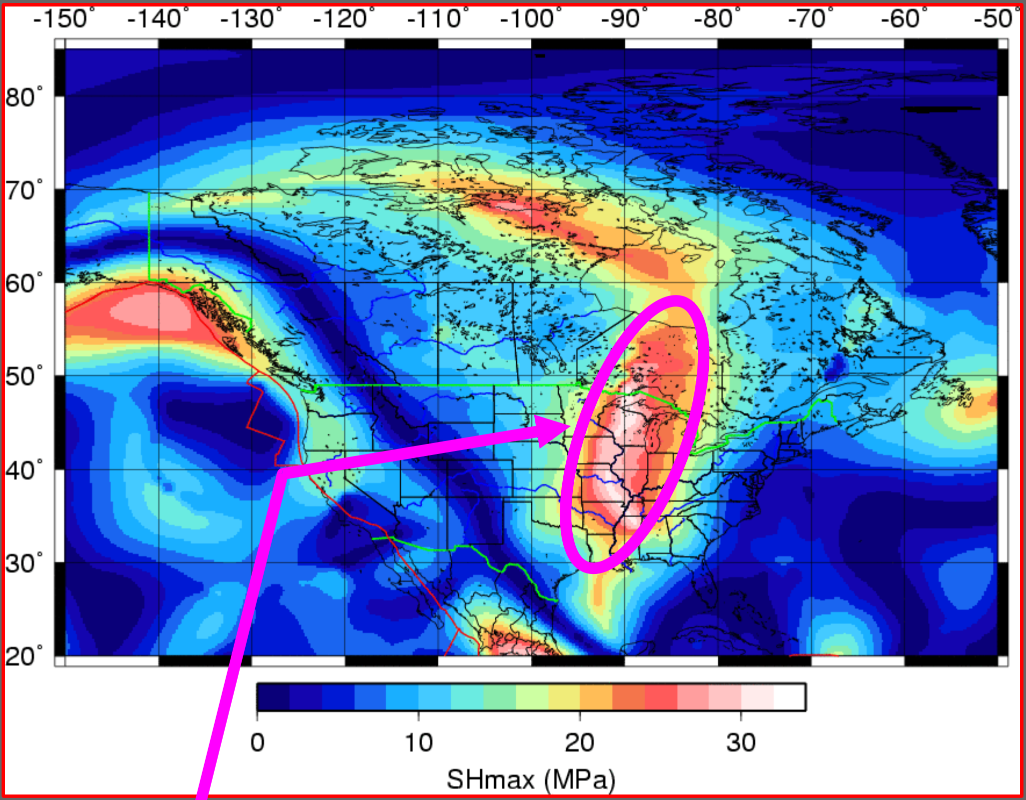
Predicted SHmax amplitudes at depth of 30km



Prediction based on TX2007 (Viscosity model V2)

Prediction based on TX2009 (Viscosity model V2)

Mantle flow-induced patterns of stress concentration → seismic source zones?



Can this region of maximum convection-driven SHmax be characterised by "episodic, clustered, migrating" seismicity? If we accept this, New Madrid may be only one of other possible locations for major activity within this stressed region.

?

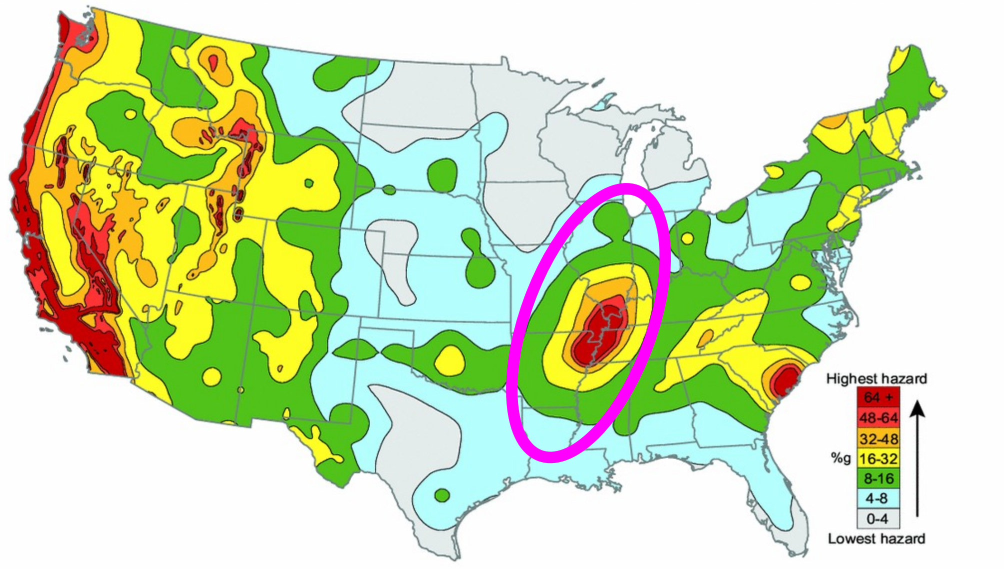


Figure 2. The U.S. Geological Survey shaking-hazard maps for the United States are based on current information about the rate at which earthquakes occur in different areas and on how far strong shaking extends from earthquake sources. Colors on this particular map show the levels of horizontal shaking that have a 1-in-50 chance of being exceeded in a 50-year period. Shaking is expressed as a percentage of g (g is the acceleration of a falling object due to gravity).

[from: Gomberg & Schweig, USGS Fact Sheet 2006-3125, 2007]

What is the effect and hence uncertainty due to large scale lateral viscosity variations (LVV)?

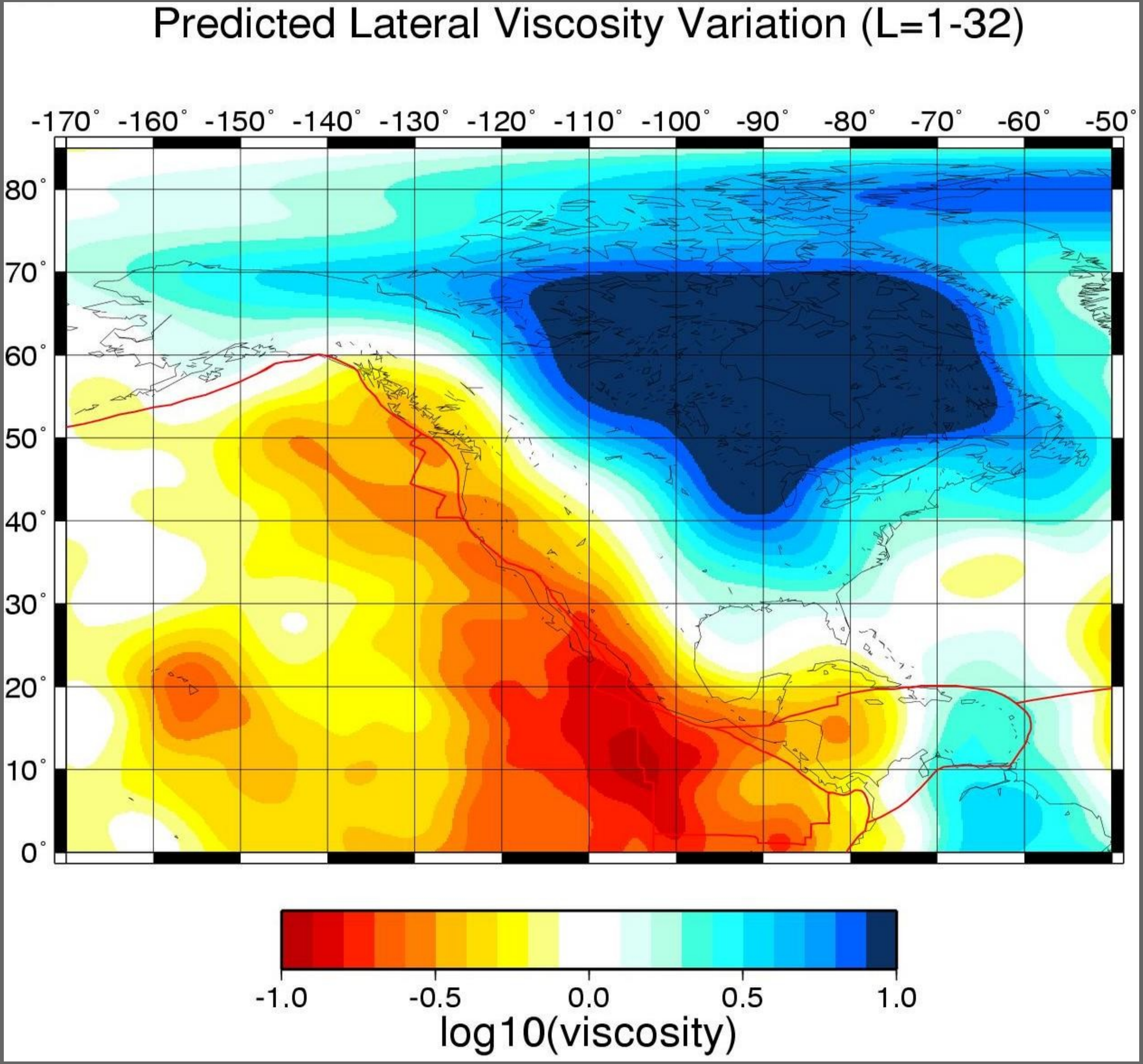
$$\nu = \nu_o \exp\left[\gamma \frac{T_{melt}}{T(r,\theta,\phi)}\right]$$

Upper Mantle: T_{melt} = 2000K

Lower Mantle: T_{melt} = 4260K

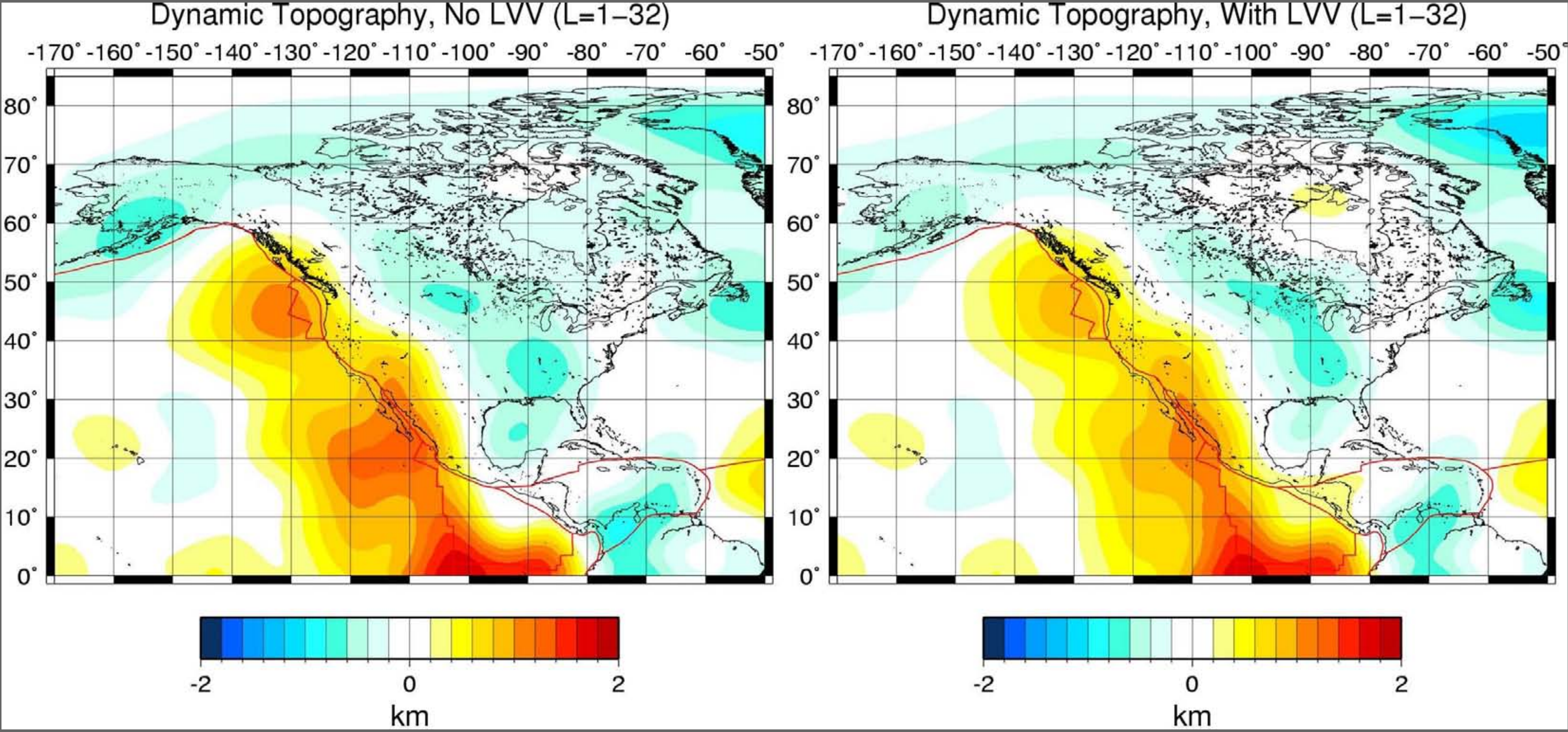
$\gamma = 10$

(*Karato & Karki* 2001: γ = 10,20)



Implications of LVV for dynamic surface topography*

$$\eta_0(r) = \exp[\ \ln \langle \eta(r,\theta,\varphi) \rangle\ ]$$



* Moucha et al., *GJI*, 2007

Main Points

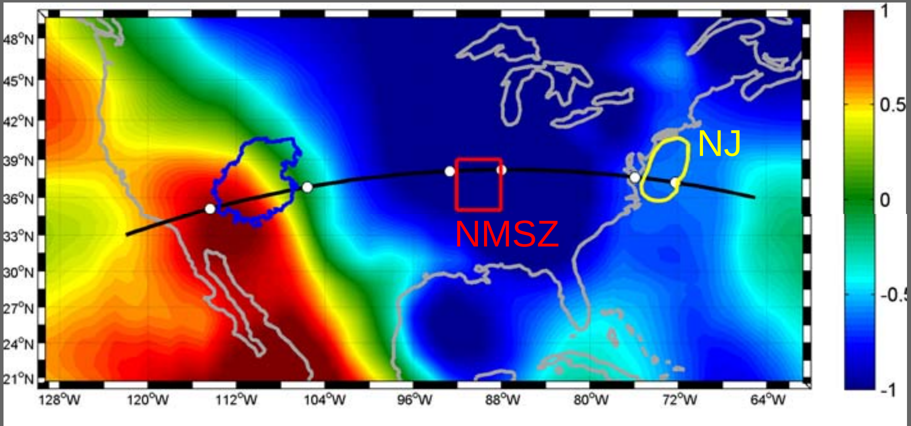
- We have derived a tomography-based mantle convection model that successfully predicts plate velocities and observations of surface gravity and topography on the North American plate.

- North American geodynamic observables are strongly affected by viscous flow driven by density anomalies in the deep upper mantle and in the lower mantle. These loads are associated with the descending Kula-Farallon plate system and an active mantle upwelling below the Southwestern US.

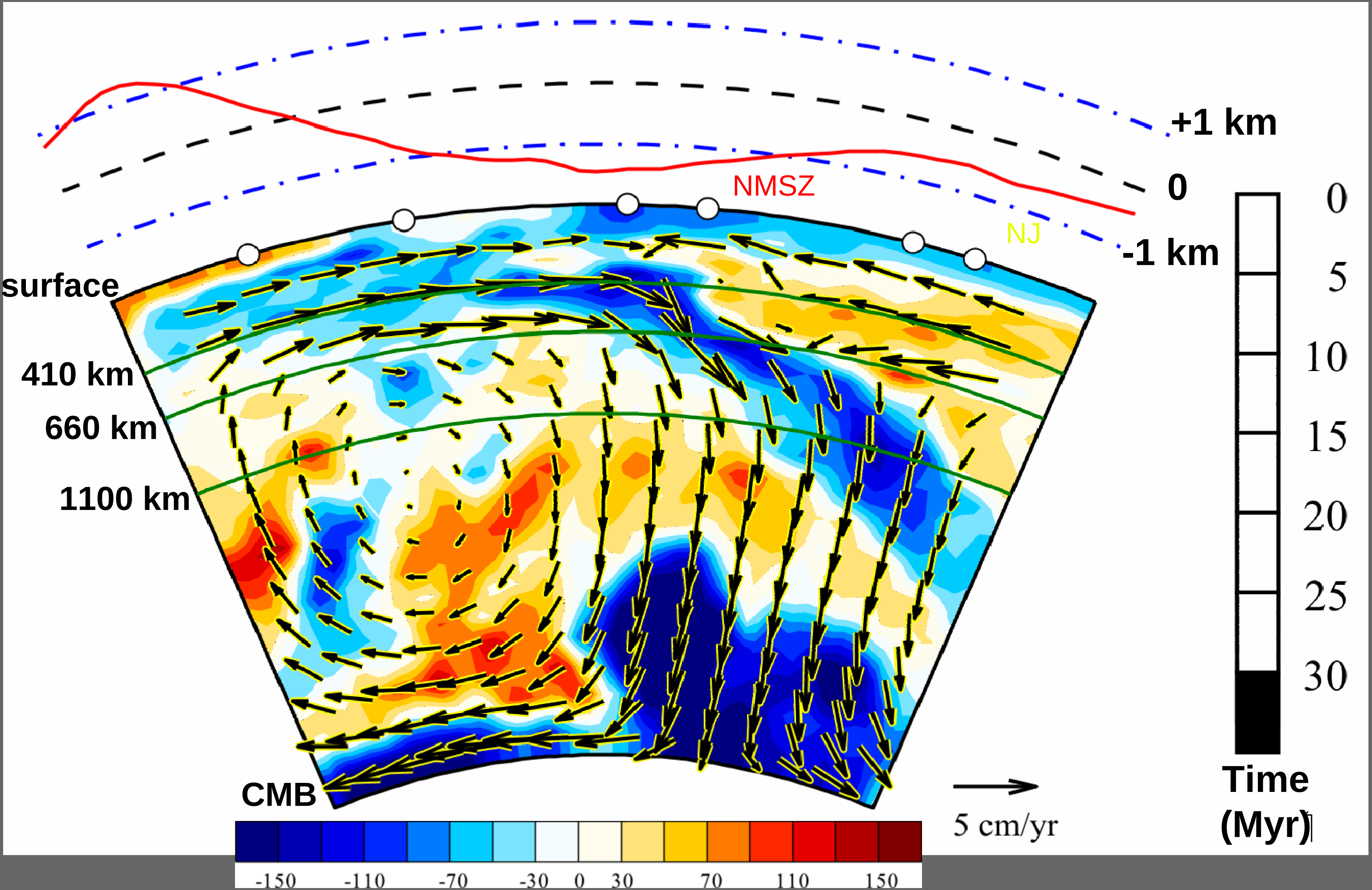
- Descent of the Farallon slab into the lower mantle induces a region of maximum horizontal flow convergence and maximum compressive surface stresses directly below the Central Eastern United States.

- Mantle-flow induced surface depression and associated bending stress (reflected in SHmax) may be an important and long-lived (Late Cenozoic) contributor to (clustered, migrating) seismic activity in the Mississippi Basin, extending from the Great Lakes to the Gulf of Mexico.

Time-dependent mantle dynamics and surface flexure over the past 30 Myrs



Dynamic Surface Topography



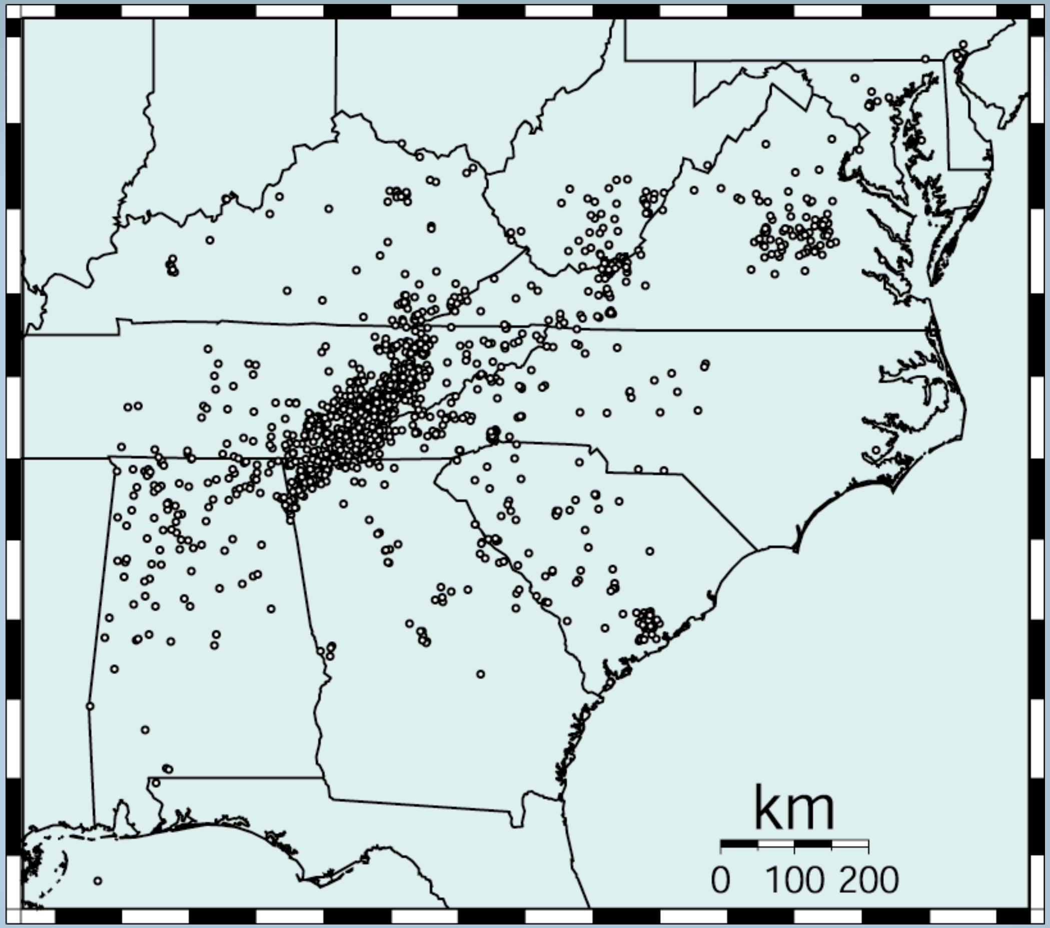
Moucha et al (submitted, 2009)

CEUS SSC Workshop

Martin Chapman
Department of Geosciences
Virginia Tech

February 20, 2009
Palo Alto, California

SOUTHEASTERN U.S. SEISMICITY



Instrumental Epicenters of Earthquakes
(M>0.0)

The Eastern Tennessee Seismic Zone

- Most seismically active area in Southern Appalachians
- Lies primarily in the Valley and Ridge Province of Tennessee
- The largest historic earthquake occurred April 29, 2003 near Fort Payne, AL (M = 4.6)
- Earthquakes typically occur at depths of 5 to 26 kilometers
- Seismicity is associated with a major potential field anomaly (New York-Alabama Lineament)

Post-1985 Studies of Eastern Tennessee

Johnston et al. (1985), ***Bull. Seism. Soc. Am.,*** 75, 291-312.

- Identified correlation between seismicity and potential field.
- Determined first focal mechanisms showing N-S and E-W nodal planes.
- Proposed that seismicity occurs in a crustal block defined by the NY-AL lineament on the west and the Ocoee lineament on the east.

Teague et al. (1986), ***Bull. Seism. Soc. Am.,*** 76, 95-109.

- Demonstrated primarily N-S and E-W trending nodal planes with strike-slip motion.
- Confirmed that seismicity occurs primarily in the basement.

Davison, F.C. (1988). ***Ph.D. dissertation***, Virginia Tech.

- Inverted focal mechanisms for stress tensor. Sub-horizontal maximum compression, trending northeast.

Powell et al., ***Science***, 264, 686-688.

- Proposed that seismicity is coalescing in a major strike-slip fault system.

Post-1985 Studies, continued

Hopkins, D.L. (1995), ***Ph.D. dissertation***, Virginia Tech

- Reprocessed industry seismic reflection profiles in southeastern Tennessee
- Proposed that the NY-AL lineament is related to a west-dipping, wedge-shaped feature in the upper crust.

Kaufmann and Long (1996), ***Journ. Geophys. Res***., 101, 8531-8542.

- Proposed that seismicity occurs in a low-velocity zone.

Vlahovic et al. (1998), ***Journ. Geophys. Res***., 103, 4879-4896.

- 3-D velocity inversion showing that earthquakes occur in regions of velocity transition
- Velocity anomalies are correlated with the NY-AL lineament and extend vertically through the mid- and upper crust.

Post-1985 Studies, continued

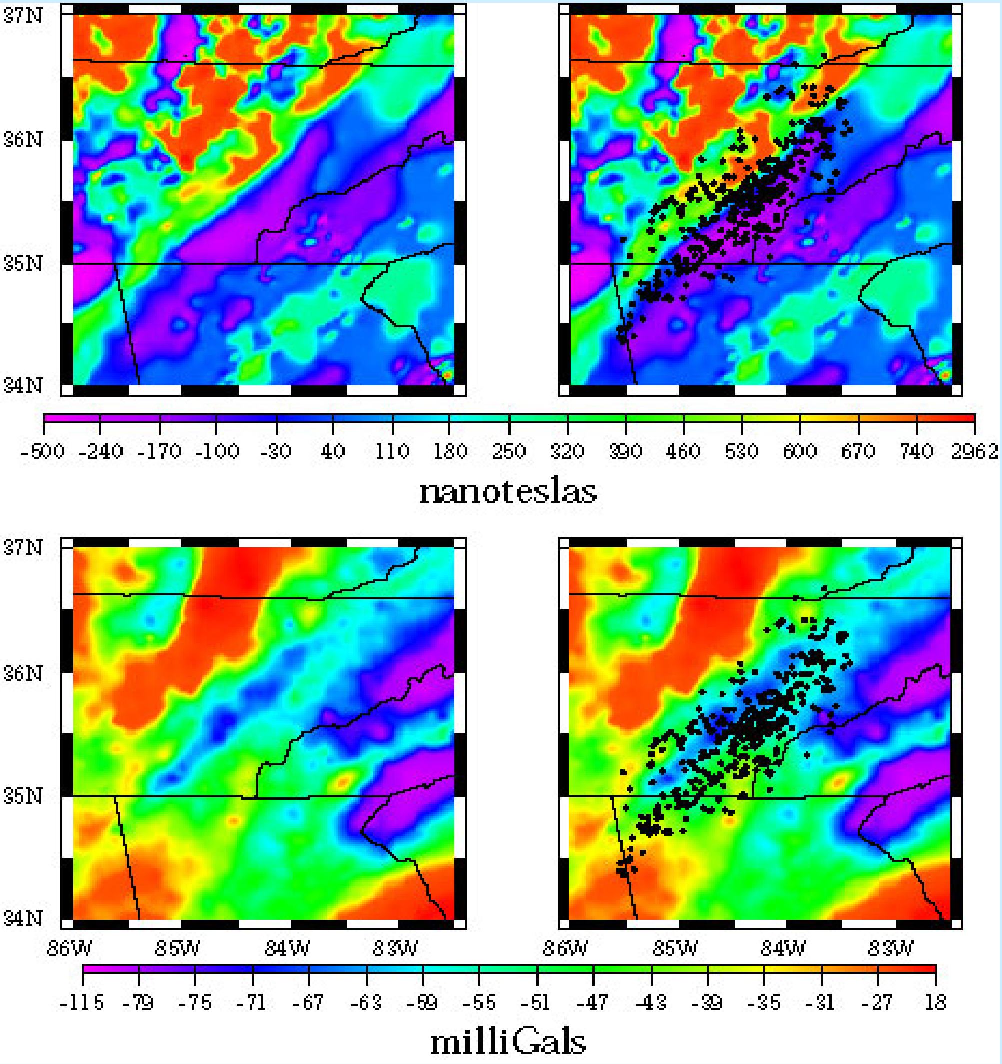
Chapman et al. (1997) ***Bull. Seism. Soc. Am***., 87, 1522-1536.

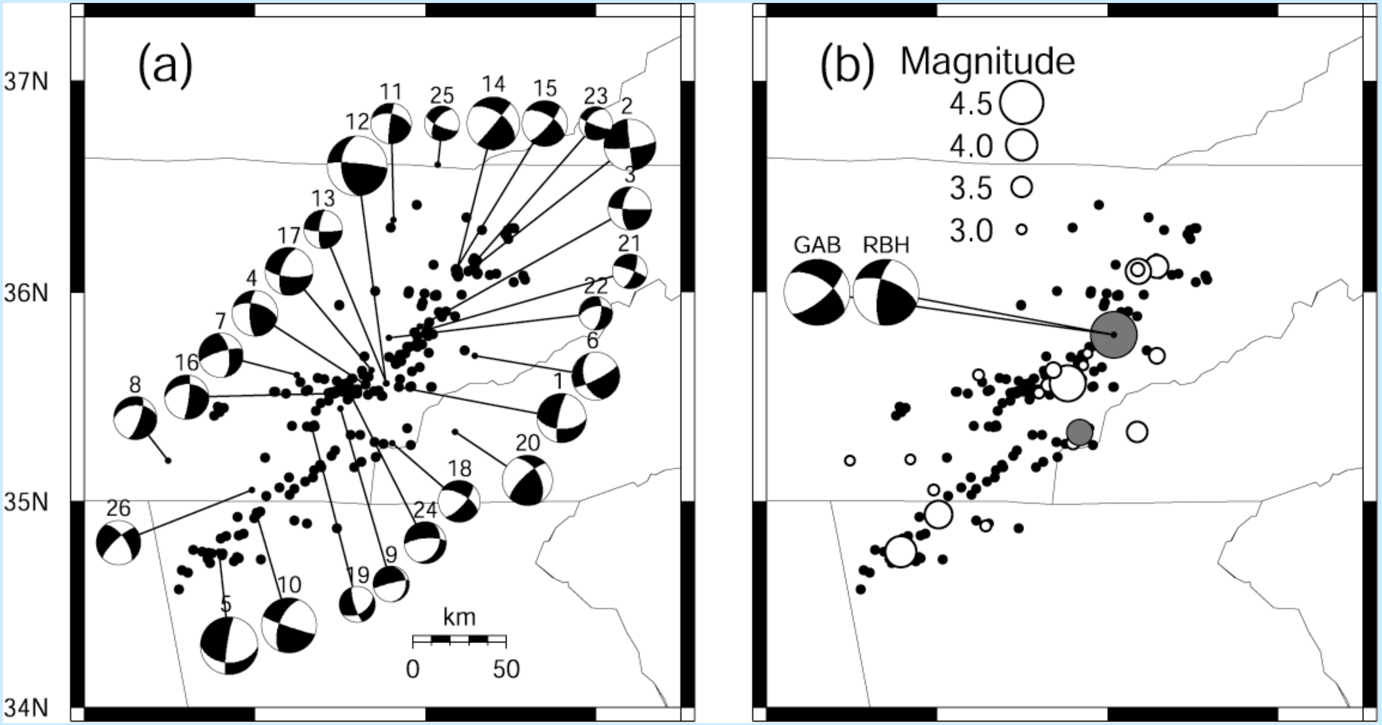
- Found statistical correlations between epicenter alignments and focal mechanism solutions.
- Proposed that the seismic zone is characterized by left-stepping, en-echelon basement faults.
- Focal mechanisms are consistently strike-slip and occur in response to a uniform regional stress field.

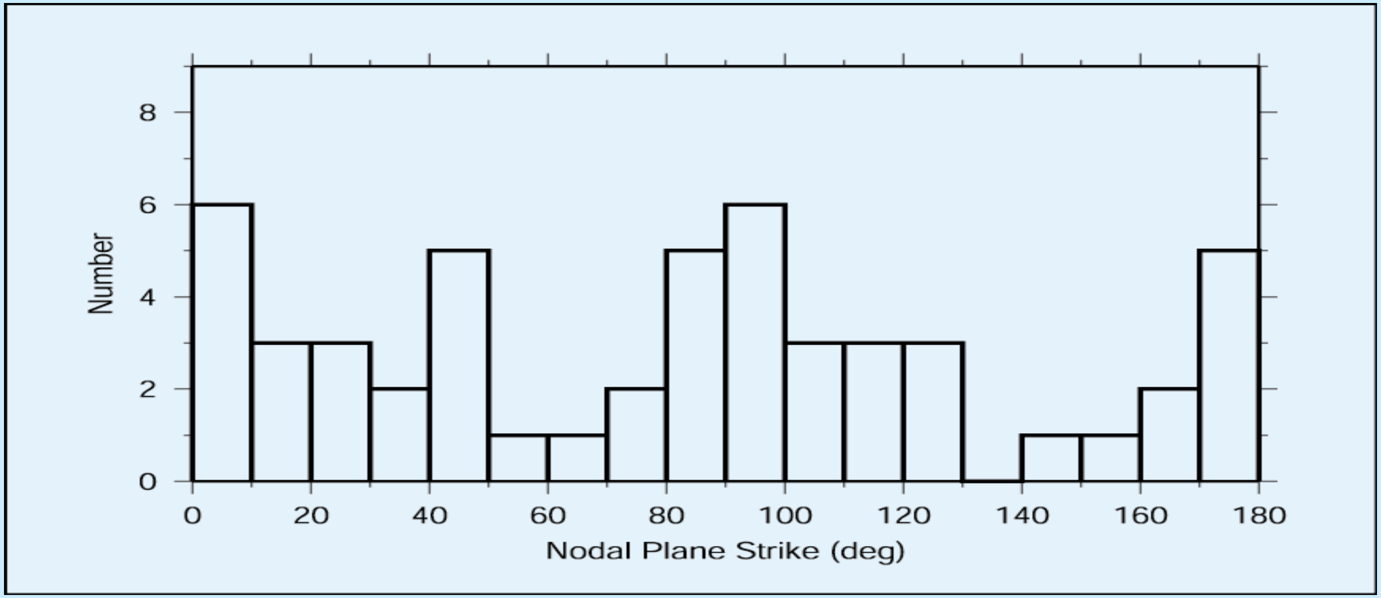
Dunn and Chapman (2006) ***Seismological Research Letters***, 77, no. 4, 494-504.

- Relocated hypocenters using HYPODD
- Seismicity in the most active area of the zone near 35.5 deg. N latitude occurs in a diffuse, west-trending, north-dipping belt that appears to correlate with a north-dipping mid-crustal reflective zone imaged on a seismic reflection profile.

NOAA magnetic and Bouguer gravity data with earthquake epicenters in the southern Appalachian region

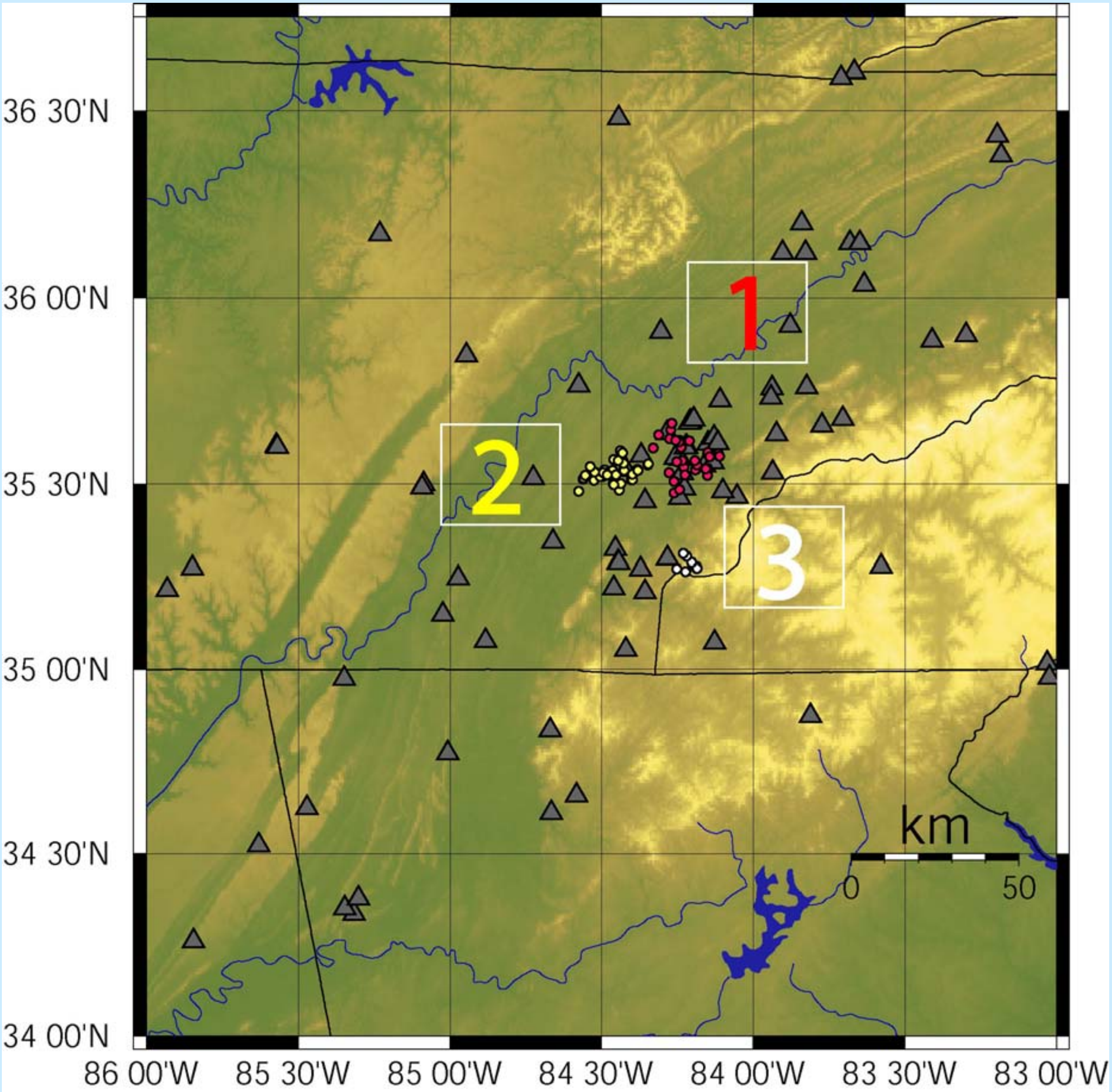






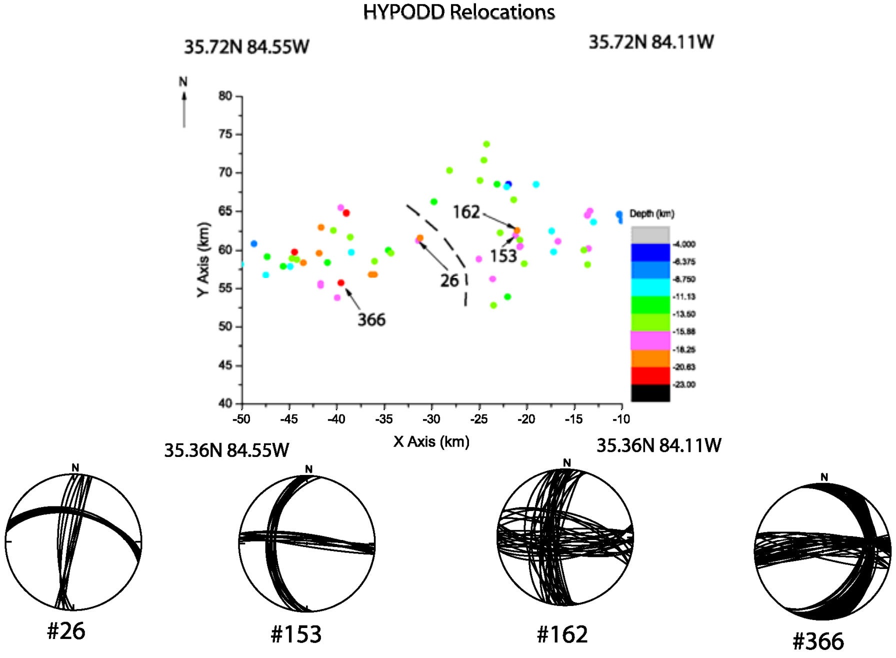
from: Chapman et al. (1997)

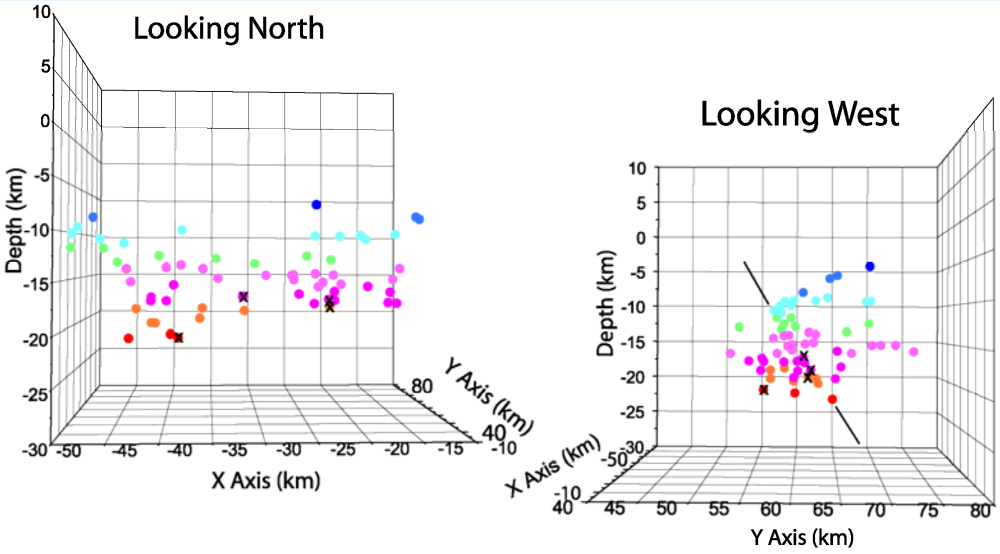
Three Largest Clusters, MAXSEP 5 km



from: Dunn and Chapman (2006)

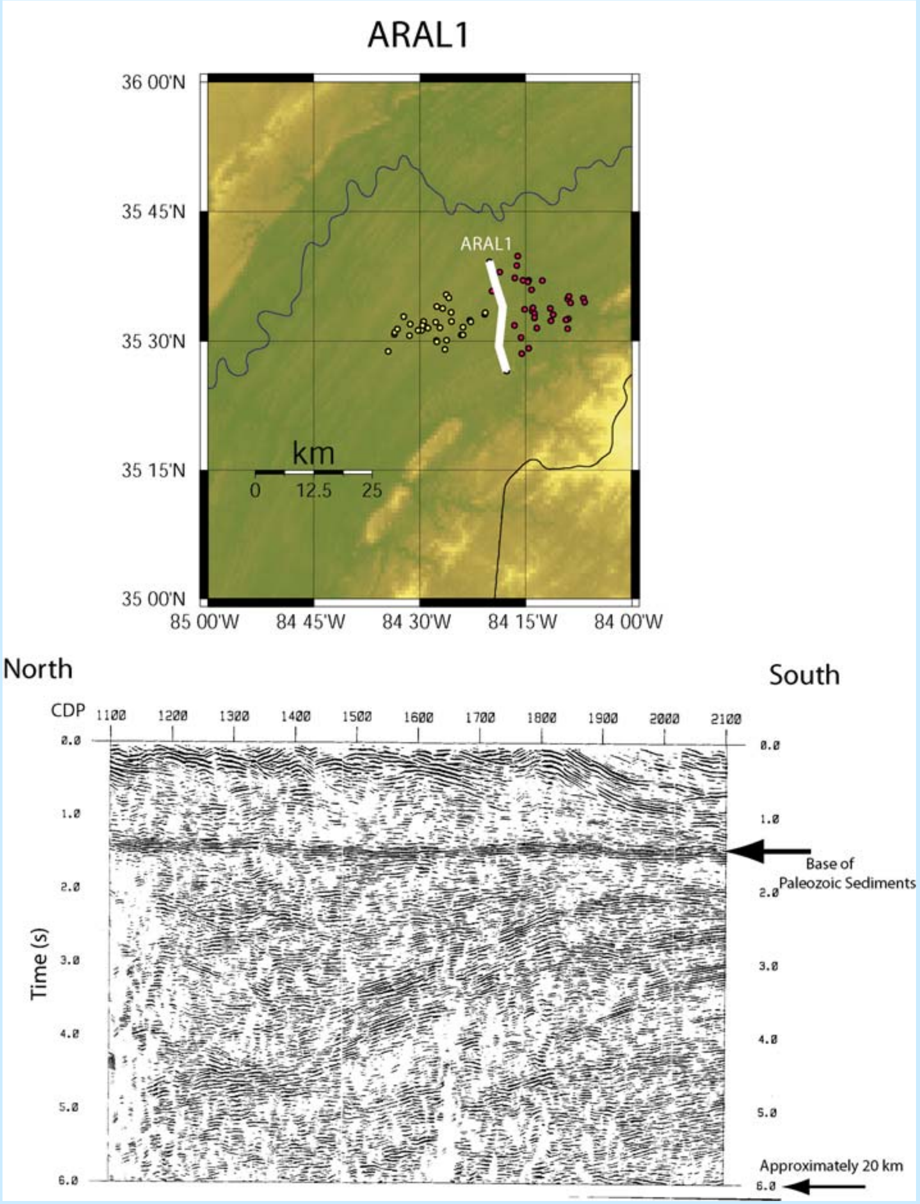
Subset of Clusters 1 and 2
MAXSEP 5 km





from: Dunn and Chapman (2006)

Reflection Profile ARAL 1 and events in Clusters 1 and 2



from: Dunn and Chapman (2006)

Some Summary Thoughts on Eastern Tennessee Seismicity

All previous studies are consistent in that eastern Tennessee earthquakes are occurring in response to a highly uniform regional stress, with strike-slip motion predominant.

Chapman (1997) suggested that the seismicity is occurring on a system of NE-trending en-echelon faults, as well as on EW trending faults. Testing that hypothesis requires precision hypocenter locations. Seismic network coverage in the area was inadequate in the period from 1995 to 2005. Network capability has improved recently.

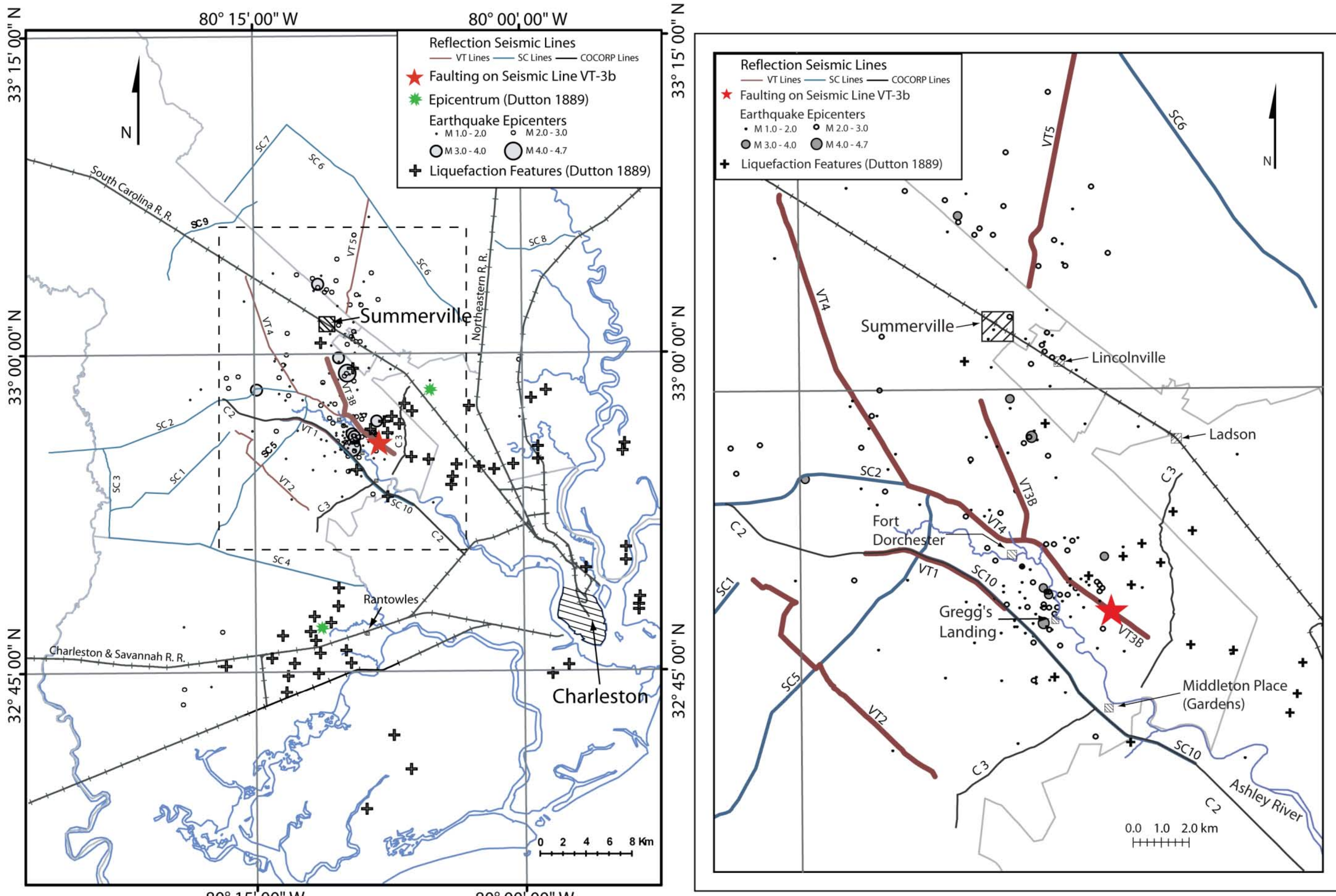
In the most active part of the seismic zone where double difference location methods can be applied, (N35.5 deg Latitude), there is some suggestion that the seismicity is correlated with the seismically imaged basement structure: however, individual fault planes are not resolved (Dunn and Chapman, 2006).

The geologic nature of the NY-AL lineament remains a mystery. It marks an abrupt vertical boundary between a very seismogenic crust to the southeast, and a less seismogenic crust to the northwest. However, between 35 and 36 deg. N latitude, many deeper events occur to the west of the magnetic gradient.

Faulting Imaged on Seismic Reflection Profiles Near Summerville, South Carolina

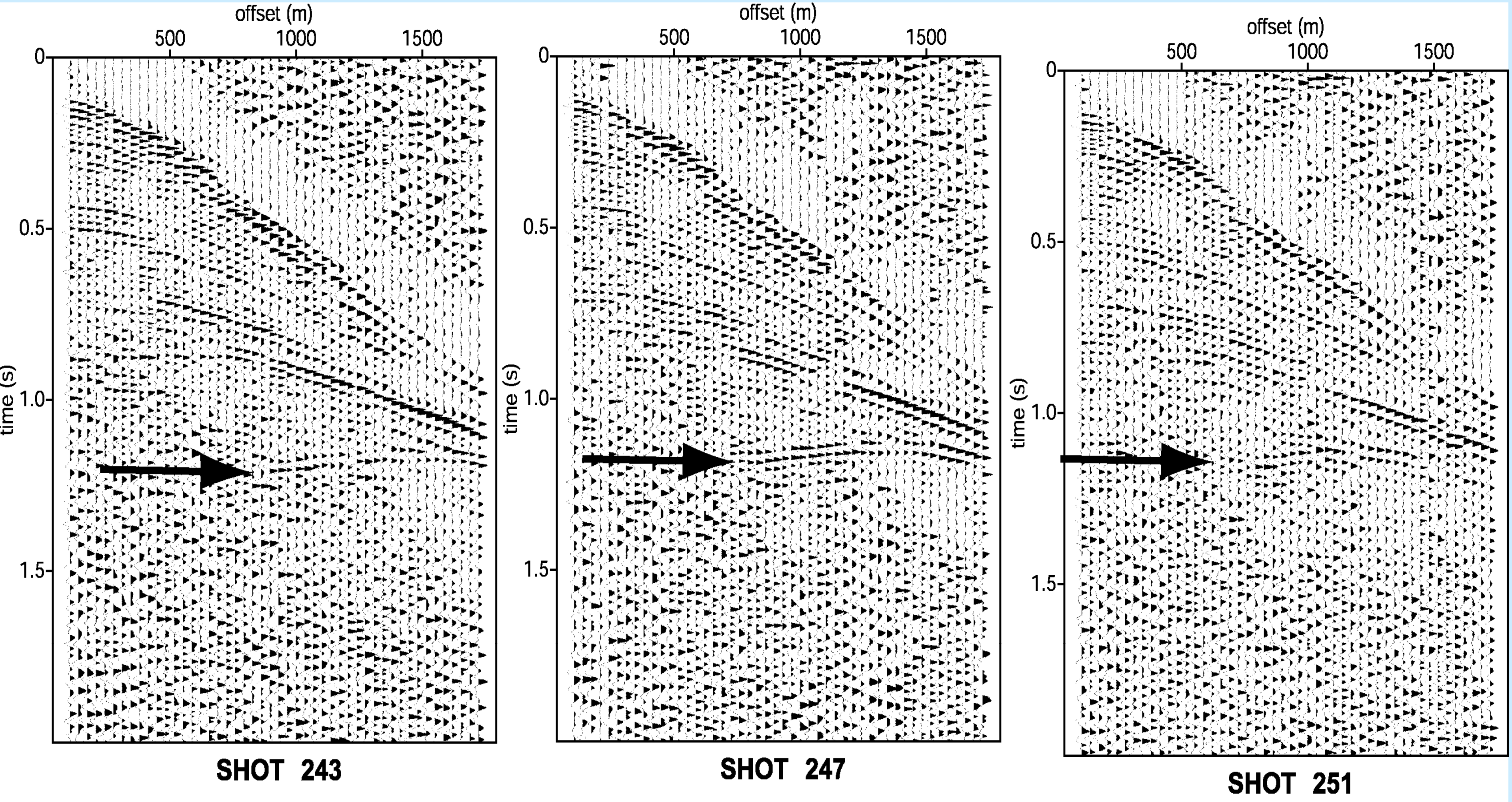
Chapman, M.C. and J.N. Beale, (2008) Mesozoic and Cenozoic Faulting Imaged at the Epicenter of the 1886 Charleston, South Carolina Earthquake, ***Bulletin of the Seismological Society of America***, Vol 98, 2533-2542.

- Reprocessing of seismic reflection data collected in 1980-1981 reveals significant faulting of the Mesozoic basement and Cretaceous and Cenozoic sediments in the epicentral area of the 1886 Charleston earthquake.



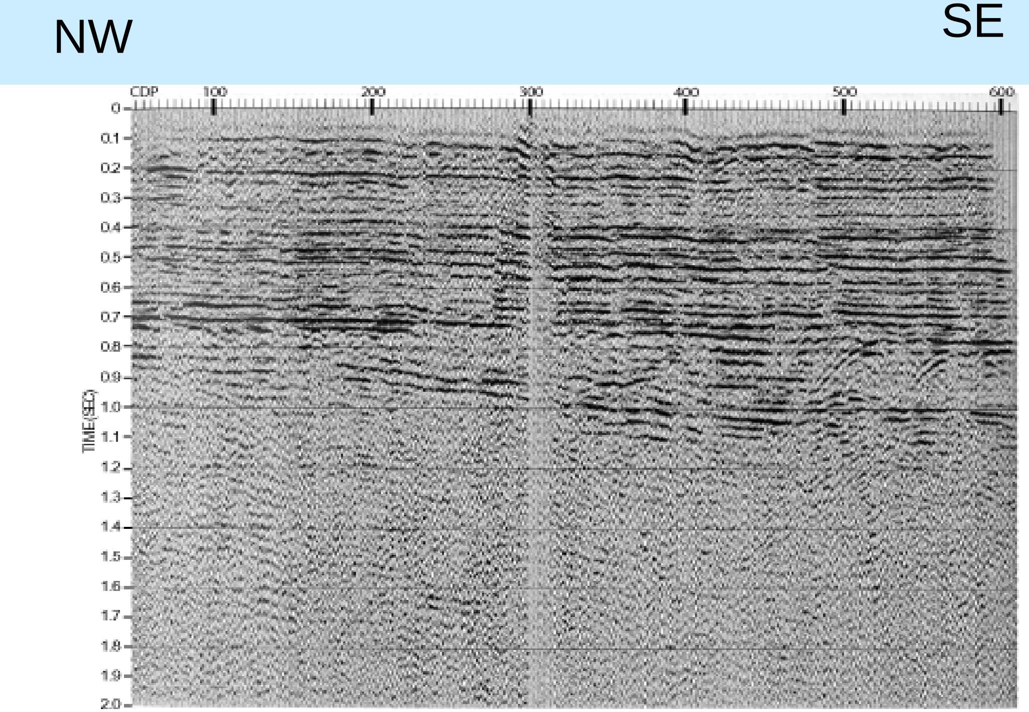
from: Chapman and Beale (2008)

Shot-gathers from Profile VT-3b in the Vicinity of Gregg's Landing showing strong event with abnormal moveout

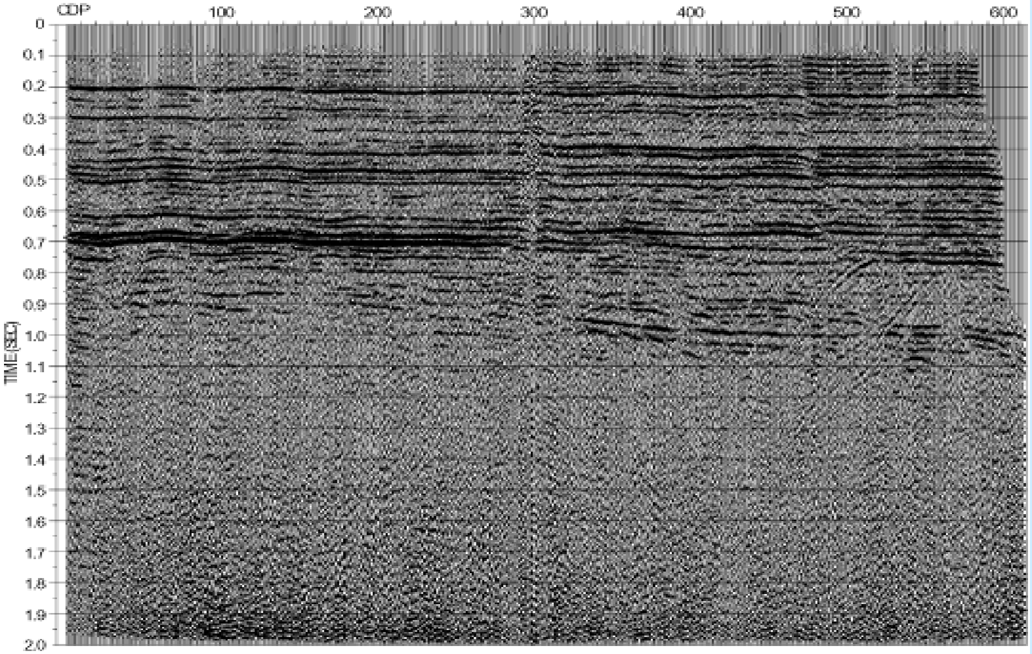


from: Chapman and Beale (2008)

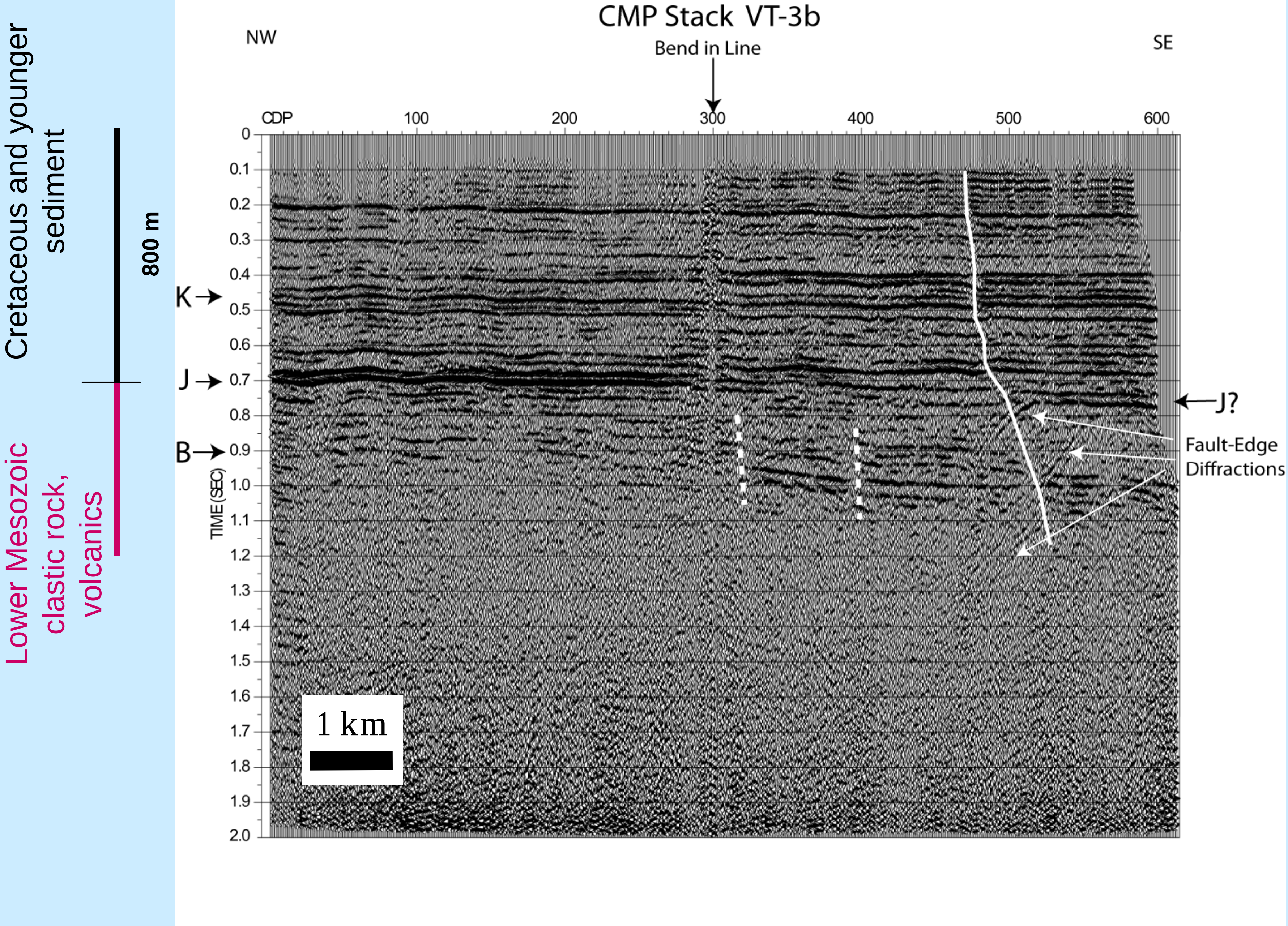
Original CMP stack of profile VT-3b



Reprocessed CMP stack

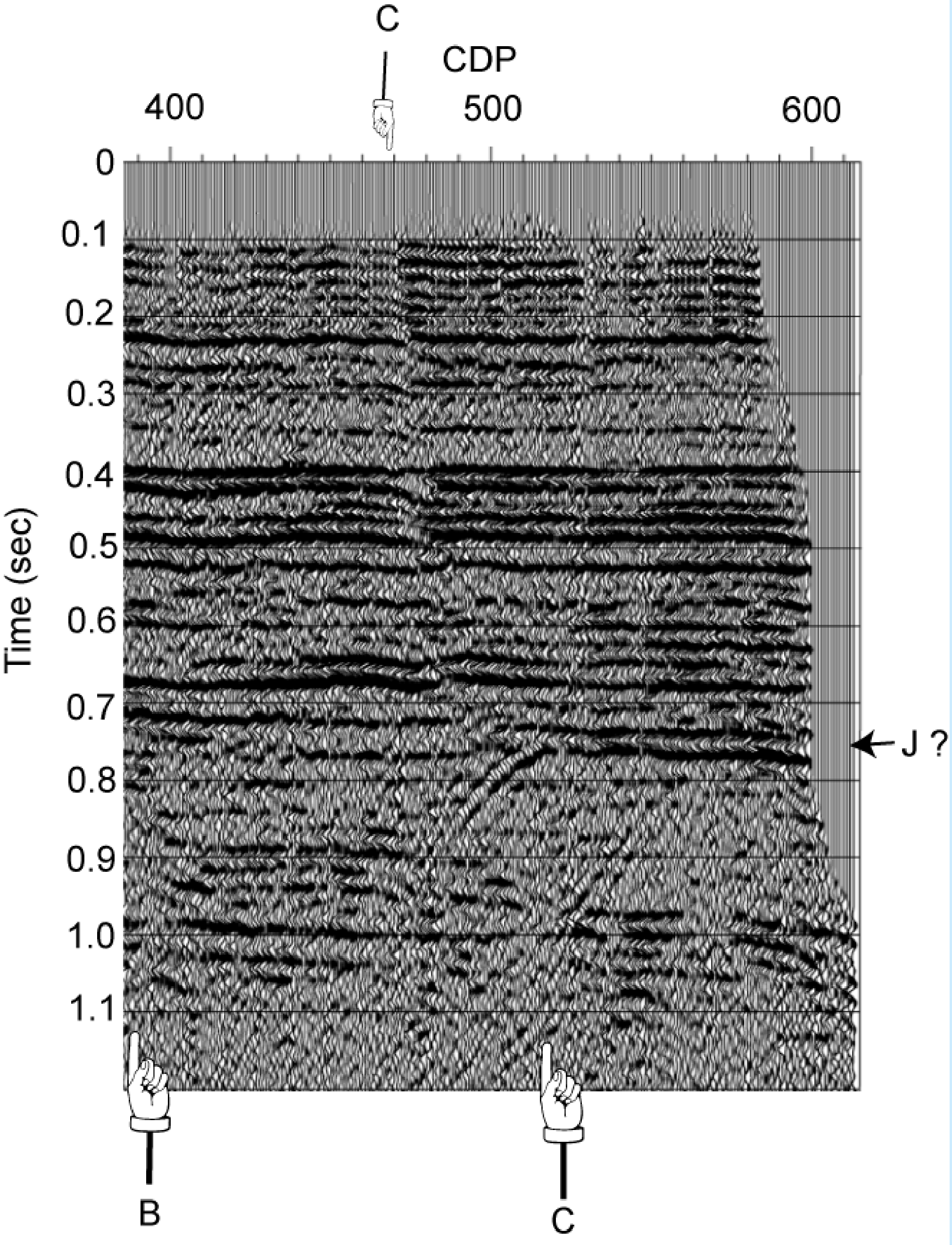


from: Chapman and Beale (2008)



from: Chapman and Beale (2008)

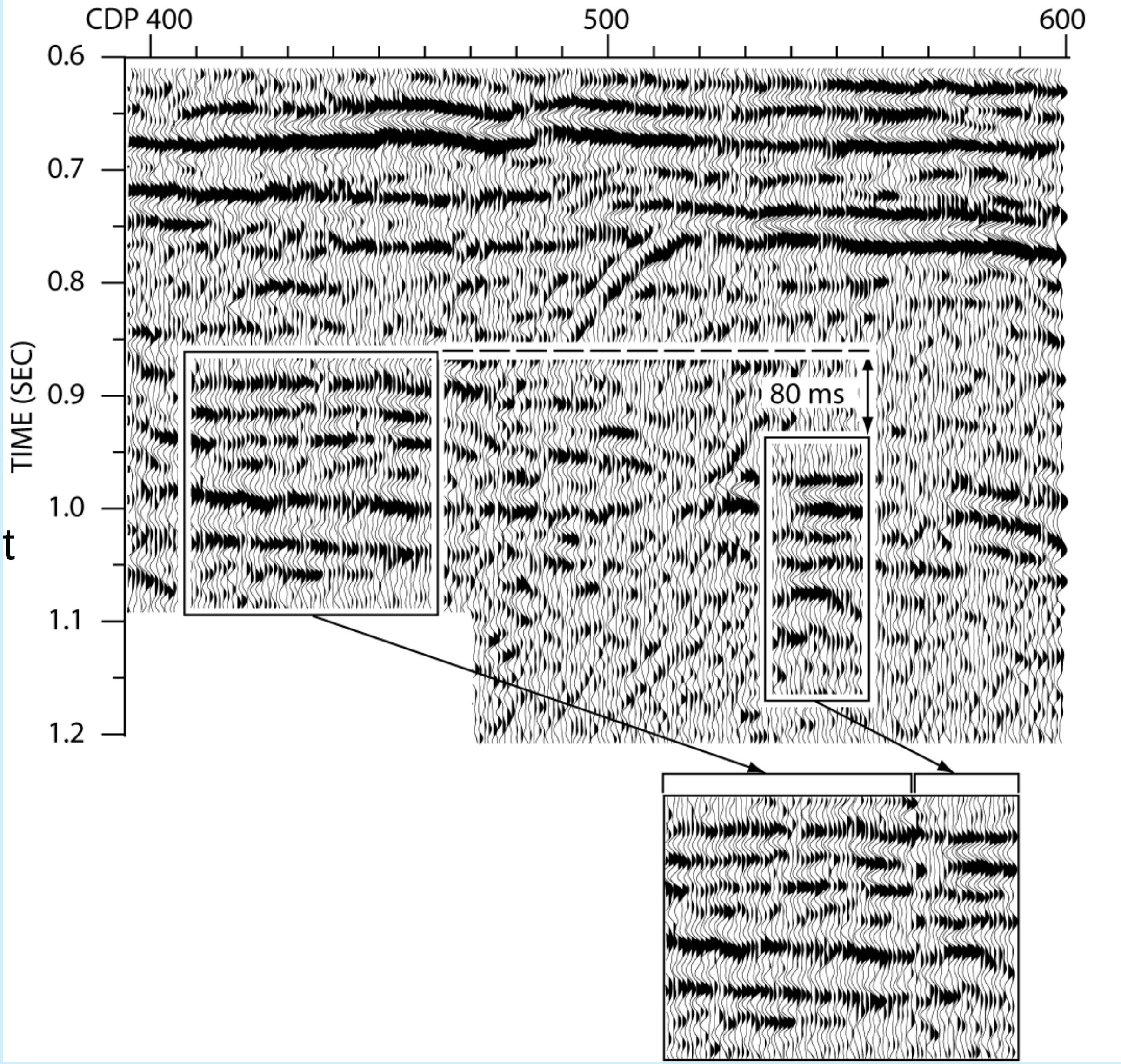
Southeastern end of VT-3b with fault C offsetting both Mesozoic basement and Cenozoic sediments.



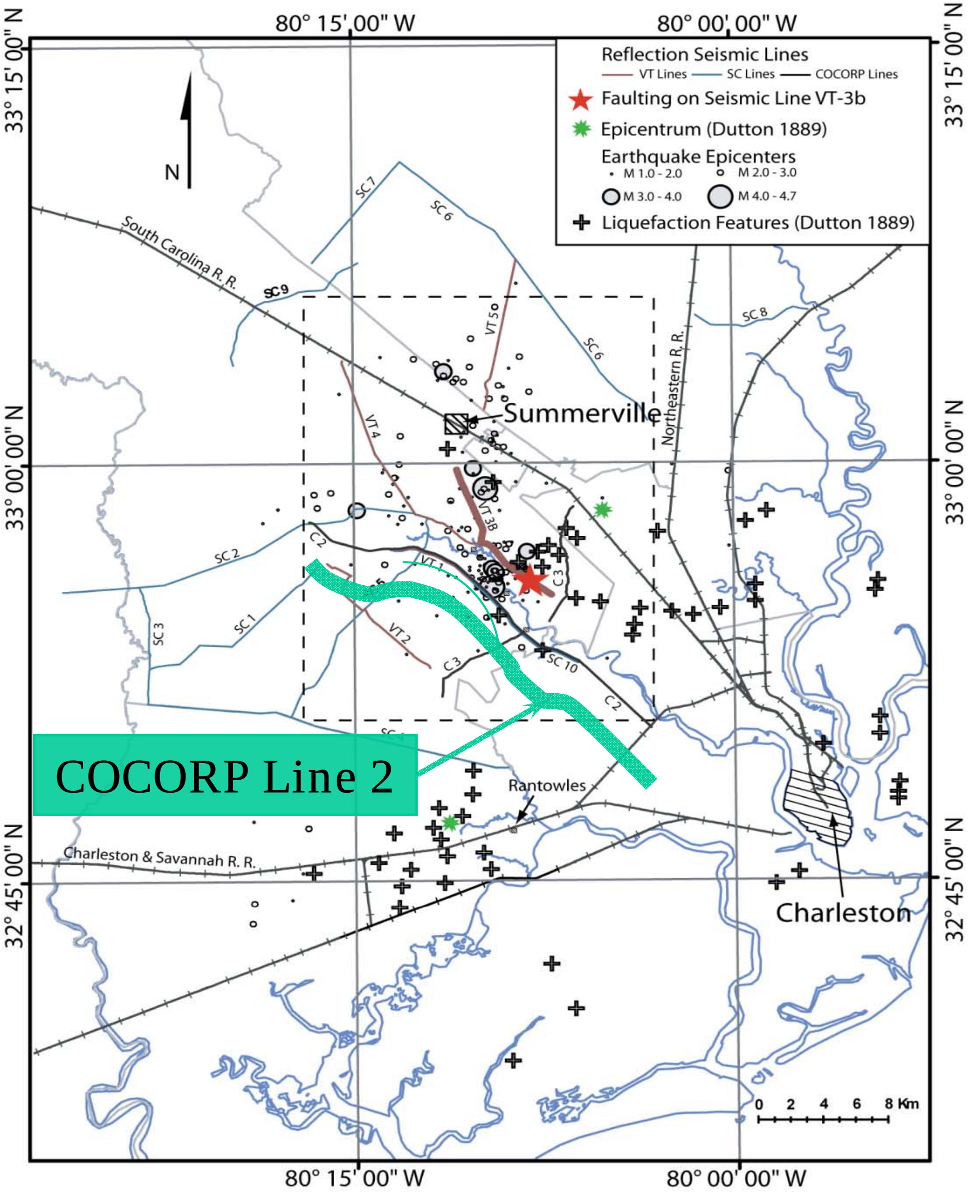
from: Chapman and Beale (2008)

Cross Correlation across fault C indicates 80 ms of down-to-east offset.

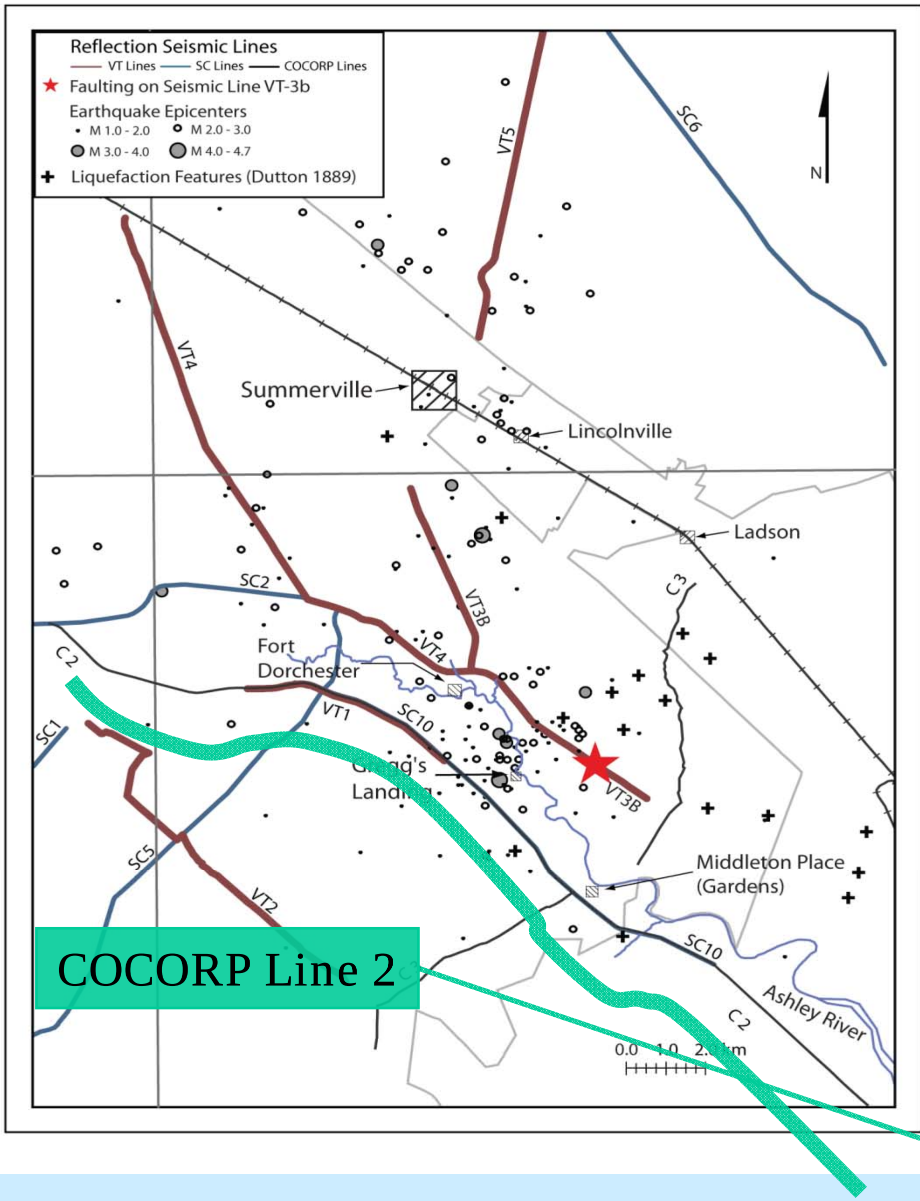
Approximately 200 m vertical offset of basement reflectors.



from: Chapman and Beale (2008)



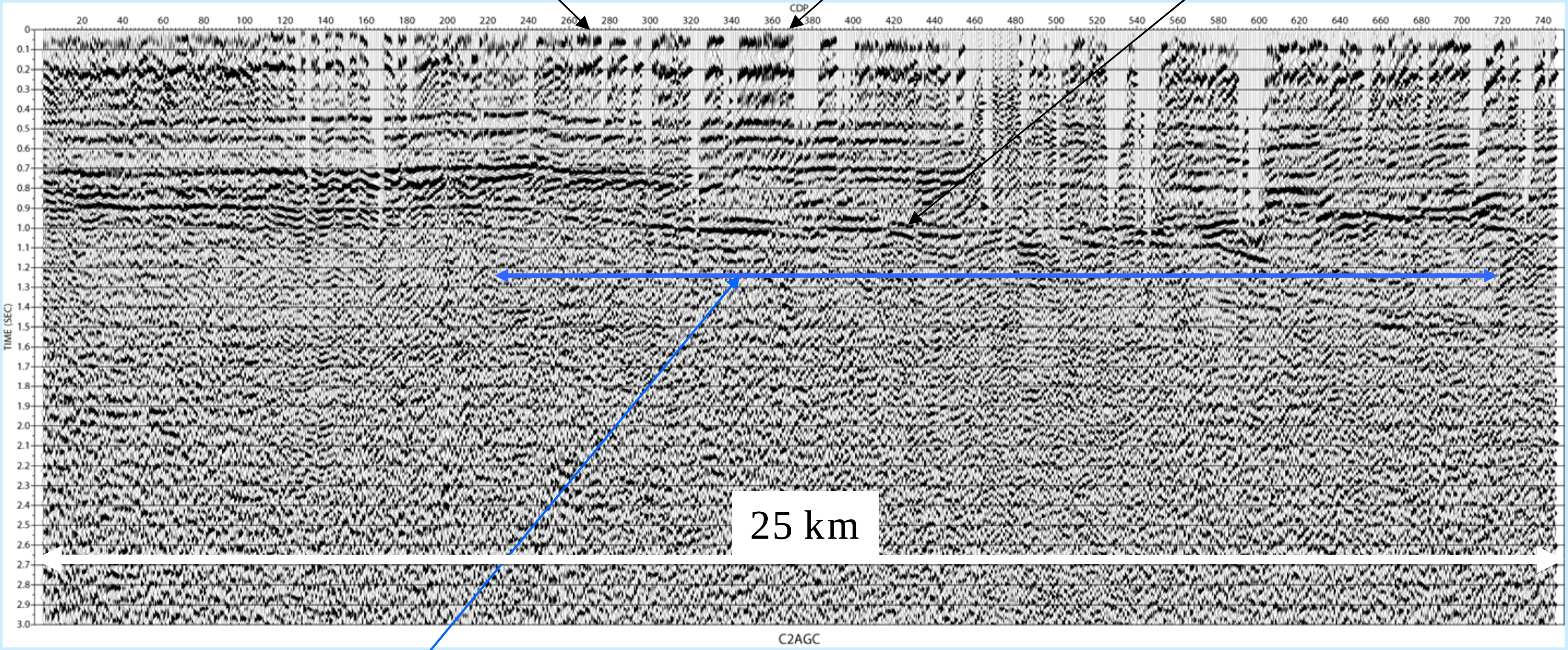
COCORP Line 2



COCORP Line 2

from: Chapman and Beale (2008)

COCORP Line 2



NW

Ft. Dorchester

Gregg's Landing

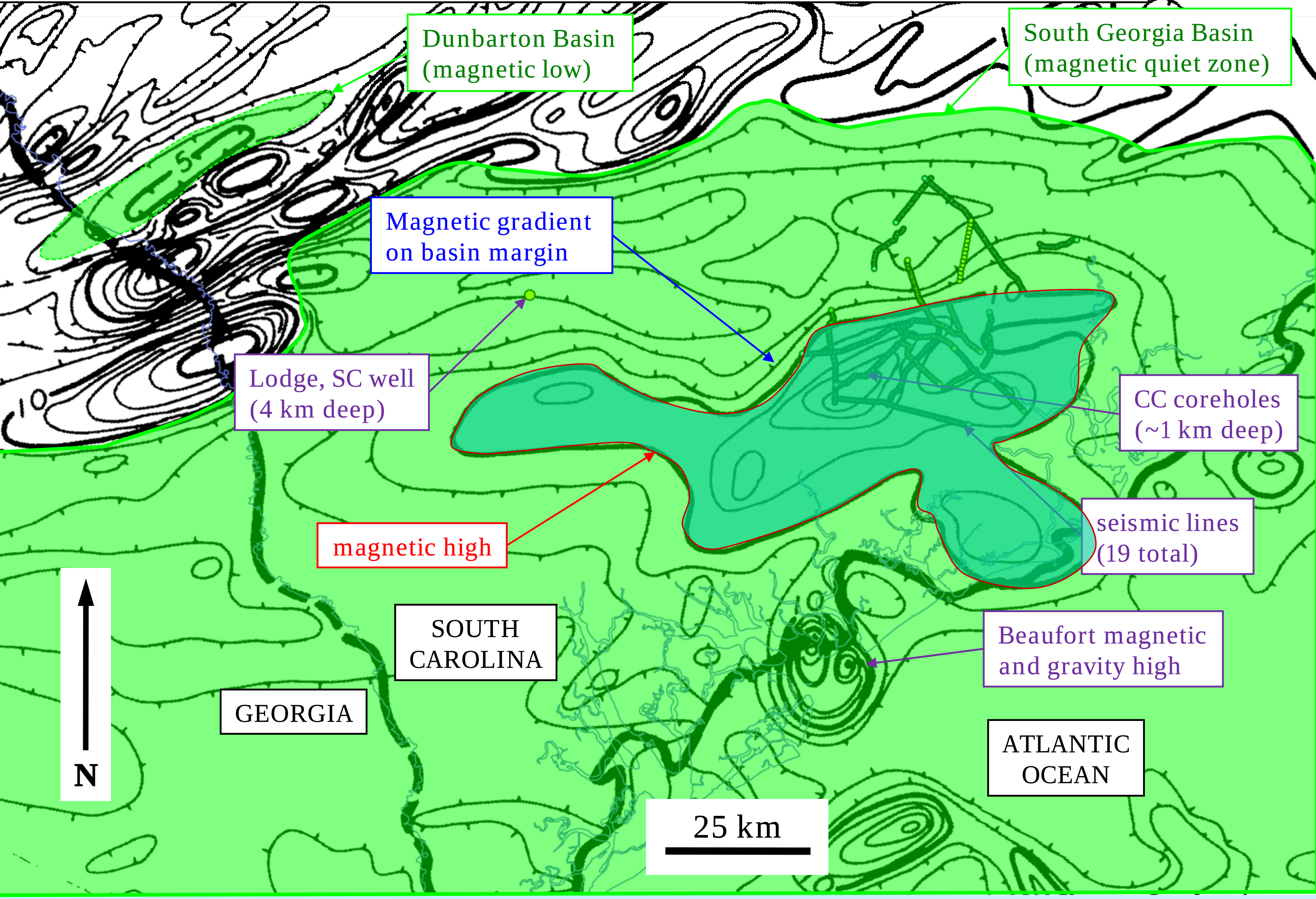
Fault on VT-3

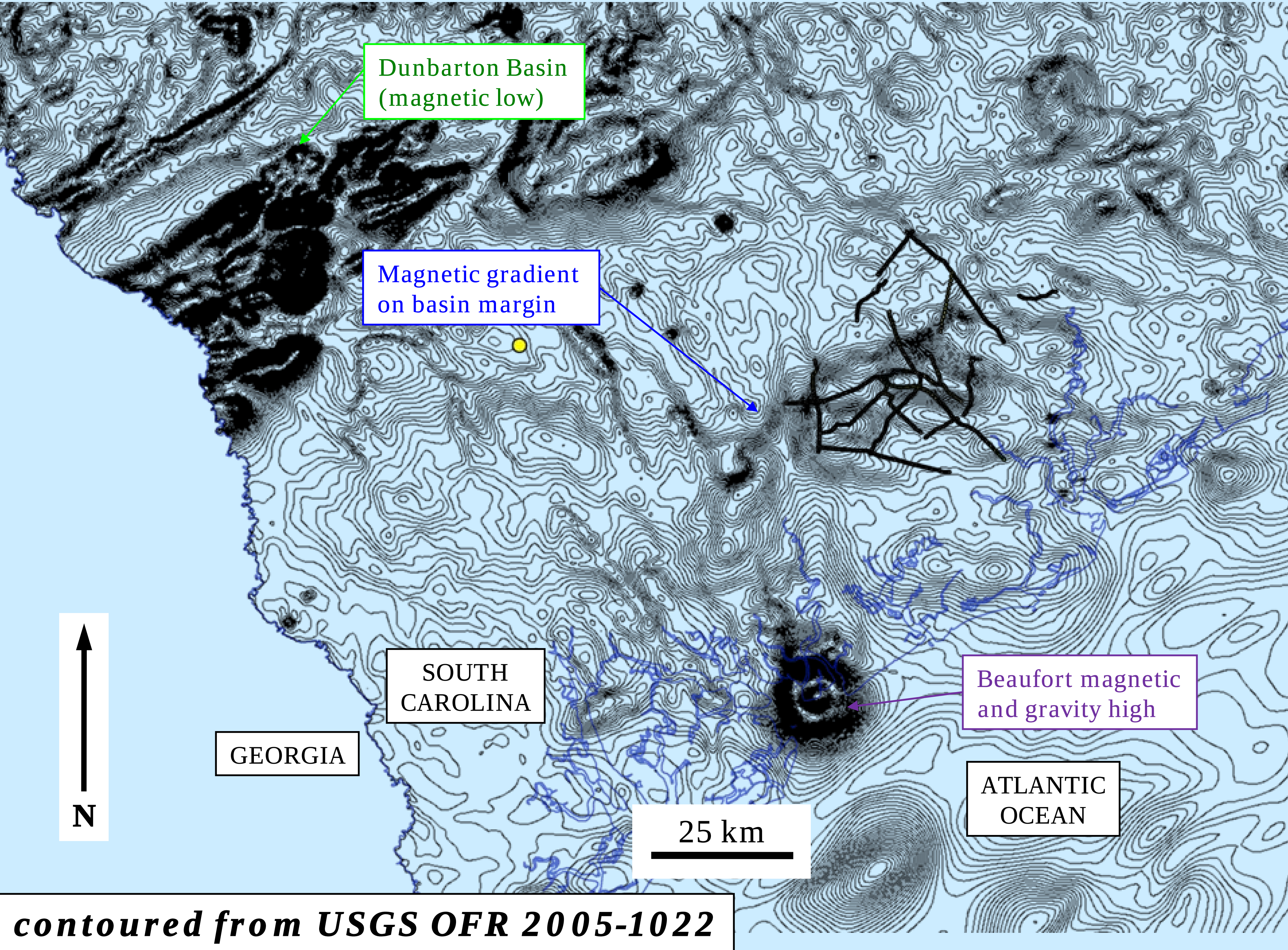
SE

25 km

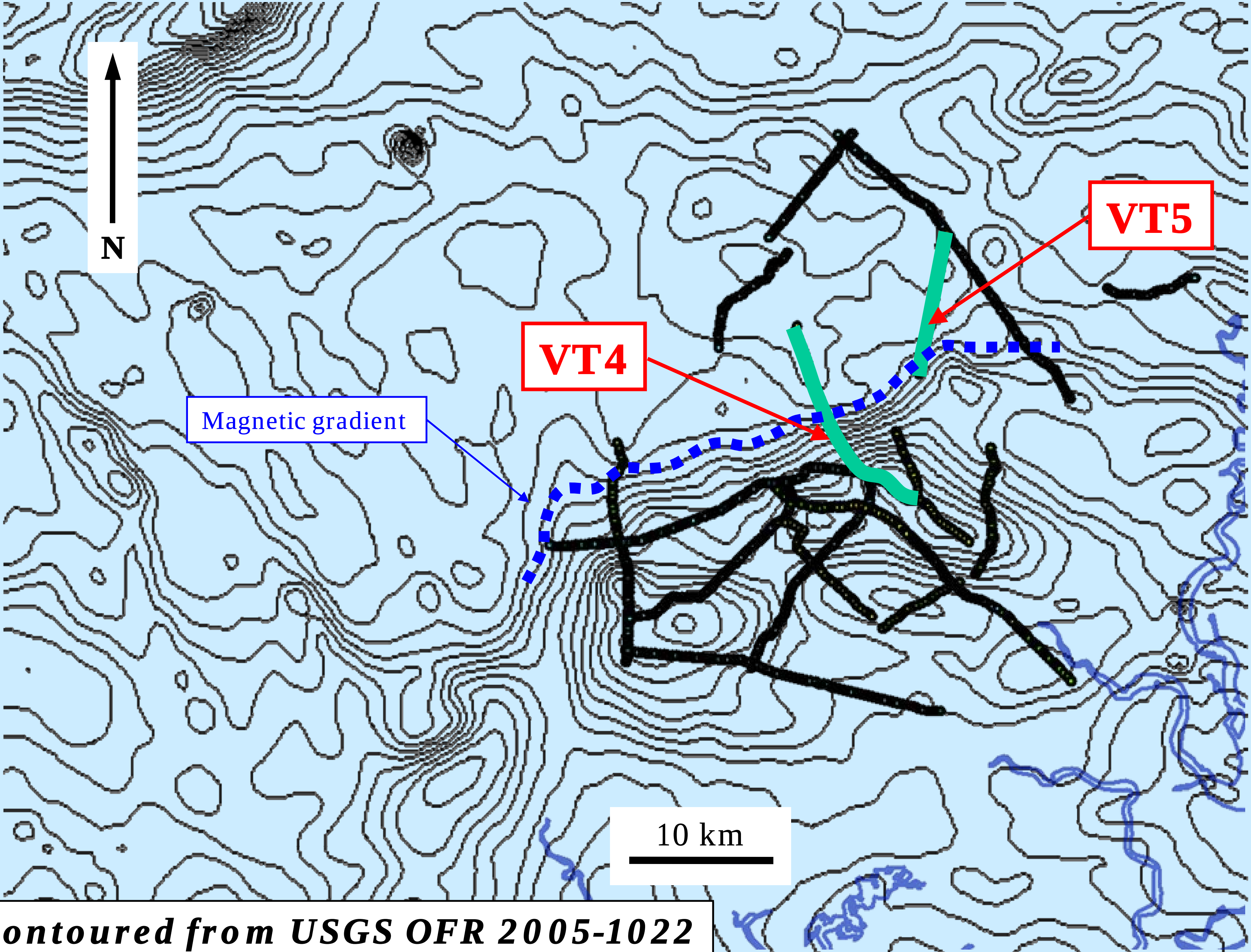
Faulted Lower Mesozoic Section

magnetic base map from Taylor, Zietz, and Dennis (1968)



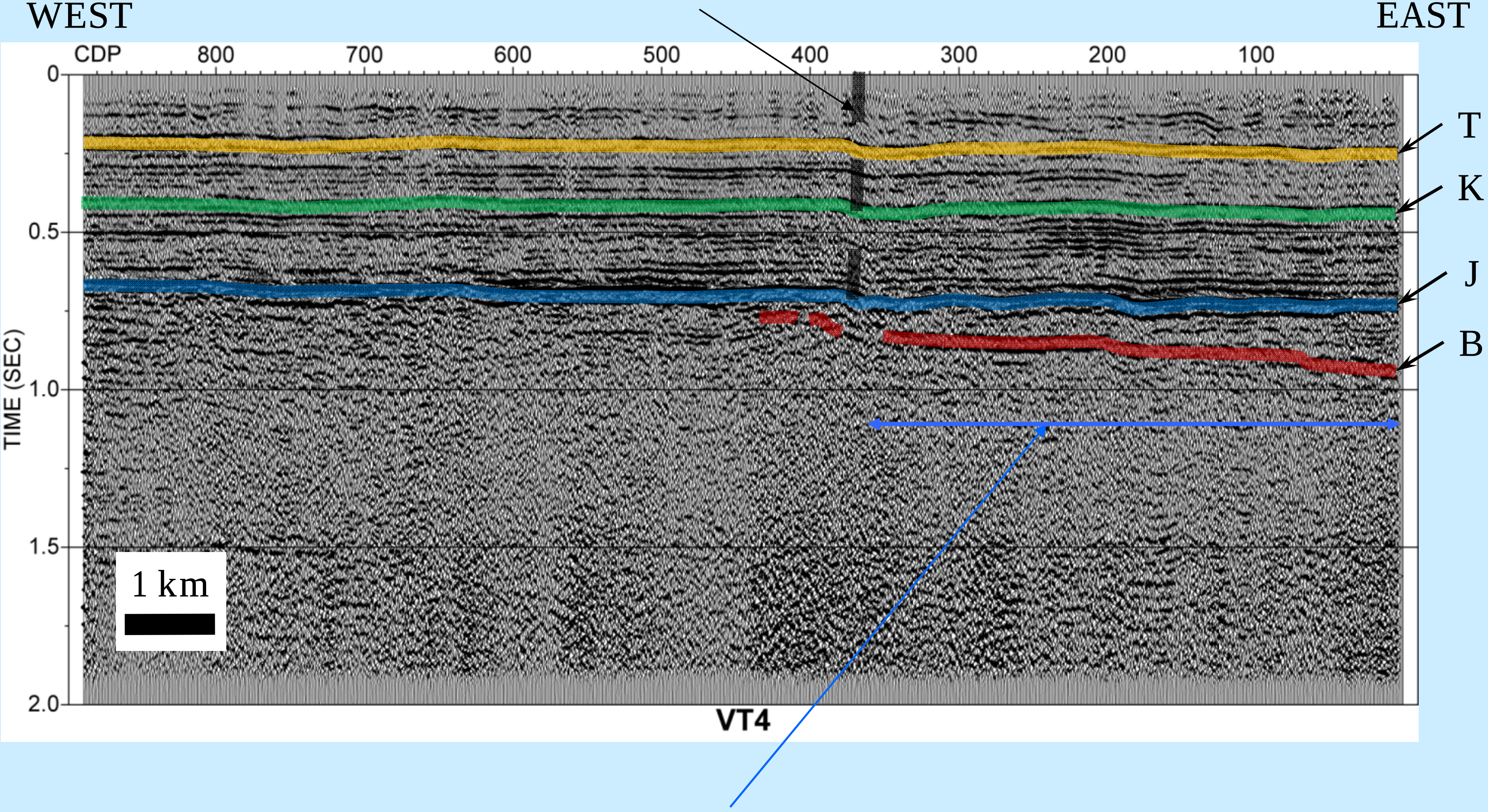


contoured from USGS OFR 2005-1022



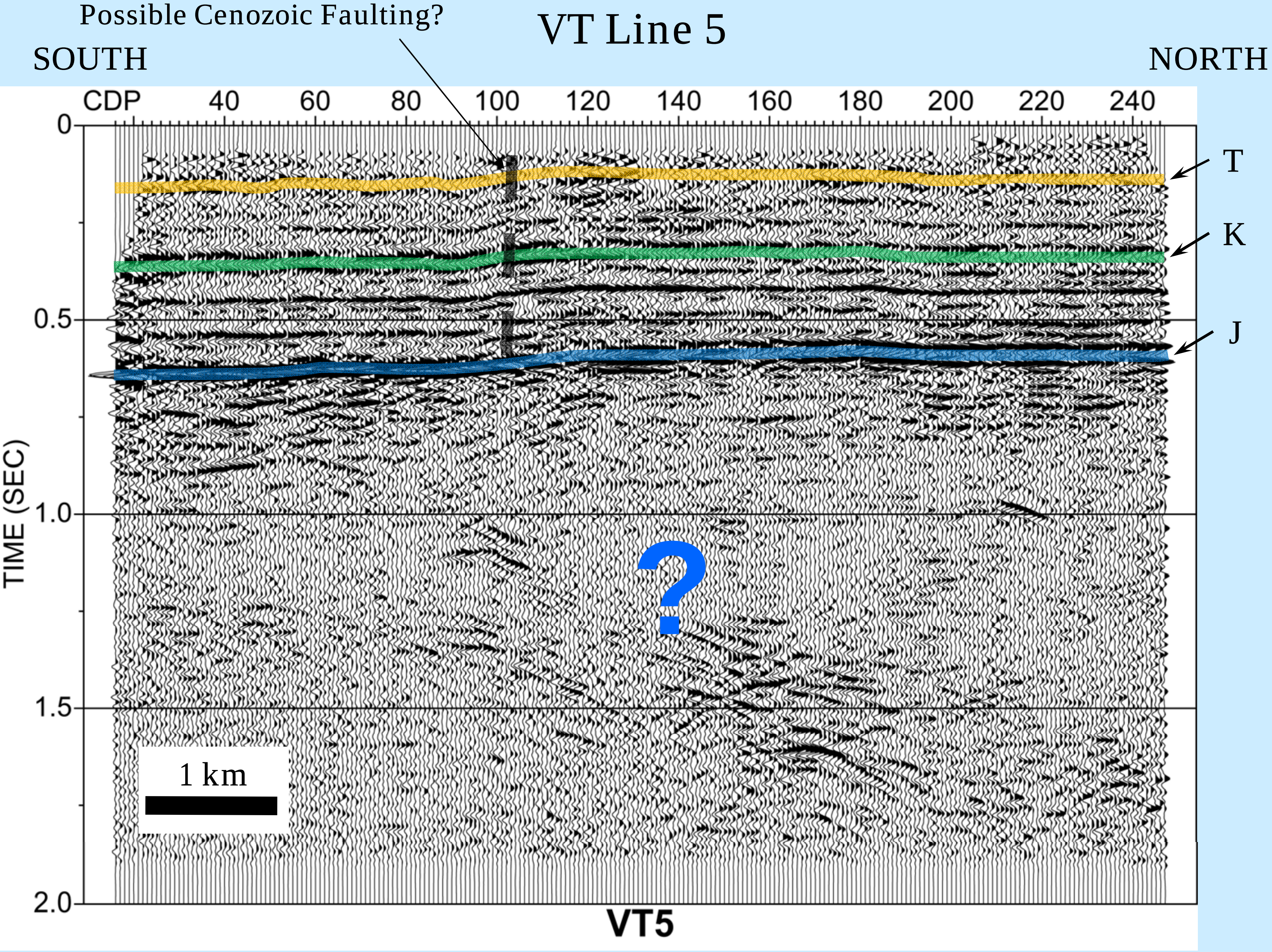
contoured from USGS OFR 2005-1022

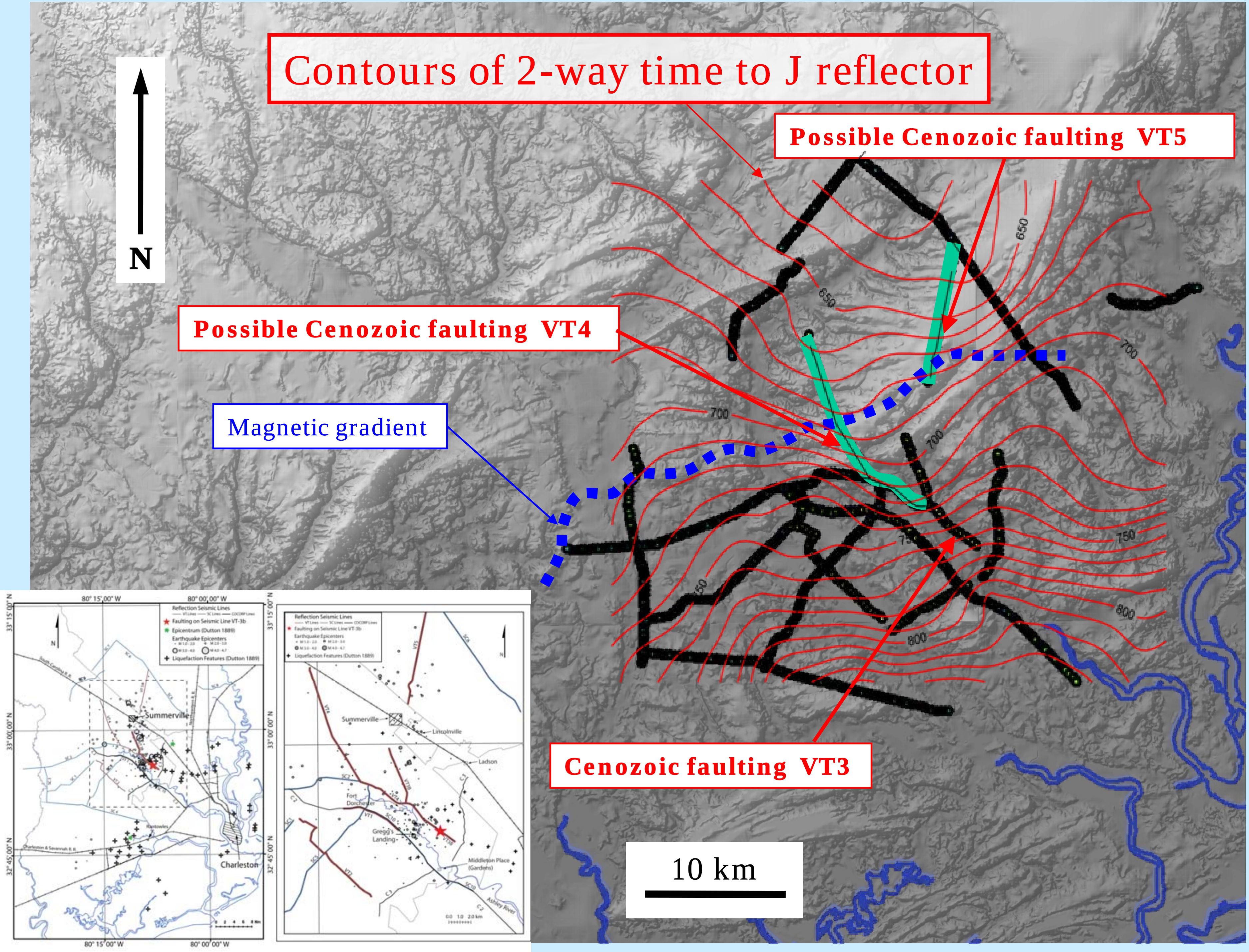
VT Line 4



Faulted Lower Mesozoic Section

VT Line 5


Possible Cenozoic Faulting?
SOUTH
NORTH
CDP
40
60
80
100
120
140
160
180
200
220
240
0
0.5
1.0
1.5
2.0
TIME (SEC)
T
K
J
?
1 km
VT5



Contours of 2-way time to J reflector

Possible Cenozoic faulting VT5

Possible Cenozoic faulting VT4

Magnetic gradient

Cenozoic faulting VT3

Summary

Line VT-3, near Gregg's Landing on Ashley River:

Clear evidence of Cenozoic reactivation of Mesozoic extensional faulting.

Mesozoic basement shows approximately 200 m of down-to-east displacement.

Cretaceous and Cenozoic sediments show associated reverse displacement resolved by the data to within 100 m of the ground surface.

Lines VT-4 and VT-5, to the southwest and northeast of Summerville:

Profiles show possible faulting of Cenozoic sediments to shallow depths in close proximity to a strong magnetic gradient. The reflection data suggest that this marks the northwest margin of a faulted basin within the lower Mesozoic basement that contains a large amount of mafic rock.

The imaged faulting on VT-3, VT-4 and VT-5 is within the zone of modern earthquake activity. Progress in understanding this area requires a long-term commitment to secure precision hypocenter locations and focal mechanism determinations. The present seismic monitoring capability is completely inadequate.

The Source and Magnitude of the Charleston earthquakes

Pradeep Talwani
Department of Geological Sciences
University of South Carolina

Workshop CEUS SSC Project

OUTLINE

- Revised tectonic framework
- Relationship with ECFS
- Sand blow on Sawmill Branch fault
- Results from GPS surveying
- Magnitude estimates

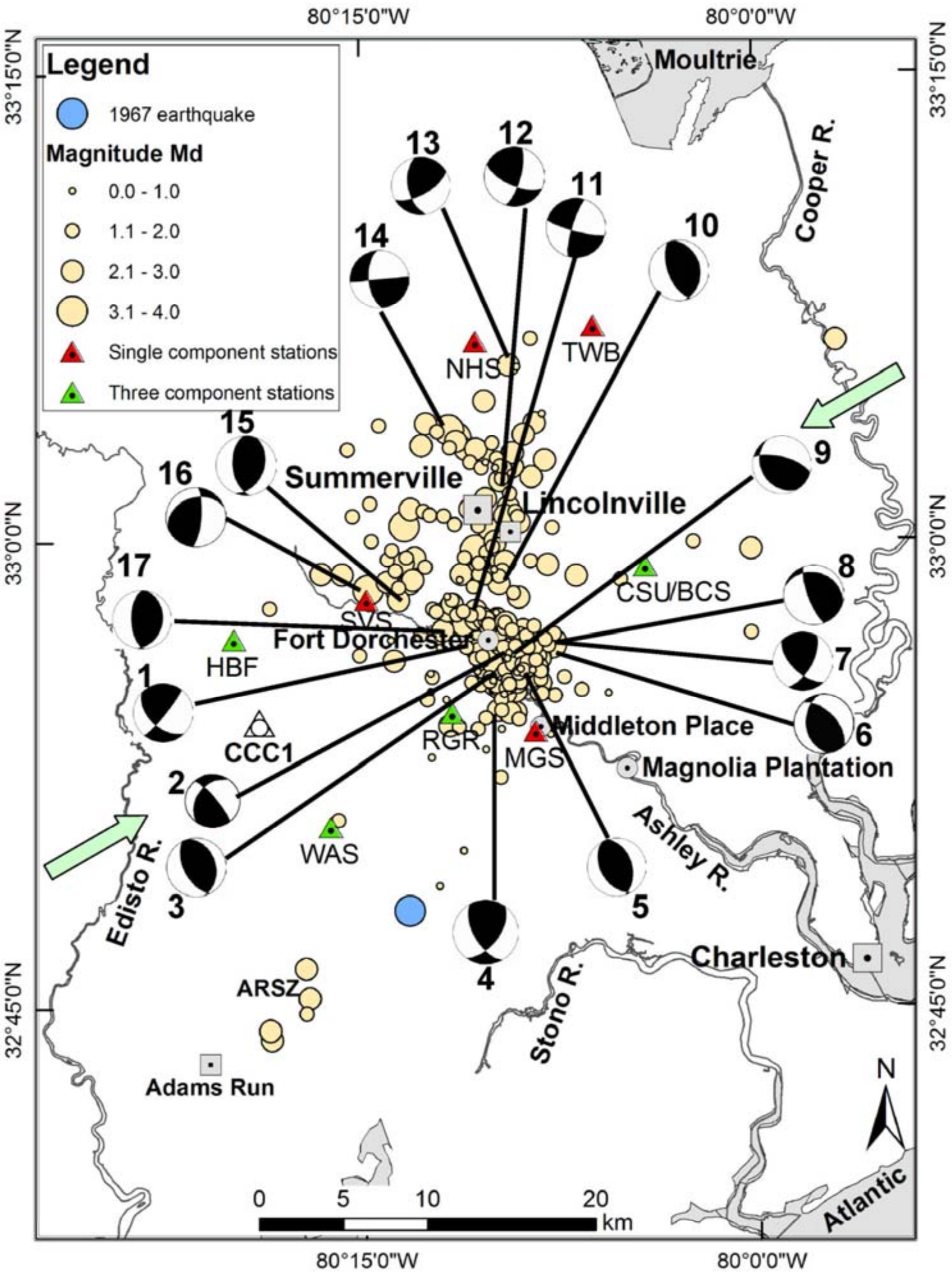
Revised tectonic framework

For details go to:
http://scsn.seis.sc.edu/Publications/publication.html

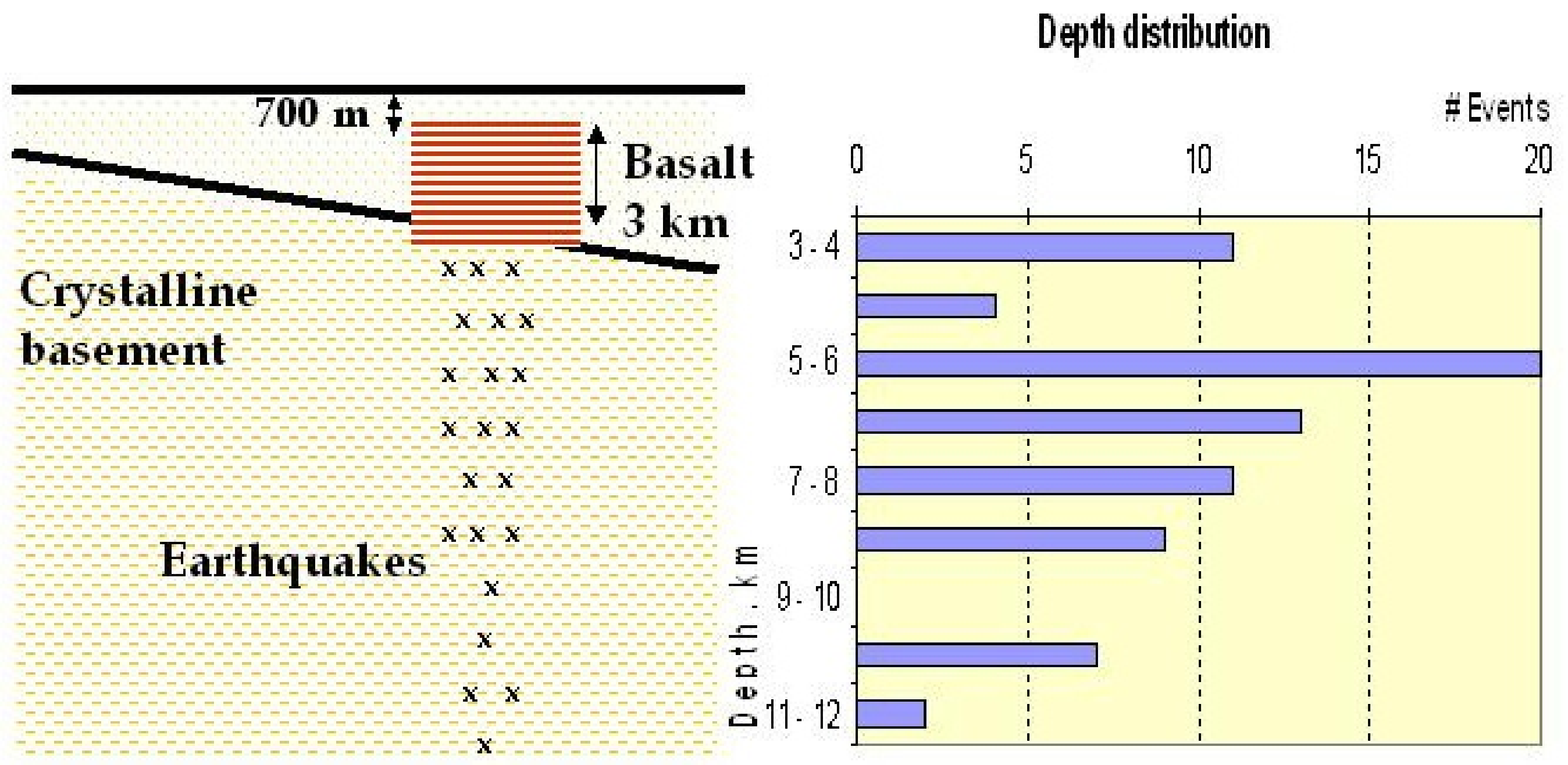
Inmaculada Dura-Gomez, and **Pradeep Talwani**, Finding Faults in the Charleston Area, South Carolina. 1. Seismological Data., submitted to Seis. Res. Letters, 2009.

Pradeep Talwani, and Inmaculada Dura-Gomez, Finding Faults in the Charleston Area, South Carolina. 2. Corroborative Data., submitted to Seis. Res. Letters, 2009.

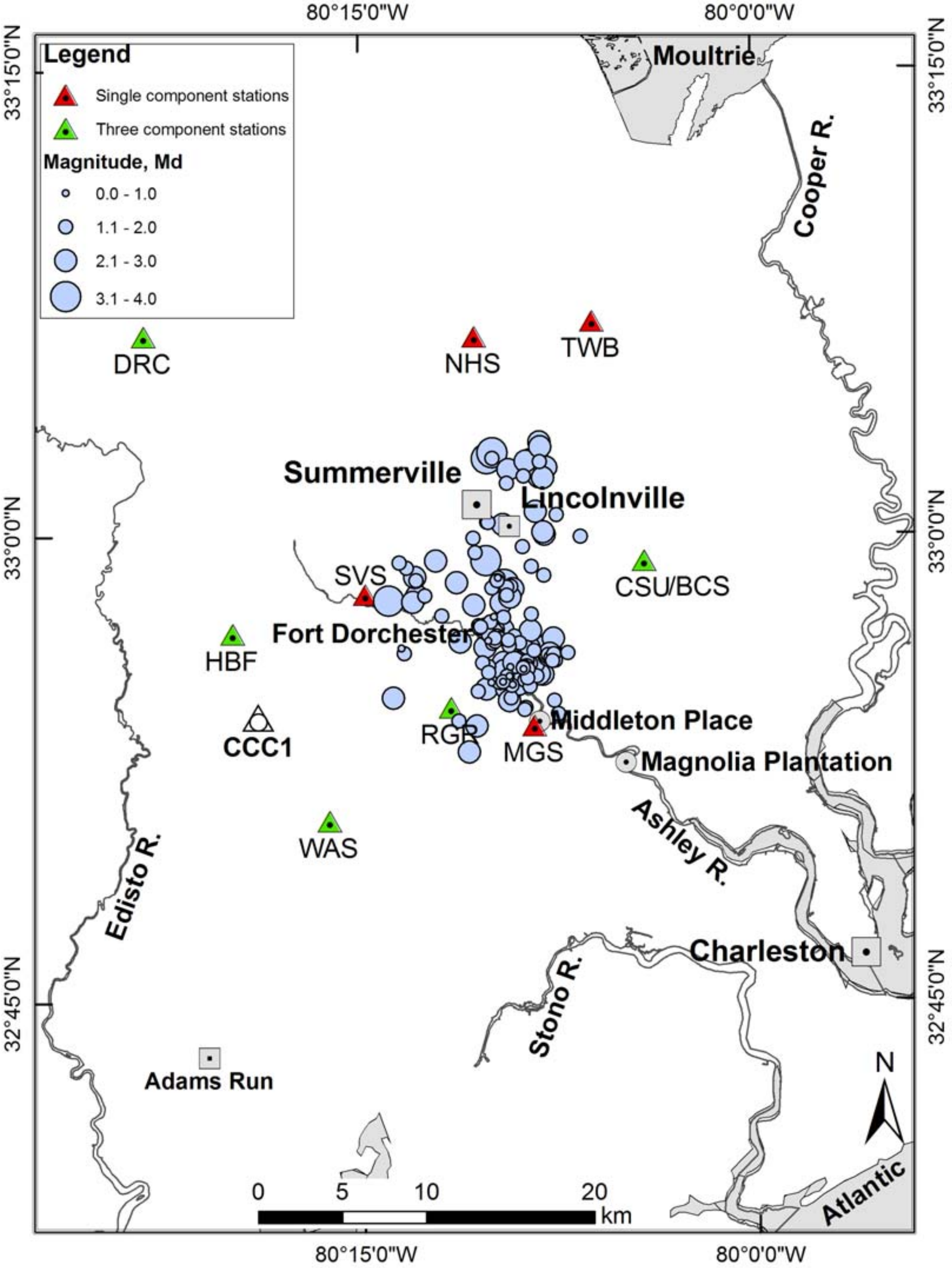
1974-2004 locations with FPS



Cross-section of wedge with basalt flows

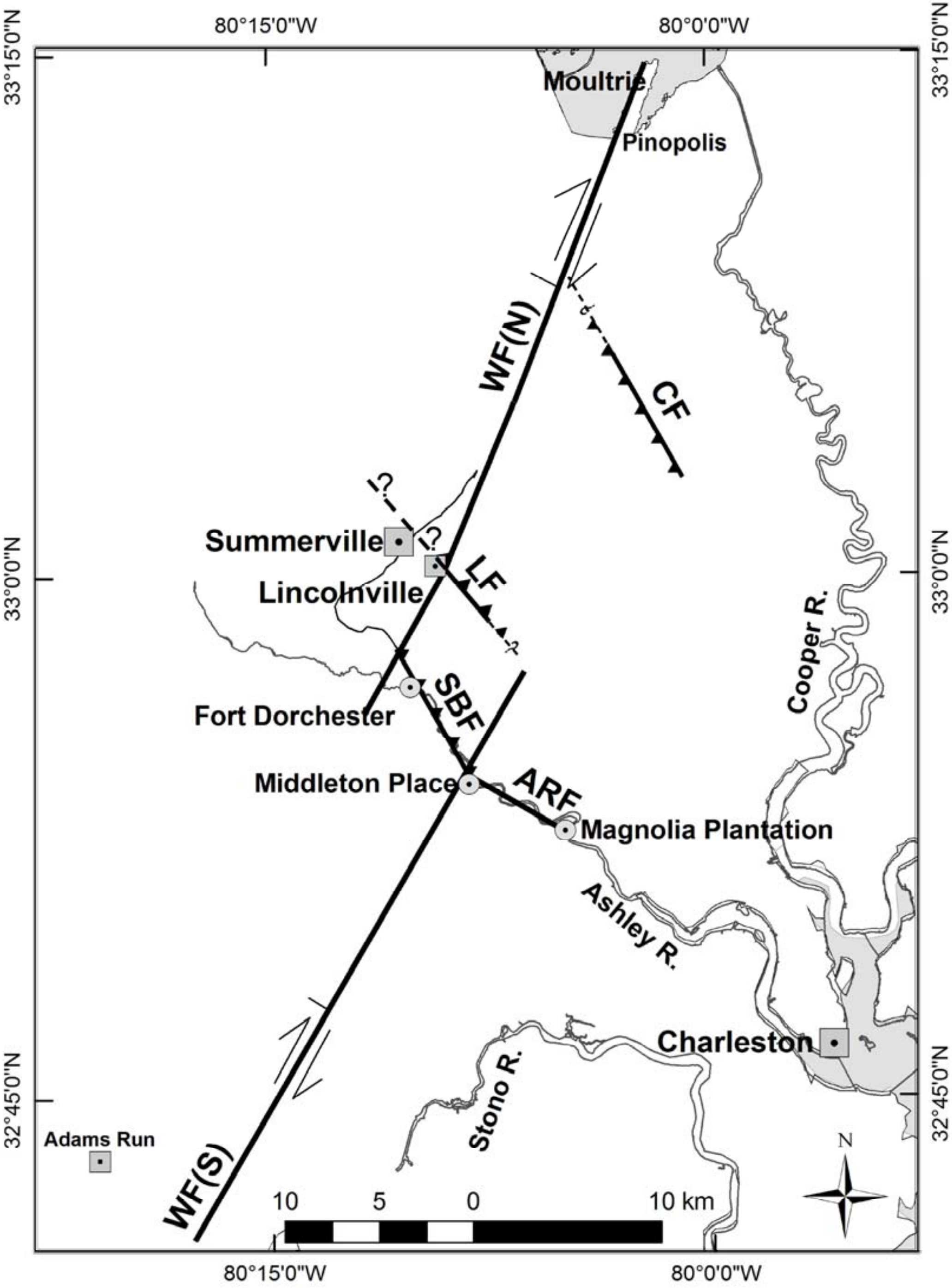


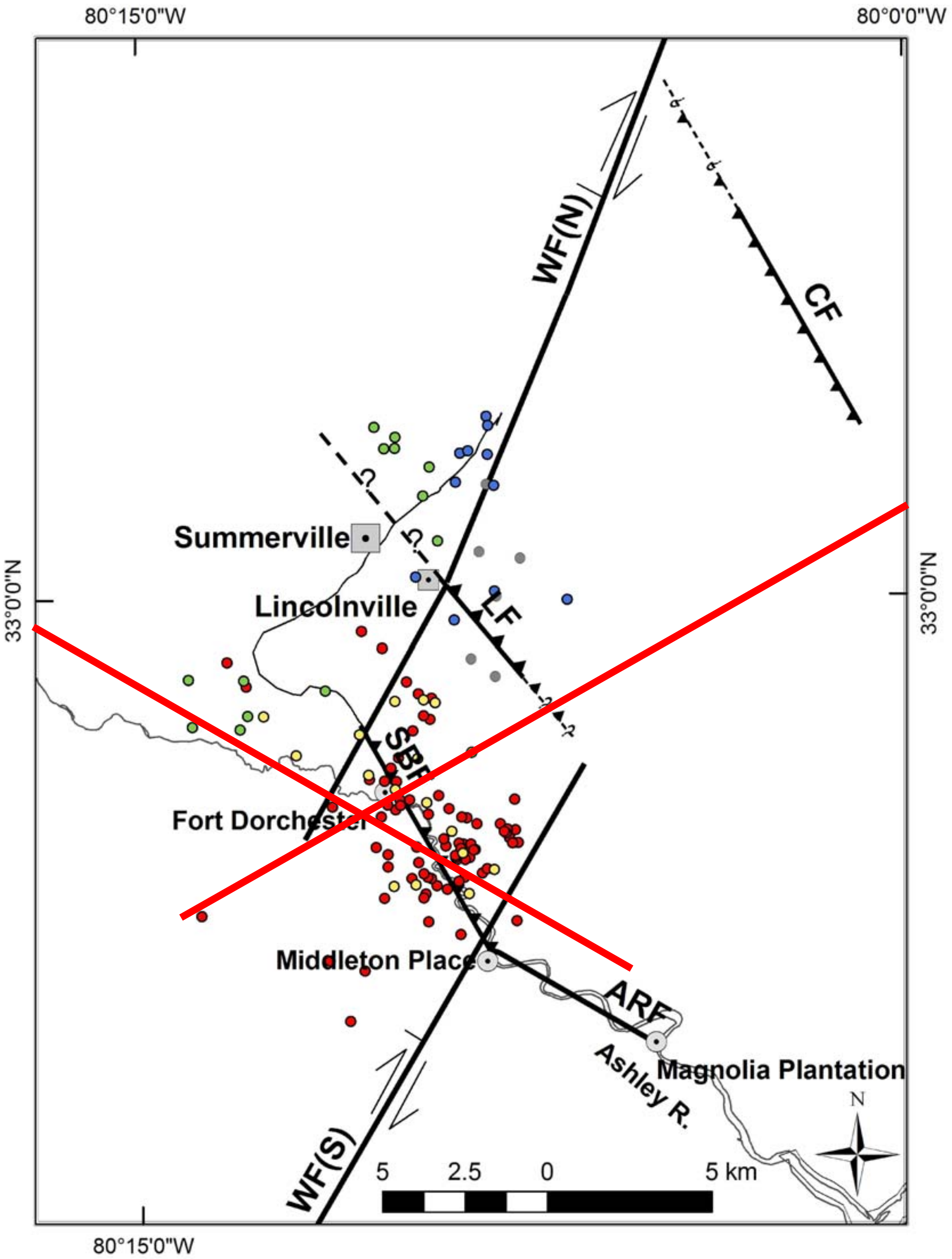
Relocations



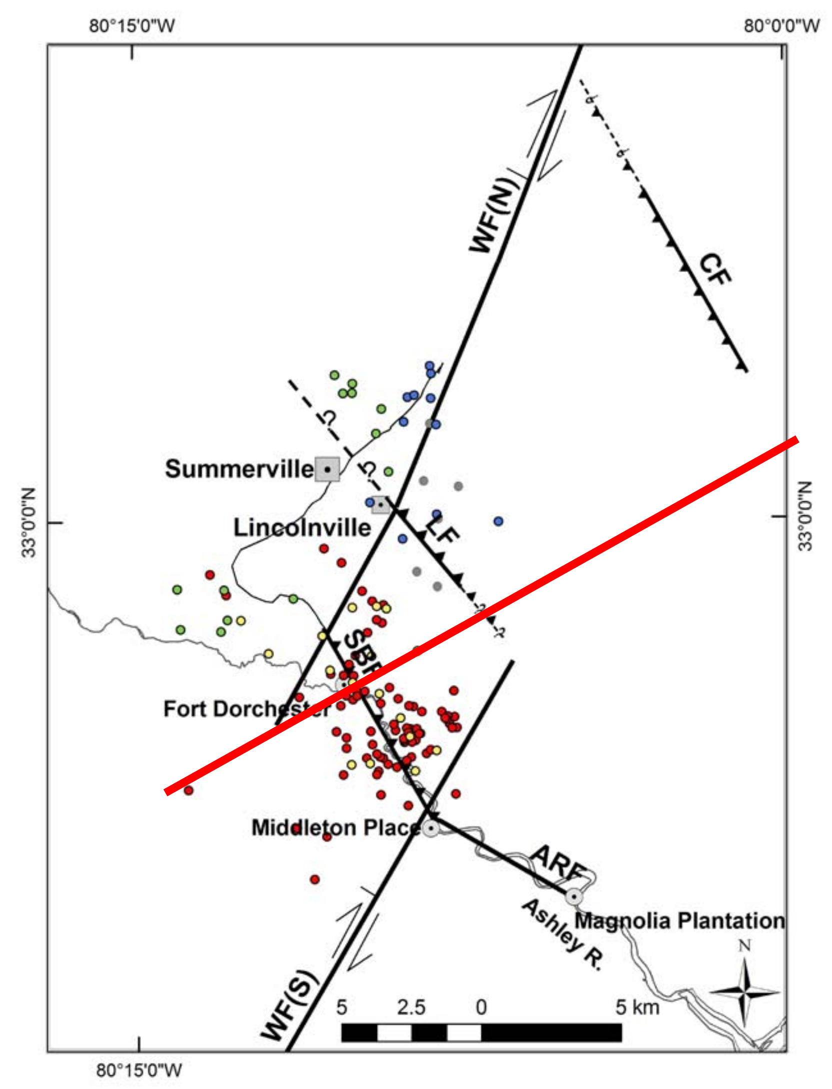
The revised STF

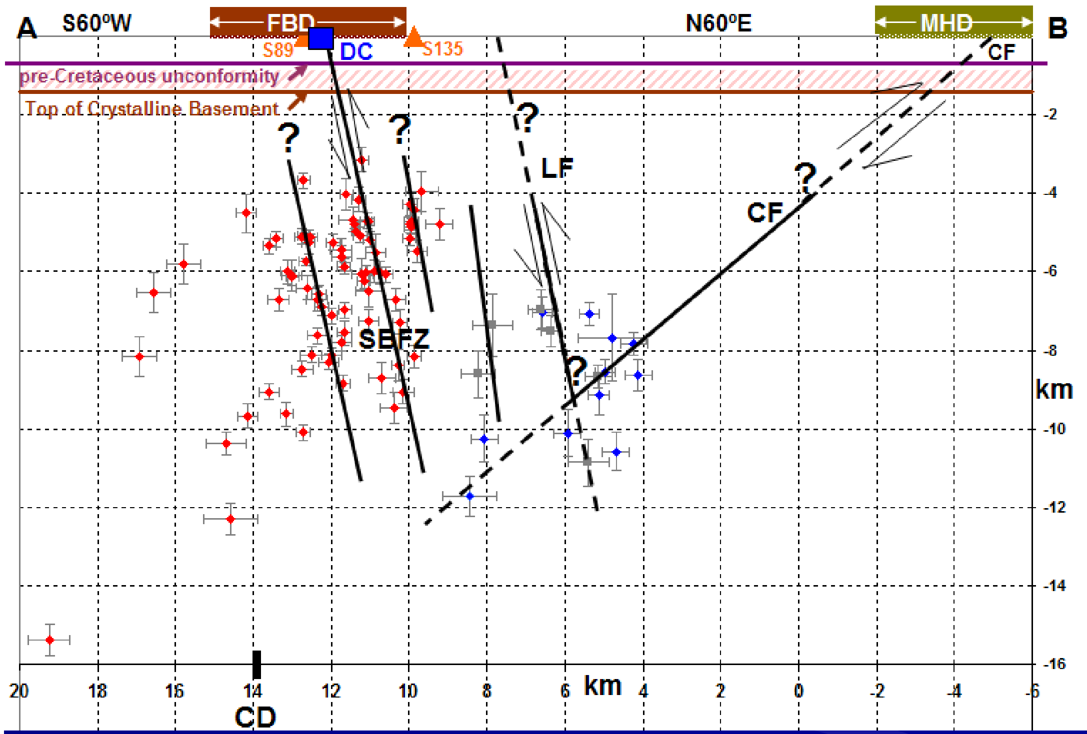
- Consists of the Woodstock fault, with a left compressional step near Middleton Place, which contains SBF, LF and CF.



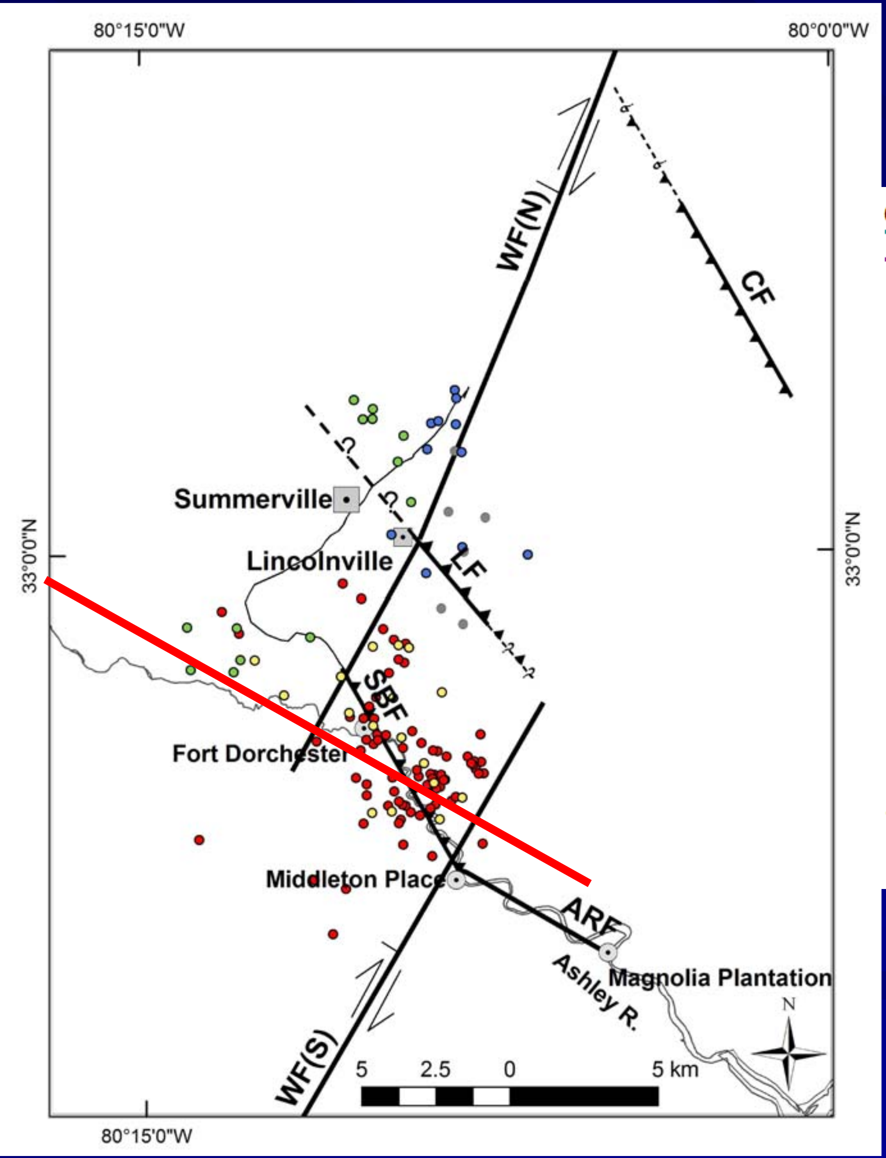

80°15'0"W
80°0'0"W
33°0'0"N
33°0'0"N
80°15'0"W
WF(N)
CF
Summerville
Lincolnville
LF
SBF
Fort Dorchester
Middleton Place
ARF
Magnolia Plantation
Ashley R.
WF(S)
N
5
2.5
0
5 km

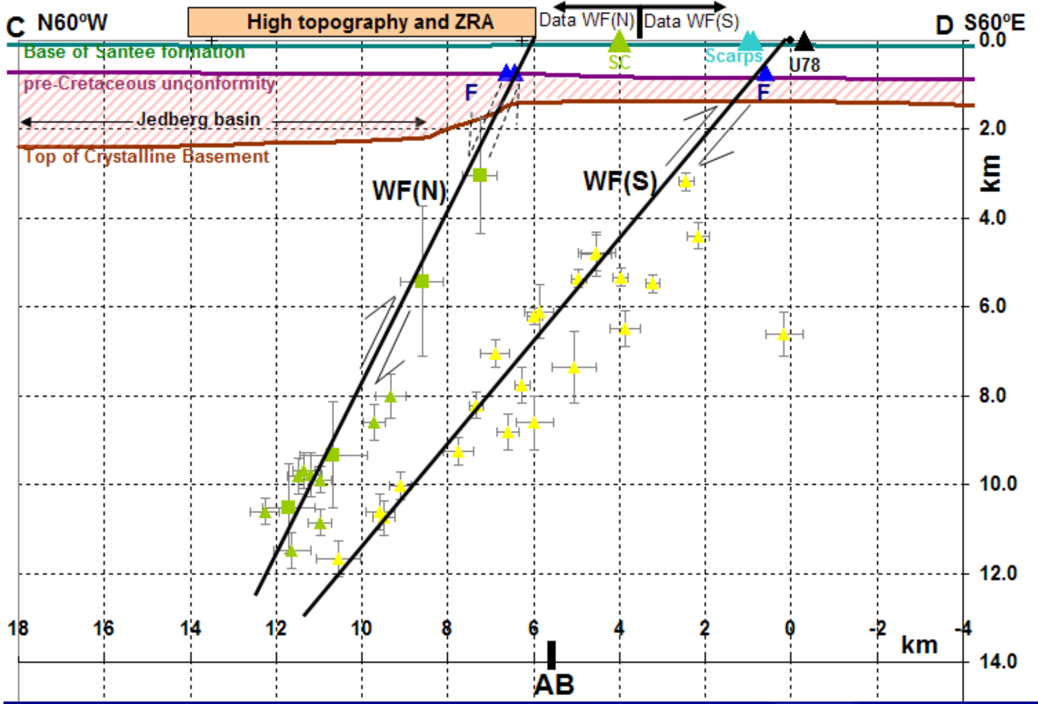
S60°W-N60°E cross-section



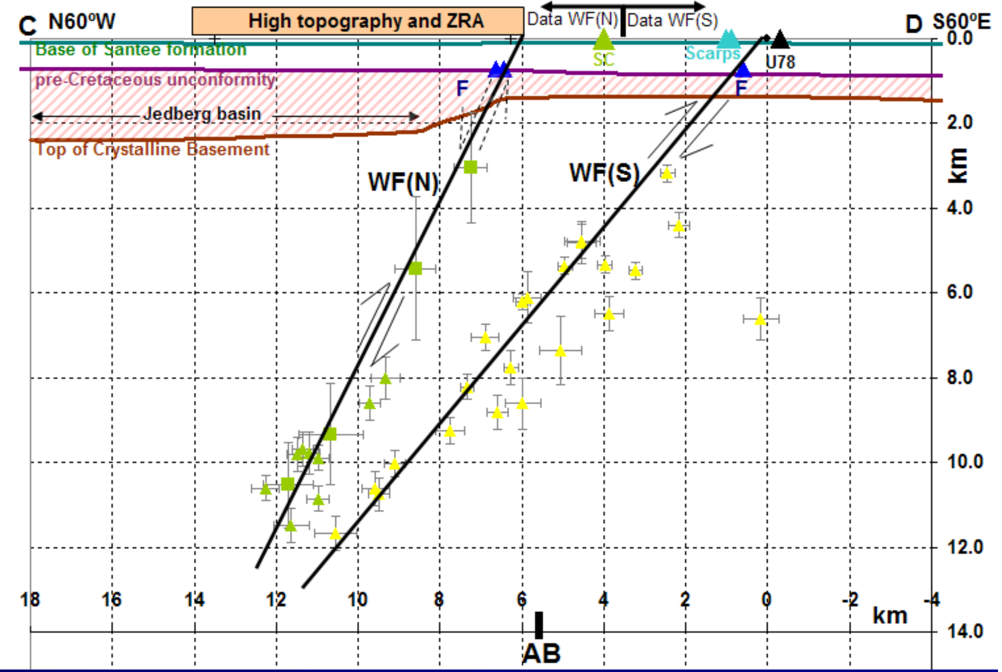


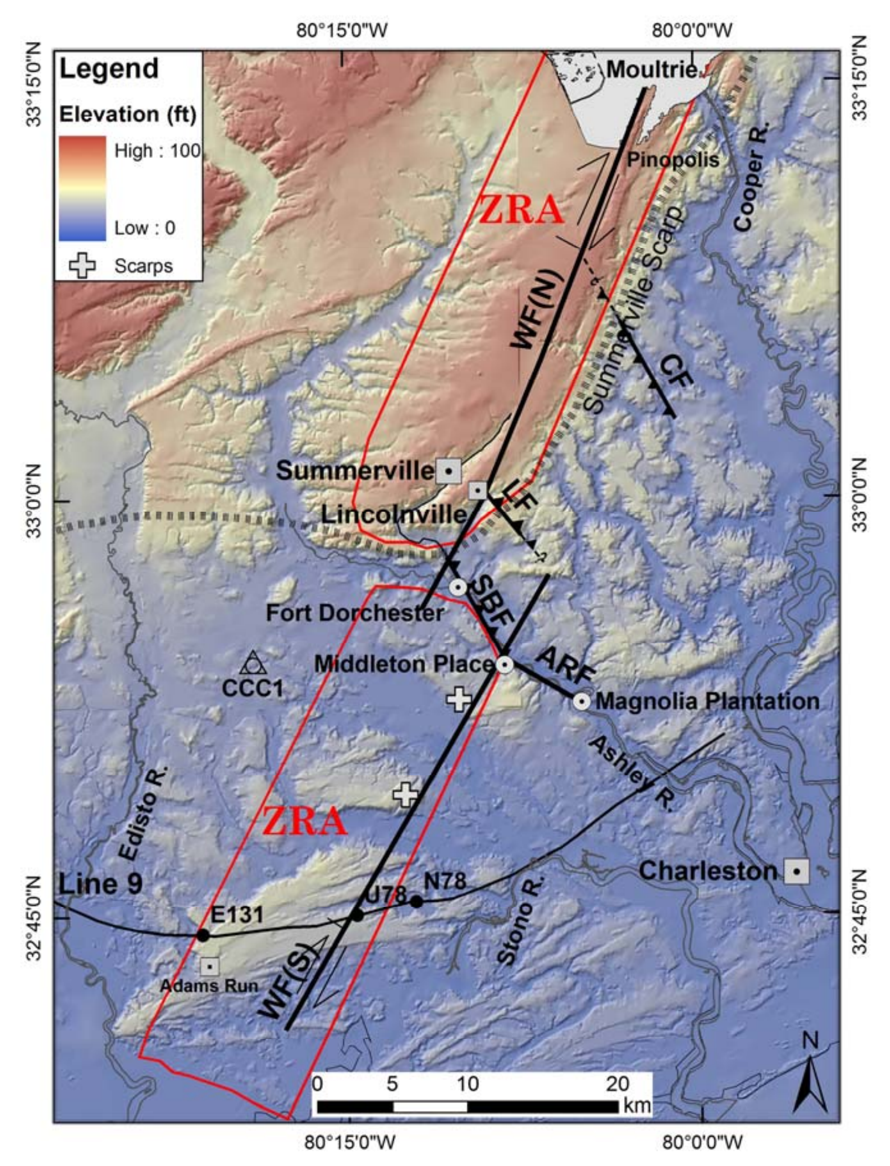
N60°W-S60°E cross-section



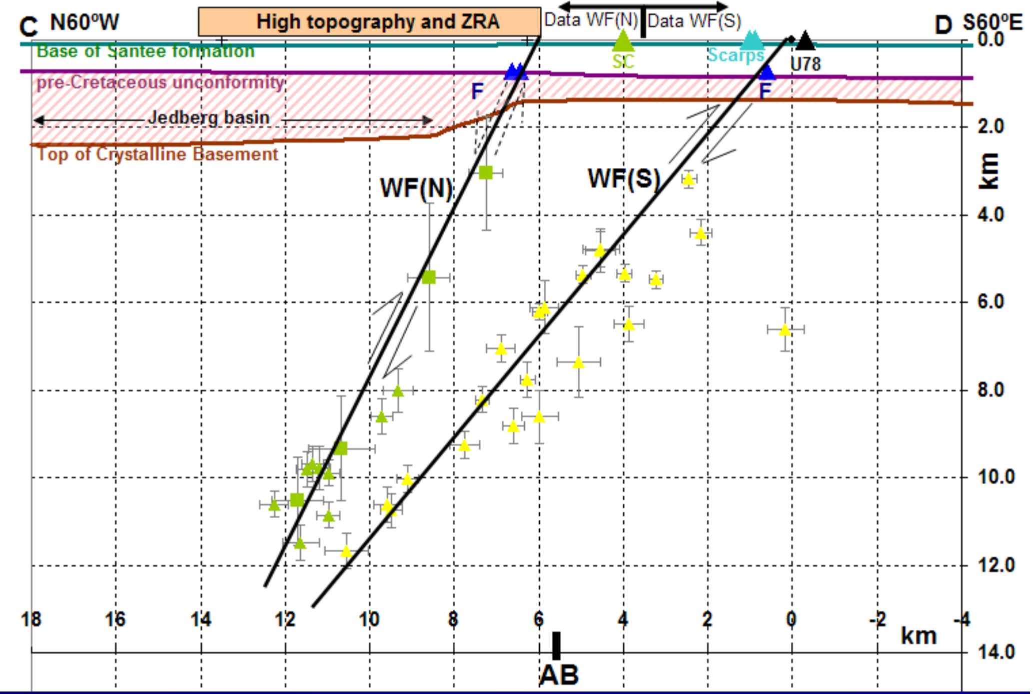


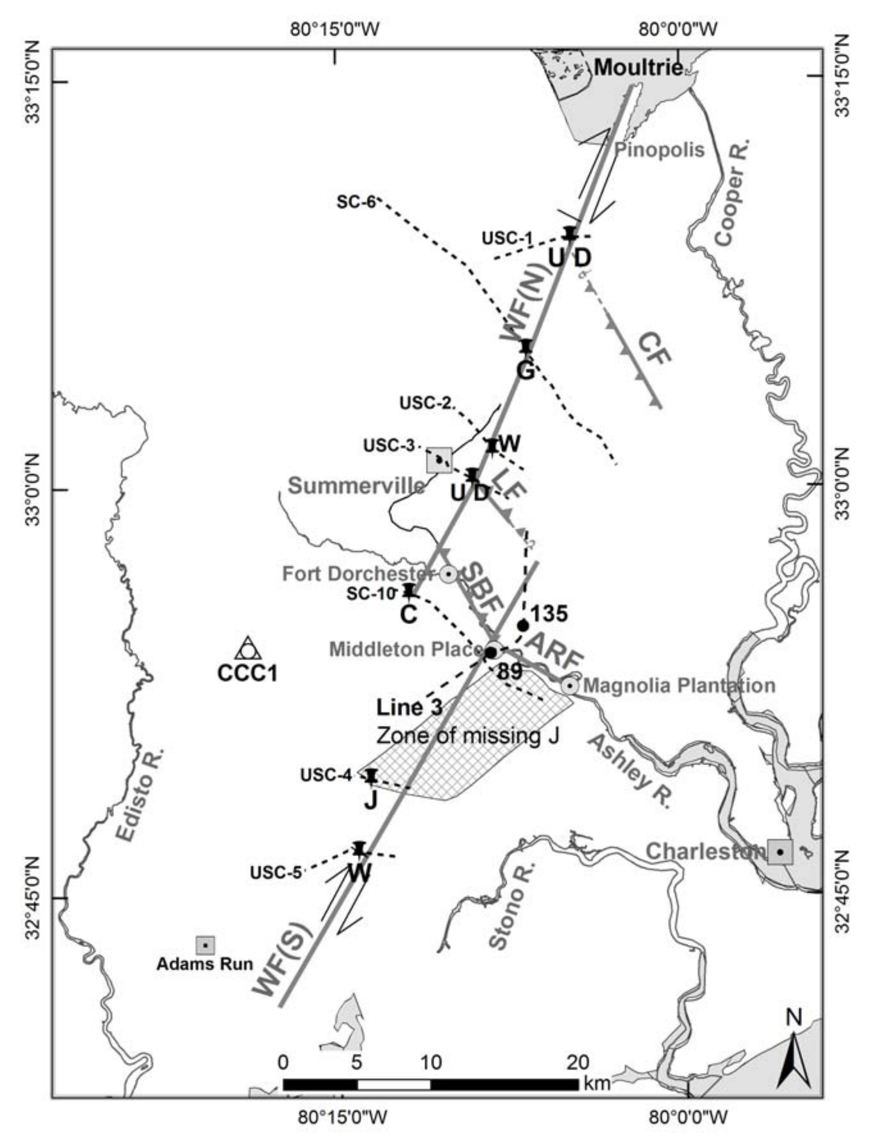
Scarps and ZRA

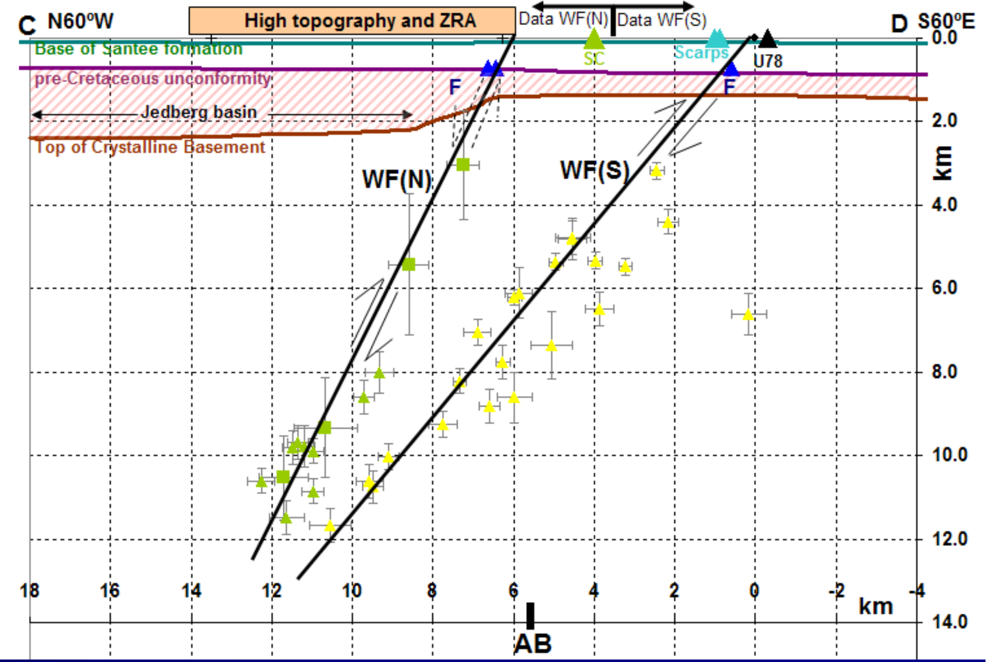


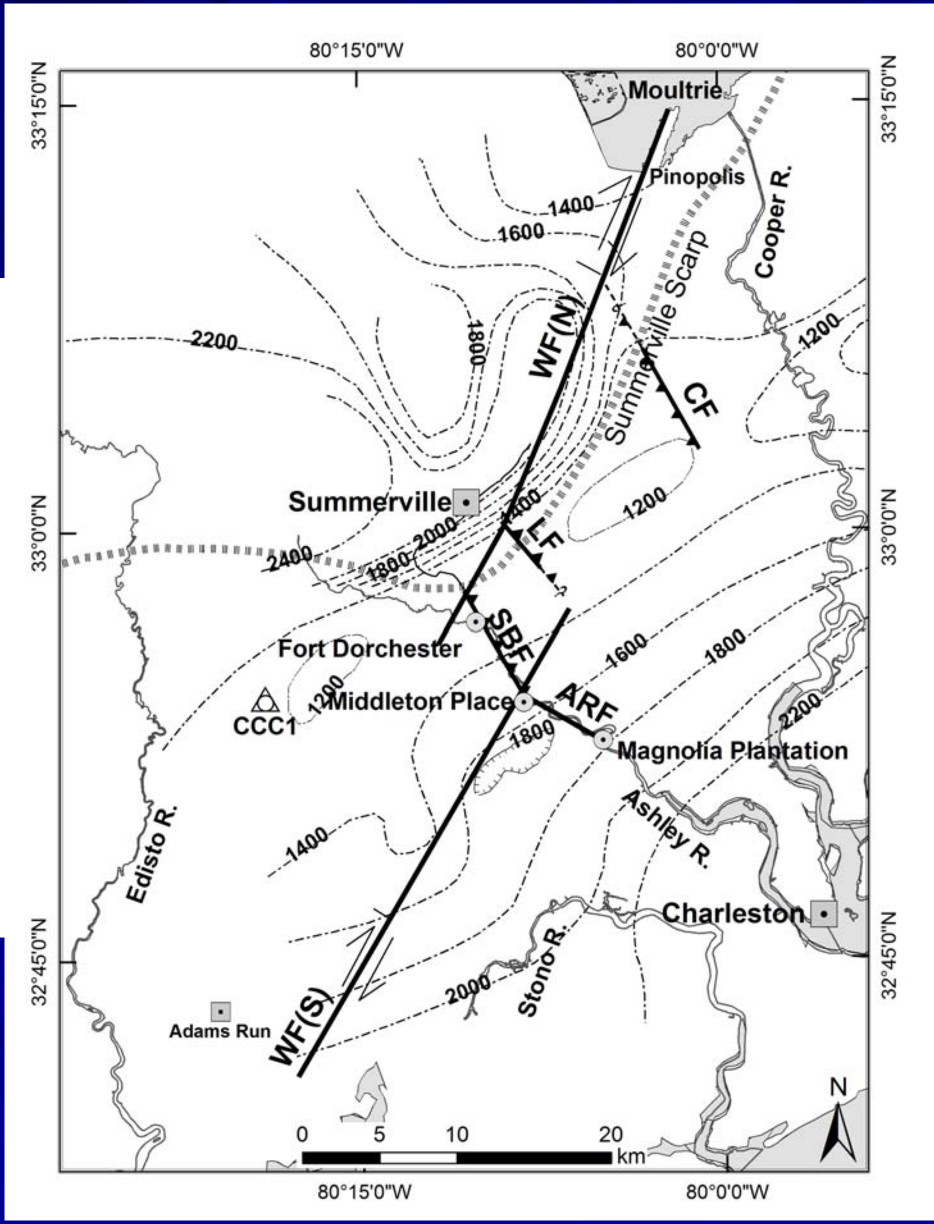


Faults on basalt

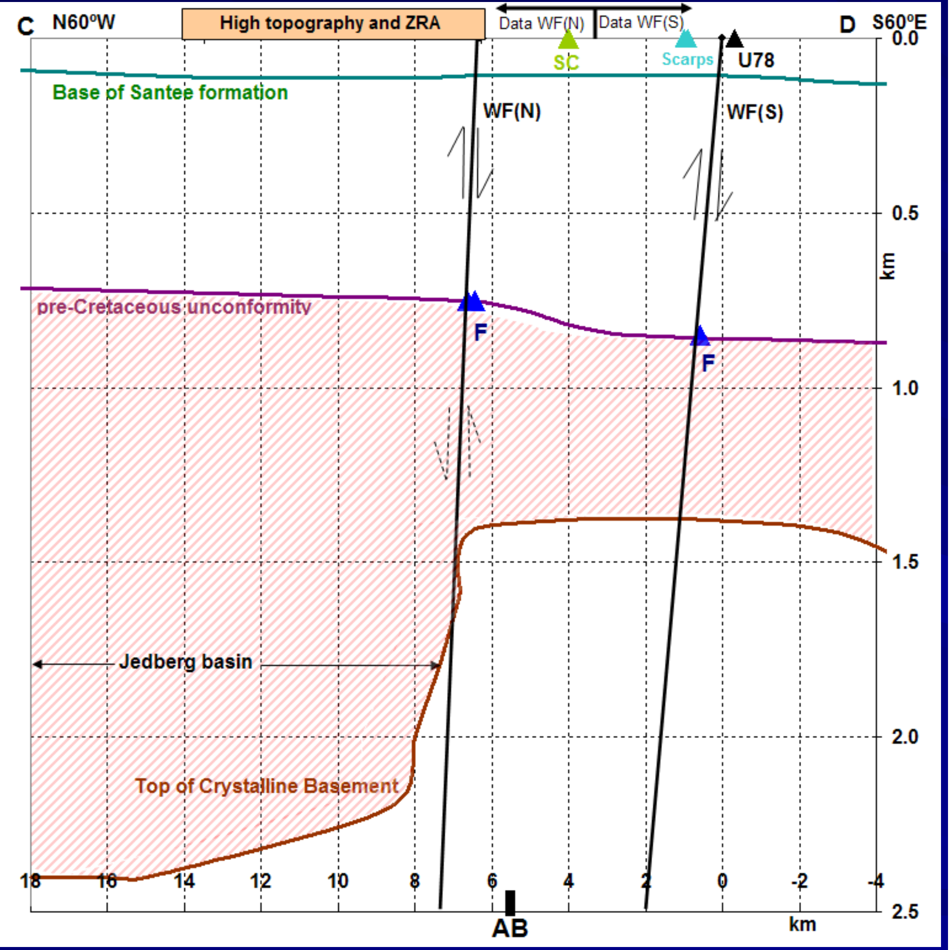


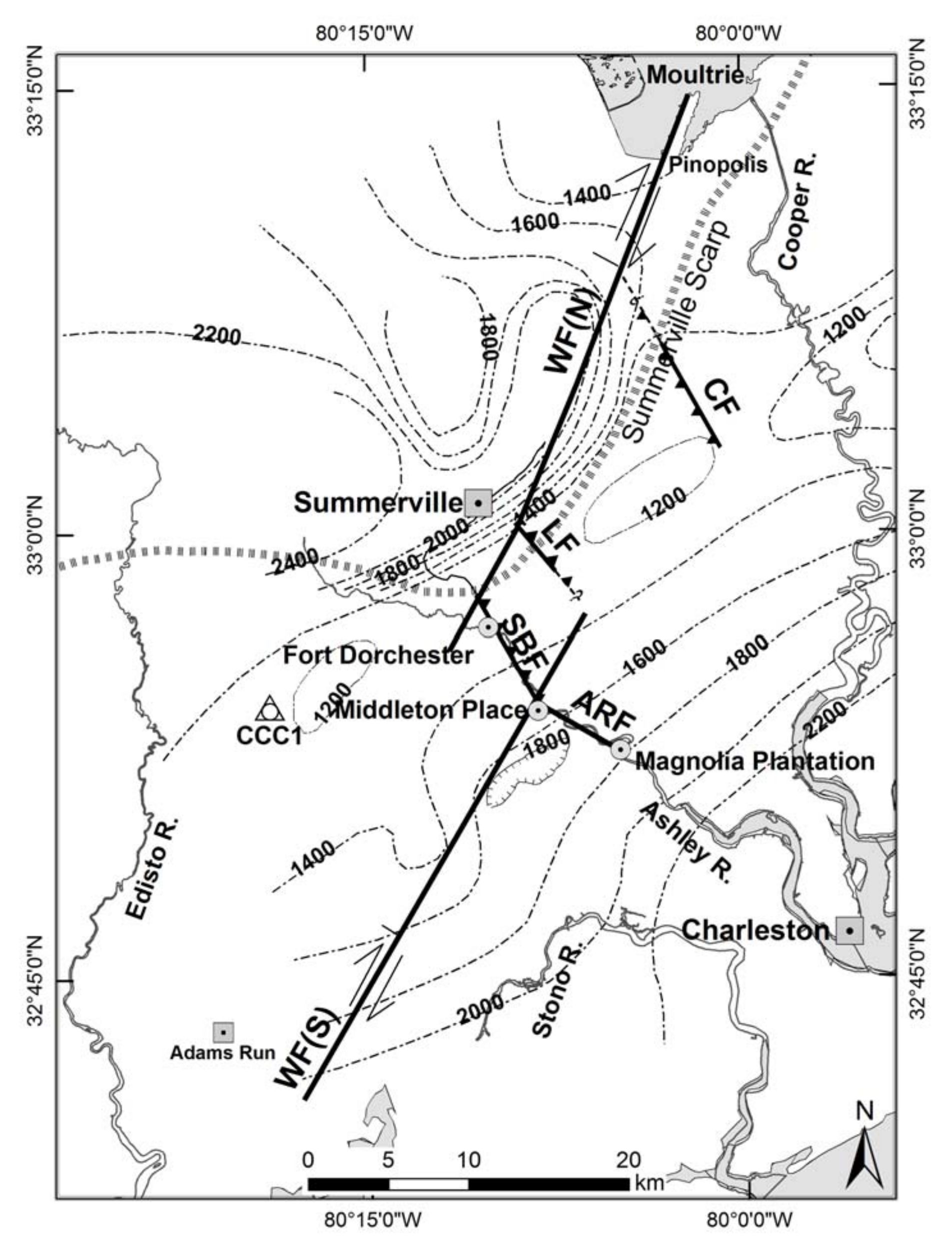



C N60ºW
High topography and ZRA
Data WF(N)
Data WF(S)
D S60ºE
Base of Santee formation
pre-Cretaceous unconformity
Jedberg basin
Top of Crystalline Basement
SC
Scarps
U78
F
F
WF(N)
WF(S)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
km
18
16
14
12
10
8
6
4
2
0
-2
-4
km
AB


80°15'0"W
80°0'0"W
33°15'0"N
33°0'0"N
32°45'0"N
Moultrie
Pinopolis
Cooper R.
Summerville Scarp
WF(N)
CF
LF
SBF
ARF
WF(S)
Summerville
Fort Dorchester
Middleton Place
Magnolia Plantation
CCC1
Ashley R.
Edisto R.
Stono R.
Charleston
Adams Run
1200
1400
1600
1800
2000
2200
2400
0
5
10
20
km
N

Reactivation

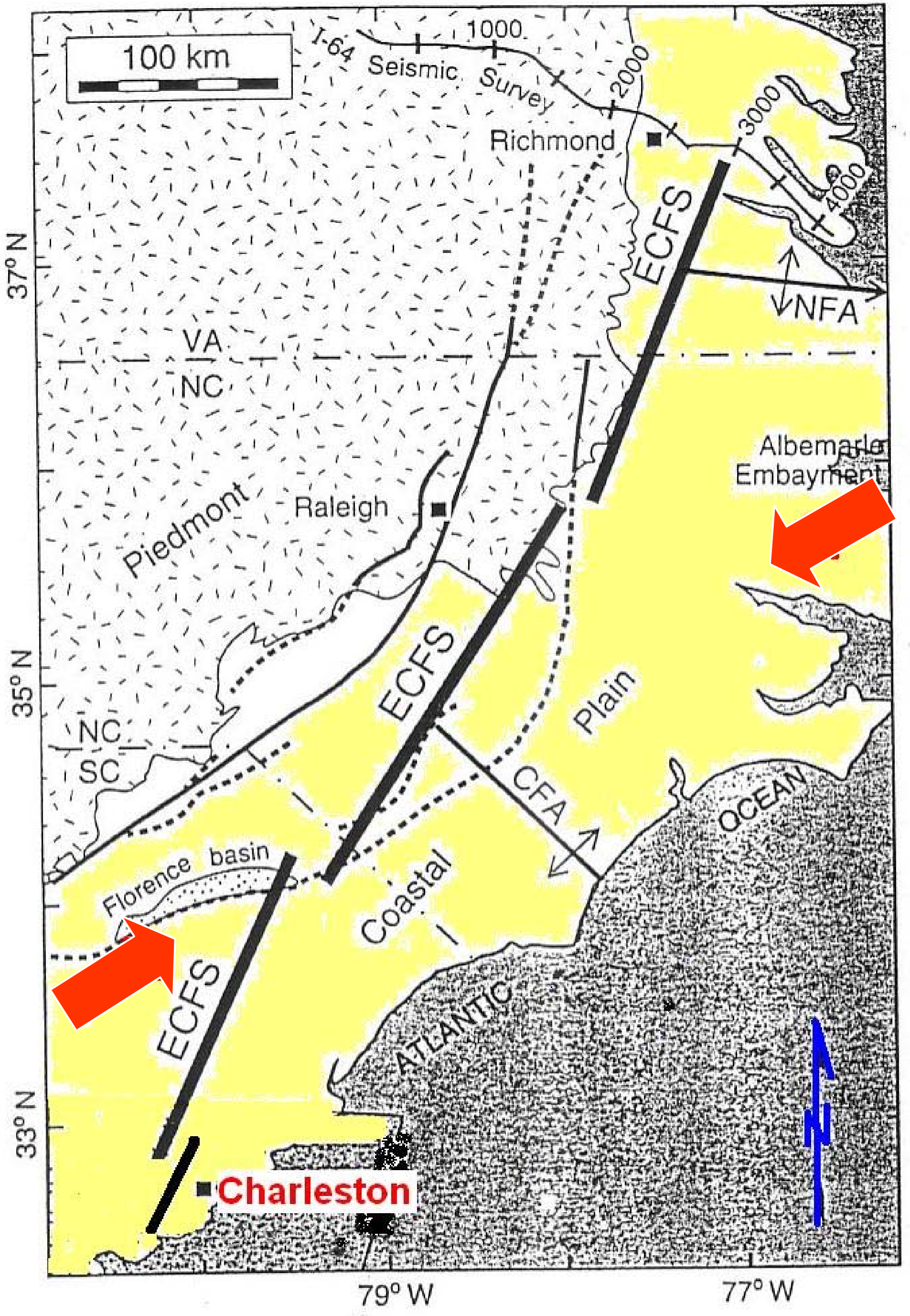




- WF(N) fault is coincident with the eastern edge of the extensional Mesozoic Riddleville basin.
- WF(N) fault is being reactivated in the current N60°E-S60°W compressional stress field.
- The seismicity is associated with faults described in the revised STF.
- The seismicity was earlier associated with the southern end of the East Coast fault system, ECFS.

The revised STF and the ECFS

- Seismicity occurs at the **compressional left step**.
- The right dilational steps between ECFS(S) and ECFS(C), and between ECFS(C) and ECFS(N) are associated with aseismic pull apart basins.



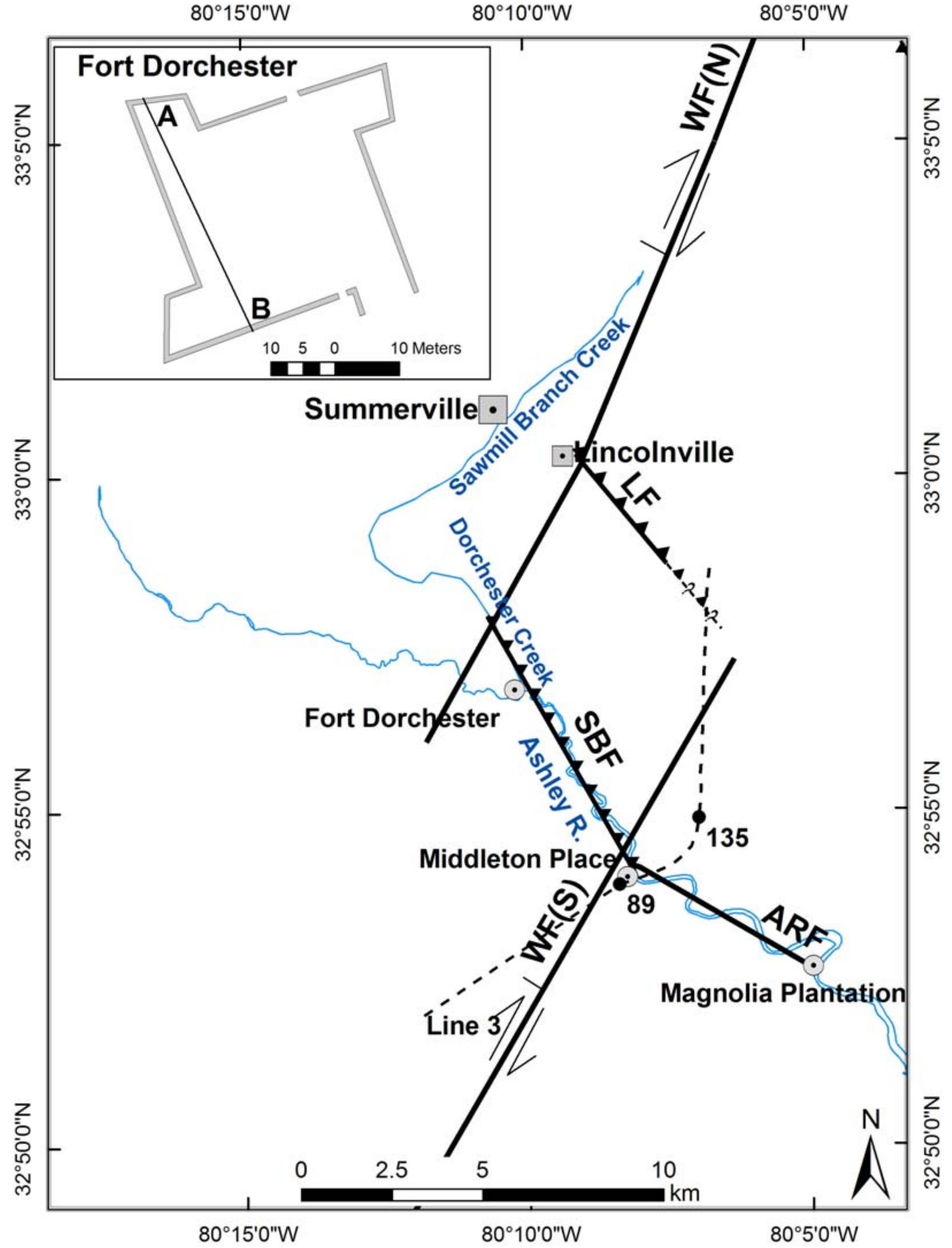
- Results of paleoliquefaction studies in the South Carolina Coastal Plain suggest the occurrence of seven prehistoric earthquakes in the last 6000 years, with an average recurrence rate of ~500 years.

(Talwani and Schaeffer, 2001)

“ …liquefaction features have identified the results of Quaternary faulting…a large liquefaction field that centers on Charleston, SC. None of these liquefaction features have been clearly linked to individual faults”

Russell Wheeler in Engineering Geology, 2006

UNTIL NOW

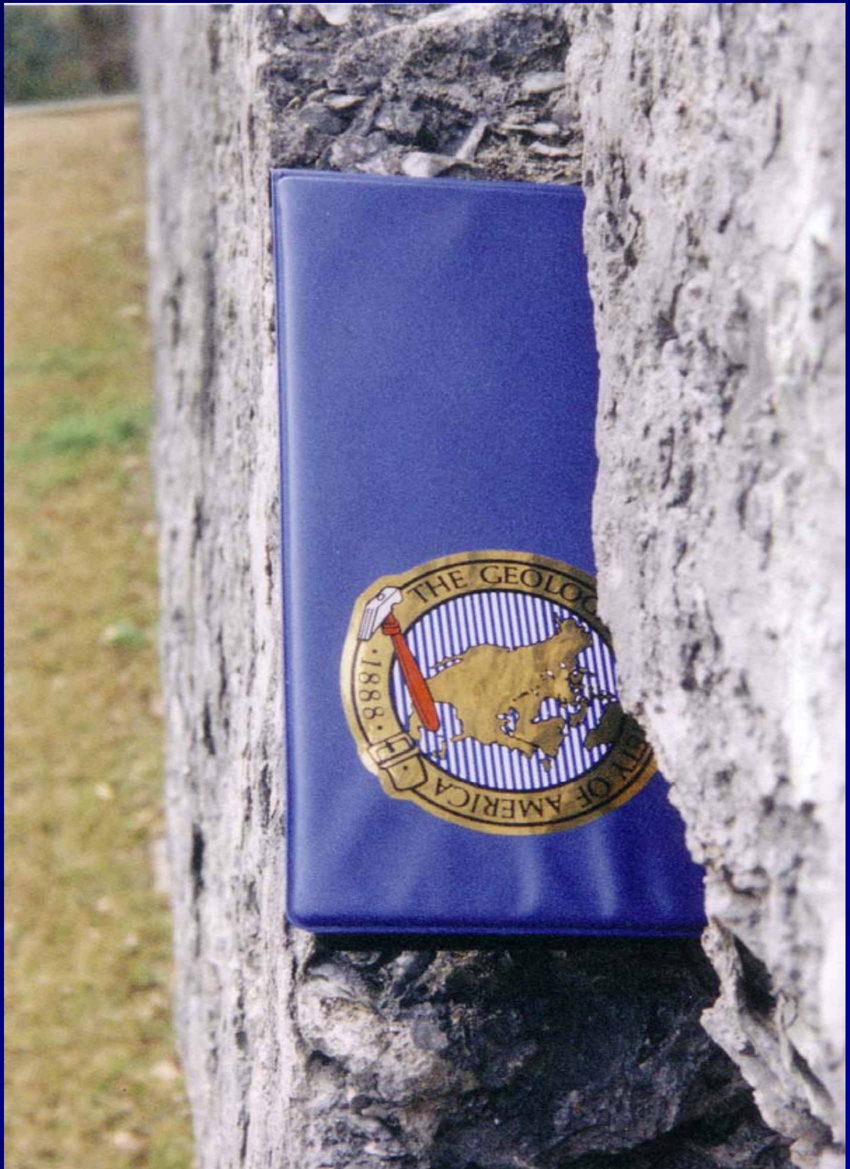

80°15'0"W
80°10'0"W
80°5'0"W
33°5'0"N
33°0'0"N
32°55'0"N
32°50'0"N
Fort Dorchester
A
B
10 5 0 10 Meters
WF(N)
Summerville
Sawmill Branch Creek
Lincolnville
LF
?
Dorchester Creek
Fort Dorchester
SBF
Ashley R.
135
Middleton Place
89
WF(S)
ARF
Magnolia Plantation
Line 3
N
0 2.5 5 10 km

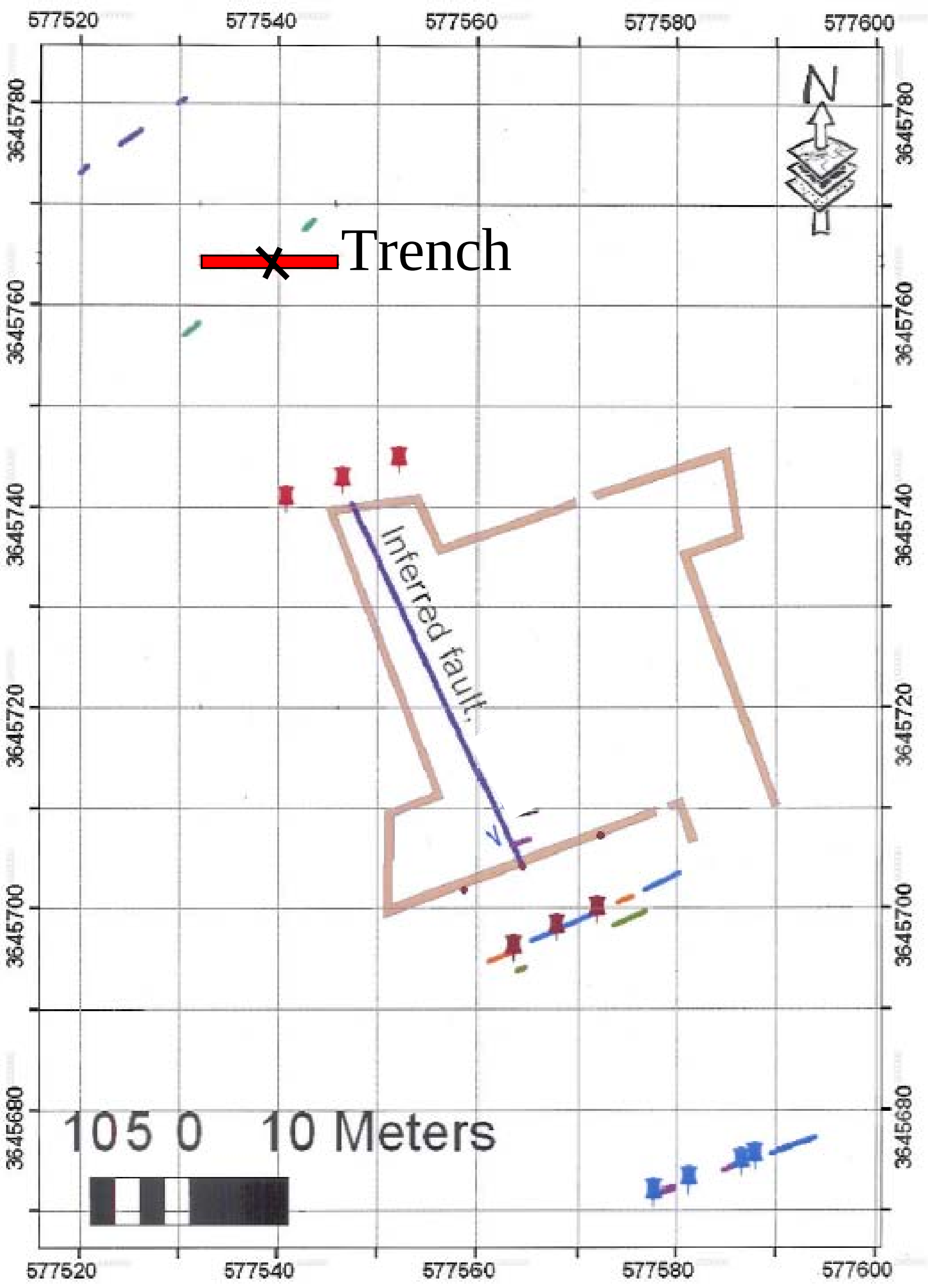
NORTHERN WALL OF THE FORT

-7 cm offset-

SOUTHERN WALL OF THE FORT

-10 cm offset-

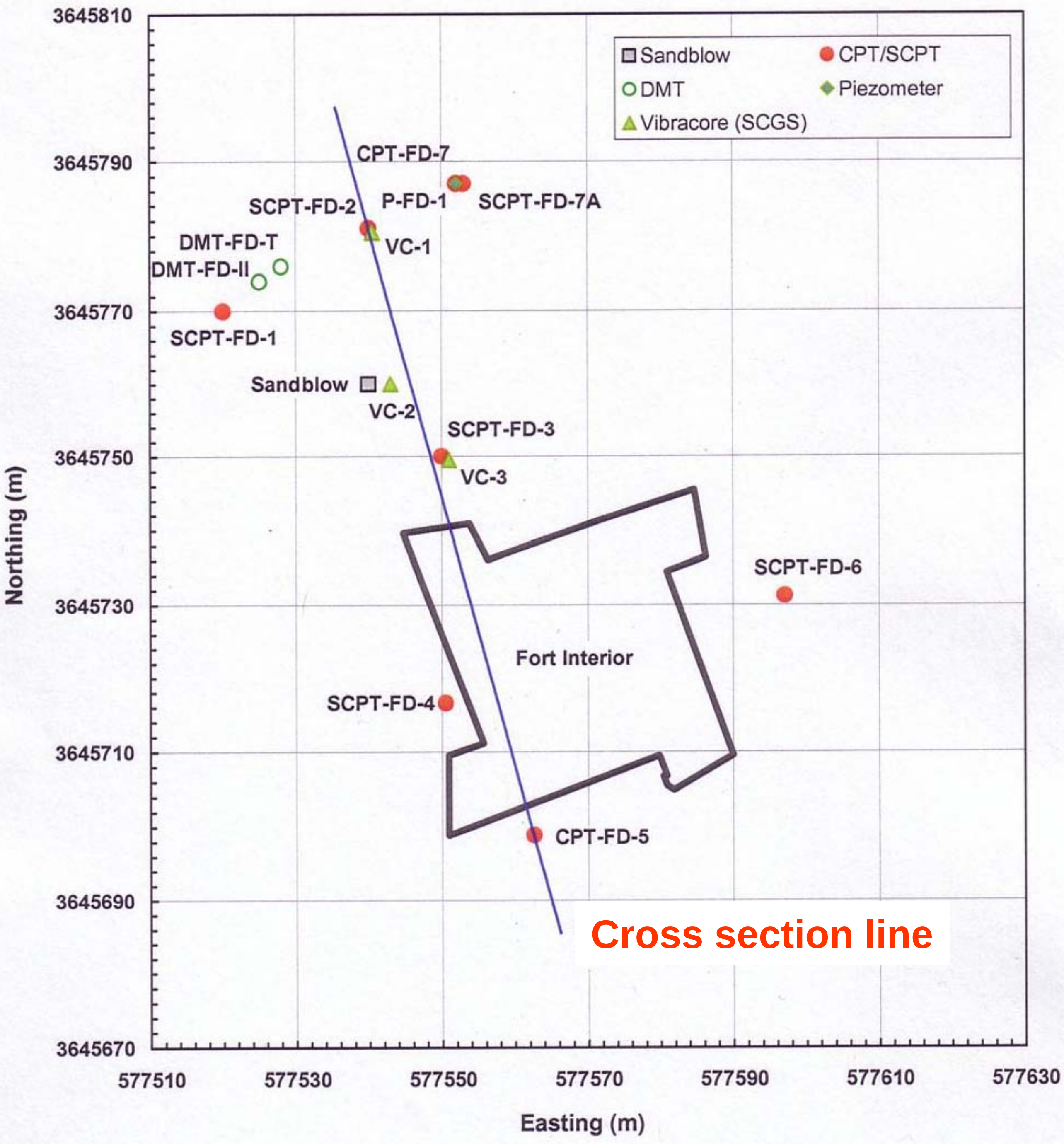



577520
577540
577560
577580
577600
3645780
3645760
3645740
3645720
3645700
3645680
N
Trench
Inferred fault
10 5 0 10 Meters

GEOTECHNICAL INVESTIGATIONS

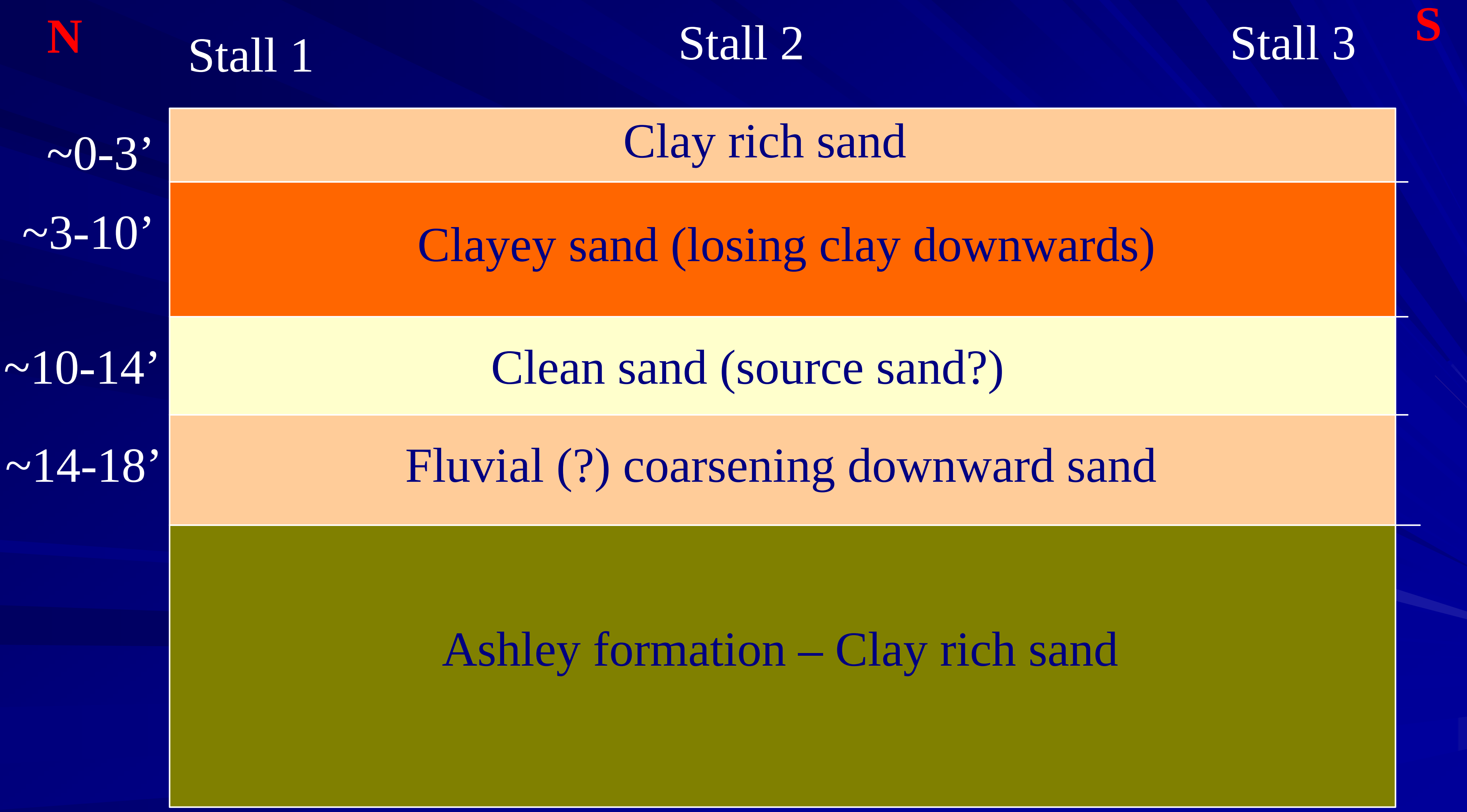
- Cone Penetration Tests
- Standard Penetration Tests
- Shear Wave Velocity

Locations of geotechnical tests



Cross section line

CROSS SECTION
(COURTESY WILL DOAR)



N

Stall 1

Stall 2

Stall 3

S

~0-3’	Clay rich sand
~3-10’	Clayey sand (losing clay downwards)
~10-14’	Clean sand (source sand?)
~14-18’	Fluvial (?) coarsening downward sand
	Ashley formation – Clay rich sand

- The location of the sand blow is associated with a prehistoric earthquake on SBF.

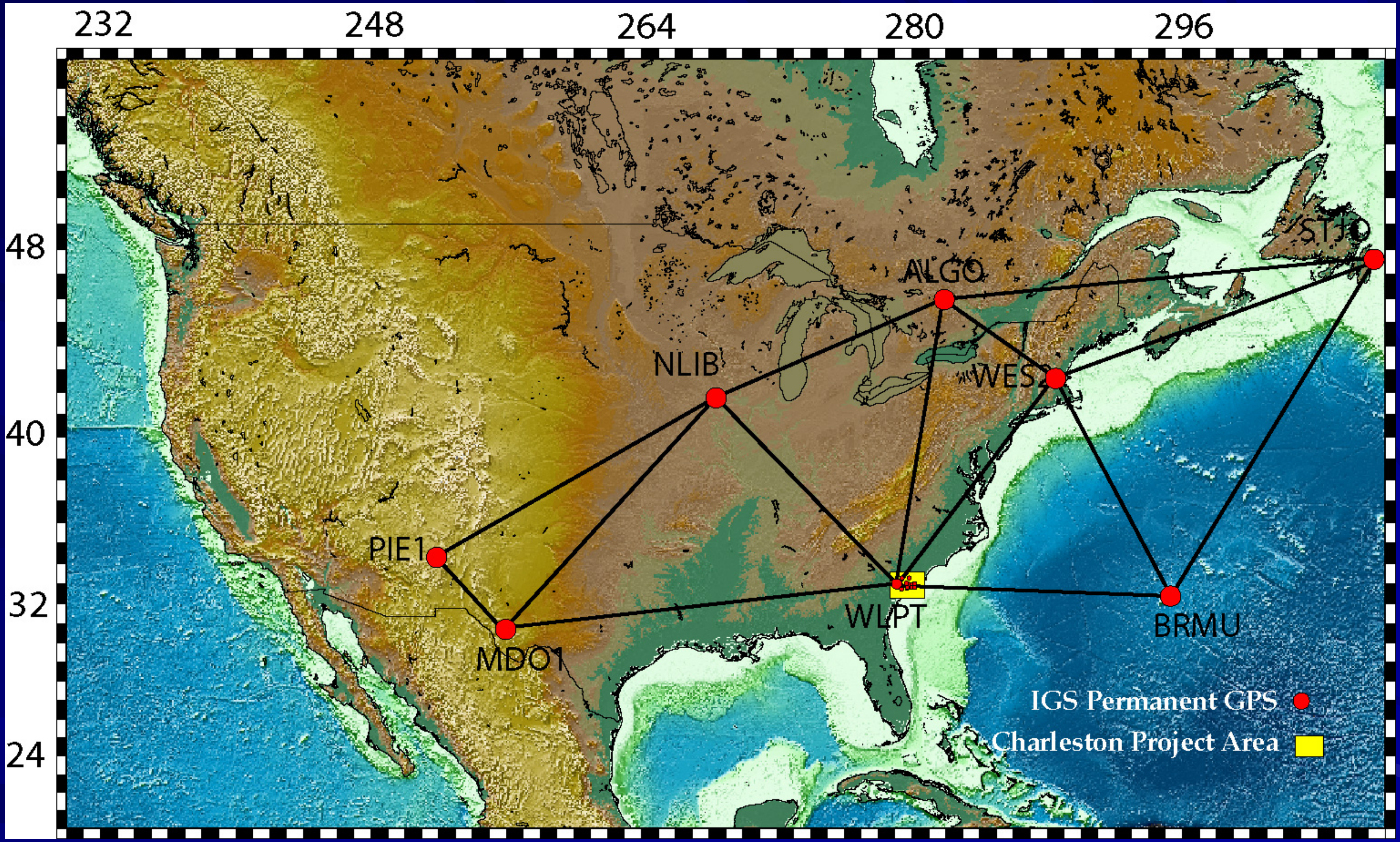
- Using the SPT data and the energy-stress method, Gassman and Hasek back calculated the magnitude of that earthquake associated with SBF to be 6.2.

Results of GPS studies (Analysis by Robert Trenkamp)

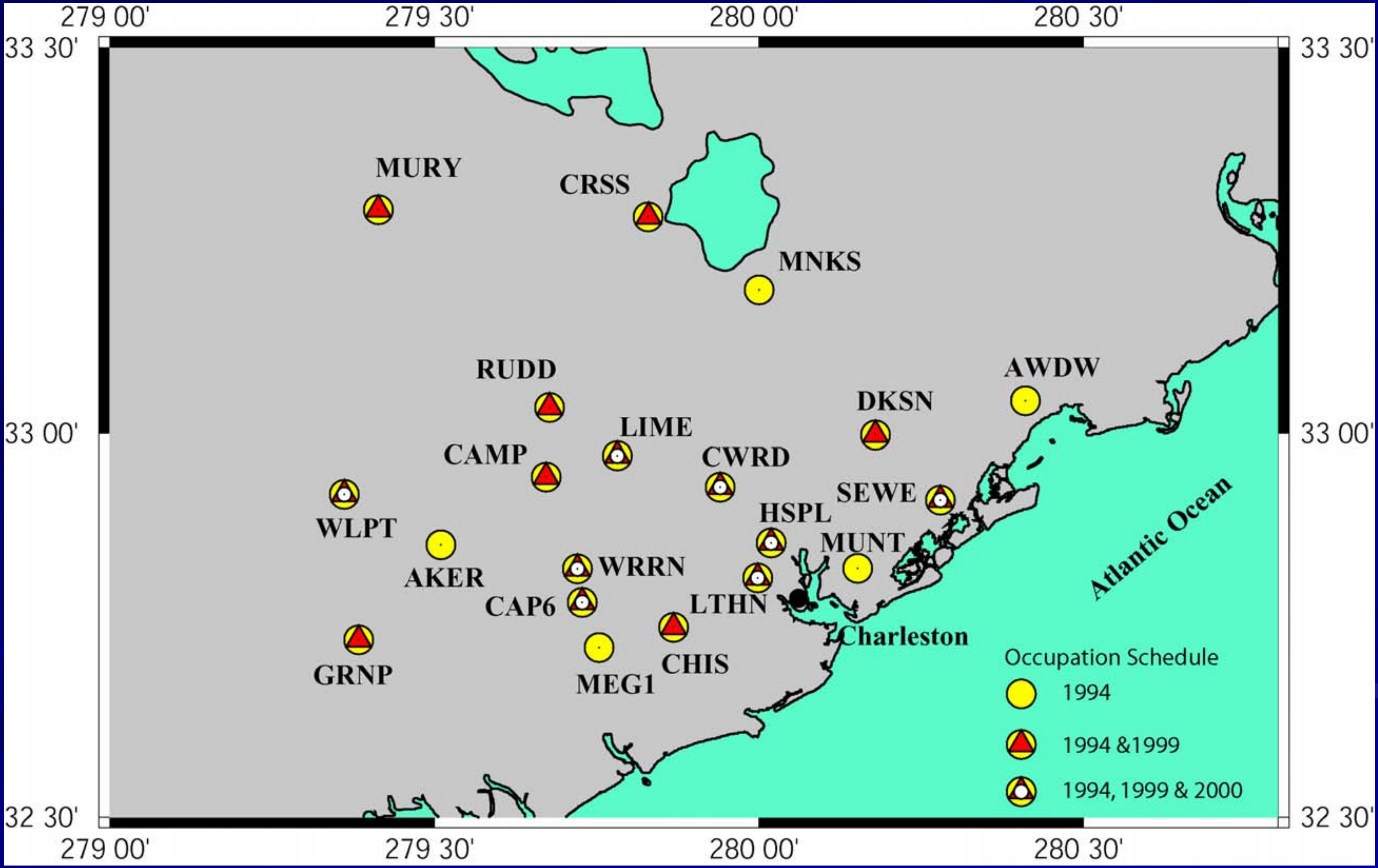
For details go to:

http://scsn.seis.sc.edu/Publications/publication.html

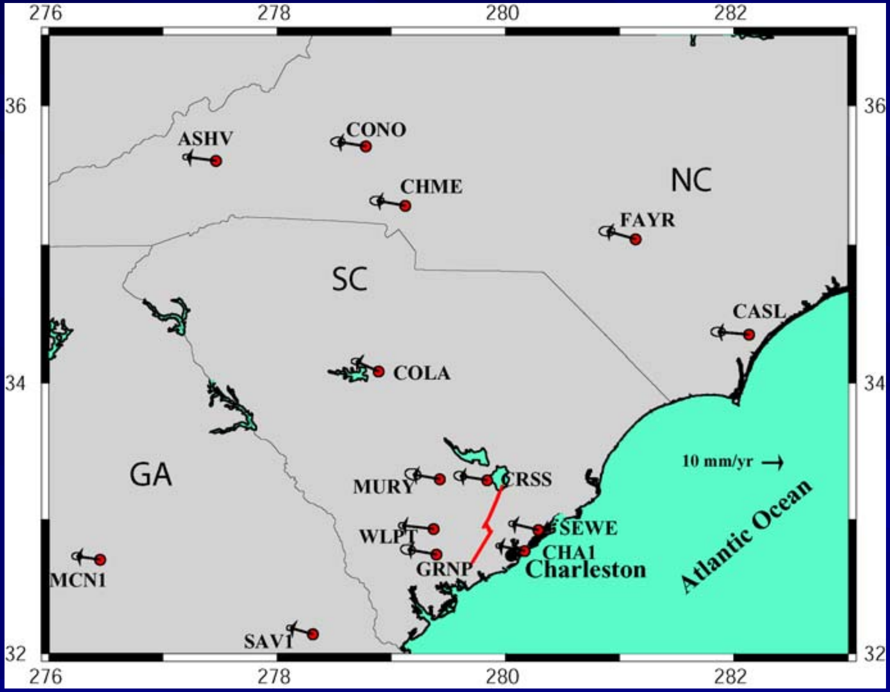
Robert Trenkamp, and **Pradeep Talwani**, GPS Derived Strain and Strain Zonation near Charleston, South Carolina, J. Geophys. Res., (In Revision).


232
248
264
280
296
48
40
32
24
STJO
ALGO
NLIB
WES
PIE1
WLPT
BRMU
MDO1
IGS Permanent GPS ●
Charleston Project Area 🟨

LOCATION MAP OF GPS STATIONS

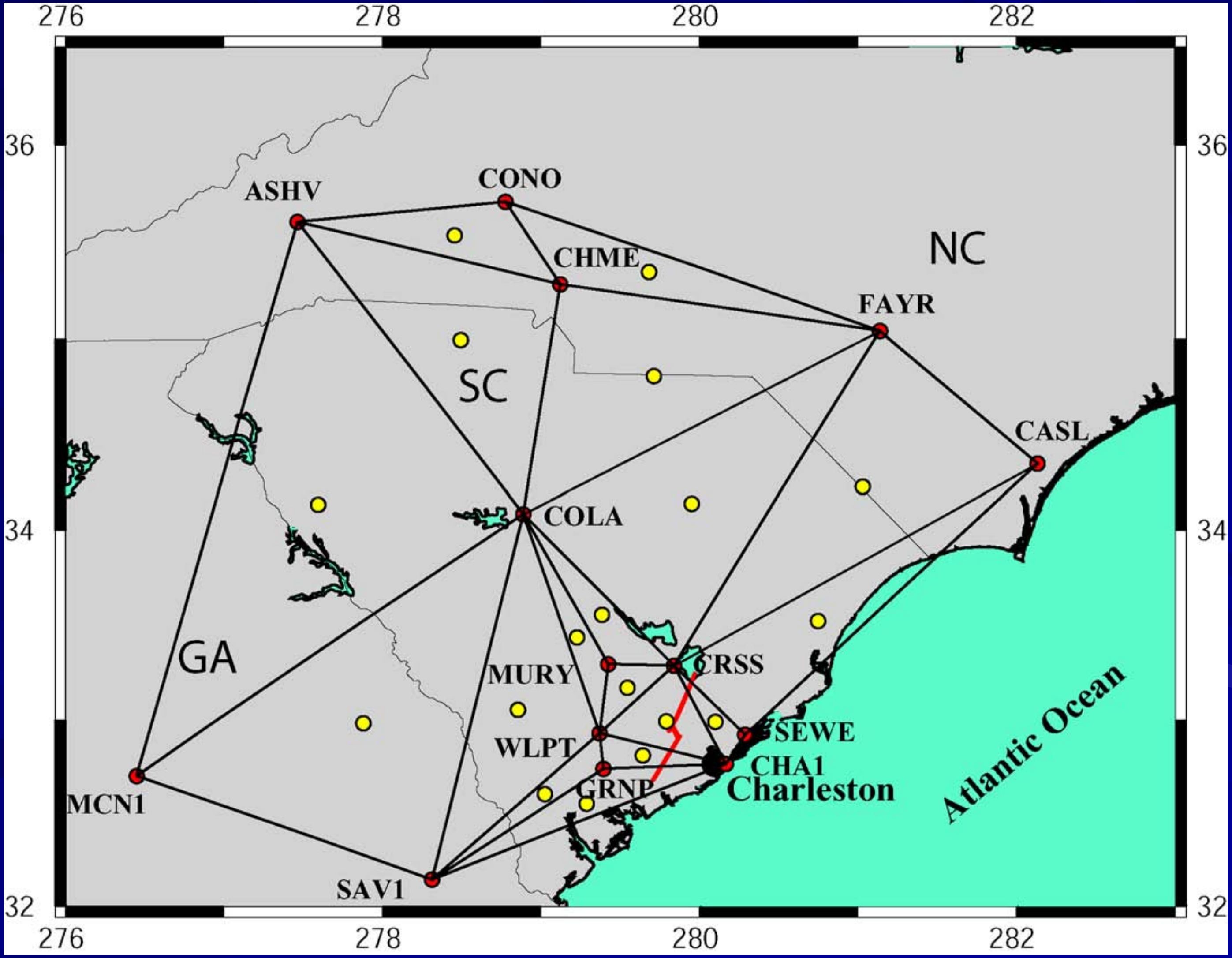


SITE LOCATIONS FOR STRAIN ANALYSIS



- Campaign sites
- Outer stations are CORS
- Positional vectors relative to the ITRF 2000 reference frame used in the strain calculations

DELAUNAY TRIANGLES USED IN STRAIN CALCULATIONS



SHEAR STRAIN RATE CONTOURS

For N. America plate

Strain rate 10^{-9}/year

↓

1 mm/ 1000 km

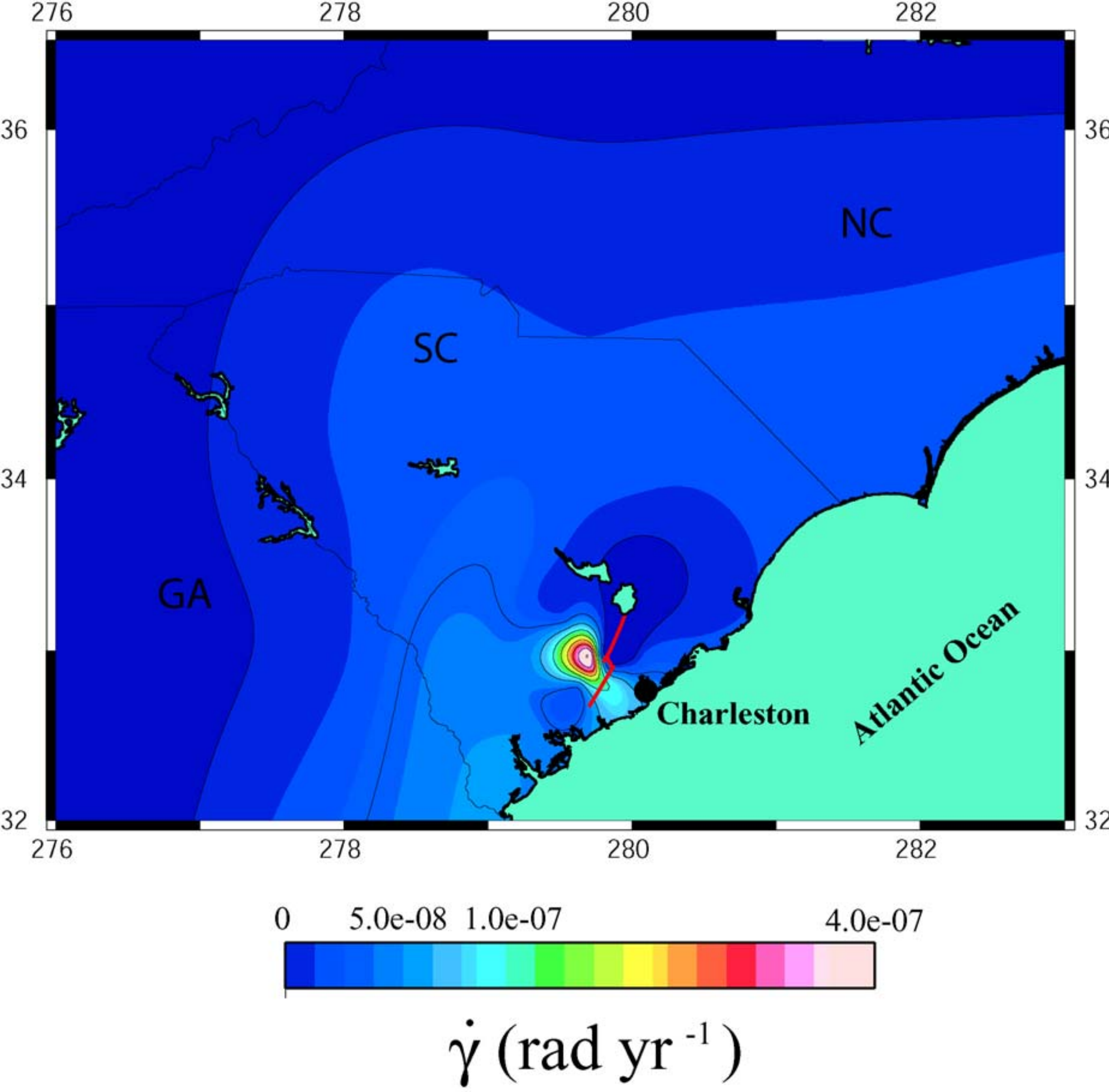
For Charleston

Strain rate 10^{-7}/year

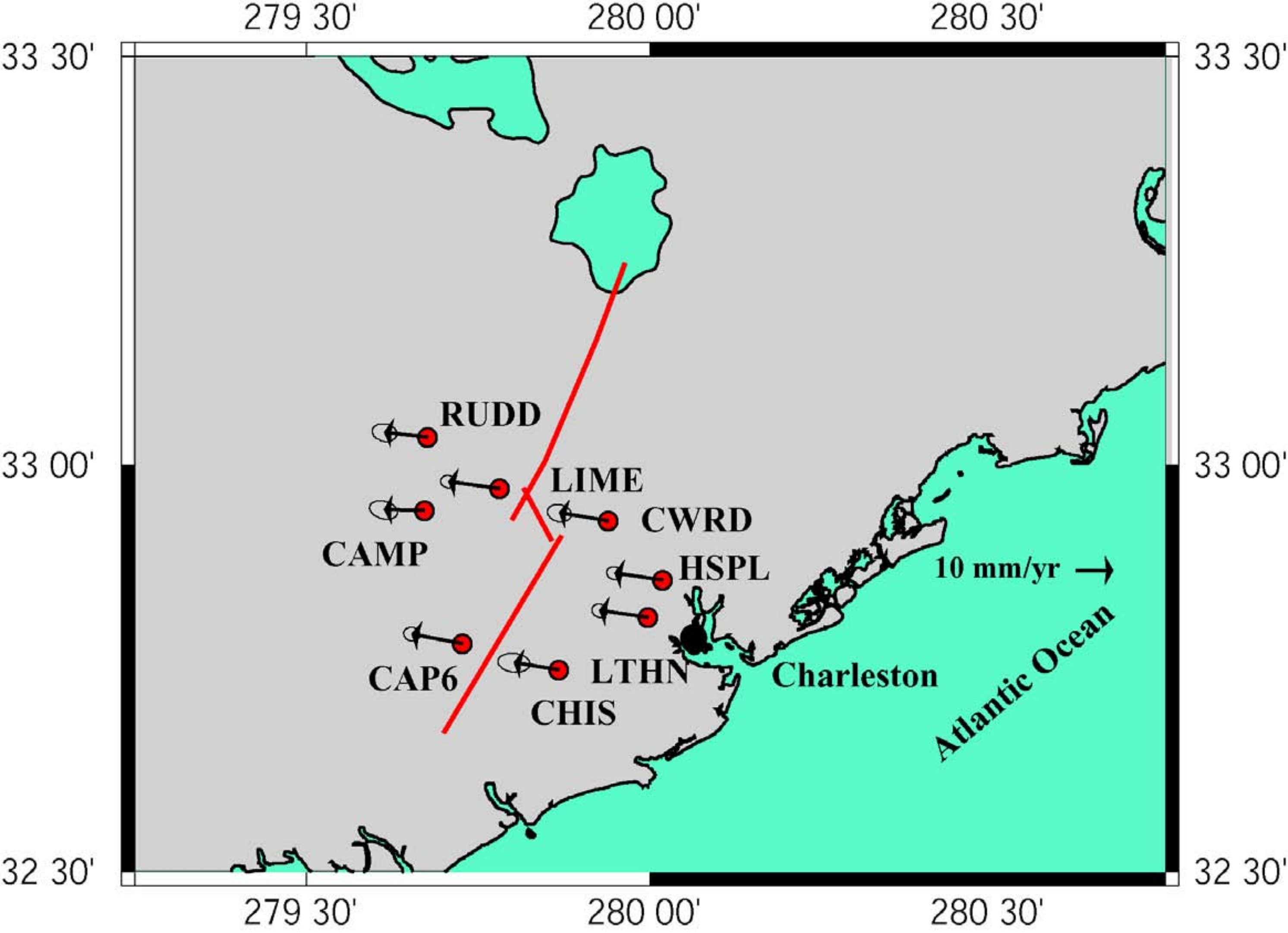
↓

1 cm/ 100 km

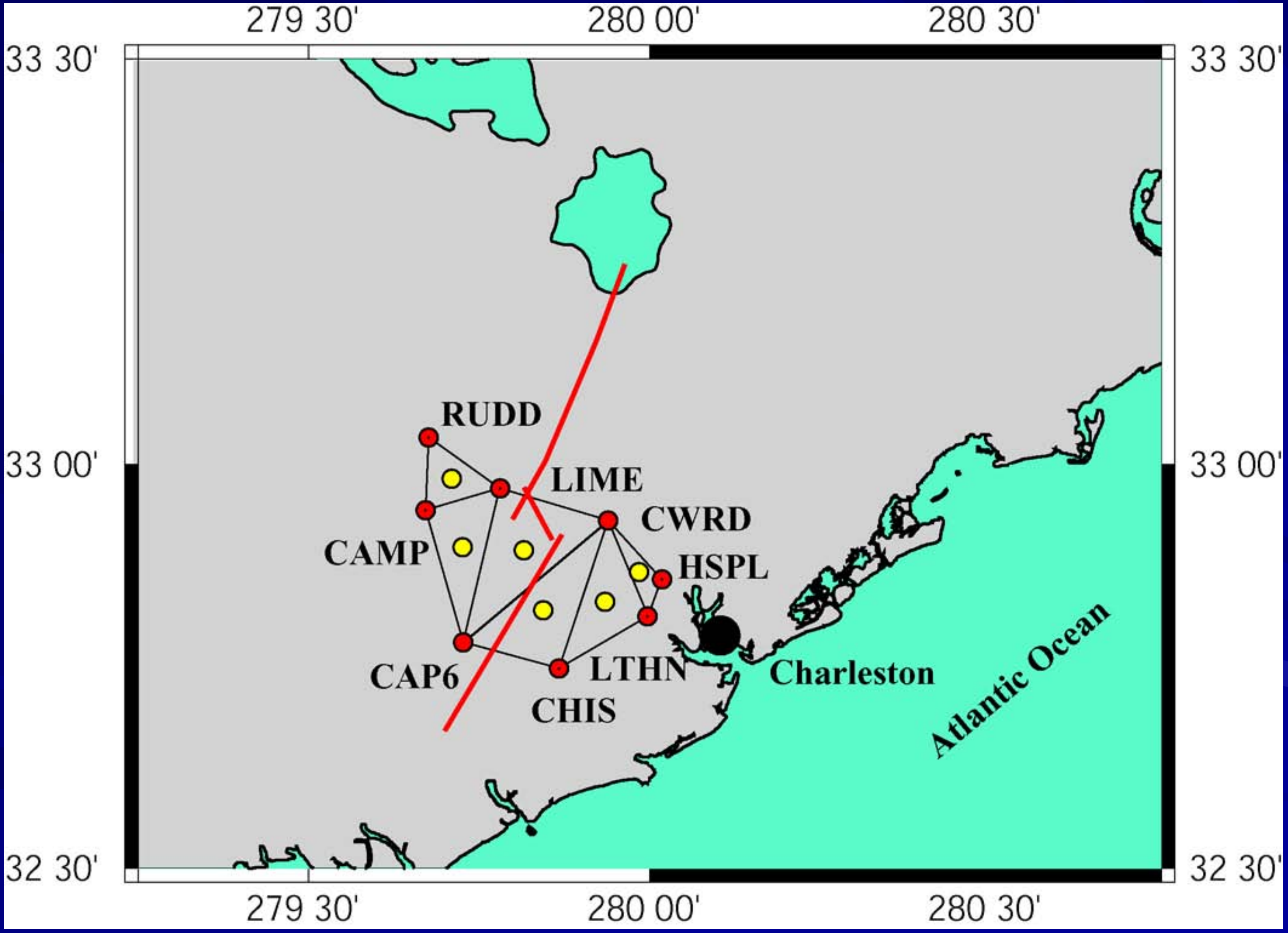
Comparable to strain rates at plate boundaries



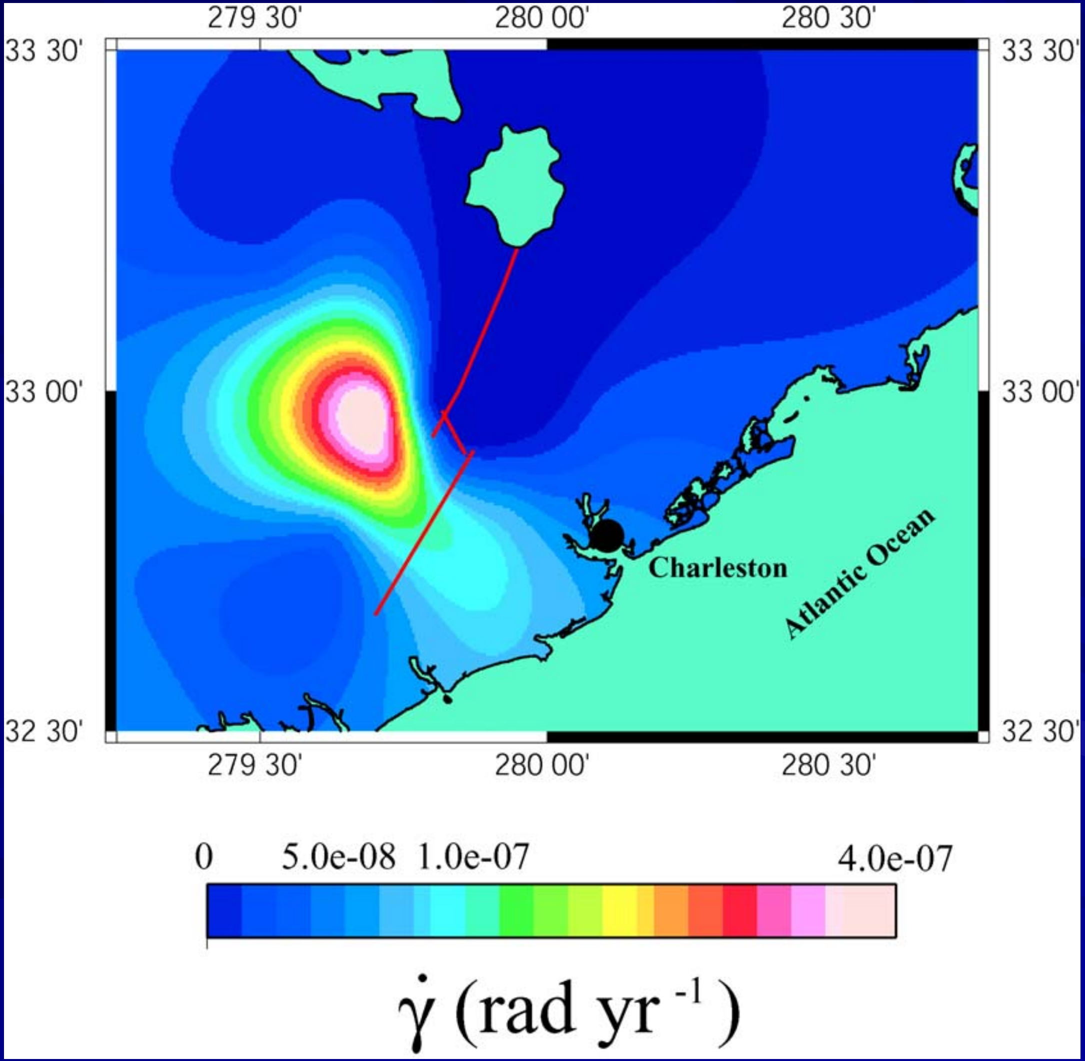
POSITIONAL VECTORS IN EPICENTRAL AREA



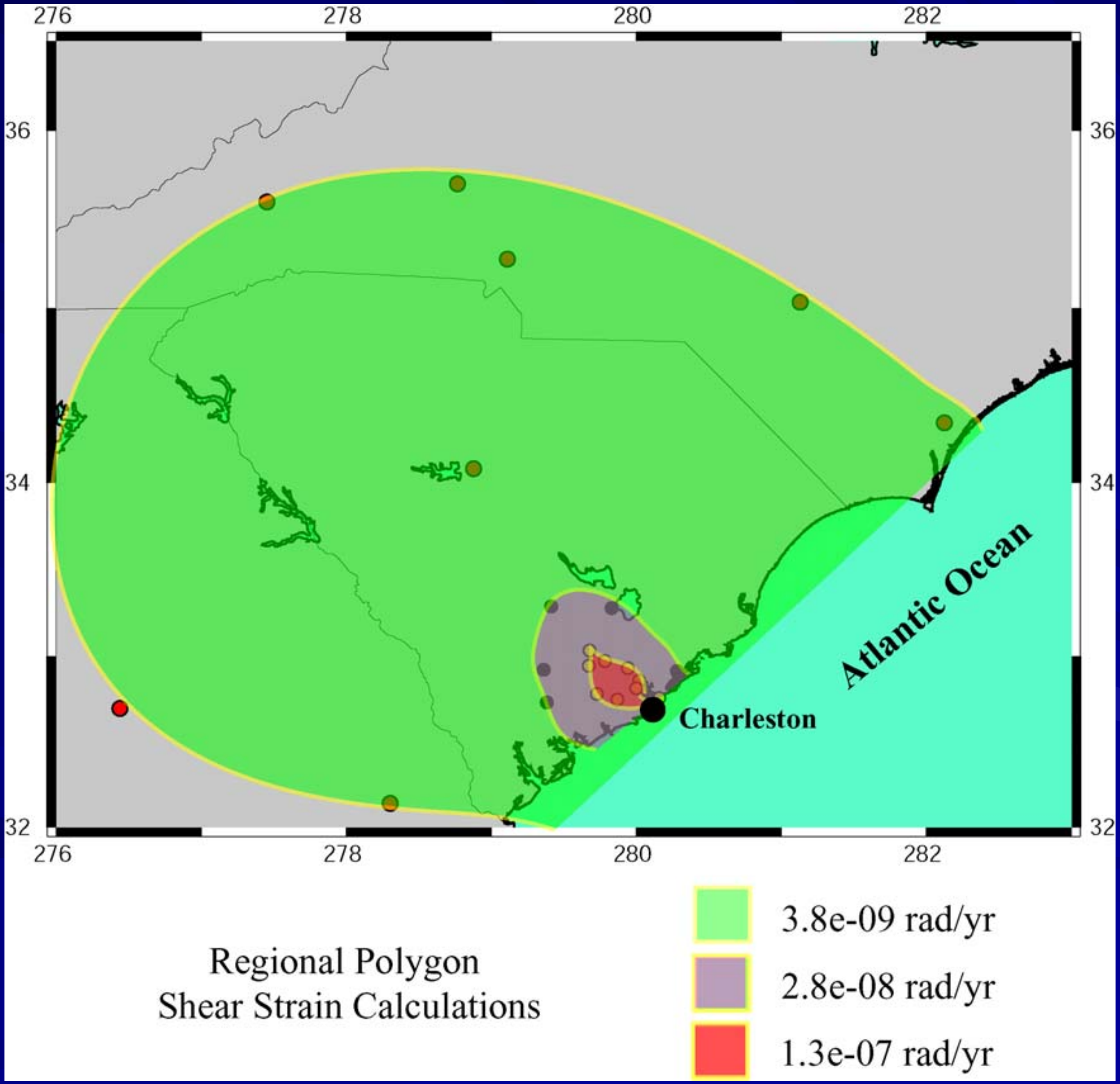
DELAUNAY TRIANGLES IN EPICENTRAL AREA



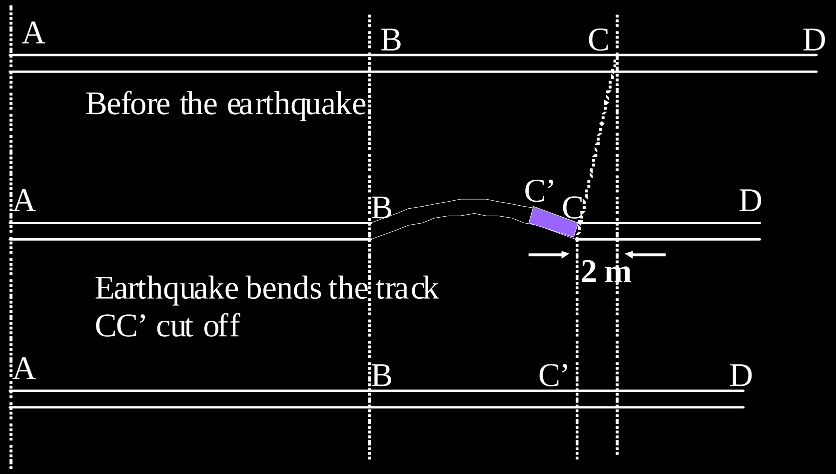
SHEAR STRAIN RATE CONTOURS



RESULTS OF GPS STUDIES (STRAIN ZONATION)



BENT TRACKS IN 1886



Before the earthquake

Earthquake bends the track
CC’ cut off

Coseismic shortening: 2m

EARTHQUAKE CYCLE

Length of the seismic zone ~50 km

Strain rates ~ 10**-7/year (from GPS)

Recurrence rates ~500 years
(from Paleoseismology)

Imply slip in one earthquake cycle ~2.5 m

Comparable to observed coseismic strain
(shortening of railroad tracks)

Magnitude estimates for the Charleston earthquake

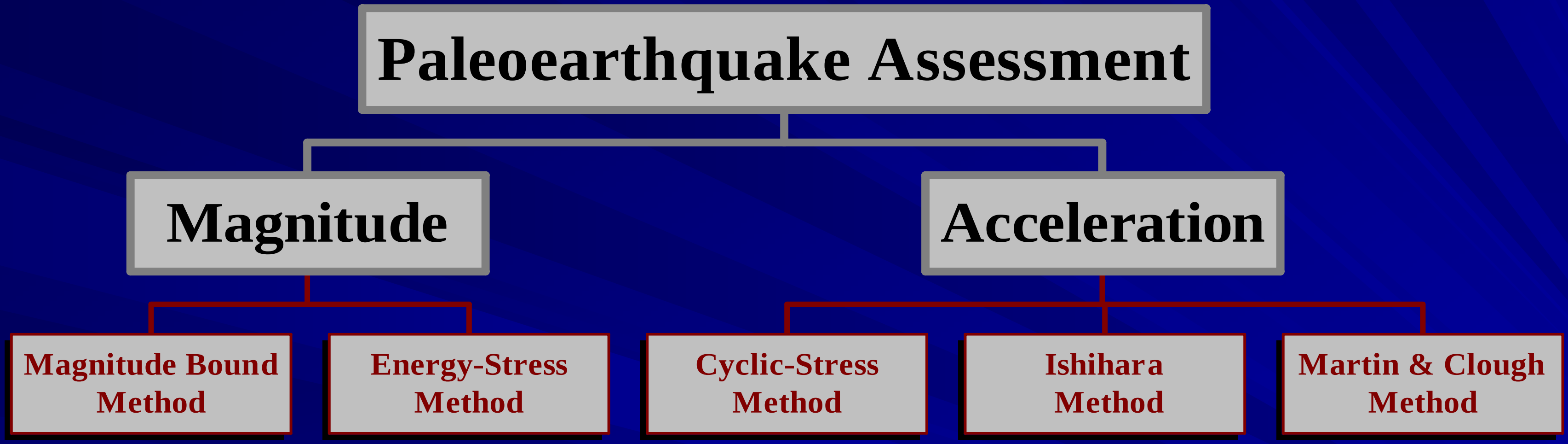
Estimates of Magnitude of the 1886 Charleston SC Earthquake from Intensity Data

Author(s)	**Magnitude**	**Remarks:**
Nuttli (1973, 1976)	m_b 6.5	m_{bLg} relation
Bollinger (1977)	m_b 6.8	Particle velocity EUS
	m_b 7.1	Particle velocity WUS
Nuttli et al. (1979)	m_b 6.6 to 6.9 Wt. av. 6.7*	1 Hz Lg ground motion 33 WUS, 8 CUS eq.
Nuttli (1983)	m_b 6.7	Source characteristics
Bollinger (1983)	m_b 6.7	Nuttli et al., 1979.
Nuttli et al. (1986)	m_b 6.7	New seismicity data
Johnston (1996)	M_w 7.3 ± 0.26	SCR data
Bakun & Hopper (2004)	M_w 6.4 to 7.2 M_w 6.9 *	Intensity magnitude algorithm

None of these studies considered in situ soil conditions

Estimating magnitude and accelerations of prehistoric earthquakes from in situ geotechnical data

Methodology



Paleoearthquake Assessment

Magnitude

- Magnitude Bound Method
- Energy-Stress Method

Acceleration

- Cyclic-Stress Method
- Ishihara Method
- Martin & Clough Method

Methods based on in-situ geotechnical data:

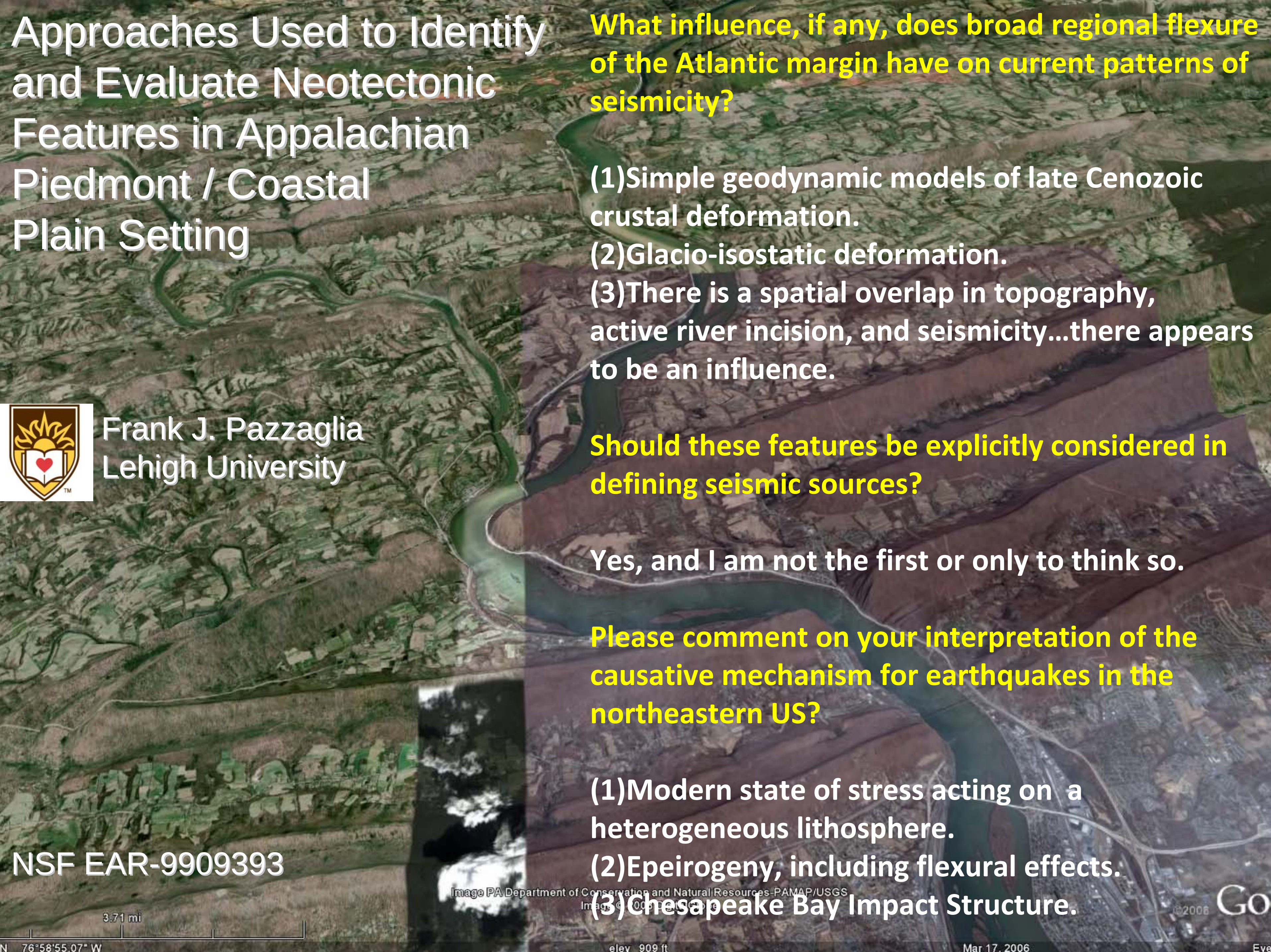
- Energy-Stress Method
- Cyclic-Stress Method (SPT, CPT, V_s)
- Ishihara Method
- Martin & Clough Method

Estimates of Magnitudes of Prehistoric S.C. Earthquakes associated with liquefaction from in situ SPT data (Energy Stress Method, Hu et al., 2002)

Location of sand blow	Inferred seismic source	Date of eq. YBP	Estimated magnitude	Reference
Sam-02	Charleston	~500	6.2 to 7.0	Leon et al. 2005
Sam-04	Charleston	~1000	6.2 to 6.8	
Sam-05	Northeast	~1650	5.1 to 6.4	
	or Charleston	~1680	6.4 to 7.2	
Gap-02	Charleston	~3500	5.6 to 6.4	
Gap-03	Northeast	~5000	4.3 to 5.6	
	or Charleston	~5000	5.5 to 6.2	
FD*	Sawmill Brach fault	Pre 1886	6.2	Gassman, 2009

Conclusions

- The 1886 Charleston earthquake and the current seismicity are associated with the Woodstock fault, and the associated faults, at a compressional left-step in the Middleton Place Summerville Seismic Zone.
- Only this segment of the ECFS is seismically active and poses a seismic hazard.
- Perhaps the M_{max} for the Charleston earthquake should be reduced to **M**7.0.



Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont / Coastal Plain Setting

Frank J. Pazzaglia
Lehigh University

NSF EAR-9909393

What influence, if any, does broad regional flexure of the Atlantic margin have on current patterns of seismicity?

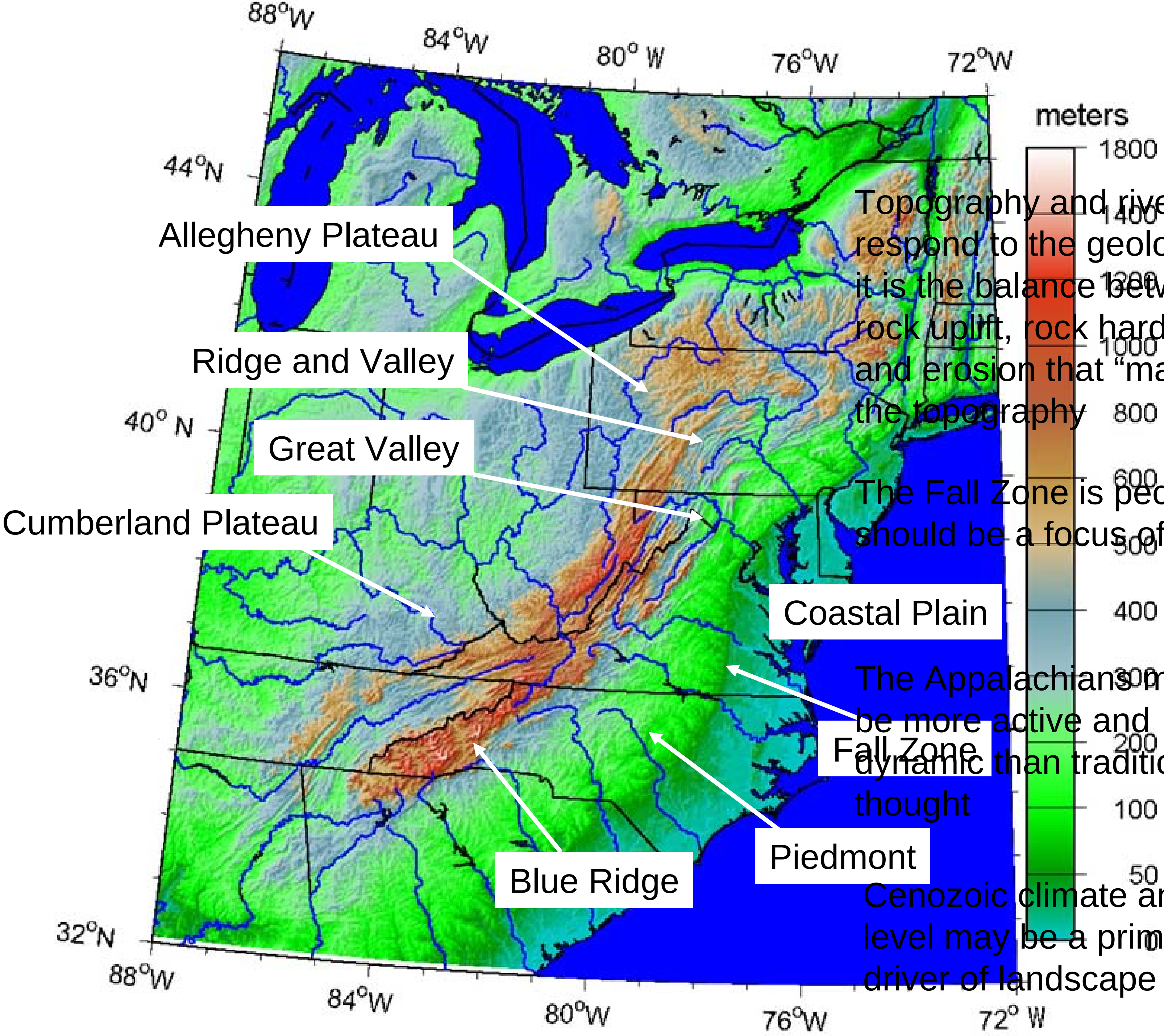
(1)Simple geodynamic models of late Cenozoic crustal deformation.
(2)Glacio-isostatic deformation.
(3)There is a spatial overlap in topography, active river incision, and seismicity…there appears to be an influence.

Should these features be explicitly considered in defining seismic sources?

Yes, and I am not the first or only to think so.

Please comment on your interpretation of the causative mechanism for earthquakes in the northeastern US?

(1)Modern state of stress acting on a heterogeneous lithosphere.
(2)Epeirogeny, including flexural effects.
(3)Chesapeake Bay Impact Structure.

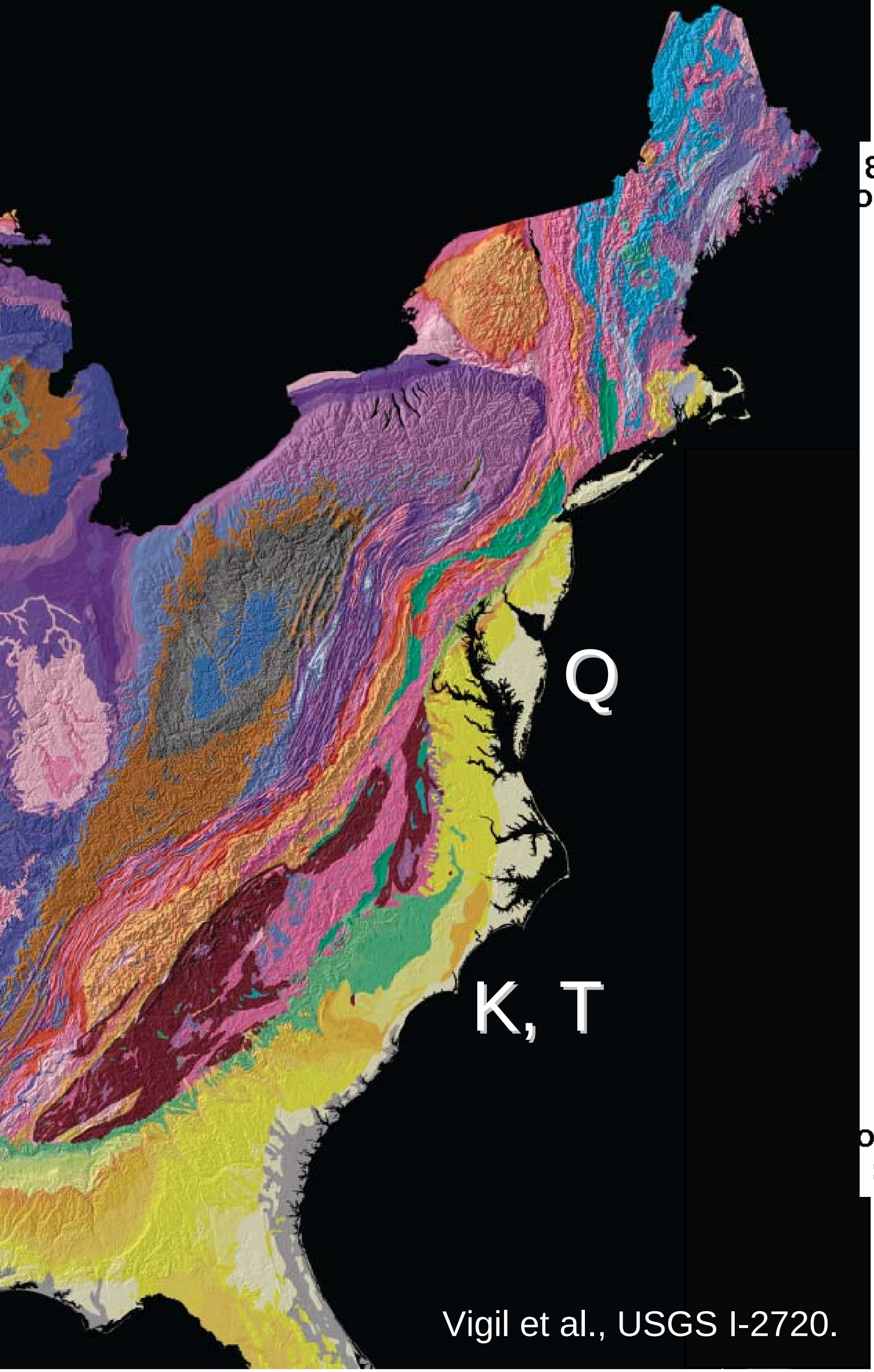


Topography and rivers respond to the geology; it is the balance between rock uplift, rock hardness, and erosion that “makes” the topography

The Fall Zone is peculiar and should be a focus of study.

The Appalachians might be more active and dynamic than traditionally thought

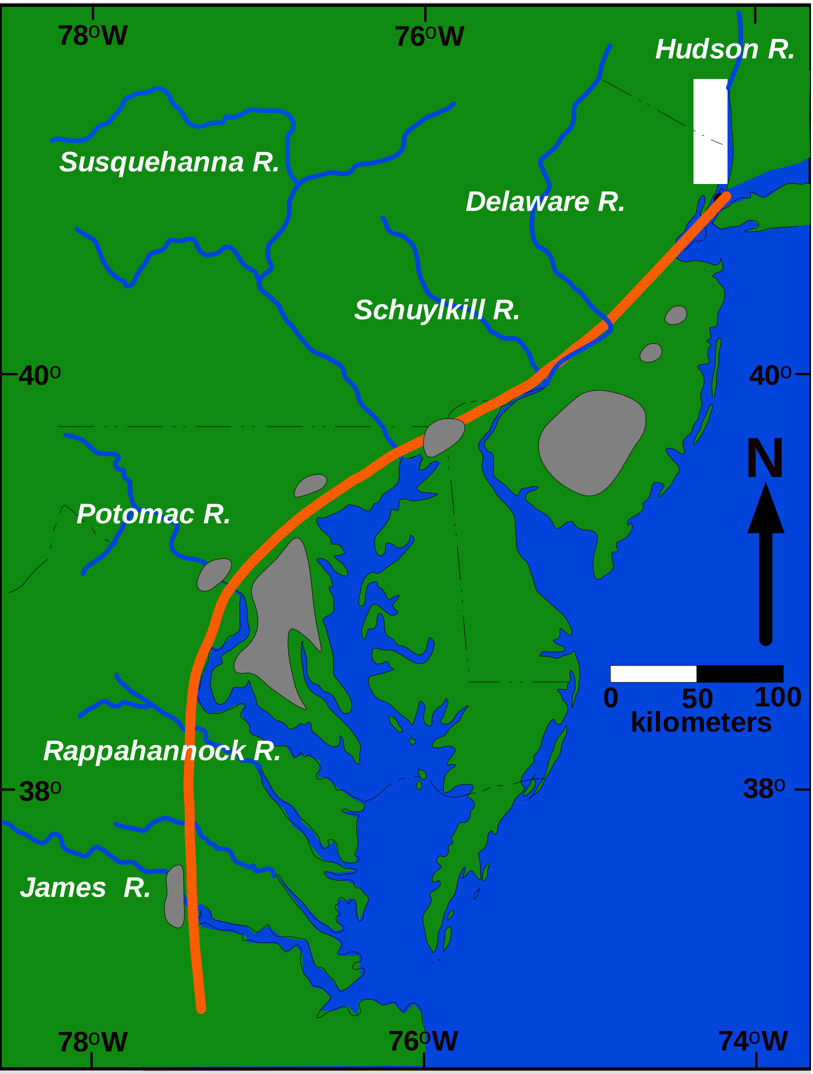
Cenozoic climate and base level may be a primary driver of landscape evolution

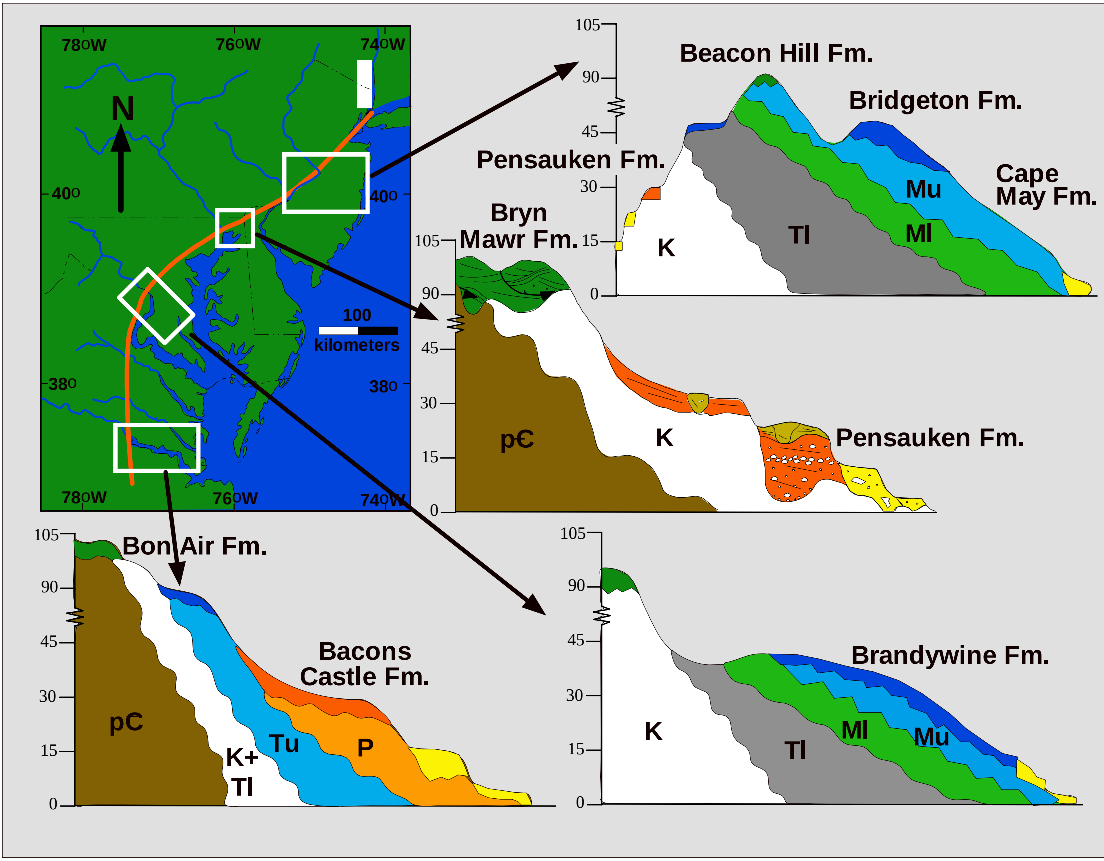


Vigil et al., USGS I-2720.

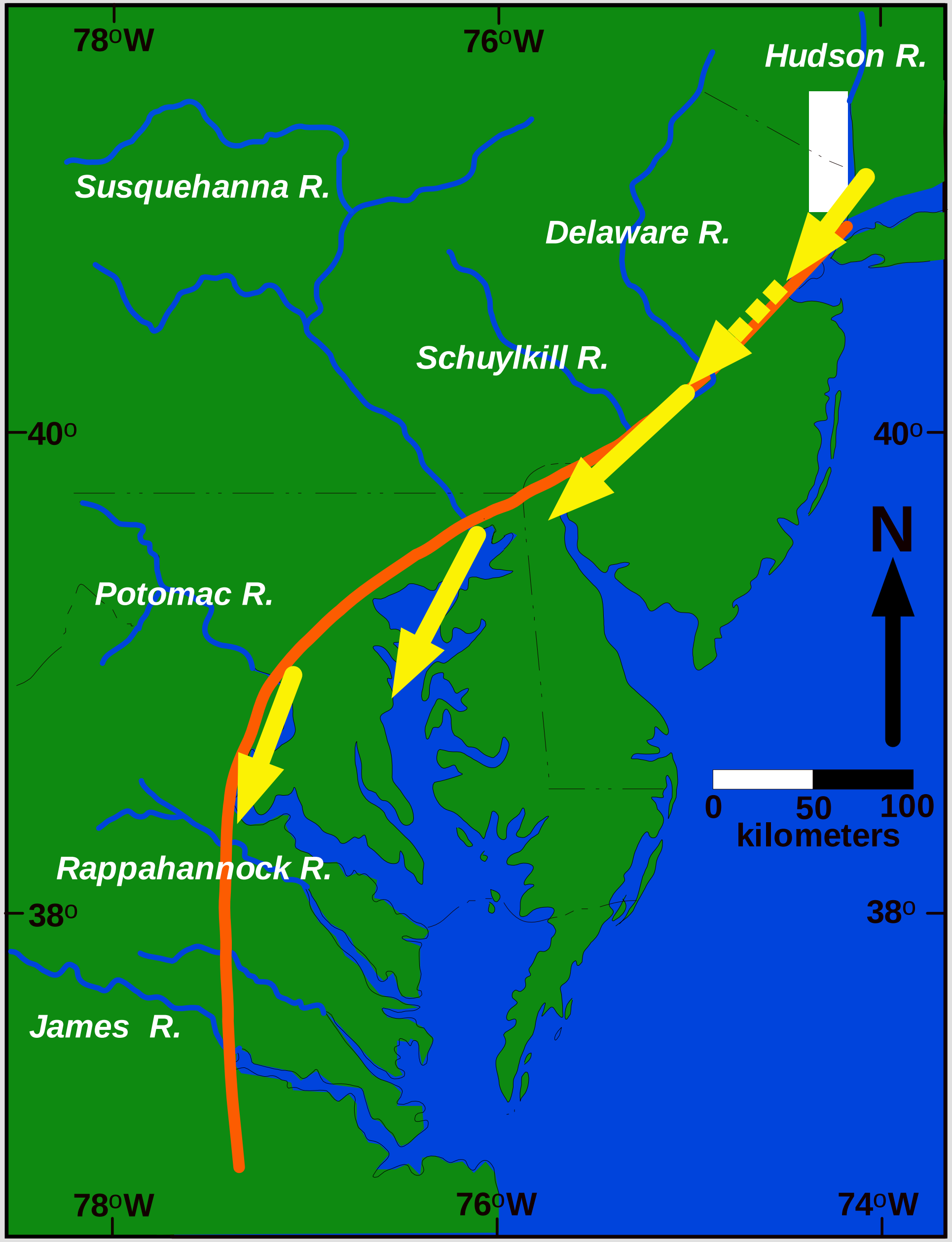
modified from Owens and Gohn (1985)

Pazzaglia, 1993, GSABull, 105,1617-1634.

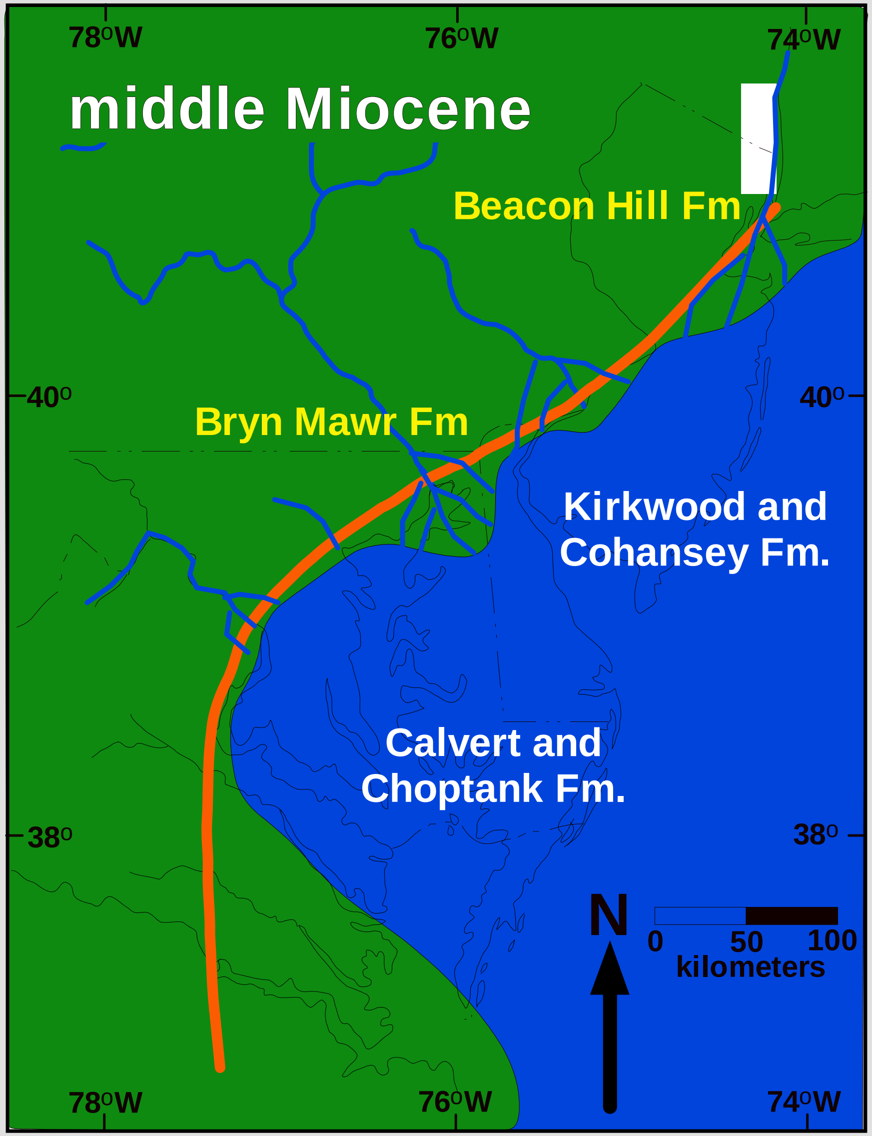


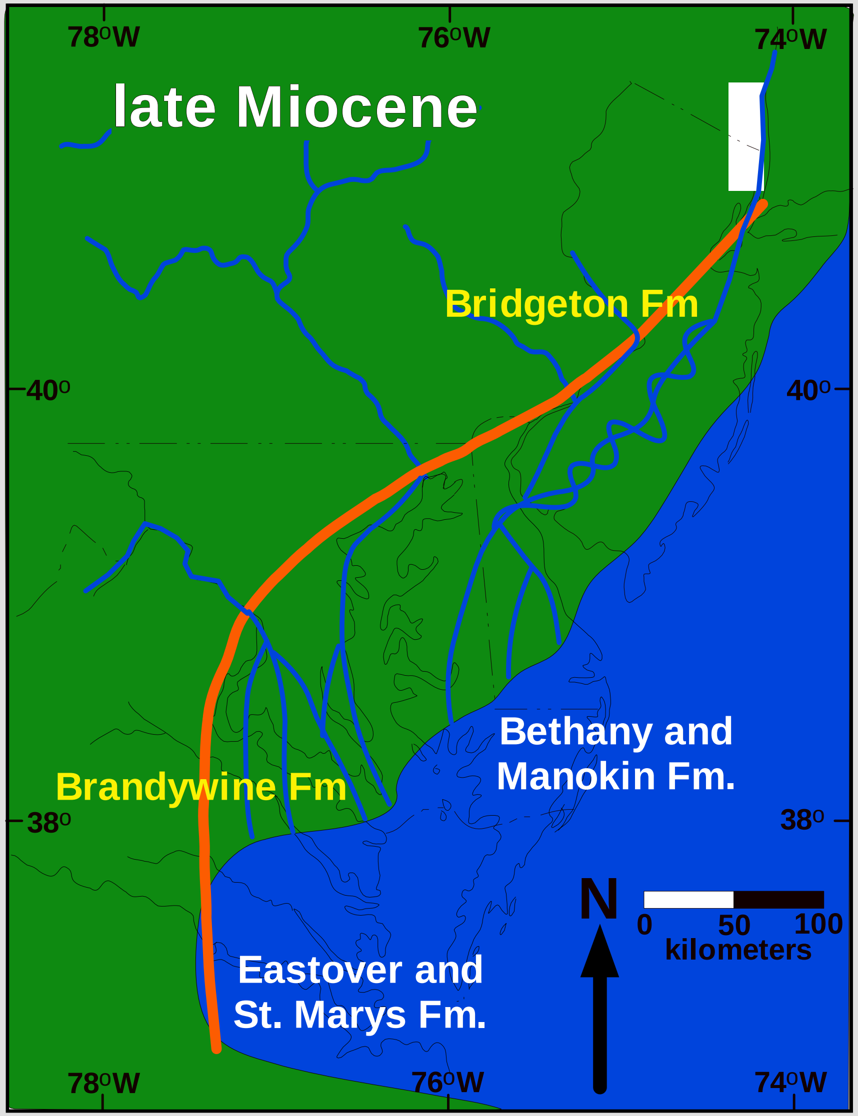


Pazzaglia, 1993, GSABull, 105,1617-1634.

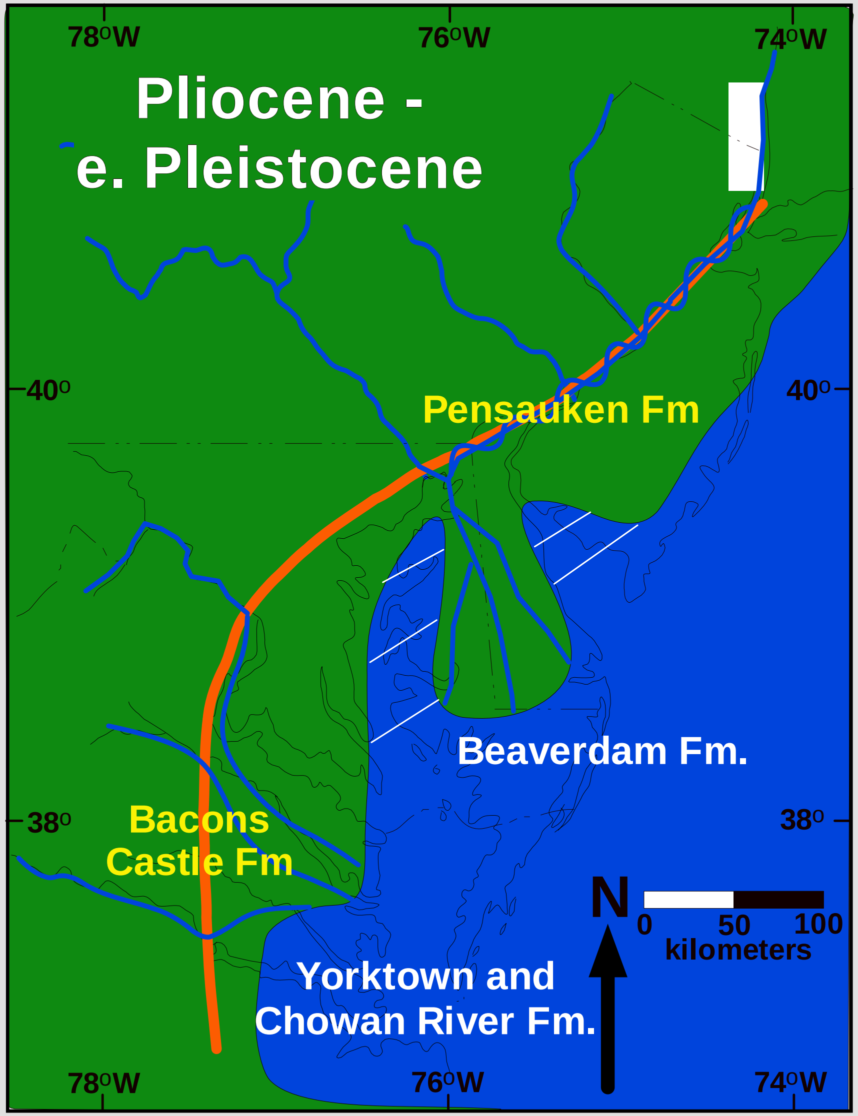


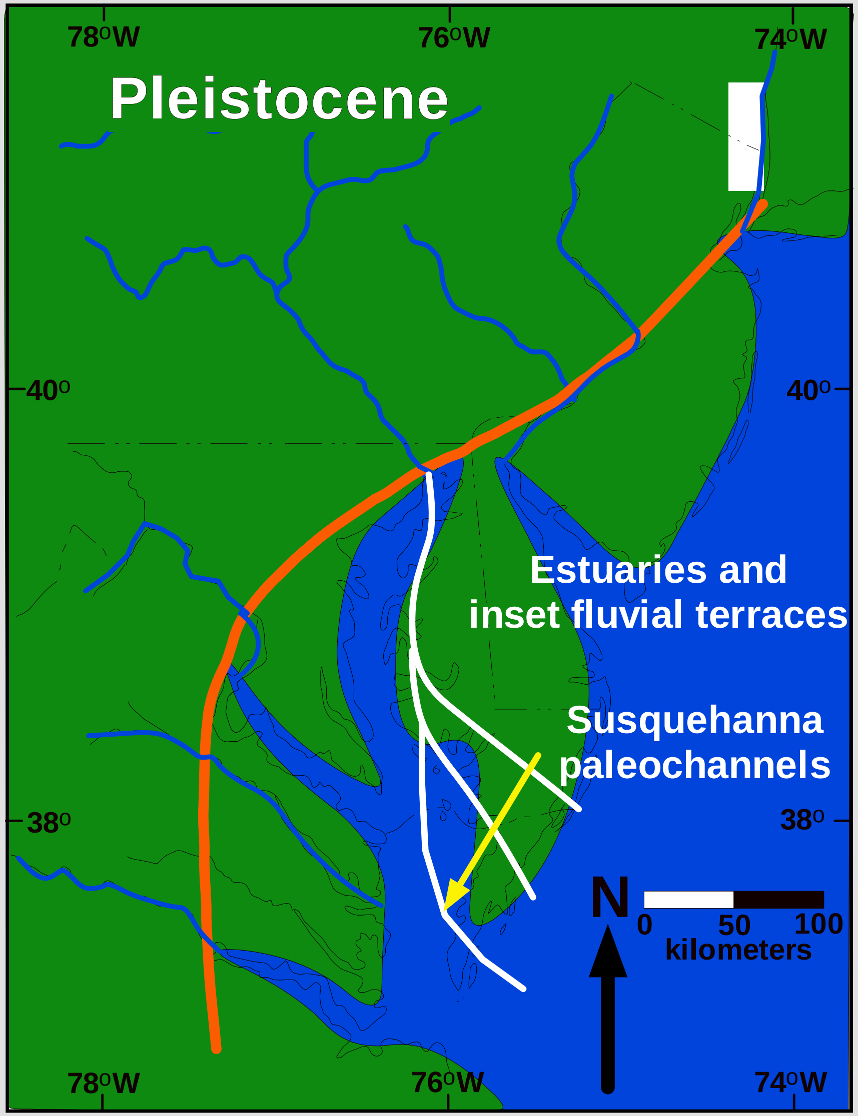
Pazzaglia, 1993, GSABull, 105,1617-1634.

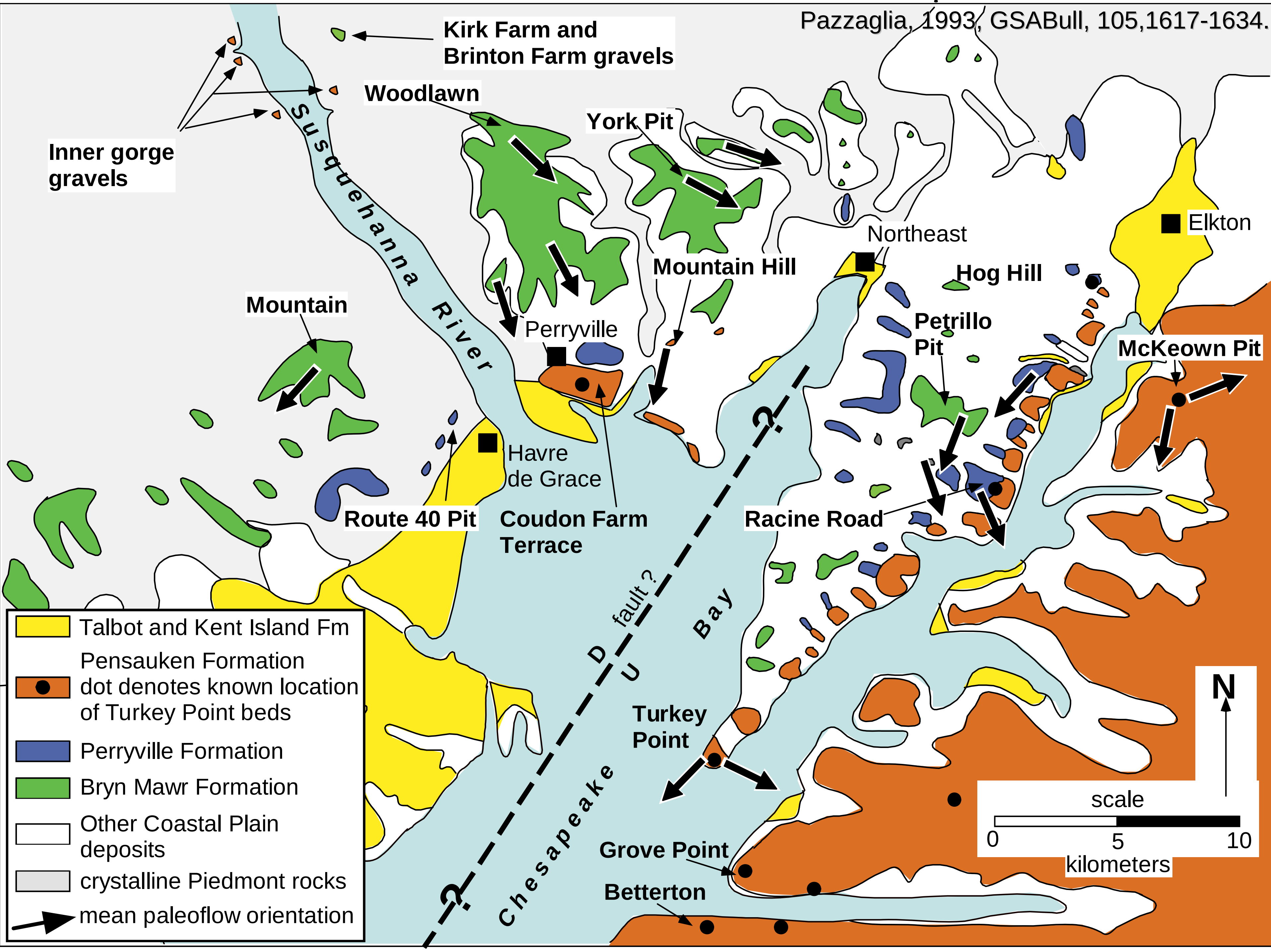




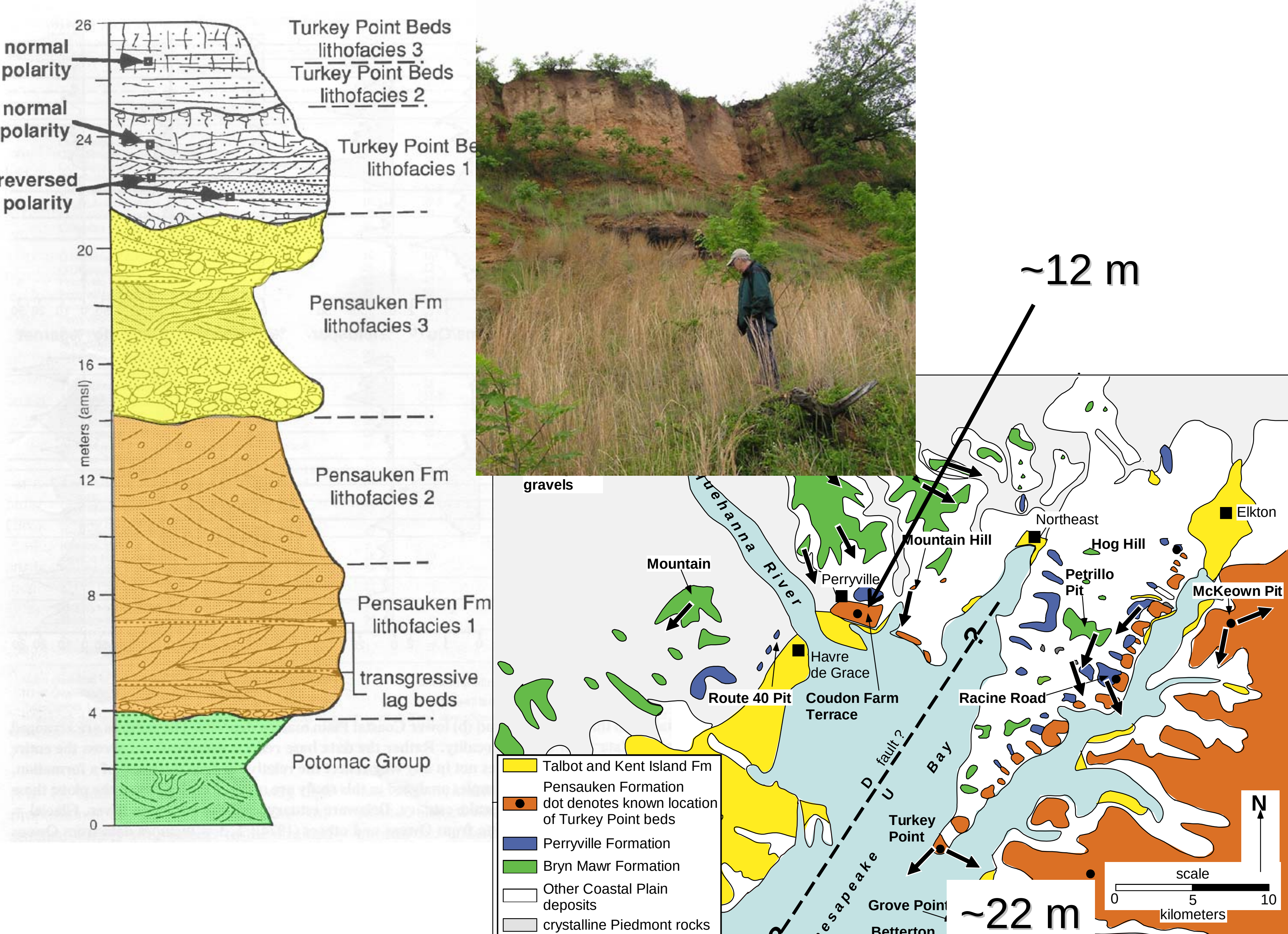
Pazzaglia, 1993, GSABull, 105,1617-1634.





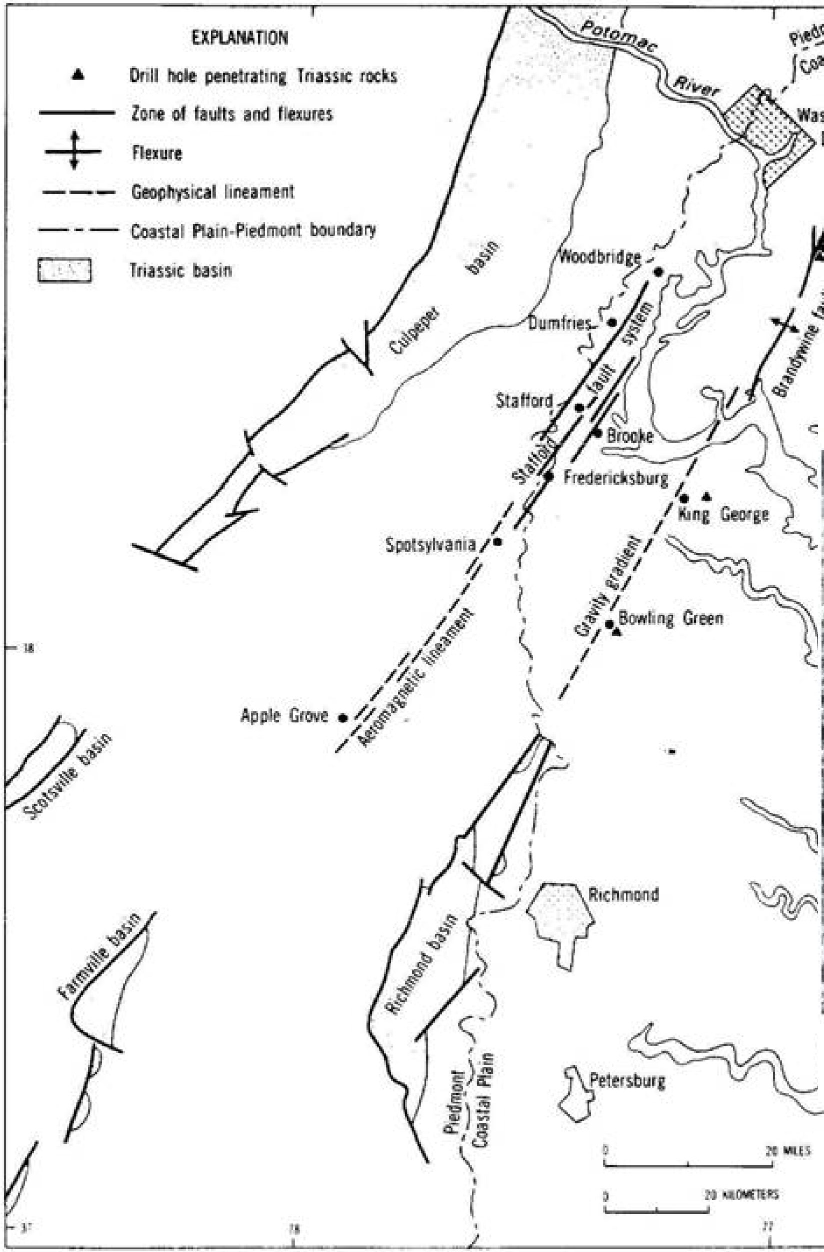


Pazzaglia, 1993, GSABull, 105,1617-1634.



Pazzaglia, 1993, GSABull, 105,1617-1634.

Calvert Ave, at Rock Creek Park
Washington, D.C.



Mixon, R. B. and Newell, W., 1978, The Faulted Coastal Plain Margin At Fredericksburg, Virginia. USGS, Tenth Annual Virginia Geology Field Conference.

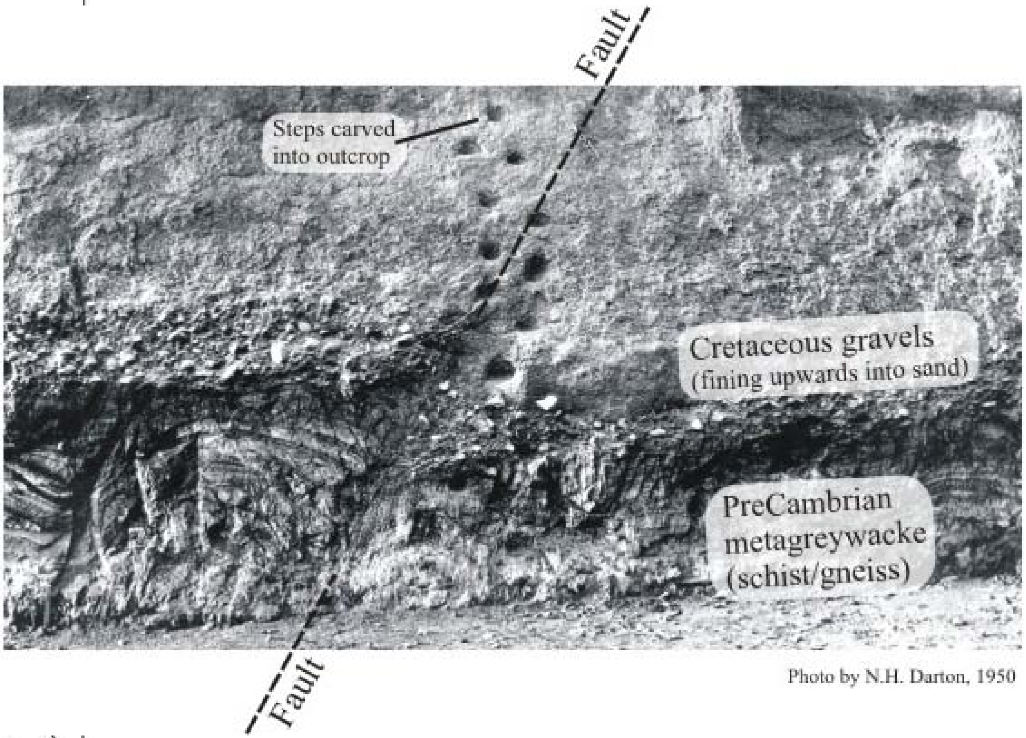
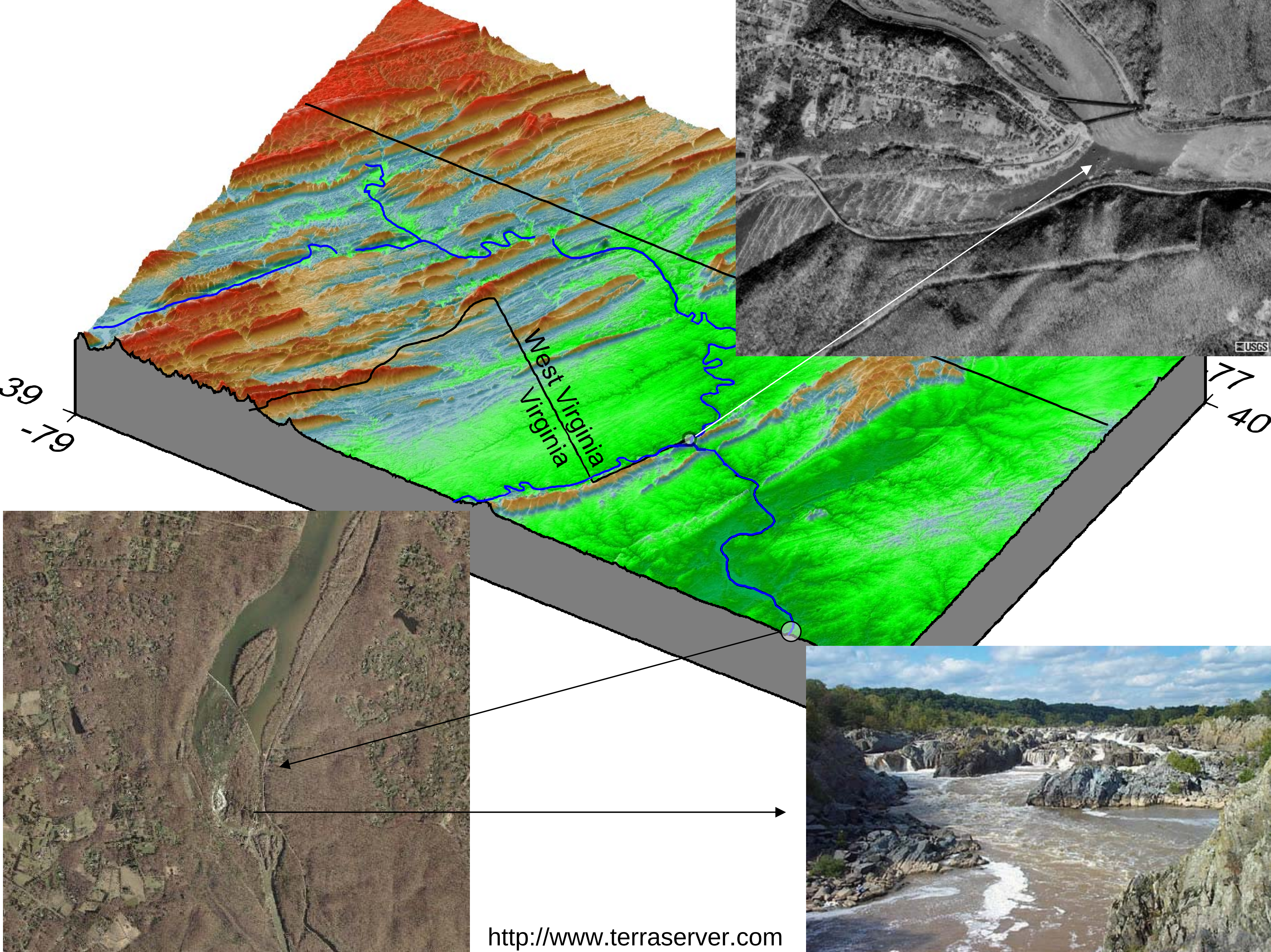


Photo by N.H. Darton, 1950

http://www.nvcc.edu/home/cbentley/dc_rocks/



http://www.terraserver.com

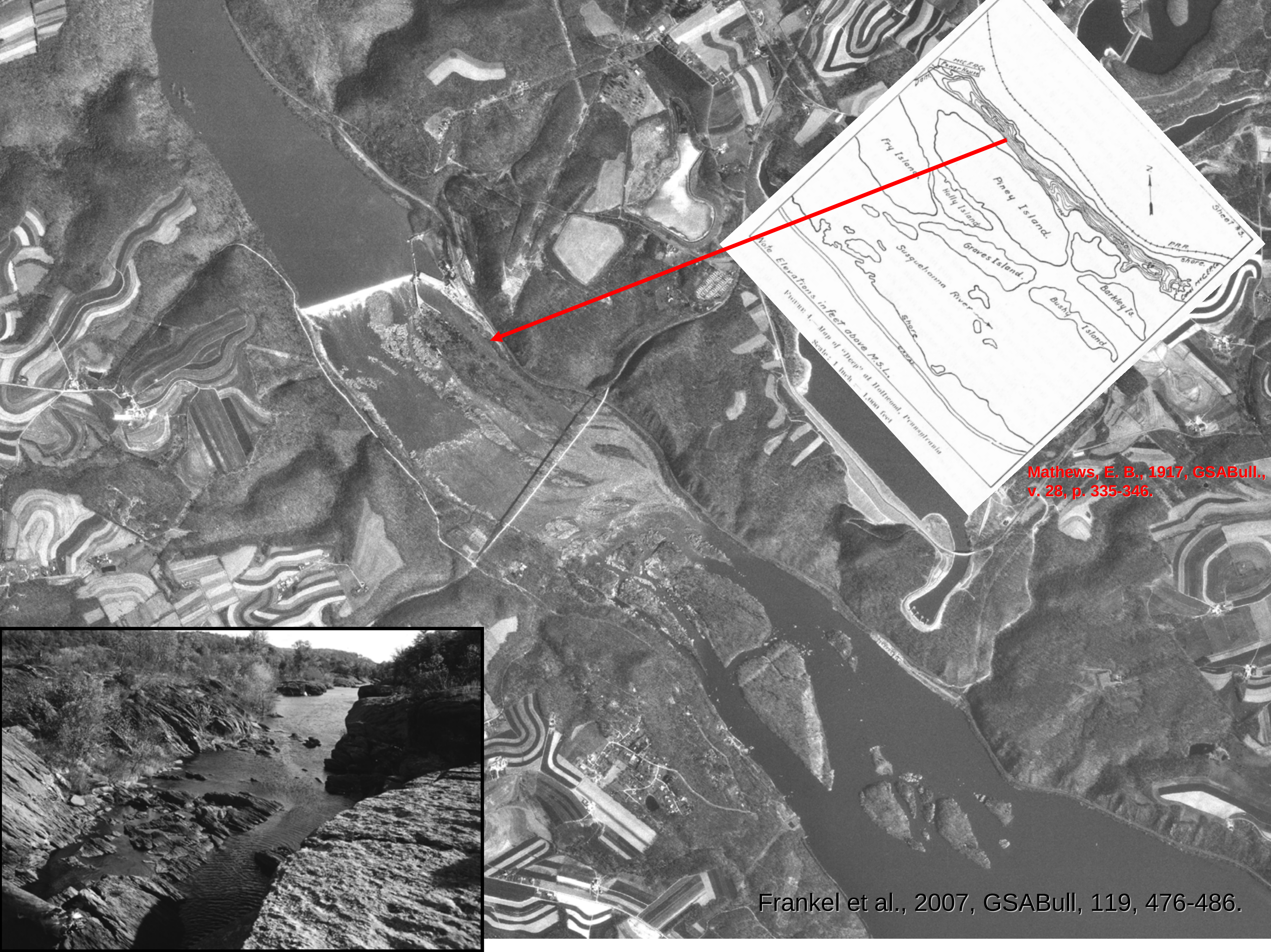
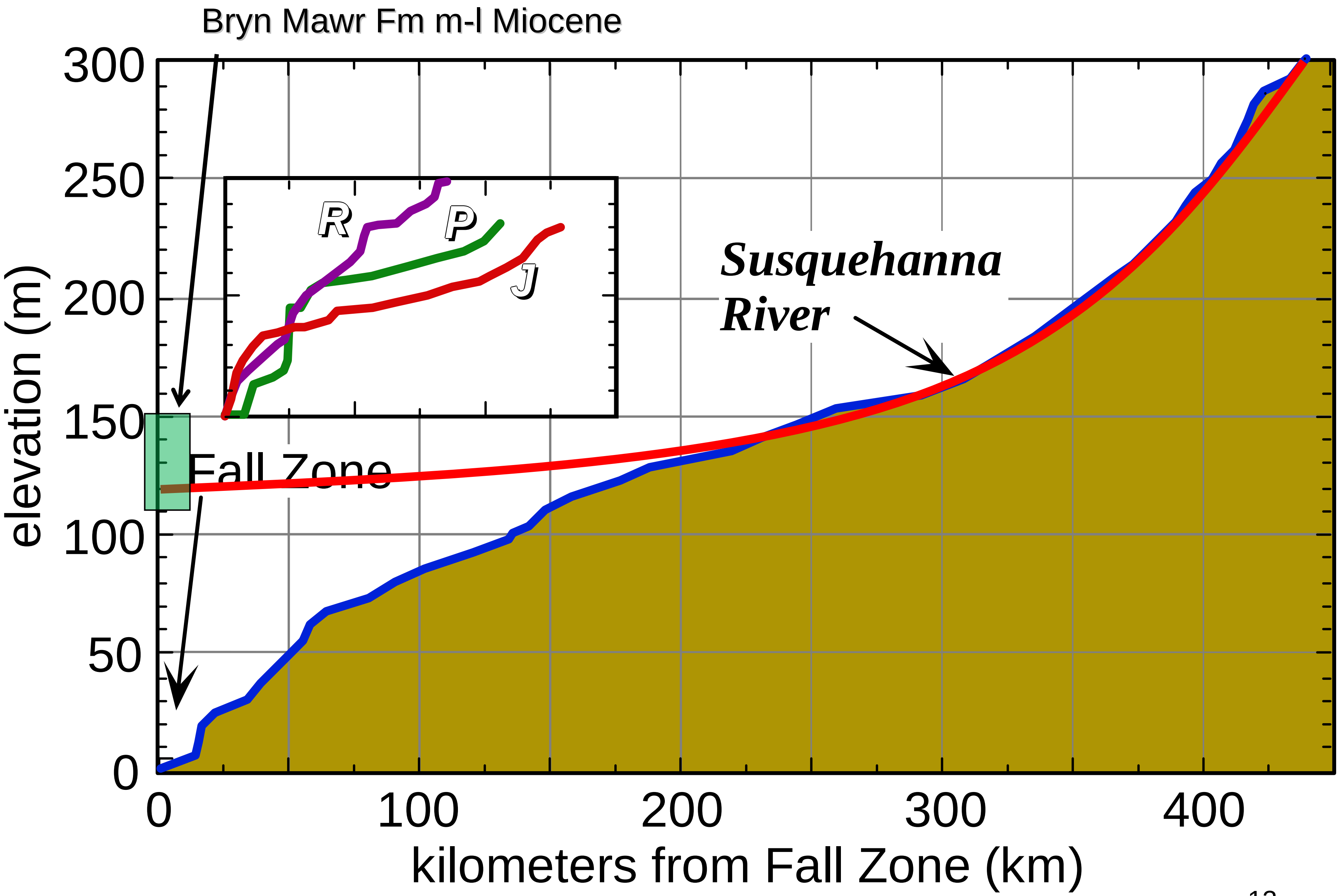
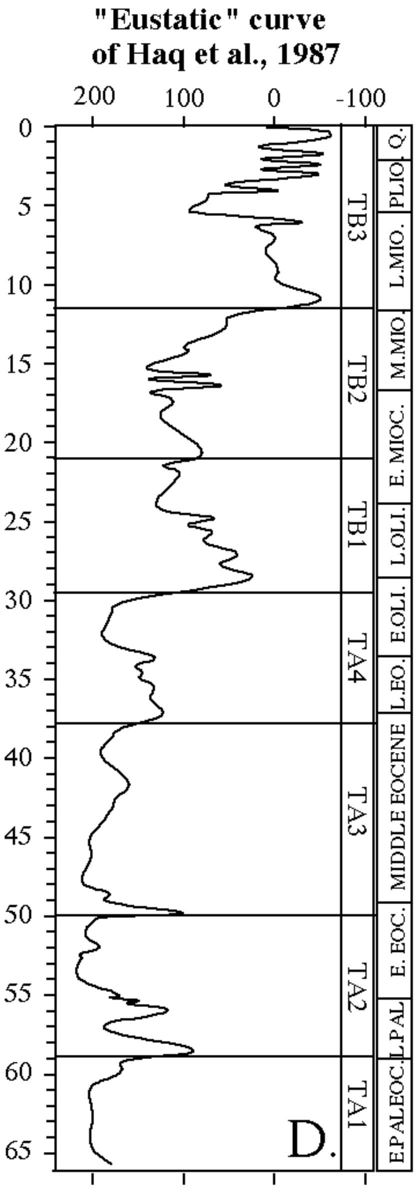


Figure 4.—Map of "Deeps" at Holtwood, Pennsylvania
Scale: 1 inch = 1,000 feet

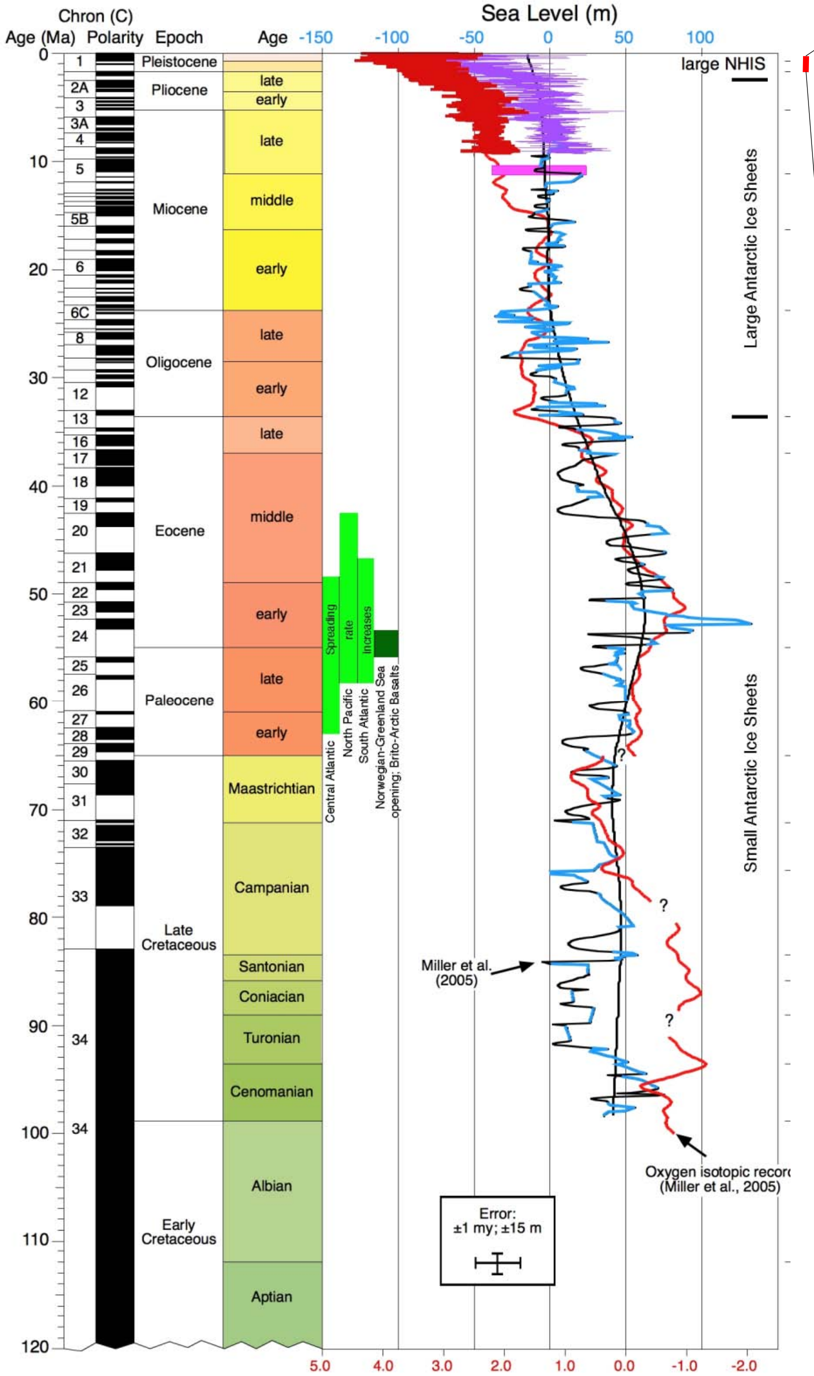
Mathews, E. B., 1917, GSABull., v. 28, p. 335-346.

Frankel et al., 2007, GSABull, 119, 476-486.

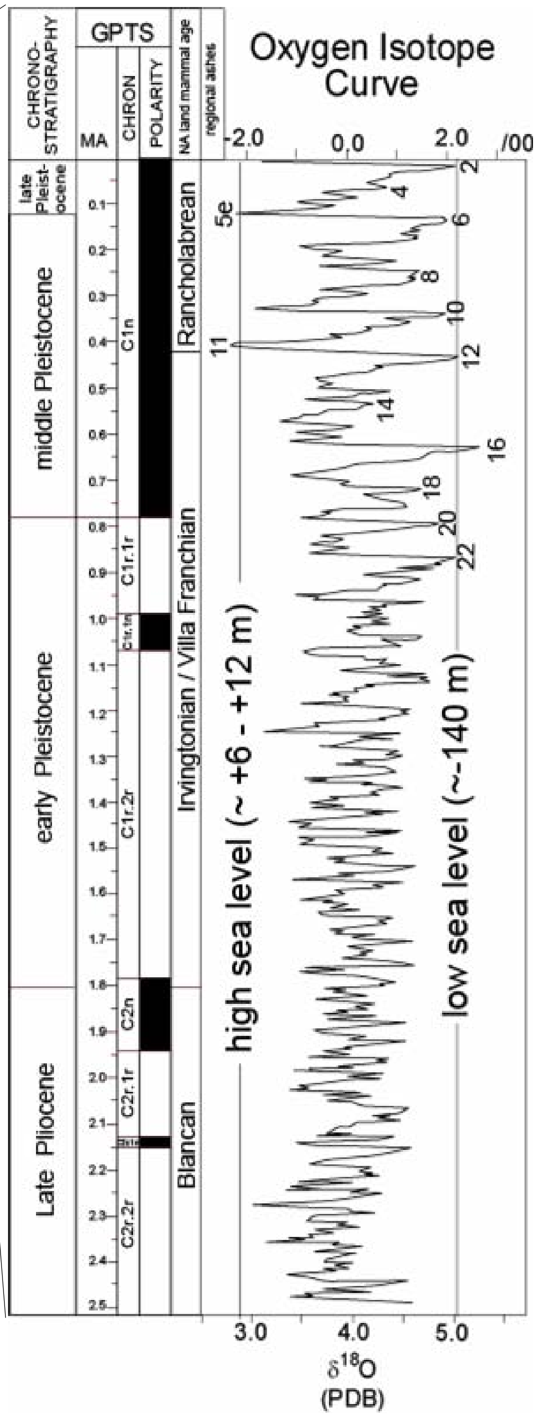

Bryn Mawr Fm m-l Miocene
300
250
200
150
100
50
0
elevation (m)
0
100
200
300
400
kilometers from Fall Zone (km)
Fall Zone
Susquehanna River
R
P
J

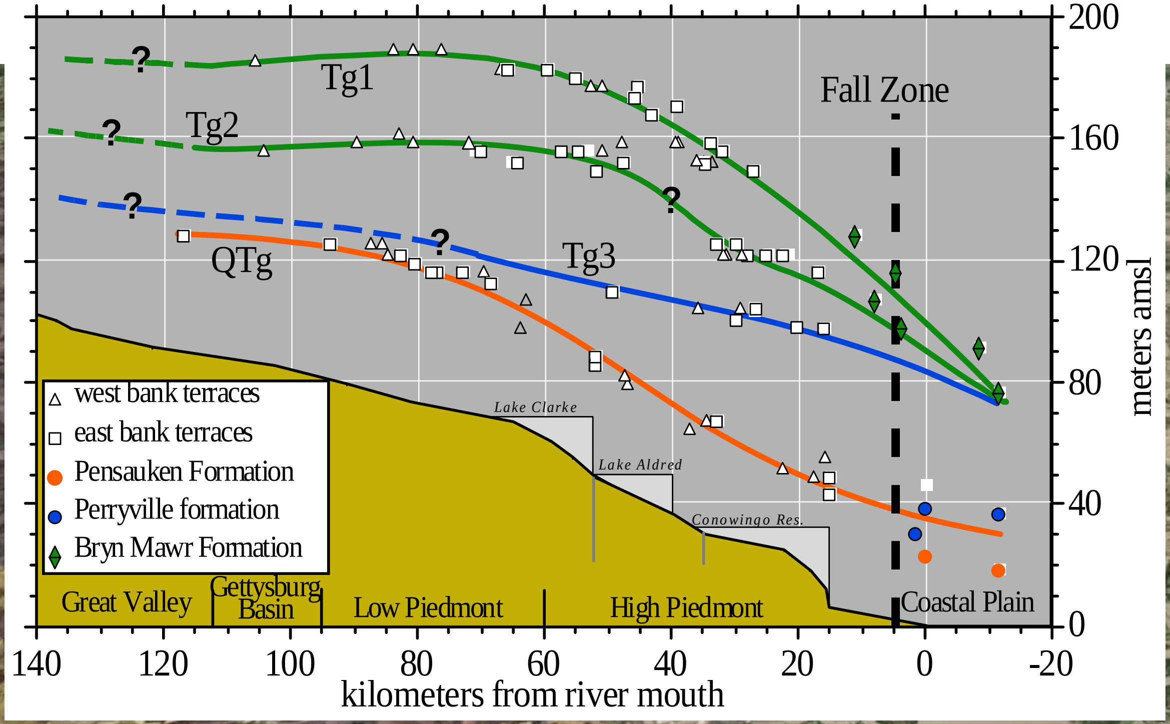


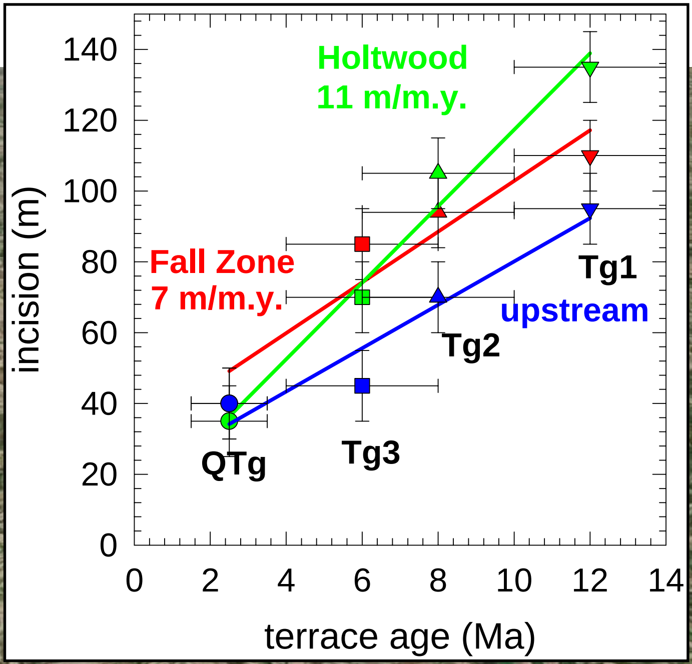
http://palaeo-electronica.org/1999_2/neptune/images/fig4_20.gif



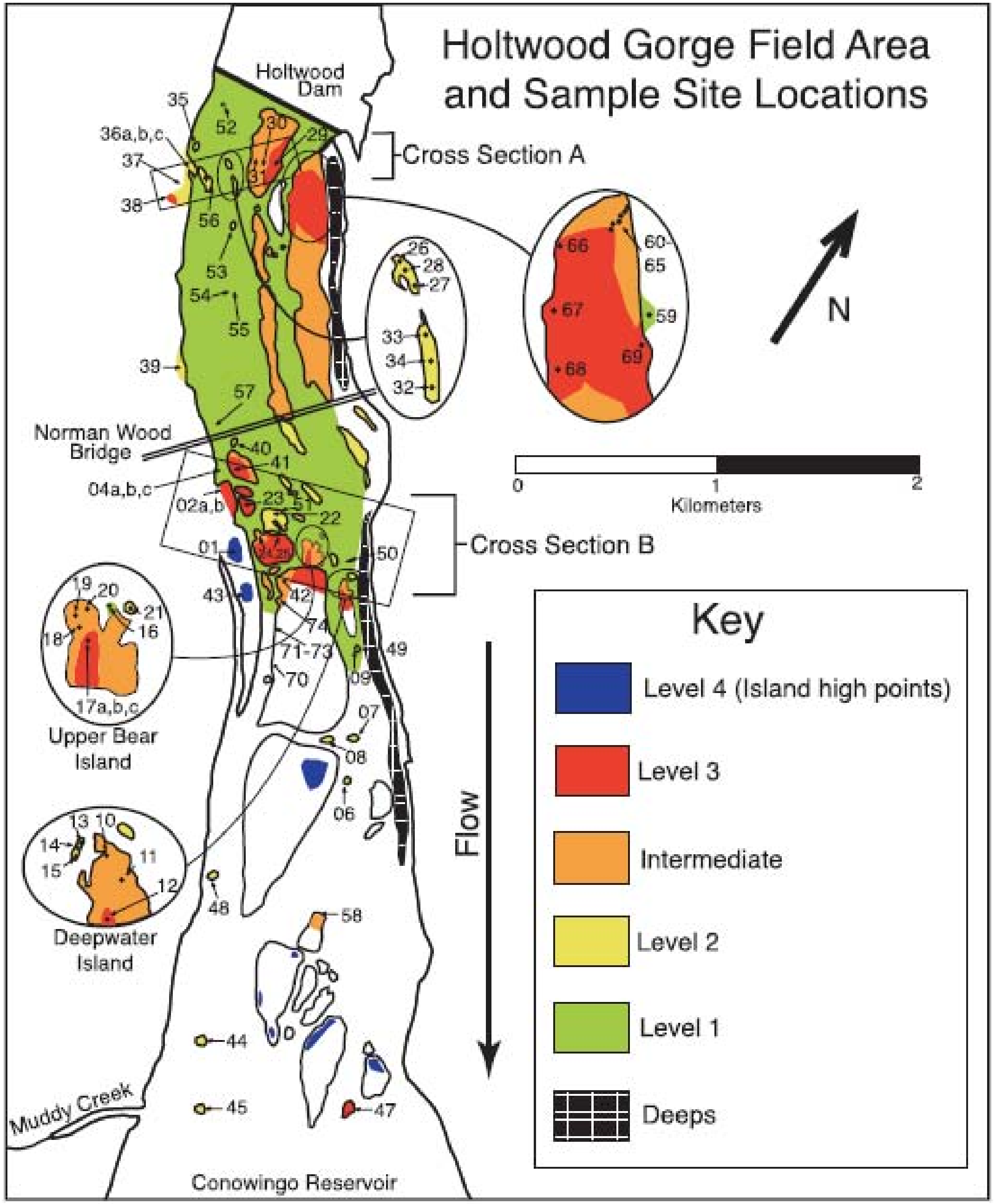
http://geology.rutgers.edu/kgm/kgmsequences.jpg

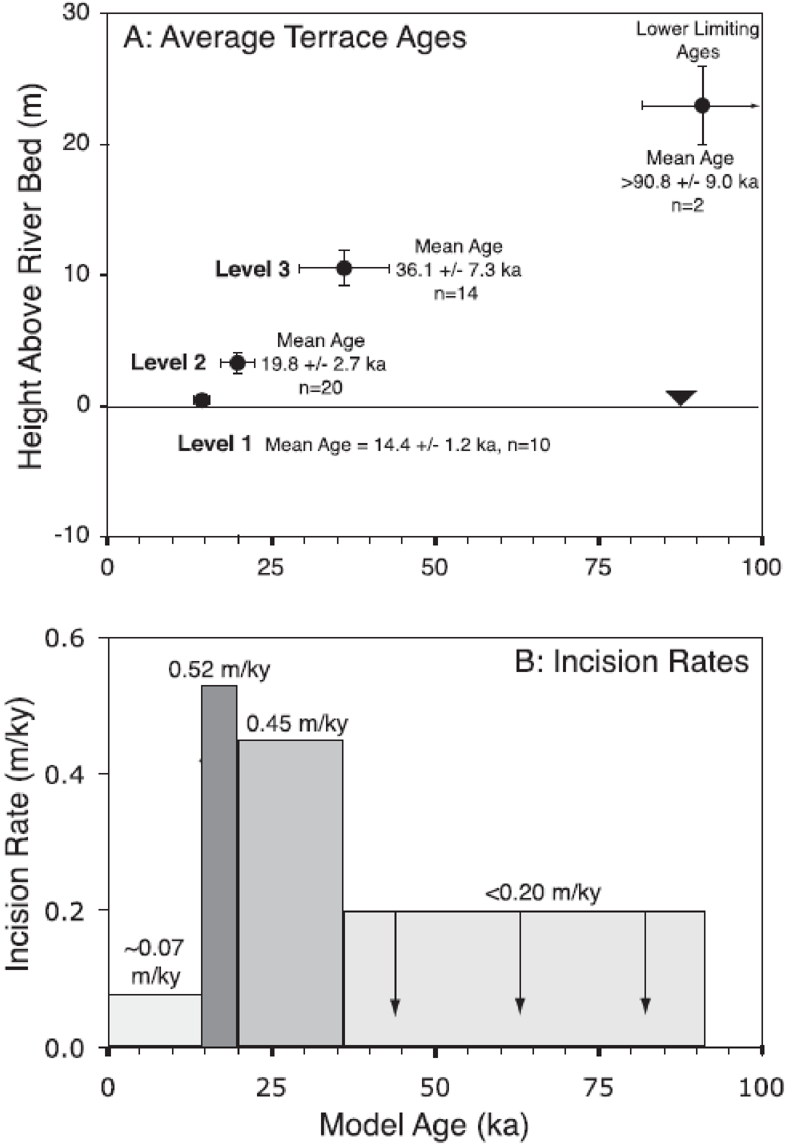






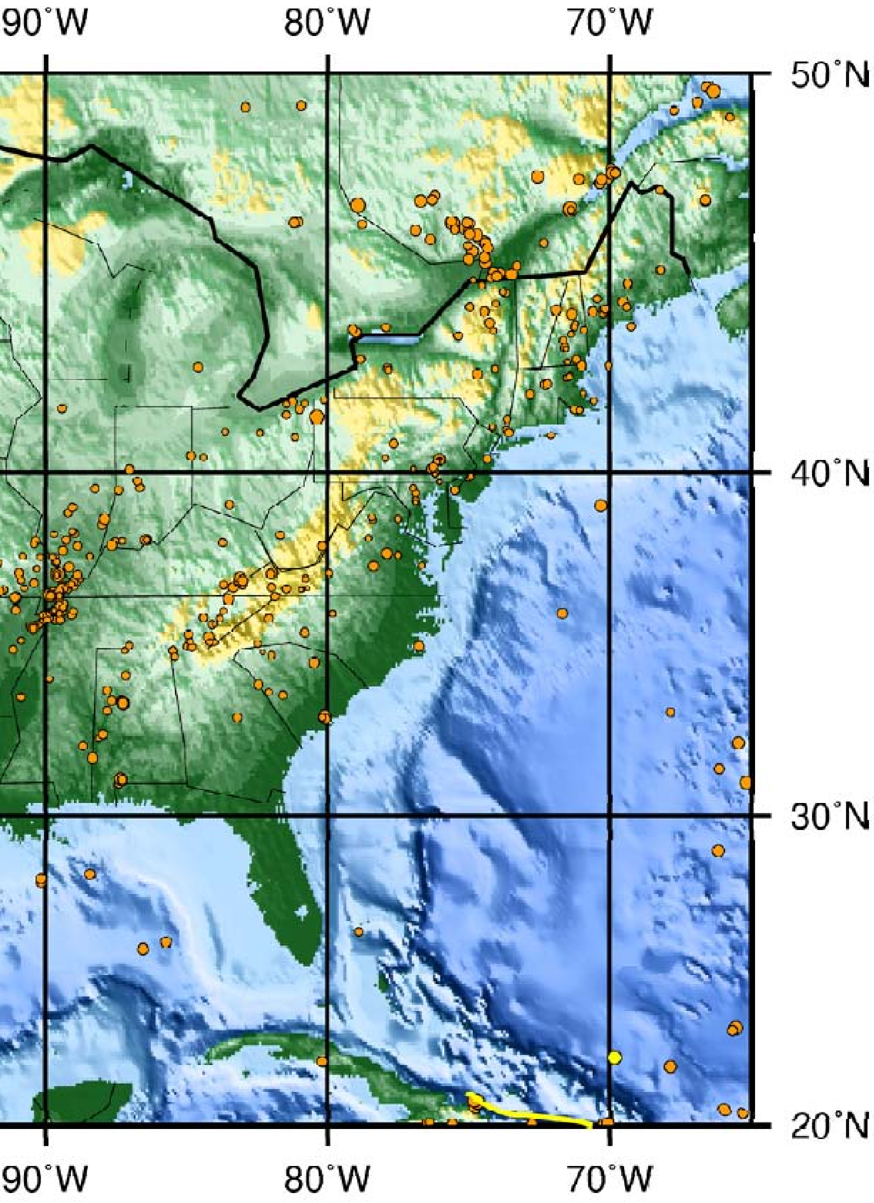
Pazzaglia, F. J. and Gardner, T. W., 1993, Geomorphology, 8, 83-113.

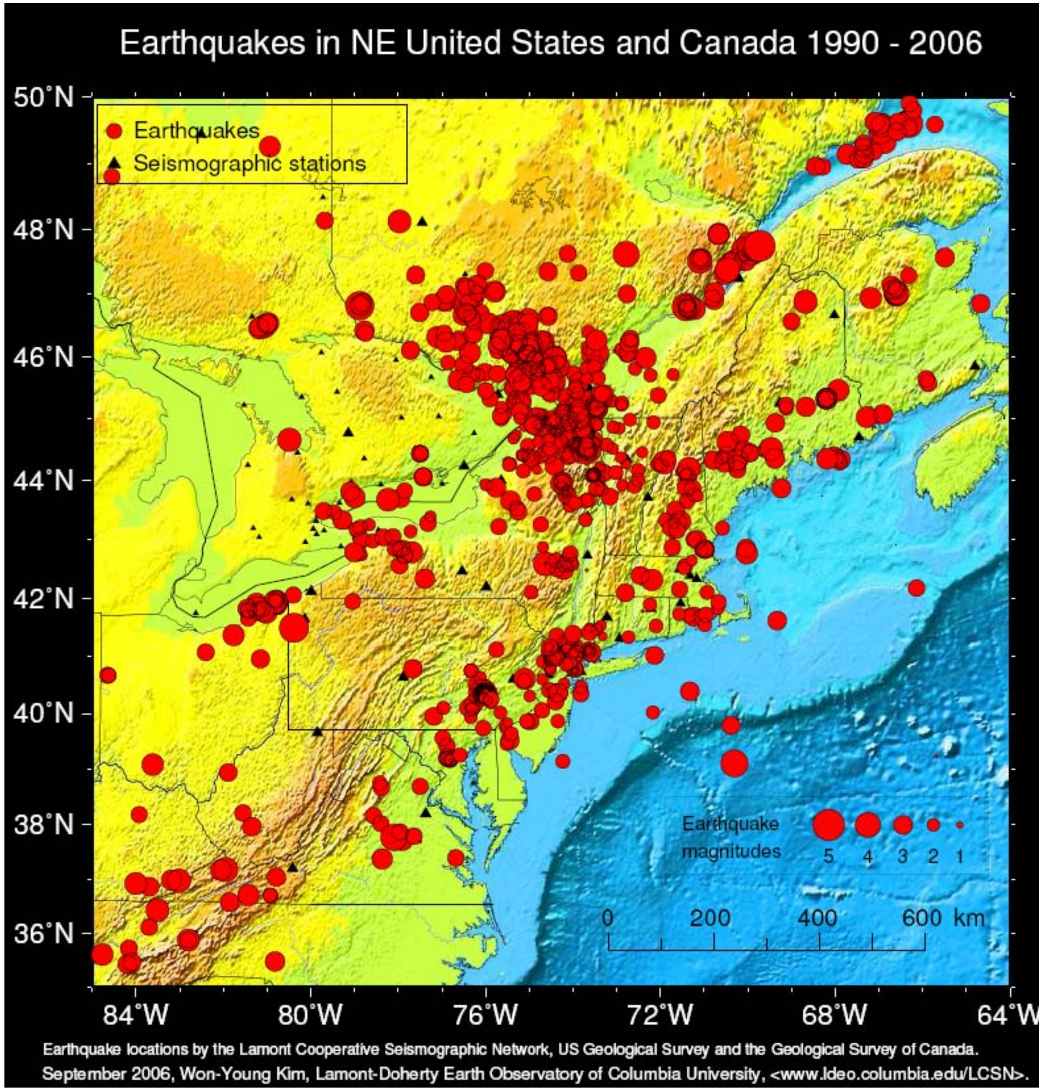




Reusser et al. 2006, AJS, 306, 69-102.

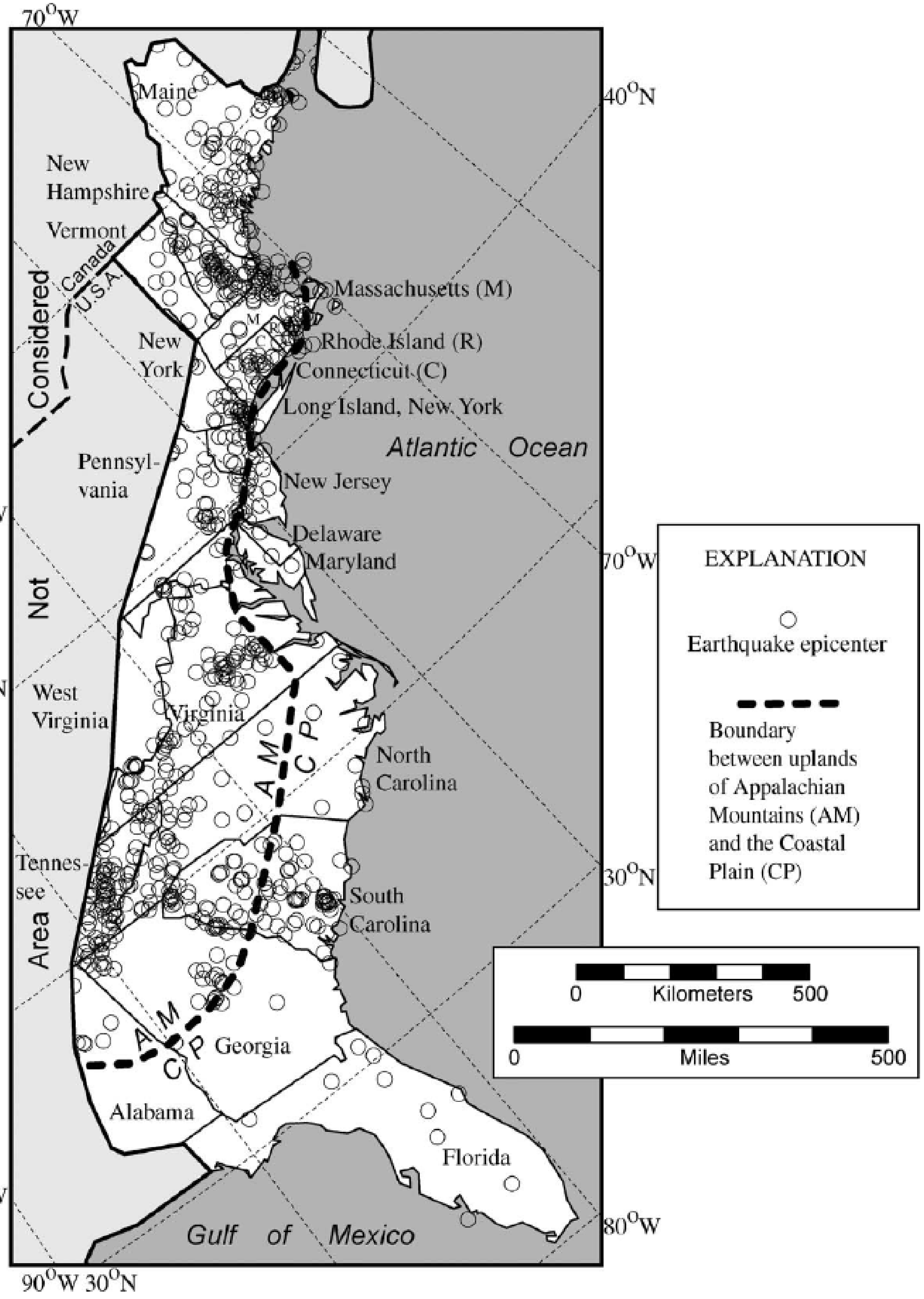
1990-2000

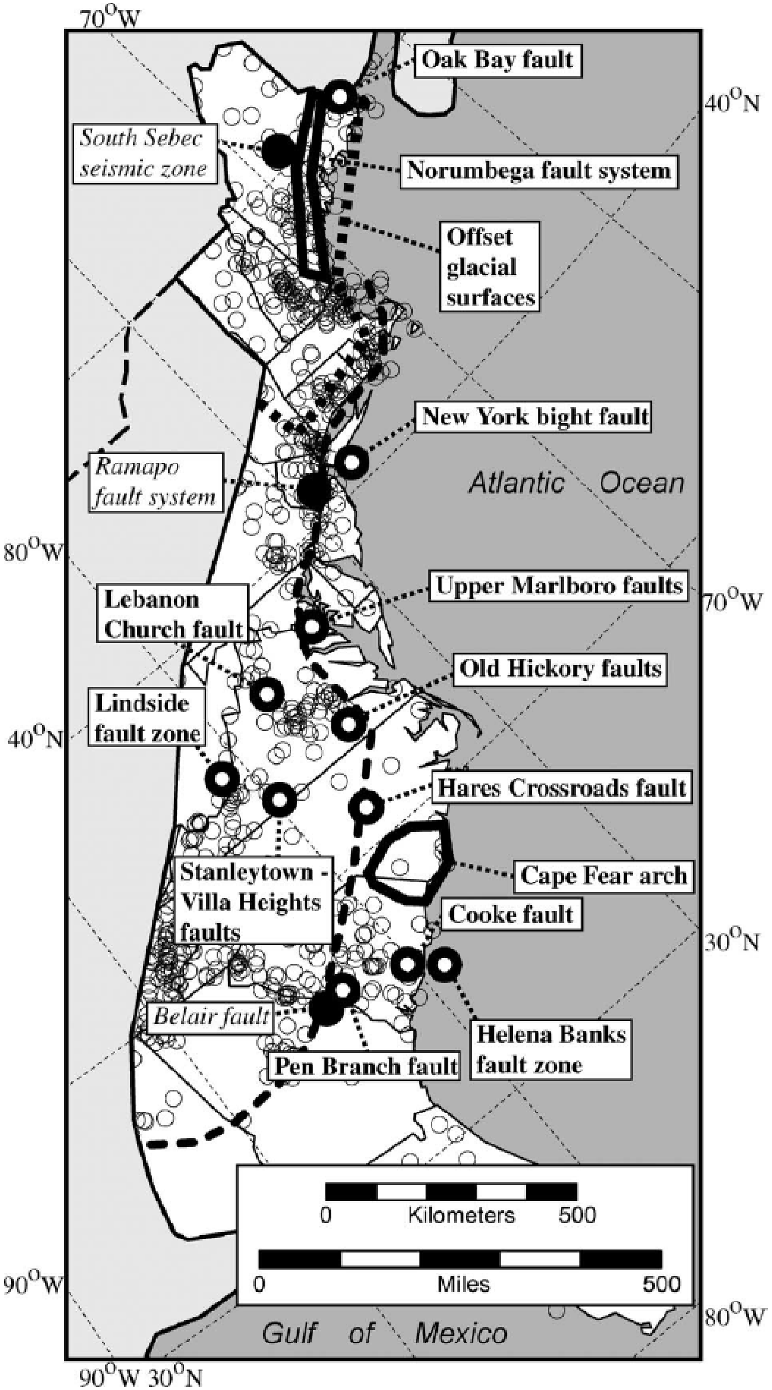




Earthquake locations by the Lamont Cooperative Seismographic Network, US Geological Survey and the Geological Survey of Canada. September 2006, Won-Young Kim, Lamont-Doherty Earth Observatory of Columbia University, <www.ldeo.columbia.edu/LCSN>.

http://earthquake.usgs.gov/regional/states/seismicity/us_east_seismicity.php



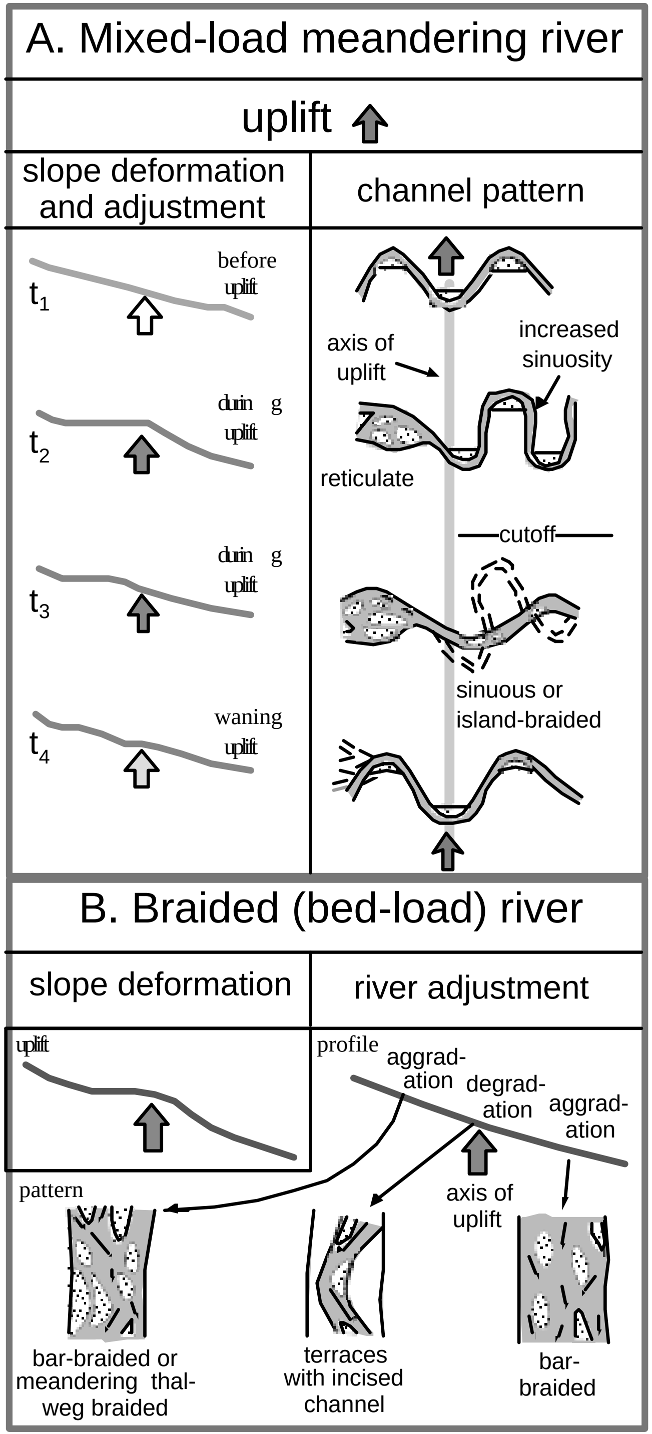


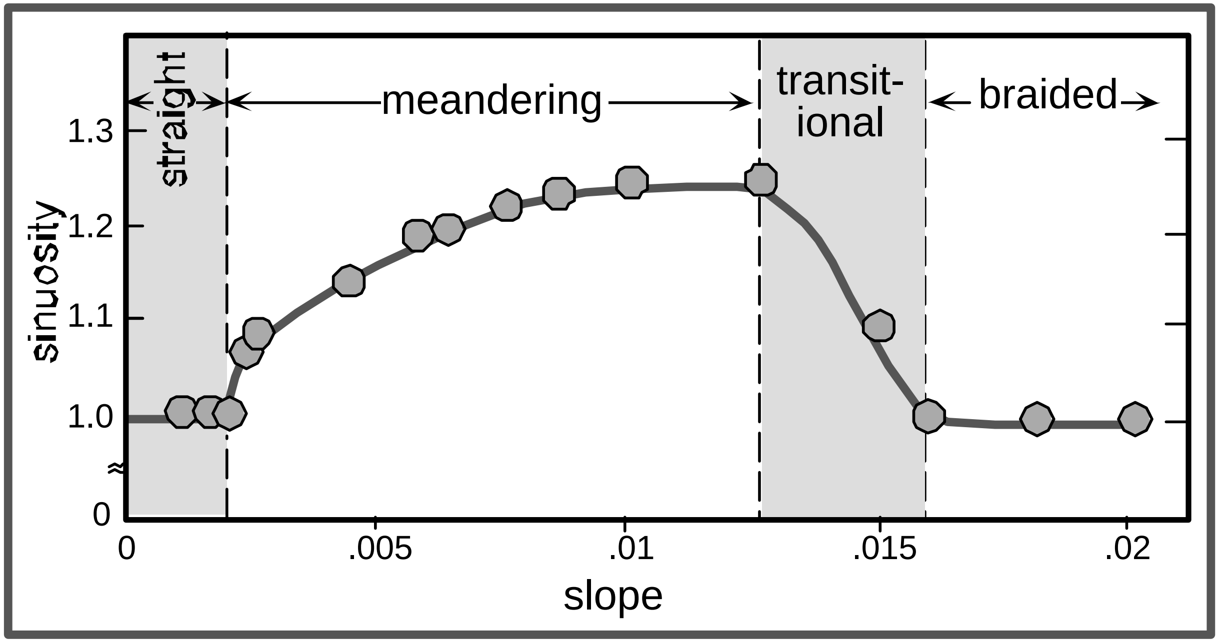
Wheeler, 2006, Engineering Geology, 82, 165-186.

…but would you be able to find…

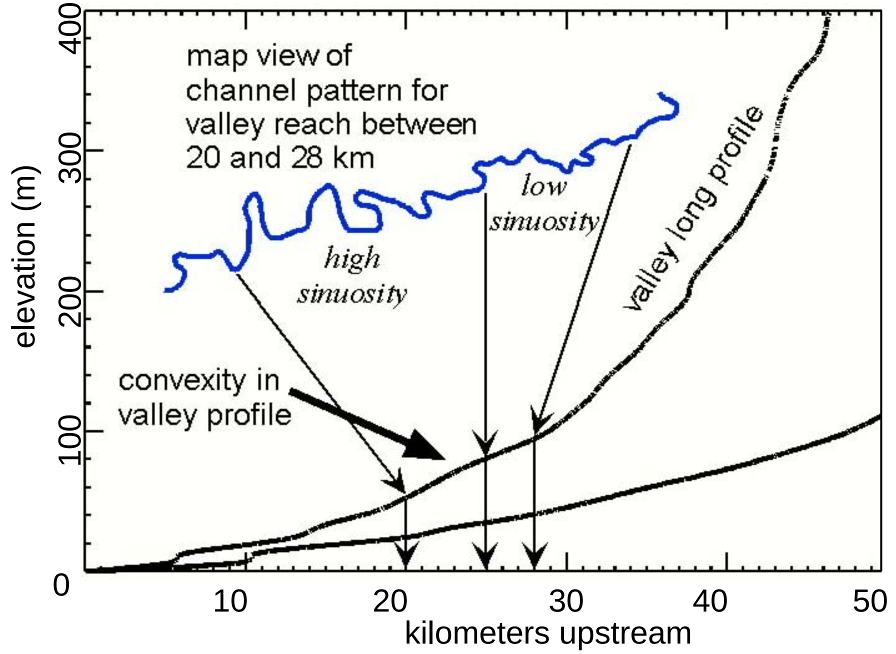

somewhere in the Po Plain

...an active fault in a landscape like this?

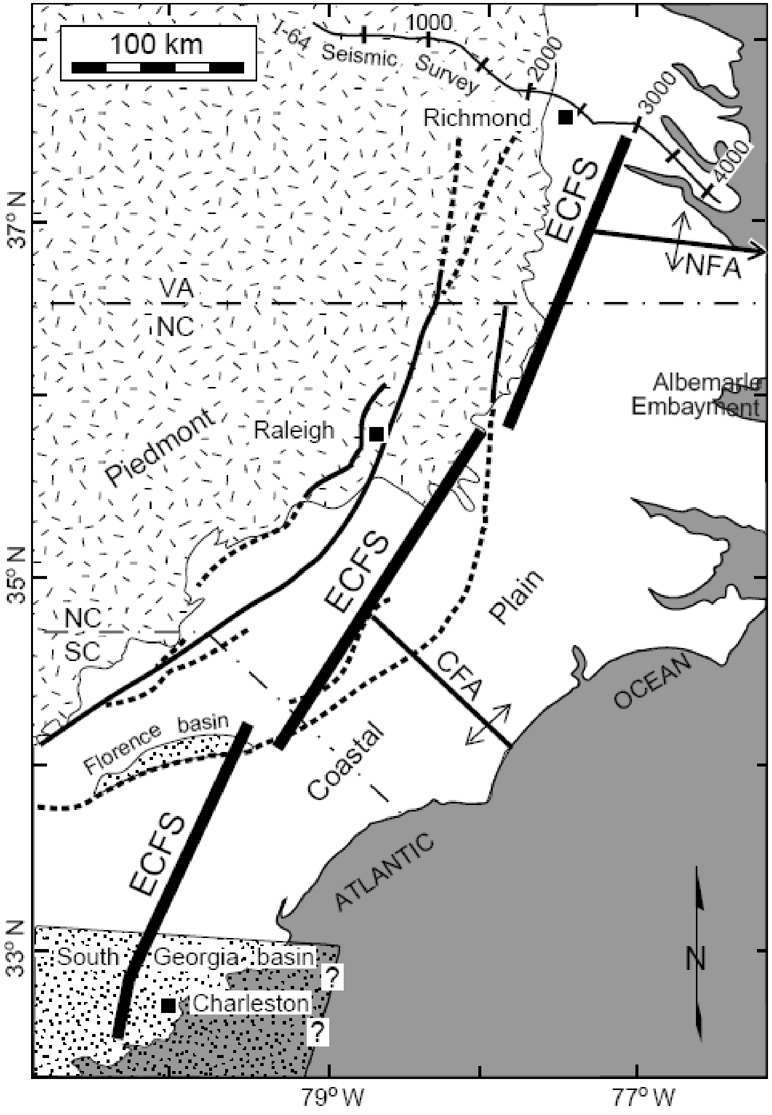


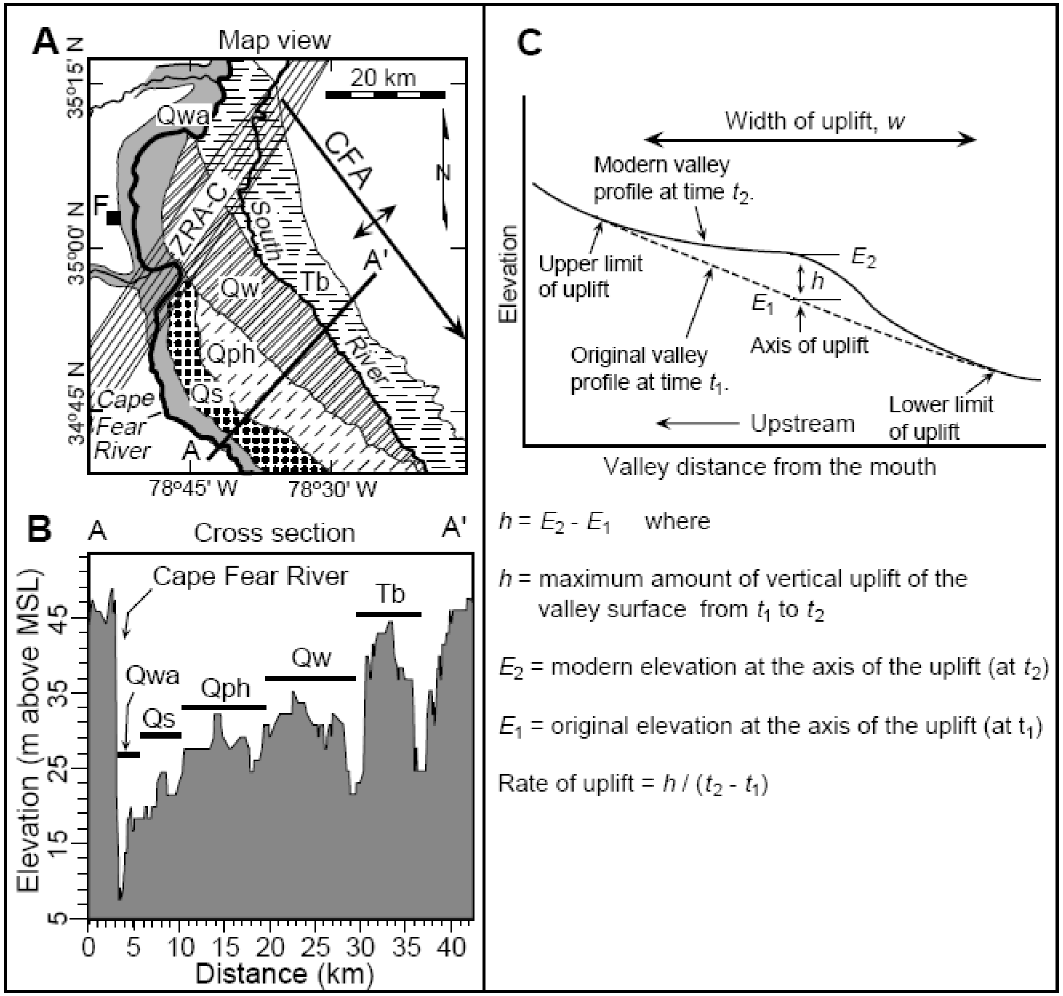


(from Burbank and Anderson, Tectonic Geomorphology,
modified from Ouchi, 1985 and Schumm et al., 1987)



Pazzaglia and Brandon, 2001, AJS





$h = E_2 - E_1$ where

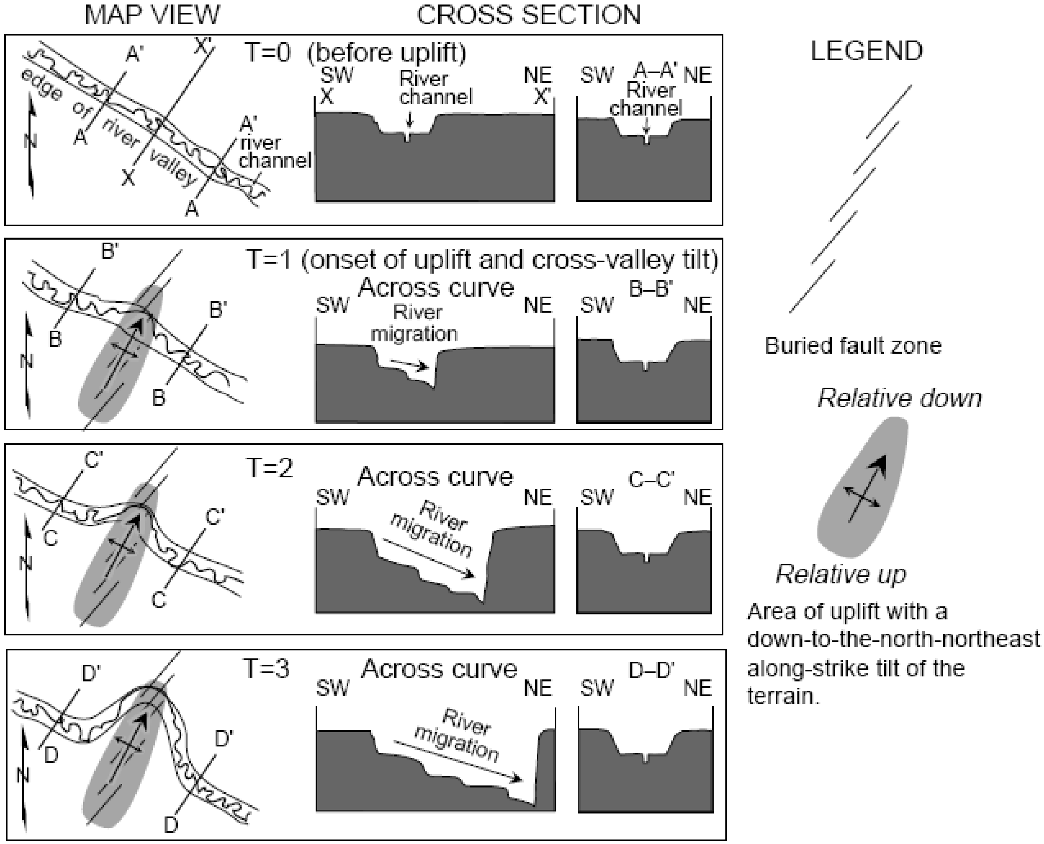
h = maximum amount of vertical uplift of the valley surface from t_1 to t_2

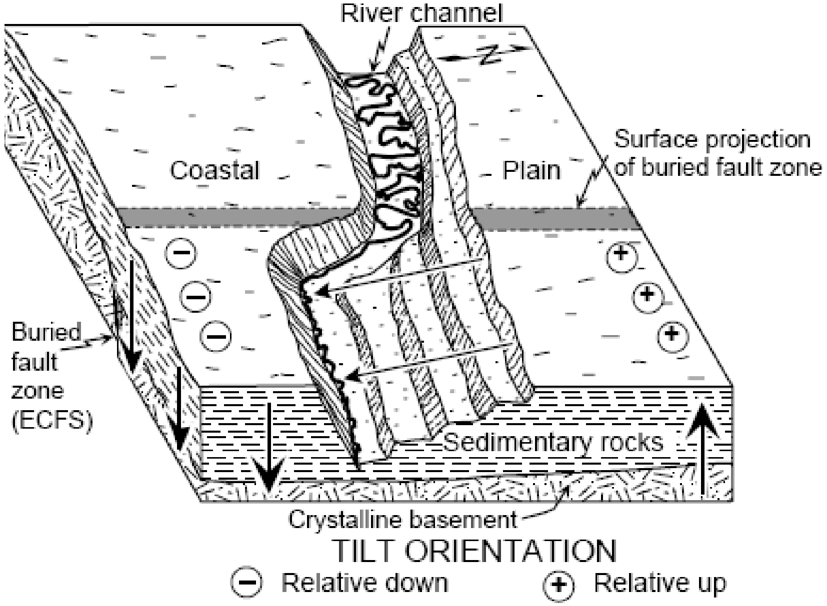
E_2 = modern elevation at the axis of the uplift (at t_2)

E_1 = original elevation at the axis of the uplift (at t_1)

Rate of uplift = $h / (t_2 - t_1)$

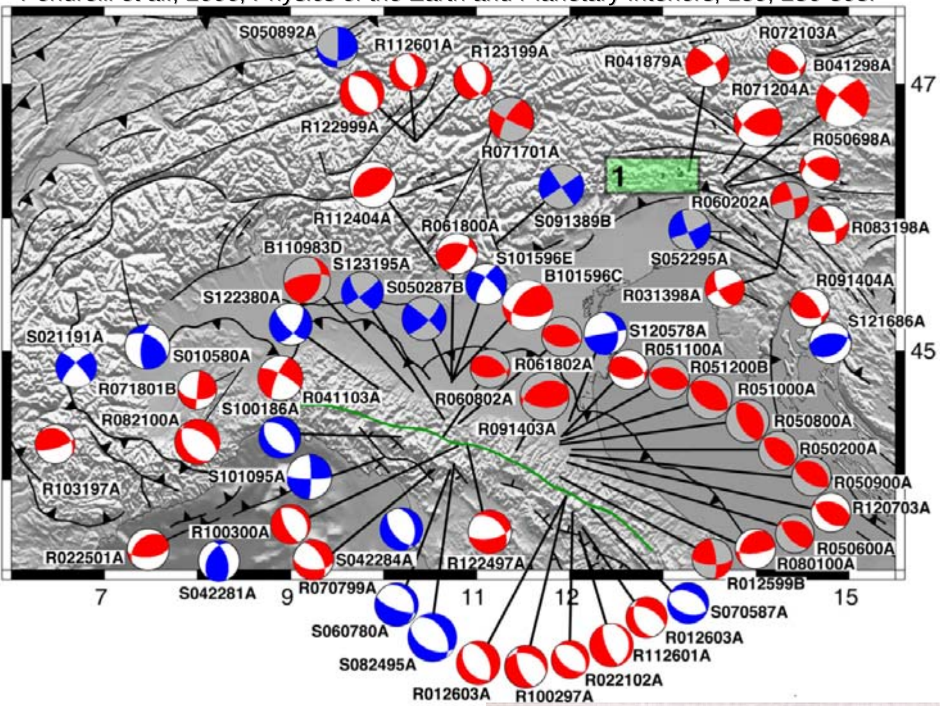
Marple R. and Talwani, P., 2000, GSABull 112, 200-220.

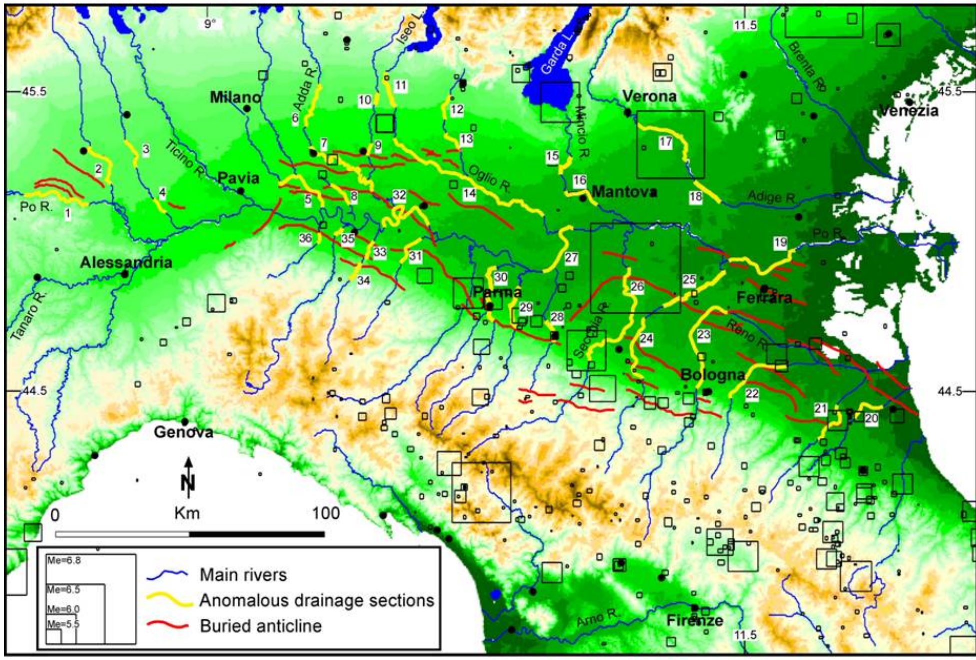




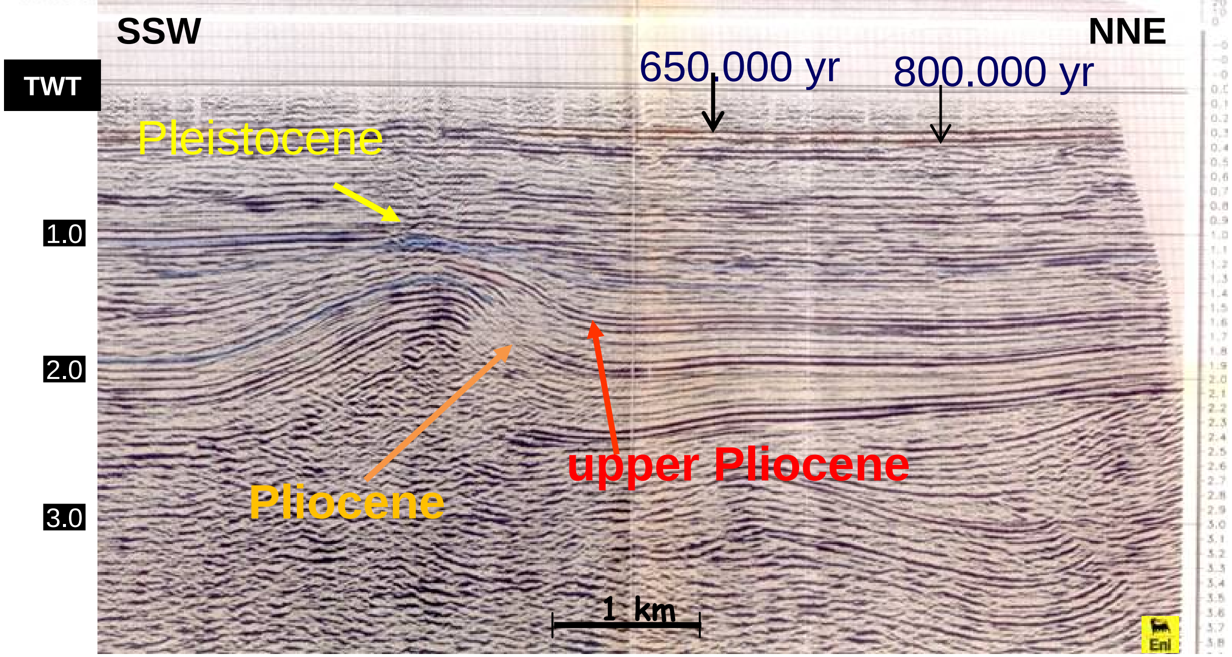
Marple R. and Talwani, P., 2000, GSABull 112, 200-220.

Pondrelli et al., 2006, Physics of the Earth and Planetary Interiors, 159, 286-303.

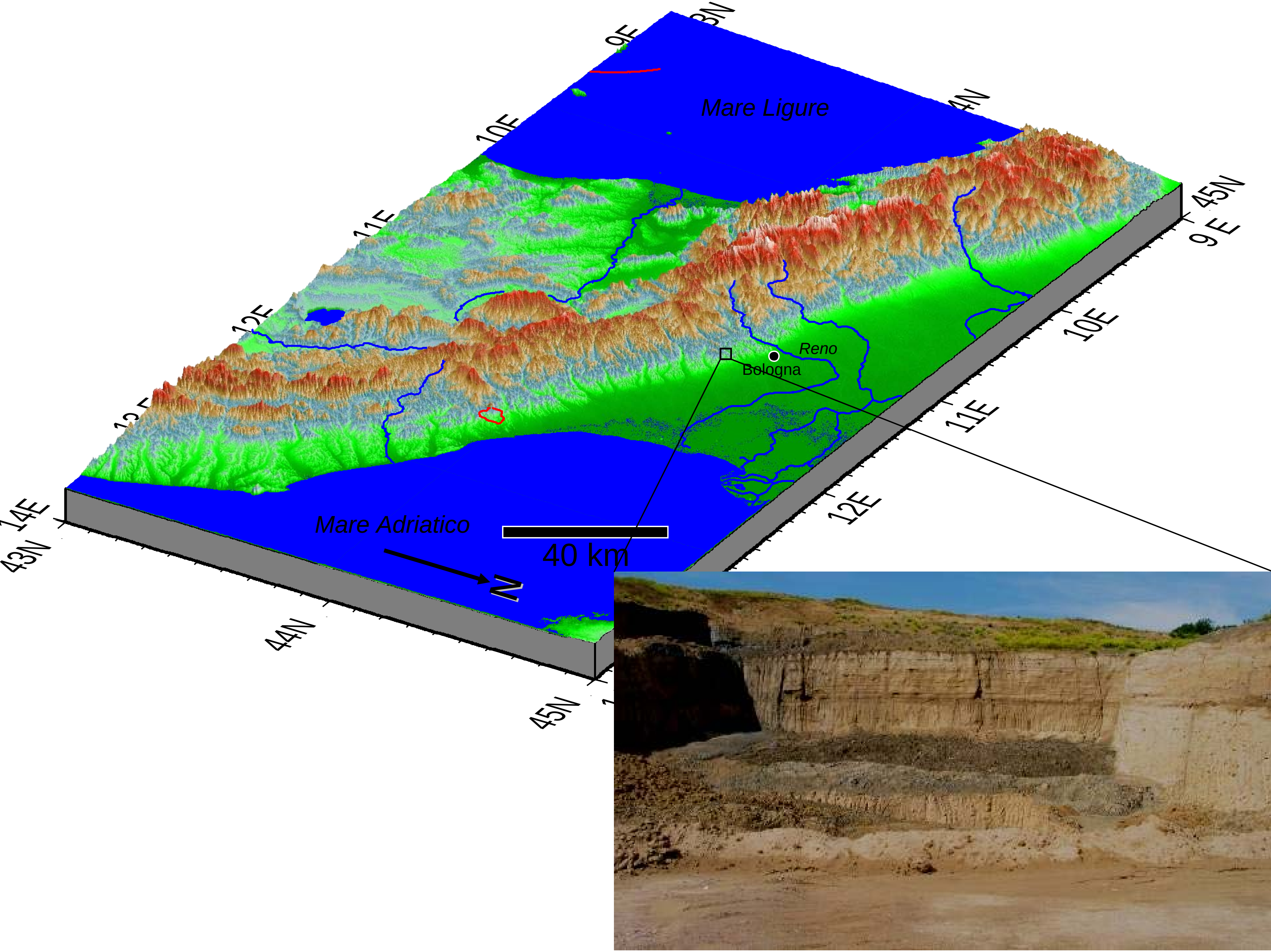


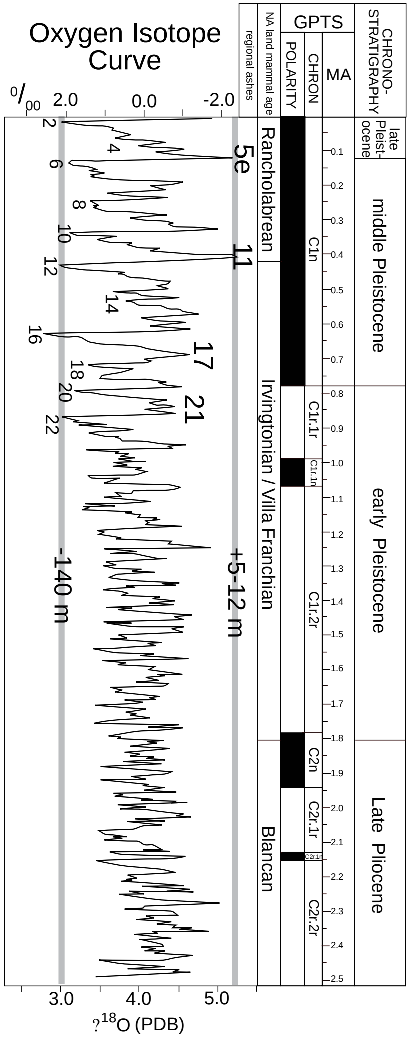


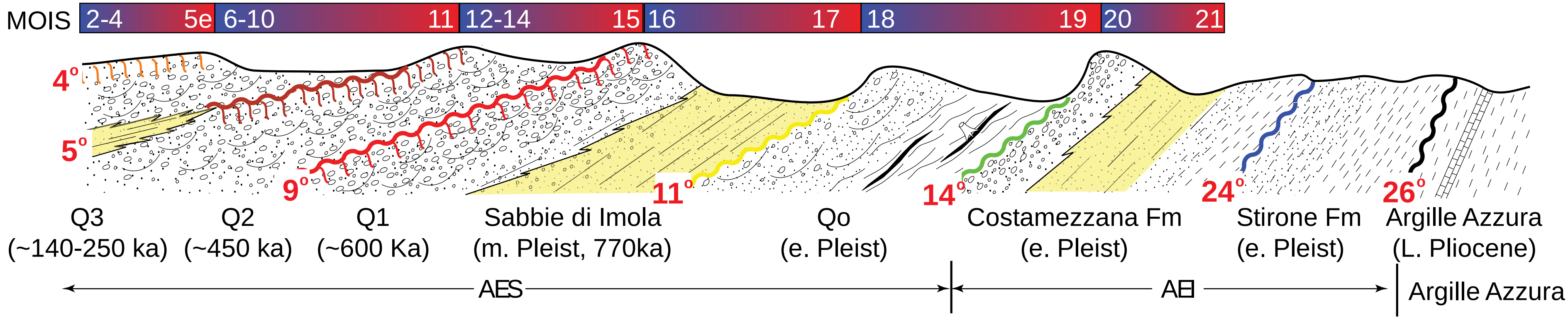
🟦	Main rivers
🟨	Anomalous drainage sections
🟥	Buried anticline

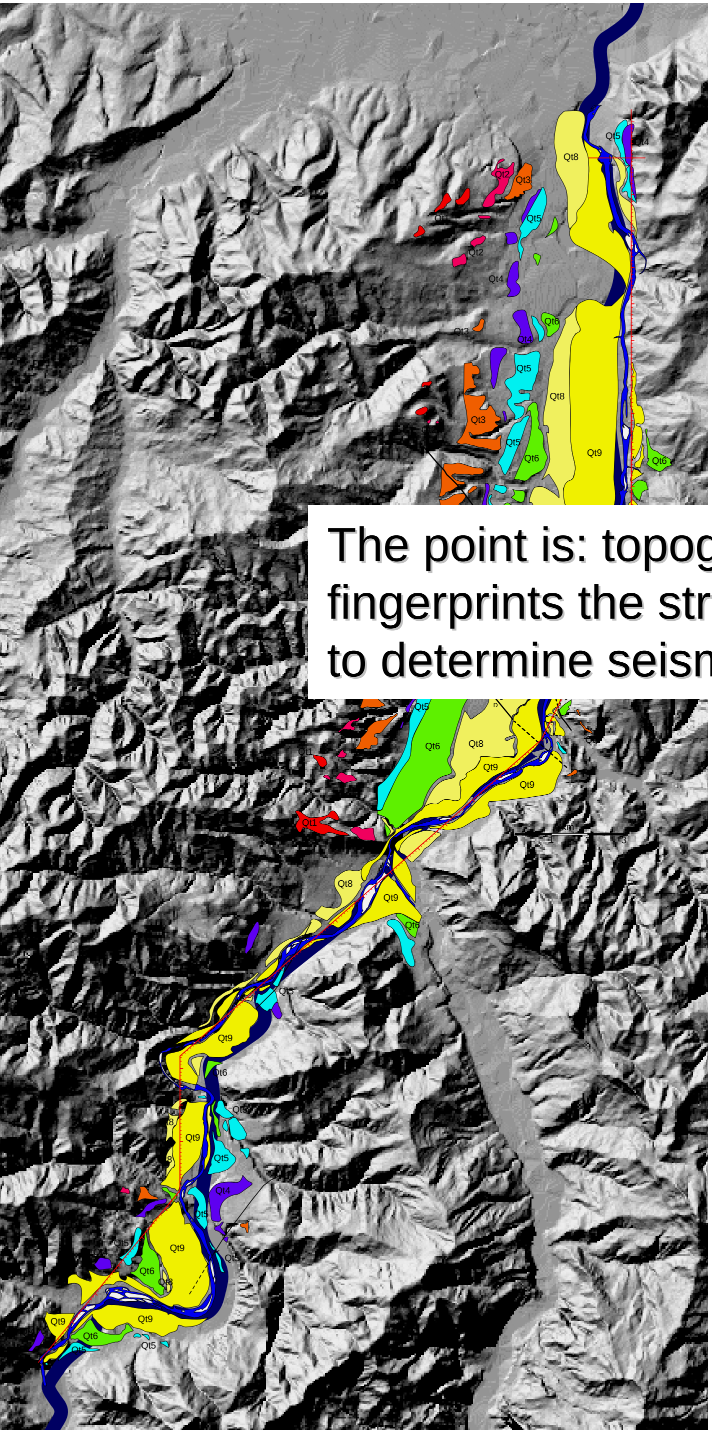


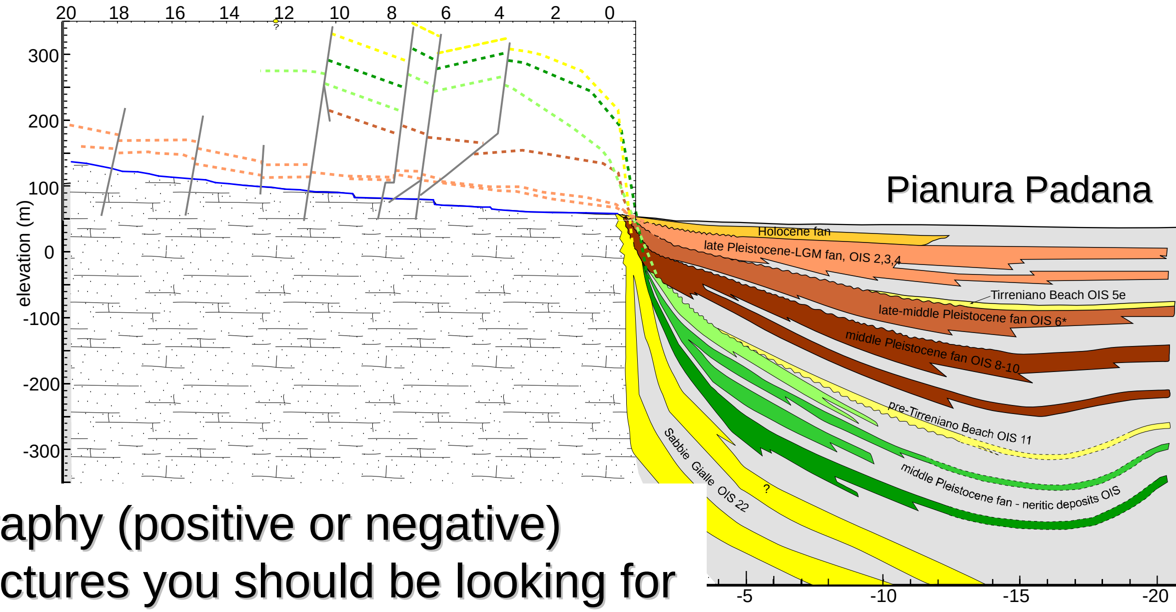
Burrato et al., 2003, Annals of Geophysics, 46, 865-882.


Mare Ligure
Mare Adriatico
Bologna
Reno
40 km
N
9E
10E
11E
12E
14E
43N
44N
45N
45N
9 E
10E
11E
12E

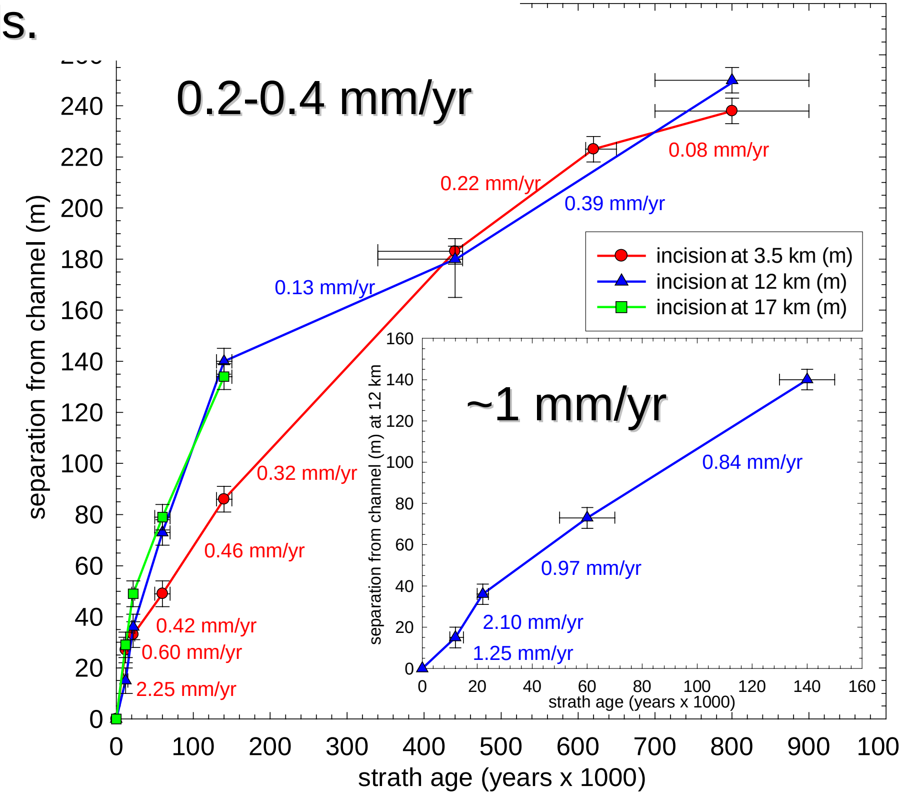

Oxygen Isotope Curve
0/00 2.0 0.0 -2.0
regional ashes
NA land mammal age
GPTS
POLARITY
CHRON
MA
CHRONO-STRATIGRAPHY
late Pleist-ocene
middle Pleistocene
early Pleistocene
Late Pliocene
Rancholabrean
Irvingtonian / Villa Franchian
Blancan
C1n
C1r.1r
C1r.1n
C1r.2r
C2n
C2r.1r
C2r.1n
C2r.2r
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2
4
5e
6
8
10
11
12
14
16
17
18
20
21
22
-140 m
+5-12 m
3.0
4.0
5.0
?18O (PDB)


MOIS
2-4
5e
6-10
11
12-14
15
16
17
18
19
20
21
4°
5°
9°
11°
14°
24°
26°
Q3
(~140-250 ka)
Q2
(~450 ka)
Q1
(~600 Ka)
Sabbie di Imola
(m. Pleist, 770ka)
Qo
(e. Pleist)
Costamezzana Fm
(e. Pleist)
Stirone Fm
(e. Pleist)
Argille Azzura
(L. Pliocene)
AES
AEI
Argille Azzura

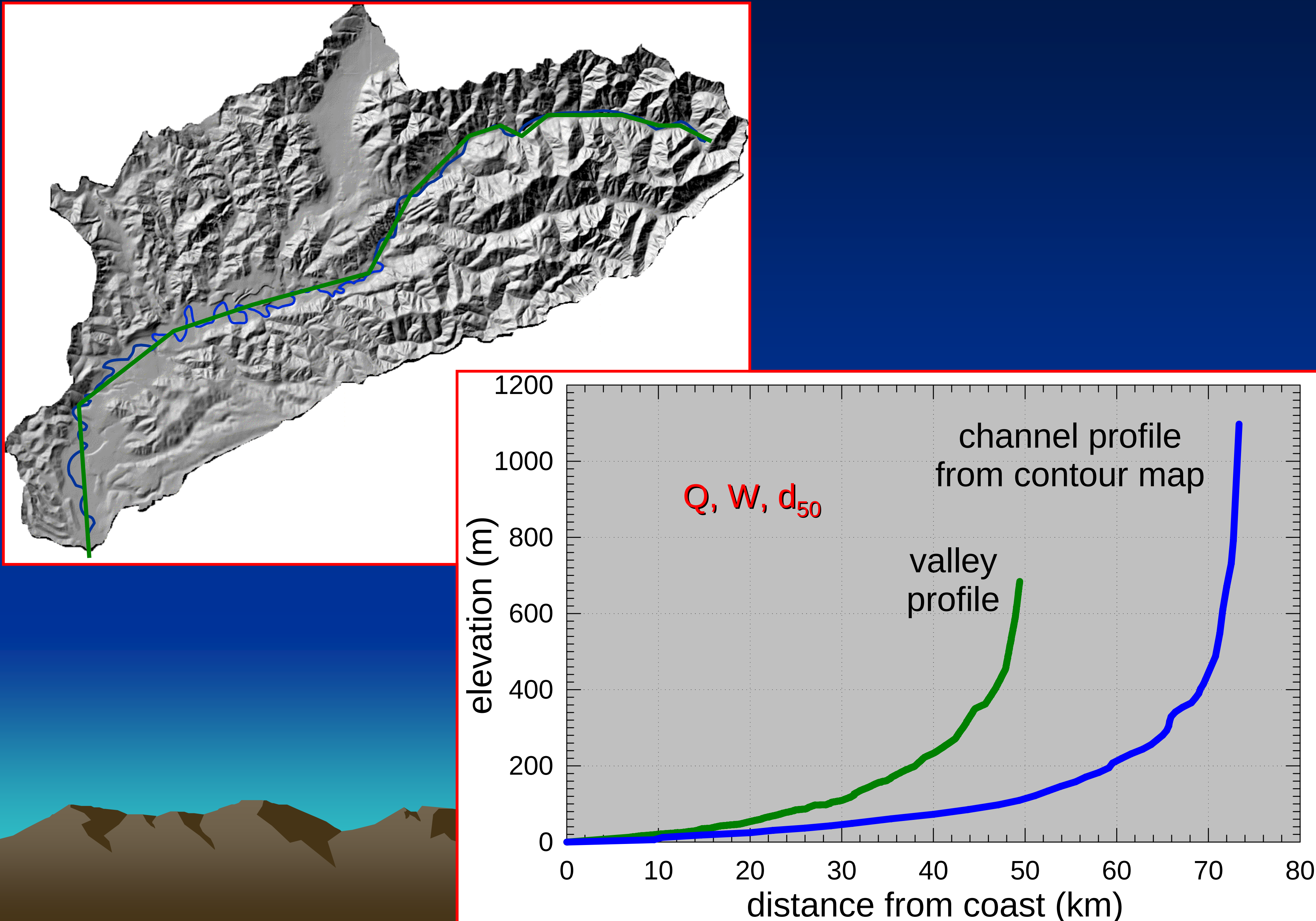


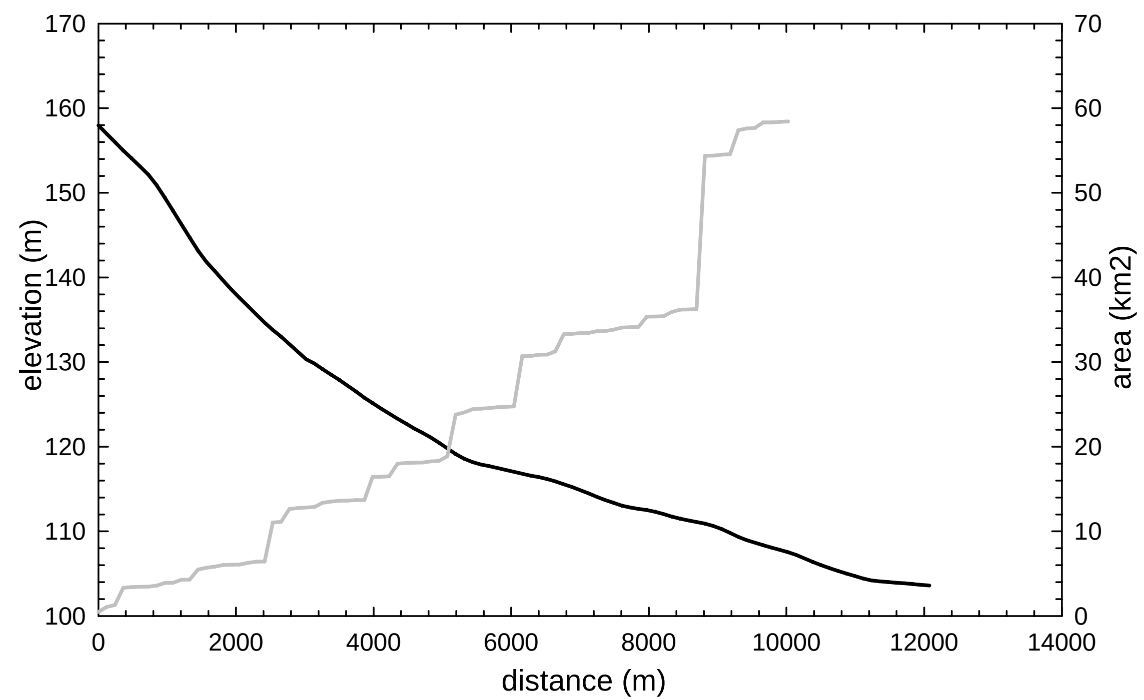


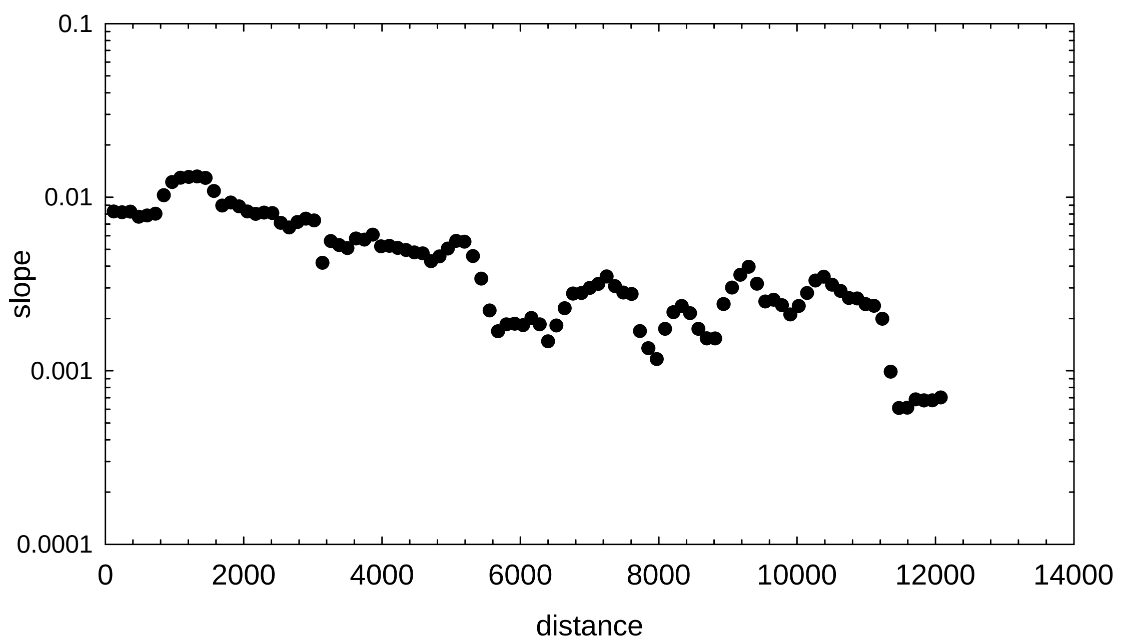
The point is: topography (positive or negative) fingerprints the structures you should be looking for to determine seismic hazards.



Long profiles




elevation (m)
area (km2)
distance (m)
170
160
150
140
130
120
110
100
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
14000


slope
distance
0.1
0.01
0.001
0.0001
0
2000
4000
6000
8000
10000
12000
14000

Hack et al., 1973, USGS J. Research

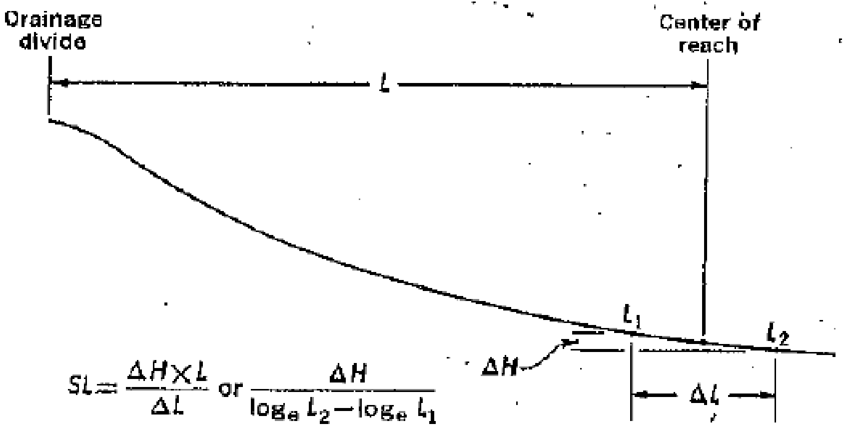


Figure 1.—Measured parameters used in calculation of gradient index. Symbols are defined in text.

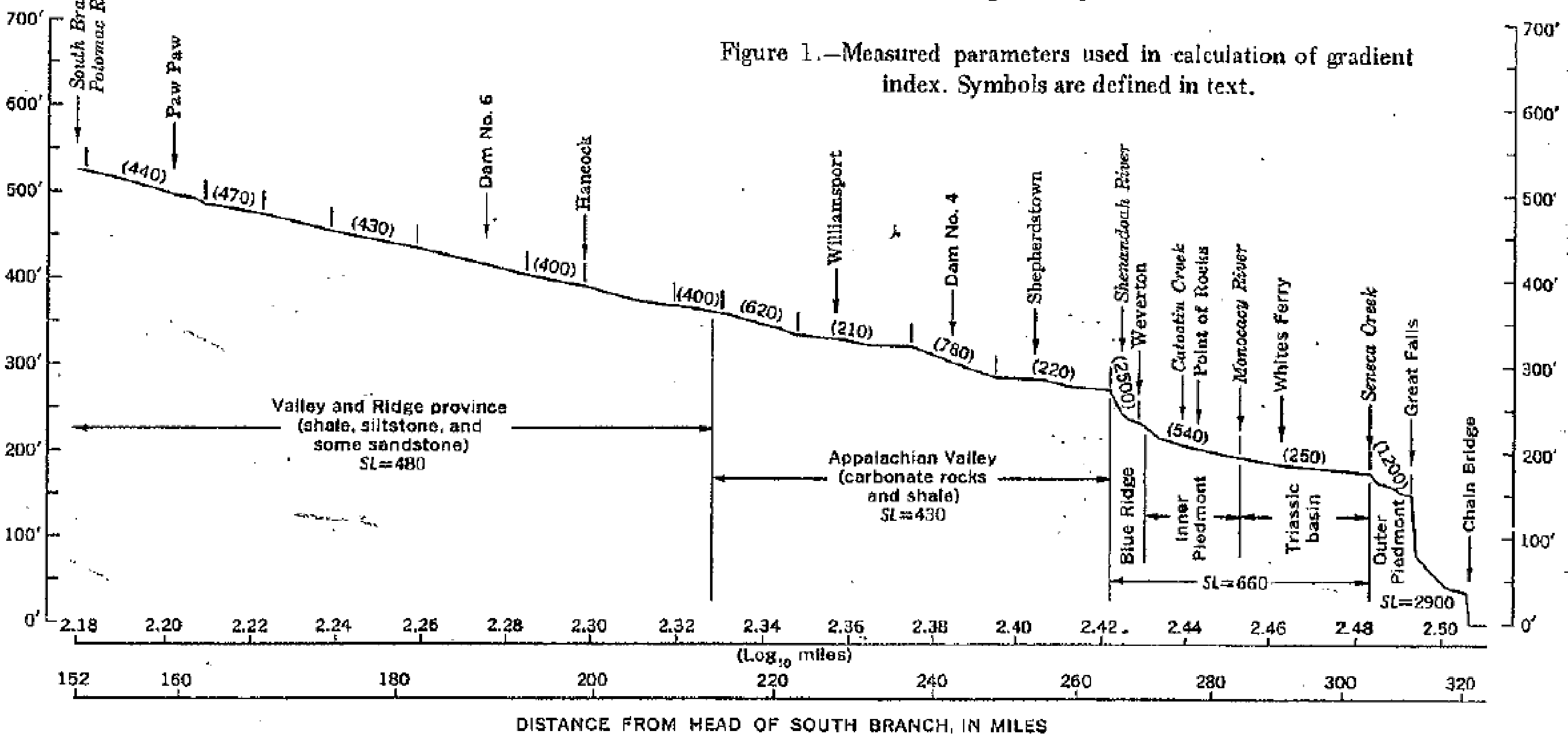
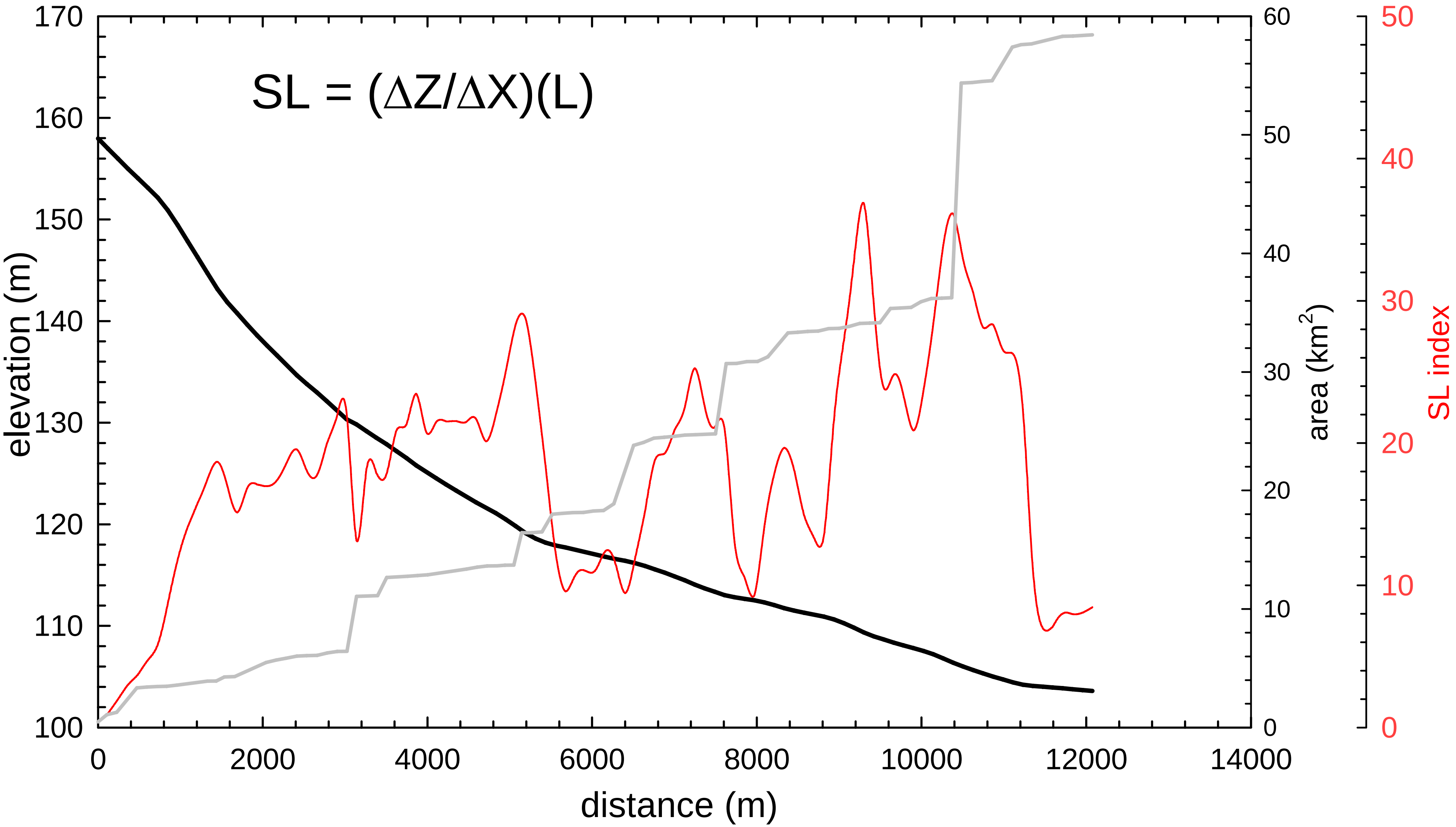
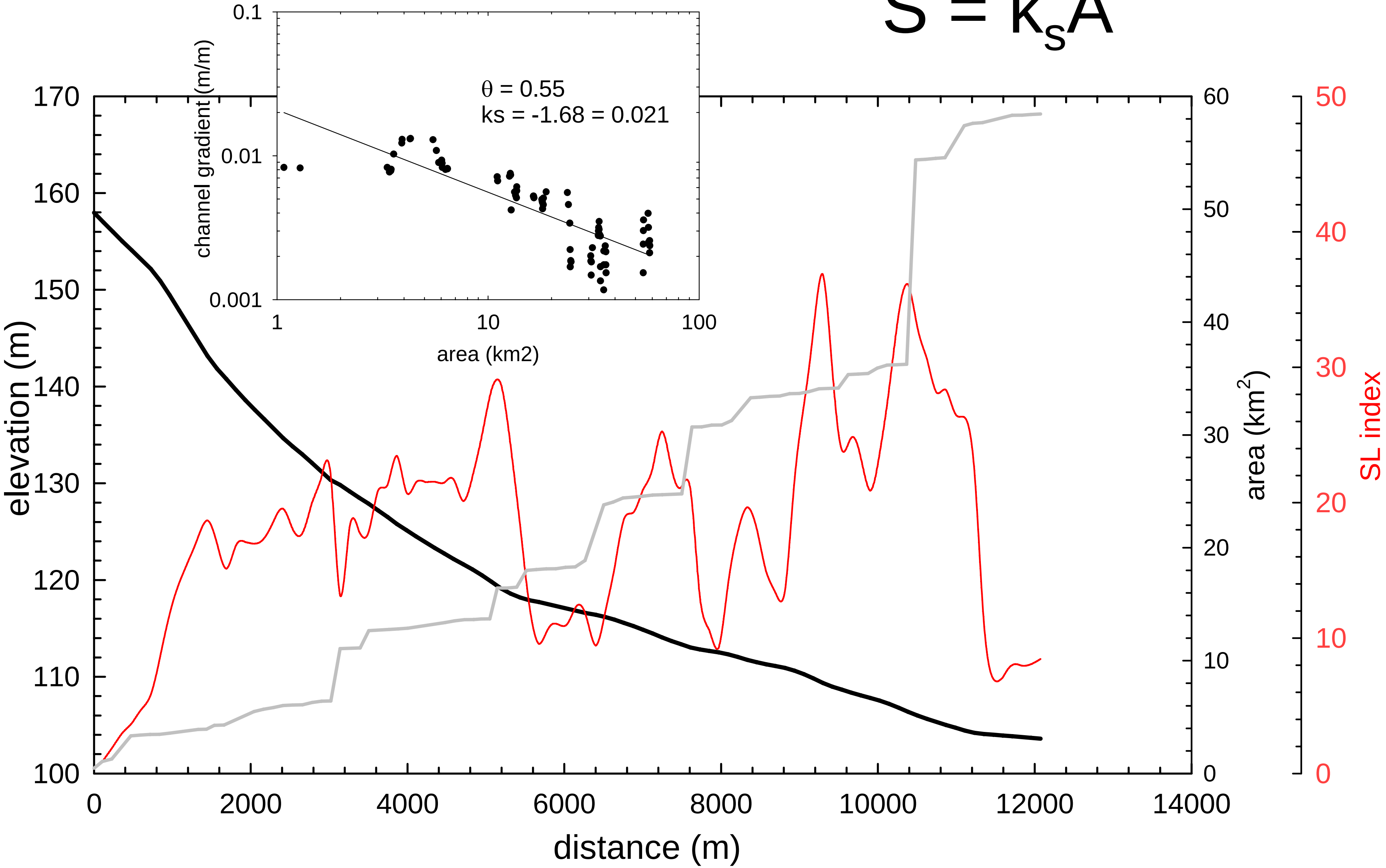


Figure 6.—Profile of the Potomac River from its junction with the South Branch to Washington, D.C. Data from Somervell, 1929 (see footnote 1). Gradient index in parentheses.


SL = (ΔZ/ΔX)(L)
elevation (m)
170
160
150
140
130
120
110
100
distance (m)
0
2000
4000
6000
8000
10000
12000
14000
area (km²)
60
50
40
30
20
10
0
SL index
50
40
30
20
10
0

$$S = k_s A^{-\theta}$$


θ = 0.55
ks = -1.68 = 0.021
channel gradient (m/m)
0.1
0.01
0.001
1
10
100
area (km2)
elevation (m)
170
160
150
140
130
120
110
100
0
2000
4000
6000
8000
10000
12000
14000
distance (m)
area (km^2)
60
50
40
30
20
10
0
SL index
50
40
30
20
10
0

Modeling bedrock incision

(1) $$E = k_b \tau_b^a$$

$1 < a < 5/2$

(2) $$\tau_b = \rho_w C_f^{1/3} \left[\frac{gSQ}{W} \right]^{2/3}$$

C_f = dimensionless friction factor

(3) $$Q = k_q A^c$$

c ~ 1 for small, steep drainages

(4) $$W = k_w Q^b = k_w k_q^b A^{bc}$$

b ~ 0.5

combine with conservation of mass and steady, uniform flow ***Q=WhU***

(5) $$E = KA^m S^n$$

$m/n = c(1-b)$

Snyder et al., 2000, GSABull, 112, 1250-1263. Calibration：Stock and Montgomery, 1999, JGR, 104, 4983-4993.

Much has been said about this equation and we have not heard the final word. It has been an honest, exploratory attempt to reduce the complexities of a system we do not fully understand into a useful, simple expression that describes incision. Many of the earlier calibration studies assumed uniform incision (uplift) and an equilibrium (graded) profile…..we are motivated to calibrate and extract useful tectonic information where incision (uplift) is not uniform along the profile.

The equilibrium (steady-state) profile

(6) $$\frac{\partial z}{\partial t} = U - KA^m S^n$$

Rate of change of channel bed elevation
= rate of uplift – incision rate

(7) $$S_e = \left(\frac{U}{K}\right)^{1/n} A^{-m/n}$$

When *dz/dt* = 0, *Se* = equilibrium slope

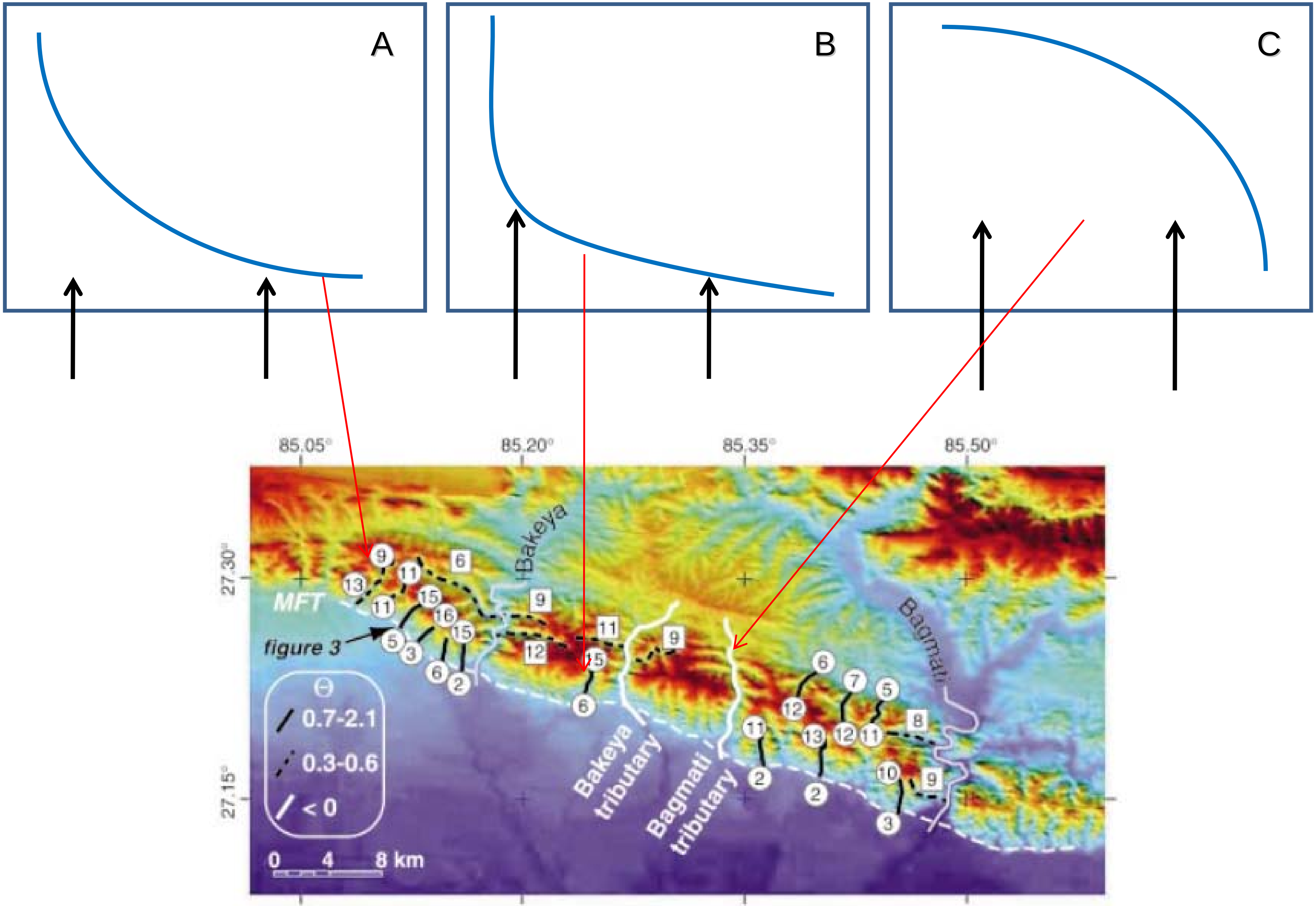
(8) $$S = k_s A^{-\theta}$$

k_s is the profile steepness
~ stream gradient index of Hack (1973, USGS J of Res.)

θ is the profile concavity
~ 0.3 – 0.6 (Hack 1957, USGS PP 294, 45-97)

…. Tested in the field by the rate of incision reconstructed from terraces

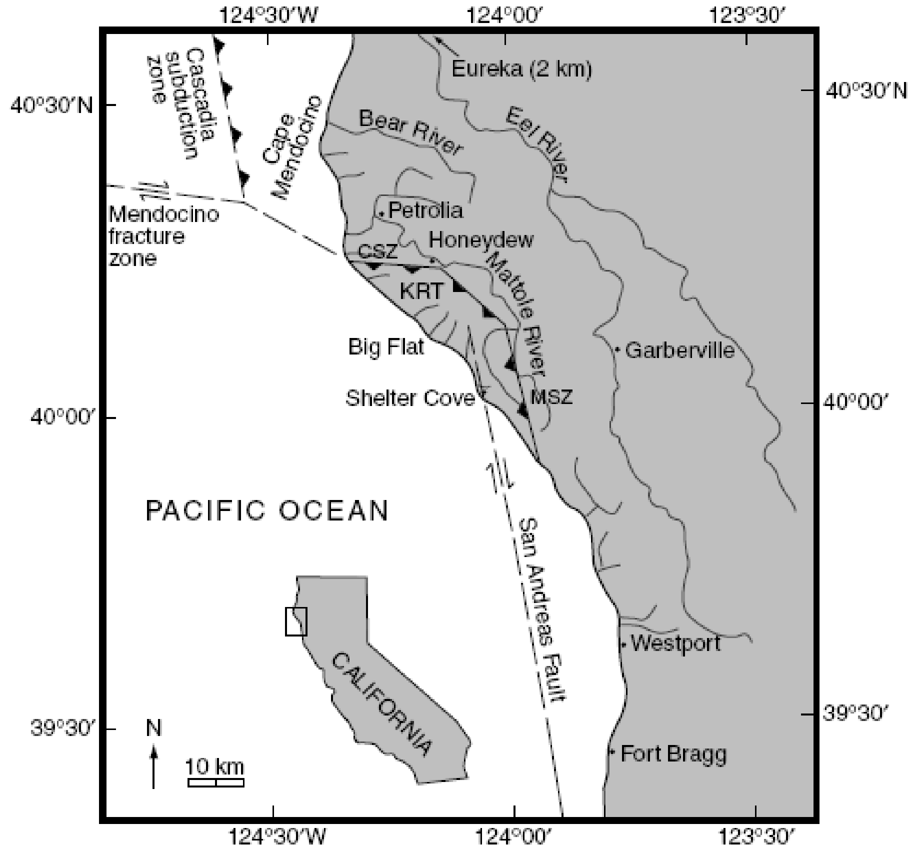
Tectonic effects on concavity…note MOST studies argue for uniform uplift (case A)

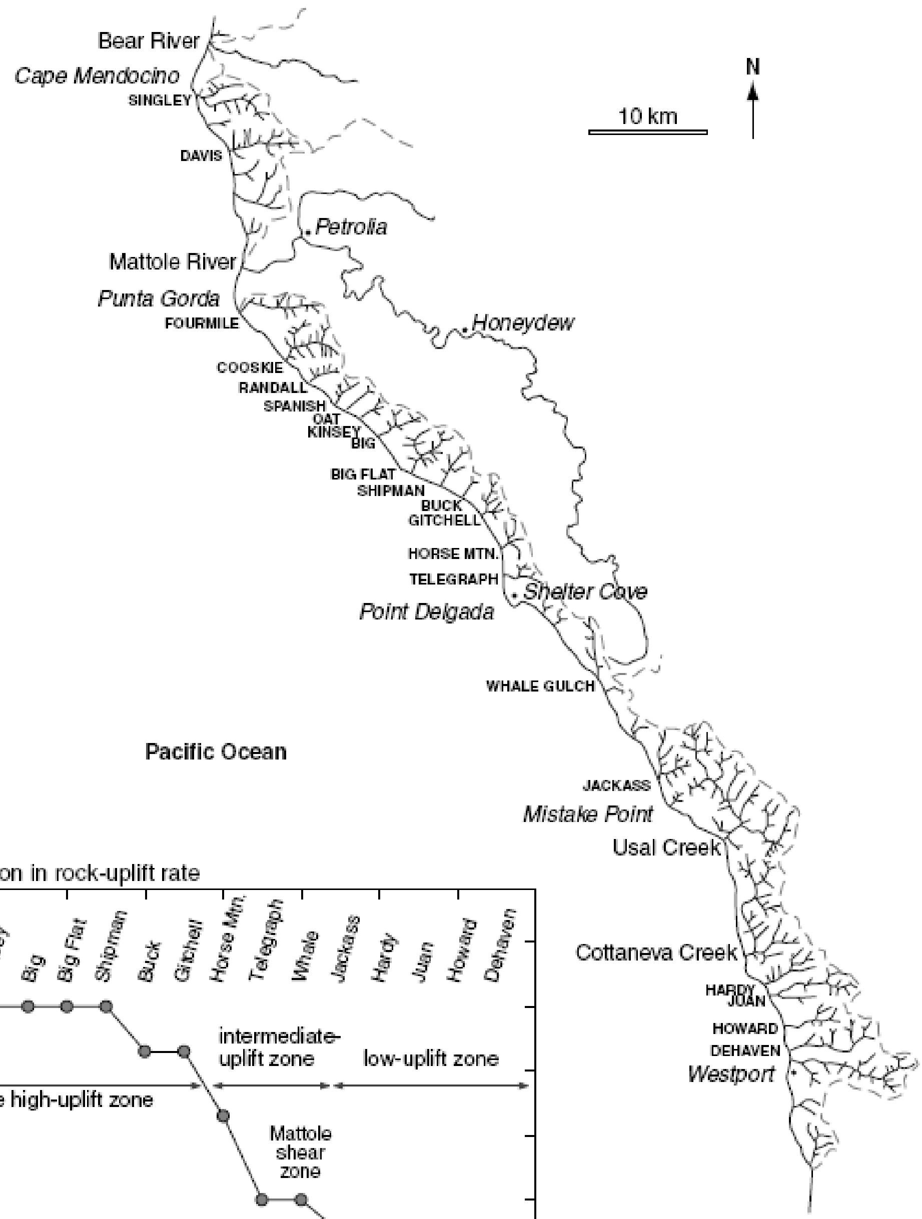


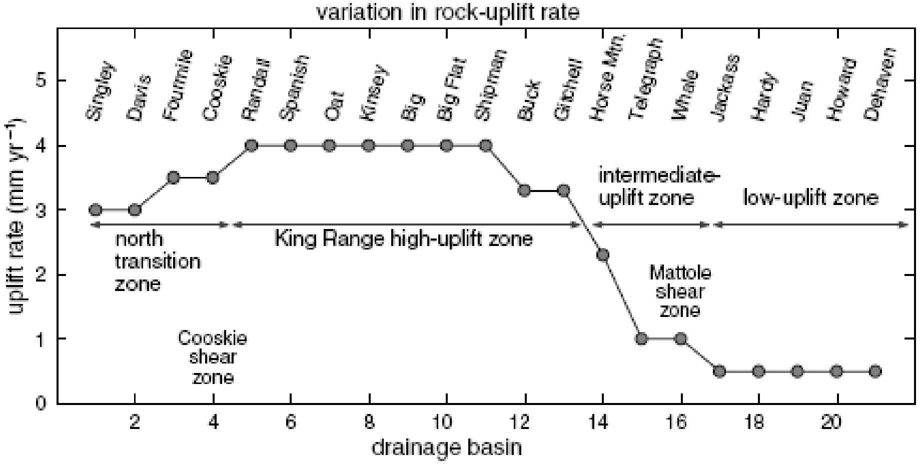
Kirby and Whipple, 2001, Geology, 29, 415-418.

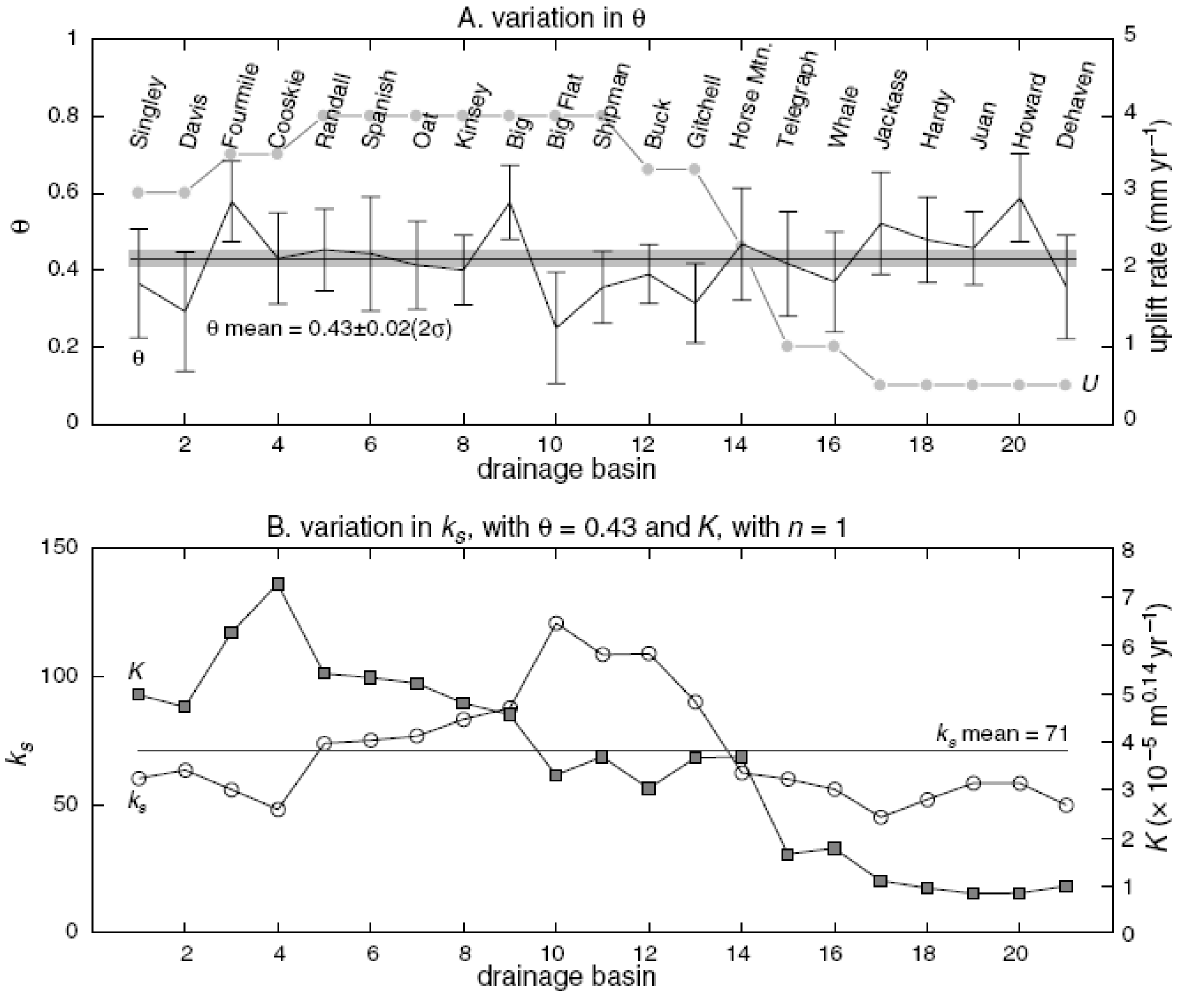
Tectonic effects on k_s

Snyder et al., 2000, GSABull, 112, 1250-1263.









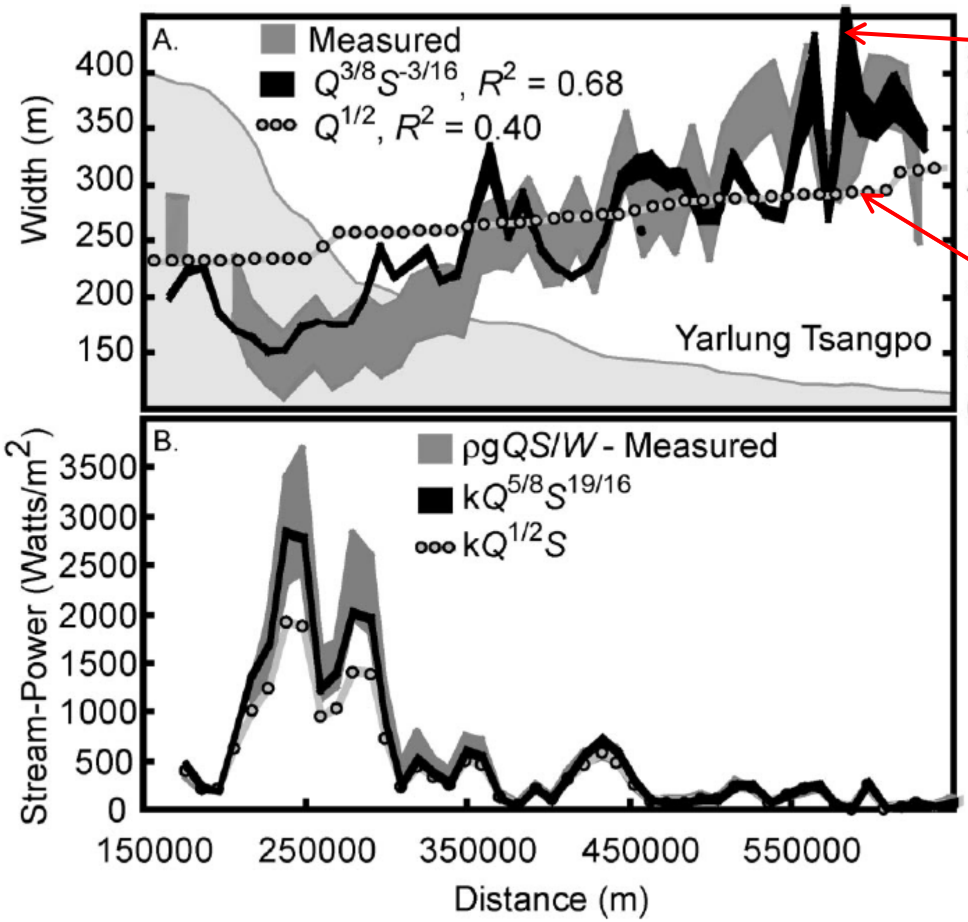
$$S = k_s A^{-\theta}$$

$$S_e = \left(\frac{U}{K}\right)^{1/n} A^{-m/n}$$

K and *n* = f(rock type, channel width, how Q scales with A)

….so, k_s scales with rock uplift ONLY when *K* and *n* are CONSTANT;
most of this variation in *K* and *n* is likely a result of changes in channel width

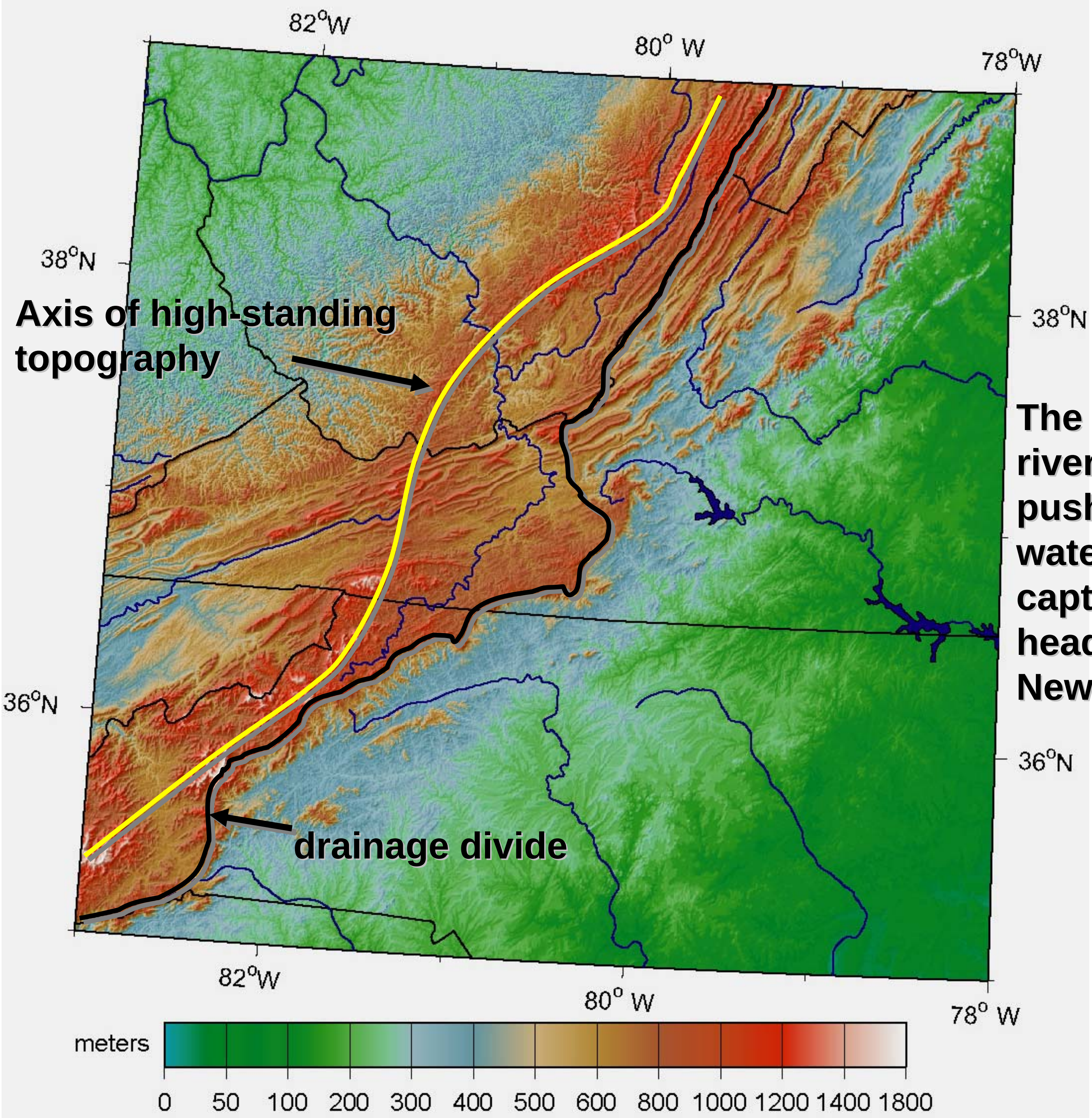
Effects of channel width (Finnegan et al., 2005, Geology, 33, 229-232.)



$$W = [\alpha(\alpha + 2)^{2/3}]^{3/8} Q^{3/8} S^{-3/16} n^{3/8}.$$

Modification of the Manning's equation

W ~ $Q^{0.5}$

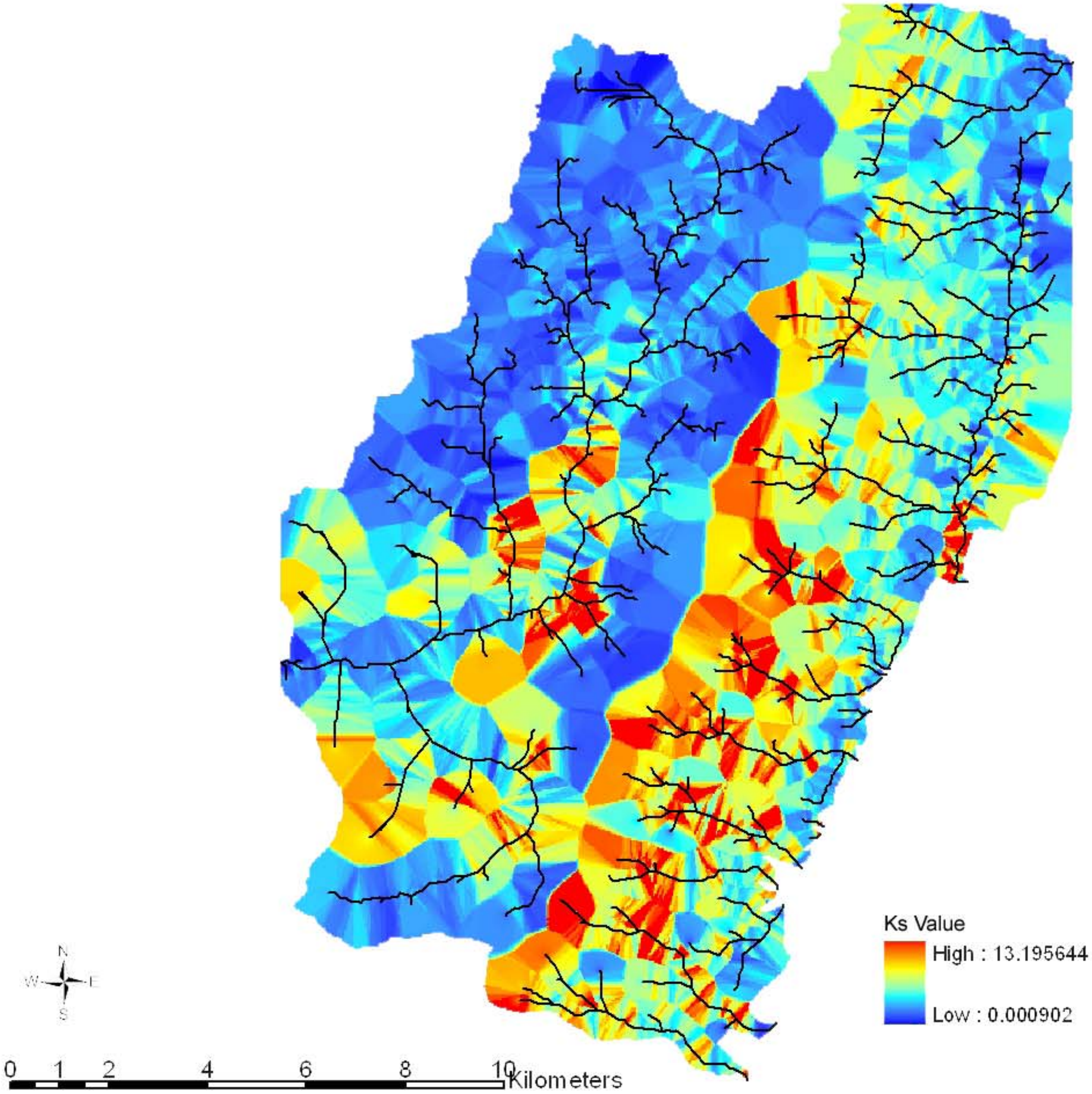


Axis of high-standing topography

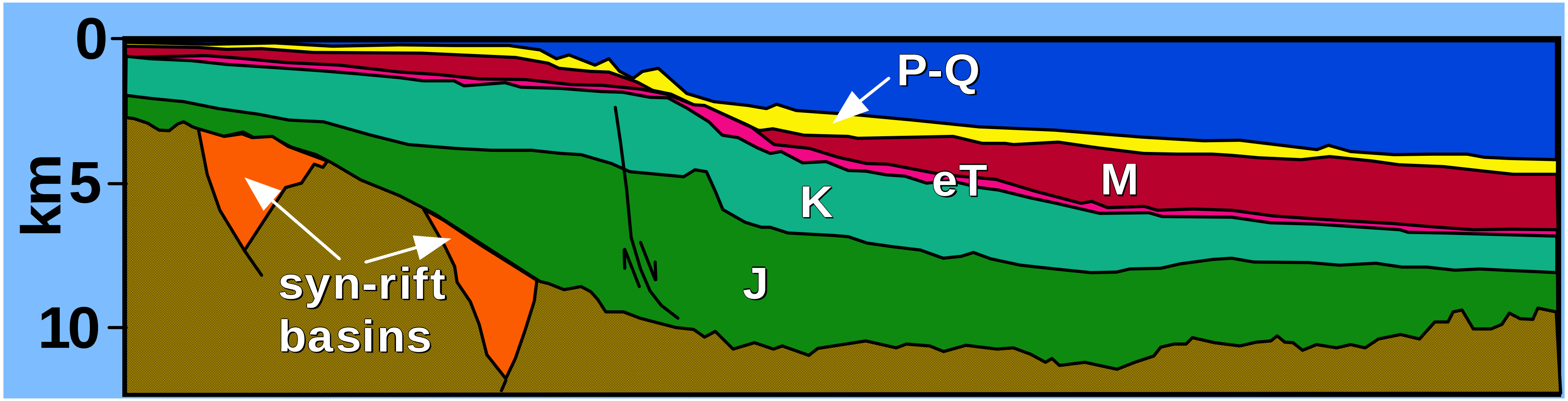
drainage divide

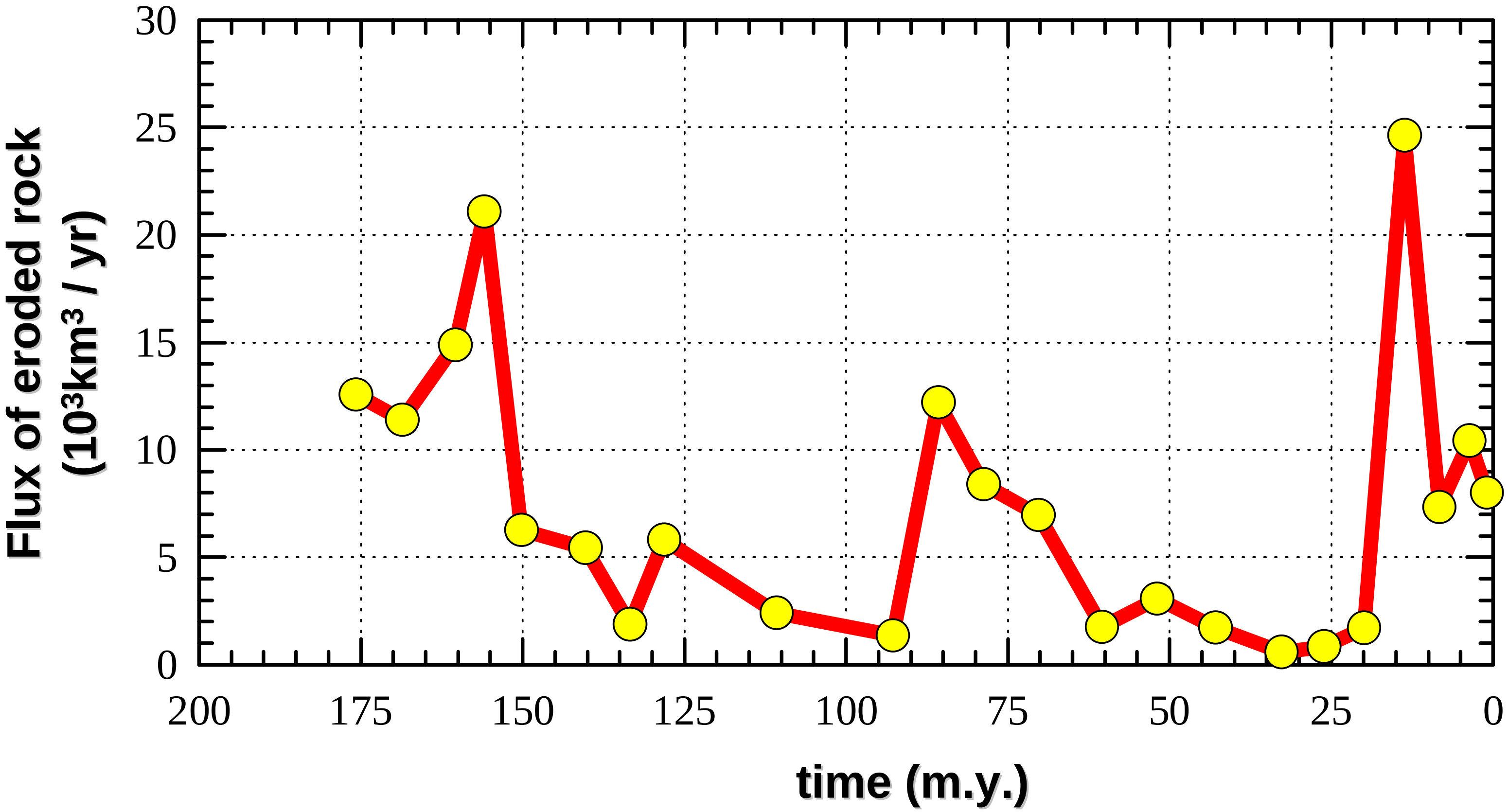
The Roanoke and James rivers have recently pushed their head-waters west, nearly capturing the headwaters of the New River.

Steepness Index (k_s) map



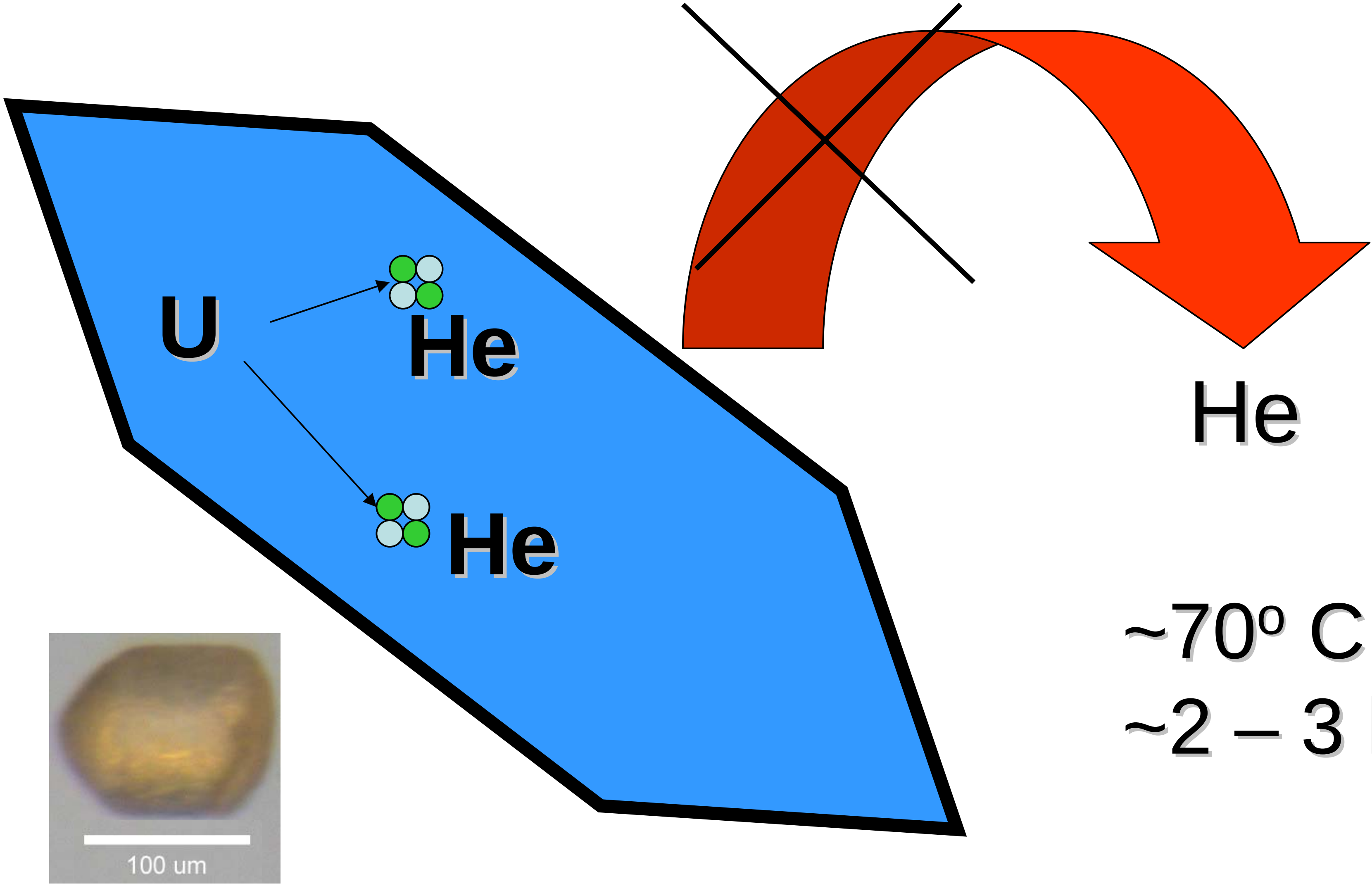
Laucks, J. 2005, MS Thesis, Lehigh Univ.





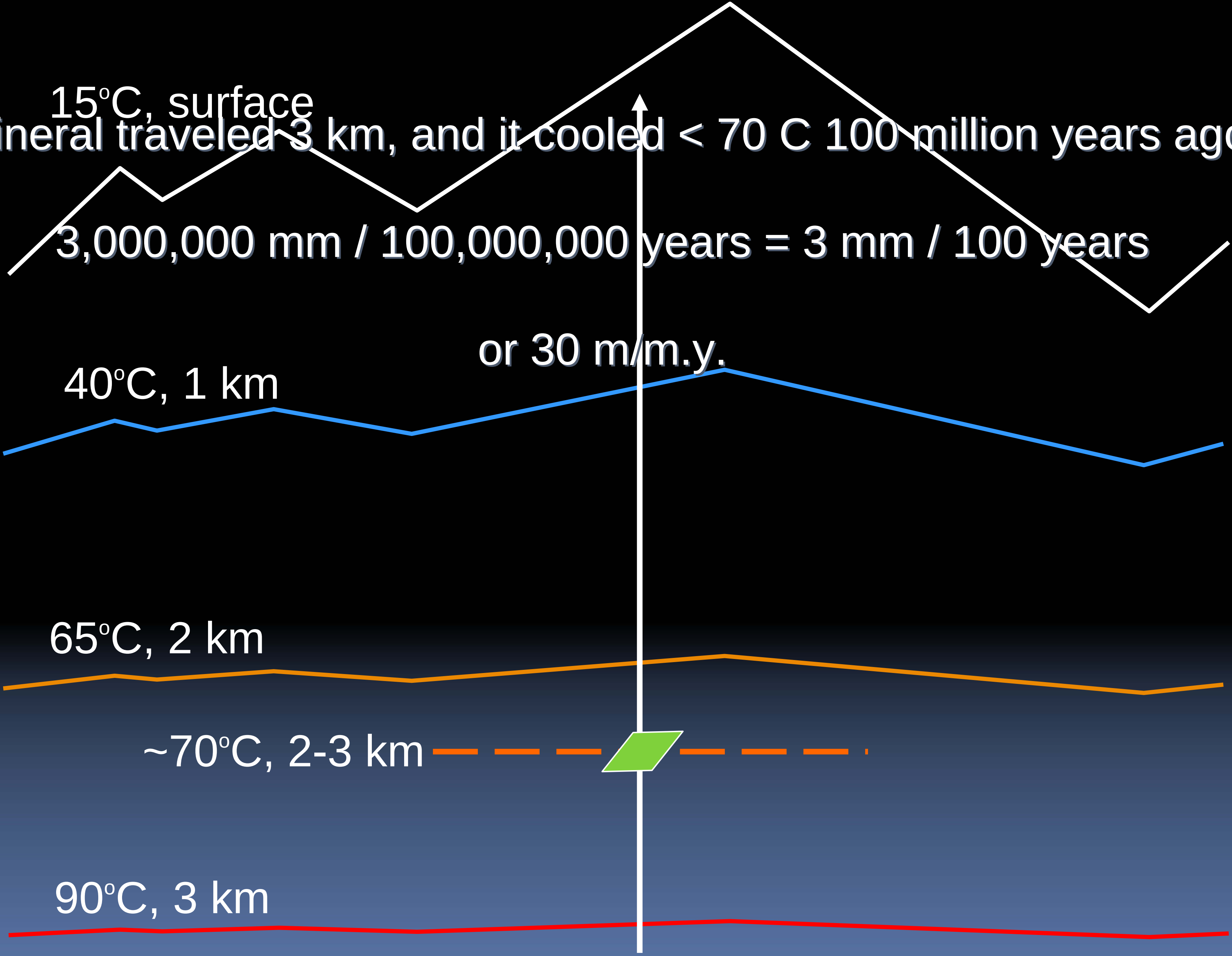
Pazzaglia F. J. and Brandon, M. T., 1996, Basin Research, 8, 255-278.

U-Th/He thermochronology



~70º C,
~2 – 3 km

Apatite = $Ca_5(PO_4)_3(F,Cl,OH)$



15°C, surface

Mineral traveled 3 km, and it cooled < 70 C 100 million years ago

3,000,000 mm / 100,000,000 years = 3 mm / 100 years

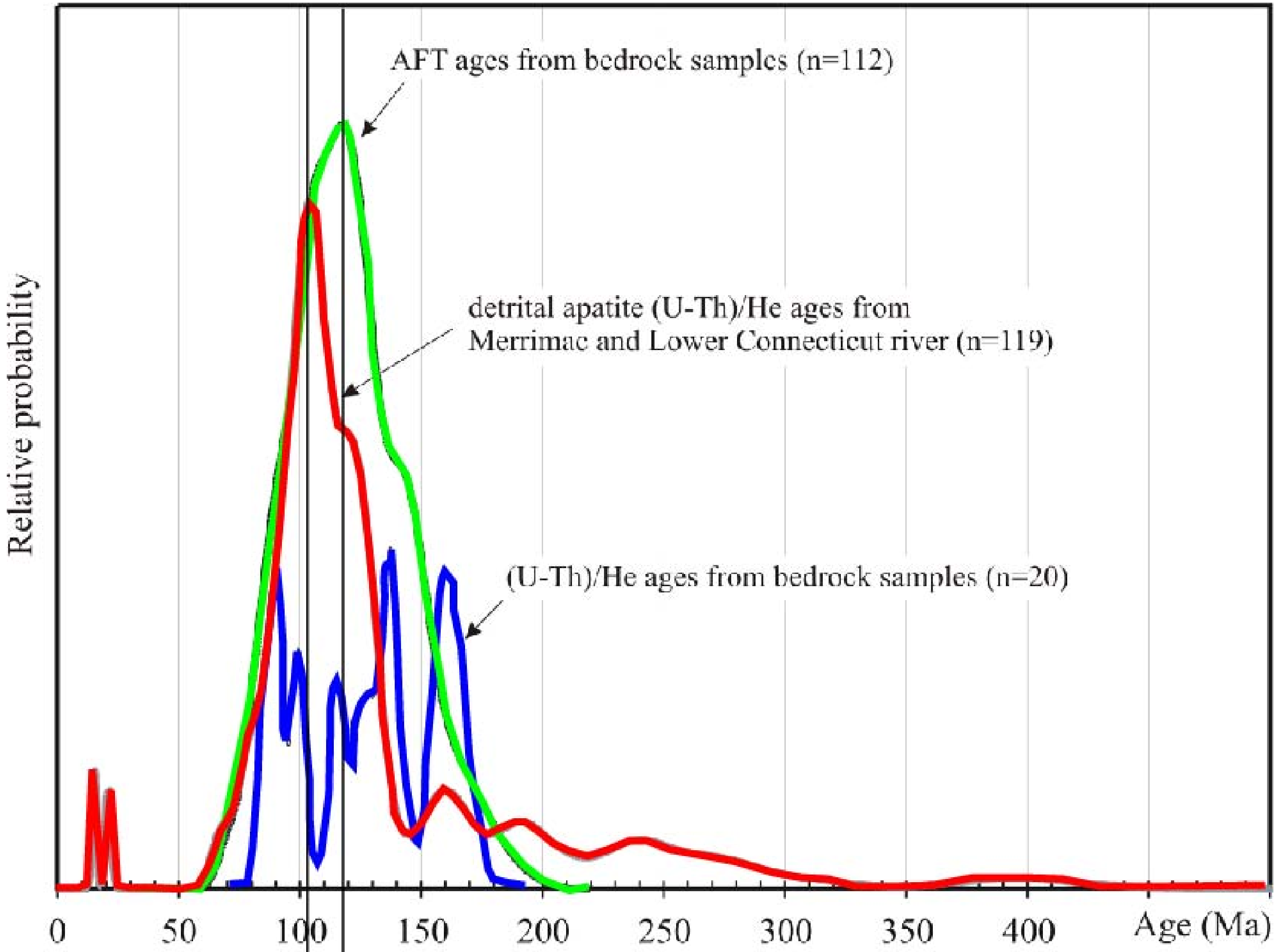
or 30 m/m.y.

40°C, 1 km

65°C, 2 km

~70°C, 2-3 km

90°C, 3 km



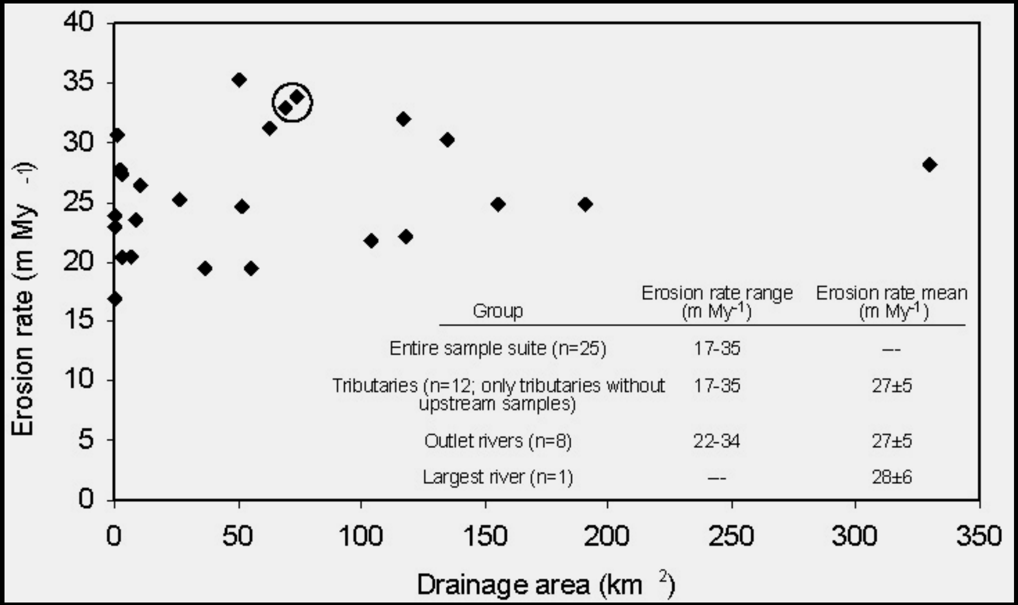
AFT = 100°C closure temperature
U-Th/He = 70°C closure temperature
at 30°C/km (post-intrusion cooling),
is 1 km erosion / 16 m.y. = **62.5 m/m.y.**
long-term average at 20°C/km,
is 3 km/100m.y. = **30 m/m.y.**

….in either case, the Appalachians were unroofed mostly by the end of the Cretaceous….

Pazzaglia et al., unpublished

How fast are the Appalachians eroding and has this rate been constant through time ?

Recall….long term average exhumation rate from thermochronology: ~30 m/m.y. BUT the short-term rates are (apparently) unsteady



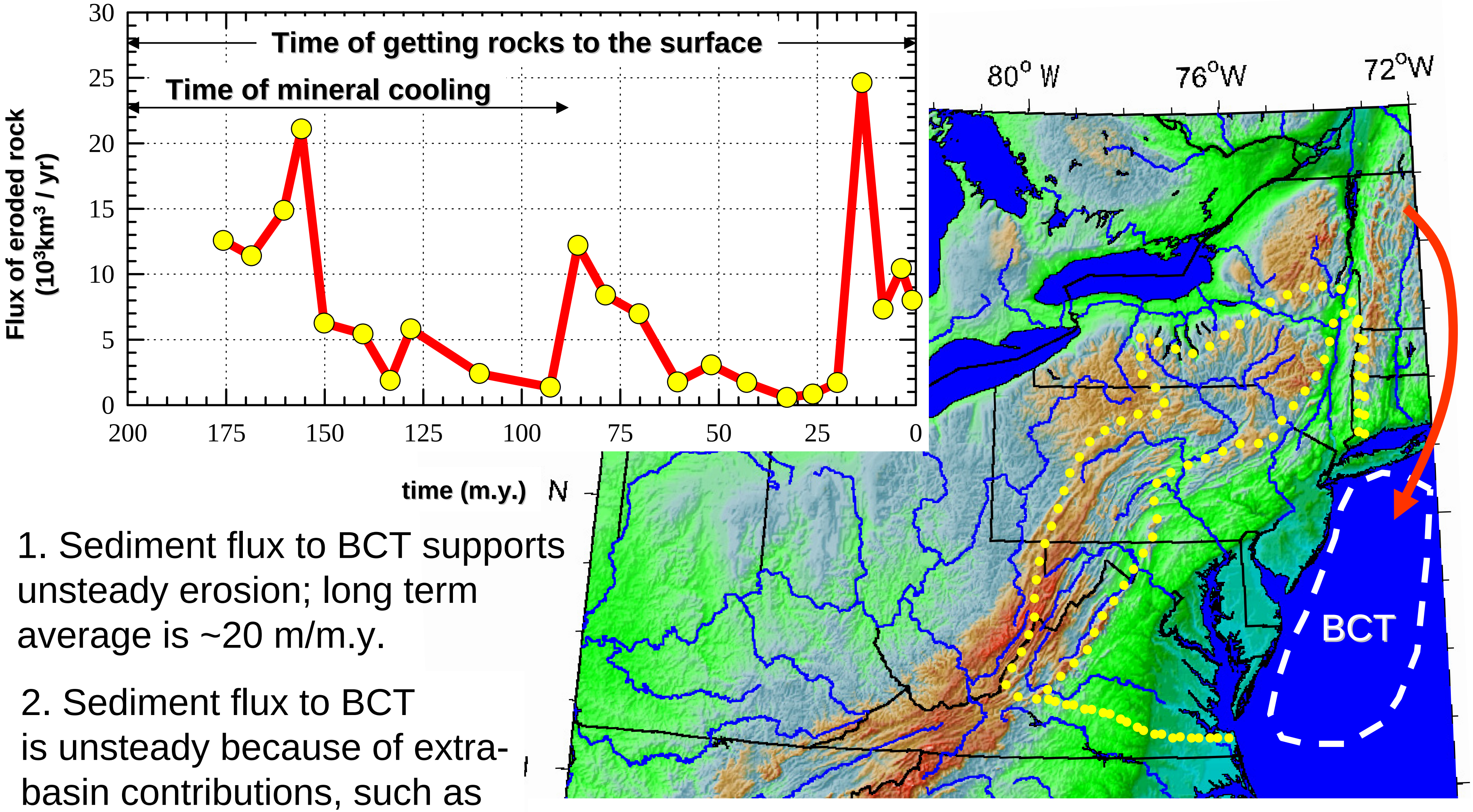
Group	Erosion rate range (m My^{-1})	Erosion rate mean (m My^{-1})
Entire sample suite (n=25)	17-35	---
Tributaries (n=12; only tributaries without upstream samples)	17-35	27±5
Outlet rivers (n=8)	22-34	27±5
Largest river (n=1)	---	28±6

Erosion rates in the Great Smoky Mountains determined from cosmogenic ^{10}Be inventories in modern river bedloads.

Non-weighted average is 27 m/m.y. (Matmon et al, 2003; Geology)

- River sed yields ~20-40 m/m.y. (Sevon, 1989; Milliman and Syvitsky, 1992)
- Colluvial hollow excavation ~80-100 m/m.y. (Braun, 1989)
- Solute loads ~5-10 m/m.y. (Cleaves et al, 1974)
- River incision rates ~5-40 m/m.y. (Pazzaglia and Gardner, 1993; Granger, 1997, 2000; Mills, 2000; Ward et al., 2005)
- Cosmogenic inventory of stream alluvium (PA) ~14±0.4 m/m.y. (Reutter, 2006)

…conclusion: the modern (Quaternary) erosion rate is "uncomfortably" similar to the long-term avg. from thermochronology. Unsteadiness in erosion (from BCT) is apparent, not real. Sediment flux changes through time because of the unroofing of New England, and/or non-steady growth of the waterhed feeding the BCT.



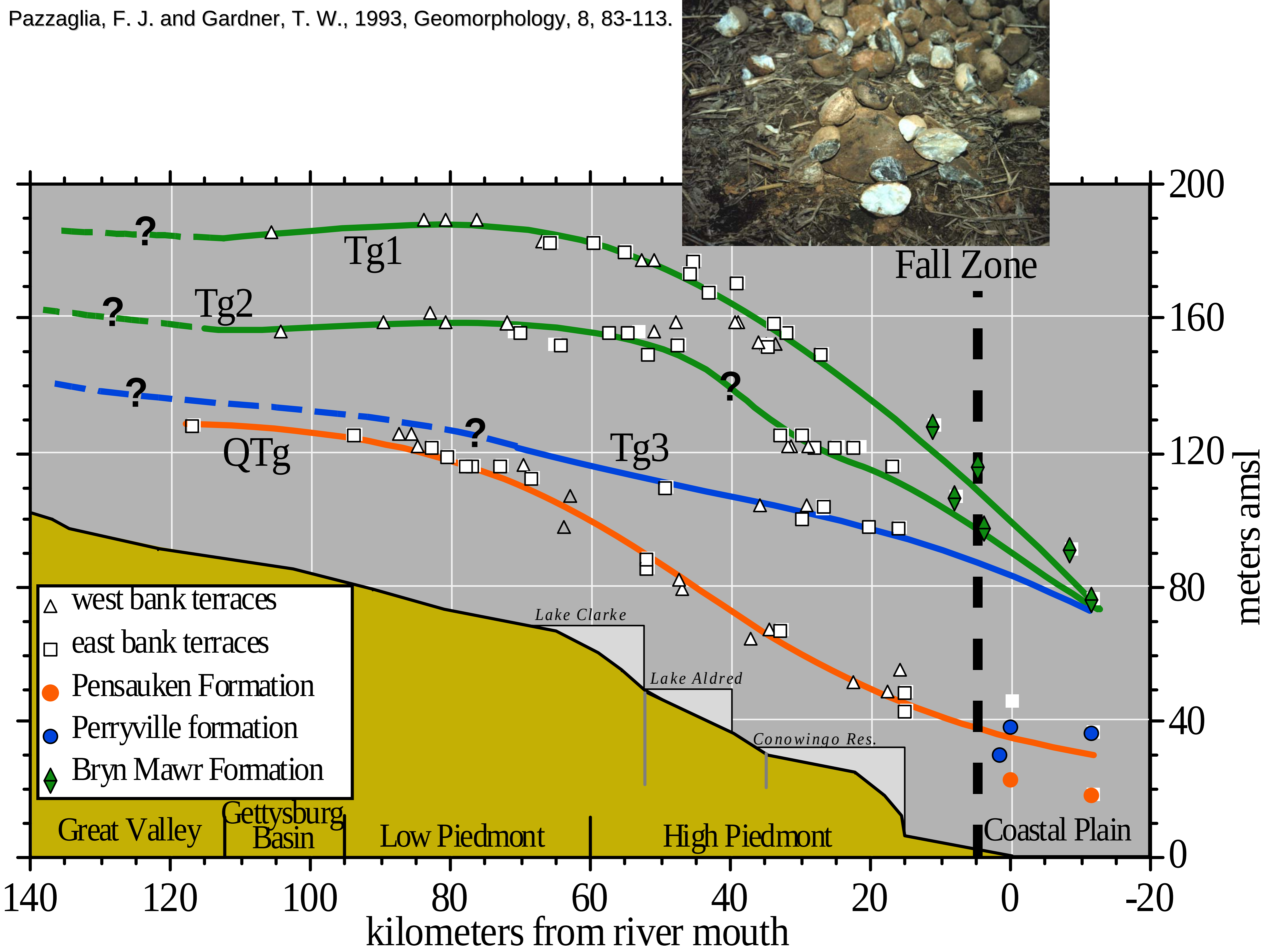
1. Sediment flux to BCT supports unsteady erosion; long term average is ~20 m/m.y.

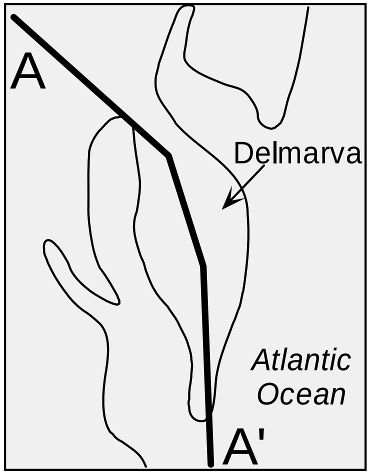
2. Sediment flux to BCT is unsteady because of extra-basin contributions, such as a post 100 Ma unroofing of New England; long term average remains ~20 m/m.y.

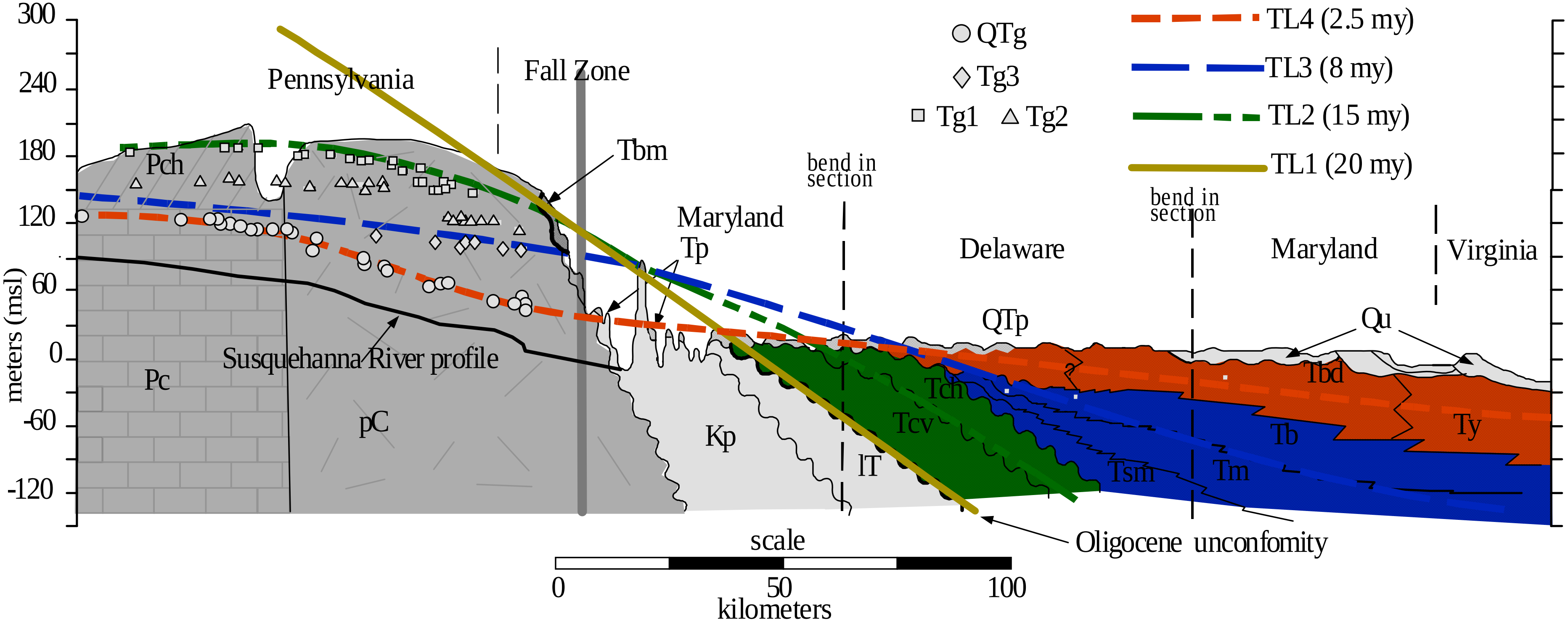
3. Sediment flux appears unsteady because mid-Atlantic drainage basin expanded rapidly in the Miocene. Not enough rock was unroofed to see Cenozoic cooling ages at the surface.

4. Westward march of drainage divide and enlargement of Atlantic drainages may be influenced by a topographic-precipitation feedback.

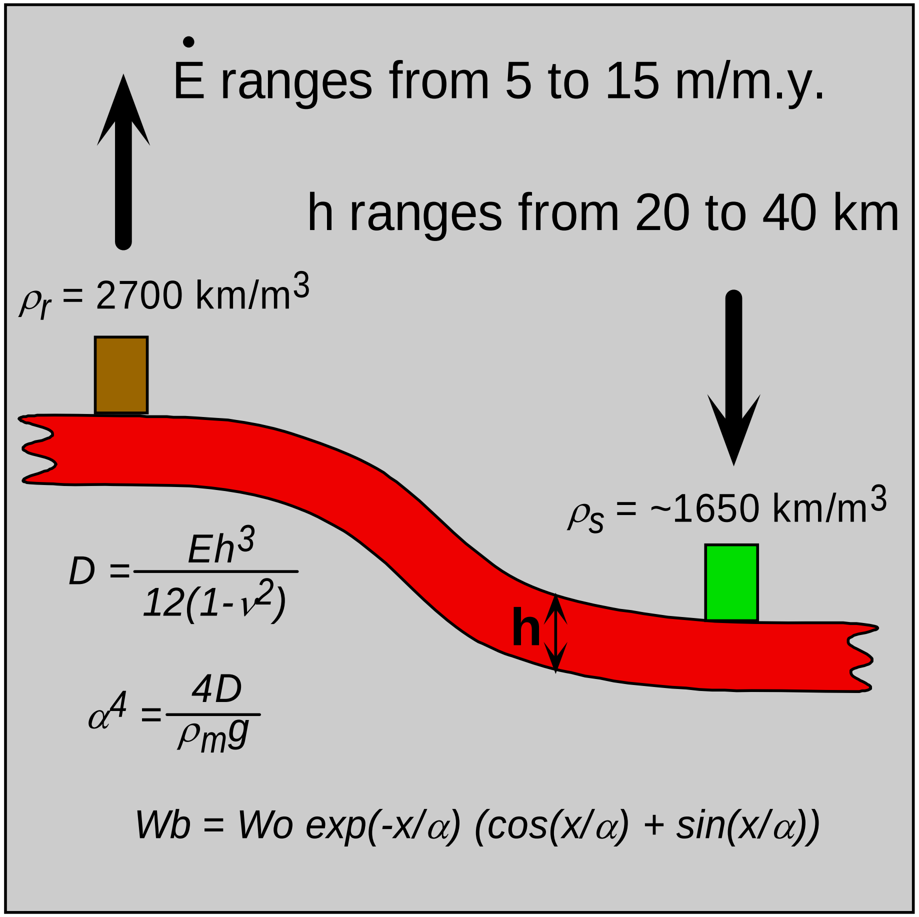
Pazzaglia, F. J. and Gardner, T. W., 1993, Geomorphology, 8, 83-113.







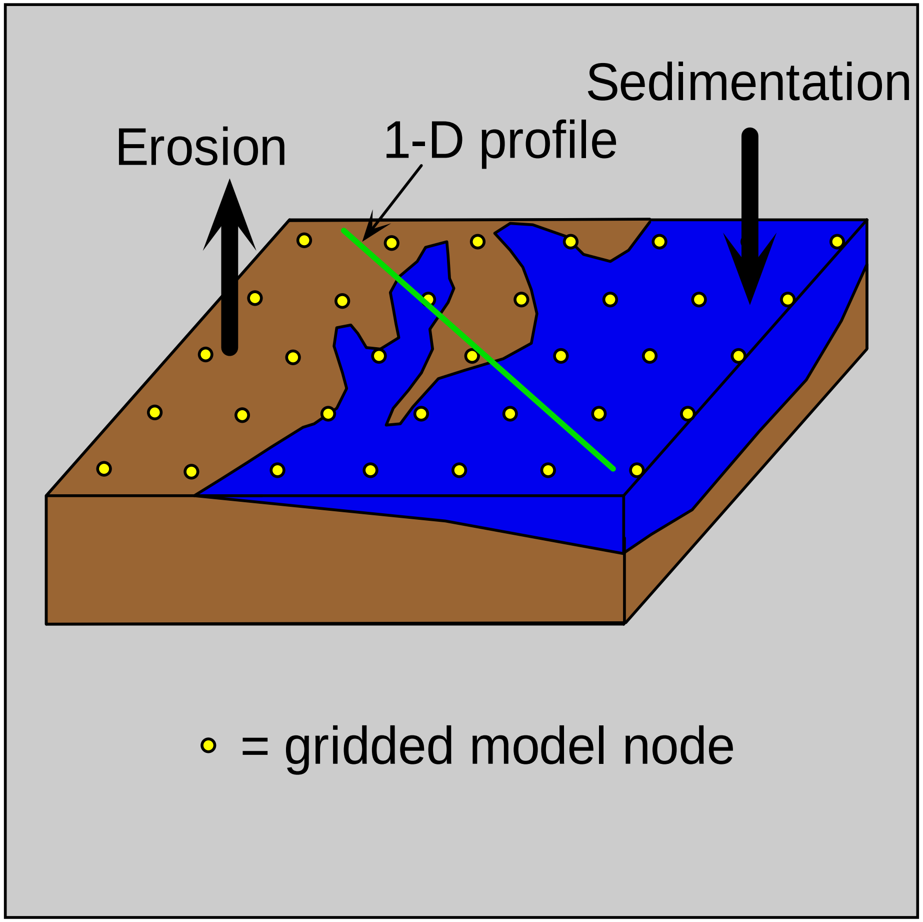
Pazzaglia, F. J. and Gardner, T. W., 1994, JGR, 99, 12,143-12,157



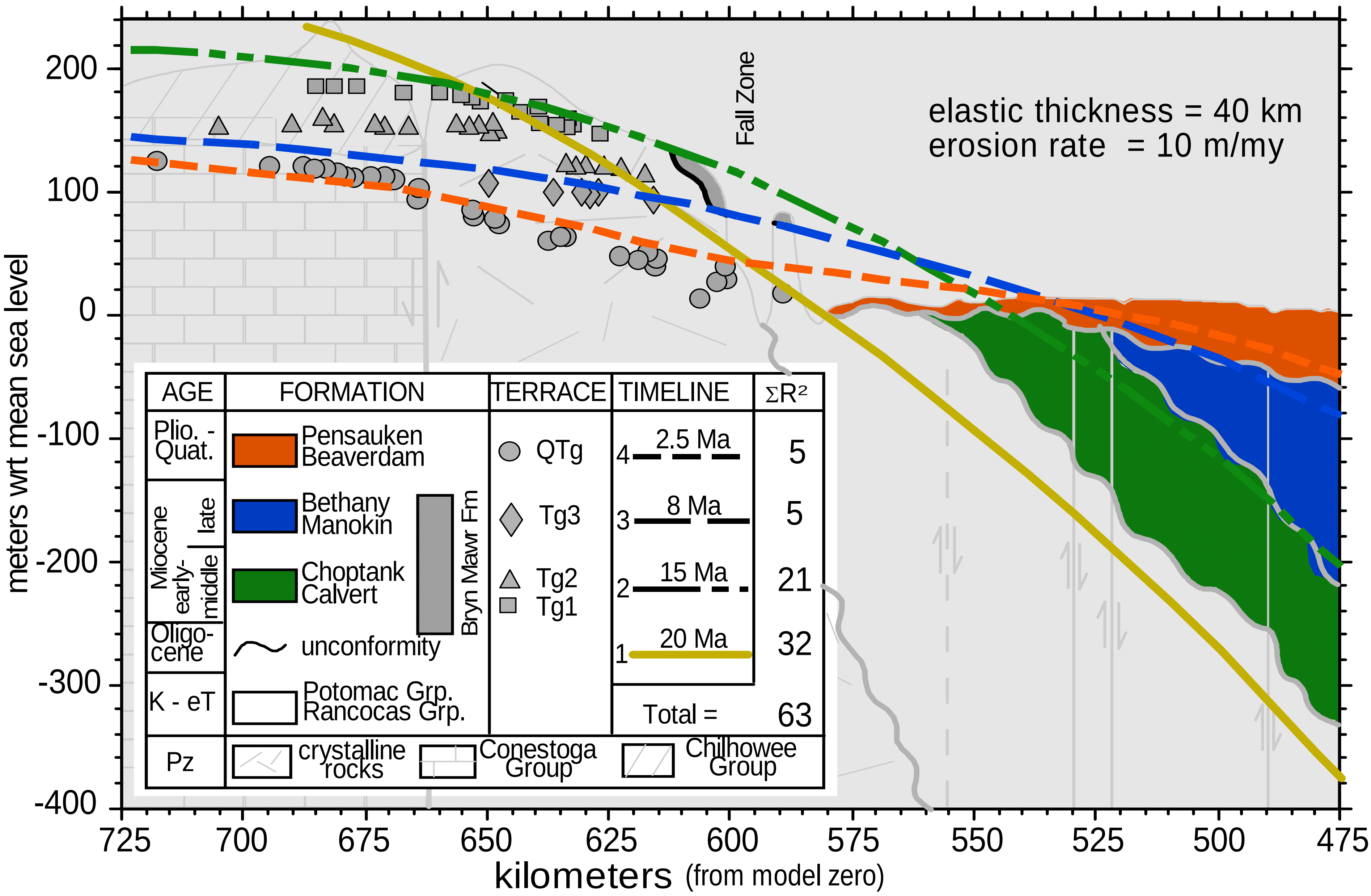
$$D = \frac{Eh^3}{12(1-\nu^2)}$$

$$\alpha^4 = \frac{4D}{\rho_m g}$$

$$Wb = Wo \exp(-x/\alpha)\,(\cos(x/\alpha) + \sin(x/\alpha))$$

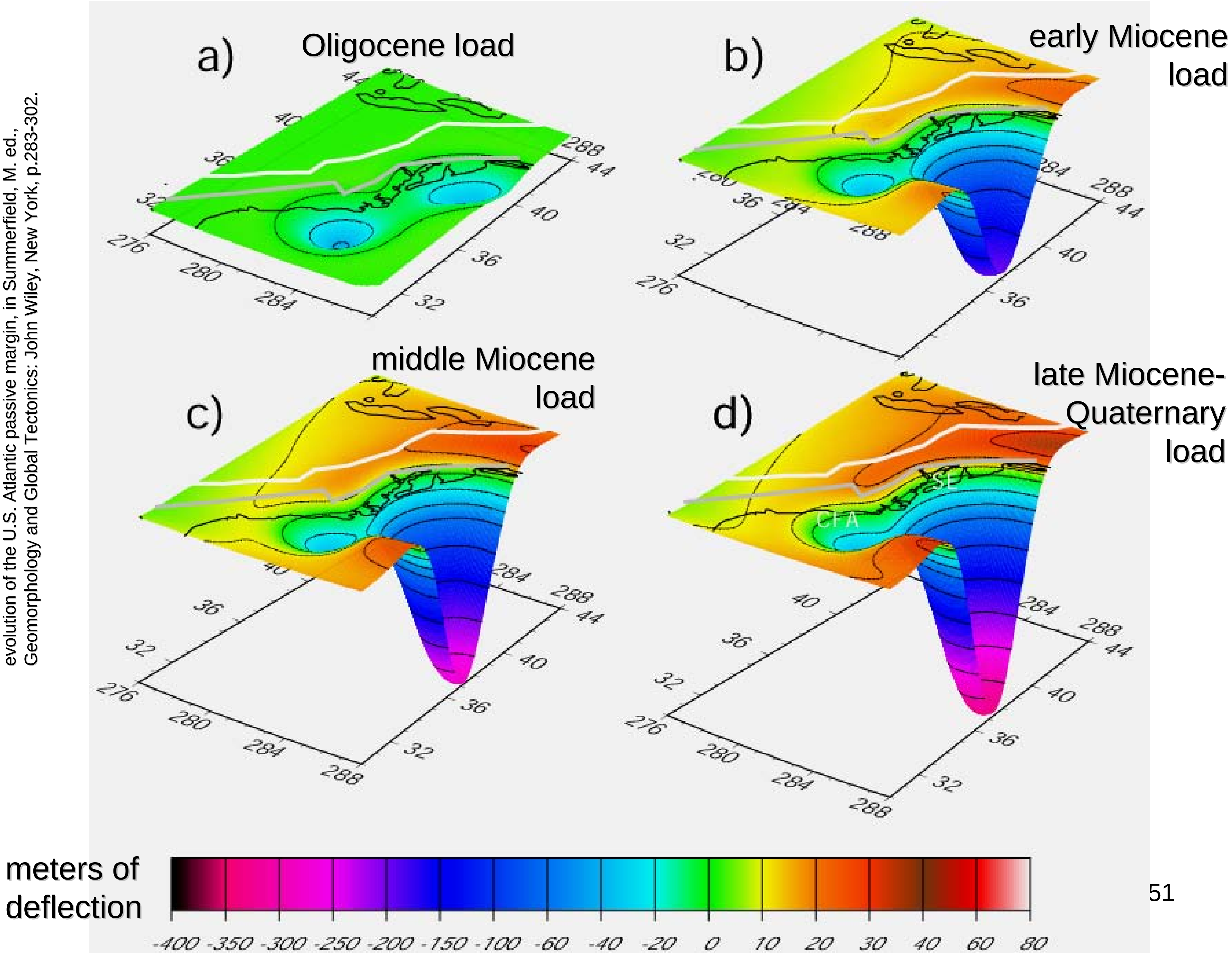


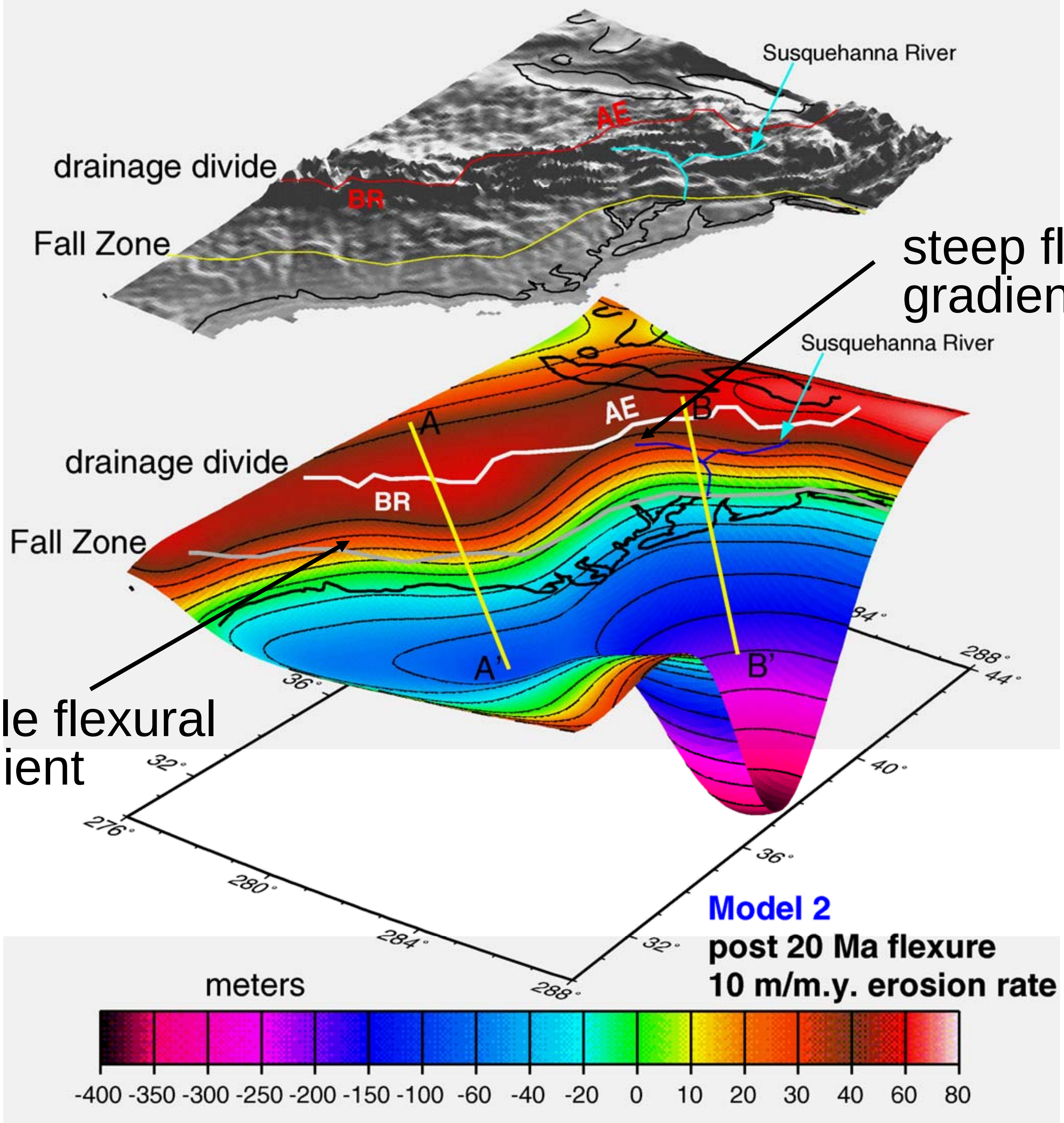
Pazzaglia, F. J. and Gardner, T. W., 2000, Late Cenozoic large-scale landscape evolution of the U.S. Atlantic passive margin, in Summerfield, M. ed., Geomorphology and Global Tectonics: John Wiley, New York, p.283-302.



Pazzaglia, F. J. and Gardner, T. W., 1994, JGR, 99, 12,143-12,157

Pazzaglia, F. J. and Gardner, T. W., 2000, Late Cenozoic large-scale landscape evolution of the U.S. Atlantic passive margin, in Summerfield, M. ed., Geomorphology and Global Tectonics: John Wiley, New York, p.283-302.

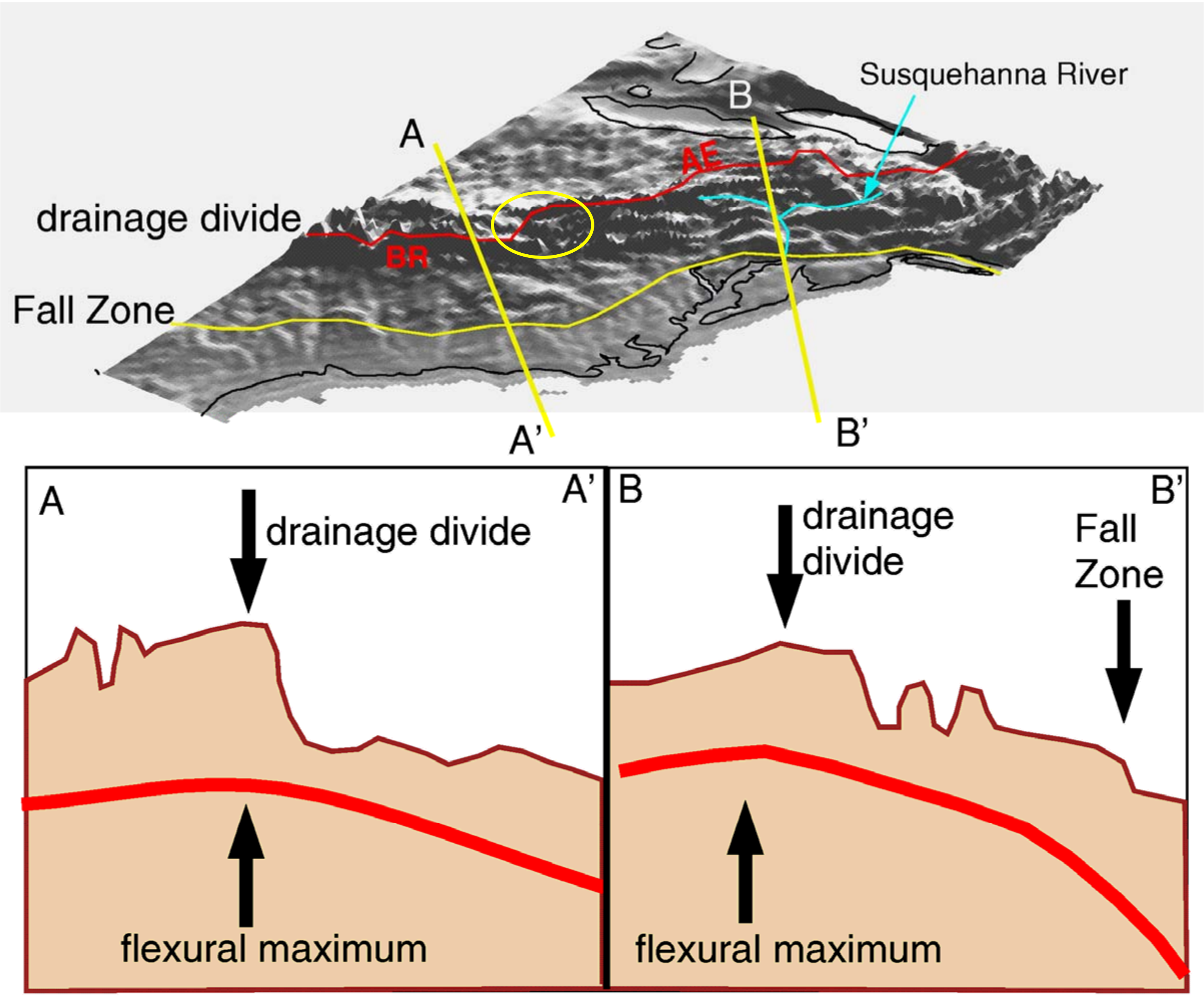




steep flexural gradient

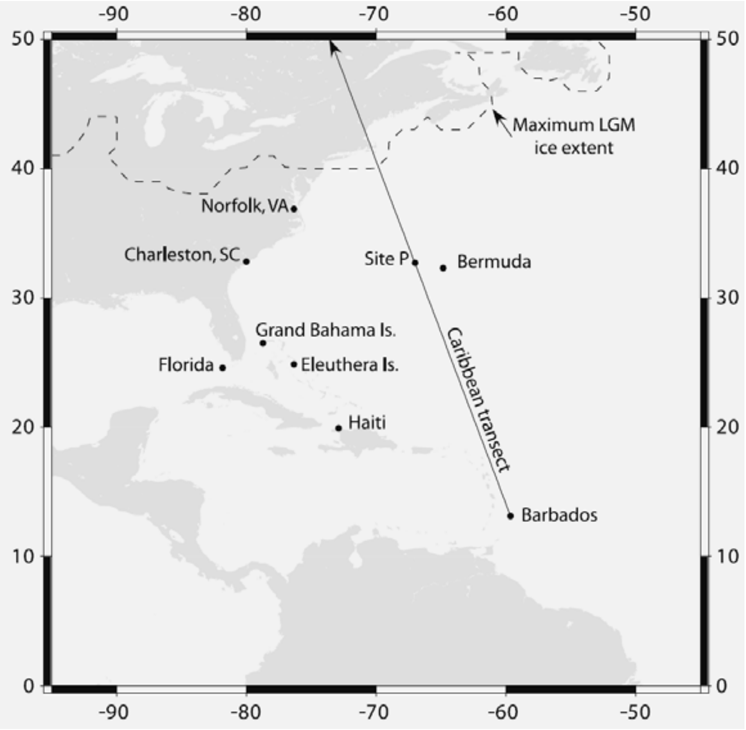
gentle flexural gradient

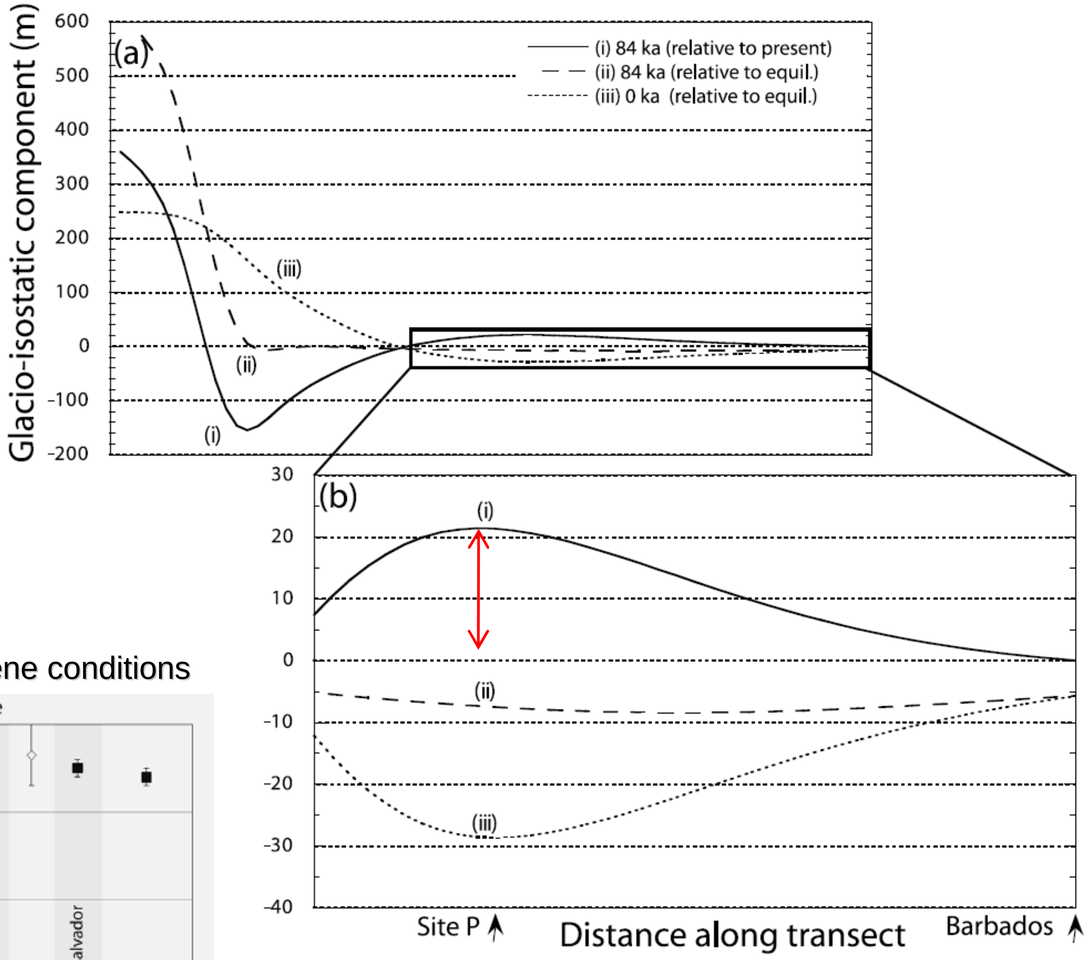
Pazzaglia, F. J. and Gardner, T. W., 2000, Late Cenozoic large-scale landscape evolution of the U.S. Atlantic passive margin, in Summerfield, M. ed., Geomorphology and Global Tectonics: John Wiley, New York, p.283-302.


Susquehanna River
B
A
AE
drainage divide
BR
Fall Zone
A'
B'
A
A'
drainage divide
flexural maximum
B
B'
drainage divide
Fall Zone
flexural maximum

Type 1

Type 2

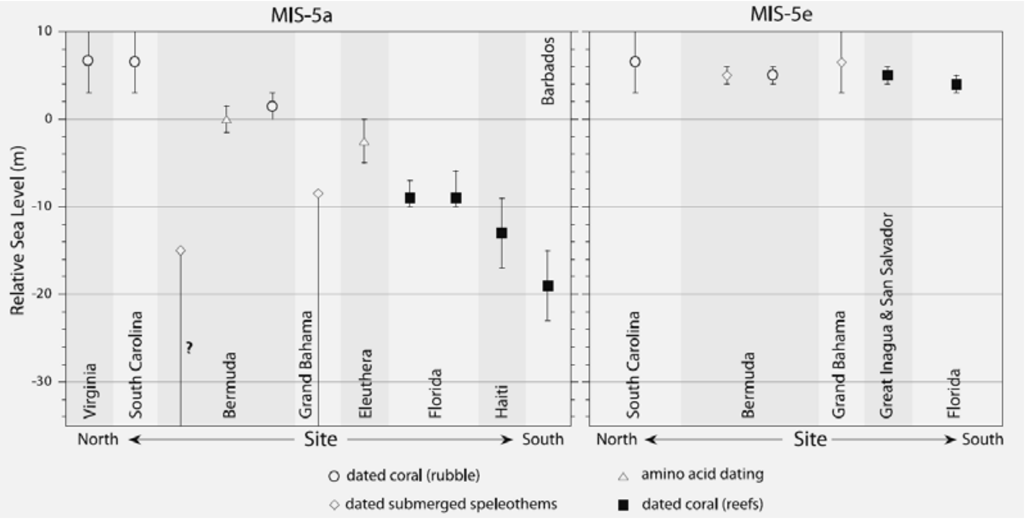




~20 m of forebuldge collapse still to go…. for northern NC through Delmarva.

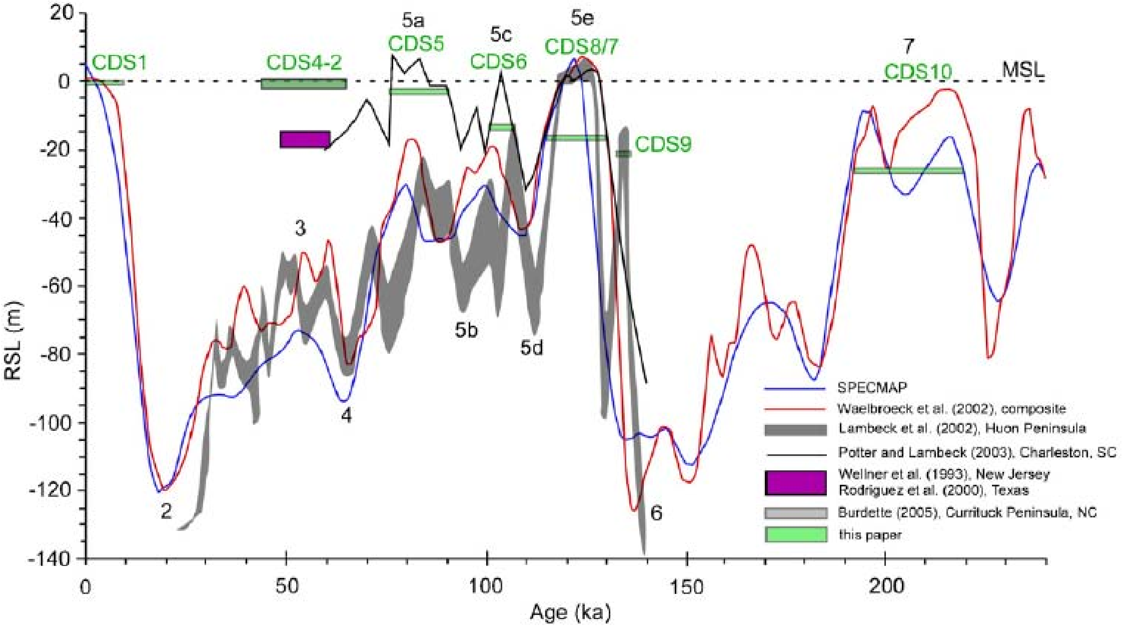
mimics conditions 40 ka in the future

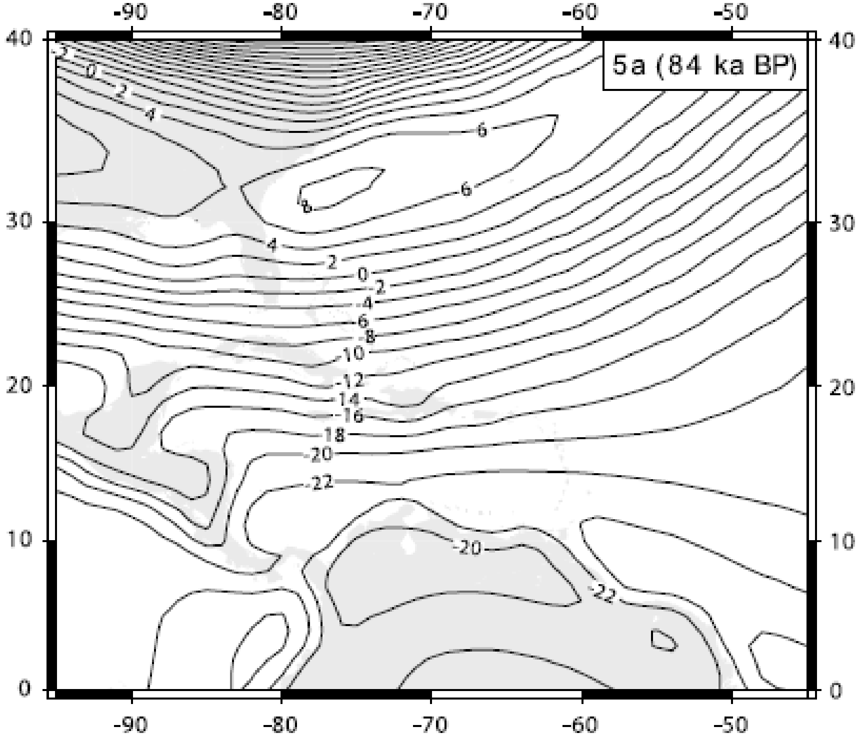
mimics Holocene conditions



Potter and Lambeck, 2003, EPSL, 217, 171-181.

Parham et al., 2007, QR, 67, 83-99.

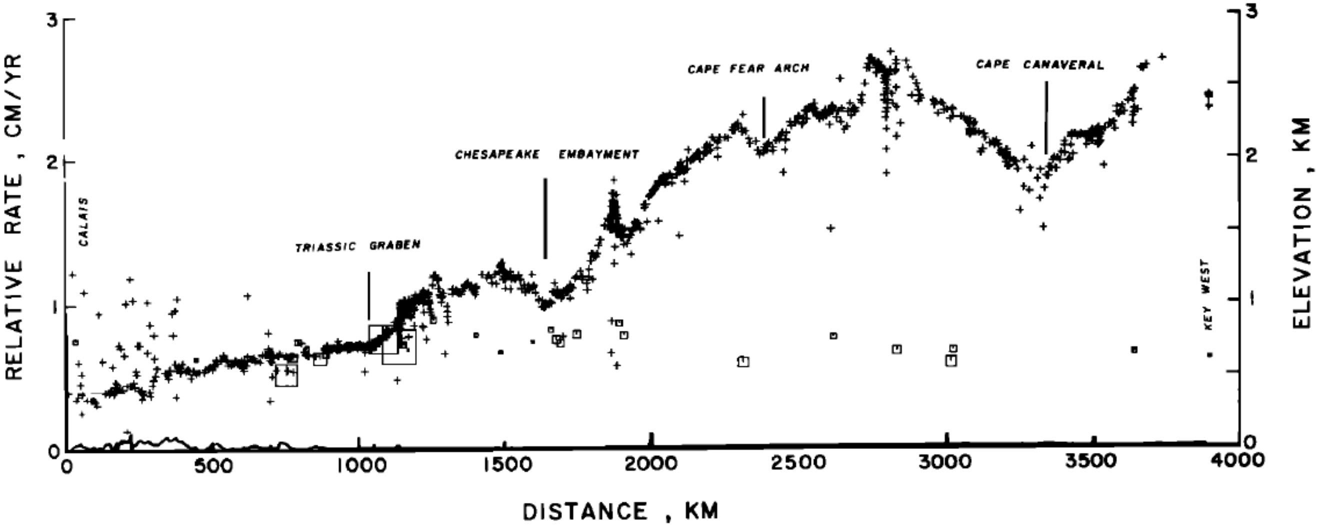


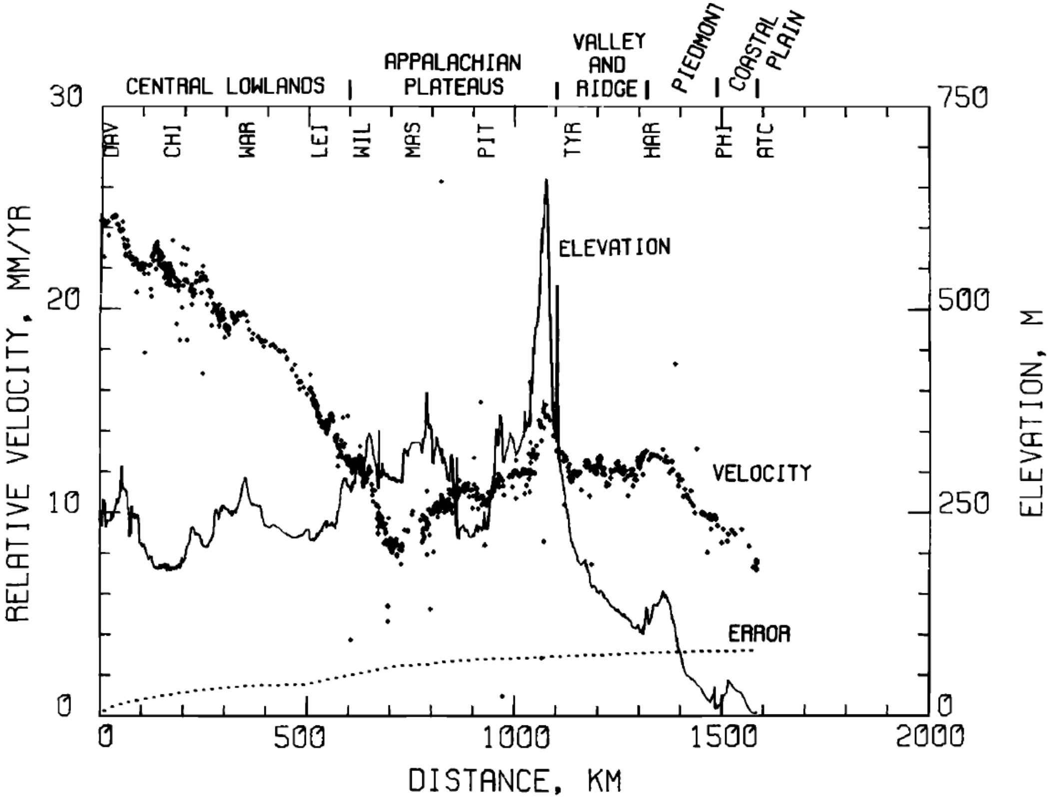


Potter and Lambeck, 2003, EPSL, 217, 171-181.

Essentially a prediction of how much forebuldge collapse (positive values) there will be in the next ~ 40,000…..

This collapse will drive stresses in the crust of the East Coast.





Old releveling data, discredited, or worth another look with GPS geodesy in the context of the glacio-isostasy results ?

Brown, L., and R. E. Reilinger, (1980), Releveling data in North America: Implications for vertical motions of plate interiors, in Dynamics of Plate Interiors, Geodyn. Ser., vol. 1, edited by A. W. Bally et al., pp. 131-144, AGU, Washington, D. C.

Chesapeake Impact Structure (35.4 Ma)

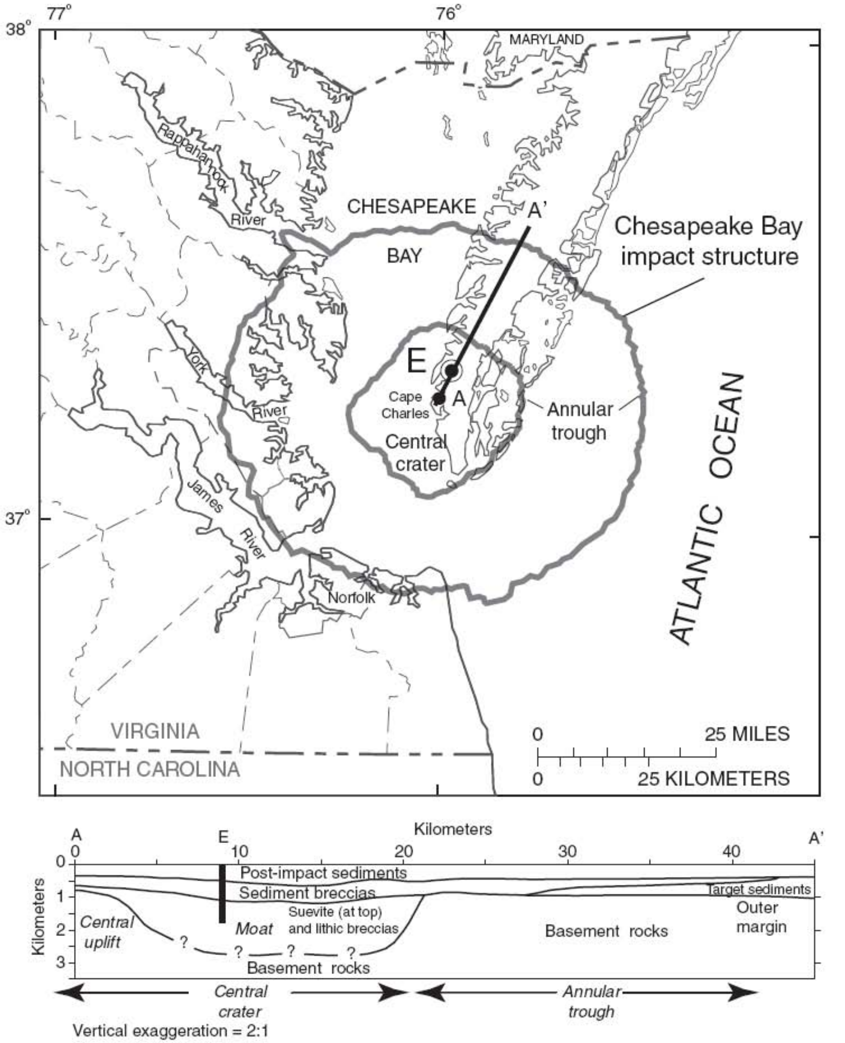


Fig. 1. Location of the Eyreville drill site (E) in the Chesapeake Bay impact structure and generalized radial cross section of the structure. The location of cross section A-A′ is shown on the map.

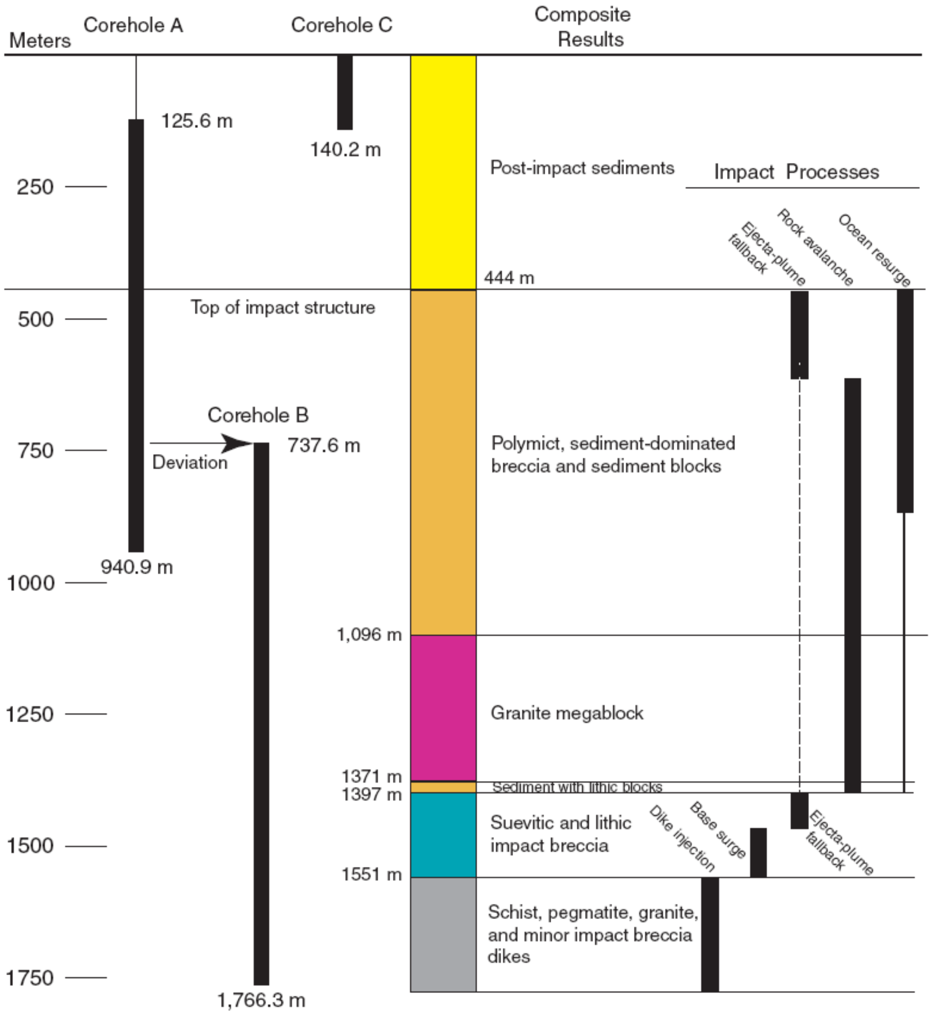
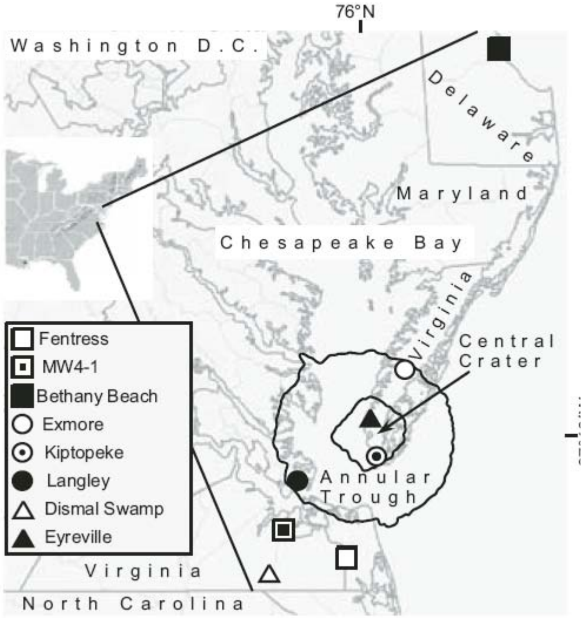


Fig. 2. Corehole depths, cored intervals, geologic column, and inferred impact processes for the A, B, and C coreholes at the Eyreville drill site. Intervals affected by selected impact processes are indicated.

Gohn, G. S., 2008, Science, 320, 1740-1744.

Syn and post-impact subsidence, uplift

Post-impact subsidence



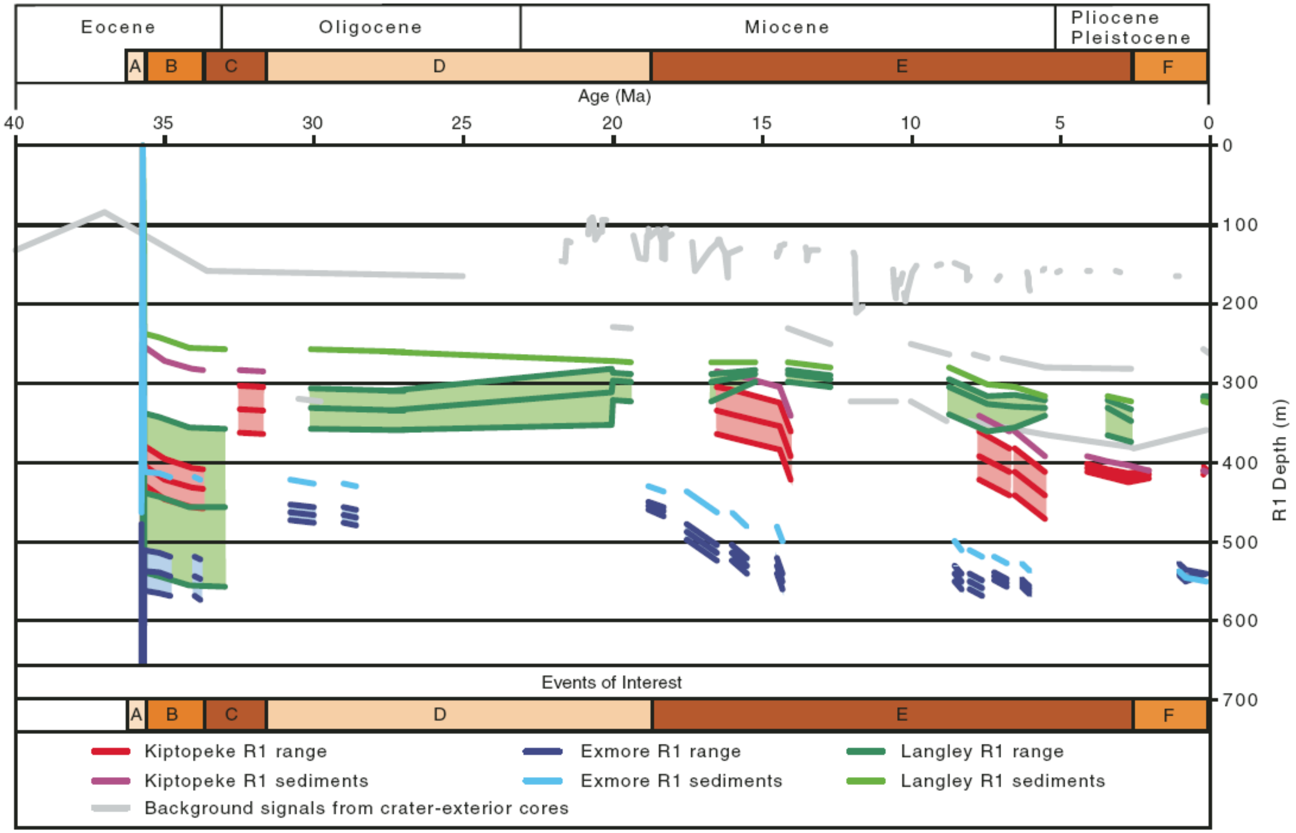
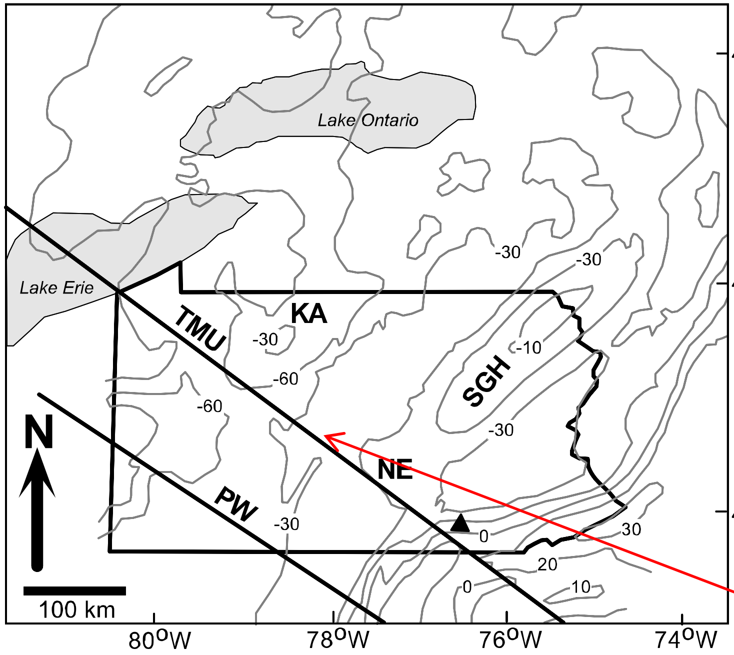


Figure 3. Results for the three crater-interior cores. Background crater-exterior results are shown in gray for comparison. R1 (first reduction) sediment lines illustrate only subsidence represented by the sediments without any water depth information. R1 ranges indicate the subsidence when water depth changes are taken into account. Event A represents the impact event. Events B and C are various stages of the post-impact response inside crater. Events E and F are regional.

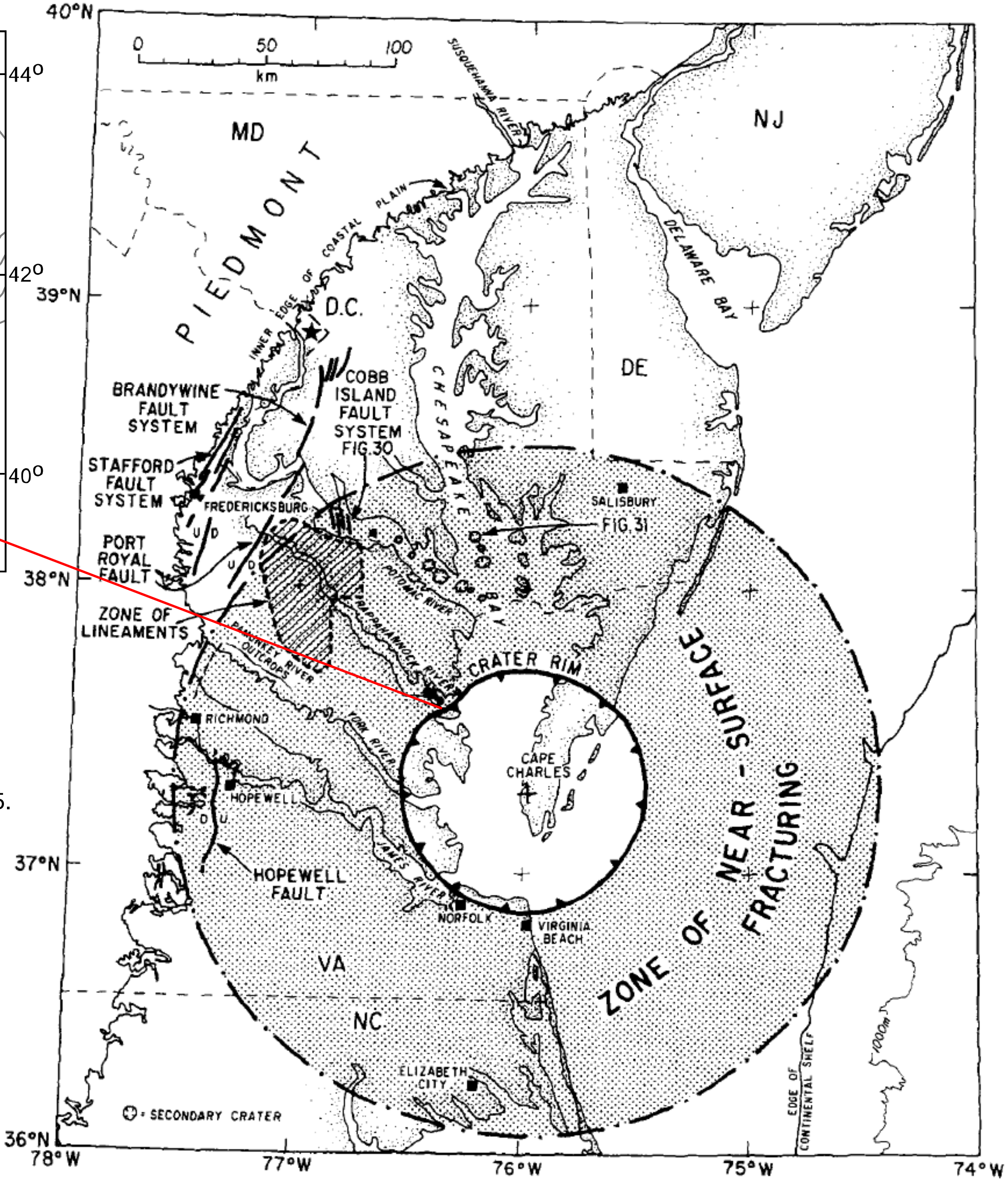
Hayden et al., 2008, Geology, 36, 327-330.



Central Pennsylvania, pyrite deposits ~35 Ma, briny, connate (mantle?), hot (~250°C) water emplaced along the Tyrone-Mt. Union lineament.

(Gold, D.P., Doden, A.G., Altamura, R.J., and Sicree, A., 2005. The Nature and Significance of Sulfide Mineralization in Bald Eagle Ridge at Skytop, near State College, Pennsylvania. Abst. NE- Section Meeting, Geol. Soc. Amer., Saratoga Springs, V.37, # 2, p. 64).

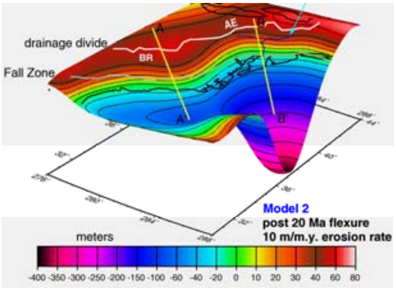
Sanford, W., 2005, A simulation of the hydrothermal response to the Chesapeake Bay bolide impact: Geofluids, 5,185–201.

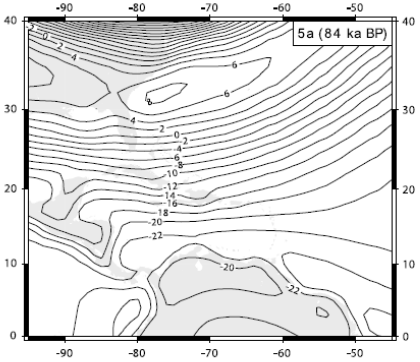


Poag, W., 1997, Sed. Geology, 108, 45-90.

What influence, if any, does broad regional flexure of the Atlantic margin have on current patterns of seismicity?

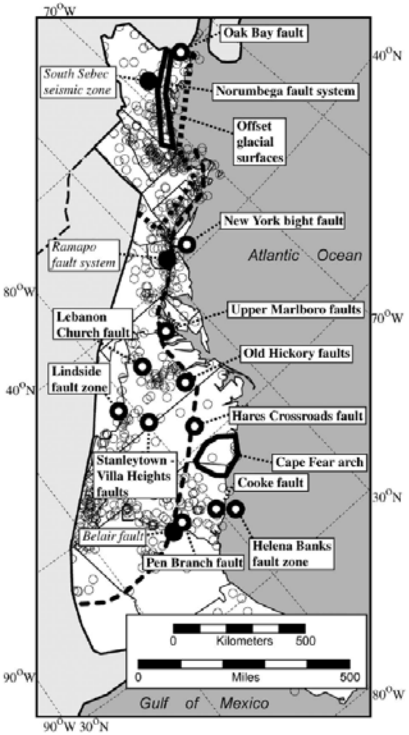
(1)Simple geodynamic models of late Cenozoic crustal deformation.
(2)Glacio-isostatic deformation.
(3)There is a spatial overlap in topography, active river incision, and seismicity…there appe
to be an influence.

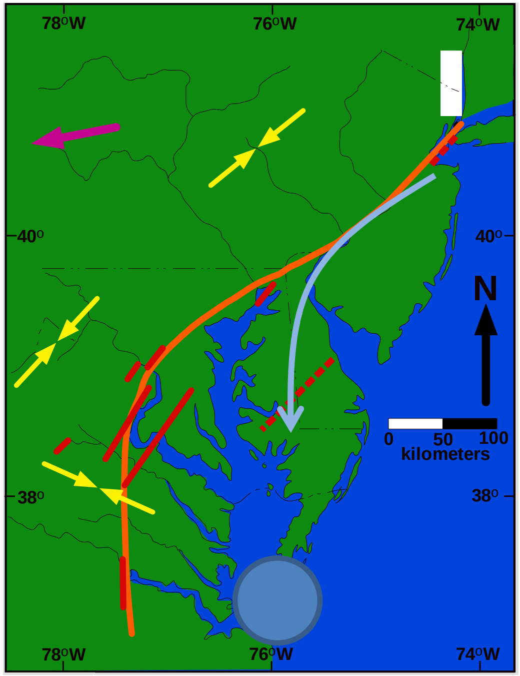




Should these features be explicitly considered in defining seismic sources?

Yes, and I am not the first or only to think so.





Please comment on your interpretation of the causative mechanism for earthquakes in the northeastern US?

(1)Modern state of stress acting on a heterogeneous lithosphere.
(2)Epeirogeny, including flexural effects.
(3)Chesapeake Bay Impact Structure.

To do….
(1) GPS Geodesy
(2) Stream profile modeling
(3) Fluvial geomorphology / Quat. Geology
(4) Reflection seismology
(5) Geodynamic modeling of epeirogenic deformation and fault interactions.

TI TEAM CEUS SSC PROJECT

Seismotectonic Setting and Seismic Sources of the Northern Gulf of Mexico

Michael Angell

William Lettis & Associates

February 20, 2009

Fundamental questions about seismic sources in the northern Gulf of Mexico.

- What are the causative mechanisms for earthquakes in the northern Gulf of Mexico?
- Are there definable seismic sources? If so, what criteria should be applied to differentiate them?
  - Seismicity pattern/rate
  - Crustal type
  - Age of crust
  - Individual (linear) structures

- If there are definable seismic sources, are they restricted to the Gulf of Mexico proper, or do some project onshore?

- Is there a connection between slip rates on growth faults and the rates of seismic activity?

- What is the maximum magnitude and distribution for seismic sources? What criteria should be applied to develop a distribution?

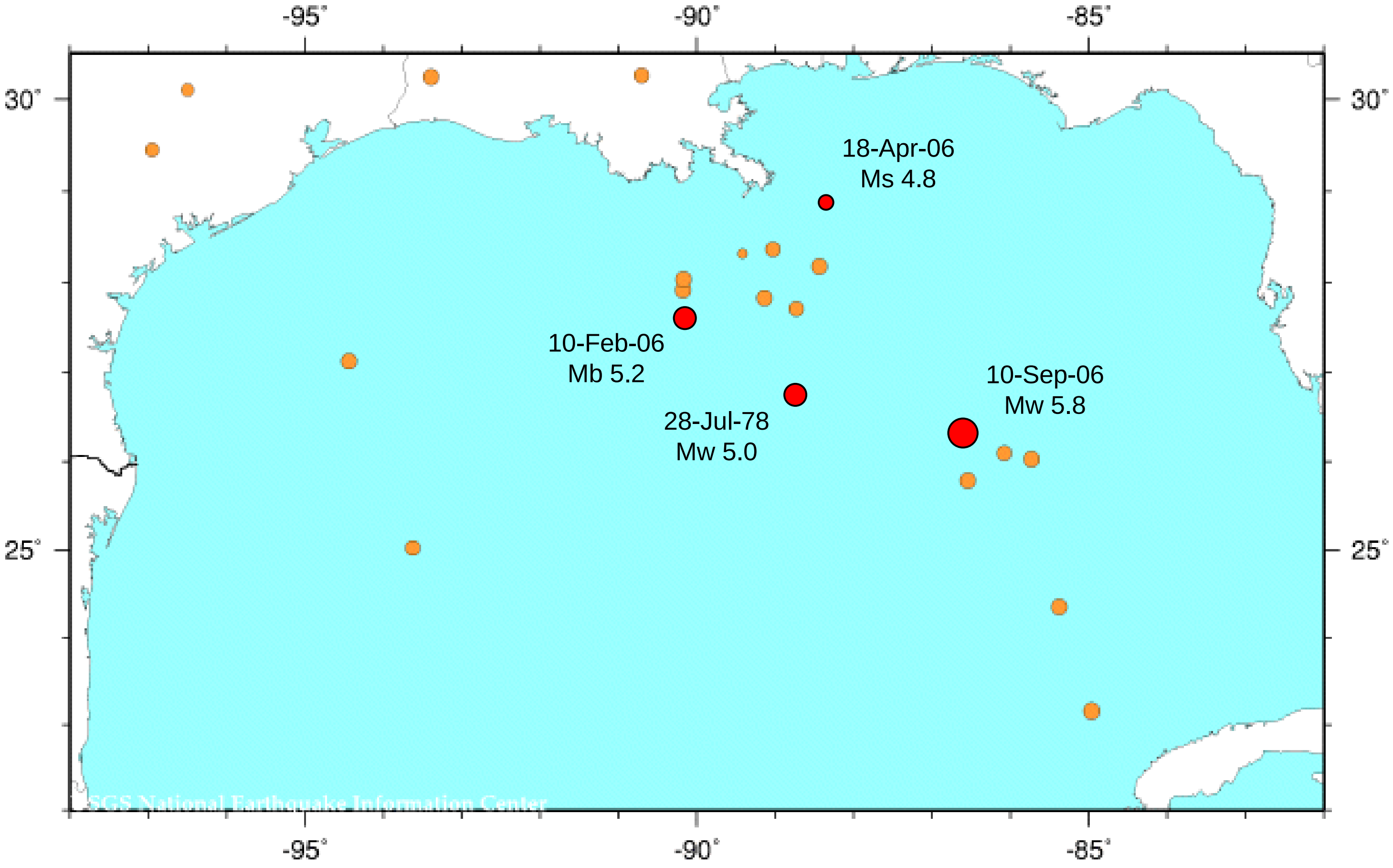
- How should rates be characterized if seismic sources were to be defined?

- What are the implications of different approaches to seismic hazard for the Gulf Coast population and infrastructure?

I - Historical Seismicity

Northern Gulf of Mexico

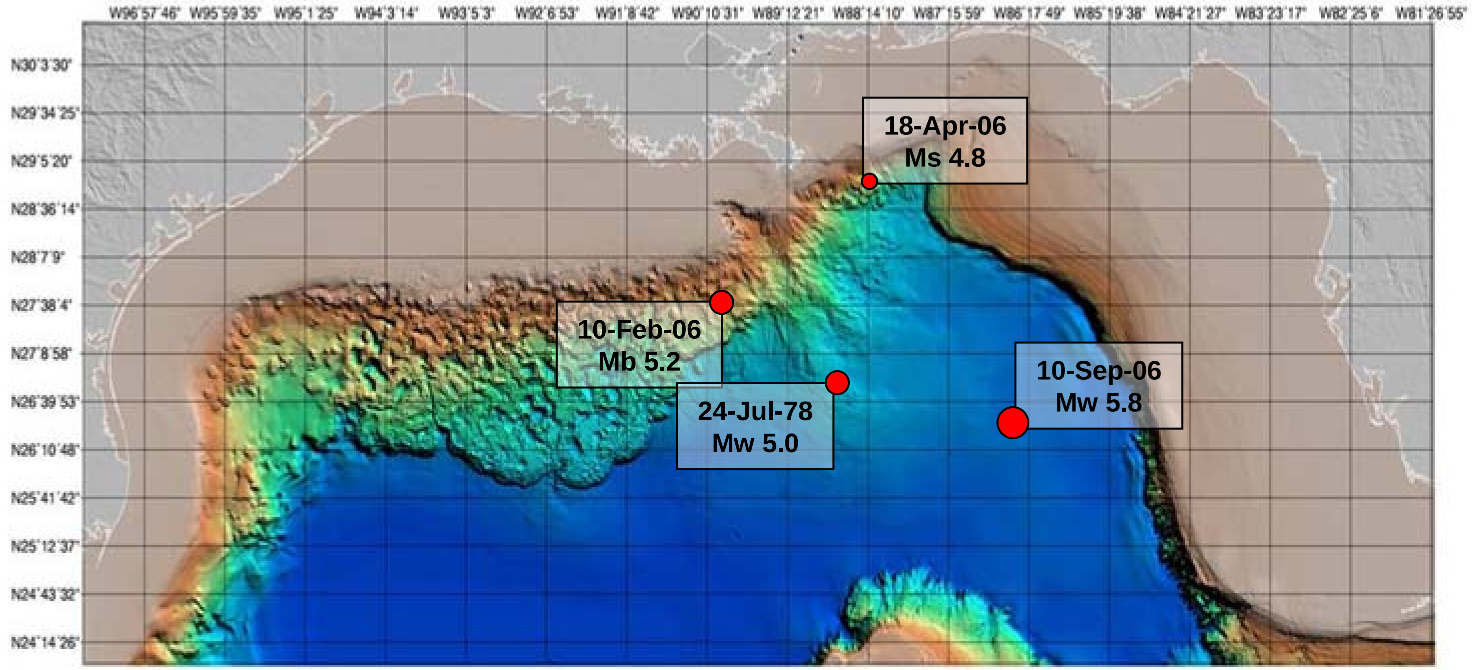
NEIC: Earthquake search results. Earthquakes of Mb >4.5 are shown in red.



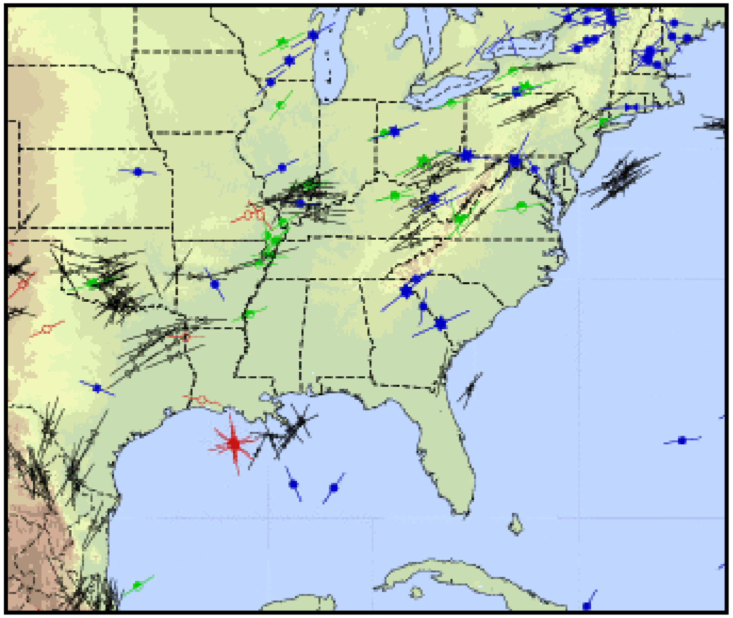
NEIC: Earthquake Search Results
Rectangular Grid Search
Latitude Range: 22 to 30.5
Longitude Range: -98 to -82
Number of Earthquakes: 21

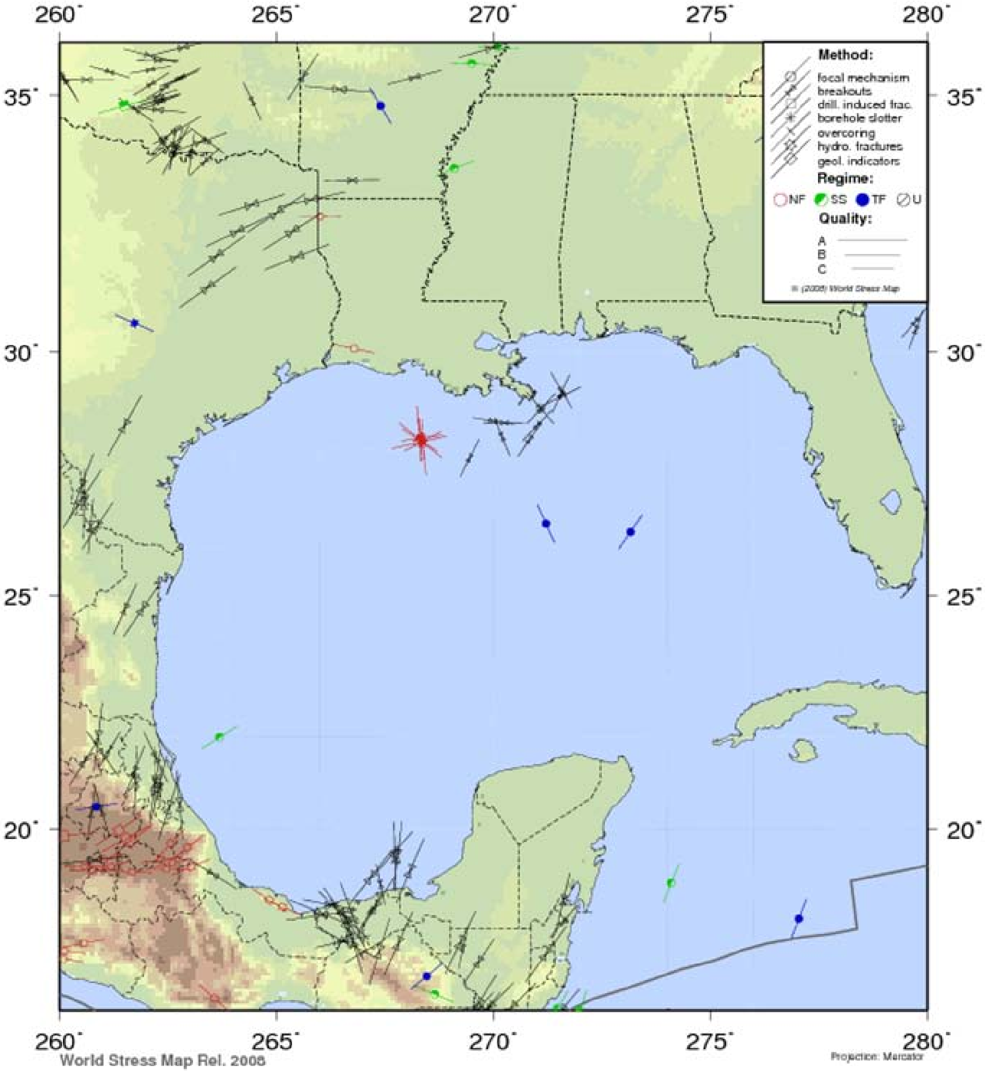
NOTE: This NEIC earthquake catalog has not been “cleaned” and may indicate an artificially higher than actual level of seismic activity. This is not the catalog being used by WLA.

Shaded relief detailed bathymetry of the northern Gulf of Mexico. The Hummocky brown region is the seafloor expression of diapirs, mini-basins and growth faults the northern Gulf of Mexico salt province. The smooth blue area represents the Mississippi fan (east) and deep ocean abyssal plain (west).



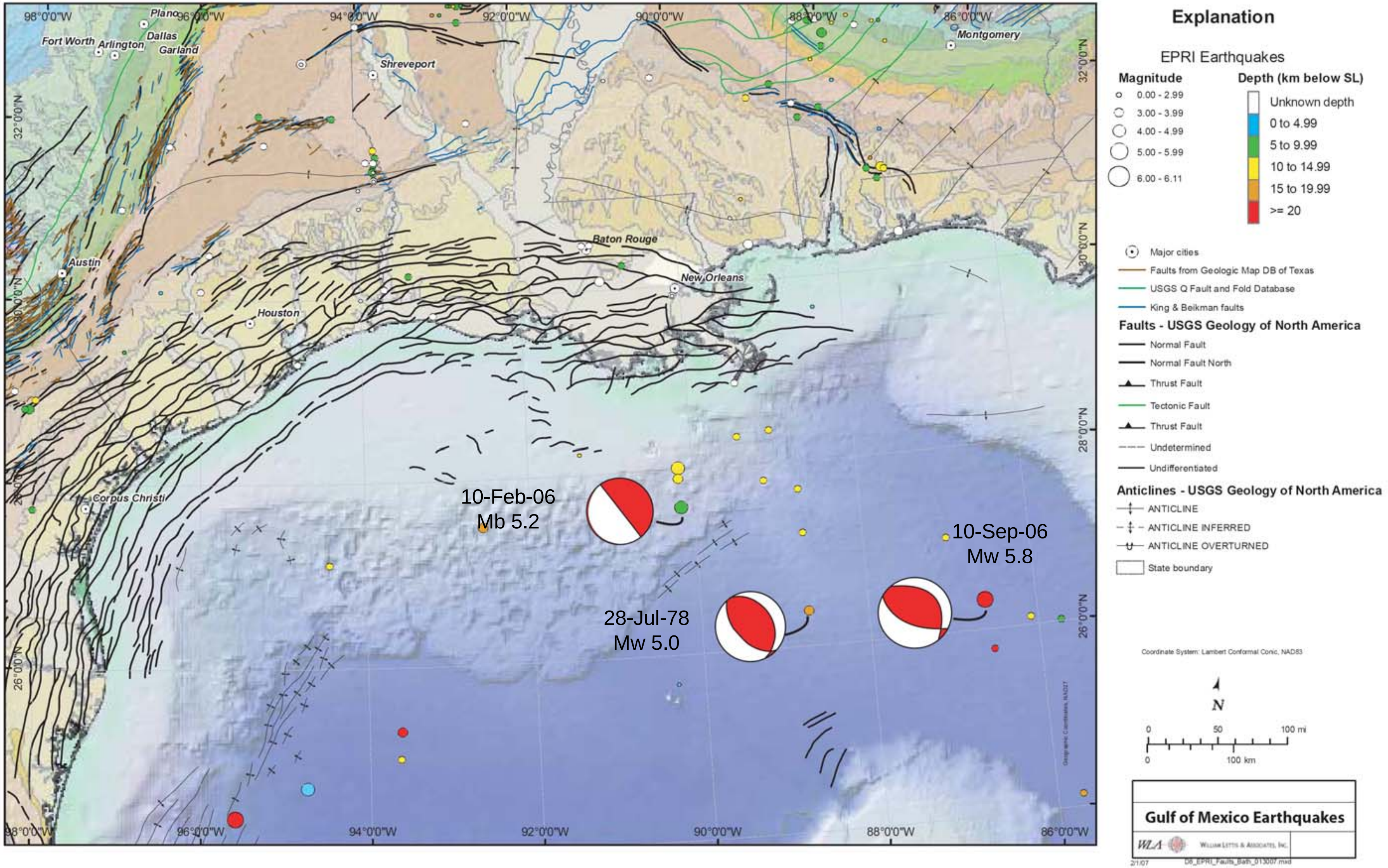
Stress indicators of the Central and Eastern US and the Gulf of Mexico (World Stress Map Project). Note anomalous stress pattern in the northern Gulf with exception of the 10 September event.





World Stress Map Rel. 2008
Heidelberg Academy of Sciences and Humanities
Geophysical Institute, University of Karlsruhe

WLA Seismicity and Fault Compilation Map. Focal mechanisms are shown for 2006 earthquakes >mb 5.0 and the 1978 Mw 5.0 event.

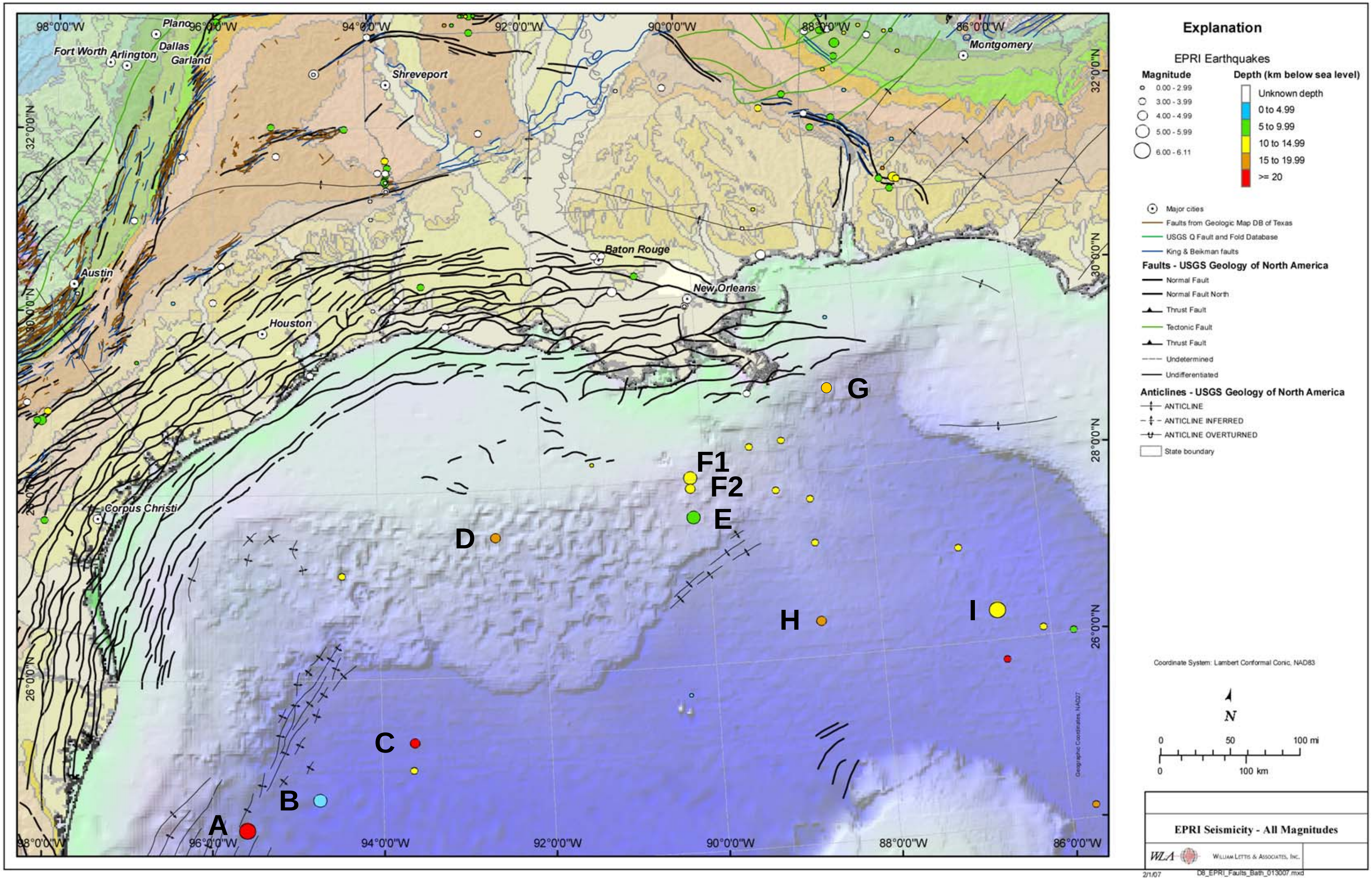


10-Feb-06
Mb 5.2

28-Jul-78
Mw 5.0

10-Sep-06
Mw 5.8

WLA Seismicity and Fault Compilation Map. Letters relate to earthquake parameter information on following two slides.



Northern Gulf of Mexico Earthquakes >M4.0 on WLA Map (26-feb-07)

ID	Catalog	Date	Mag	Depth	Loc’n	Mechanism
A[2]	ISC	30-jan-02	mb6.0	120	24.4/-95.6	NA
	NEIC		*Mw5.9*	*109*	*18.18/-95.91 (S GoM)*	NA
B[1]	ISC	18-sep-05	mb5.8	NA	24.72/-94.75	NA
			Mw5.7		*24.48/94.71 (India)*	
C[1]	ISC	13-may-93	mb4.06	20	25.31/-93.62	NA
			<mb4.1 (no surface waves)			NA
D	NEIC	05-nov-63	mb4.71	15	27.40/-92.58	NA
E	NEIC	10-feb-06	mb4.2	5	27.60/-90.16	NA
	LDEO		Ms5.2	>6		N,90/0,NE-SW
F1[2]	ANSS	09-dec-00	mb5.2	10	28.03/-90.17	NA
	NEIC		*mb4.2/Ms4.3 (larger?)*			
F2	NEIC	30-Jun-94	mb4.2	10	27.91/-90.18	NA
	LDEO		*>mb4.2? (on surface waves)*			
G[1]	LDEO	18-apr-06	Ms4.8	NA	28.25/-88.25	N,~90/0,NW-SE
H	NEIC	24-jul-78	mb4.9	33	26.73/-88.74	NA
	Frohlich ’82		Mw5.0	15+/-2	26.49/-88.79	R,~45,NW-SE
I	NEIC	10-sep-06	mb5.9	14	26.34/-86.57	R,28/65,NE-SW
	USGS		Mw5.8	10	26.33/-86.58	R,47/52,NE-SW
	ANSS		mb6.11	NA		

[1] Not present in NEIC/PDE catalog

[2] Check this EQ

Notes in *italics* are comments from M. Nettles (LDEO)

Notes on Specific Earthquakes (comments by M. Nettles, LDEO: email of 23 February 2007)

Event A: This is probably a mislocation of an earthquake (which is in the NEIC catalog) at 18.18, -95.91, depth = 109 km, MW 5.9. The location comes from ETH Zurich, not directly from the ISC.

Event B: Nettles does not think this is a real earthquake. The earthquake identification and location comes from an Algerian organization, not the ISC directly, and I think they have misidentified phases belonging to an MW 5.7 earthquake near the India/Burma border (at 24.48 N, 94.71 E) at 07:25:59.5.

Event C: This earthquake is reported by the Central American Seismic Agency; it may be a real event, but there is no sign of any surface waves, which means it probably was substantially smaller than the reported md 4.2.

Event E: According to Nettles the MS for this event is 5.2, but the mb is 4.1, consistent with a relative depletion in high-frequency energy. (Of course, there were only 4 observations for mb, so the value of 4.1 is probably pretty uncertain -- but the lack of high-f energy also explains a lack of mb observations). Interpreted as consistent with landslide source mechanism.

Event F1: Nettles had not had a chance to model the seismograms, but there is definitely energy in the surface waves. I actually see values of mb 4.2/MS 4.3 in the NEIC catalog, rather than the 5.2 you list – but the surface waves are big enough that I would guess the true size of the earthquake might be substantially larger than 4.2/4.3.

Event F2: As for F1, I have not modeled the seismograms, but again I would say that the surface waves look like the event could be somewhat bigger than the reported mb 4.2.

Event G: Possible slide event. Magnitude of Ms 4.8. Represented by Nettles (2006) as downslope movement of salt diapir on the lower continental slope.

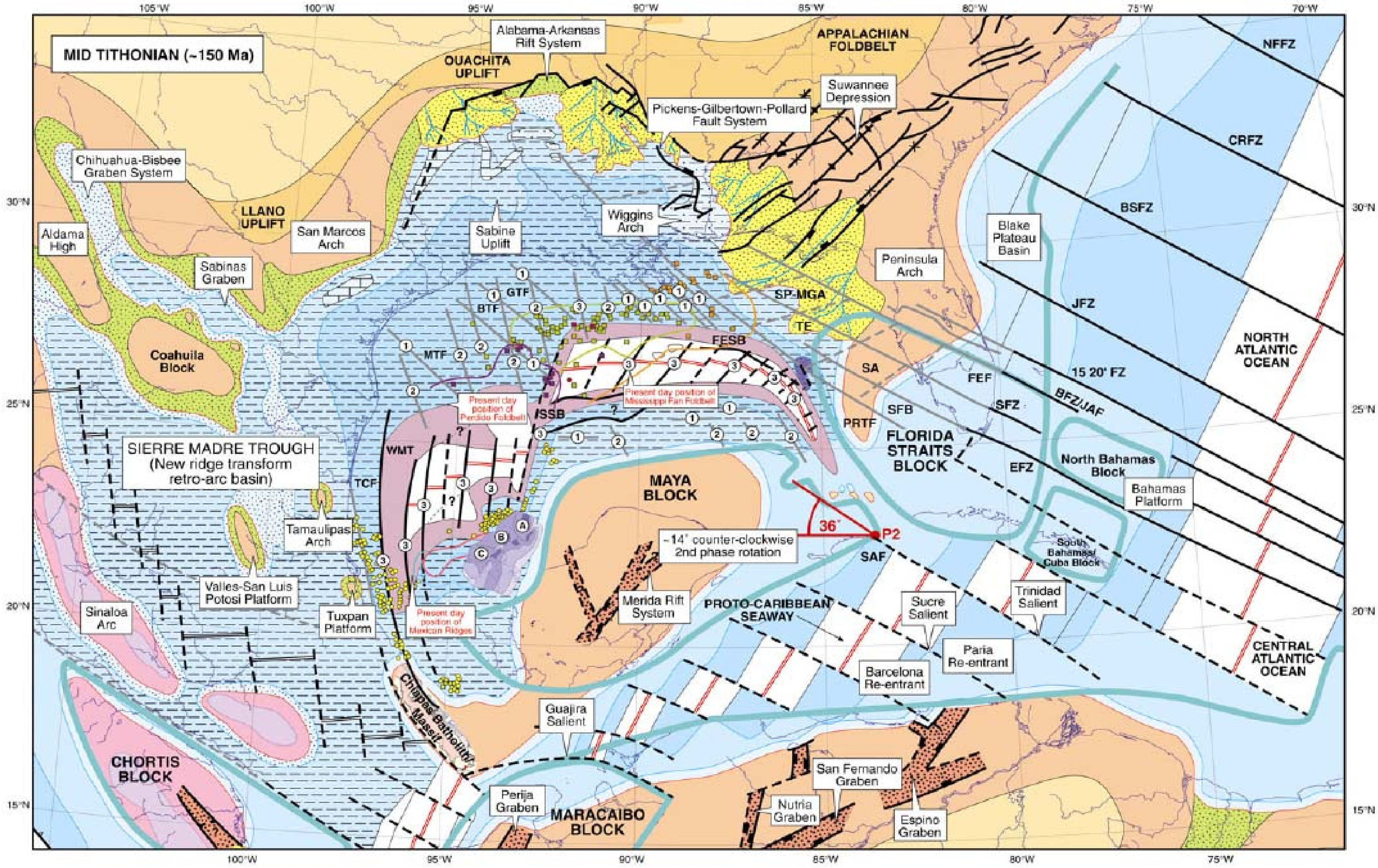
Event H: Magnitude MW 5.0. Focal mechanism indicates NW-SE directed compression, not consistent with the regional tectonic stress direction. Interpreted as tectonic event by Frohlich (1984).

Event I: Magnitude Mw 5.8. Focal mechanism indicates NE-SW compression, consistent with regional tectonic stress. Interpreted as tectonic event by Nettles (personal communication, 2006).

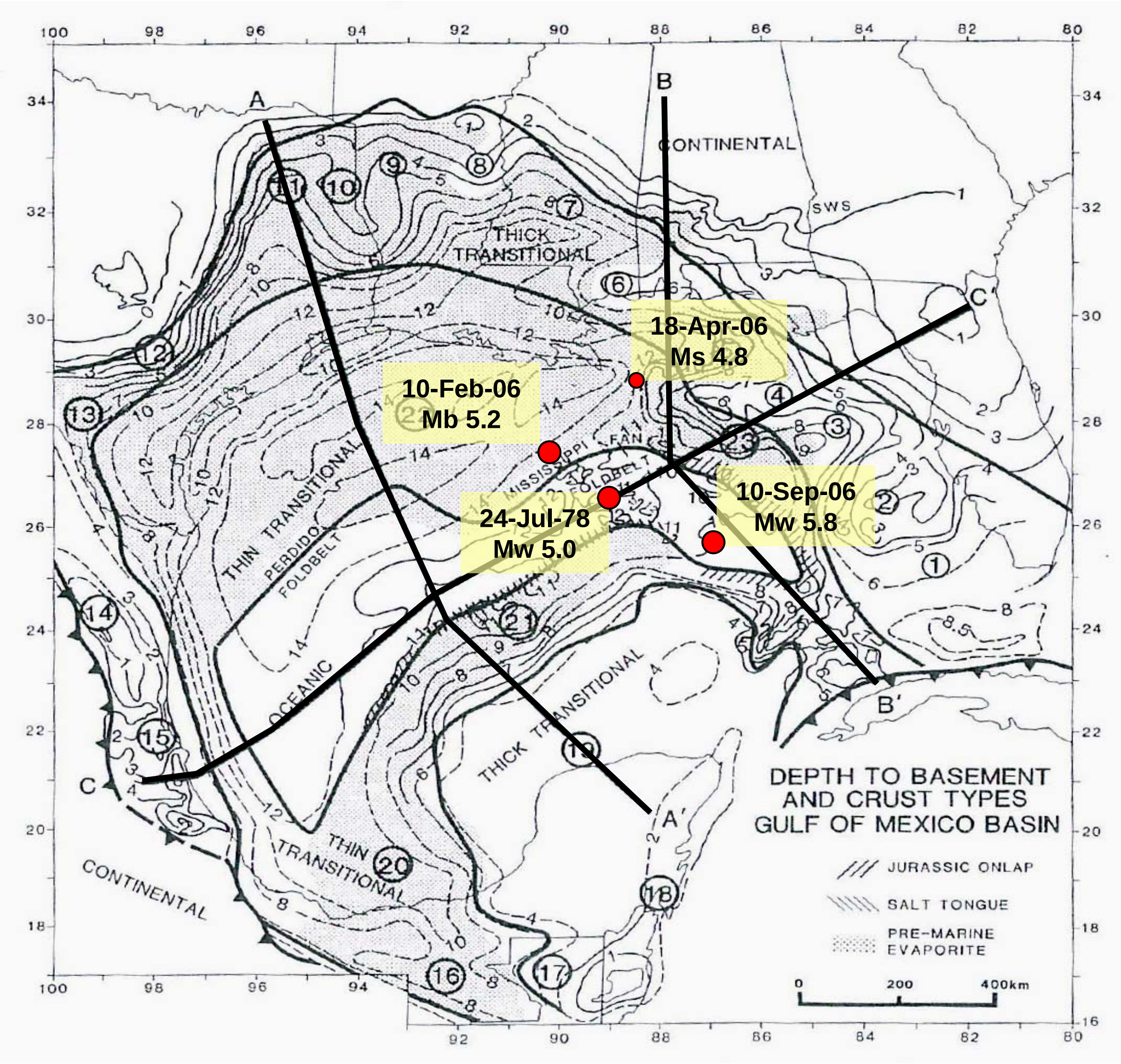
II - Tectonic Setting

Northern Gulf of Mexico

Latest Jurassic (Tithonian) tectonic reconstruction of the Gulf of Mexico and Caribbean region (from Jacques et al., 2004).



Basement map of the Gulf of Mexico (Sawyer et al, 1991; Figure 1, Chap 2, DNAG-J). Cross sections are shown in the following figures.



DEPTH TO BASEMENT AND CRUST TYPES GULF OF MEXICO BASIN

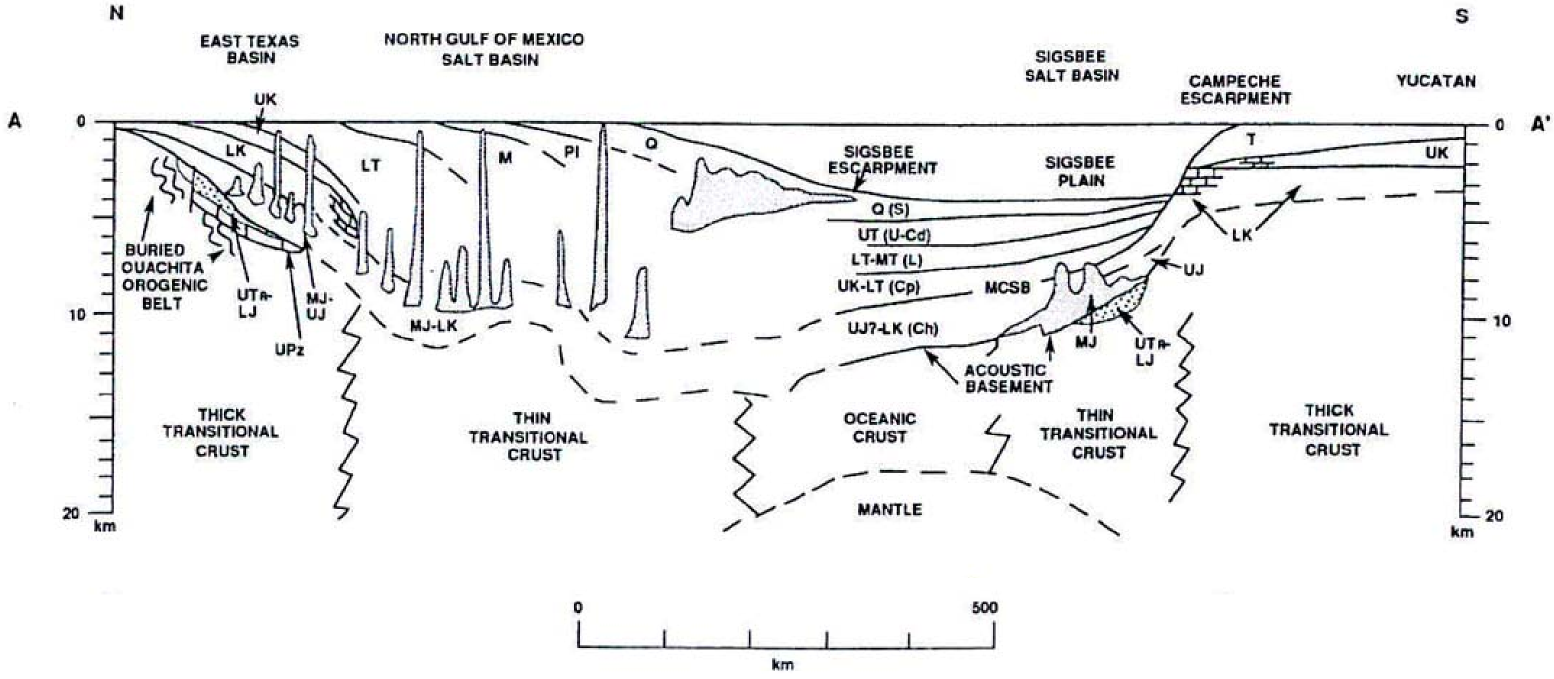
18-Apr-06 Ms 4.8

10-Feb-06 Mb 5.2

10-Sep-06 Mw 5.8

24-Jul-78 Mw 5.0

Schematic north-south cross section A-A' of the central Gulf of Mexico Basin. Location on slide 16 (Sawyer et al, 1991; Figure 1, Chap 2, DNAG-J).



Q - QUATERNARY

Pl - PLIOCENE

M - MIOCENE

UT - UPPER TERTIARY

MT - MIDDLE TERTIARY

LT - LOWER TERTIARY

T - TERTIARY

UK- UPPER CRETACEOUS

MCSB - MID-CRETACEOUS SEQUENCE BOUNDARY

LK - LOWER CRETACEOUS

UJ - UPPER JURASSIC

MJ - MIDDLE JURASSIC

LJ - LOWER JURASSIC

J - JURASSIC

UTR - UPPER TRIASSIC

UPz - UPPER PALEOZOIC

Pz - PALEOZOIC

LK PLATFORM MARGIN

DEFORMED MJ SALT

SEISMIC SEQUENCES (SHAUB AND OTHERS, 1984)

Ch - CHALLENGER

Cp - CAMPECHE

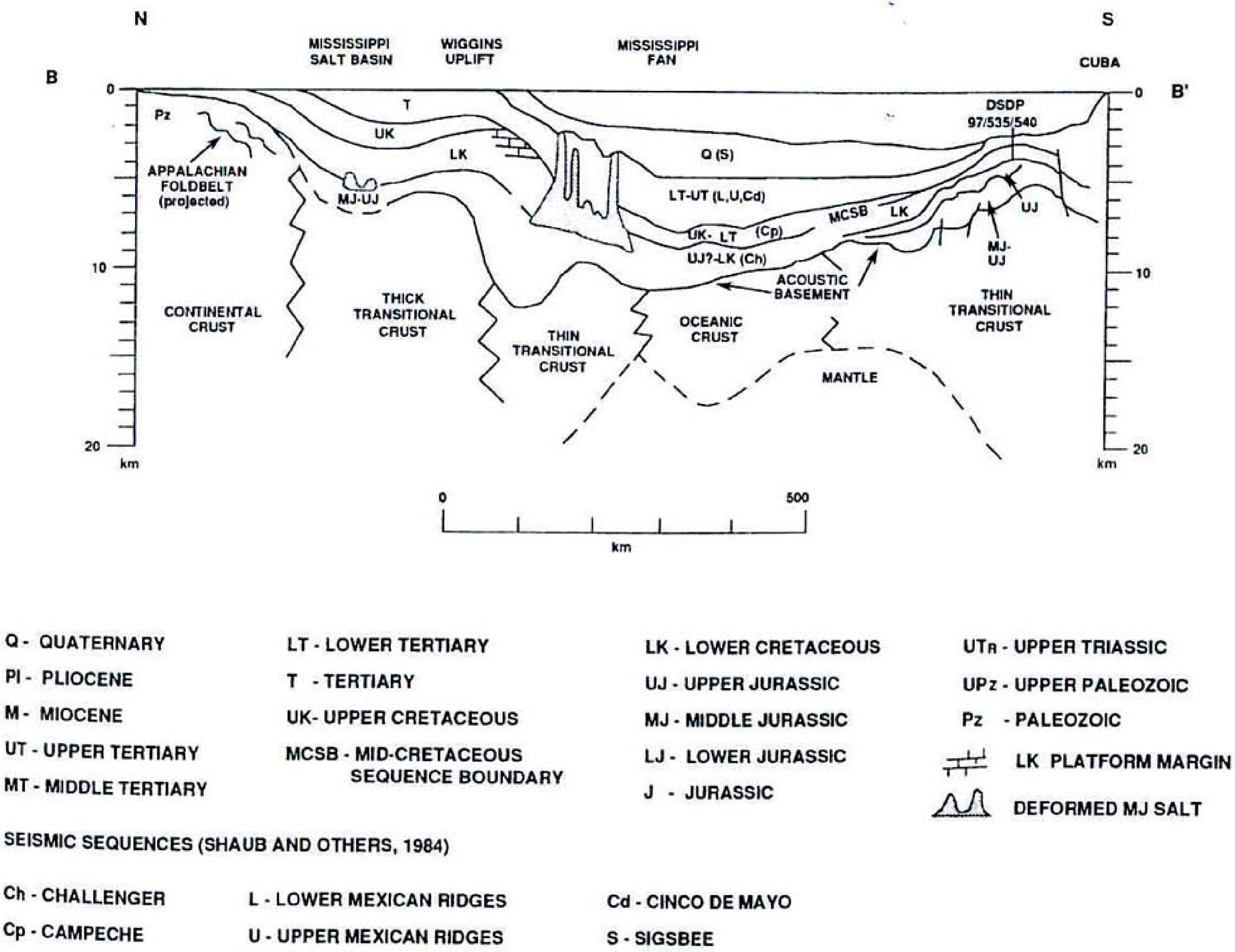
L - LOWER MEXICAN RIDGES

U - UPPER MEXICAN RIDGES

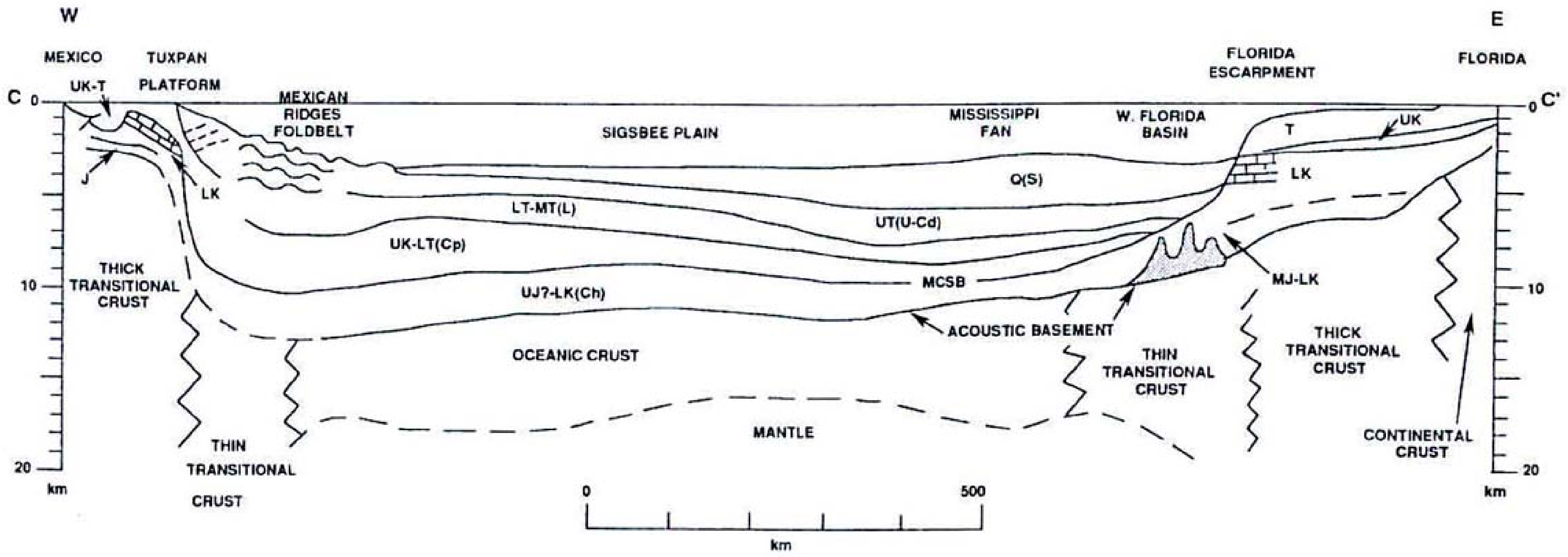
Cd - CINCO DE MAYO

S - SIGSBEE

Schematic north-south cross section B-B' of the eastern Gulf of Mexico Basin. Location on slide 16 (Sawyer et al, 1991; Figure 1, Chap 2, DNAG-J).



Schematic northeast-southwest cross section C-C' across the Gulf of Mexico Basin. (Sawyer et al, 1991; Figure 1, Chap 2, DNAG-J).



Q - QUATERNARY

PI - PLIOCENE

M - MIOCENE

UT - UPPER TERTIARY

MT - MIDDLE TERTIARY

LT - LOWER TERTIARY

T - TERTIARY

UK- UPPER CRETACEOUS

MCSB - MID-CRETACEOUS SEQUENCE BOUNDARY

LK - LOWER CRETACEOUS

UJ - UPPER JURASSIC

MJ - MIDDLE JURASSIC

LJ - LOWER JURASSIC

J - JURASSIC

UTR - UPPER TRIASSIC

UPz - UPPER PALEOZOIC

Pz - PALEOZOIC

LK PLATFORM MARGIN

DEFORMED MJ SALT

SEISMIC SEQUENCES (SHAUB AND OTHERS, 1984)

Ch - CHALLENGER

Cp - CAMPECHE

L - LOWER MEXICAN RIDGES

U - UPPER MEXICAN RIDGES

Cd - CINCO DE MAYO

S - SIGSBEE

Four published interpretations (pre-1980) showing the distribution of oceanic crust in the Gulf of Mexico (Hall et al, 1982).

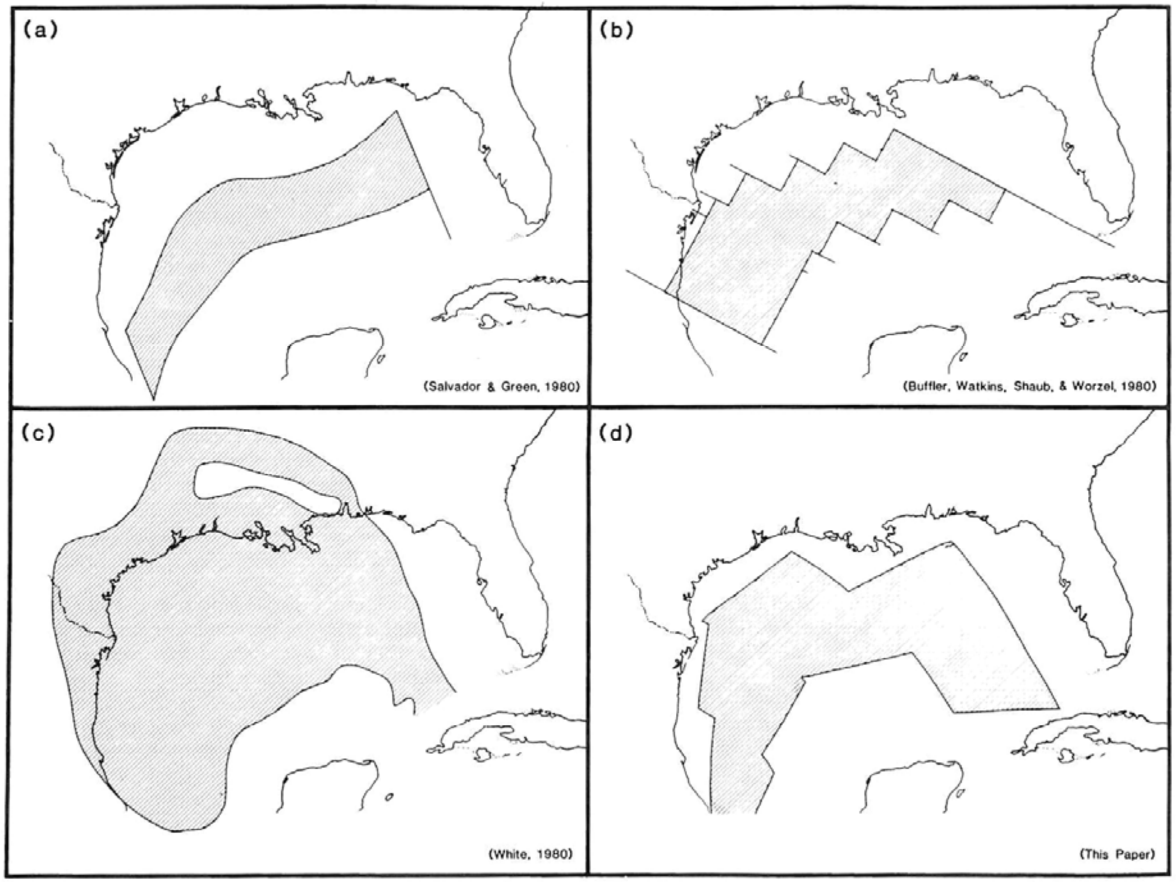
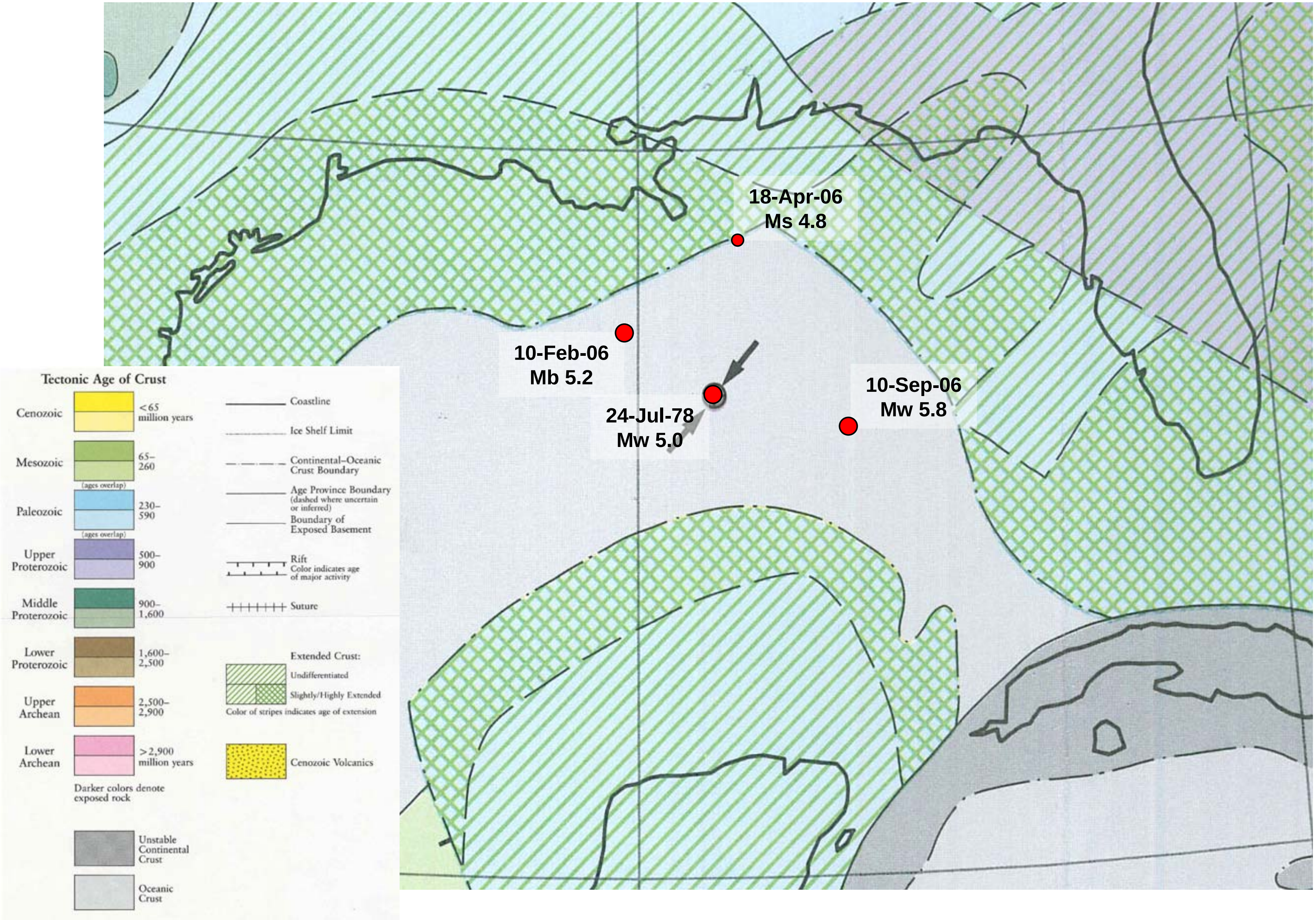
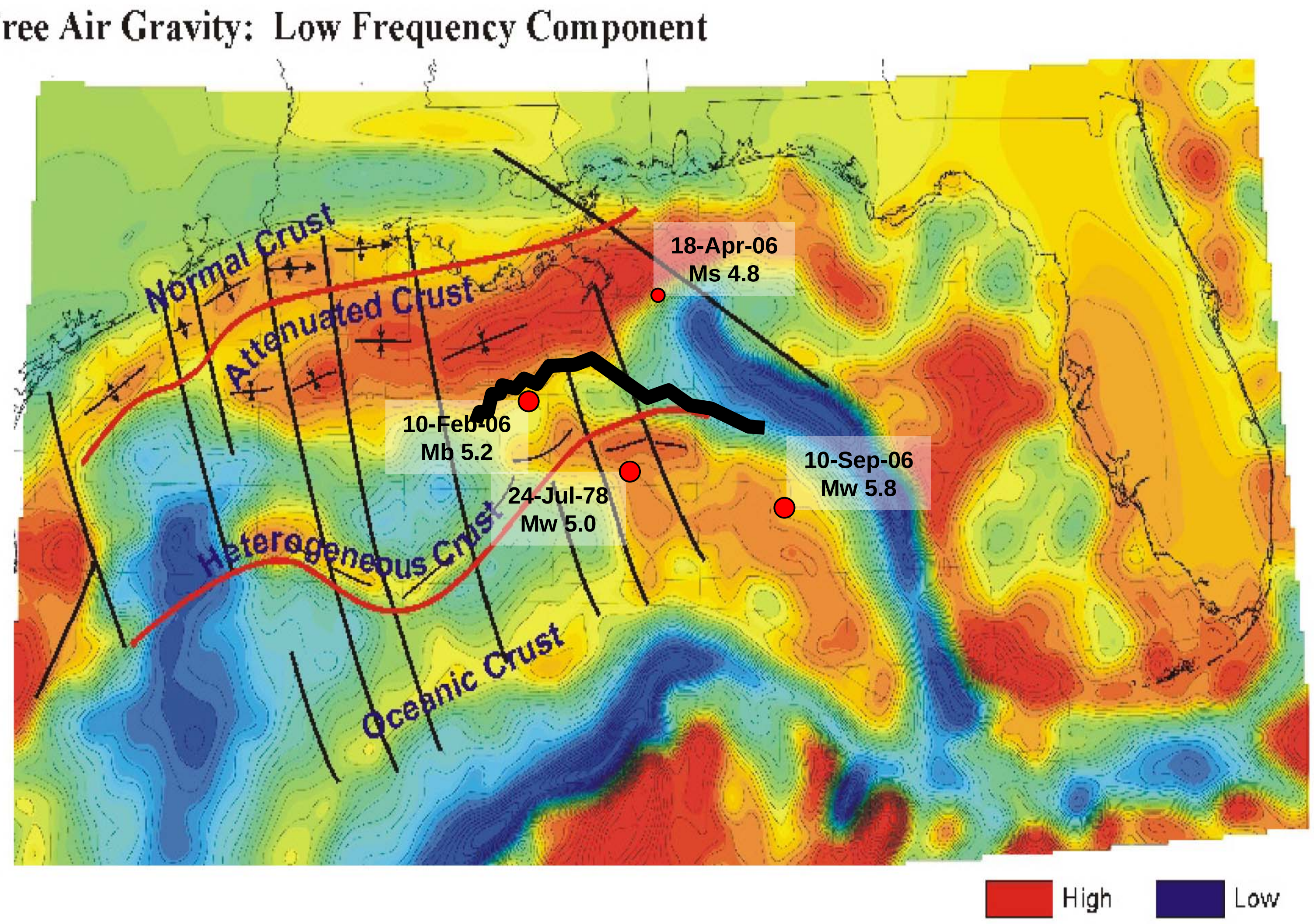


Figure 1 — Distribution of crustal types around the Gulf of Mexico according to four different recent interpretations.
a. Kimmeridgian reconstruction after Salvador and Green (1980). Ruled area is oceanic crust.
b. Diagrammatic Late Jurassic oceanic spreading pattern after Buffler et al (1980). Ruled area is oceanic crust. Surrounding area is largely transitional crust.
c. Limits of pre-Mesozoic continental crust after White (1980). Ruled area is oceanic or greatly attenuated continental crust. White area in Louisiana is the Wiggins Arch.
d. Outline of oceanic crust based on interpretation of free-air gravity data in this paper (Figure 4).

Tectonic map of northern Gulf of Mexico region of the North American Stable Cratonic Region. Divisions of crust type and age by EPRI (1994).

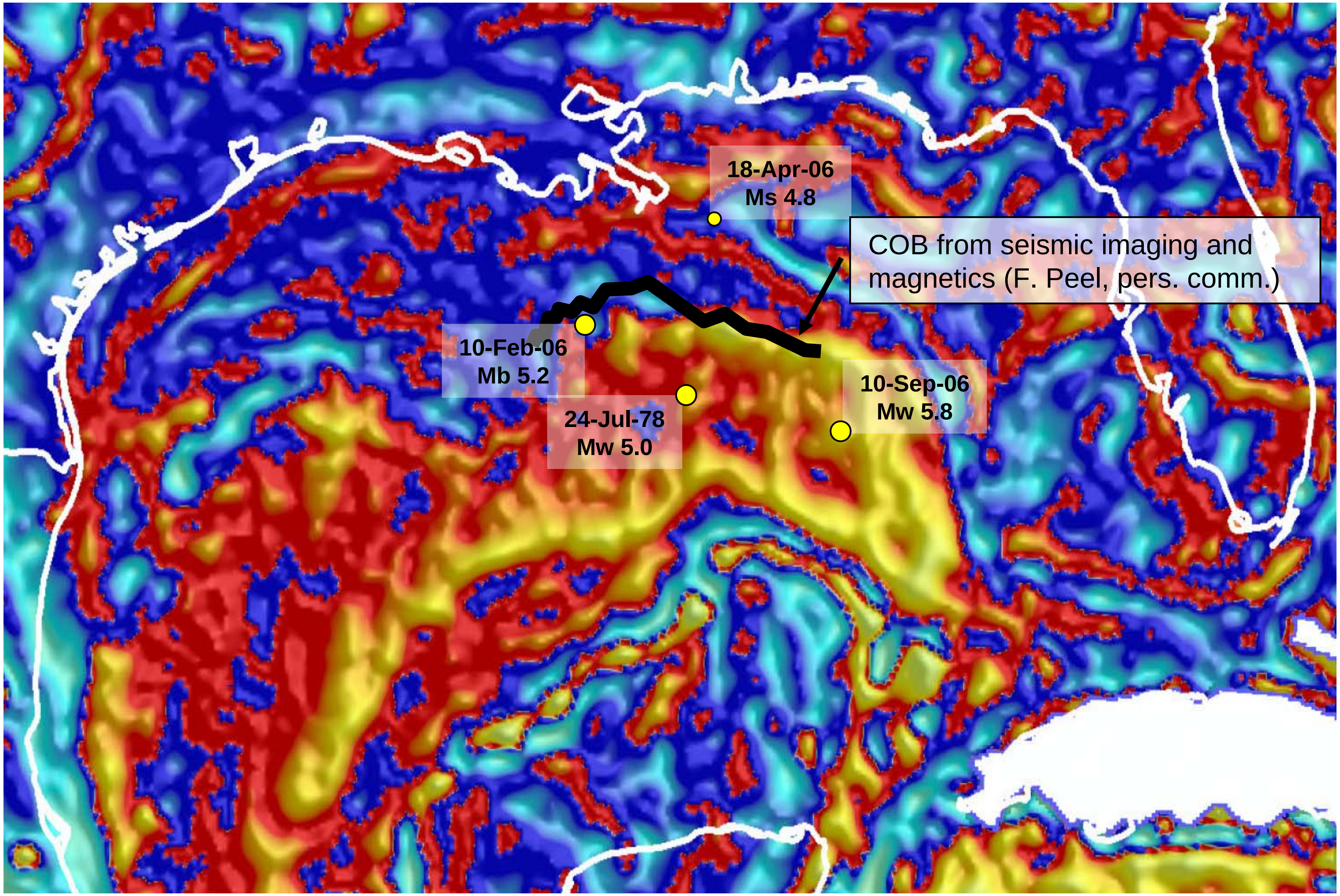


Regional free air gravity map (low-frequency), Northern Gulf of Mexico (from Karlo and Shoup, 2000).



Continent-ocean boundary from F. Peel, pers. Comm.

Pseudo-lithology map of the Gulf of Mexico from compilation of gravity and magnetic data. The central region in warm colors is inferred to be oceanic crust (from Jacques et al., 2004).

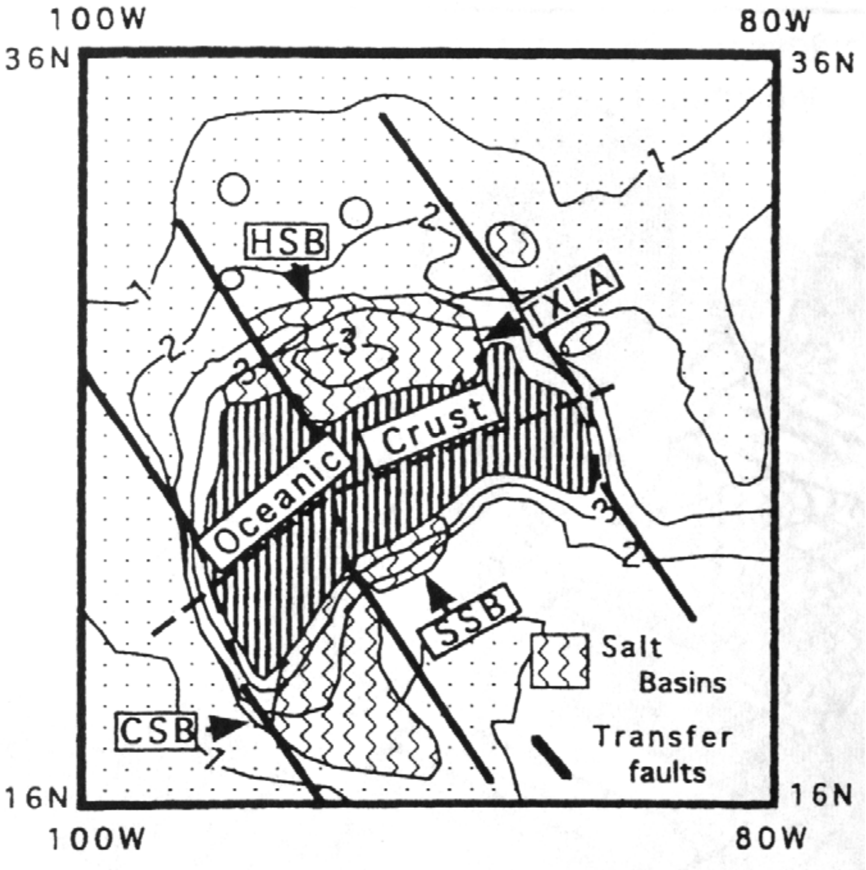


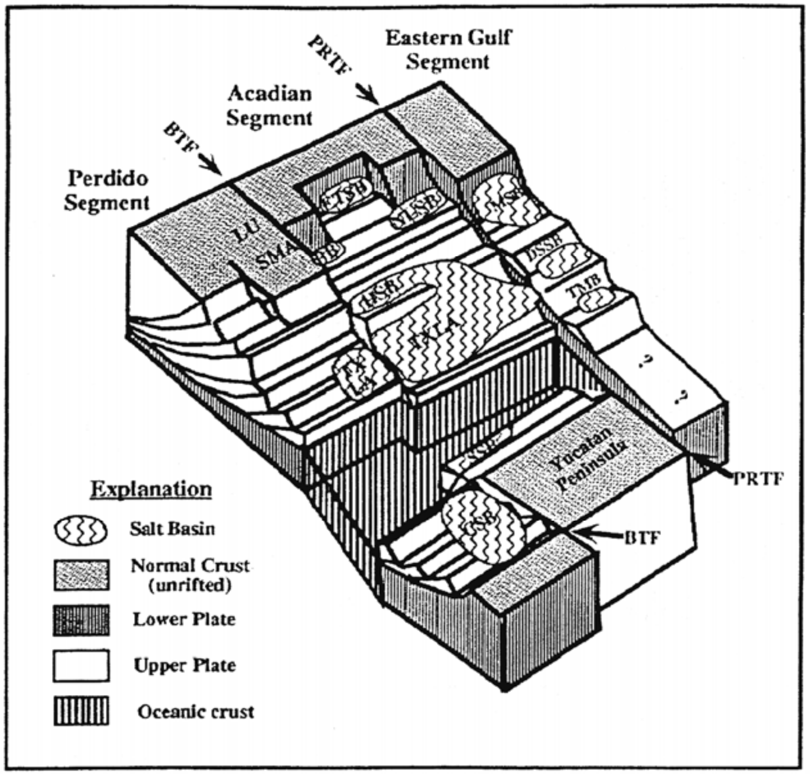
COB from seismic imaging and magnetics (F. Peel, pers. comm.)

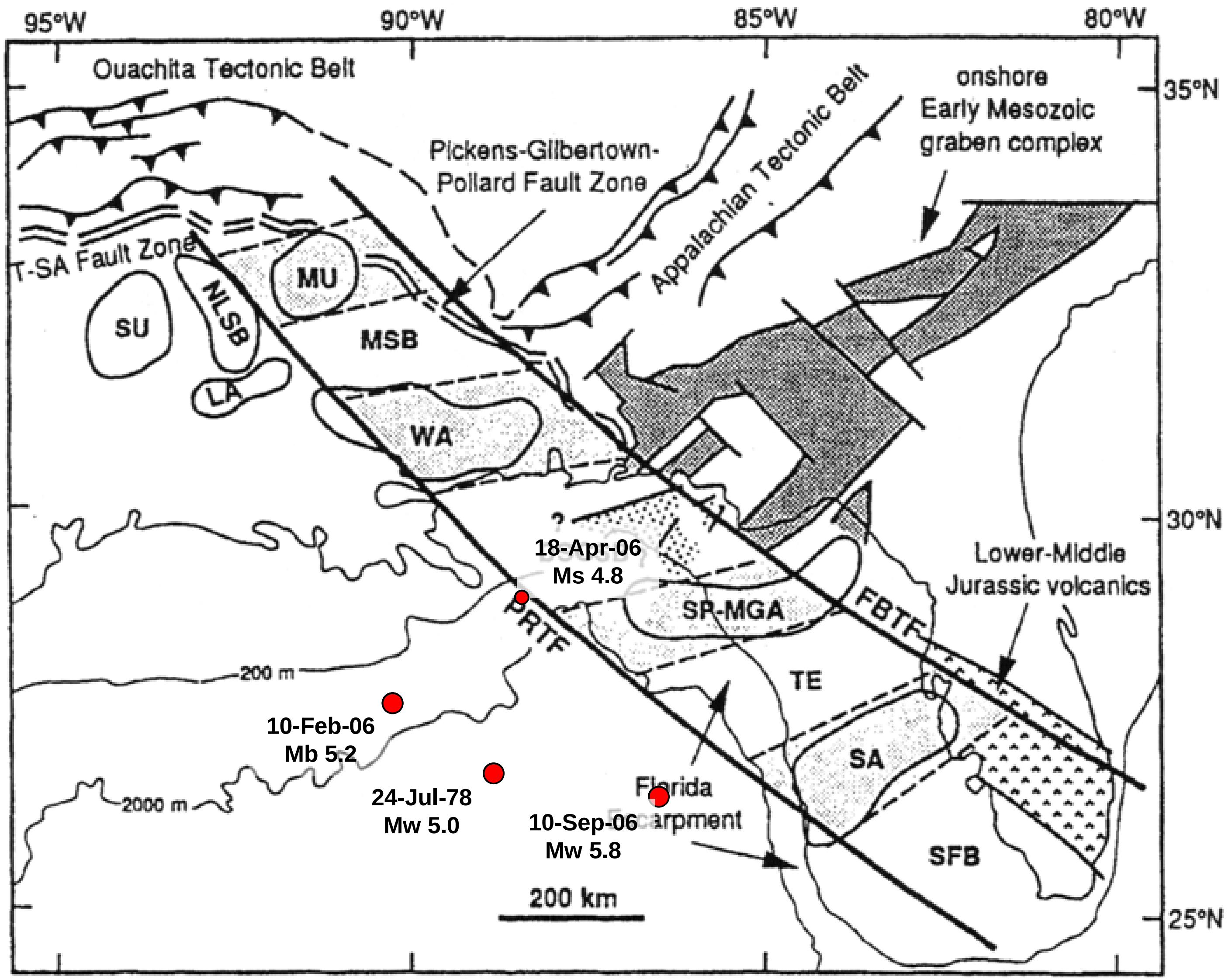
Continent-ocean boundary from F. Peel, pers. Comm.

Regional basement structures beneath the Gulf of Mexico (from Watkins et al, 1996).

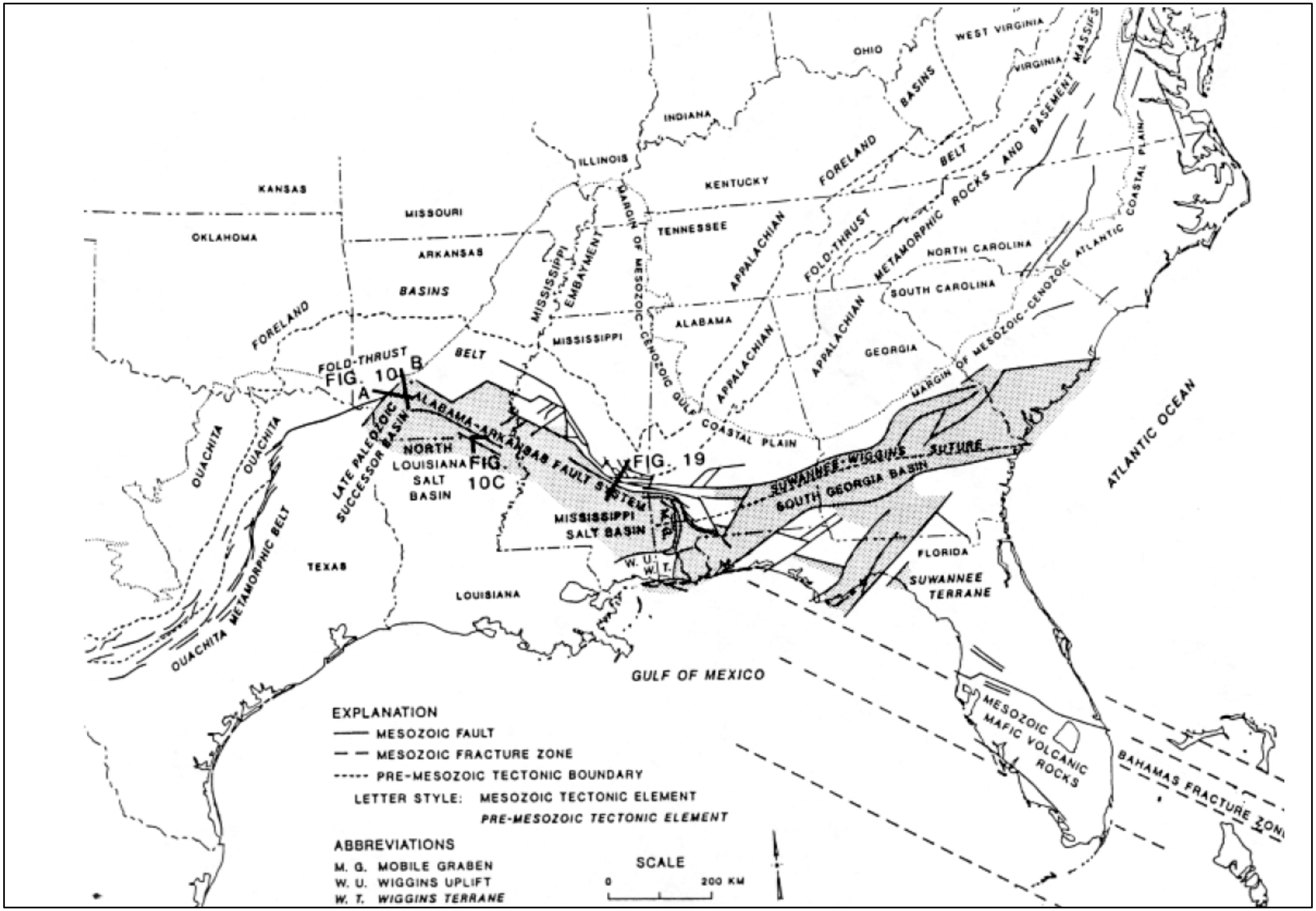
These regional basement structures may be possible sources of seismicity.






95°W
90°W
85°W
80°W
35°N
30°N
25°N
Ouachita Tectonic Belt
Pickens-Gilbertown-
Pollard Fault Zone
Appalachian Tectonic Belt
onshore
Early Mesozoic
graben complex
T-SA Fault Zone
MU
SU
NLSB
MSB
LA
WA
?
18-Apr-06
Ms 4.8
SP-MGA
PRTF
FBTF
Lower-Middle
Jurassic volcanics
TE
200 m
10-Feb-06
Mb 5.2
SA
2000 m
24-Jul-78
Mw 5.0
Florida
Escarpment
10-Sep-06
Mw 5.8
SFB
200 km

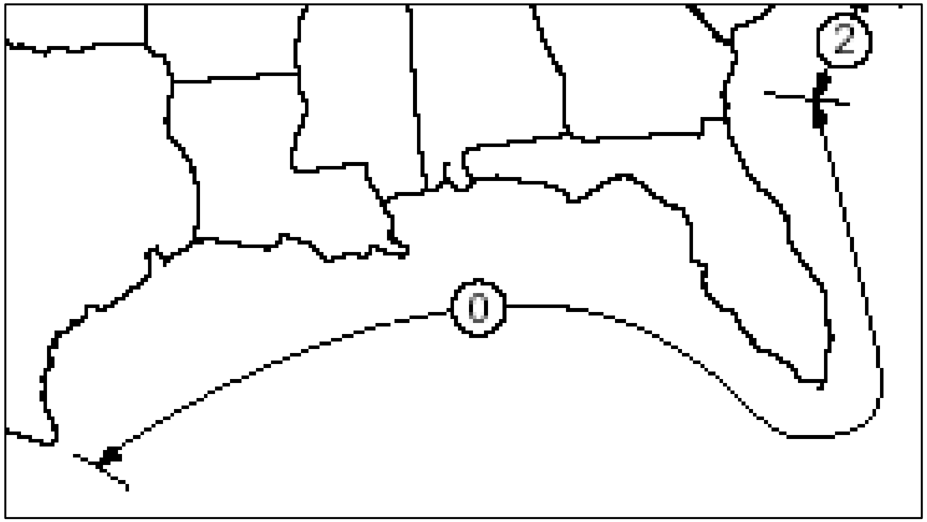
Early Mesozoic transform fault system and regional tectonic elements related to the formation of the Gulf of Mexico (Figure 4 of Bird, 2001; map after Buffler and Thomas, 1994).



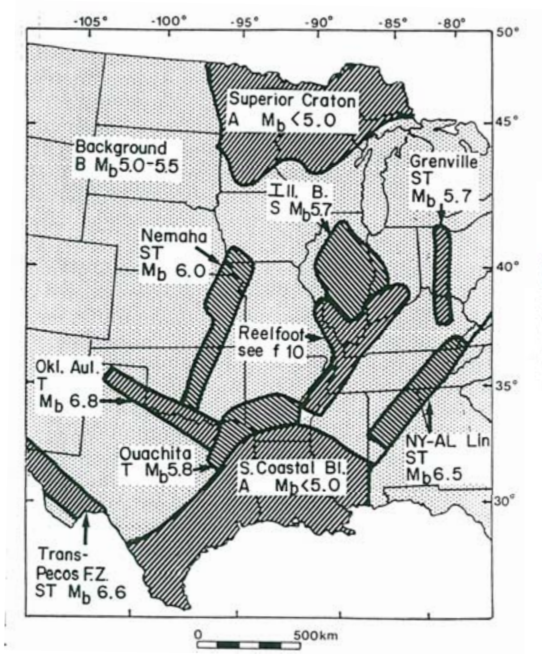
III - Seismic Source Models

Northern Gulf of Mexico

American Petroleum Institute Seismic Risk Zonation for Offshore United States. The Gulf of Mexico is assigned Level 0, indicating no expected hazard from earthquakes (design level ground motion of 0.2 g).



Seismic source zones for the central US. Note boundary and Mmax for the Gulf of Mexico coastal plain according to Johnston and Nava (1990).



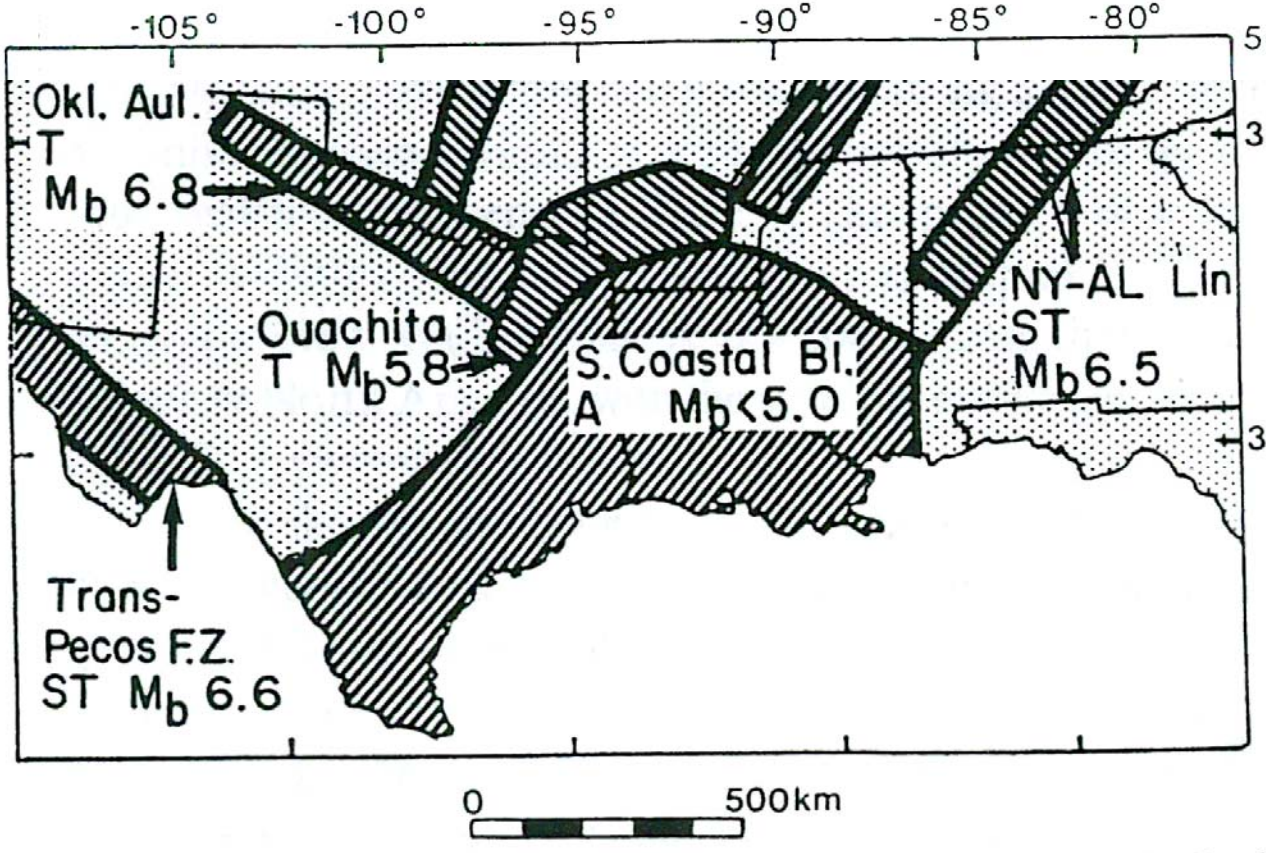
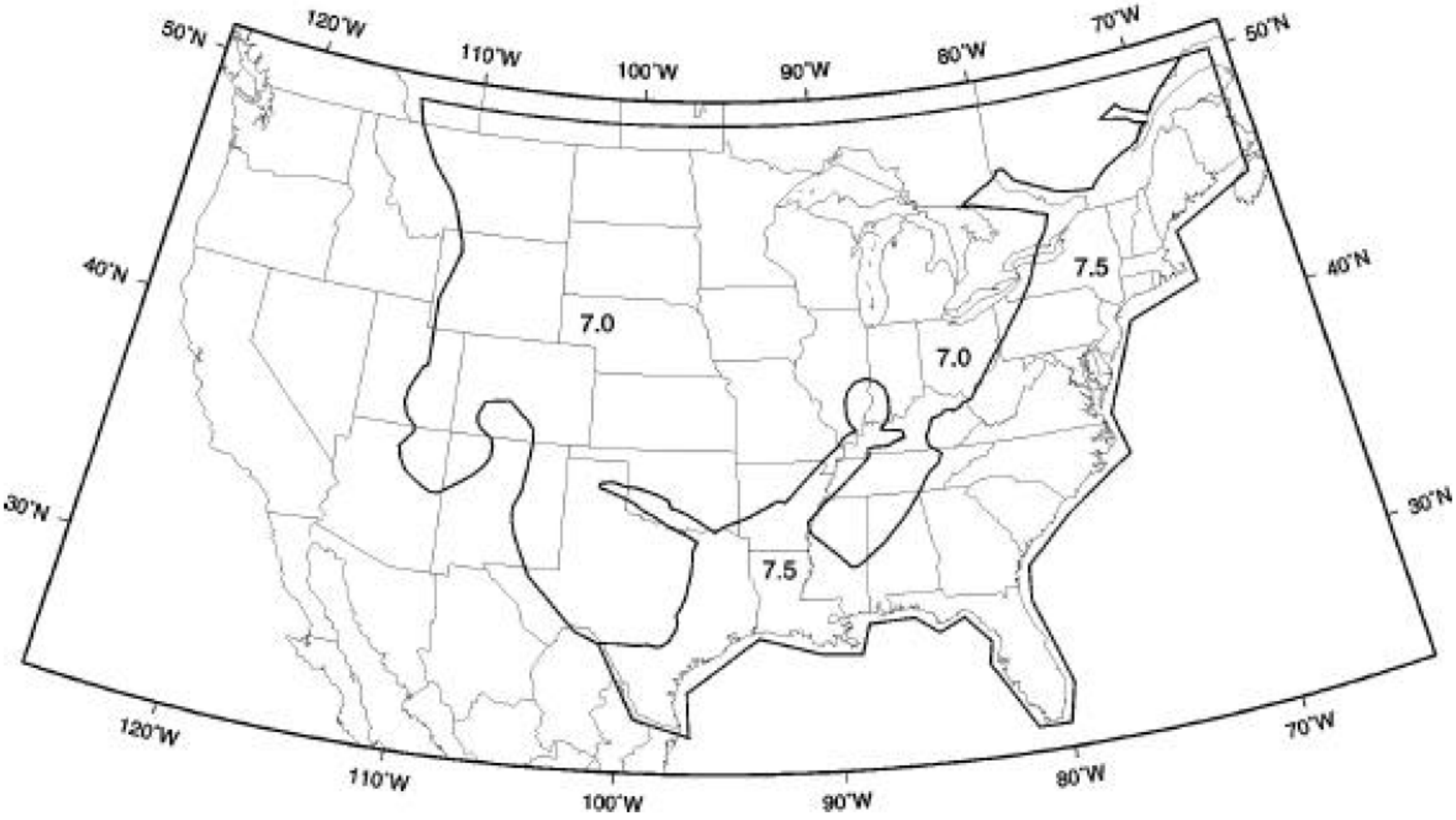


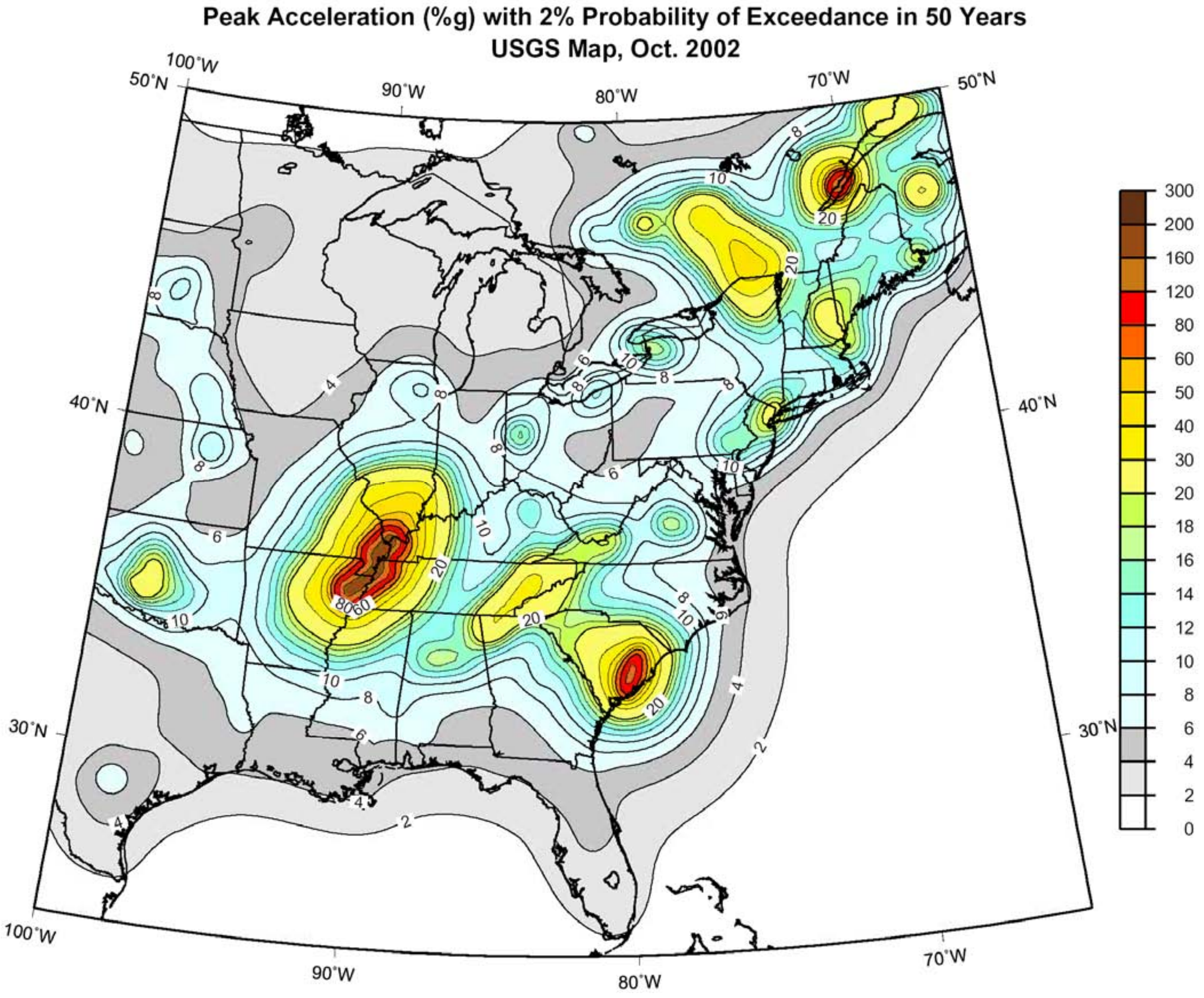
Figure 9 from Johnston and Nava, 1990 - Seismic hazard assessment in the central United States: GSA Reviews in Engineering Geology

Maximum magnitude source zones for the Central and Eastern U.S. used for the USGS National Seismic Hazard Maps (Frankel et al, 2002)

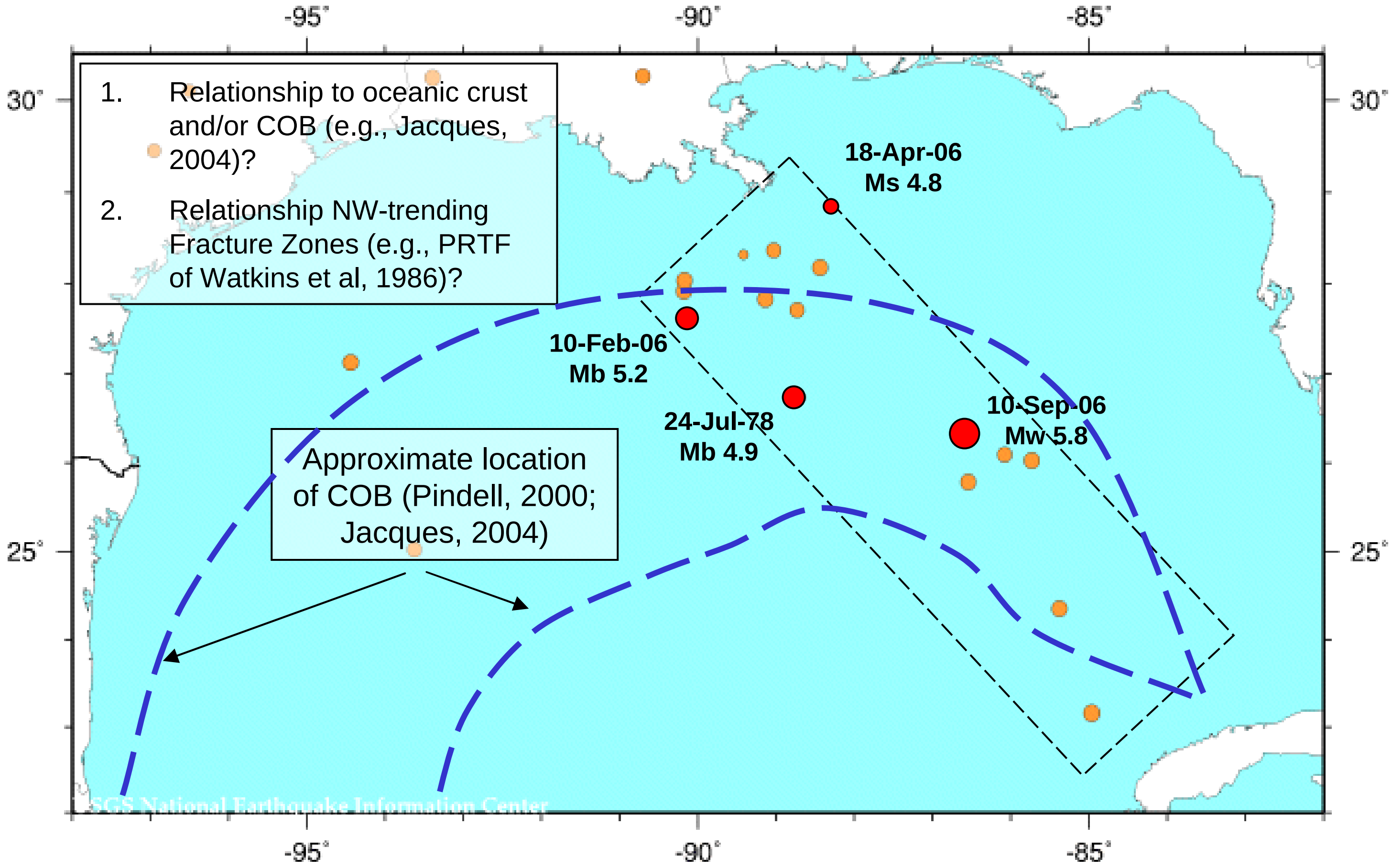
CEUS maximum-magnitude zones



USGS Seismic Hazard Map for the Eastern and Central US. The higher expected ground motions result from a conservative estimate of Mmax=7.5 for the entire Northern Gulf of Mexico.



Apparent alignment of seismicity suggests a possible underlying source and association with deep structure. Note: This northwest trend is reflected in the distribution of major offshore oilfields. Possible source models include seismicity trend, crustal types and contacts, and individual structures.



1. Relationship to oceanic crust and/or COB (e.g., Jacques, 2004)?
2. Relationship NW-trending Fracture Zones (e.g., PRTF of Watkins et al, 1986)?

Approximate location of COB (Pindell, 2000; Jacques, 2004)

NEIC: Earthquake Search Results

Rectangular Grid Search

Latitude Range: 22 to 30.5

Longitude Range: -98 to -82

Number of Earthquakes: 21

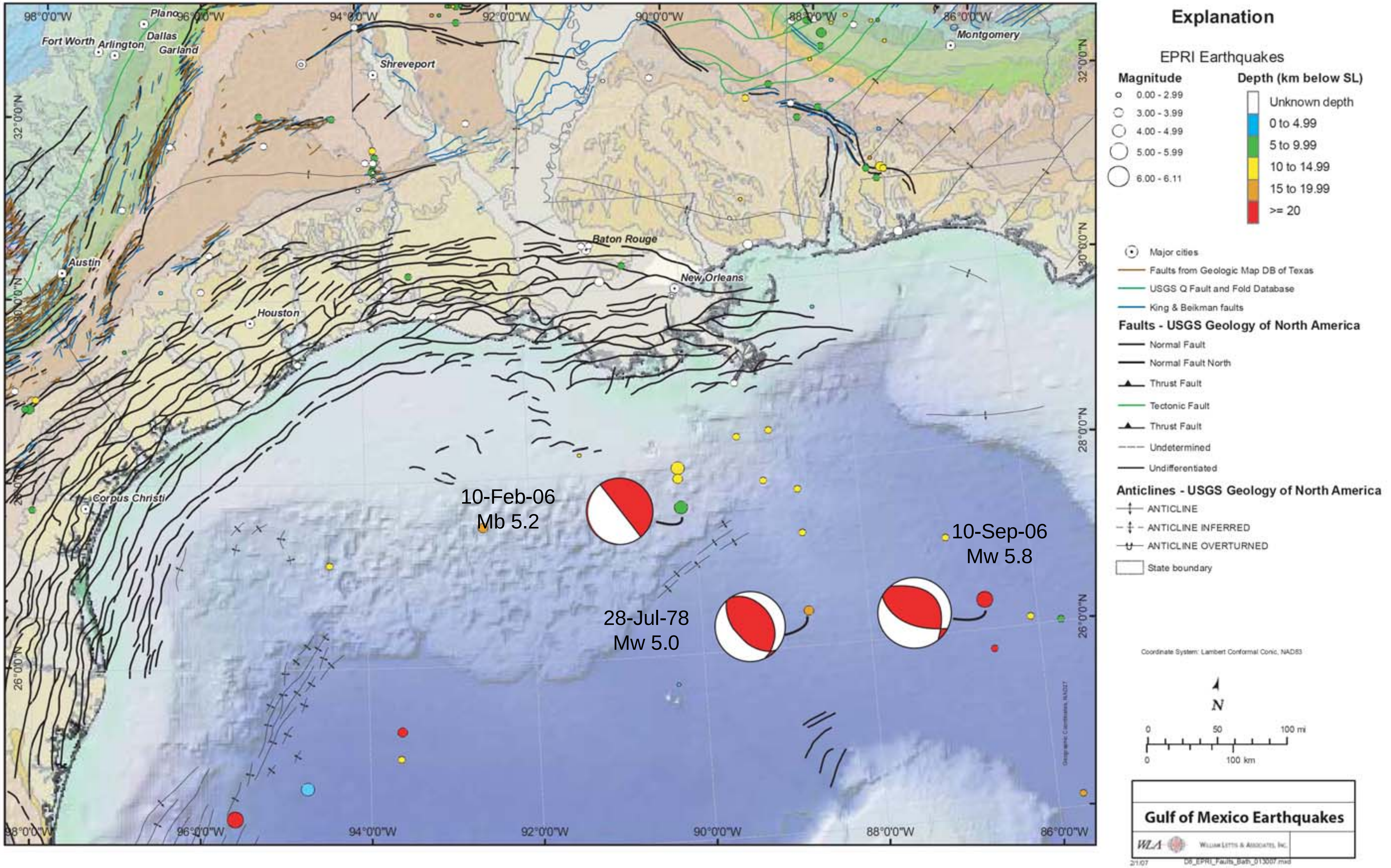
IV - Growth Fault Tectonic Setting and Seismicity

Northern Gulf of Mexico

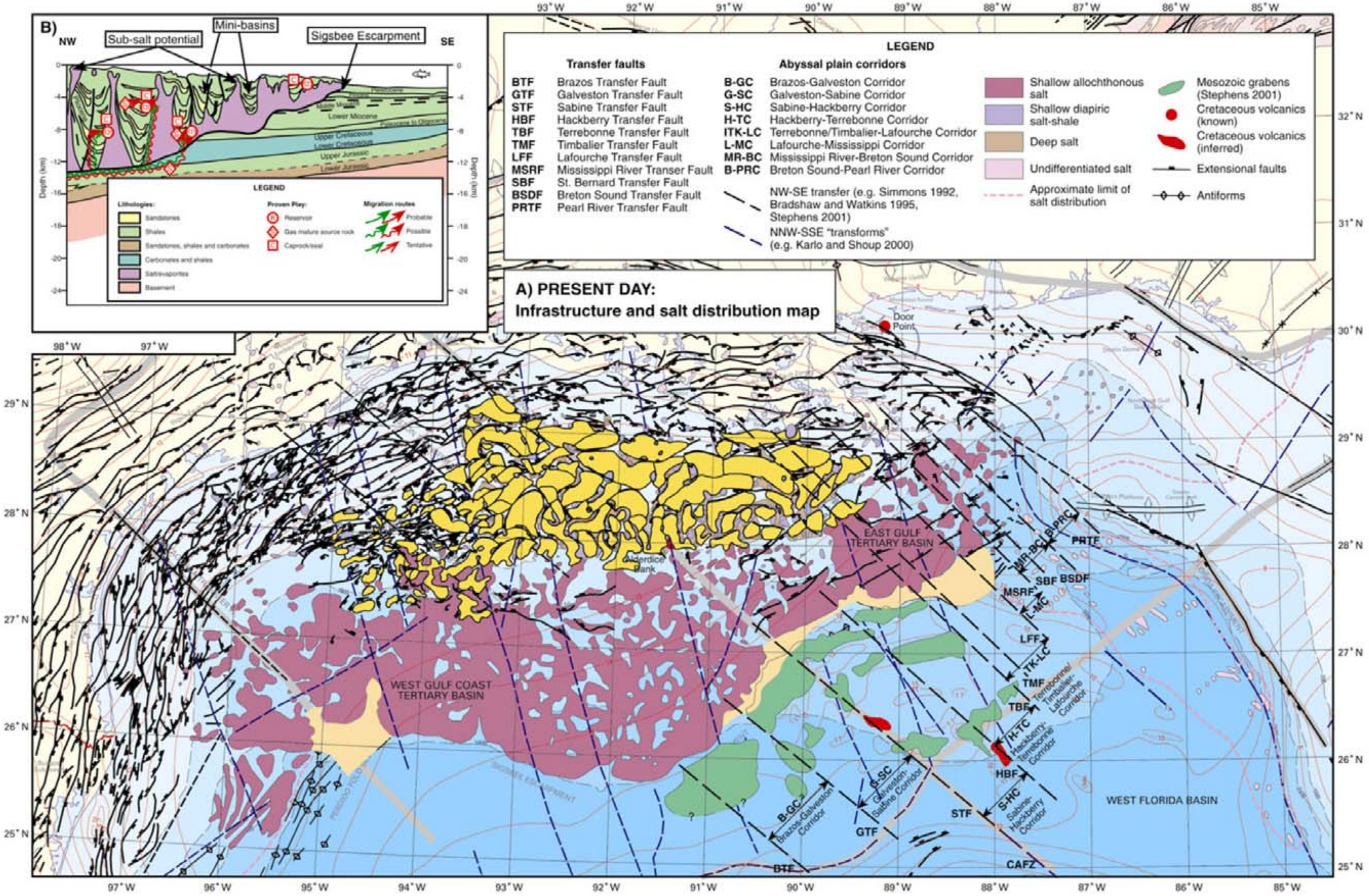
Fundamental questions associated with growth faults and seismic activity.

- Are growth faults capable of producing moderate minimum maximum magnitude earthquakes?
- If so, does the energy release have fundamentally different characteristics than that of typical crustal earthquakes?
- Do different types and environments of growth faults effect seismogenic capability?
- Is there a relationship between crustal neotectonic activity and movement on growth faults?
- Is there a connection between slip rates on growth faults and the rates of seismic activity?

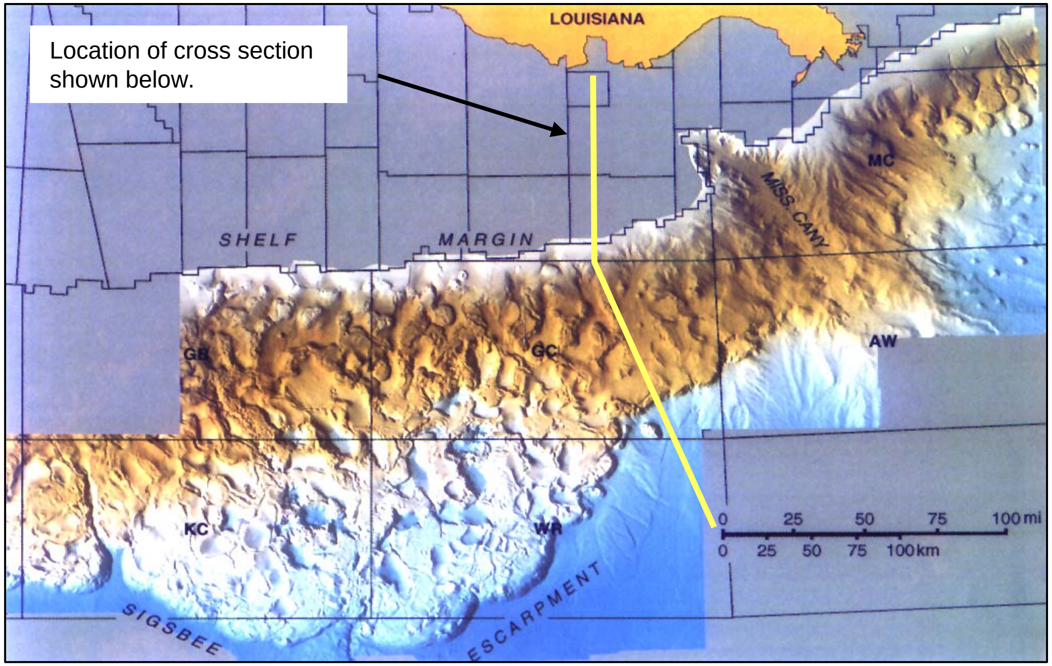
WLA seismicity and fault compilation Map. Focal mechanisms are shown for 2006 earthquakes >mb 5.0 and the 1978 Mw 5.0 event.



Geologic map of the northern Gulf of Mexico showing basement structures, growth faults and characteristics of allocthonous salt (cross section inset modified from Peel et al., 1995).



Seafloor morphology and subsurface geology the northern Gulf of Mexico.
The cross section illustrates the gravitational “linked system” of growth faults.

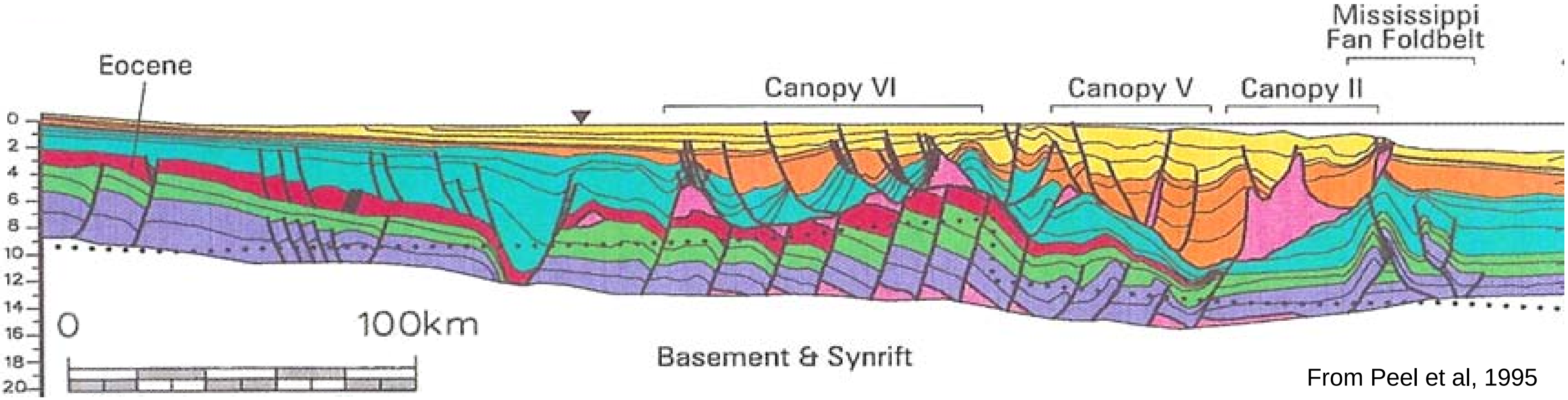


Location of cross section shown below.

Stratigraphy: Passive Margin**,** Salt Basin, Deltaic sedimentary cover over extended continental and transitional continental-oceanic crust.

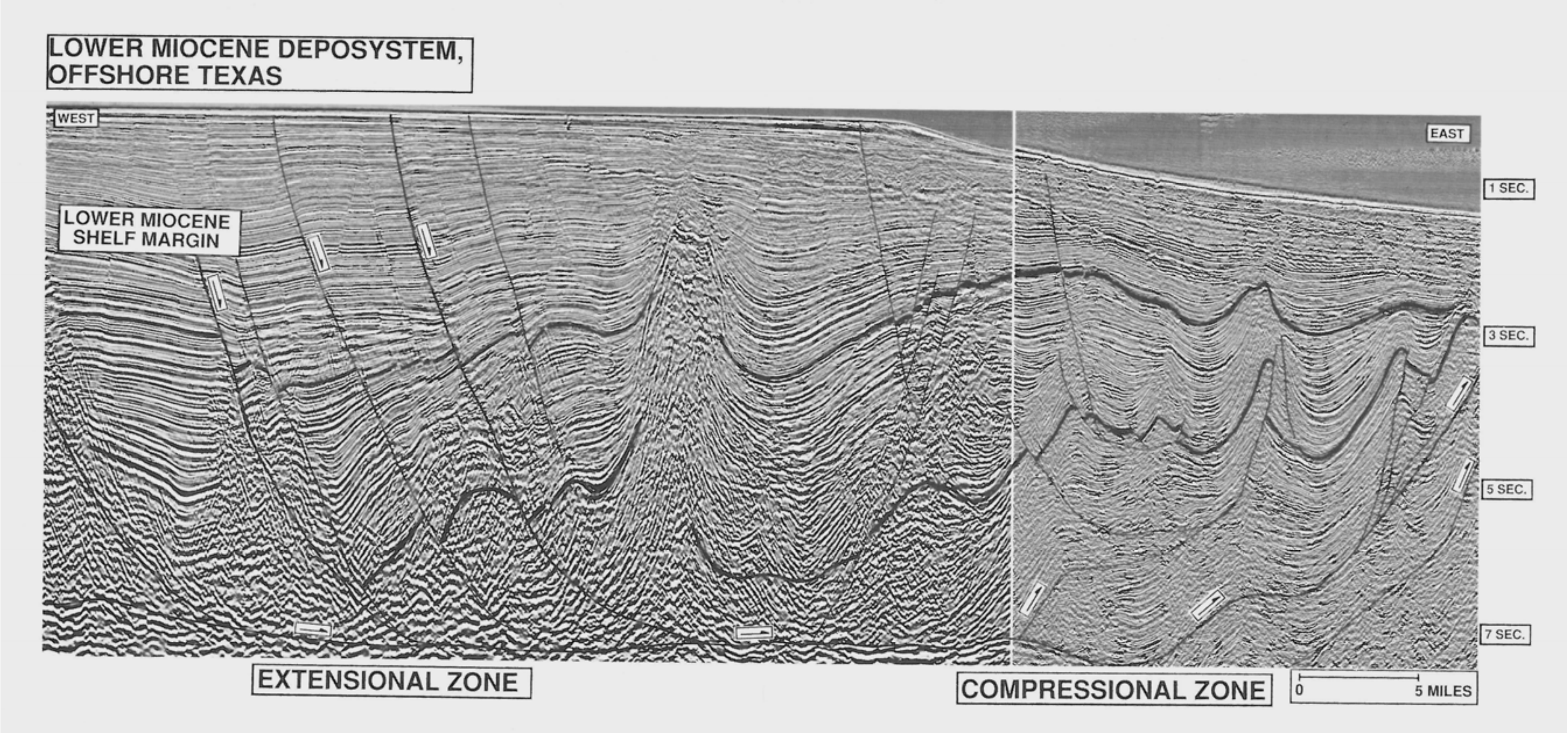
Structure: Linked Updip Extension and Downdip Contraction; Basement is characterized by NW-trending fracture zones.

Updip zone of extension ⟷ Downdip dip zone of contraction

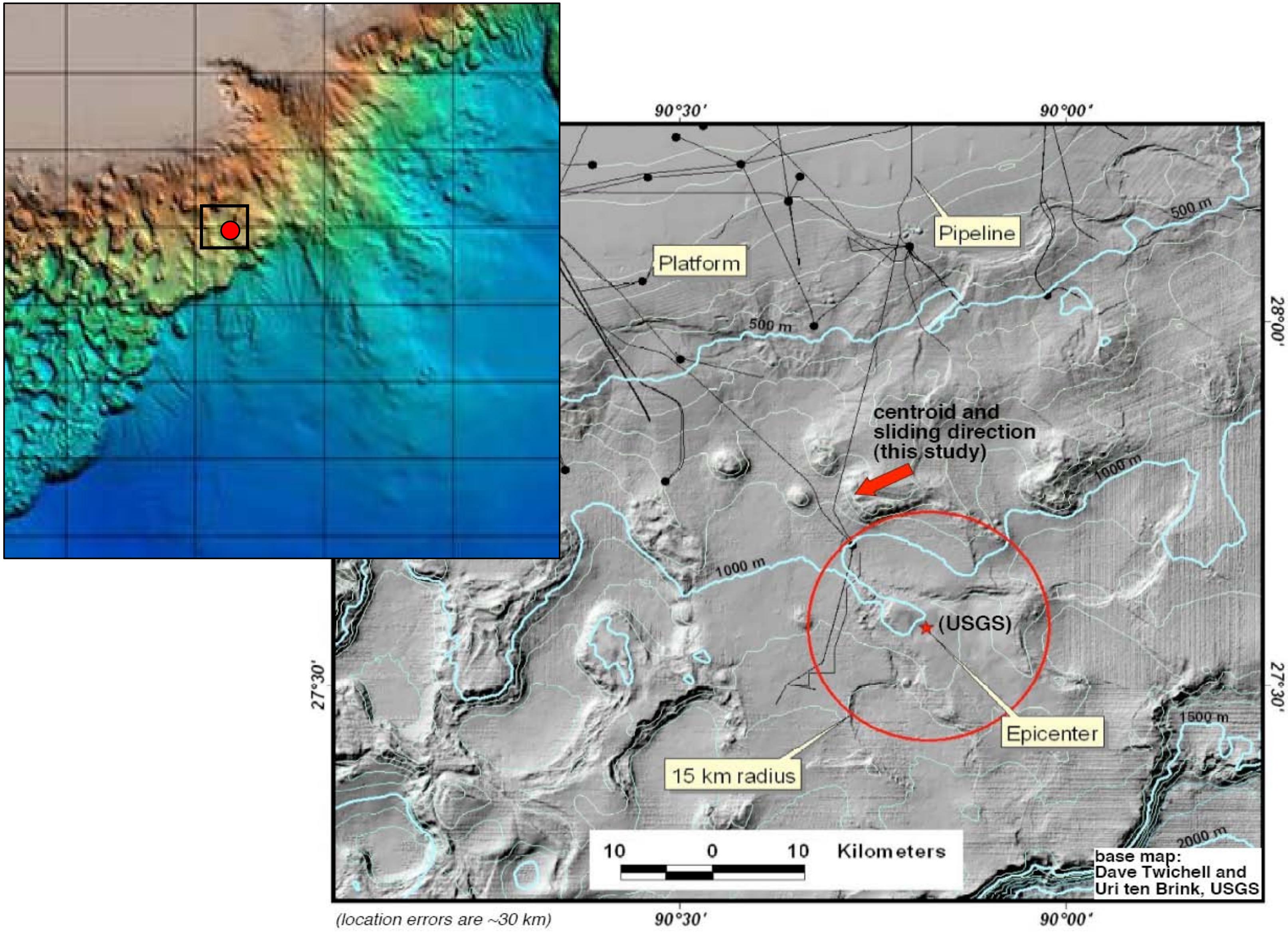


From Peel et al, 1995

Linked system of growth faults – updip extension and downdip contraction (from Peel, 1995).

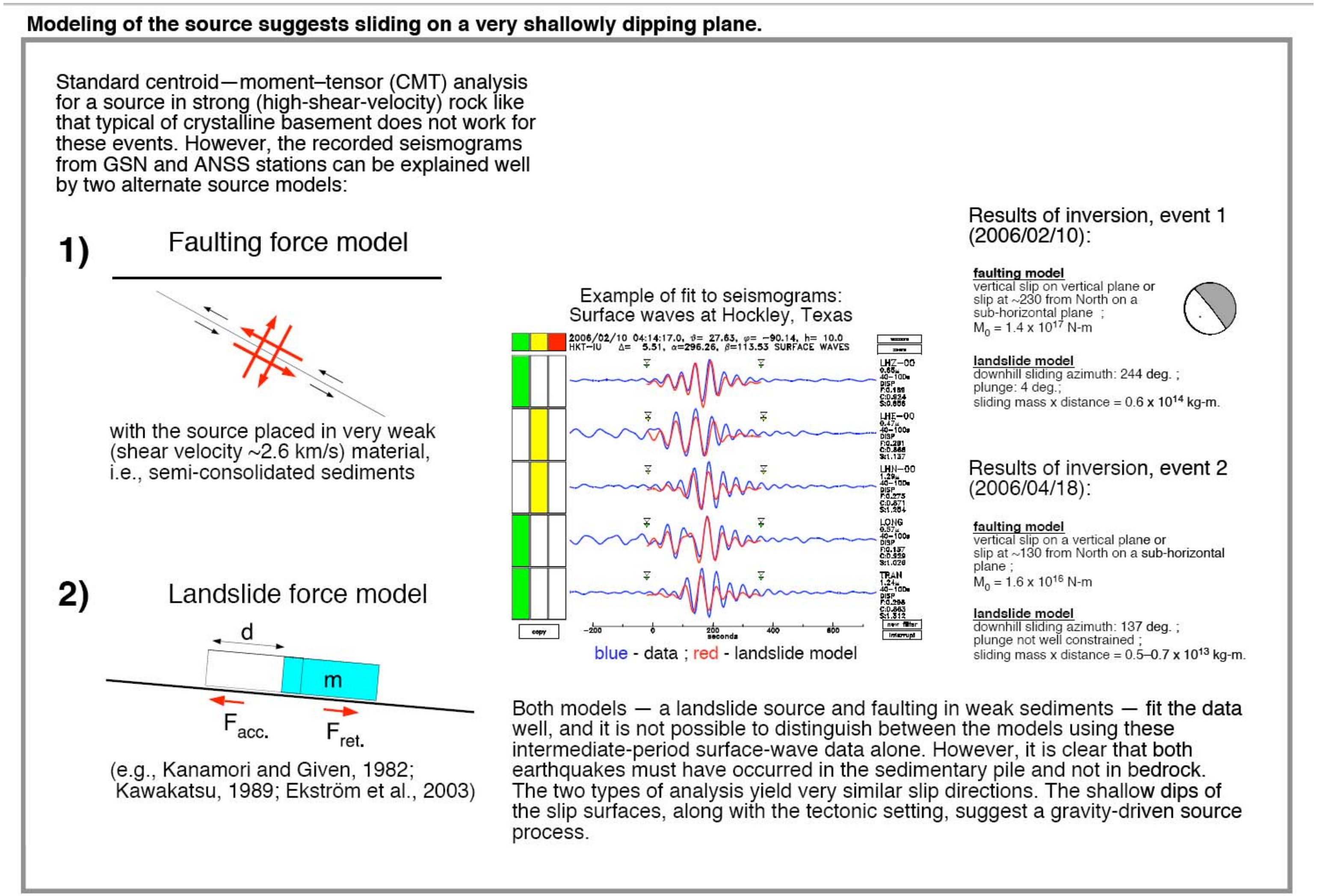


Location of the February 10 2006 event within the growth fault environment of the Gulf of Mexico salt basin on the continental slope (from Nettles, 2006).



(location errors are ~30 km)

Analysis of the February and April earthquakes as “landslide” events (from Nettles, 2006).



Modeling of the source suggests sliding on a very shallowly dipping plane.

Standard centroid—moment–tensor (CMT) analysis for a source in strong (high-shear-velocity) rock like that typical of crystalline basement does not work for these events. However, the recorded seismograms from GSN and ANSS stations can be explained well by two alternate source models:

1) Faulting force model

with the source placed in very weak (shear velocity ~2.6 km/s) material, i.e., semi-consolidated sediments

2) Landslide force model

(e.g., Kanamori and Given, 1982; Kawakatsu, 1989; Ekström et al., 2003)

Example of fit to seismograms:
Surface waves at Hockley, Texas

blue - data ; red - landslide model

Results of inversion, event 1 (2006/02/10):

faulting model
vertical slip on vertical plane or slip at ~230 from North on a sub-horizontal plane ;
$M_0 = 1.4 \times 10^{17}$ N-m

landslide model
downhill sliding azimuth: 244 deg. ;
plunge: 4 deg.;
sliding mass x distance = 0.6×10^{14} kg-m.

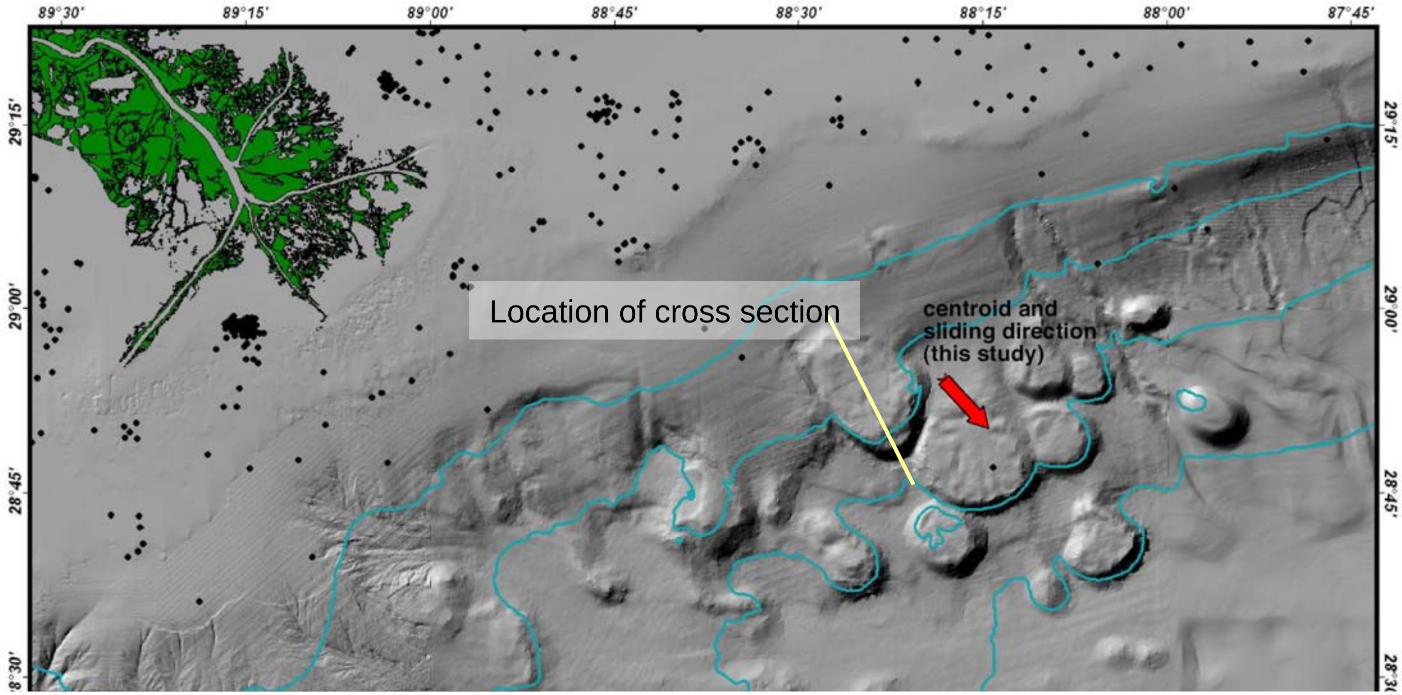
Results of inversion, event 2 (2006/04/18):

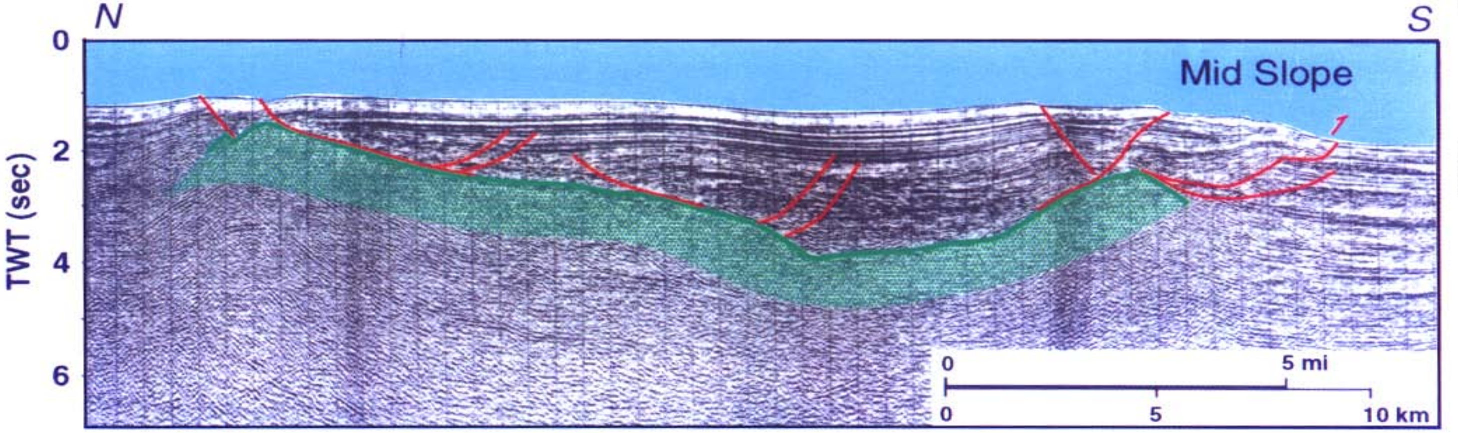
faulting model
vertical slip on a vertical plane or slip at ~130 from North on a sub-horizontal plane ;
$M_0 = 1.6 \times 10^{16}$ N-m

landslide model
downhill sliding azimuth: 137 deg. ;
plunge not well constrained ;
sliding mass x distance = $0.5–0.7 \times 10^{13}$ kg-m.

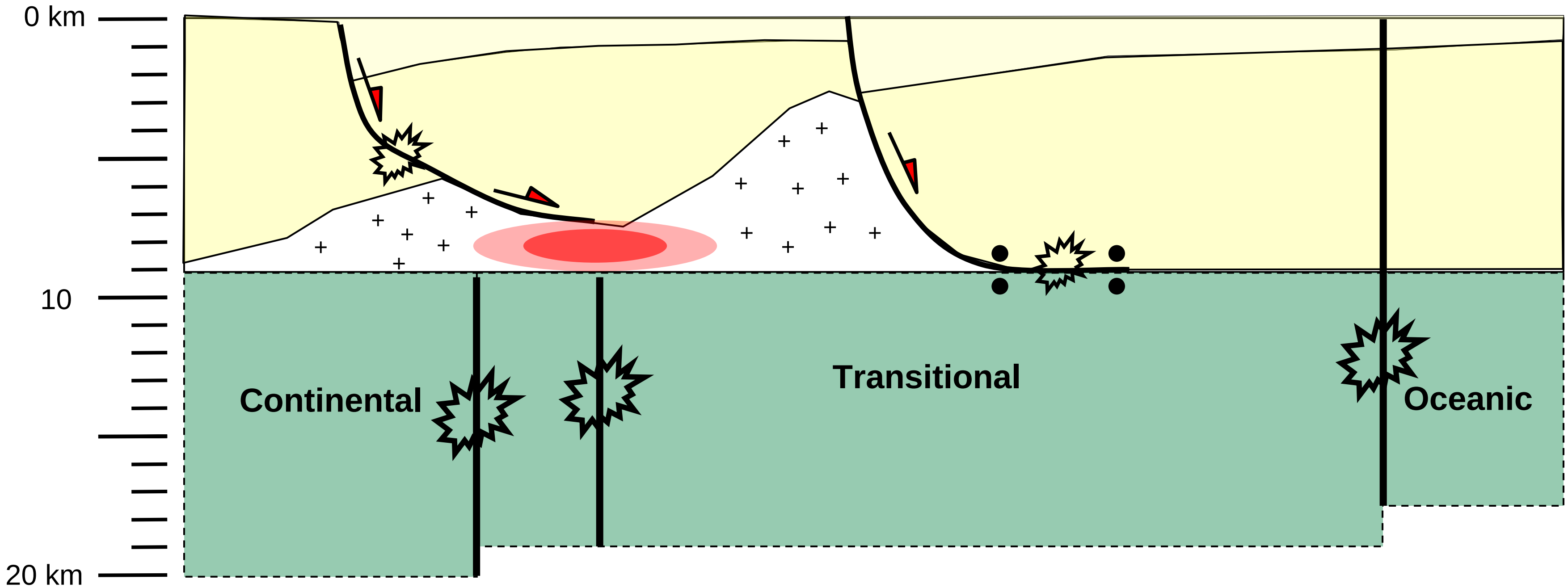
Both models — a landslide source and faulting in weak sediments — fit the data well, and it is not possible to distinguish between the models using these intermediate-period surface-wave data alone. However, it is clear that both earthquakes must have occurred in the sedimentary pile and not in bedrock. The two types of analysis yield very similar slip directions. The shallow dips of the slip surfaces, along with the tectonic setting, suggest a gravity-driven source process.

April 17 2006 Ms 4.8 event as a possible slide mechanism associated with downslope movement of a diapir (from Nettles, 2006).





Schematic cross section showing two-layer source model including growth fault sources in cover sediments and seismotectonic faults in basement.



Generalized Mechanical Stratigraphy

🟨 Weak Cover Sediment

⬜ Very Weak Evaporite

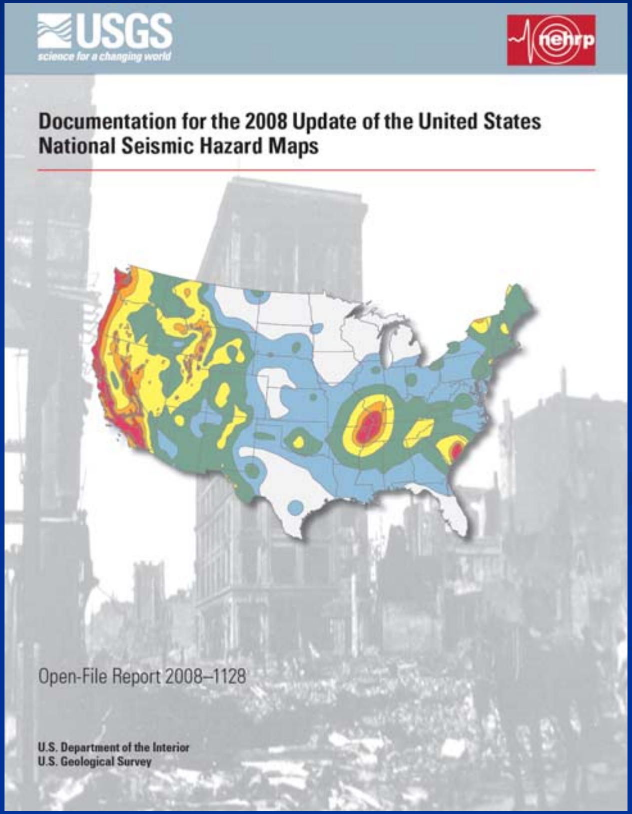
🟩 Strong Seismogenic Basement

Schematic seismotectonic fault in basement

Schematic growth fault in cover sediments; arrows indicate movement direction; dots indicate welded portion of fault surface

“Soft” structural link between deep and shallow faulting

2008 USGS Seismic Source Model for the Central and Eastern U. S.



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nehrp

Documentation for the 2008 Update of the United States National Seismic Hazard Maps

Open-File Report 2008–1128

U.S. Department of the Interior
U.S. Geological Survey

http://earthquake.usgs.gov/research/hazmaps/

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2008 USGS Seismic Source Model for the Central and Eastern U. S.

- Model based on 1996 and 2002 models consisting of gridded seismicity and fault models – use simple models unless we have evidence to subdivide zones
- We include the northern and central Rocky Mountains and the Colorado Plateau in the CEUS region – Chuck Mueller will discuss seismicity models
- The CEUS fault model includes four finite fault sources (New Madrid, Mo., and adjacent States; Charleston, S.C.; Meers, Okla.; and Cheraw, Colo.)
- Potential source model changes discussed at workshop in Boston, MA - MAY, 2006

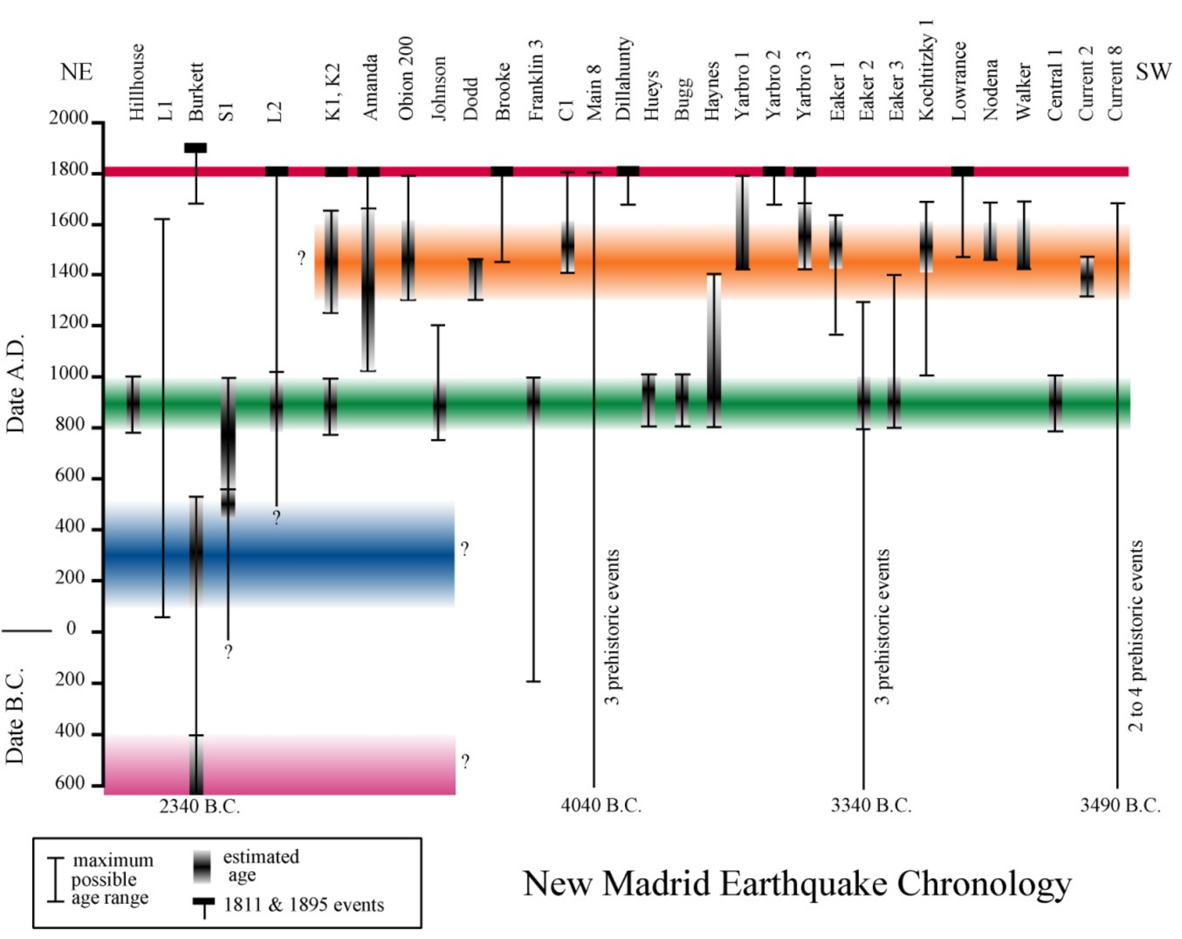
Changes to the 2008 CEUS model

- Advisory panel members suggested that we needed to discuss Mmax - M max workshop held in 2008; also suggested workshop on Charleston zone
- a. Updated catalog through 2006 and accounted for magnitude uncertainty
- b. Reduced magnitudes in northern New Madrid seismic zone by 0.2 unit and added logic-tree branch for recurrence rate of 1/750 years
- c. Added logic-tree branch for 1/1,000-year recurrence rate of earthquakes in New Madrid

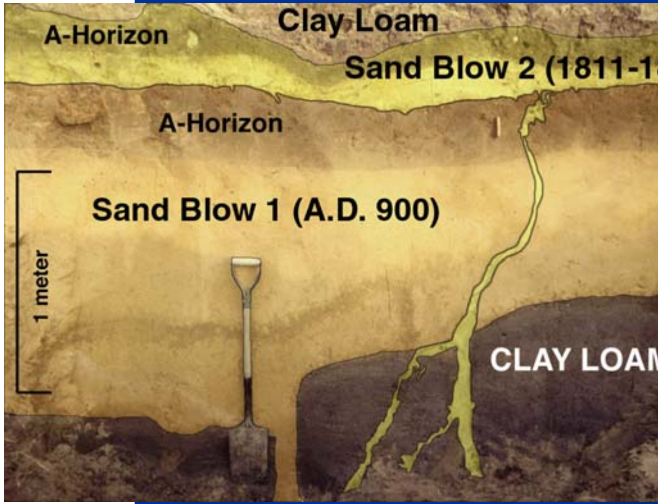
Changes to the 2008 CEUS model

- d. Implemented temporal cluster model for New Madrid earthquakes
- e. Modified fault geometry for New Madrid to include five hypothetical strands and increased weight on central strand to 0.7
- f. Revised dip of Reelfoot fault to 38°
- g. Developed maximum magnitude distribution for seismicity-derived hazard sources
- h. Revised geometry of large Charleston zone, extending it farther offshore to include the Helena Banks fault zone
- i. Added documentation for logic trees

New Madrid Fault Zone



New Madrid Earthquake Chronology



New Madrid seismicity

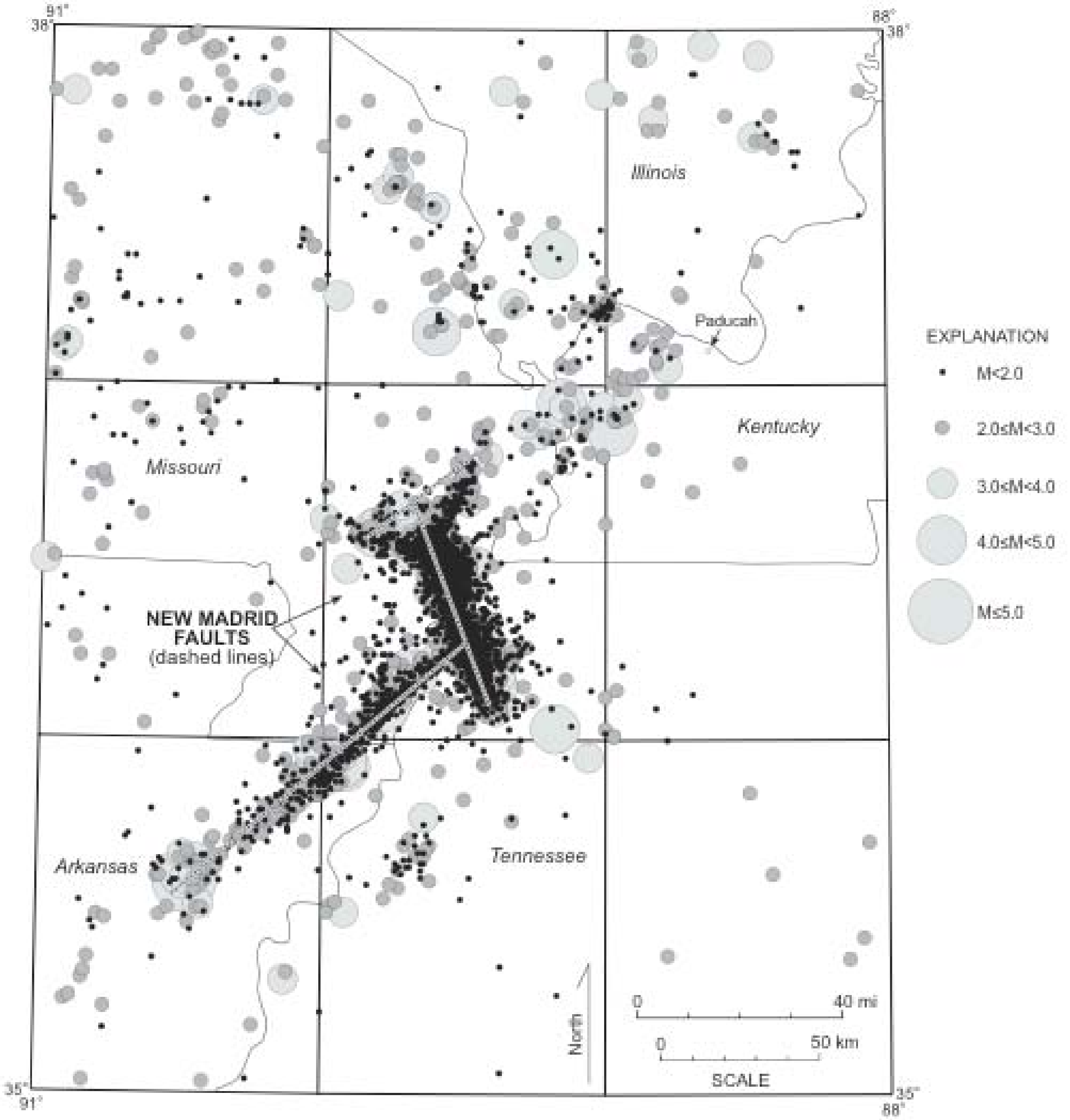


Figure 10. Locations of earthquakes in the central United States since 1974 (from the Center for Earthquake Research and Information).

Figure 6

cal Survey SP6

NEW MADRID LOGIC TREE

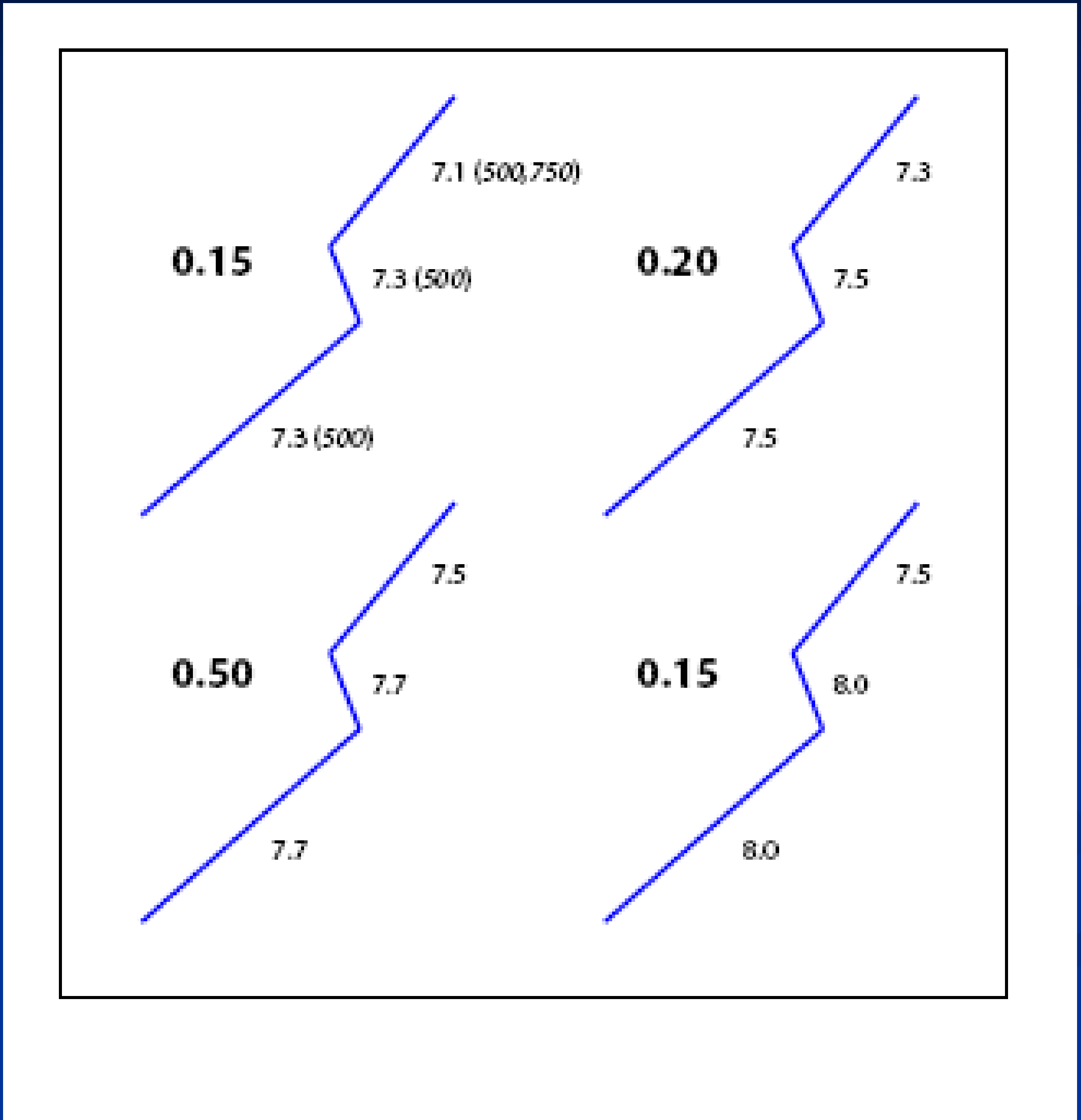
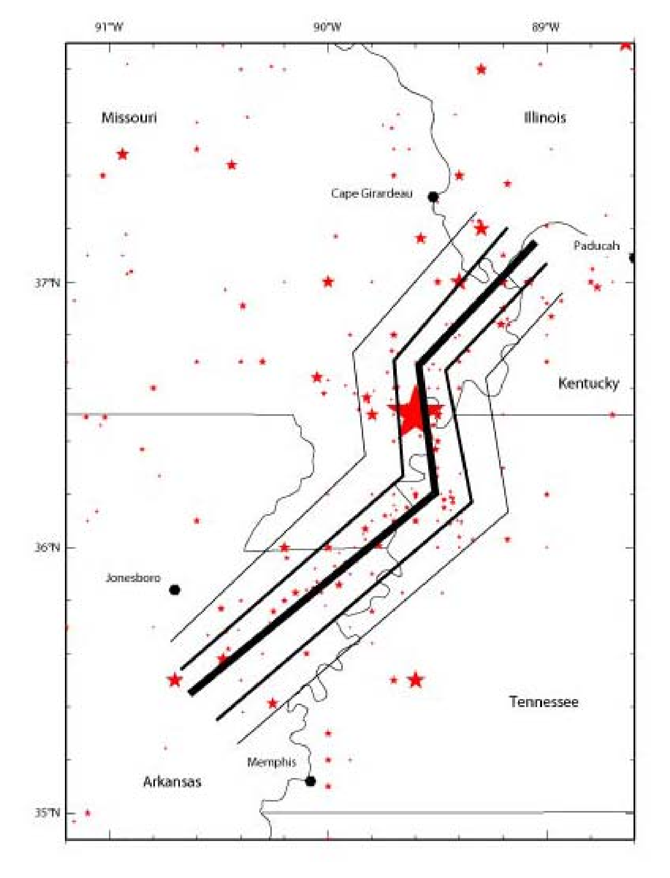
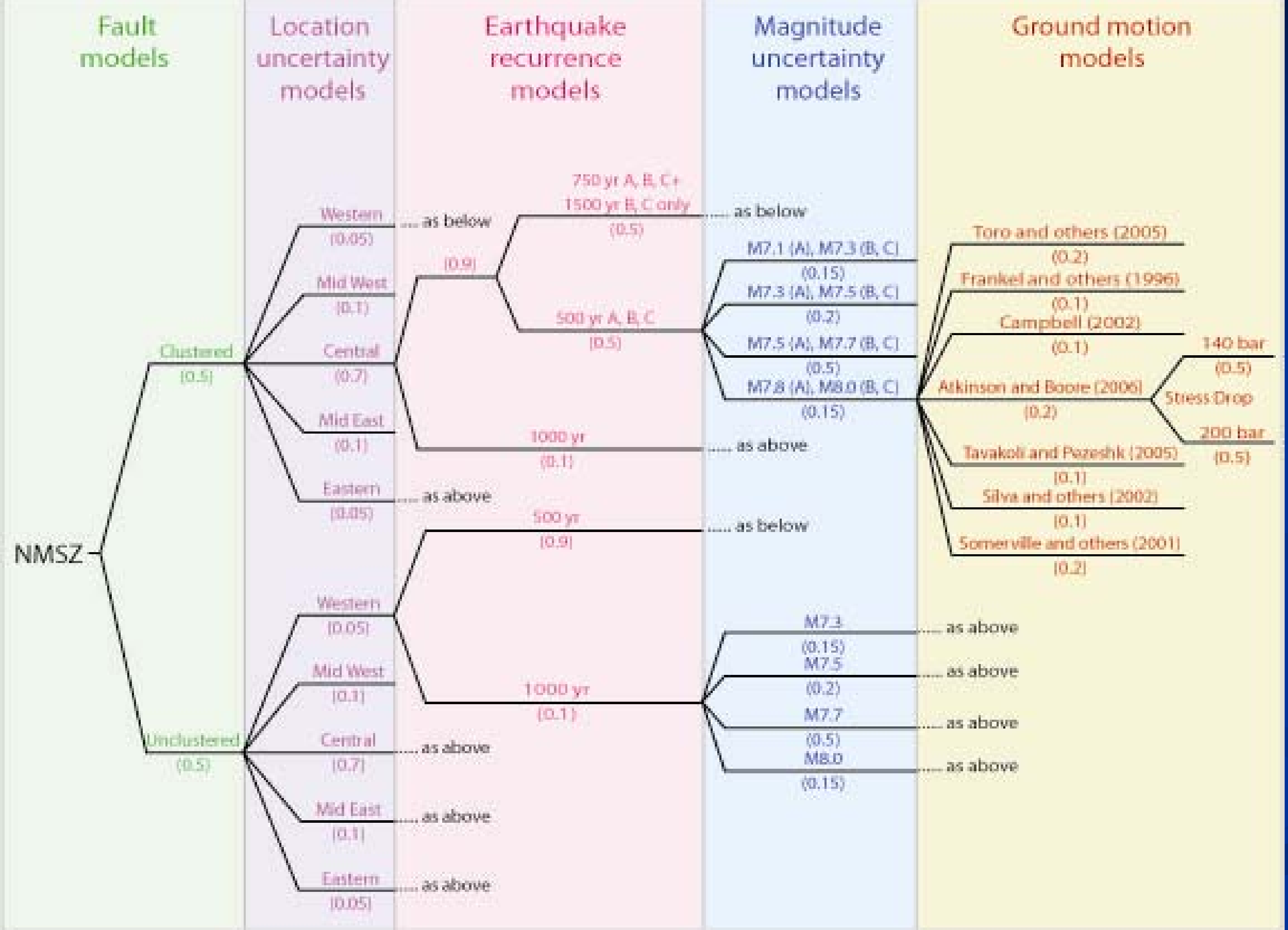


Figure 7:

NEW MADRID

Temporal Clustering of 1811-12 type earthquakes





Fault models

Location uncertainty models

Earthquake recurrence models

Magnitude uncertainty models

Ground motion models

NMSZ

Clustered (0.5)

Unclustered (0.5)

Western (0.05) .... as below
Mid West (0.1)
Central (0.7)
Mid East (0.1)
Eastern (0.05) ..... as above

Western (0.05)
Mid West (0.1)
Central (0.7) ..... as above
Mid East (0.1) ..... as above
Eastern (0.05) ..... as above

(0.9)
750 yr A, B, C+
1500 yr B, C only
(0.5) ..... as below
500 yr A, B, C (0.5)
1000 yr (0.1) ..... as above

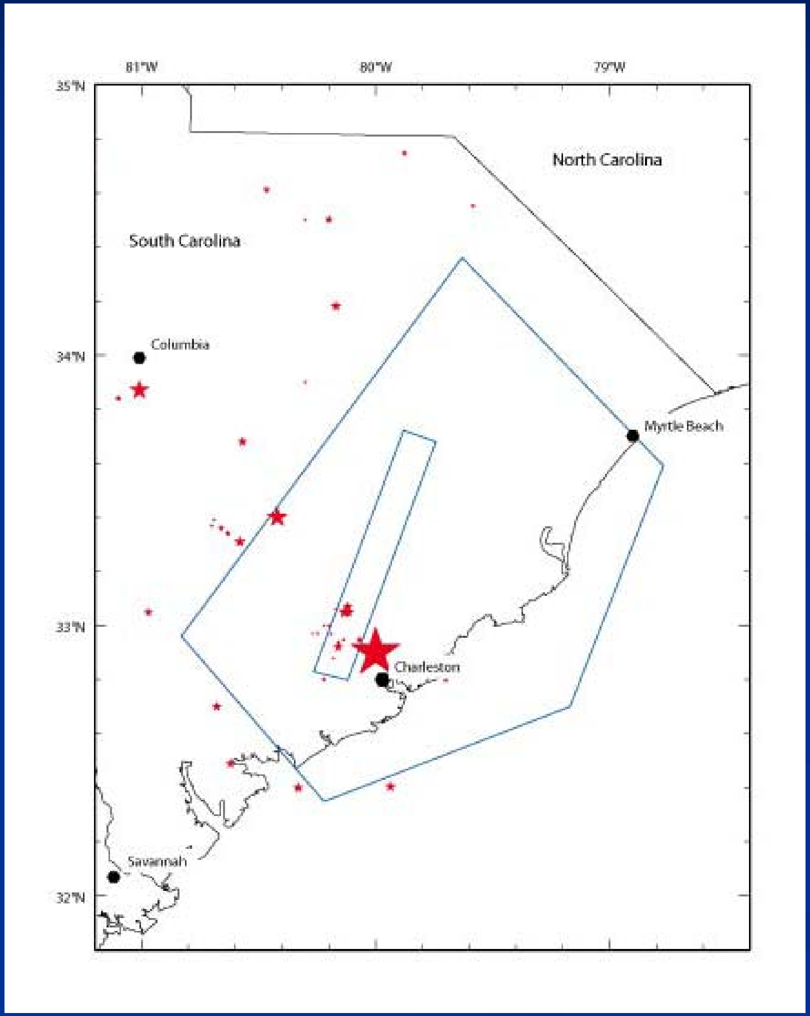
500 yr (0.9) ..... as below
1000 yr (0.1)

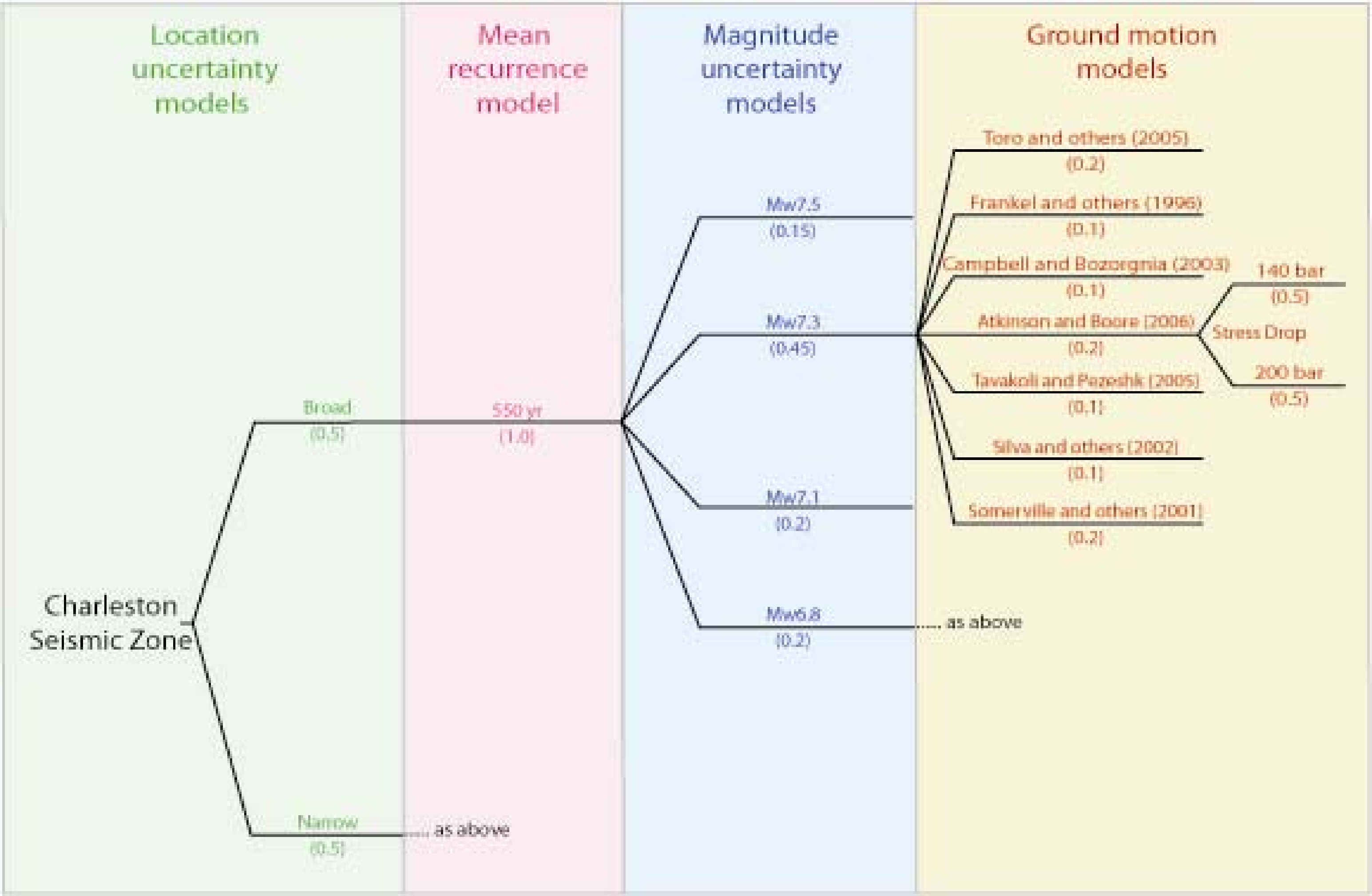
M7.1 (A), M7.3 (B, C) (0.15)
M7.3 (A), M7.5 (B, C) (0.2)
M7.5 (A), M7.7 (B, C) (0.5)
M7.8 (A), M8.0 (B, C) (0.15)

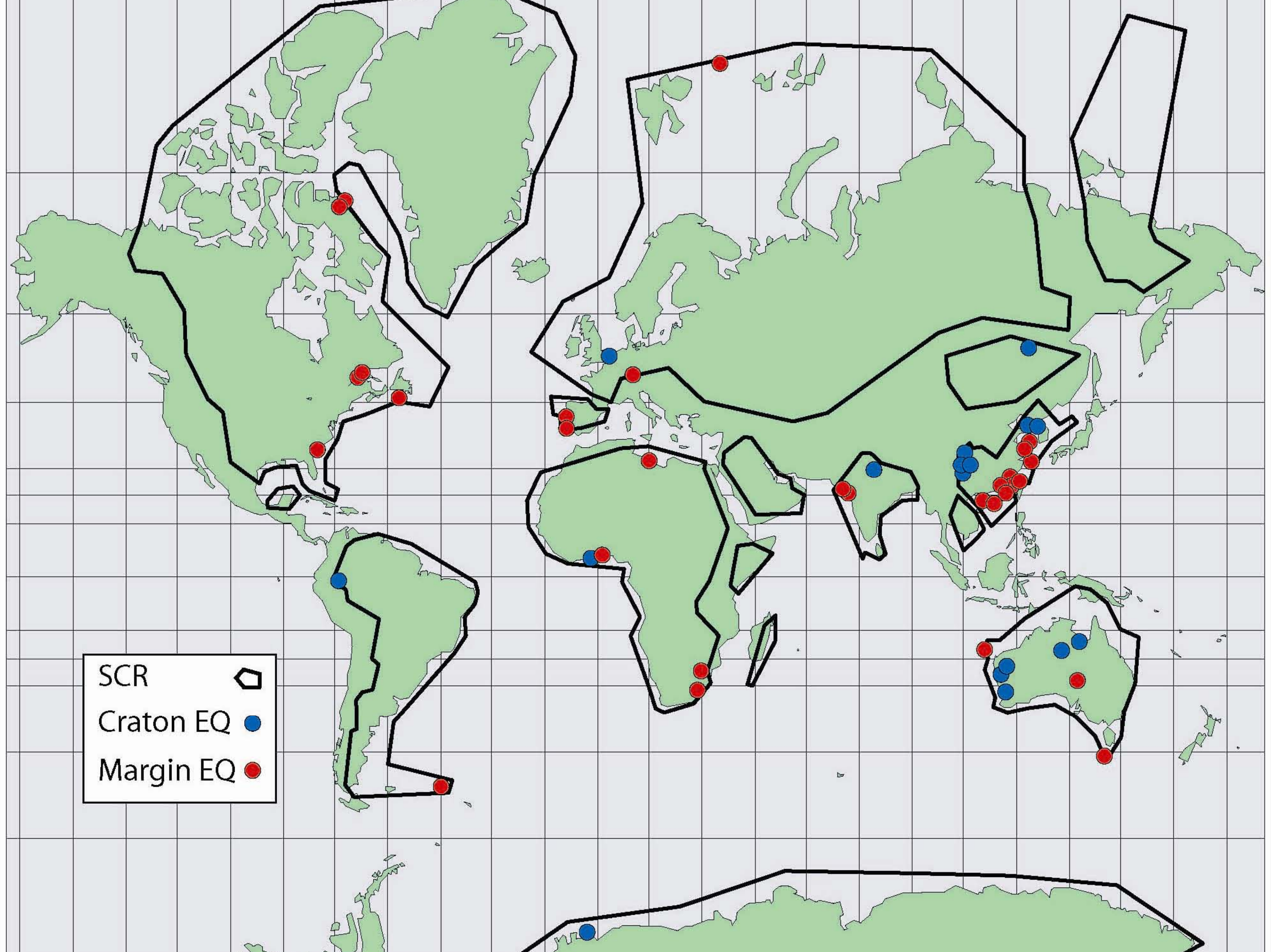
M7.3 (0.15) ..... as above
M7.5 (0.2) ..... as above
M7.7 (0.5) ..... as above
M8.0 (0.15) ..... as above

Toro and others (2005) (0.2)
Frankel and others (1996) (0.1)
Campbell (2002) (0.1)
Atkinson and Boore (2006) (0.2)
Stress Drop
140 bar (0.5)
200 bar (0.5)
Tavakoli and Pezeshk (2005) (0.1)
Silva and others (2002) (0.1)
Somerville and others (2001) (0.2)

Charleston


81°W
80°W
79°W
35°N
34°N
33°N
32°N
North Carolina
South Carolina
Columbia
Myrtle Beach
Charleston
Savannah


Location uncertainty models
Mean recurrence model
Magnitude uncertainty models
Ground motion models
Charleston Seismic Zone
Broad
(0.5)
Narrow
(0.5)
...... as above
550 yr
(1.0)
Mw7.5
(0.15)
Mw7.3
(0.45)
Mw7.1
(0.2)
Mw6.8
(0.2)
...... as above
Toro and others (2005)
(0.2)
Frankel and others (1996)
(0.1)
Campbell and Bozorgnia (2003)
(0.1)
Atkinson and Boore (2006)
(0.2)
Tavakoli and Pezeshk (2005)
(0.1)
Silva and others (2002)
(0.1)
Somerville and others (2001)
(0.2)
140 bar
(0.5)
Stress Drop
200 bar
(0.5)


SCR
Craton EQ ●
Margin EQ ●

Maximum Magnitude (M 7.1-7.7 – Ext. Margin; M 6.6-7.2 – Craton; wt from low to high: 0.1, 0.2, 0.5, 0.2)

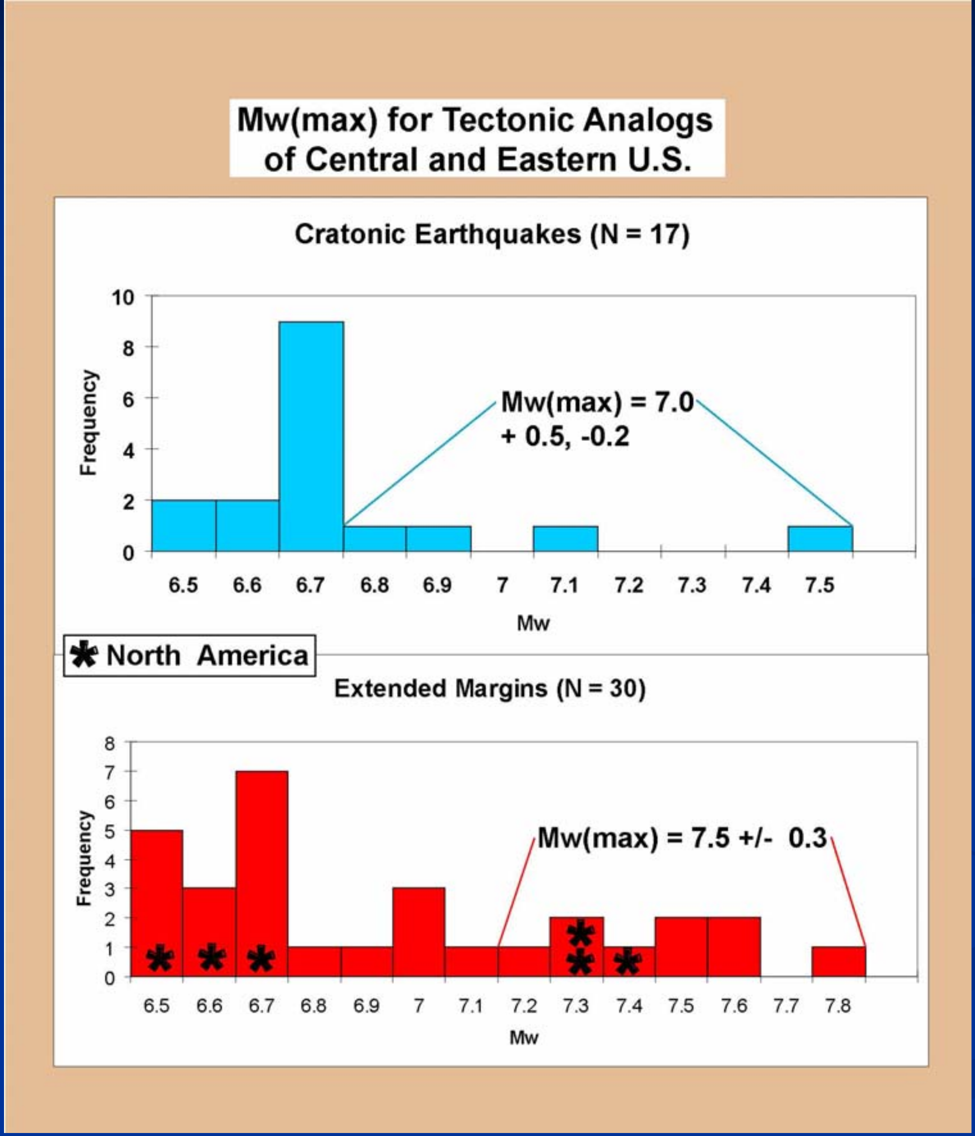


Figure 4: Histograms showing magnitudes for craton and margin earthquakes.

Outcomes of NRC-USGS Workshop “Mmax in the CEUS”

Golden, CO, Sept. 8-9, 2008

Consensus

- (1) Estimate Mmax from global tectonic analogues with
  - (a) Bayesian analysis (aggregates small regions and their eqs)
  - (b) USGS approach (divides the sum of Earth’s SCRs into regions)

Weaker Agreements

- (2) Set aside some methods that are based on local seismicity of small areas
- (3) Most-urgent research needs:
  - (a) Characterize uncertainties of all inputs
  - (b) More paleoseismology
  - (c) Correct historical intensities worldwide for site effects

Hazard From Seismicity:
the USGS Approach

Charles S. Mueller
USGS, National Seismic Hazard Mapping Project

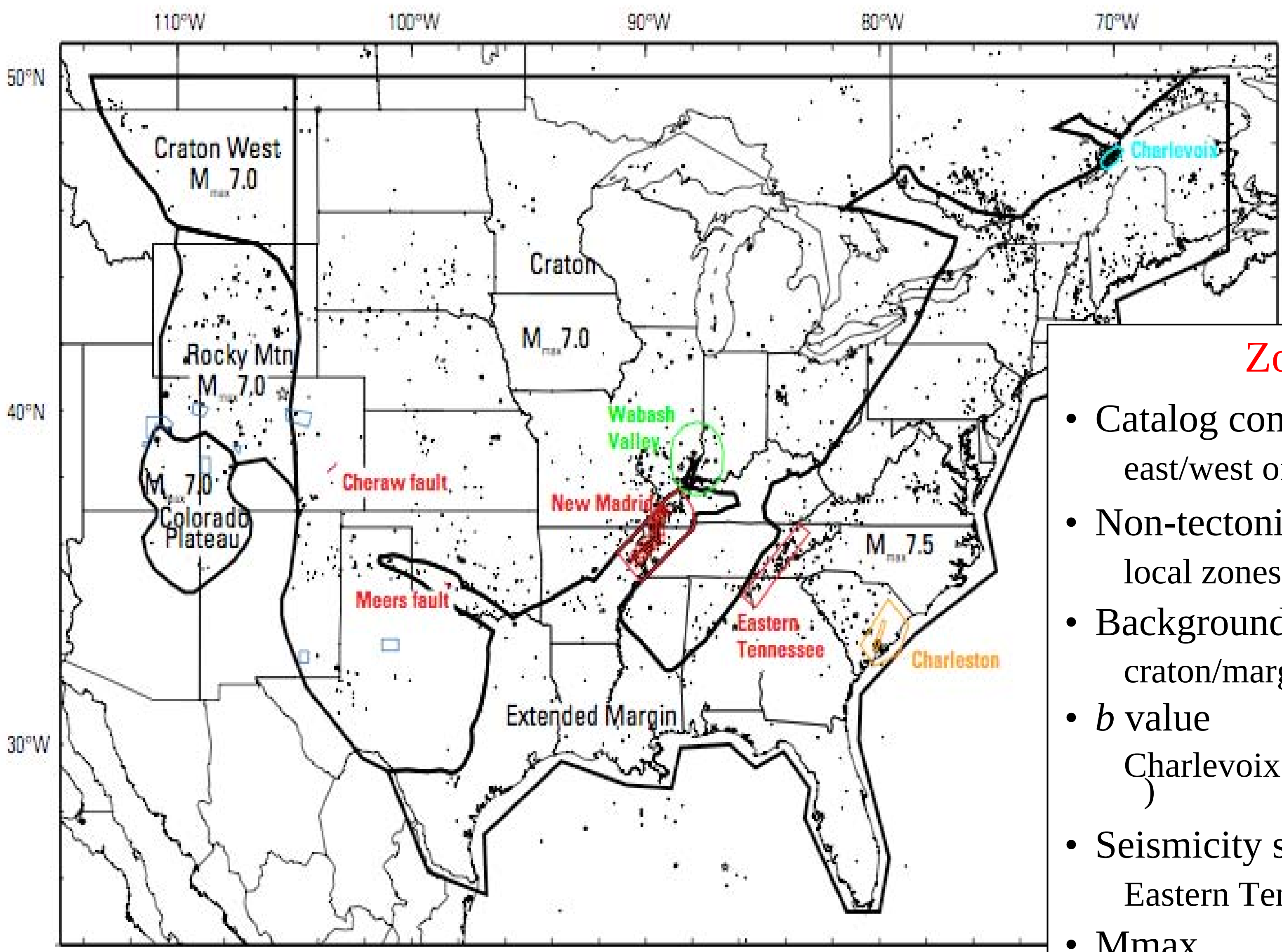
EPRI SSC Workshop, 20 February 2009

Organizing Principles

1) Specific fault sources
   - New Madrid, Charleston, Meers, Cheraw
   - recurrence from paleoseismology/paleoliquefaction
2) Historical seismicity, gridded & smoothed
   - based on the expectation that future damaging earthquakes will occur near previous, smaller (m3+, m4+, m5+) events
   - alternative to traditional source zones
   - controls hazard in much of the CEUS
3) Large background zones based on geologic criteria
   - provide some protection in areas with little historic seismicity, but the potential for damaging earthquakes

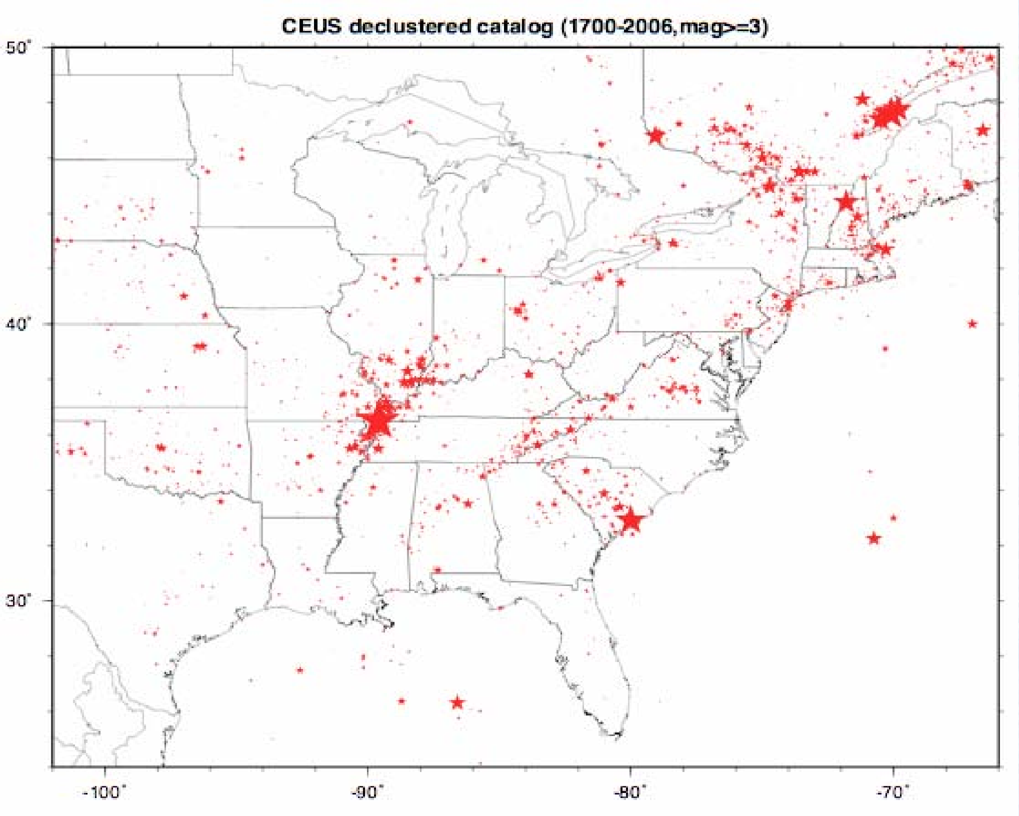
Presentation Outline

- Zones
- Catalogs (mbLg); regional completeness levels & *b* values
- Four gridded seismicity models:
    1) Model 1: rate of mag >= 3
    2) Model 2: rate of mag >= 4
    3) Model 3: rate of mag >= 5
    4) Model 4: regional background (“floor”)
- Special Cases
- Smoothing
- Adjust rates for over-optimistic completeness assumptions
- Final rates: weighted sum of Models 1–4



Zones

- Catalog completeness
  east/west of longitude -105
- Non-tectonic earthquakes
  local zones (blue polygons)
- Background rates
  craton/margin/RM/CP
- *b* value
  Charlevoix(0.76)/other(0.95)
- Seismicity special cases
  Eastern Tenn, New Madrid
- Mmax
  craton,RM,CP(M7.0)
  margin,WV(M7.5)
- Rate Adjustment
  craton/margin



Catalog

- Combine national-scale catalogs:
  - Special cases
  - NCEER-91 (~2370; thorough & consistent treatment of pre-instrumental eqs)
  - Stover & Coffman (~30; large US eqs since 1568)
  - Stover and others (~240; USGS state-by-state catalogs)
  - USGS PDE (~630)
  - DNAG (~60)
- Eliminate duplicates (using source-catalog preference order)
- Delete non-tectonic ("man-made") events (if they are not hazardous)
- Decluster (Gardner & Knopoff windowing scheme)

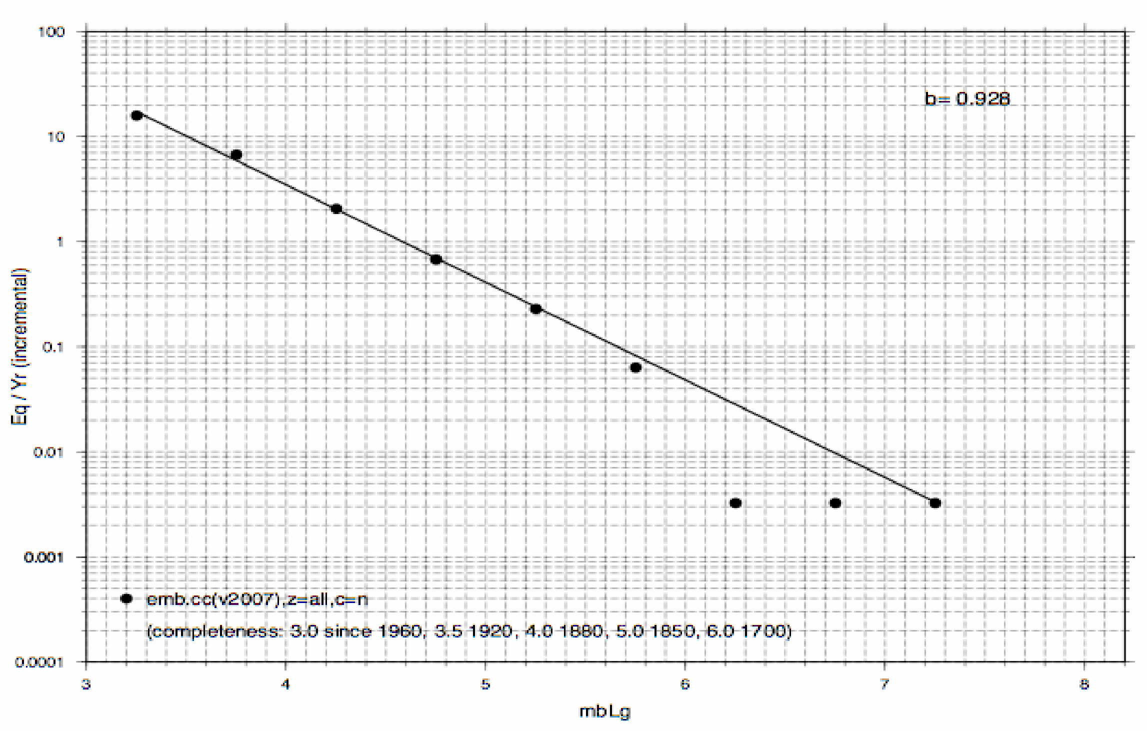
```
         Example: catalog completeness levels & b value

            3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00 7.50
1700-1719      2    0    0    0    0    0    0    0    0    0
1720-1739     21    1    0    0    2    1    0    0    0    0
1740-1759      4    2    0    1    0    1    0    0    0    0
1760-1779      8    1    2    1    0    0    0    0    0    0
1780-1799      7    1    2    2    1    0    0    0    0    0
1800-1819     19    5    4    2    2    0    0    0    1    0
1820-1839     21   11    4    4    1    0    0    0    0    0
1840-1859     53   23   18    2    2    0    0    0    0    0
1860-1879     75   30    9   10    6    0    0    0    0    0
1880-1899    155   89   33   10    7    1    0    1    0    0
1900-1919    116   77   26   11    6    2    0    0    0    0
1920-1939    178  103   28   17    1    0    1    0    0    0
1940-1959    207  104   65   12    3    3    0    0    0    0
1960-1979    340  151   37   18    1    1    0    0    0    0
1980-1999    320  172   49   13    8    2    0    0    0    0
2000-2006     81   58   24    5    3    1    0    0    0    0

mag_bin  n_eqs    yr1    yr2  n_yrs     eqs/yr
  3.250    741   1960   2006     4    16.
  3.750    588   1920   2006    87     6.8
  4.250    262   1880   2006   127     2.1
  4.750     86   1880   2006   127     0.68
  5.250     36   1850   2006   157     0.23
  5.750     10   1850   2006   157     0.064
  6.250      1   1700   2006   307     0.0033
  6.750      1   1700   2006   307     0.0033
  7.250      1   1700   2006   307     0.0033
  7.750      0   1700   2006   307     0

b = 0.928 +/- 0.018
```

Completeness

- Exponential magnitude-frequency distribution
- Weichert's (1980, BSSA) variable-completeness, maximum-likelihood method

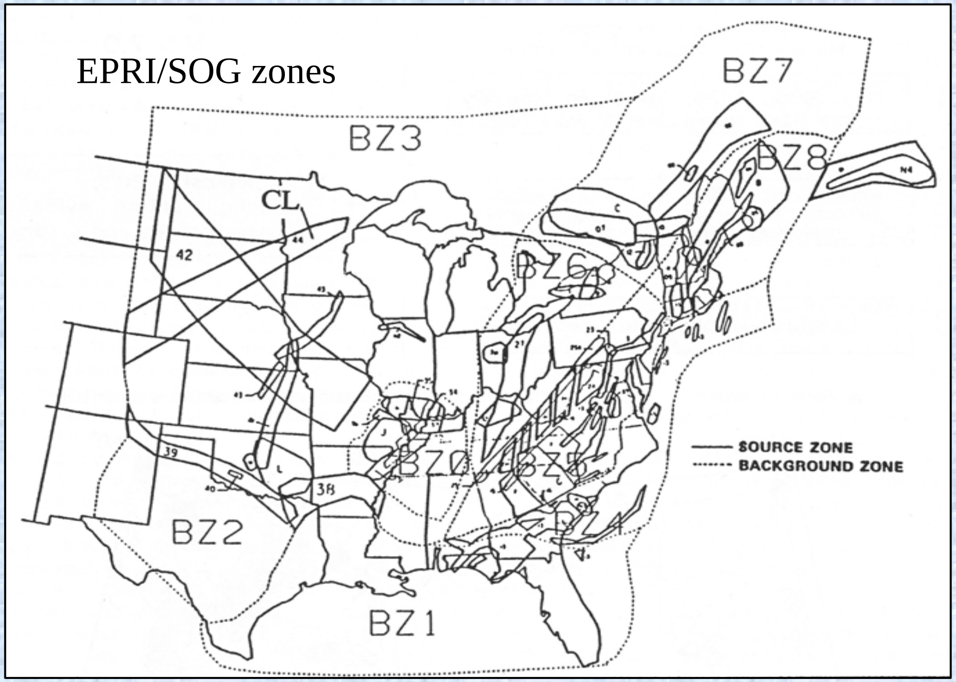
b value

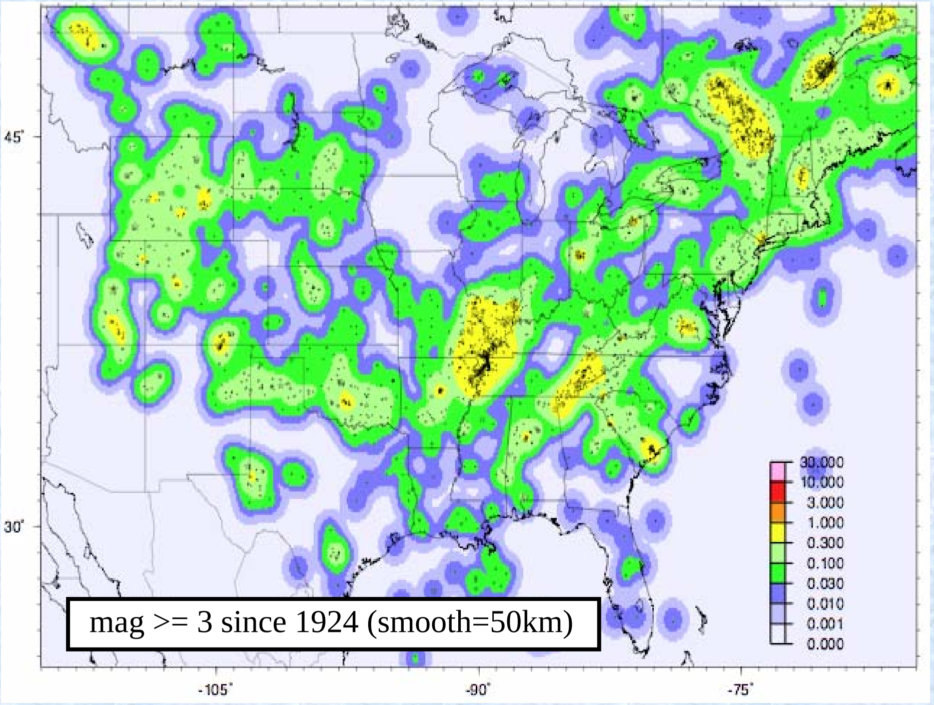
- *b* = 0.76 for Charlevoix, 0.95 everywhere else
- Frankel tried gridded / zoned *b* values for 1996 maps, didn't like the results



Gridded Historical Seismicity

- Grid: 0.1 x 0.1 degree
- Four models (incremental 10^{a})
  1) Model 1: count mbLg 3+ since 1924 east, 1976 west (of longitude -105 degrees)
  2) Model 2: count mbLg 4+ since 1860 east, 1924 west
  3) Model 3: count mbLg 5+ since 1700 east, 1860 west
  4) Model 4: regional background rate (mbLg 3+ since 1976 in craton,margin,RM,CP)
- Uniform rates: Eastern Tennessee SZ & New Madrid SZ (mbLg 3+ since 1976)
- Smooth: 2-D Gaussian w/ “correlation dist” = 50 km for Model 1, 75 km for M 2 & 3
- Adjust rates for over-optimistic completeness assumptions (factors 1.0 to 2.1, based on 1976/assumed rate ratios)
- Final rates: weighted (“adaptive”) sum of Models 1–4
- For 2008 we make 2 grids:
  1) Rates corrected for magnitude uncertainty (*e.g.*, Karen Felzer’s work)
  2) Rates not corrected

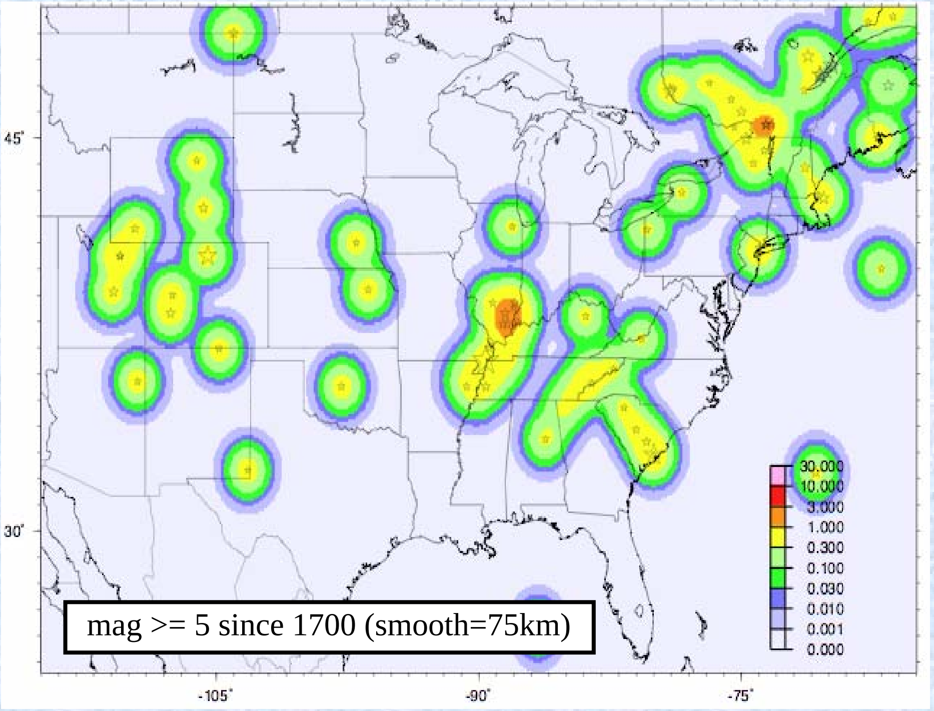




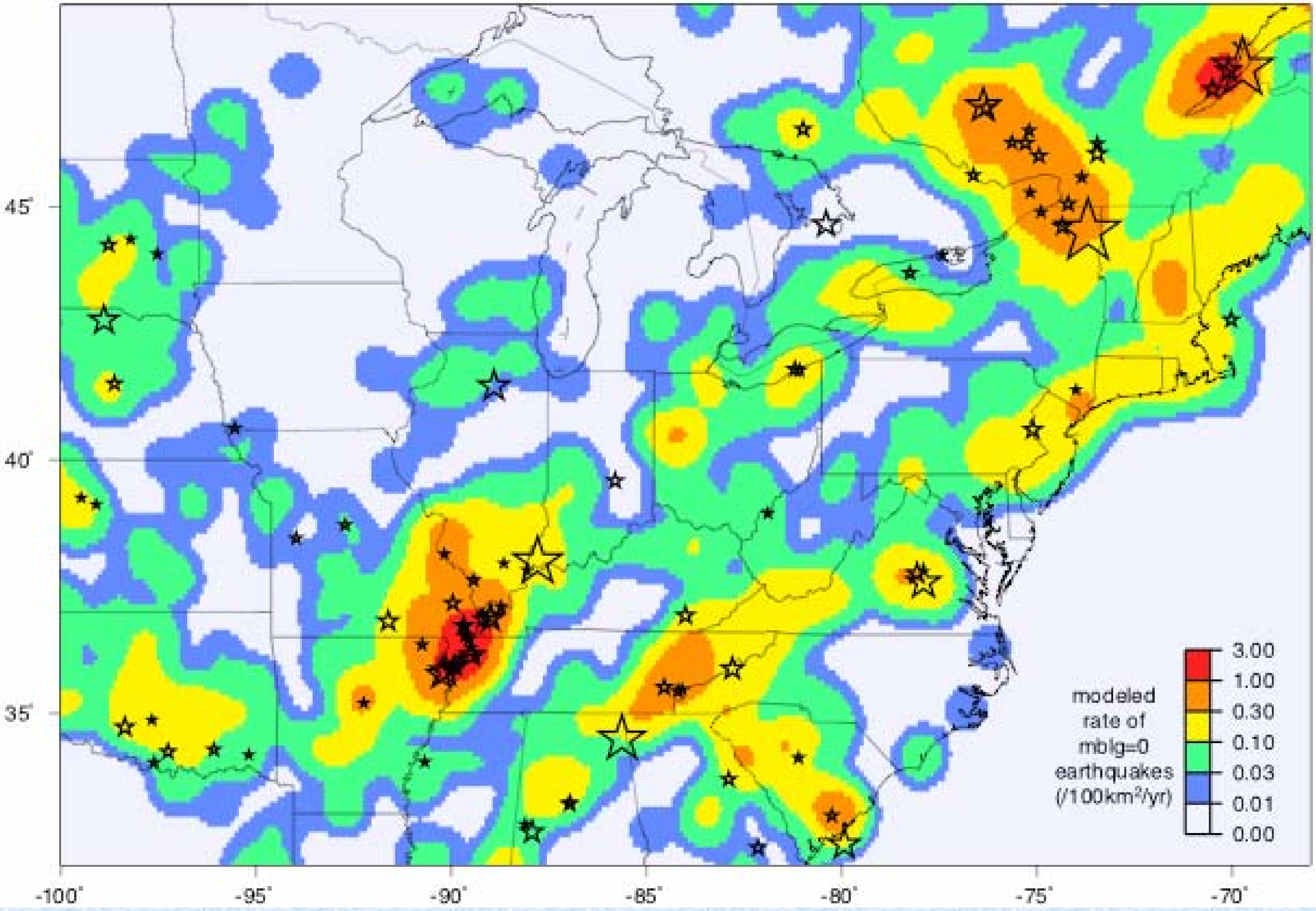
Smoothed Seismicity Method:

Avoid judgments about the seismogenic potential of enigmatic tectonic features

Assume that future hazardous earthquakes will occur near past small and moderate-size earthquakes (+background zones)



How well does the 2001 Model 1 (based on 1924-2001 eqs) predict post-2001 seismicity?



Why 3 Gridded Seismicity Models?

- The maximum-likelihood method counts a magnitude-5 earthquake the same as a magnitude-3 earthquake
- In places where moderate-size earthquakes have occurred, but small earthquakes are under-represented (*e.g.*, the Nemaha Ridge), a single model may underestimate the hazard
- Another way to think about it: like a localized, variable *b* value

Combining rate grids (“adaptive weighting”)

- Define “historical” rate =

  (Model 1 x 0.50) + (Model 2 x 0.25) + (Model 3 x 0.25)
- If historical rate > background rate: final rate = historical
- Otherwise: final rate = historical x 0.8 + background x 0.2
- Implications:
  - If historical = 0, then final = 20% of the observed regional average rate
  - Nowhere is final < historical
  - Violates the CEUS historical seismicity budget by ~ 10%

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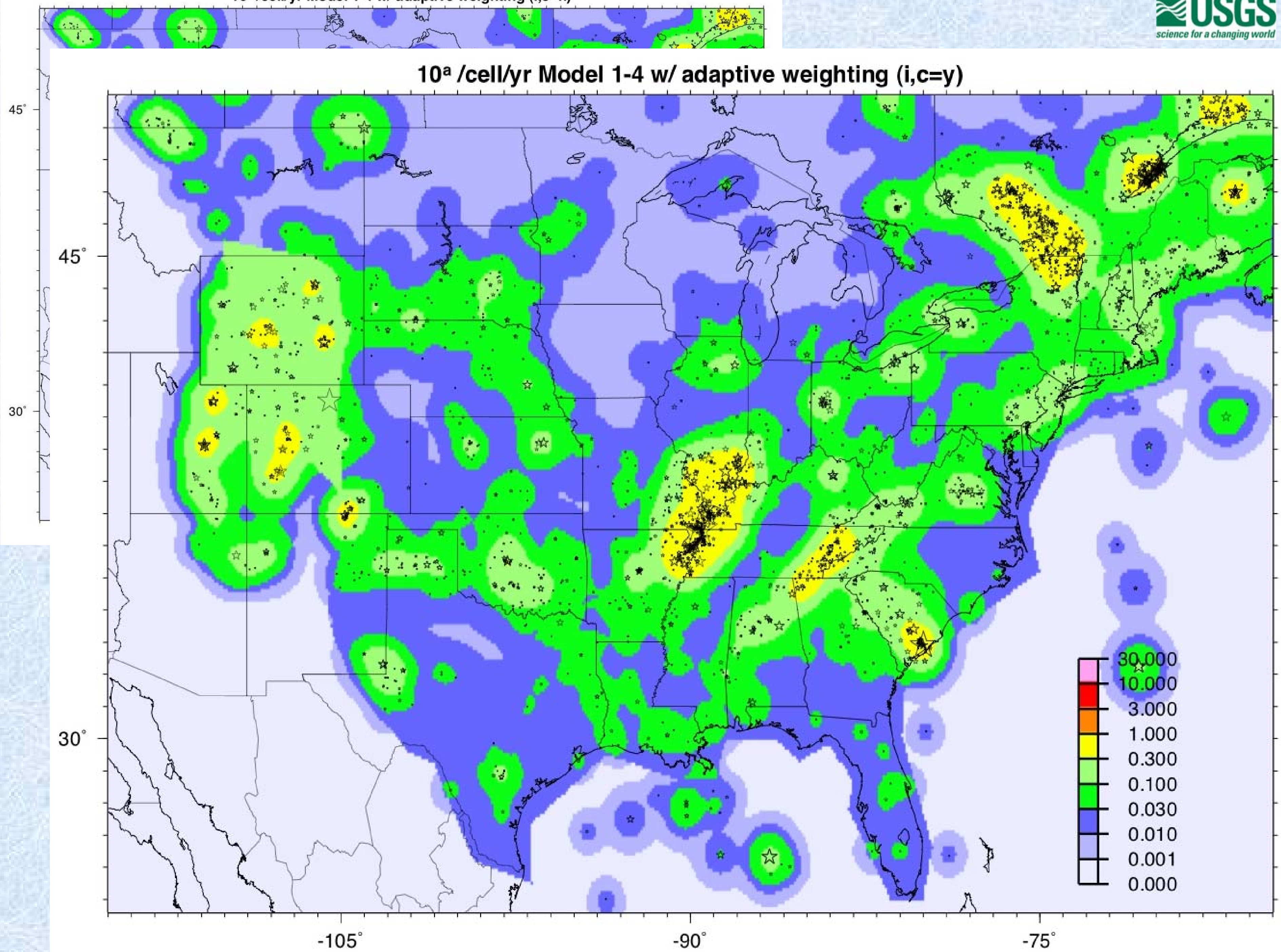
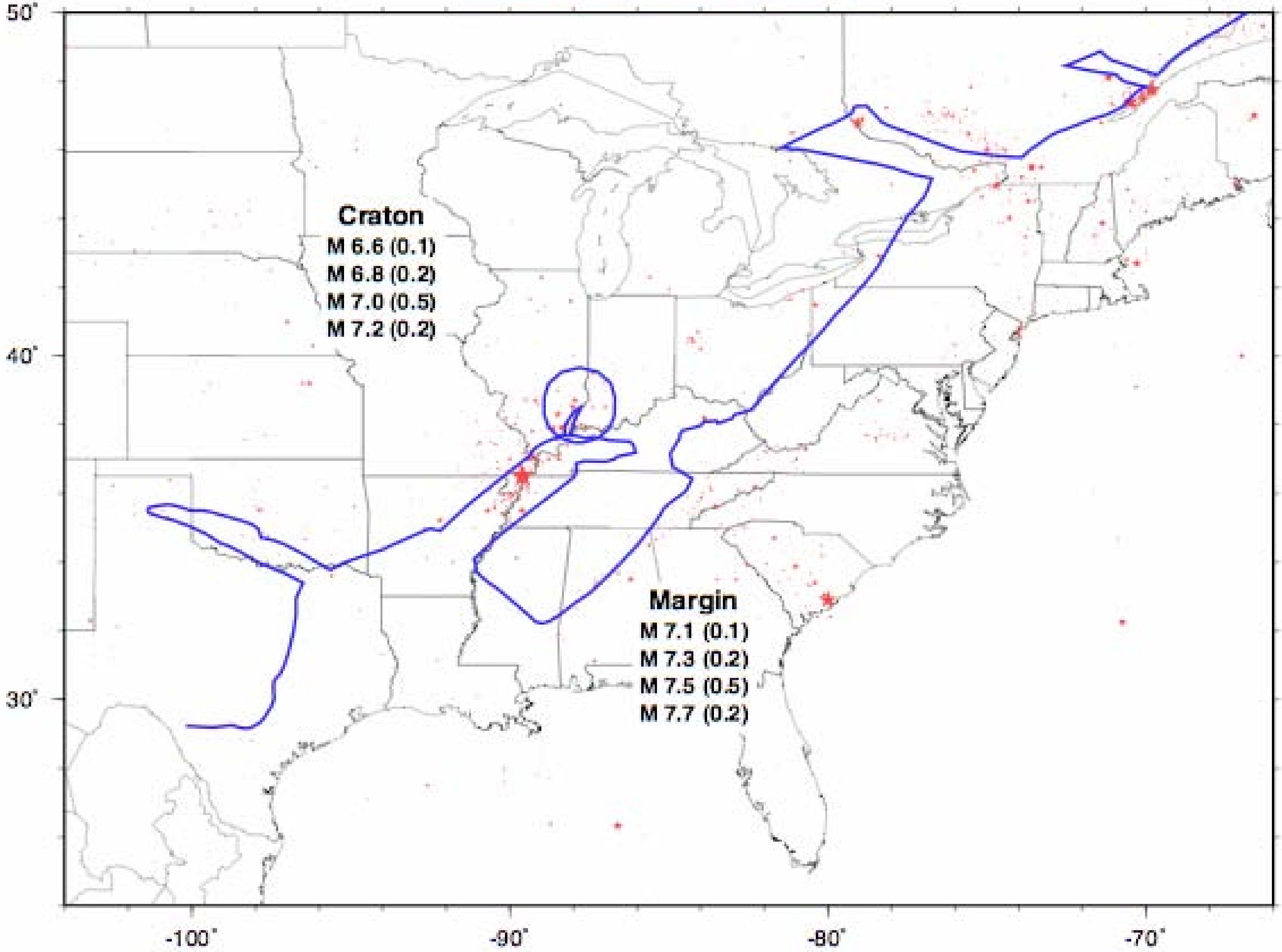
10ª /cell/yr Model 1-4 w/ adaptive weighting (i,c=n)

10ª /cell/yr Model 1-4 w/ adaptive weighting (i,c=y)



CEUS Mmax: USGS model



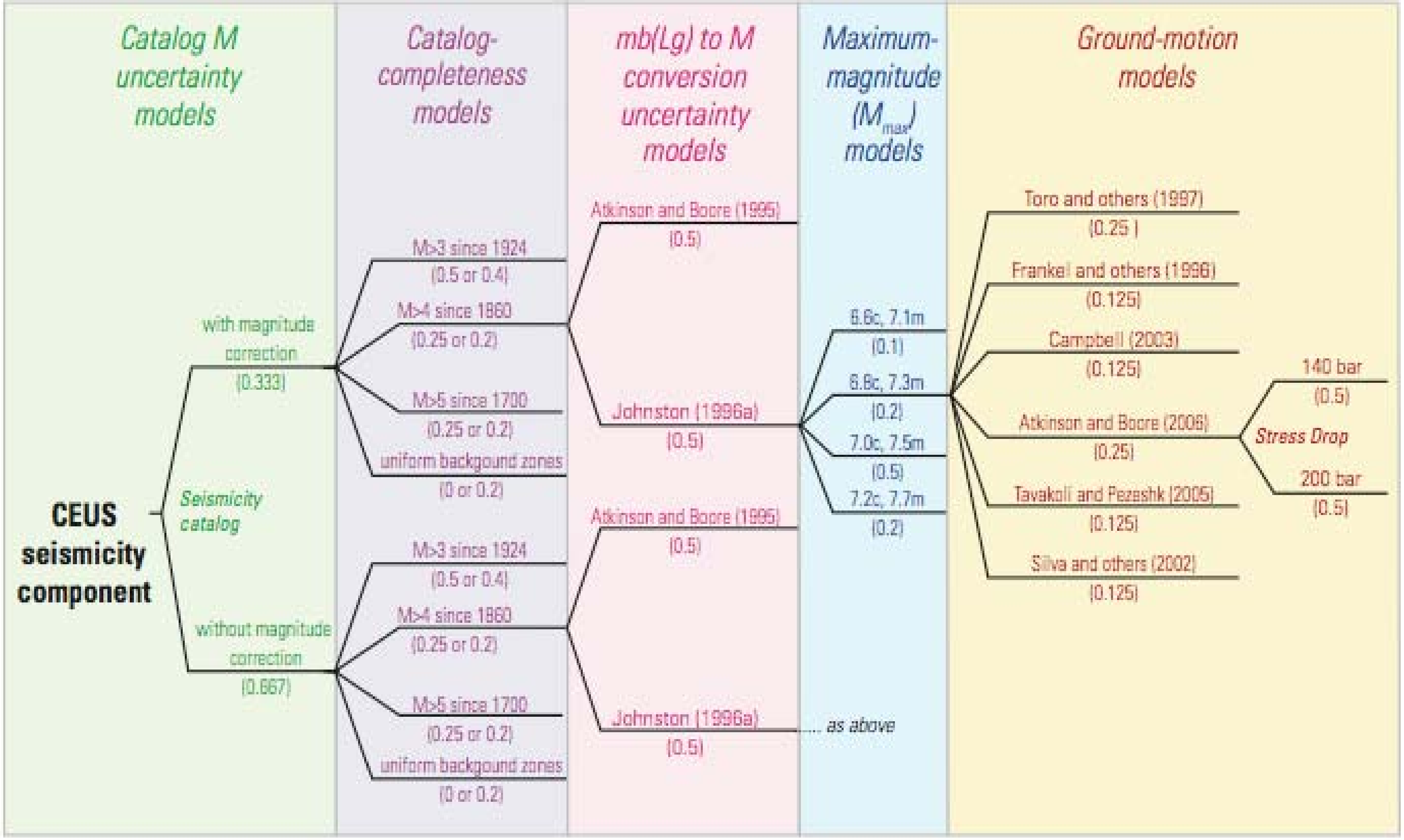
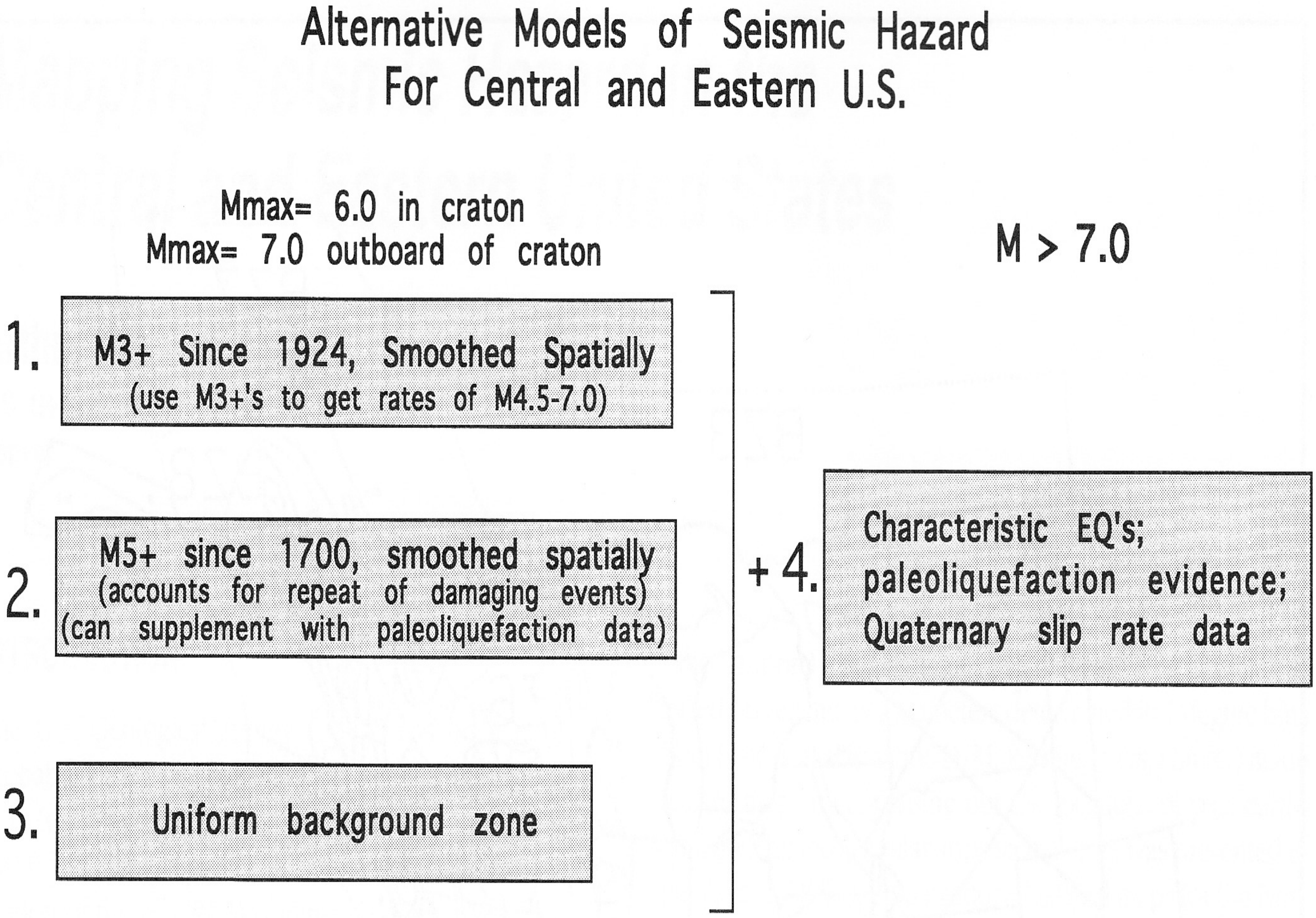


Figure 2. Logic tree for seismicity-derived hazard component in the Central and Eastern United States (CEUS). Each maximum-magnitude branch includes craton (c) and margin (m) estimates. Parameters in this figure include some aleatory variability as well as depicted epistemic uncertainty. We treat aleatory variability in ground motion in the hazard code.

Frankel 1995 SRL

from Frankel (1995, SRL)



Alternative Models of Seismic Hazard For Central and Eastern U.S.

Mmax= 6.0 in craton
Mmax= 7.0 outboard of craton

M > 7.0

1. M3+ Since 1924, Smoothed Spatially
(use M3+'s to get rates of M4.5-7.0)

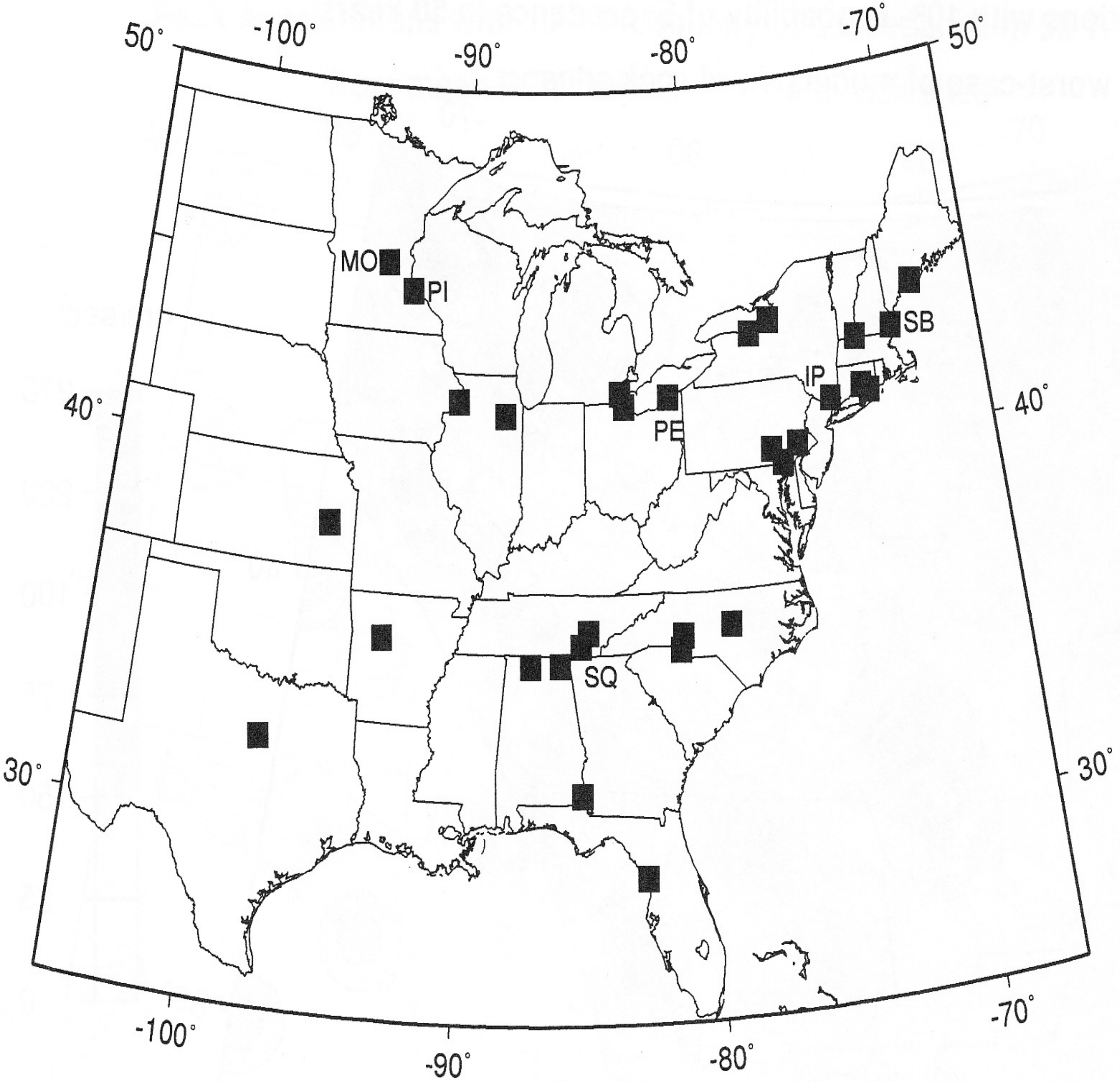
2. M5+ since 1700, smoothed spatially
(accounts for repeat of damaging events)
(can supplement with paleoliquefaction data)

3. Uniform background zone

+ 4. Characteristic EQ's;
paleoliquefaction evidence;
Quaternary slip rate data

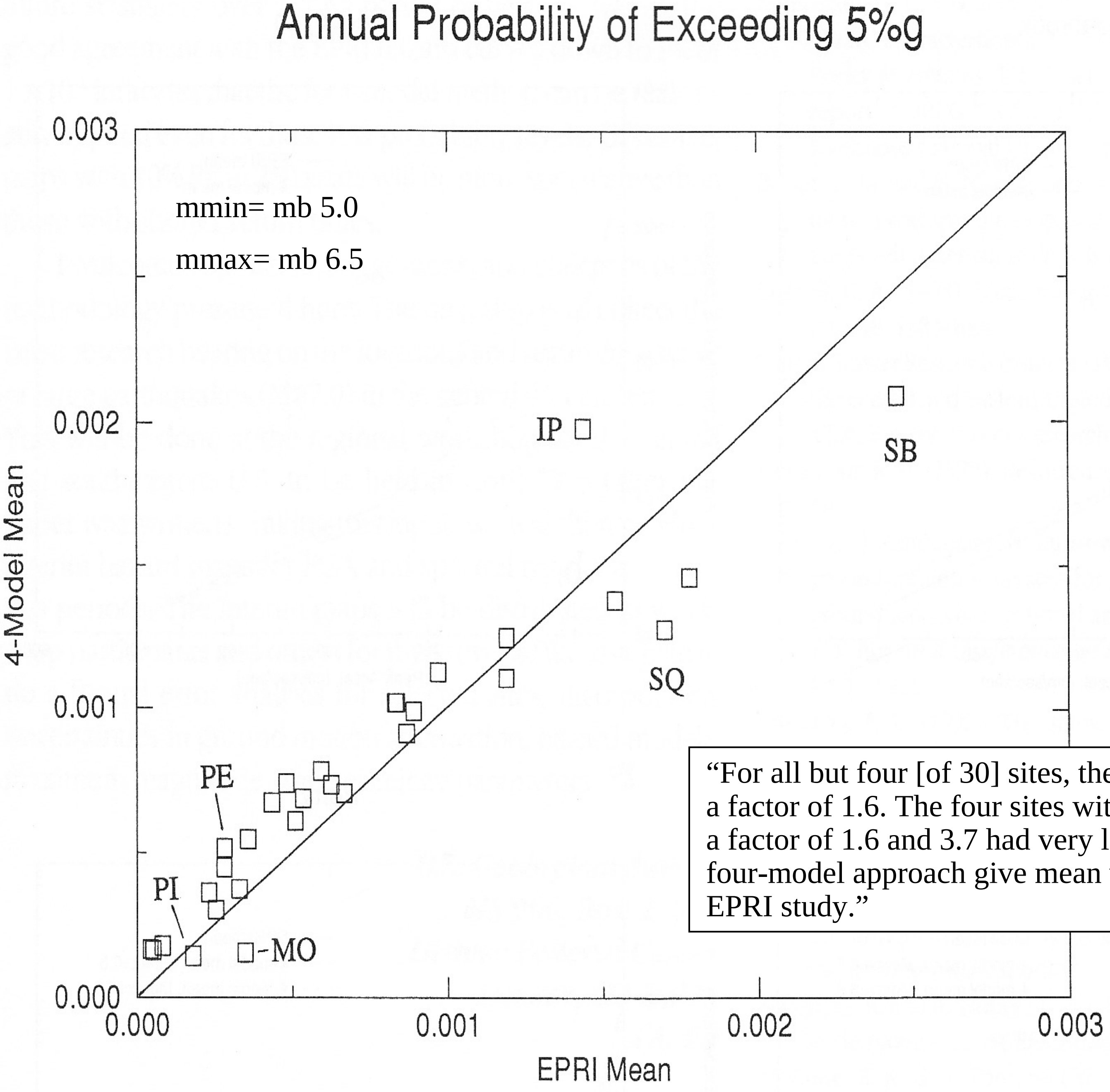
▲ **Figure 2** Chart of four models used in this paper to make seismic hazard maps in the central and eastern U.S.

from Frankel (1995, SRL)



▲ **Figure 10** Map showing reactor sites used in comparison of four-model and EPRI methods. Labeled sites are discussed in text: SB (Seabrook), SQ (Sequoyah), IP (Indian Point), PE (Perry), MO (Monticello), and PI (Prairie Island).

from Frankel (1995, SRL)

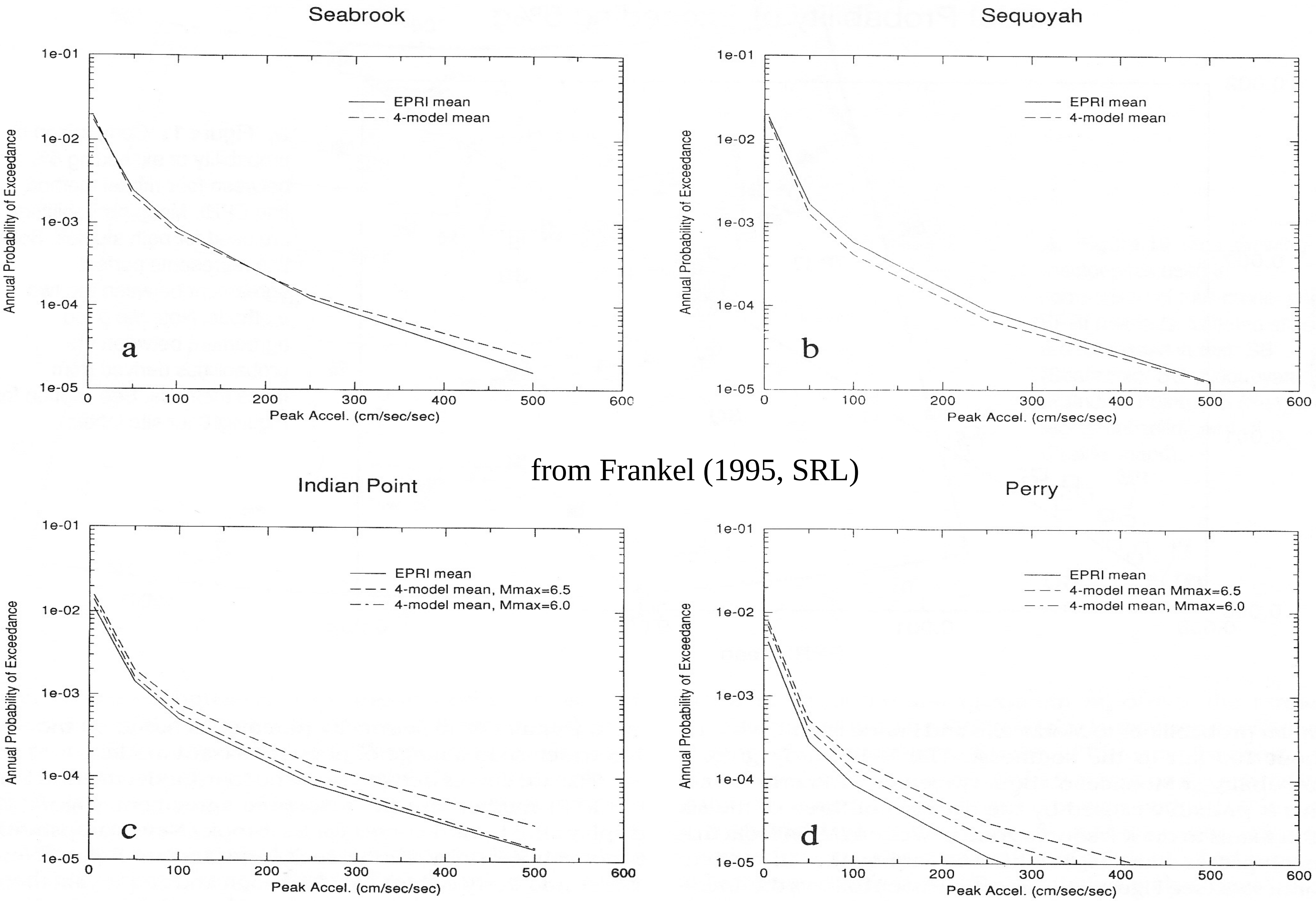

Annual Probability of Exceeding 5%g

mmin= mb 5.0

mmax= mb 6.5

▲ **Figure 11** Comparison of probability of exceeding 5% g between four-model method and EPRI. Mean probabilities are used for both studies. Solid line represents perfect agreement between the two methods. Note the good agreement between the probabilities derived from these methods. See caption for Figure 10 for site labels.

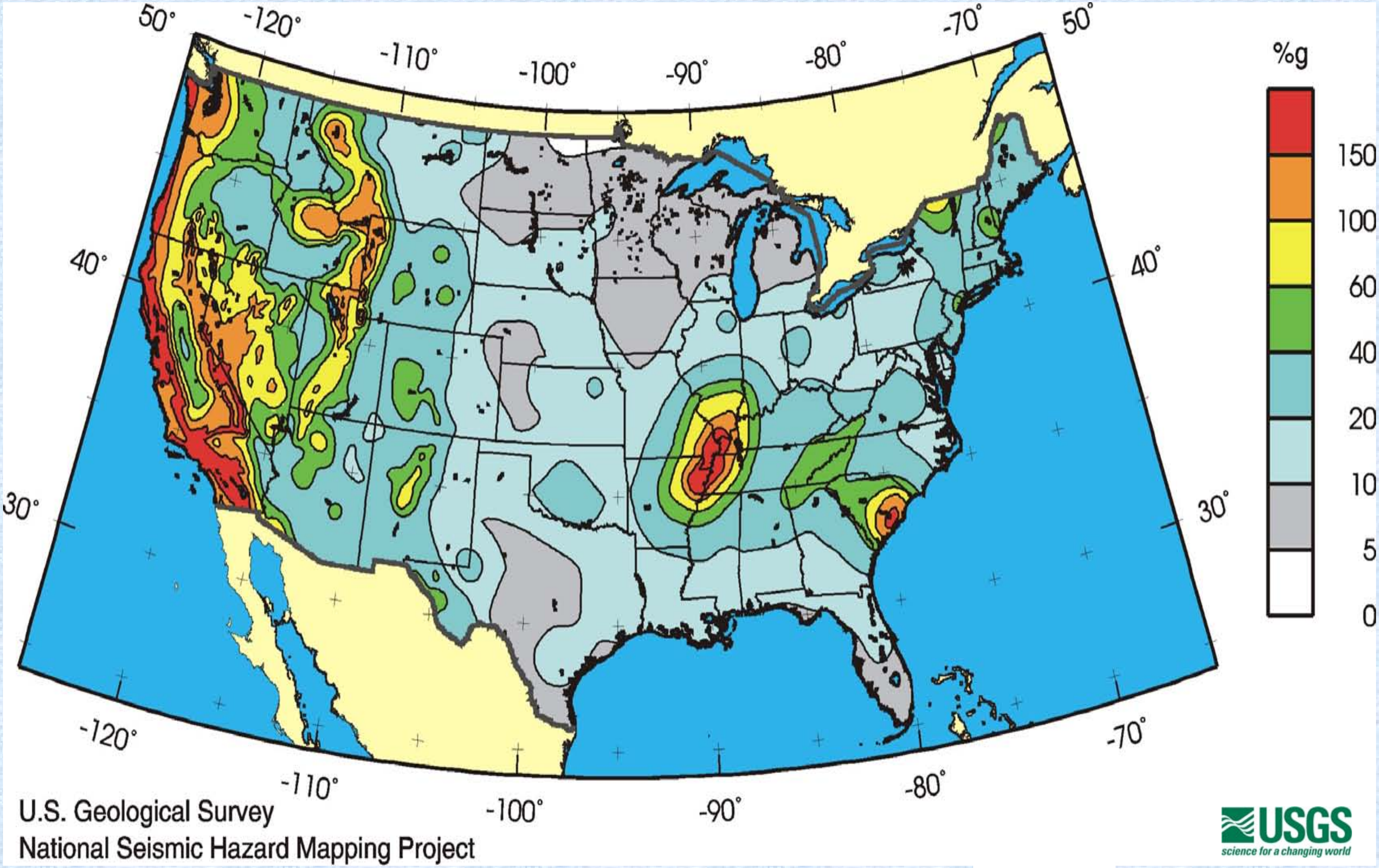
“For all but four [of 30] sites, the methods agree to within a factor of 1.6. The four sites with discrepancies between a factor of 1.6 and 3.7 had very low hazard.” … “The four-model approach give mean values comparable to the EPRI study.”



from Frankel (1995, SRL)

▲ **Figure 12** Hazard curves derived by the four-model (M_{max} = 6.5) and EPRI methods for a) Seabrook, b) Sequoyah, c) Indian Point, and d) Perry. Note the good agreement between the two methods for probability levels down to 1 x 10^{-4} (and lower for Seabrook and Sequoyah). For Indian Point and Perry, hazard curves are also shown for the four-model method using a M_{max} of 6.0.

Thank You


50°
-120°
-110°
-100°
-90°
-80°
-70°
50°
40°
40°
30°
30°
-120°
-110°
-100°
-90°
-80°
-70°
%g
150
100
60
40
20
10
5
0
U.S. Geological Survey
National Seismic Hazard Mapping Project
USGS
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CEUS SSC Workshop #2
Alternative Interpretations
Path Forward

Kevin Coppersmith
February 20, 2008
EPRI, Palo Alto, CA

CEUS SSC Task Schedule

Task	Schedule
Retain Participatory Peer Review Panel	April – May 2008
Database Development	April 2008 – May 2009
Seismicity Catalog	April 2008 – June 2009
Assessment of Hazard-Significant Issues	April - July 2008
Workshop 1 Significant Issues and Databases	July 22-23 2008
Workshop 2 Alternative Interpretations	February 18 – 20 2009
Construct Preliminary SSC Model	December 2008 – Aug 2009
Develop Hazard Input Document and SSC Sensitivity Analyses	May – June 2009
Perform Preliminary Hazard Calculations and Sensitivity Analyses	June - July 2009
Workshop 3 Feedback	25-26 August 2009
Finalize SSC Model	August –November 2009
Document CEUS SSC Project in Draft Report	Oct 2009 – February 2010
Review of Draft Report by PPRP and Others	Feb – March 2010
Finalize and Issue CEUS SSC report	April – July 2010
Meeting with NRC and DNFSB	August 2010

Between Now and Workshop #3

- Preliminary SSC Model Development
  - Working meetings with TI team
  - Implement conceptual SSC framework
    - Data evaluation process
    - Establish criteria for defining seismic sources
      - Variations in Mmax, recurrence, p(A) of tectonic features, characteristics of future events
    - Implement criteria to capture range of approaches within technical community
- Seismicity Catalog
  - Complete catalog development including merging all component parts, moment magnitudes, uncertainties
  - Completeness, de-clustering for recurrence analysis

Between Now and Workshop #3 (continued)

- Use SSC tools developed for hazard analysis
  - Spatial smoothing, including adaptive kernels
  - Source boundary uncertainties
- Develop and incorporate specialized databases
  - Reprocessed aeromag, gravity
  - Update to stress map
  - Paleoliquefaction data
- Develop Hazard Input Document
  - Summarizes preliminary model for use in hazard and sensitivity analyses
- Conduct SSC sensitivity analyses
  - Mmax distributions
  - Recurrence relationships and their implications
    - Comparisons to observed rates
    - Implications to strain rates

Between Now and Workshop #3 (continued)

- Conduct PSHA calculations and sensitivity analyses
  - Seven demonstration sites to represent range of conditions
  - Deaggregation
  - Identify dominant contributors to mean hazard, to uncertainty
  - Evaluate the significance of particular models identified by the TI team
  - Comparisons with USGS hazard and explore differences

Between Now and Workshop #3 (continued)

- Conduct WS3 Feedback in August 2009
  - Review and discuss SSC sensitivities
  - Review and discuss hazard sensitivities
  - Identify most important issues and most important contributors to uncertainties
  - Discuss and debate the degree to which the preliminary model captures the views of the technical community
    - Identify any overlooked hypotheses
    - Examine uncertainty quantification
  - Establish process for finalizing SSC model and developing documentation

CEUS SSC Project Workshop #2 - Agenda and Administrative Forms
Feb 18-20, 2009
Palo Alto, CA

Last Name	First Name	Company
Adams	John	Geological Survey Canada
Ake	Jon	Nuclear Regulatory Commission
Angell	Mike	William Lettis & Associates
Arabasz	Walter	University of Utah
Baltay	Anne marie	Stanford University
Baumont	David	IRSN/DES/SAMS
Berge	Catherine	French Safety Authority
Boyd	Oliver	U.S. Geological Survey
Calais	Eric	Purdue University
Chapman	Martin	Virginia Polytechnic Institute
Coppersmith	Kevin	Coppersmith Consulting, Inc.
Cox	Randy	University of Memphis
Drahovzal	James	University of Kentucky
Ebel	John	Boston College
Forte	Alessandro	University of Quebec at Montreal
Fukushima	Yoshimitsu	Ohsaki Res. Inst.
Glaser	Laura	AMEC Geomatrix
Green	Russell	Virginia Polytechnic Institute
Hamel	Jeff	Electric Power Research Institute
Hanks	Thomas	U.S. Geological Survey
Hanson	Kathryn	AMEC Geomatrix
Hartleb	Ross	William Lettis & Associates
Heuberger	Stefan	Swiss Nuclear
Hinze	William	Purdue University
Kafka	Alan	Boston College
Kammerer	Annie	Nuclear Regulatory Commission
Kassawara	Bob	Electric Power Research Institute
Kenner	Shelley	DBA Shellley Kenner
Kimball	Jeffrey	Defense Nuclear Facilities Safety Board
Knepprath	Nichole	U.S. Geological Survey
Lettis	William	William Lettis & Associates
Li	Yong	Nuclear Regulatory Commission

CEUS SSC Project Workshop #2 - Agenda and Administrative Forms
Feb 18-20, 2009
Palo Alto, CA

Last Name	First Name	Company
Lindvall	Scott	William Lettis & Associates
Mazzotti	Stephane	GS Canada
McBride	John	Brigham Young University
McDuffie	Stephen	U.S. Dept. of Energy
McGuire	Robin	Risk Engineering, Inc.
Mooney	Walter	U.S. Geological Survey
Moore	Donald	Southern Nuclear Operating Co.
Mueller	Charles	U.S. Geological Survey
Mulford	Tom	Electric Power Research Institute
Munson	Clifford	Nuclear Regulatory Commission
Murphy	Andrew	Nuclear Regulatory Commission
Neveling	Johann	Council for Geoscience
Olson	Scott	University of Illinois
Orbovic	Nebojsa	Canadian Nuclear Safety Commission
Pazzaglia	Frank	Lehigh University
Perman	Roseanne	AMEC Earth & Environmental, Inc.
Petersen	Mark	U.S. Geological Survey
Renault	Philippe	Swiss Nuclear
Salomone	Larry	Savannah River Nuclear Solutions, LLC
Schmitt	Timo	Bundesanstalt für Geowissenschaften und
Scotti	Onna	IRSN/DES/SAMS
Smalley	Bob	University of Memphis
Stein	Seth	Northwestern University
Stepp	Carl	DBA Carl Stepp
Stirewalt	Gerry	Nuclear Regulatory Commission
Talwani	Pradeep	University of South Carolina
Thomas	Bill	University of Kentucky
Toro	Gabriel	Risk Engineering, Inc.
Tuttle	Tish	M. Tuttle & Associates
Van Arsdale	Roy	University of Memphis
Youngs	Robert	AMEC Geomatrix

SUMMARY

CENTRAL AND EASTERN UNITED STATES

SEISMIC SOURCE CHARACTERIZATION

(CEUS SSC) PROJECT

WORKSHOP 2: ALTERNATIVE INTERPRETATIONS

February 18 -20, 2009

SUMMARY

CENTRAL AND EASTERN UNITED STATES SEISMIC SOURCE CHARACTERIZATION (CEUS SSC) PROJECT

WORKSHOP 2: ALTERNATIVE INTERPRETATIONS

February 18–20, 2009

Electric Power Research Institute
3420 Hillview Ave.
Palo Alto, California 94304

The Workshop on Alternative Interpretations was the second in a series of workshops jointly sponsored by the Electric Power Research Institute (EPRI) Advanced Nuclear Technology (ANT) Program, U.S. Nuclear Regulatory Commission, and the U.S. Department of Energy (DOE) in support of the Central and Eastern U.S. Seismic Source Characterization (CEUS SSC) for Nuclear Facilities Project. The objective of the CEUS SSC is to develop a comprehensive and up-to-date SSC for a probabilistic seismic hazard analysis (PSHA) that is appropriate for use at any site in the CEUS. The Technical Integration (TI) team and TI Staff are charged with developing a seismic source model that captures the knowledge and uncertainties within the larger informed technical community. The goals of this workshop were to (1) review the project Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 methodology, ground rules, expert roles, and peer review processes; (2) provide an opportunity for the TI team and TI Staff to understand proponent views regarding important technical issues; (3) discuss the range of alternative views and uncertainties within the larger technical community; and (4) discuss the path forward for the CEUS SSC project. The goals were accomplished by a series of presentations and discussions designed to provide the TI team and TI Staff with the information it needs to develop a preliminary seismic source characterization model.

DAY 1 – WEDNESDAY, FEBRUARY 18

Workshop participants were welcomed by **Mr. Jeffrey Hamel**, the EPRI ANT Project Manager for the CEUS SSC project, who also reviewed some workshop logistics. **Mr. Lawrence Salomone**, Project Manager for the CEUS SSC project, then welcomed workshop participants and thanked them for attending. He reviewed some of the project logistics. Next Mr. Salomone reviewed the project goals: (1) replace the previous EPRI Seismicity Owners Group (EPRI-SOG, 1988) and Lawrence Livermore National Laboratory (LLNL; Bernreuter et al., 1989) seismic hazard studies that were conducted in the 1980s; (2) capture the knowledge and uncertainties of the informed scientific community using the SSHAC process, and (3) present a new CEUS SSC model to the Nuclear Regulatory Commission, DOE, and others for review. Transparency of the project process is a key goal. He reviewed the management chart for the project and showed samples of the data sets available for the study region. Mr. Salomone summarized the project milestones, including the preliminary SSC model feedback to be reviewed at Workshop 3, which is scheduled to be held August 25–26, 2009. In his concluding remarks he noted that the project is on track to meet the target completion date in 2010.

Dr. Kevin Coppersmith, the lead of the TI team, then welcomed the workshop participants. His talk focused on the goals of the workshop and the ground rules. Dr. Coppersmith began by reviewing aspects of the SSHAC project, which is documented in NUREG/CR-6372 (Budnitz et al., 1997) and will be implemented in the CEUS project. He reviewed the SSHAC basic principles for a PSHA, key attributes of the process, and expert roles, with their application to the current workshop. He indicated that the focus of the workshop would be on providing information that the TI team can use in developing the preliminary SSC model, which will be completed prior to the third workshop. As such, the workshop would be structured to allow the TI team maximum opportunity to have their questions answered by the resource experts making the presentation. He reviewed the CEUS SSC task schedule and the process to be followed for Workshop 2. Prior to the workshop, key questions and issues were posed to the presenters to address in their talks (see Table 1); the knowledge and uncertainties of these members of the larger informed technical community are what the TI team is charged with capturing.

The first of the talks was given by **Dr. Stephane Mazzotti** of the Geological Survey of Canada. His talk was titled Strain (and Stress) Constraints on Seismicity in the St. Lawrence Valley. Dr. Mazzotti began by discussing the distribution of earthquakes and the definition of seismic zones based on concentrations of earthquakes in regional “hot spots,” in this case, the Charlevoix and lower St. Lawrence Seaway regions. He noted that earthquakes are concentrated along Iapetus rifted margins and grabens that formed about 600 million years ago (Ma). He also noted that seismic moment and deformation rates for eastern Canada can be based on two alternative models for earthquake distribution: (1) earthquake statistics in historical source zones, which indicate a few high-strain zones and relative motion of 0.0 to 2.5 millimeters per year (mm/yr); and (2) geological source zones, which have no high-strain zone and motion of only 0.0 to 0.5 mm/yr. Dr. Mazzotti reviewed GPS (global positioning systems) observations from regional networks and showed the vertical and horizontal velocities obtained from this data, noting that there is very good agreement between continuous data (3 to 6 years) and campaign data (7 to 12 years). Next he discussed preliminary results of GPS measurements in the Charlevoix and lower St. Lawrence seismic zones. This data shows very low strain rates overall, as expected, but east-west horizontal strain rates appear to be higher in high-seismicity zones. Within these zones, the recurrence rates derived from the observed seismicity are in good agreement with rates derived from geodetic data translated into seismic moment rates. Current strain rates and seismicity are not steady-state on a million-year time scale, inasmuch as the rates imply cumulative deformation over million-year time scales that are not observed. Within a resolution of approximately 1 mm/yr at 95 percent, it is not possible to discriminate between alternative models.

Next Dr. Mazzotti described the potential role of glacial isostatic adjustment (GIA) processes and models. GIA is very small and it is debatable as to whether or not it is associated with earthquakes. Dr. Mazzotti's work shows there may be a significant role of GIA and local weak rheology in seismicity for some seismic zones, as indicated in the Charlevoix and lower St. Lawrence regions. In his conclusions, Dr. Mazzotti mentioned that the observed seismic strain signal (<1 mm/yr) is at the limit of GPS precision and that GPS data cannot yet represent earthquake hazard over the next 500 to 5,000 years. He believes GPS strain rates should be used in combination with other data sets, including rheology, geology, and historical seismicity, to define seismic source zones and rates, but only once a robust integrative geodynamic model has been developed.

The following talk was given by **Dr. John Ebel** of Boston College, who addressed M_{max} for Eastern North America: An Examination of the 1663 Charlevoix Earthquake. Dr. Ebel began by stating that many of the small earthquakes in the northeastern part of North America may be aftershocks of strong earthquakes that took place hundreds or even thousands of years ago. To provide a frame of reference, he first showed examples of seismicity in California, which indicate that aftershock zones can be active for decades after a main shock. Next he described the methods he used to estimate the magnitude of the 1663 Charlevoix earthquake. This event was felt strongly in Canada, with major ground deformations in what is today recognized as the Charlevoix seismic zone. Dr. Ebel obtained data from damage reports in Boston and Roxbury in Massachusetts that were possibly associated with this earthquake, and he used the data to estimate the intensity and magnitude of the 1663 event. (The Charlevoix seismic zone is between 560 and 640 kilometers [km] from Boston.) He also compared the reported earthquake effects with isoseismal maps from the 1811–1812 New Madrid earthquakes and estimated the earthquake magnitude from the length of the "aftershock" zone that is currently active in the Charlevoix region. The best estimate of the moment magnitude (M_w) of the 1663 Charlevoix earthquake from his study is M_w ~7.3–7.5.

Next, Dr. Ebel began speculation on the characteristics of large earthquake events in stable continental regions. He believes that larger aftershocks concentrate at the edges of an earlier earthquake rupture due to stress concentration at the crack tip. This appears to be the pattern at Charlevoix, where recently occurring M 4 events have been located at the edges of the 1663 event. Dr. Ebel also speculated on recurrence rates of $M > \sim 7$ for the CEUS and eastern North America. The observed rate of $M > \sim 7$ earthquakes is greater than expected from extrapolations from the smaller earthquakes recorded in these regions. If small events reflect aftershocks of larger events, then the rate of $M > \sim 7$ earthquakes during the past few thousand years may be approximately two to three times greater than predicted by recurrence relationships that extrapolate the number of large events from small events.

The next presenter was **Dr. Alan Kafka** of Boston College, who spoke on Use of Seismicity to Define Seismic Sources: Application to Eastern North America. Dr. Kafka discussed how "cellular seismology" can be used to delineate future seismicity based on what is known about past seismicity. Empirical analysis of earthquakes is based on historical and instrumental earthquake history, but this information does not address causes of earthquakes and whether analysis of what is currently observed will show persistence over long time scales. Is the "tendency for future earthquakes to occur near past earthquakes" a real, measurable, physical phenomenon? Dr. Kafka has investigated this question and uses a simple method of analysis based on separating observed seismicity data into two parts before and after some point in time. He then looks at the percentage of events after that time (future events) that fall within zones defined by various radii from earthquakes prior to that time (past events). As the radii increase, of course, the probability that a future event will fall within the zone for past events increases even for a random process. However, Dr. Kafka has found that the probability increases more rapidly than a random process, suggesting that future events are more likely to occur near past events. He has looked at many regions in the United States and worldwide for these patterns. He has found that future large earthquakes in the CEUS have about 86 percent probability of occurring within 36 km of past earthquakes. He has compared the accuracy of cellular seismicity to other methods, including rate-based forecasts (percentage of hits vs. percentage of defined mapped areas). In general, he finds that for his method, greater than 60 percent hits are obtained (whereas a random process would be about 30 percent). In his conclusions, Dr. Kafka noted that he has not found any other method of forecasting locations of future earthquakes that performs better than cellular seismology.

Following a lunch break, **Dr. John Adams** of Natural Resources Canada discussed the Canadian seismic hazard models in a talk titled <u>Eastern Canadian Experience with Geological Source Zones and M_{max}</u>. He briefly reviewed aspects of the third- and fourth-generation seismic hazard models developed for Canada. He believes that smoothed seismicity is interesting but not sufficient for assessing future hazard levels. As an example, he cited the 1988 M 5.9 Saguenay earthquake in an area that had no prior earthquake activity of $M_N > 3$ for more than 50 years prior. He believes geological sources provide essential information, and noted that geological sources were proposed in Canada as early as 1983 for the passive continental margin. For the United States, he noted that Russell Wheeler did good work on geological sources in the early 1990s, but these were not explicitly incorporated in USGS hazard maps. Dr. Adams described the association of large earthquakes ($\mathbf{M} \geq 7$) with rifted margins, noting the 1933 Baffin Bay and 1929 Grand Banks events, which occurred on large through-going faults that were reactivated in the Mesozoic. He then showed a map of seismic source zones in eastern Canada and into the eastern United States and described how various zones were modeled, based on both geologic history (ancient rifted margins and failed rift arms) and seismicity. He noted geological structures/source zones form a way of "filling in" between historical earthquake clusters.

The eastern Canadian experience with maximum magnitude (M_{max}) was described in the next part of Dr. Adams's talk. He described how the M_{max} estimates in previous generations of seismic hazard maps had been exceeded by significant earthquakes that occurred in Canada between 1982 and 2001. Accordingly, M_{max} estimates chosen for the fourth-generation studies were larger and based on continent-scale and global analogs, using methods similar to the EPRI Stable Continental Region (Johnston et al., 1994) study. A study of M_{max} in Australia was described as an analog for the CEUS and Canada. M_{max} choices for eastern Canada were also described, including weights assigned to a range of observed M_{max} for different tectonic environments; these included Mesozoic rifted margins, Paleozoic rifted margins, and plate interiors. In his concluding remarks, Dr. Adams stated that earthquakes of M_{max} ~M_w 7.0 could not be ruled out anywhere, although probabilities will be very low in many stable continental regions. Phanerozoic rifted crust typically contains enough long and deep faults (or fault systems) that M_{max} ~8.0 M_w seems plausible. In his final slides, Dr. Adams showed how Canadian seismic source zones can be extended into the CEUS. Extensions of Canadian source zones could be postulated to extend into the US, such as the Atlantic Rifted Zone extended to Charleston, South Carolina; the Iapetan Rifted Margin extending to Giles County Virginia and the Eastern Tennessee seismic zone.

Dr. Coppersmith announced that the next scheduled speaker, Dr. Leonardo (Nano) Seeber (Lamont-Doherty Earth Observatory) was unable to attend the workshop. A talk originally scheduled for Day 3 of the workshop was substituted.

Dr. Frank Pazzaglia of Lehigh University presented a talk titled Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont/Coastal Plain Setting. The focus of the talk was the geology and geomorphology of the passive margin in the Atlantic states. Dr. Pazzaglia addressed the influence of broad regional flexure of the Atlantic margin on current patterns of seismicity, noting that there is spatial overlap in topography, active river incision, and seismicity. He described how topography and rivers respond to rock uplift, rock hardness, and erosion. He showed maps of many of the rivers along the Atlantic coast and described different geographic areas and their association with seismic activity. He discussed the Fall Zone and its location on the classic passive margin, emphasizing that the Coastal Plain is narrow and no waterways are navigable, which doesn’t make logical sense for that type of setting. Coastal margin topography suggest that this area has been undergoing uplift, thus leading to convex upward longitudinal profiles for the rivers. He suggested that the Appalachians might be more tectonically active than previously thought. For example, New England has been uplifted since the Miocene, and over time, the Hudson River has moved the sediments of the former Coastal Plain to the south. Dr. Pazzaglia described the stratigraphy along the edges of Chesapeake Bay. He provided evidence for faults up and down the coastal margin that are concentrated around the Fall Zone.

Dr. Pazzaglia believes that future earthquakes could occur in areas with low seismicity that also have apparent fault structures. He showed nick points along the Fall Zone, noting that it is clear that a base-level fall has occurred since the Miocene, although within this 10-million-year (m.y.) period we cannot tell if this occurred early or late. It is now known that the Miocene sea level was about the same as at present, so the Piedmont is clearly rising. Faults located coincident with the Fall Zone would be useful targets for detailed studies to see if river anomalies are related to tectonics. Dr. Pazzaglia continued by discussing flexural effects from glaciations and ice unloading during the Quaternary. Finally, he described the Chesapeake Bay impact structure emplaced approximately 35.4 Ma. Rivers drained into the low area created by the impact, and pulses of subsidence are apparent. Dr. Pazzaglia believes that this impact structure could be a causative structure for some of the seismicity in the eastern United States.

Dr. William Thomas of the University of Kentucky gave the next talk, titled Ouachita Sub-Detachment Structures. He described the geology of the CEUS at 250 Ma, showing major structural features based on data from wells and seismic reflection lines. He indicated the leading edge of aulacogen (tectonic trough) locations for the Alabama-Oklahoma transform and Ouachita thrust sheets. He discussed the stratigraphy and timing of activity of faults at about 308 Ma, showing the Mississippi embayment and other major structural features in palinspastic restorations. He also noted that episodes of movement were coincident with Iapetan rifting and then thrusting. He showed several seismic reflection profiles and cross sections that indicated stratigraphy and structure. The Ouachita thrust belt was compared with the Appalachian thrust belt, and different styles of deformation were described. The Ouachita accretionary prism was emplaced about 310 to 307 Ma, and to the east, the Suwannee terrane was emplaced about 306 to 300 Ma. Reconstructions give information about the timing of faulting. Dr. Thomas next discussed the Southern Oklahoma fault system, including the Wichita uplift, which is located above a leaky transform fault. In his conclusion, he noted that major structures were formed in the CEUS about 550 to 530 Ma and 310 to 300 Ma (late Paleozoic); some structures were reactivated in 245 Ma.

After a short break, **Dr. James Drahovzal** of the University of Kentucky gave a talk titled Rifts in the Midcontinent: East Continent Rift Basin, Rough Creek Graben and the Rome Trough. In his talk he discussed these structures and the associated Grenville and Hoosier thrust belts, along with the Fort Wayne rift, which is coincident with the Anna seismic zone. Dr. Drahovzal began by showing the classic CEUS “basement” bedrock geology and then noted that more complex stratigraphy and structure have been constructed from well data. Sedimentary and volcanic rocks underlie many areas of granite and other igneous rocks in the midcontinent. Dr. Drahovzal described drillhole and seismic data for portions of Ohio, Kentucky, and Indiana; seismic data indicates layered reflectors within sequences of as much as 20,000 to 25,000 feet of Mesoproterozoic rocks that are folded and faulted. He provided a preliminary Proterozoic chronology that indicates alternating episodes of extension and compression in the midcontinent. Next he described the sequence of geologic events that formed structures within the East Continent rift basin, including the aseismic Rough Creek graben and Rome trough. Both of the latter structures are likely to have experienced Mesozoic reactivation but are currently aseismic. The Rome trough is a symmetrical Cambrian rift basin that contains three major fault zone boundaries. Several reactivations since the Paleozoic are recognized for this structure. The Rough Creek graben in western Kentucky also shows evidence of Mesozoic reactivation, with Precambrian rock offsets of up to 17,000 feet. Dr. Drahovzal described the east continent gravity high and the relationship of this structure to the Rome trough and East Tennessee seismic zone. The 1980 **M** 5.2 Sharpsburg earthquake was located close to the East Continent gravity high.

The next talk was by **Dr. John McBride** of Brigham Young University, who discussed Geophysical Characterization of Faulting and Folding in the Illinois Basin and Relation to Seismicity. Seismic reflection data is used to understand fault deformation and seismicity in an area of the midcontinent centered on the Illinois Basin and the New Madrid seismic zone (NMSZ). Dr. McBride noted that reactivation of faults is not always clear, even in a well-constrained area like California, so fault reactivation is even more difficult to recognize in the Midwest. However, a large amount of geophysical data is available for the Illinois basin, particularly seismic profile data, because of oil production in the state that peaked in 1937. Dr. McBride showed a map displaying a CEUS earthquake catalog and questioned if an area showing little seismicity is real or an artifact of limited instrumental coverage. Next he showed a map of major structures in the southern Illinois basin and described some of these, including the La Salle deformation belt. He reviewed information for recent earthquakes in the region and showed a seismic reflection profile of the La Salle anticline. A 1987 earthquake and aftershocks associated with a frontal thrust, plus evidence of paleoliquefaction in the region, provide evidence of this anticline as a possible seismic source zone.

Next Dr. McBride described several possibly seismogenic structural features in the Illinois basin. The Fairfield subbasin (a deep part of the Illinois basin) includes a zone of locally more intense faulting, in which three fault zones can be mapped from seismic reflection profiles. Earthquakes that occurred in 1974 and 1987 were within the interpreted zone of rifting beneath the Fairfield subbasin. Dr. McBride showed the Wabash Valley fault system as imaged on a seismic profile. A 1968 earthquake event occurred in this region and may possibly have originated on a blind thrust fault. The Commerce geophysical lineament corresponds locally to disrupted geologic structures that may be seismogenic. The Du Quoin monocline complex was described. This monocline and the overlying Centralia fault zone may be an overlooked possible seismic source. Folds in this area provide some evidence for reactivation along an older reverse fault. The Cottage Grove fault system corresponds to a major crustal boundary, although the seismicity rate in the area appears to be low. The Fluorspar Area fault complex trends towards the New Madrid seismic zone; there is complexity in Fluorspar Area structures and evidence for Tertiary displacements. In his conclusions, Dr. McBride noted that the area where the La Salle anticline and Wabash Valley fault systems meet may have a high potential for fault reactivation.

After this talk, Dr. Coppersmith invited comments from observers. The participants discussed improvements in data available for smaller earthquakes, including better-constrained focal mechanisms. The group listed Paleozoic rifts that have not been reactivated. These include the Birmingham graben and the southern part of the Mississippi graben; the Ouachita graben also may not have been reactivated, but the underlying rocks are too old to indicate this history. At the conclusion of the discussions, the meeting was adjourned for the day.

DAY 2 – THURSDAY, FEBRUARY 19

Dr. Coppersmith welcomed the group to the second day of the workshop. The first talk was given by **Dr. Roy Van Arsdale** (University of Memphis) on <u>Quaternary Deformation within the Reelfoot Rift, Rome Trough, and Wabash Valley Fault System</u>. Dr. Van Arsdale began by showing the location of the Mississippi embayment and its relationship to the New Madrid seismic zone (NMSZ); earthquakes in the NMSZ define faults in the region. He showed a cross section of the Reelfoot fault with “kink bands” or back thrusts, as well as photos of trenches on the Reelfoot scarp trench. The recurrence interval for earthquakes is estimated to be approximately 500 years. He noted that the trench data is in good agreement with the regional earthquake chronology developed from paleoliquefaction features.

Dr. Van Arsdale described displacement history and slip rate on the Reelfoot fault from the late Cretaceous to the present. The slip rate increased dramatically in the Holocene, indicating an active period of fault history, but the end of this period may be near. Seismic reflection lines indicate deep basement faults with as much as 3 km displacement. Trenches opened above the seismic reflection lines show faults with transpressive right-lateral strike-slip movement. Right-lateral shear across the Reelfoot rift is responsible for the NMSZ earthquakes at the northern end of the rift. Rift margin faults are “big players” in the picture. Dr. Van Arsdale described features in the Shelby County and Memphis region, where liquefaction deposits (sand blows) and a broad fold forming an anticline are present. The anticline appears to be a tectonic feature formed about 400 A.D.

Dr. Van Arsdale then described work he did many years ago in the Rome trough near the area of the 1980 Sharpsburg earthquake, where he focused on the Kentucky River fault system. He showed the log of a trench excavated in a terrace that exhibited folding and an apparent shear zone. He estimated the timing of fault movement as within the past 5 m.y. Next he described the Hovey Lake fault in the Wabash Valley fault system and the Stull trench site in Union County, Kentucky. He concluded his talk by showing a schematic of fault scarp evolution based on the information obtained from the trench.

Mr. Robert Givler of William Lettis & Associates, Inc., gave the next talk, which was co-authored with Mr. John Baldwin. The title of the talk was Commerce Geophysical Lineament and Northwestern Margin of the New Madrid Seismic Zone. The Commerce geophysical lineament (CGL) is a 400- to 600-km-long feature that exhibits Quaternary strike-slip and normal faulting along a 75 to 120 km portion of its length in the New Madrid region. Mr. Givler described the regional geologic setting for the CGL and the detailed studies conducted at Qulin Ridge. This locality contains Late Wisconsin glacial outwash deposits; seismic profiles show Quaternary offset along a fault, and four paleoliquefaction events have been identified. Next Mr. Givler described the Holly Ridge locality associated with the Idalia Hills fault. Seismic reflection profiles show displacement of Quaternary deposits that project upwards and correlate with surface geomorphic features. Trench data from the Bloomfield Hills locality on the Idalia Hills fault indicate two poorly constrained faulting events. Mr. Givler described trench studies for localities on the Commerce fault and the Penitentiary fault. The Benton Hills locality is on the Commerce fault, where strike-slip faulting is recognized for four late Quaternary events. The Quaternary-active Penitentiary fault is located in the Cache River valley. The Penitentiary fault is a step-over from the Commerce fault and has a prominent east-facing scarp. Seismic lines in the area were used to further test the hypothesis that the Penitentiary fault is a seismic source; these data indicate multiple faults disrupting Pleistocene and possible early Holocene deposits. A fault segment 75 to 120 km in length is recognized in southeast Missouri and southern Illinois along the Commerce fault. A weak alignment of microseismicity is associated with this fault. Based on all of this data, the CGL appears to have been active into the early Holocene. The fault has long earthquake recurrence intervals of 5 to 10 thousand years and possibly episodic activity.

Next, **Dr. Randy Cox** of the University of Memphis gave a talk titled Some Mississippi Valley Holocene Faulting and Liquefaction beyond the New Madrid Seismic Zone. He began by discussing southeast Reelfoot rift margin surface faulting. He showed a map of the topographic lineament of the southeast rift margin and the locations of trenches excavated to study this feature. He described the Porter Gap trench site where a late Holocene earthquake was recognized, showing the trench logs and a shallow seismic reflection line. Structural relief and topographic relief are consistent with faulting. Evidence of faulting in the trenches indicated an event with >4 meters (m) vertical displacement and horizontal (strike-slip event) displacement of about 8 to 15 m. Earlier events of approximately equal magnitude were also observed in early Holocene deposits. Next Dr. Cox described a newly recognized sand blow field in the southern Mississippi embayment area of northeastern Louisiana, south of the New Madrid area, which was identified from an aerial photo survey. He has delineated five separate fields containing clusters of sand blows. A trench log across an area of sand blows, and photographs of sand blows were shown. The earthquakes that caused the liquefaction are estimated to be **M** > 6 on the basis of the minimum radii of the fields and on cone penetration tests in the region. Multiple events are indicated, and based on limited data, the earthquake recurrence rate is roughly 1,000 to 2,000 years. The earthquake events that Dr. Cox recognizes can be correlated with multiple regional events that affected more than one of his five zones, or they could be related to local earthquakes that are separate for each zone.

He concluded his talk by describing his studies of the Saline River fault system in the craton margin area of the Alabama-Oklahoma transform. Seismicity data is sparse in this region but he has examined many exposures containing features that suggest deformation. Seismic lines show Triassic grabens and flower structures that extend upward into Cenozoic deposits. The trenches that have been excavated show faulting in mid-Pleistocene deposits; overlying Holocene deposits may be warped. Paleoliquefaction features of dense sand blows have been recognized in the area, indicating multiple earthquake events in the late Pleistocene through the late Holocene. Dr. Cox believes the paleoliquefaction features were caused by local earthquakes and are not related to far-field events such as those in the New Madrid area to the north.

After a break, **Dr. Russell Green** of Virginia Polytechnic Institute gave a talk titled Paleoliquefaction Interpretation of the Vincennes Earthquake, Wabash Valley Seismic Zone. Dr. Green began his talk by reviewing liquefaction phenomena. He showed photographs of classic liquefaction phenomena as well as video footage of liquefaction phenomena resulting from the 1964 Niigata, Japan, earthquake. He described a “simplified” liquefaction evaluation procedure to assess cyclic resistance or the capacity of a soil to resist liquefaction. He described combinations of conditions that can be used to assess when liquefaction will or will not occur, related to peak ground acceleration and other factors. His work has been focused on the Wabash Valley seismic zone and specifically, the effects of the Vincennes earthquake that occurred approximately 6,100 years BP. Dr. Green has estimated the probable M_{max} of this earthquake by using plots of the severity of liquefaction with distance from the epicenter. The method he has developed to assess magnitude from data at various field sites incorporates an assessment of overall uncertainty.

Dr. Green discussed constraints on seismic sources, noting that the dimensions of a source can be estimated by contouring maximum dike width. Distinguishing between a small local earthquake event vs. a large distant earthquake event is difficult. Next he discussed sources of uncertainty, including ground-motion predictive relationships and field interpretations. To properly assess the uncertainties and their influence on a back-calculated M_{max}, input is needed from geologists, geotechnical engineers, and seismologists, depending on the information to be evaluated. Dr. Green then reviewed ground-motion attenuation relationship information for the CEUS and described alternative presentations of site amplification data. Based on his analyses, the Vincennes earthquake may have been an **M** 7.3–7.5 event, with the epicenter located within an area having a defined radius of about 160 km.

In a related talk, **Dr. Scott Olson** of the University of Illinois at Urbana-Champagne described a geotechnical approach to evaluate the strength of shaking associated with liquefaction phenomenon. His talk was titled <u>Quantifying Uncertainties in Paleoliquefaction Studies</u>. Dr. Olson began by reviewing existing methods for paleoliquefaction back-analysis, including the cyclic stress method, the magnitude bound method, and several other approaches. The cyclic stress method is suitable for evaluating a lower bound for a best estimate of an earthquake magnitude. Dr. Olson noted the variety in worldwide estimates of different magnitude bounds, which are a function of source characteristics, transmission characteristics (attenuation and site effects), and regional soil liquefaction susceptibility. To develop a magnitude bound for the CEUS, he examined historical earthquakes having **M** > ~5 and the liquefaction features associated with these events. He compiled the best estimates of magnitudes made by seismologists and then looked for the farthest-distance liquefaction features that could be associated with a specific earthquake. From this data he developed a CEUS magnitude bound, in which **M** 5.5 is the minimum magnitude for liquefaction at close-in locations; increasingly larger-magnitude events can trigger liquefaction at greater distances.

Sources of uncertainties in liquefaction susceptibility, field observations, seismicity, in situ testing techniques, and the magnitude bound approach were described. Then, Dr. Olson discussed aging, the process by which soils develop a structure that results in improved soil properties (e.g., shear strength); he noted that there may not be a need to make any correction for aging in many cases. He described characteristics of liquefaction severity (based on size of liquefaction features), and the factors of safety for different levels of liquefaction severity. A better tool than factor of safety, however, is a liquefaction potential index that incorporates stratigraphy, especially the depth and thickness of potentially liquefiable layers. Dr. Olson went on to discuss failure mechanisms and their relationship to liquefaction resistance. He listed a number of sources of uncertainty in field data, including depth of groundwater at the time of an earthquake, and variability of geologic settings. He then illustrated his approach by using data on the Vincennes earthquake. For this event he has calculated M_w 7.5 ± 0.3. He noted that the Wabash Valley work was based on the availability of abundant geotechnical field data; by contrast, few sites in the New Madrid seismic zone have sufficient geotechnical data for conducting a good back-analysis of magnitude.

Following a lunch break, the first talk of the afternoon session was given by **Dr. Eric Calais** of Purdue University, who talked about Geodetic Interpretations of New Madrid Rates. Dr. Calais began by describing the notion of a steady-state "elastic rebound" model, in which geodesy and paleoseismology should agree. This model works particularly well for plate boundary faults, as present-day strain has predictive power. Current GPS measurements indicate an upper-bound movement of 0.02 mm/yr at New Madrid. Dr. Calais also showed velocities measured at about 500 sites in North America with respect to a constant reference frame. Velocity analyses on deformation east of the Rocky Mountains have indicated that most measured velocities are not significant at a 95 percent confidence level. However, patterns in velocities, especially radial patterns, are apparent. Residual velocities of 0.6 mm/yr have been measured in the CEUS.

Next, Dr. Calais showed residual velocities for areas worldwide, including Europe and Australia, where these velocities are about 0.4 mm/yr. Velocity results have been stable over the past 5 years, so there can be high confidence in the measured rates. Available information indicates that velocities of 0.2 to 0.4 mm/yr are typical of stable continental areas as an upper bound. GPS detects with confidence only velocities of higher than 0.5 mm/yr and strain rates of approximately 10^{-9}. The New Madrid region may contain the only "active" intraplate system in the world where a local, continuous GPS network is available. Dr. Calais discussed the varying levels of precision and accuracy generally obtained from the 500 GPS stations in North America, and specific results for the New Madrid region. In the past few years, velocity uncertainties have decreased by at least a factor of two at all sites; residual velocities have decreased as well. In the same region, there are no significant strain rates at 95 percent confidence level.

Dr. Calais then addressed recurrence of earthquakes indicated by paleoliquefaction. Assuming steady-state strain accumulation and release, there is a 500-year average repeat time over 12,000 years. Dr. Calais concluded that the current strain accumulation rate in the New Madrid region cannot be sustained and is not in steady state. As a counterexample, he referred to the Wasatch fault in Utah, where GPS and paleoseismology are in good agreement. His hypothesis is that some slow faults are in steady state at the 10,000-year time scale but some are not. The New Madrid region is not in steady state because the loading (equal to stressing) rate varies with time, and/or fault strength varies with time. Dr. Calais remarked that it is time to think outside the "rebound model box," noting that the more we measure, the closer to zero we get, but the more we look, the more potential active faults we seem to find. Local strain accumulation may not be a prerequisite for large earthquakes, as perhaps earthquakes can "tap into" larger-scale reservoirs of strain.

Dr. Seth Stein of Northwestern University gave the next talk, titled Rethinking Midcontinental Seismicity and Hazards. He explained the evolution of his thinking about seismicity patterns. Previously he believed that focused, quasi-periodic long-term seismicity occurred in weak zones , but lately he has been moving toward the concept of episodic, clustered, and migrating patterns of seismicity. The latter suggests that the past is an extremely poor predictor of the future and that seismicity migrates between zones of rocks of similar strength. Dr. Stein noted that GPS campaigns were started in the NMSZ in 1991. Initially, fairly high rates of movement were expected but by 1999 the GPS results indicated essentially no motion. In 1999 he postulated that we could be near the end of a seismic sequence; this idea has held up over time. Maximum motion steadily converges to zero, as rate precision improves with longer observations. Dr. Stein now believes that the past 2,000 years are not representative of long-term NMSZ behavior and that the recent large earthquake cluster in this zone may be ending. He noted that geology implies NMSZ earthquakes are episodic and clustered through the Holocene; similar episodic patterns are seen in other continental plate regions. He stated that the NMSZ is not hot, weak, or special relative to surrounding regions of the CEUS. He also discussed differences between time-independent hazard and time-dependent hazard; the latter approach generally predicts lower hazard levels in the CEUS.

Dr. Stein then asked: how we can make better progress in understanding seismic hazard? He believes more and better data are needed, and that the dynamics of forces, faulting, and fault interactions in the plate interior need to be incorporated in a model and explored in detail. He noted that GPS is giving constraints on effects like postglacial rebound. In his conclusions he noted that geodetic deformation is probably required for large earthquakes, so its absence argues against large earthquakes any time soon.

Continuing on the topic of using geodetic data, **Dr. Bob Smalley** of the University of Memphis gave a talk titled Geodetic Interpretations of New Madrid Rates. Dr. Smalley noted that his work was based on the same data set that was described by the previous two speakers. He began by noting that maps of worldwide strain rates indicate that plate boundaries have the highest rates, which is in good agreement with plate tectonics. Multiple occurrences of large earthquakes in a few areas, like the NMSZ, are not explained by either plate tectonic or rebound paradigms. Dr. Smalley discussed theories of how plates might deform, and the extent to which deformation can be recognized using GPS. He noted that in concentrated zones of deformation within inactive regions, it is “challenging” to see this deformation with GPS. From examination of plate tectonic dynamics, it is clear that strain rates in stable plate interiors are bound at very low rates. The challenge is to detect a small signal buried in a larger signal. Dr. Smalley believes that GPS is on the verge of not being significant for the NMSZ, thus it is difficult to see how this zone is different from the rest of North America. However, just because we see nothing there now, we cannot say this information is significant. Within the next 10 years, better data may be obtained for the New Madrid region.

Dr. Smalley went on to discuss a number of explanations for stable continental region earthquakes, including reactivation of zones of weakness, crustal weakening by fluids, and stress changes due to deglaciation or sediment loading. For the design of a continuous GPS network for the NMSZ, local, crustal, and regional scales were considered in the placement of monuments. Questions about monument stability were acknowledged and are related to factors that include water level changes in the Mississippi River, and the rise and fall of groundwater levels due to pumping. A longer time period and a larger number of stations providing higher density and redundancy are needed to collect data. Dr. Smalley then gave GPS results for other stable continental regions in the United States, Europe, and India: rates are low, but in general there are few stations in these stable areas. He believes that short-term geodetic signals should be integrated with long-term geologic deformation rates. In his conclusion he noted that GPS will continue to improve, but both denser sampling at the scale of seismic structures and longer observation times are needed.

Following a short break, **Dr. Mark Zoback** of Stanford University gave a talk titled <u>Intraplate Stress and Strain in the Central and Eastern United States and Their Relation to Intraplate Seismicity</u>. The work he has conducted indicates relatively uniform stress orientations across complex geologic boundaries. He noted that during the past several years (since the last World Stress Map effort) there has been little progress on mapping intraplate stress in the CEUS, but for the CEUS SSC project he has gathered the new stress information available and plotted it. He showed a series of Google Earth photographs with the stress data plotted, and discussed the new data, including 38 earthquake focal mechanism data points. In the New Madrid area the new stress data indicates strong east-to-west trends, whereas the surrounding craton and eastern margin shows dominantly northeasterly stress directions. This area may have an anomalous crust and upper mantle structure in which the viscosity of the upper mantle may be lower than that of the surrounding mantle, thus leading to stress rotation.

Next, Dr. Zoback reviewed focal mechanism data for recent earthquakes, including the 2002 M_w Caborn earthquake in the Wabash area, which had slip on a west-northwest plane consistent with east-to-west stress. He noted that with uncertainties incorporated, significantly different results could be obtained, and additional well-constrained data are needed. The characteristics of New Madrid seismicity were then reviewed. Dr. Zoback. discussed the hypothesis that the retreat of the glacial ice sheets triggered Holocene earthquakes. The use of a localized weak-mantle model indicates there will be concentrated deformation locally for tens of thousands of years, as that is the amount of time needed for the mantle to recover. Dr. Zoback concluded by asserting that the New Madrid region is unique and that he believes earthquake recurrence rates are not likely to change in the near future.

Dr. Coppersmith opened the workshop to questions from all participants. After further discussion about New Madrid seismicity, the association of earthquakes with glacial unloading, stress accumulation in the crust vs. the mantle, and other topics, Dr. Coppersmith commented that these topics could be discussed again on Day 3 of the workshop. He thanked all the presenters and noted that the meeting would reconvene the following morning.

DAY 3 -- FRIDAY, FEBRUARY 20, 2009

Dr. Coppersmith welcomed the workshop participants to the third and final day of the workshop. The first talk of the day was by **Dr. Martitia (Tish) Tuttle** of USGS and was titled <u>Clustered Model for New Madrid Earthquakes</u>. Dr. Tuttle began with a review of the timing, location, magnitude, and recurrence times estimated for New Madrid region paleoearthquakes. She described evidence for paleoliquefaction, noting that sand blows usually provide the best opportunities to provide minimum and maximum age estimates for paleoearthquakes because they may contain in situ materials (e.g., charcoal, sticks) that can be dated. Dating methods include radiocarbon and OSL (optically stimulated luminescence) dating, artifact analysis, and dendrochronology; age date uncertainties can range from ± 1 to 1,000 years. The New Madrid earthquake chronology based on paleoliquefaction has age estimate clusters at 1450 a.d., 900 a.d., and 2350 b.c. Independent paleoseismic studies have provided data that support these event ages. Dr. Tuttle believes the clusters formed during very large New Madrid–type events. In addition to the 1811–1812 New Madrid earthquakes, possible analog events include the 2001 **M** 7.6–7.7 Bhuj, India, earthquake. Available information suggests the New Madrid region earthquakes have an approximately 500-year repeat time. Clustered earthquakes (i.e., separated by days or months) are indicated by stratigraphic information associated with sand blows.

Dr. Tuttle reviewed all the paleoseismology information available for the Reelfoot Rift. Faults in the rift region were active at different times during the past 5,000 to 15,000 years; the most recent earthquake activity in the migration pattern is focused on the New Madrid region. She went on to discuss negative evidence for paleoearthquakes. Certain conditions need to be present (e.g., loose and sandy sediments, water-saturated conditions, and good exposures of older deposits) to conclude that liquefaction could have occurred; however, even if these conditions are met and no liquefaction features are found, the occurrence of earthquakes cannot be ruled out. Next, Dr. Tuttle discussed studies in the Charlevoix seismic zone. Three generations of liquefaction features within the past 10,000 years were identified along rivers in this region. These features were likely produced by earthquakes of **M** ≥ 6.2. In the Quebec City–Trois Rivieres region, which is located in a historically seismically quiet part of the St. Lawrence Valley, similar river exposures were examined but no paleoliquefaction features were found; however, the occurrence of paleoearthquakes cannot be ruled out.

The following talk by **Dr. Shelley Kenner** was titled <u>New Madrid Model for Repeated Events: Geodetic Signature along the Southeast Margin and Elsewhere</u>. Dr. Kenner began by reviewing intraplate seismicity, noting that the majority of knowledge of earthquake physics has been developed from plate boundary regions. She then noted key differences between intraplate and plate boundary regions with respect to the (1) kinematics and temporal characteristics of seismicity; (2) reason for stress localization; and (3) source of stress that drives seismicity. She reviewed reasons for stress accumulation along faults and described the crustal stress cycle that consists of localized loading, coseismic rupture, postseismic relaxation, and associated localized loading that induces clusters of earthquakes. She also reviewed aspects of the NMSZ, emphasizing the location above a failed rift that has been reactivated repeatedly, and the increase in seismicity during the Holocene.

Dr. Kenner discussed aspects of weak zone model behavior and the question of whether such a zone could be present in regions of concentrated intraplate seismicity. Triggers for seismicity may include glaciation and sedimentation in the Mississippian embayment. Dr. Kenner then spoke about weak zone relaxation and described aspects of associated seismicity over time, including earthquake recurrence intervals. Analyses have indicated that the total duration of transient relaxation processes is very long and may last more than 20 times longer than the characteristic relaxation time of weak zone material even though surface deformation rates are low. To examine the temporal evolution of where shear zones take place, three-dimensional (3-D) weak zone models were developed and their behavior assessed. Total plastic strain plots show that with increasing time, shear zones move toward weak zone boundaries. In summary, stress loading from an underlying weak zone is a physically plausible mechanism for earthquake generation. Sequences of earthquakes due to weak zone relaxation may be triggered by temporally variable localized stress transients

Dr. Coppersmith asked Dr. Stein and Dr. Zoback for their thoughts about Dr. Kenner’s model. Dr. Stein commented that if the New Madrid region is special or representative of a large number of faults everywhere, then does that indicate a weak zone is present under each of the many places where large intraplate earthquakes have occurred? Many crustal faults are known and he dislikes the concept of having to associate a weak zone with each of these faults. Dr. Zoback indicated that he agreed with Dr. Stein in terms of the global implications of Dr. Kenner’s model. He noted that conceptually, Dr. Kenner’s model is similar to other models proposed to explain the Holocene record of earthquakes in the New Madrid region, and it would satisfy the other criteria that are unique to New Madrid, such as the absence of a geodetic signature and the small amount of cumulative deformation. He suggested exercising caution in applying models too broadly.

Dr. **Alessandro Forte** of the University of Quebec at Montreal gave the next talk, titled Physical Processes Occurring in the Mantle under the EUS and Their Implications for Surface Stress and Deformation. He noted that plate tectonics is a 3-D process, in which deep-seated forces that drive horizontal motions also drive substantial vertical displacements that contribute to crustal stress. Vertical motions, however, are below the current level of resolution of GPS. Dr. Forte reviewed several previously proposed dynamic models of the origin of stress and seismicity in the NMSZ. He then showed his work on tomographic imaging of the shallow mantle structure below North America. In the past five years he has been working on modeling present-day mantle flow dynamics in fully global calculations of mantle flow. His tomography-based mantle convection model successfully predicts plate velocities and observations of surface gravity and topography on the North American Plate.

With viscosity structure and driving forces available, the differences in direction of subcontinental mantle flow at various depths can be evaluated. Dr. Forte showed a cross section of mantle flow below the CEUS that indicates downward movement (flow foundering) beneath the New Madrid and Mississippi region at depths below approximately 400 km. He showed a map of mantle-flow-induced horizontal tractions on the crust in the region of NMSZ. He noted that the Mississippi Valley region is being pulled down dynamically because of drag from the descending Kula-Farallon slab below. Descent of the slab into the lower mantle induces a region of maximum horizontal flow convergence and maximum compressive surface stresses directly below the CEUS oriented in a northeasterly direction. Stress directions are modeled as the same along the eastern margin of the continent, but their amplitude is lower. These stresses are generated on mantle-convection time scales, which are on the order of millions of years and can therefore support long-lived seismicity. Dr. Forte showed a video of time-dependent mantle dynamics and surface flexure (topography) over the past 30 million years. He noted that mantle-flow-induced surface depression and associated bending stress may be an important and long-lived contributor to the clustered and migrating seismic activity in the Mississippi Basin, extending from the Great Lakes to the Gulf of Mexico.

Following a short break, **Dr. Martin Chapman** of Virginia Polytechnic Institute spoke about seismicity in the southeastern United States, in a talk on Update on Eastern Tennessee and Charleston: Fault Model for These Sources. The Eastern Tennessee seismic zone (ETSZ) is the most seismically active area in the Southern Appalachians. Seismicity in the zone is associated with a major potential field anomaly known as the New York–Alabama lineament. Dr. Chapman reviewed key findings of previous studies of Eastern Tennessee seismicity. He showed maps that indicated correlation of NOAA magnetic data and Bouguer gravity data with earthquake epicenters in the southern Appalachian region. From focal mechanism data, earthquake epicenters are northeast trending and many appear to be aligned along a north-dipping plane. Studies indicate that earthquakes are occurring in response to a highly uniform regional stress, with strike-slip motion predominant. The New York–Alabama lineament marks an abrupt boundary between zones of different seismicity; however, the geologic nature of this feature remains a mystery.

Dr. Chapman then talked about seismicity in the Charleston area, noting liquefaction features and the identified earthquake epicenters. Greggs Landing on the Ashley River is the focus of current seismicity and is also the location of strong shaking in the 1886 Charleston event. A seismic reflection profile in this area provides clear evidence of Cenozoic reactivation of Mesozoic extensional faulting. In the Summerville area, seismic profiles show possible faulting of Cenozoic sediments to shallow depths in close proximity to a strong magnetic gradient. Dr. Chapman also showed COCORP lines that indicate a faulted Mesozoic section underlying the Summerville and Charleston region. The imaged faulting in these areas is within the zone of modern earthquake activity. Dr. Chapman concluded his talk by saying that progress in understanding the seismicity of this area requires a long-term commitment to secure precision hypocenter locations and focal mechanism determinations.

Following a lunch break, **Dr. Pradeep Talwani** of the University of South Carolina gave a talk titled The Source and Magnitude of the Charleston Earthquake. He began by describing the revised tectonic framework for the region that he and his colleagues have developed. He showed a map of seismicity from 1974 to 2004 and the varied focal mechanisms associated with these events. Earthquakes were relocated to develop the revised tectonic framework that shows a series of faults, which he showed projected onto a series of cross sections. Dr. Talwani described structural features in the region, including the uplifted zone of river anomalies (ZRA) and the East Coast fault system (ECFS). Results of the new seismotectonic framework indicate that seismicity is occurring primarily at the compressional left step within the southernmost segment of the ECFS. Dr. Talwani discussed paleoliquefaction studies that indicate seven separate earthquake events. Using his new work, he can link these events to faults. He described offset in the thick walls of Fort Dorchester during the 1886 earthquake event. A trench was excavated on the projection of the fault that offset the fort walls. Although the fault was not seen in the trench, a sand blow was revealed. Age dating indicated the sand blow formed in a pre-1886 event. Geotechnical data, including piezometer tests and cores, were collected in the area. Using these data, the magnitude of the earthquake was back-calculated to be ~**M** 6.2.

Next Dr. Talwani reviewed results of GPS studies in the Charleston region. Delaunay triangle modeling indicates that the strain rate in the vicinity of Charleston is high. Dr. Talwani showed magnitude estimates for the 1886 Charleston earthquake from intensity data; the latest value is **M** 6.9. He also provided a list of magnitudes of prehistoric regional earthquakes associated with liquefaction from in situ SPT (Standard Penetration Test) data. In his conclusions, Dr. Talwani noted that the 1886 Charleston earthquake and seismicity that is currently being recorded are related to the Woodstock fault and associated faults at a compressional left step in the Middleton Place–Summerville seismic zone. He believes that only this southernmost segment of the ECFS is seismically active and poses a seismic hazard.

The next talk, titled “Seismotectonic Setting and Seismic Sources of the Northern Gulf of Mexico,” was given by **Mr. Michael Angell** of William Lettis & Associates. Mr. Angell began by stating that although the Gulf of Mexico region has generally low seismicity, three earthquakes having $M_b > 4.5$ (M_w 5.8 was the largest) occurred in the northern Gulf in 2006. Causative mechanisms for these earthquakes were a topic of his talk, and he proceeded to describe the historical seismicity, bathymetry, and stress indicators in the Gulf region. He noted that numerous growth faults (faults driven by gravitational forces) are located above salt diapirs (mobile salt beds). Then he reviewed the information available on the 2006 earthquakes. Two of these events occurred within an area containing growth faults.

Next Mr. Angell reviewed the tectonic setting of this region. Interpretations of the tectonic history indicate that a block of oceanic crust was emplaced in the late Jurassic. Oceanic crust can be delineated on seismic lines and with gravity and magnetic data. Mr. Angell described different models that show the distribution of the oceanic crust in the Gulf of Mexico. Some of the largest recorded earthquakes occurred within this crust. Large, northwest-southeast-trending fracture zones are located to the east of the earthquakes. Turning to a discussion of seismic source models for the Gulf, Mr. Angell reviewed existing alternative models for seismic hazard. Apparent alignments of seismicity suggest a possible underlying source and association with deep structure.

Mr. Angell went on to describe growth fault settings and the associated seismicity. He discussed aspects of the February and April 2006 earthquakes, which have been modeled as gravity-driven on a shallow-dipping plane. He noted that the most appropriate model for the Gulf may be two-layered, having shallow seismic sources in growth fault areas and deeper seismotectonic sources in the basement. He discussed the possibility of a link between upper and lower faulting, mentioning that a trigger could originate from an event in either the upper or lower zone. He concluded by stating that earthquakes associated with growth faults have limited depth extent (to about 5 km), are “slow” (i.e., they do not radiate high-frequency energy), and have low magnitudes ($M < 5$); therefore they may not be significant in seismic hazard assessments.

The next talk was given in two parts by **Dr. Mark Petersen** and **Dr. Chuck Mueller**, both of the U.S. Geological Survey. Dr. Petersen spoke first in a talk titled <u>2008 USGS Seismic Source Model for the Central and Eastern U.S</u>. The national hazard maps released in April 2008 were based on the 2002 and 2006 USGS models. Dr. Petersen briefly described some of the changes made for the 2008 CEUS model, including development of maximum magnitude distributions for seismicity. He reviewed New Madrid and Charleston area site-characterization details. Branches of a logic tree were used to evaluate fault rupture models (clustered and unclustered), location uncertainty, recurrence intervals, and M_{max} alternatives. To obtain alternative M_{max}, the recorded **M** 7.1 to 7.7 magnitudes of earthquakes in stable continental regions worldwide were considered.

During the second part of the talk, Dr. Mueller focused on how seismicity was used in the USGS seismic hazard model. His talk was titled <u>Hazard from Seismicity: the USGS Approach</u>. He listed organizing principles for the hazard model: specific fault sources considered, historical seismicity gridded and smoothed, and large background zones defined based on geologic criteria. He described the various zones delineated on the hazard map and what earthquake catalogs were used, and he addressed regional completeness levels and *b* values. He reviewed how historical seismicity was gridded based on analyses from four different models, and he showed example results of smoothed seismicity for the different models used. He noted that gridded seismicity models are essentially a localized, variable *b*-value model. Dr. Mueller concluded his talk by describing seismic hazard studies previously conducted for the CEUS and associated hazard assessed for selected nuclear power plant sites.

With the workshop’s technical talks completed, Dr. Coppersmith commented on the path forward for the project. He showed the task schedule and described the work to be completed in the next few months. The tasks include constructing the preliminary SSC model, compiling the seismicity catalog, and completing preliminary hazard calculations and sensitivity analyses that will be presented at Workshop 3. Dr. Coppersmith then thanked the presenters and complimented them on the high professional level of their interactions.

Mr. Salomone closed the meeting with several remarks. First he described the role of the Participatory Peer Review Panel (PPRP) and their review relationship with the TI team. He acknowledged the members of the PPRP, beginning with the co-chairs, Drs. Carl Stepp and Walter Arabasz. Then he acknowledged the participation at the workshop of the international observers as well as the younger professionals, who will ultimately take over the process of hazard assessment. He thanked EPRI for its support of the workshop. Finally, he observed that the original vision of what the workshop organizers had hoped would occur had, indeed, happened.

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Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Geodetic observations in St. Lawrence and implications to Mmax; big picture tectonic framework; limits of glacial rebound	Mazzotti, Stephane	What criteria should be used to define seismic sources? Do glacial rebound processes influence seismicity (rates-focal mechanisms) and should this be considered in defining seismic source zones? What are rates and uncertainties on geodetic observations? What is geographic area of coverage for geodetic observations? What is your confidence that observed geodetic rates reflect long-term tectonic deformation rates or short term seismicity pattern and rates? What weight would you give geodetic vs seismicity in establishing rate of EQ occurrence?
Size of 1663 Charlevoix earthquake; treating St. Lawrence seismicity zones as aftershocks	Ebel, John	What is your confidence that current patterns of seismicity represent aftershocks from large historic or prehistoric events? What maximum magnitude range and source zone geometry would you assign to sources in the St Lawrence-Charlevoix area?
Use of seismicity to define seismic sources, application in the eastern North America region.	Kafka, Alan	What approaches should be used to capture uncertainty in stationarity of seismicity with regard to defining seismic sources?
Use of geological structures and assessing Mmax for Canadian national hazard maps	Adams ,John	What methodology is being used to define Mmax distributions for source zones? What is the Canadian perspective on the limitations of the Johnston et al. (EPRI) approach and prior distributions? What are reasonable worldwide analogs for stable continental regions appropriate for CEUS and Canada?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Seismicity and potential faults in NYC, Pennsylvania, Ohio, New England	Seeber, Leonardo (Nano)	What are reasonable criteria for defining seismic source zones in NE US? Previous models have used hotspot tracks, onshore extensions of older transforms, evidence for reactivated structures along the Fall Zone and Mesozoic rift basins—are these still valid concepts? What is your preferred causative mechanism for seismicity in the region? What is your preferred seismic source model (geometry, Mmax) for the NY region?
Ouachita, sub-detachment structures	Thomas, Bill	What is the influence of any of older structures (e.g., Iapetan transforms) are present seismicity. What is the evidence for reactivation of these structures in the Mesozoic? What is your confidence that the Ouachita basement structure represents a seismogenic source?
Rift structures in the mid-continent (Rough Creek Graben, Rome Trough, East Continent rifts)	Drahovzal, James	Is there evidence to suggest that the Rough Creek and Rome Trough may be continuous features? Is there any evidence of Mesozoic reactivation of either structure? What is the relationship of the East Continent gravity high to the Rome Trough and to regions of elevated seismicity in Eastern Tennessee?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Integration of seismic reflection, geopotential field, and subsurface information in southern Illinois Basin	McBride, John	Previous publications suggest that moderate earthquakes (like the 1968 event may have occurred on thrust faults in the basement? What if any structural relationship is there between these structures and the Commerce Geophysical lineament? Is there sufficient evidence to model other structures such as the DuQuoin monocline as potential fault sources? What are your thoughts on the distributed paleoliquefaction 'energy centers'—is there other geologic information to suggest local sources of moderate events or are these features more likely due to more distant larger magnitude events? Should the faults in the Flurospar Area complex region be modeled as independent active faults in the current tectonic environment and if so, what are your thoughts on the timing, maximum magnitude, and recurrence of events on these structures?
Margins of Reelfoot and update on Kentucky River fault zone	Van Arsdale, Roy	What are the constraints on the continuity and length of possible fault sources along the margins of the Reelfoot rift? Are there paleoseismic data that can be used to estimate Mmax? Is there evidence of paleoliquefaction associated with events on the margin fault sources? Please comment on the southern continuation on potential continuity of the NM and Saline River source zones.
Commerce lineament and northwest boundary of New Madrid	Baldwin, John	What data is available to constrain or estimate Mmax for fault-specific sources along the northwestern margin of the Reelfoort rift? What is the extent, origin, and seismogenic potential of the Commerce Geophysical lineament?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Saline River and Reelfoot Rift	Cox, Randy	What are the uncertainties in the timing and relationships of paleoliquefaction events in the Saline River area relative to the central part of the NMSZ? Please comment on the southern continuation or potential continuity of the NM and Saline River source zones. Have you identified a tectonic feature as a potential seismic source responsible for observed liquefaction in the Saline River area?
Geotechnical evaluation of the Vincennes event in southern Illinois	Green, Russell	How can this analysis be used to constrain the dimensions of the Vincennes earthquake seismic source? Can you use similar approaches to evaluate smaller energy centers that have been identified elsewhere in southern IL and IN—i.e., what methods can be used to assess the issue of local small events versus larger more distant earthquakes? What is your uncertainty in using liquefaction to assess Mmax?
Magnitude bound relation for the Wabash Valley seismic zone; Geotechnical analysis of paleoseismic shaking using liquefaction effects	Olson, Scott	What are limitations of the magnitude bound approach? What is your uncertainty in using liquefaction to assess Mmax? What Mmax would you assign to NM ,Charleston, Wabash, based on paleoliquefaction observations? Please comment on the minimum magnitude required to generate liquefaction?
Geodetic interpretations of New Madrid rates	Calais, Eric	What is your confidence that observed geodetic rates reflect long-term tectonic deformation rates or short term seismicity pattern and rates? What weight would you give geodetic vs seismicity in establishing rate of EQ occurrence? Do current data allow one to discern tectonic rates from measurement uncertainties?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Rates and recurrence in New Madrid	Stein, Seth	What is the relationship between geodetic deformation and earthquake occurrence? Have you compared the geodetic signature of other zones of seismicity in stable continental regions? Is the absence of evidence for geodetic deformation a definitive indicator of future earthquake potential?
Geodetic interpretations of New Madrid rates	Smalley, Bob	What is the relationship between geodetic deformation and earthquake occurrence? How do you relate relatively short-term geodetic deformation rates to longer-term geologic deformation rates? Have you compared the geodetic signature of other zones of seismicity in stable continental regions?
Update of stress map, strain localization, New Madrid rates	Zoback, Mark	Do available stress and strain data provide sufficient resolution to aid in defining local source zones? What is the cause of stress of intraplate stress? What are mechanisms to localize stress? Are observed rates of historic and prehistoric seismicity consistent with observed stress and strain rates?
Clustered model for New Madrid events	Tuttle, Tish	What are the resolution issues for identifying individual events and estimating the size of such events? What is your confidence that the regional absence of liquefaction in susceptible deposits reflects an absence of large magnitude (>6) earthquakes?
New Madrid model for repeated events; geodetic signature along the southeast margin and elsewhere	Kenner, Shelley	What are likely triggering events? Is the absence of a significant geodetic signal across the NMSZ consistent with this model? What are implications of the model for future large magnitude earthquakes (location, timing)?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Physical processes occurring in the mantle under the Eastern US and their implications for surface stress and deformation	Forte, Alessandro	Do mantle processes influence current seismicity? Can these patterns be used as criteria for defining seismic source zones? Do mantle processes occur at rates that should influence short term (10^{-1}) or long-term (10^{-3}) seismicity? What is your confidence that available heat flow data can be used to detect mantle anomalies?
Update on eastern TN and Charleston; fault model for these sources	Chapman, Martin	Please comment on your interpretation of the causative mechanism for the events in ETSZ? Do current seismicity analyses support previous models of alignments of seismicity as potential fault sources? What is the influence of the NYAL lineaments on patterns of seismicity? Are there unique conditions (fluid pressures, basement rocks, etc.) that distinguish ESTZ from other seismically active regions of the Appalachians, (i.e., Giles Co.)? Is there any current new information that can be used to assess Mmax? Please comment on your interpretation of the causative mechanism for the Charleston earthquake?
The source and magnitude of the Charleston earthquakes	Talwani, Pradeep	Please comment on your interpretation of the causative mechanism for the Charleston earthquake? Is there evidence to suggest that the tectonic features (i.e., Woodstock fault, and related thrust faults in the step over regions) that appear to be likely candidates for the source of the repeated large magnitude Charleston events extend along the full length of the postulated ECFS-S?

Table 1 – Questions Presenters Were Asked to Address
(continued)

Topic	Presenter	Questions/Topics to Address at WS2
Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont/Coastal Plain Setting	Pazzaglia, Frank	What influence if any do the broad regional flexures have on current patterns of seismicity? Should these features be explicitly considered in defining seismic sources? Please comment on your interpretation of the causative mechanism for earthquakes in the northeastern US?
Gulf coast faulting and seismicity	Angell, Mike	Please comment on your interpretation of the causative mechanism(s) for earthquakes in the Gulf?
Seismic source model for the US National Hazard maps	Petersen, Mark	Current modeling tools (smoothed seismicity) reduce the need for using discrete seismic source zones to capture areas of elevated seismicity. Please comment on what characteristics (i.e., Mmax) would warrant defining a separate source zone?

March 10, 2009 Via e-mail

Lawrence A. Salomone
Washington Savannah River Company
Savannah River Site
Building 730-4B, Room 3125
Aiken, SC 29808

Dear Mr. Salomone:

Reference: *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities:* Participatory Peer Review Report on Workshop No. 2.

Acronyms

CEUS	Central and Eastern United States
EPRI	Electric Power Research Institute
GPS	Global Positioning System
PPRP	Participatory Peer Review Panel
PSHA	Probabilistic Seismic Hazard Analysis
SSC	Seismic Source Characterization
SSHAC	Senior Seismic Hazard Analysis Committee
TI	Technical Integrator

This letter constitutes the report of the Participatory Peer Review Panel (PPRP) on Workshop No. 2 (WS-2), “Alternative Interpretations,” for the referenced project. The workshop was held February 18–20, 2009, at EPRI headquarters in Palo Alto, California.

Following guidance described in the Project Implementation Plan for the PPRP[1], and consistent with the expectations of the SSHAC process[2], the PPRP participated in WS-2 in order to be informed and to review both procedural and technical aspects of the workshop. All eight members of the PPRP (J. P. Ake, W. J. Arabasz, W. J. Hinze, A. M. Kammerer, J. K. Kimball, D. P. Moore, M. D. Petersen, and J. C. Stepp) attended WS-2 and were able to fully observe all aspects of the workshop.

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[1] *Implementation of the PPRP’s Participation in the CEUS SSC Project*: Written statement communicated by J. Carl Stepp to L. Salomone and the TI Team on June 16, 2008.

[2] Budnitz, R. J., G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, and P. A. Morris, 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts.* NUREG/CR-6372, Washington, DC, U.S. Nuclear Regulatory Commission.

General Observations

We observed that the workshop generally achieved the goal of compiling the range of basic data and proponent experts' interpretations that together constitute the current state of knowledge of the technical community, which the TI Team must evaluate for assessing the seismic source model for the CEUS region. We noted that potential field data remain to be compiled and incorporated into the TI Team's evaluation. We understand from the discussion of actions remaining to be taken prior to WS-3 that this important compilation and evaluation will be accomplished as part of planned working meetings of the TI Team prior to WS-3.

We observed that the skillful organization of the workshop stimulated lively inquiry and debate among proponent experts and members of the TI Team. The results will be useful for the TI Team in subsequent evaluations and assessments of uncertainties both in elements and parameters of the CEUS seismic source model. The questions provided by the TI Team to the proponent experts in advance of the workshop proved to be useful and effective. The questions focused the presentations by the invited experts and they stimulated interactions not only between the TI Team and proponents of specific hypotheses and interpretations of data but also among proponent experts.

Specific Comments and Recommendations

Provided below are comments and recommendations for follow-up actions by the TI Team for completing its evaluations and the CEUS seismic source model assessment. We note that many of these comments were touched on by Kevin Coppersmith in the final presentation of the workshop in which he described the actions that the TI Team already plans to take to complete its evaluations and the model assessment. If the TI Team successfully implements those actions, then most of the items described below would be adequately addressed.

1. *Need for a Tectonic Framework:* The range and complexity of alternative hypotheses and interpretations presented at WS-2 reinforce our previous recommendations concerning the need, first, to evaluate an overall tectonic framework for the study region and, second, to properly incorporate this evaluation into the CEUS seismic source model assessment. We consider a transparent evaluation of uncertainty to be a necessary element of the tectonic framework evaluation. The tectonic framework should have a universal role in the seismic source model assessment. This would establish the approach and scale for the seismic source model assessment, and it would provide a transparent, consistent assessment (weighting) of the complex alternative interpretations and hypotheses that constitute the current state of knowledge of the technical community.

We observed that some proponent interpretations regarding seismic sources and the origin of the seismicity in the CEUS pointed to the significance of evaluating the geological and seismological characteristics of the entire lithosphere—including the upper brittle crust, the ductile lower crust, and the upper mantle. Geological and geophysical evidence indicates that these various zones of the lithosphere are laterally heterogeneous, which could have profound impact on the seismicity of the brittle upper crust. As a result, we recommend that the TI Team should include the attributes of the entire lithosphere in their evaluation of the tectonic framework and their seismic source model assessment.

2. *Approach to Seismic Source Assessment and Scale:*

a) "Granularity" of Seismic Source Model (i.e., the scale of uniform scrutiny): During the workshop, geological structures ranging in scale from very local to continental-scale were described and discussed. We recommend that the TI Team provide early assurance, through assessment criteria that are explained and justified, that a systematic approach and procedure are being used for defining and assessing seismic sources in terms of scale. These assessment criteria will facilitate subsequent use of the model for a site-specific PSHA at any site in the study region. The assessment criteria should be at a level of detail that appropriately incorporates the state of knowledge of the sources and the current understanding of their inherent complexity. Using the criteria, one should be able to distinguish specific sources that have significant, identifiable, and relatively consistent seismic hazard potential. This systematic approach should be applied consistently across the study region.

b) Approach to Smoothing: We observed that there was little discussion or consideration of uncertainty involved in smoothing recorded seismicity versus deductive seismic source assessment, and there was no evaluation of alternative smoothing parameters. We consider this to be an important part of the assessment for the CEUS seismic source model and we recommend greater attention to the issue of smoothing and corresponding documentation.

3. *Integrated Evaluation of Paleoliquefaction and Interpretations of Paleo-Fault Displacements:*

a) Uncertainties in age dating: Multiple proponent experts discussed their interpretations of evidence for recent fault movement or the dating of geologic surfaces related to the formation of paleoliquefaction features. The proponents did not sufficiently describe the uncertainties in the age dating within their respective studies, and as such, the overall quality and reliability of this information is in question. The TI Team should strive to better understand the overall quality of these studies and develop a cohesive understanding of how the results can and cannot be used to establish recurrence information for various seismic sources. We recommend that the TI Team perform an integrated analysis of the body of paleoseismic investigation results in the vicinity of the New Madrid Seismic Zone using appropriate statistical methods. The study should incorporate uncertainty in the interpretations, to the extent that the uncertainty is described in or can be reasonably interpreted from the study results, in order to better correlate event times and rates of activity.

b) Size of paleoearthquakes: Paleoliquefaction is widely accepted to be a useful basis for assessing a seismic source model for the CEUS region; it is likely to gain even more importance in the future. The new approaches presented at WS-2 for assessing uncertainty in the observed data and interpretations and for using the interpretations for estimating the size of causal earthquakes have great promise and should be pursued in the future. At present, the uncertainties resulting from both the current and the newly presented methods are poorly constrained. We recommend that particular care be taken in estimating magnitude and in assigning corresponding uncertainties. We further recommend that the lack of evidence of paleoliquefaction not be used to determine maximum magnitude.

c) Time-dependent models: Given the importance of paleoliquefaction studies for evaluating the New Madrid and Charleston seismic zones, the TI Team should make a fundamental decision whether the incorporation and use of time-dependent recurrence models should be pursued. While this topic came up during the workshop, there was no discussion focused on what weight should be given to time-dependent recurrence models. It was not clear how the TI Team would assess the views of the technical community on this issue.

4. *Documentation of how alternative views are used:* At WS-2 a wide range of proponent views within the scientific community were presented about a number of important seismic source related issues. It is clear that, when assessed in detail, most CEUS locations are complex, with heterogeneities playing an important role in creating the data observed in the field. The TI Team needs to document how alternative views are accounted for in the assessment of the seismic source model to be presented in May 2009.

5. *The hypothesis of late aftershocks:* During the workshop, a proponent, using chiefly qualitative evidence, offered the view that much of the contemporary seismicity observed in the CEUS represents late aftershock activity of prior moderate to large earthquakes. If this view is used by the TI Team as a working hypothesis, it should first be critically examined. Standard seismological and statistical tools exist for verifying whether observed contemporary seismicity can plausibly be related to prior earthquakes, consistent with aftershock decay models such as the modified Omori model or Ogata’s epidemic-type aftershock sequence (ETAS) model. Modern aftershock sequences in the CEUS, for example, can provide Omori parameters that can be used to test the hypothesis of long-lived aftershock sequences in the region.

6. *Temporal Clustering:* One uncertainty that was briefly discussed is whether the New Madrid seismic source zone is coming out of a cluster in terms of short repeat times for larger earthquakes. Some proponents cited GPS data that indicate little if any measurable strain in the New Madrid seismic zone region over the past 20 years, and one proponent presented geologic evidence that could be interpreted to indicate a history of clustering with very long geologic time intervals between clusters. The available data and overall lack of understanding of the mechanisms that may drive a clustering model for the New Madrid seismic source zone warrant caution about the supposition that a clustered sequence of higher recurrence behavior is ending.

7. *SSHAC process issues:* Under SSHAC guidelines, the makeup of the TI team has implications for ownership issues relating to the seismic source model and subsequent hazard results. As evident during the workshop, there are blurred boundaries between the TI Team specified in the CEUS SSC organization chart and the TI Staff. The working “TI

Team" appears to consider itself a larger group than listed in the Project Plan. The makeup of the "TI Team" in terms of individuals who will be responsible for ownership of the SSC inputs should be clarified.

We also note that in the SSHAC framework there conventionally is a distinction between the TI (or TI Team) and the hazard analyst. In the CEUS SSC project this distinction is blurred with Robin McGuire having a dual role as a member of the TI Team and as one of the key analysts responsible for computing hazard at seven demonstration sites. This is not a conflicting role and indeed adds strength to the project. We suggest, however, that this circumstance be explained in the final project report.

Do not hesitate to contact us if you wish to discuss any of our observations, comments, or recommendations.

Sincerely,

J. Carl Stepp
871 Chimney Valley Road
Blanco, TX 78606-4643
Tel: 830-833-5446
cstepp@moment.net

Walter J. Arabasz
2460 Emerson Avenue
Salt Lake City, UT 84108
Tel: 801-581-7410
arabasz@seis.utah.edu

Copy:
PPRP Members
Sponsor Representatives

Workshop # 2 Pre-Meeting with International Observers on February 17, 2009

Central and Eastern United States (CEUS)
Seismic Source Characterization (SSC) Project Workshop # 2

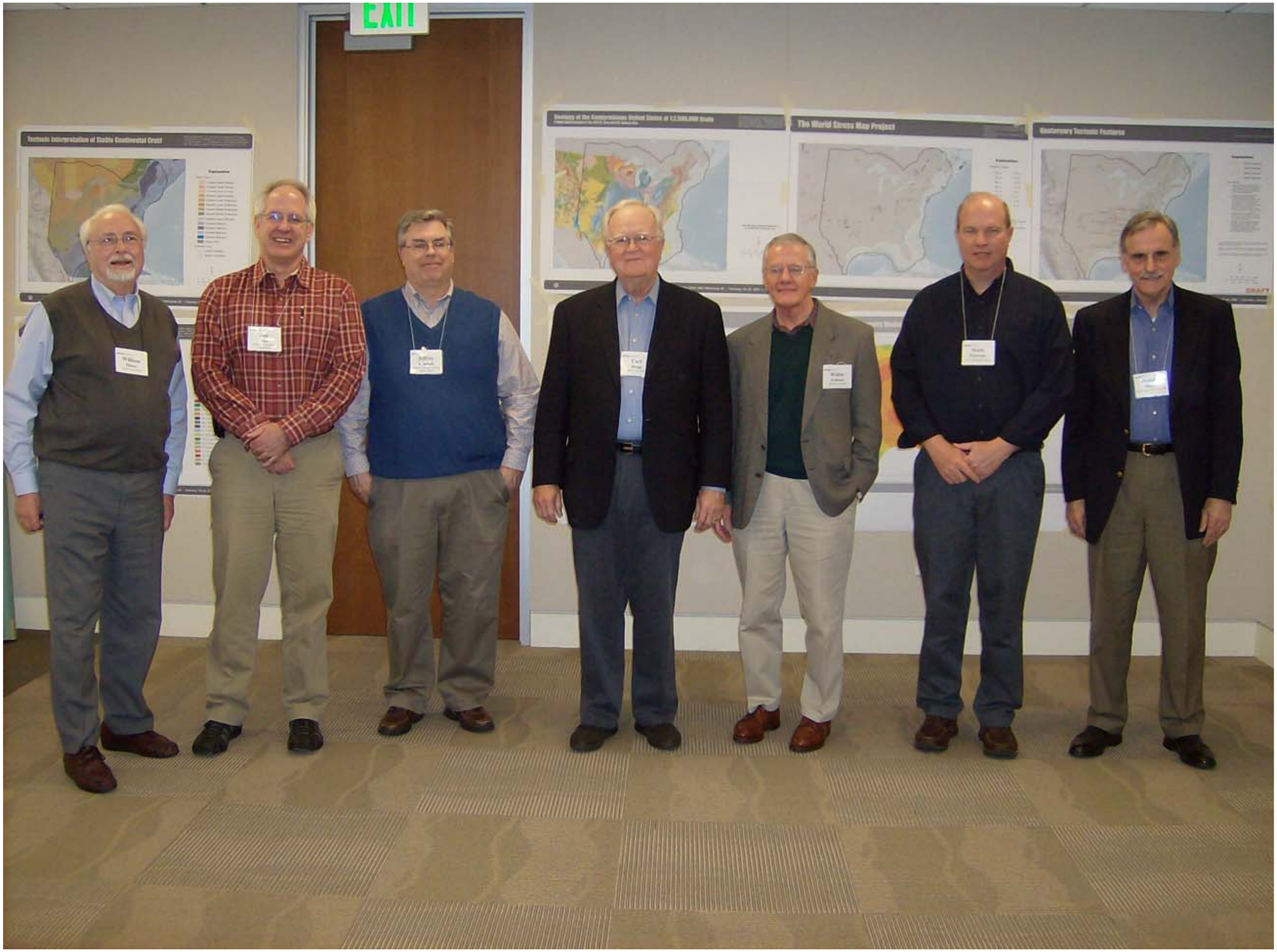
Central and Eastern United States (CEUS)
Seismic Source Characterization (SSC) Project Workshop # 2

Central and Eastern United States (CEUS)
Seismic Source Characterization (SSC) Project Workshop # 2

Central and Eastern United States (CEUS)
Seismic Source Characterization (SSC) Project Workshop # 2

Workshop #2 Resource Experts

Participatory Peer Review Panel



Technical Integration Team and Staff and Project Manager

Workshop #2 Observers

Development of CEUS Seismic Source Characterization Model

Advisory Committee on Reactor Safety (ACRS)
Meeting
April 16-17, 2009
Washington, DC

L.A. Salomone
Project Manager

Savannah River
Nuclear Solutions, LLC
A Fluor Daniel Partnership

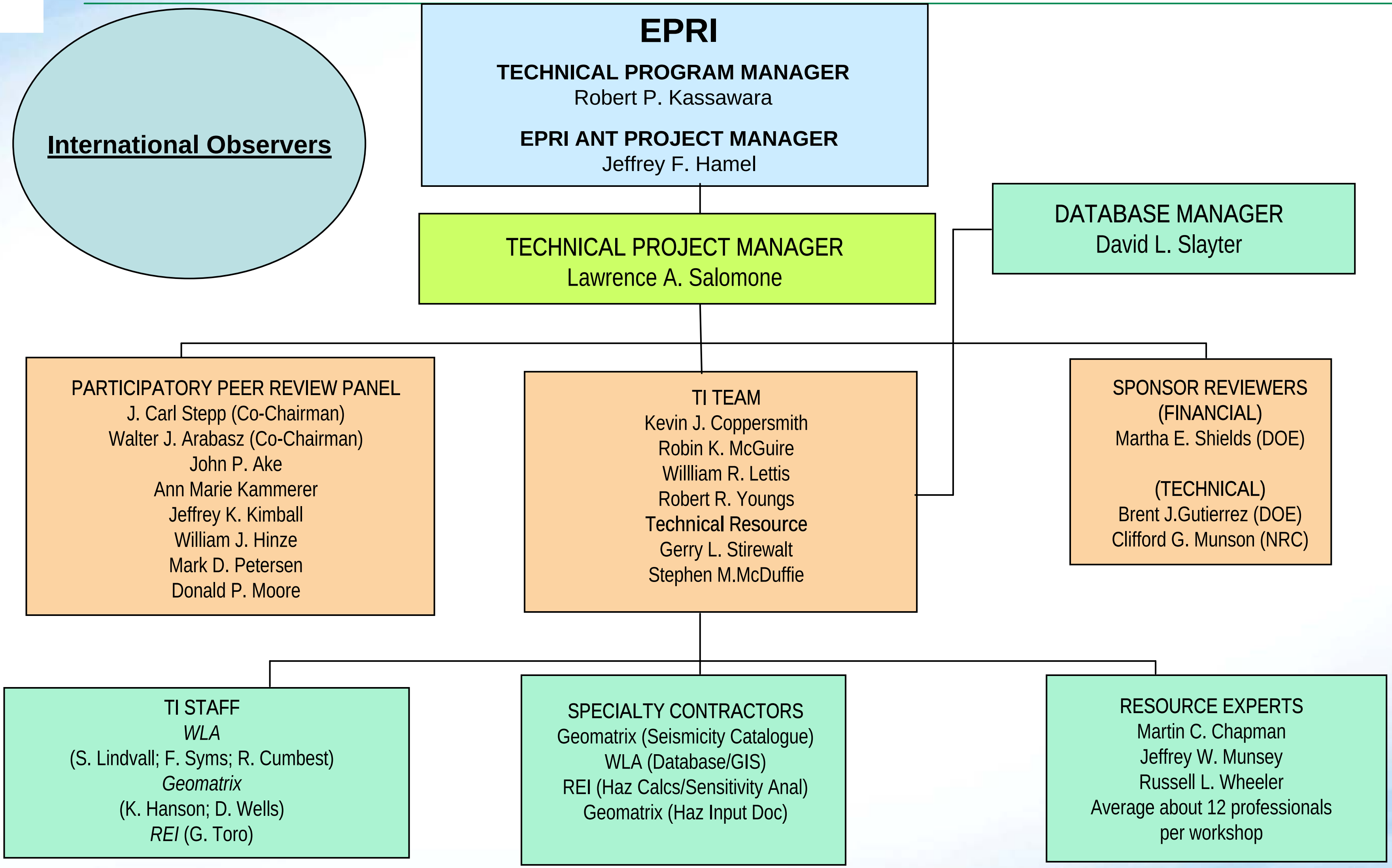
Project Goals

- Replace the EPRI (1989) and LLNL (1993) seismic source characterization models for the CEUS.

- Capture the knowledge and uncertainties of the informed scientific community using the SSHAC process.

- Present New CEUS Seismic Source Characterization Model to NRC, DOE and DNFSB for Review .

Organization Chart



International Observers

EPRI

TECHNICAL PROGRAM MANAGER
Robert P. Kassawara

EPRI ANT PROJECT MANAGER
Jeffrey F. Hamel

TECHNICAL PROJECT MANAGER
Lawrence A. Salomone

DATABASE MANAGER
David L. Slayter

PARTICIPATORY PEER REVIEW PANEL
J. Carl Stepp (Co-Chairman)
Walter J. Arabasz (Co-Chairman)
John P. Ake
Ann Marie Kammerer
Jeffrey K. Kimball
William J. Hinze
Mark D. Petersen
Donald P. Moore

TI TEAM
Kevin J. Coppersmith
Robin K. McGuire
Willliam R. Lettis
Robert R. Youngs
Technical Resource
Gerry L. Stirewalt
Stephen M.McDuffie

SPONSOR REVIEWERS
(FINANCIAL)
Martha E. Shields (DOE)

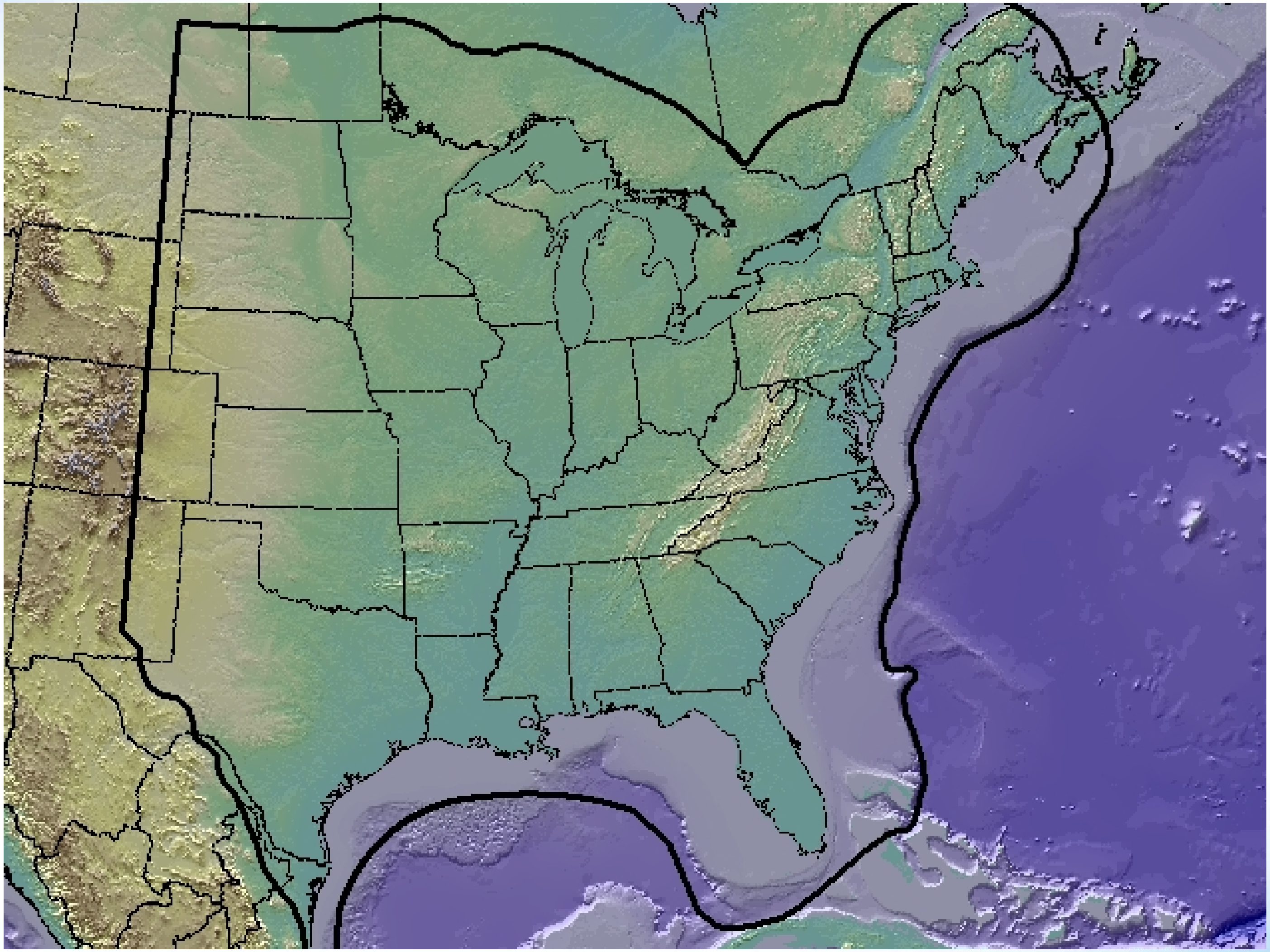
(TECHNICAL)
Brent J.Gutierrez (DOE)
Clifford G. Munson (NRC)

TI STAFF
WLA
(S. Lindvall; F. Syms; R. Cumbest)
Geomatrix
(K. Hanson; D. Wells)
REI (G. Toro)

SPECIALTY CONTRACTORS
Geomatrix (Seismicity Catalogue)
WLA (Database/GIS)
REI (Haz Calcs/Sensitivity Anal)
Geomatrix (Haz Input Doc)

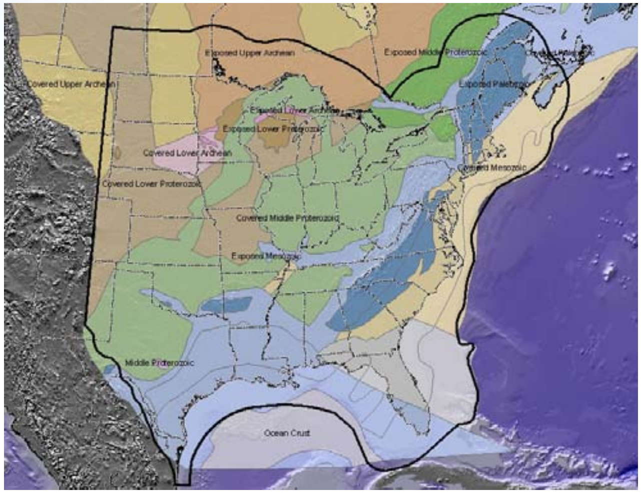
RESOURCE EXPERTS
Martin C. Chapman
Jeffrey W. Munsey
Russell L. Wheeler
Average about 12 professionals
per workshop

CEUS Seismic Source Characterization Study Area

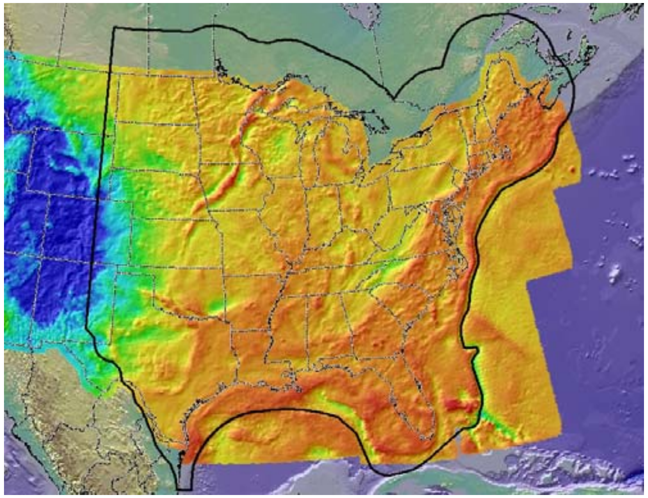


Savannah River
Nuclear Solutions, LLC
A Fluor Daniel Partnership

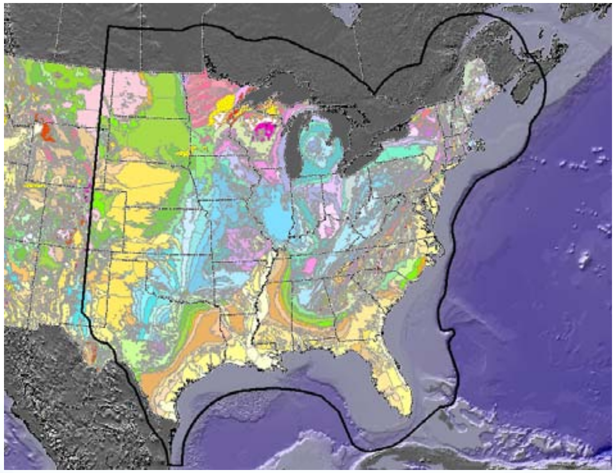
Sample Datasets from CEUS Study

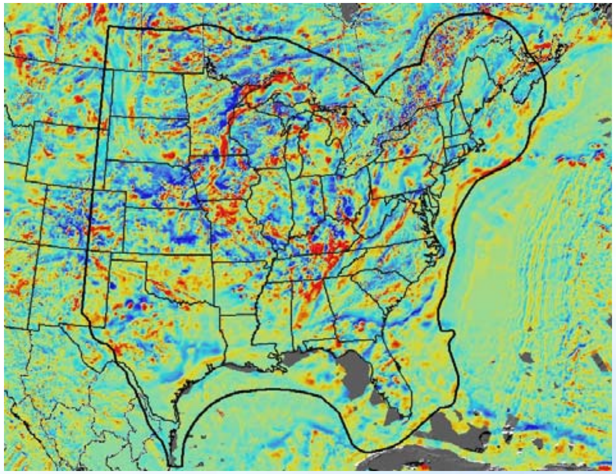


Geology Data



Gravity and Aeromagnetic Data





Seismic Source Characterization (SSC) Model - Project Milestones

- Project Plan as EPRI Technical Update – June, 2008 <u>(Completed)</u>
- Workshop #1: Significant Issues and Databases – July 21-23, 2008 <u>(Completed)</u>
- Workshop #2: Alternative Interpretations – February 18-20, 2009 <u>(Completed)</u>
- Complete Database and Seismicity Catalog Development – June 30, 2009
- Workshop #3: Feedback on Preliminary CEUS SSC Model – August 25-26, 2009
- Construct Final CEUS SSC Model and Prepare Draft Technical Report – February 2010 to December 31, 2010
  - Review of Draft Report by PPRP
  - Incorporate Review Comments
  - Review project documentation for transparency
  - Prepare internal documentation package to document computer codes and archive hazard calculations
  - Obtain copyright releases for GIS database as required
  - Present New SSC Model to Industry, NRC, DOE and DNFSB
- Publish Final Technical Report – December 31, 2010

PPRP Communications

- Tracking Milestones (PM Tool to Assess Project Progress)
- Six Conference Calls Prior to Workshop #2
- Other Conference Calls and Meetings with PPRP as needed
- Six Working Meetings (PPRP member can be invited to serve as a Resource Expert)
- Meeting and Conference Call following each Workshop:
  - PPRP Comment Letter
  - TI Team and Project Manager Response to PPRP Comment Letter
  - Meeting with PPRP to discuss preliminary seismic source characterization model (May 13, 2009)

PPRP Communications

- Intermediate Documents for PPRP:
  - Process to document TI response to PPRP comment letter – September 30, 2008
  - Criteria and Timeline for identifying demonstration sites:
    - Draft sites – October 1, 2008
    - Final sites following PPRP review – November 15, 2008
    - Sensitivity Analyses – August, 2009
  - Working Plan for conducting CEUS SSC assessments
  - Map of seismic reflection lines in GIS database
  - Sensitivity analyses from Workshop #1
  - List of candidate proponents/resource experts and Agenda for Workshop #2 for PPRP review
  - Specialized tools for SSC
  - Workshop #2 List of Participants
  - Workshop #2 Agenda

- FTP Site for PPRP and CEUS SSC Team Access to Project Information

Technical Developments

- Tectonic Framework - Criteria for Identifying Seismic Sources Being Developed
- Review of Seismic Source Characterization Models Developed for Key Regions
  - New Madrid, Central and Southern Illinois, Charleston, Meers
  - East Tennessee, Central Virginia, St. Lawrence River, Gulf Coast
- Review of Alternative Mmax Approaches
- Review of Approach to Characterize “Background” Zones
- Develop New Seismicity Catalog Based on Moment Magnitude

Preliminary SSC Model Validation

- Use Preliminary SSC Model to Develop Sensitivity Studies on Seismic Hazard at Seven (7) Generic Test Sites With Different Soil Profiles and Hazard Environments
- Compare With USGS SSC Model at Seven (7) Generic Test Sites
- Make Adjustments As Required

Challenges Being Met

- Aggressive Schedule Causes Administrative Challenges
  - Authorization for New Data and Processing Needs and Tasks Identified from Workshop #1
    - Gravity Field Compilation and Processing
    - Magnetic Field Compilation and Processing
    - Paleoliquefaction Data Compilation and Use
    - World Stress Map Update
    - Add 7th Demonstration Site
    - Comparison of CEUS SSC Model and USGS SSC Model
    - Additional PPRP Participation
    - Additional GIS Support
  - Flow of funds to meet project schedule

Status

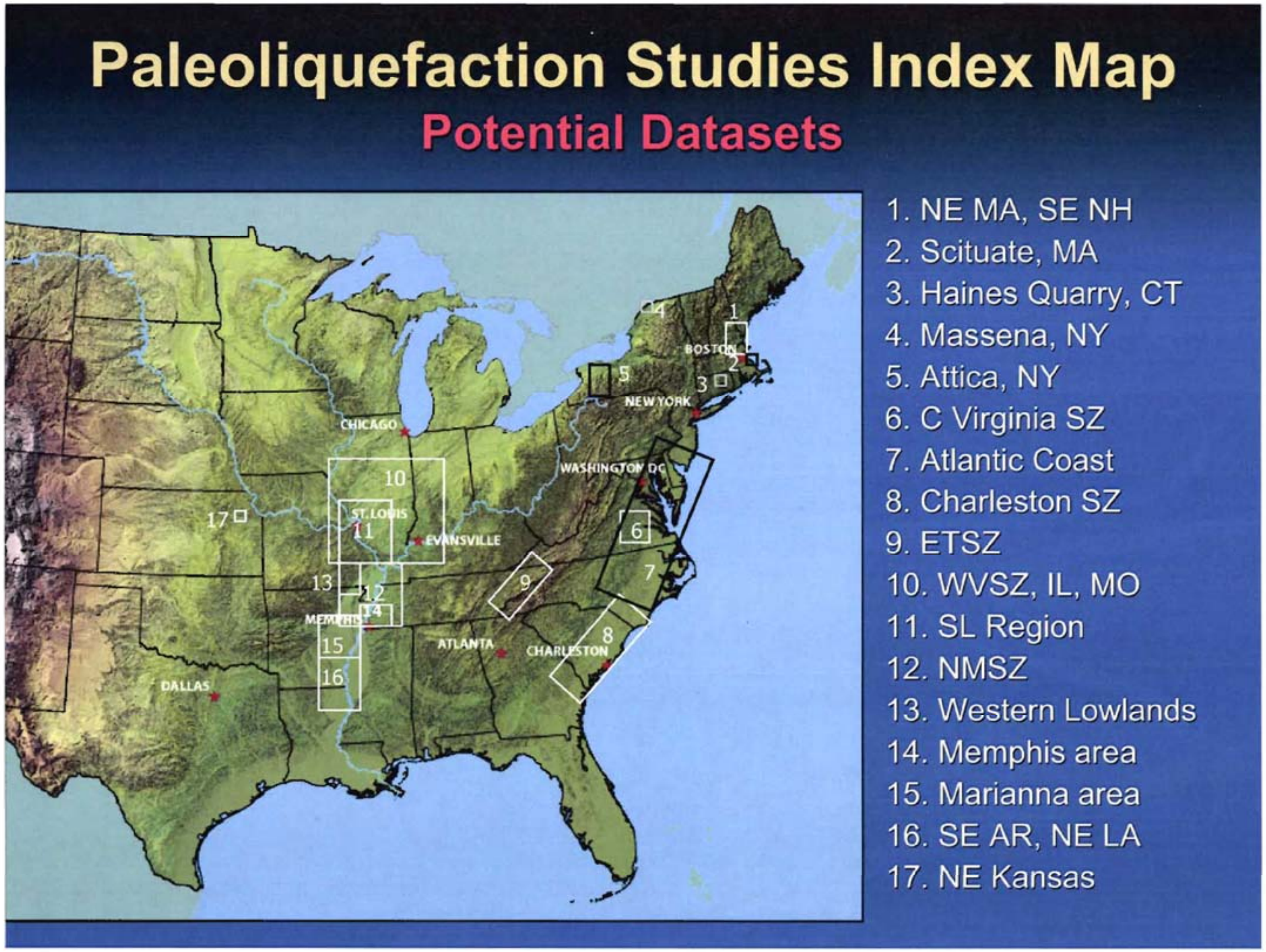
- Completed tasks
  - Project plan
  - Initial funding
  - Workshop #1
  - Workshop #2

- On Track to Meet Target Completion Date (2010)

Next Steps

- Distribute CD documenting Workshop #2 (<u>Completed</u>):
  - Agenda
  - List of Participants
  - Presentations
  - Summary of the Proceedings
  - List of Questions Sent to Resource Experts Prior to Workshop 2
  - Participatory Peer Review Panel (PPRP) Letter Report
  - Photo Album of Participants including International Observers

- Develop CEUS Preliminary Seismic Source Characterization Model (Ongoing)
- Meet with PPRP to Present Preliminary CEUS SSC Model (May 13, 2009)
- Perform Sensitivity Analyses (May – August, 2009)
- Workshop #3 (August 25-26, 2009)



Paleoliquefaction Studies Index Map

Potential Datasets

1. NE MA, SE NH
2. Scituate, MA
3. Haines Quarry, CT
4. Massena, NY
5. Attica, NY
6. C Virginia SZ
7. Atlantic Coast
8. Charleston SZ
9. ETSZ
10. WVSZ, IL, MO
11. SL Region
12. NMSZ
13. Western Lowlands
14. Memphis area
15. Marianna area
16. SE AR, NE LA
17. NE Kansas

SOURCE: M.P. TUTTLE 2008

DRAFT

CEUS Seismic Source Characterization (SSC) Project

EPRI Website Input (4/1/2009)

Introduction:

The EPRI website for the CEUS SSC Project will be populated with information in two categories: (1) Background information to understand the basis for the CEUS SSC Model, and (2) Information to use the CEUS SSC Model for hazards calculations performed for a Probabilistic Seismic Hazard Assessment (PSHA). The information contained in each category follows.

A. Background Information:

1. CEUS SSC Project Plan – EPRI Technical Update (1016756), 6/2008

2. CDs for Workshops 1-3

3. CEUS SSC Final Report in digital form

4. Bibliography

5. New computer codes used to estimate seismicity rates and b-values

6. Sensitivity analyses to show significant issues affecting hazard not already provided in the CEUS SSC Final Report (Figures)

7. CEUS SSC model validation results not contained in CEUS SSC Final Report:
    - Seismic hazard at demonstration sites (Figures)
    - Comparison of CEUS SSC Model with USGS Model (Figures)

8. Sample hazard calculations for end user to check results using the CEUS SSC Model (mean rock hazard and fractiles) (Tables or ASCII)

A. **<u>Background Information</u> (continued):**

9. Seismicity Catalogue (EXCEL file) (Earthquake name, date, location, size, etc.)

10. GIS Datasets (PDF) (cleared for public release)

- **Images of Figures in CEUS SSC Final Report**
- **Images of Figures considered but not used (provide reference and statement whether processed)**

B. **<u>Information to Use CEUS SSC Model</u>**

1. Hazard Input Document (documents and summarizes the key elements of the CEUS SSC model including logic trees, parameter distributions, and derived M_{max} and recurrence parameters)

- **List of files (ASCII)**

  a. Geometry (boundaries of sources)
  b. Seismicity rates for each source (latitude, longitude, rate)
  c. M_{max} information