

**AGENDA
WORKSHOP 2
ALTERNATIVE INTERPRETATIONS
CENTRAL AND EASTERN UNITED STATES (CEUS)
SEISMIC SOURCE CHARACTERIZATION (SSC) PROJECT**

February 18-20, 2009
Electric Power Research Institute
3420 Hillview Ave.
STARR Auditorium
Palo Alto, California 94304

GOALS OF THE WORKSHOP: The goals of Workshop #2 are:

- To review the project SSHAC Level 3 methodology, ground rules, expert roles, and peer review processes
- To provide an opportunity for the TI team to understand proponent views regarding important technical issues
- To discuss the range of alternative views and uncertainties within the larger technical community
- To discuss the path forward for the CEUS SSC project

APPROACH: The goals of the workshop will be accomplished by a series of presentations and discussions designed to provide the TI team with information they need in order to develop a preliminary seismic source characterization model. Resource experts have been asked to provide their views regarding certain key technical issues, including a discussion of the uncertainties associated with those views. The TI team is charged with developing a seismic source model that captures the knowledge and uncertainties within the larger informed technical community. Accordingly, this workshop is an important opportunity for the TI team to gain a better understanding of the community's views and to directly probe the experts regarding the technical bases for their interpretations. To the extent practical, presentations have been arranged topically to encourage focus on pertinent issues. Ample time has been provided for discussion.

Time	Topic	Presenter
WEDNESDAY FEBRUARY 18, 2009		
9:00 – 9:15	Welcome Opening Remarks	Hamel, Jeffrey Salomone, Larry
9:15 – 9:30	Purpose of workshop and ground rules	Coppersmith, Kevin
9:30 – 10:00	Geodetic observations in St. Lawrence and implications to Mmax; tectonic framework; limits of glacial rebound	Mazzotti, Stephane
10:00 – 10:30	Size of 1663 Charlevoix earthquake; treating St. Lawrence seismicity zones as aftershocks	Ebel, John
10:30 – 11:00	Break	
11:00 – 11:30	Use of seismicity to define seismic sources, application in the eastern North America region.	Kafka, Alan
11:30 – 12:00	Discussion	
12:00 – 1:30	Lunch	

1:30 – 2:00	Use of tectonic structures and assessing Mmax for Canadian national hazard maps	Adams ,John
2:00 – 2:30	Seismicity and potentially active faults in NYC, Pennsylvania, Ohio, New England	Seeber, Leonardo (Nano)
2:30 – 3:00	Ouachita, sub-detachment structures	Thomas, Bill
3:00 – 3:30	Break	
3:30 – 4:00	Rift structures in the mid-continent (Rough Creek Graben, Rome Trough, East Continent rifts)	Drahovzal, James
4:00 – 4:30	Integration of seismic reflection, geopotential field, and subsurface information in southern Illinois Basin	McBride, John
4:30 – 5:00	Discussion	
5:00	Adjourn	
THURSDAY FEBRUARY 19, 2009		
8:30 – 9:00	Quaternary Deformation within the Reelfoot Rift, Rome Trough, and Wabash Valley Fault System	Van Arsdale, Roy
9:00 – 9:30	Commerce lineament and northwest boundary of New Madrid	Baldwin, John
9:30 – 10:00	Saline River and Reelfoot Rift	Cox, Randy
10:00 – 10:30	Break	
10:30 – 11:00	Geotechnical evaluation of the Vincennes event in southern Illinois	Green, Russell
11:00 – 11:30	Magnitude bound relation for the Wabash Valley seismic zone; Geotechnical analysis of paleoseismic shaking using liquefaction effects	Olson, Scott
11:30 – 12:00	Discussion	
12:00 – 1:30	Lunch	
1:30 – 2:00	Geodetic interpretations of New Madrid rates	Calais, Eric
2:00 – 2:30	Rates and recurrence in New Madrid	Stein, Seth
2:30 – 3:00	Geodetic interpretations of New Madrid rates	Smalley, Bob
3:00 – 3:30	Break	
3:30 – 4:00	Update of stress map, strain localization, New Madrid rates	Zoback, Mark
4:00 – 5:00	Discussion	
5:00	Adjourn	
FRIDAY FEBRUARY 20, 2008		
8:30 – 9:00	Clustered model for New Madrid events	Tuttle, Tish
9:00 – 9:30	New Madrid model for repeated events; geodetic signature along the southeast margin and elsewhere	Kenner, Shelley
9:30 – 10:00	Physical processes occurring in the mantle under the Eastern US and their implications for surface stress and deformation	Forte, Alessandro
10:00 – 10:30	Break	
10:30 – 11:00	Update on eastern TN and Charleston; fault model for these sources	Chapman, Martin
11:00 – 11:30	The source and magnitude of the Charleston	Talwani, Pradeep

	earthquakes	
11:30 – 12:00	Discussion	
12:00 – 1:30	Lunch	
1:30 – 2:00	Approaches Used to Identify and Evaluate Neotectonic Features in Appalachian Piedmont/Coastal Plain Setting	Pazzaglia, Frank
2:00 – 2:30	Gulf coast faulting and seismicity	Angell, Mike
2:30 – 3:00	Seismic source model for the US National Hazard maps	Peterson, Mark
3:00 – 3:45	Path Forward on CEUS SSC	Coppersmith, Kevin
3:45 – 4:00	Closing Remarks	Salomone, Larry
4:00	Adjourn	



Development of CEUS Seismic Source Characterization Model

CEUS Seismic Source Characterization Project
Workshop #2
February 18-20, 2009
Palo Alto, CA

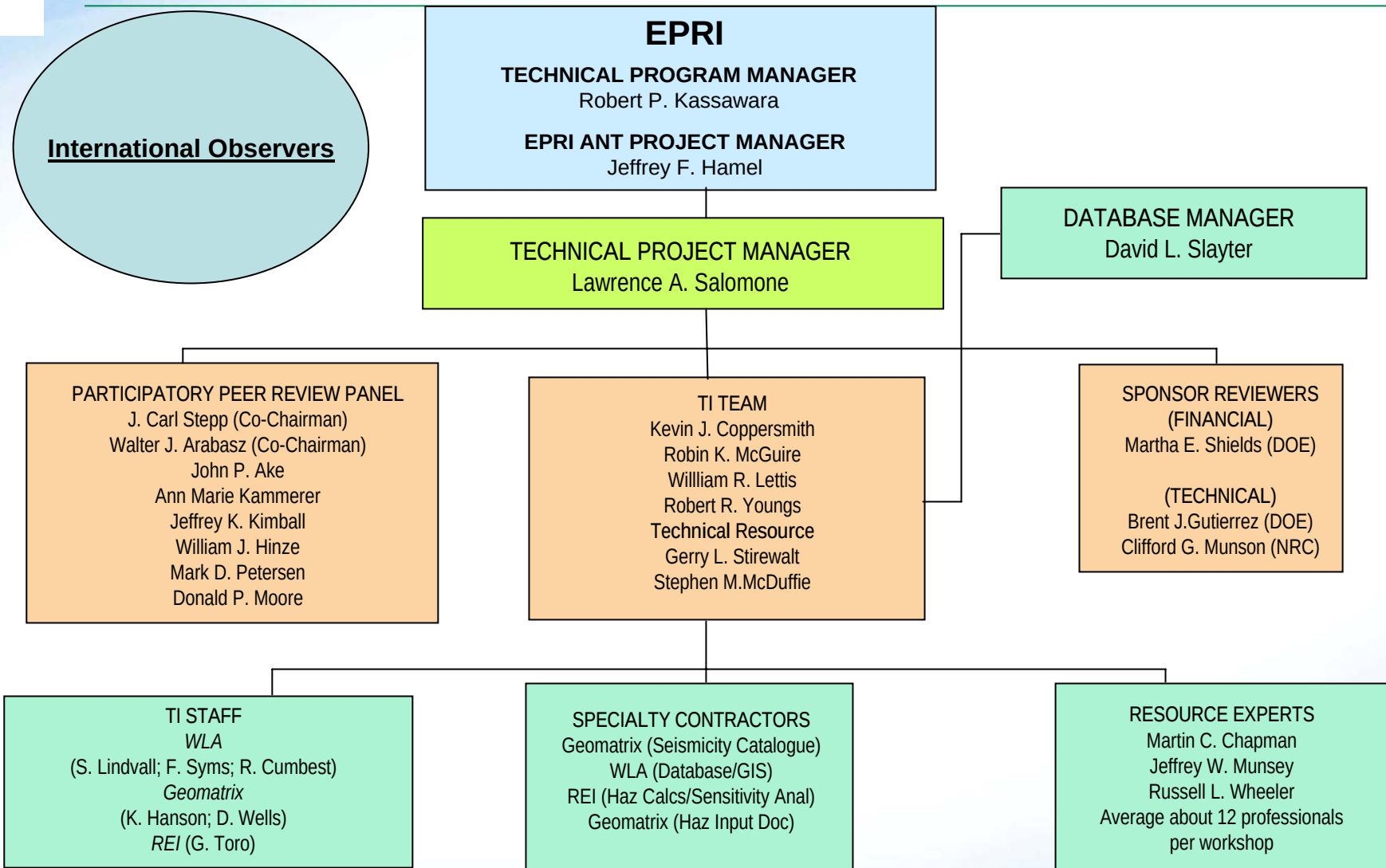
L.A. Salomone
Project Manager



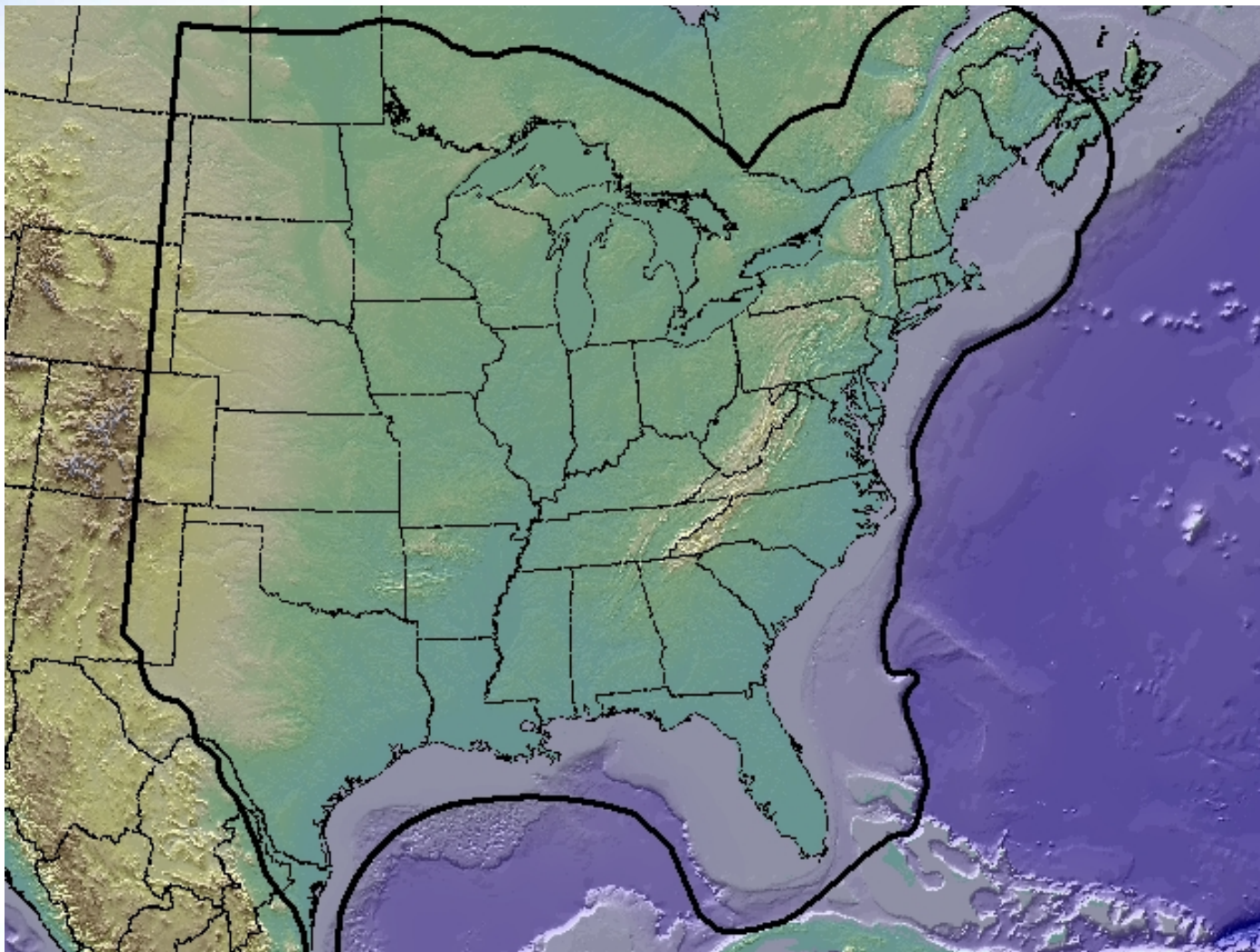
Project Goals

- 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 .

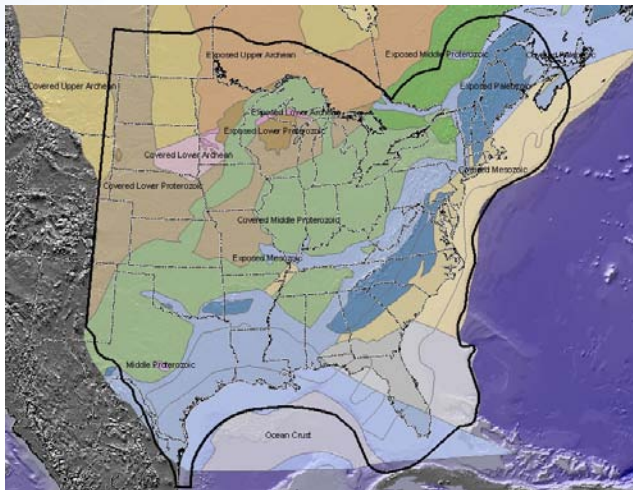
Organization Chart



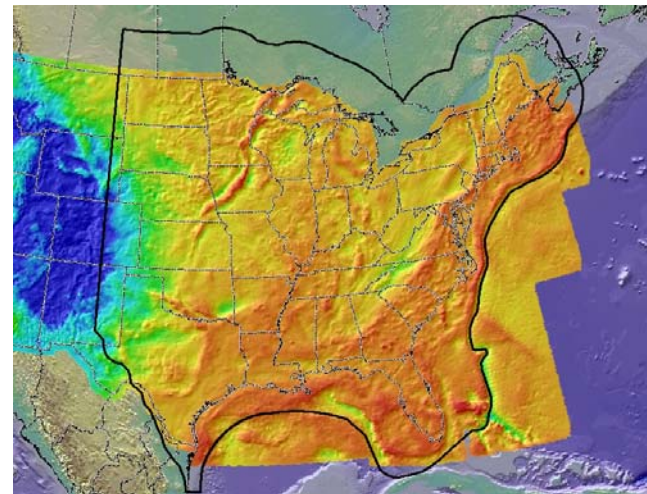
CEUS Seismic Source Characterization Study Area



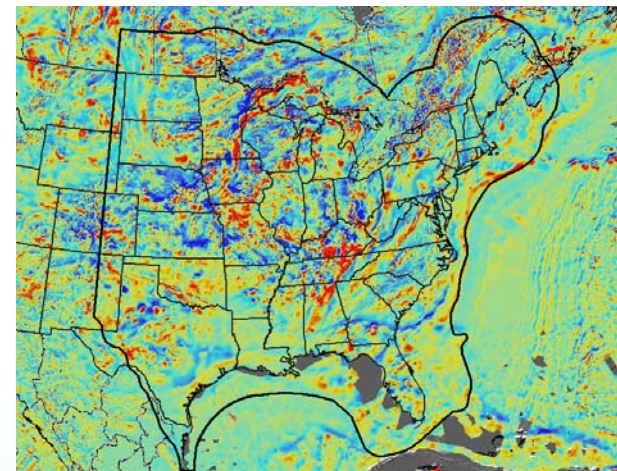
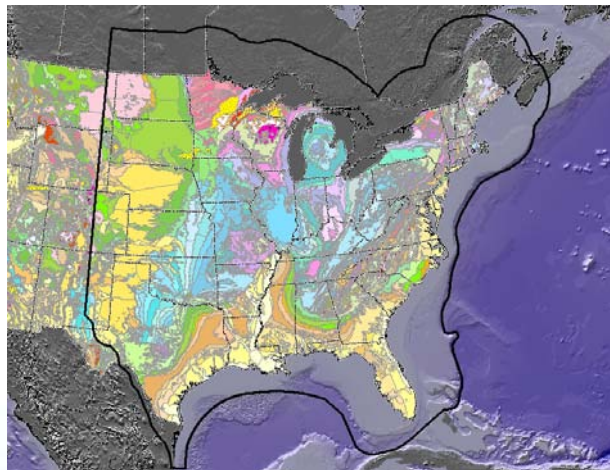
Sample Datasets from CEUS Study



Geology Data



Gravity and Aeromag Data



Seismic Source Characterization (SSC) Model - Project Milestones

- Project Plan as EPRI Technical Update – June, 2008 (Completed)
- Workshop #1: Significant Issues and Databases – July 21-23, 2008 (Completed)
- Workshop #2: Alternative Interpretations – February 18-20, 2009
- 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

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



Status

- **Completed tasks**
 - Project plan
 - Initial funding
 - Workshop #1
- **On Track to Meet Target Completion Date (2010)**

Goals of Workshop and Ground Rules

Kevin J. Coppersmith
CEUS SSC Workshop #2 Alternative Interpretations
EPRI, Palo Alto, CA
18–20 February 2009

NUREG/CR-6372
UCRL-ID-122160
Vol. 1

Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Prepared by

Senior Seismic Hazard Analysis Committee (SSHAC)

R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission
U.S. Department of Energy
Electric Power Research Institute

SSHAC Objective

- ▶ Develop methodology for obtaining reproducible, stable estimates of probabilistic seismic hazard at a site, including explicit quantification of uncertainty
 - Assumed basic PSHA computational model is established
 - Focused on methods for assessing uncertainty in the PSHA model input assessments and for quantifying the uncertainty in PSHA results

SSHAC Basic Principles for a PSHA

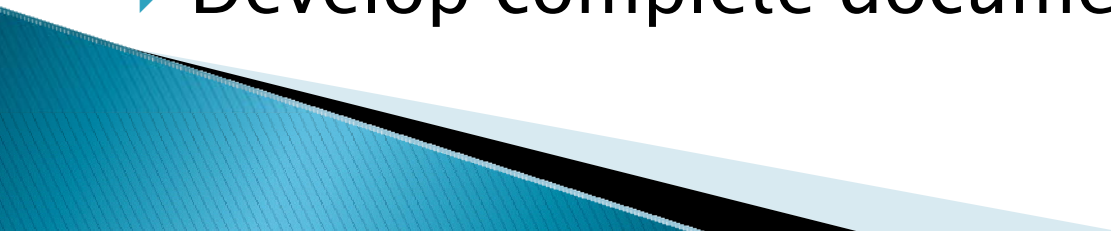
- ▶ Principle 1: The goal of a PSHA is “*to represent the center, the body, and the range of technical interpretations that the larger technical community would have if they were to conduct the study*”
 - Focuses experts on the larger purpose of the PSHA and on the critical importance of their role as scientific evaluators of processes and models, given available data
 - Experts must abandon all proponent bias – personal and peer
- ▶ Termed the “informed technical community” (ITC)

SSHAC Basic Principles for a PSHA

(continued)

- ▶ Principle 2: *“It is absolutely necessary that there be a clear definition of ownership of the inputs into the PSHA, and hence ownership of the results of the PSHA”*
 - Ownership means intellectual responsibility
 - For SSHAC Level 3, Technical Integrator (TI) assumes ownership

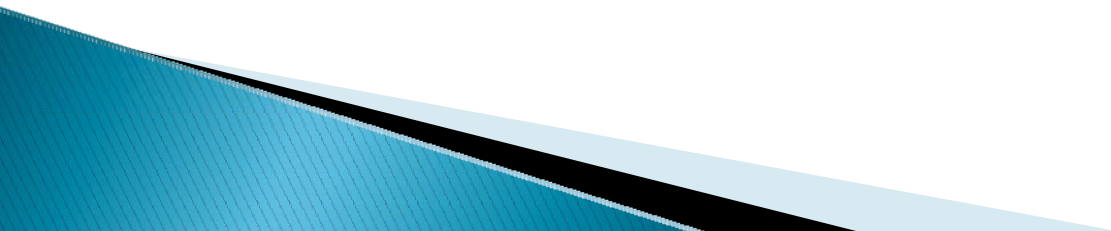
Key SSHAC Attributes: Any PSHA Must

- ▶ Define specific roles of all participants
 - ▶ Develop and disseminate complete database
 - ▶ Consider views of larger informed technical community in evaluating uncertainties
 - ▶ Encourage interactive debate and learning
 - Workshops for Levels 3 and 4
 - ▶ Provide feedback to understand implications of preliminary models and uncertainties
 - ▶ Conduct peer review
 - ▶ Develop complete documentation
- 

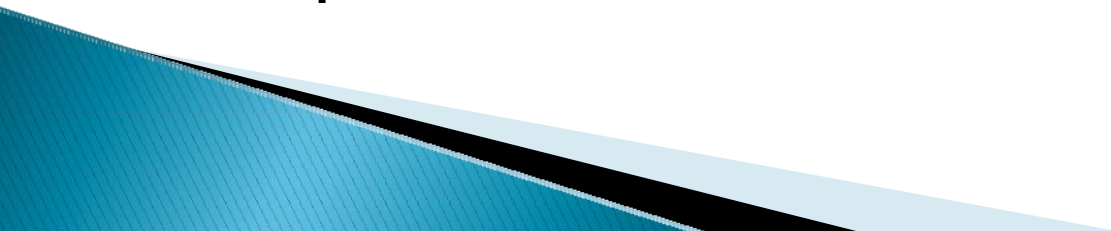
Expert Roles

- ▶ *Evaluator*. an expert capable of evaluating the relative credibility of multiple alternative hypotheses to explain the observations
- ▶ To evaluate the alternatives, the evaluator:
 - Considers the available data
 - Listens to proponents and other evaluators
 - Questions the technical basis for their conclusions
 - Challenges the proponents' position
- ▶ Interacts with other experts in workshops, to understand basis for their assessments
- ▶ Considers feedback regarding the implications of assessments
- ▶ Interacts with hazard analyst to ensure assessments are properly modeled for the PSHA computations
- ▶ Documents the basis for assessments

Expert Roles (continued)

- ▶ *Proponent*: an expert who advocates a particular hypothesis or technical position
 - ▶ Common role in science
 - ▶ Peer review in professional debates and literature
 - ▶ Ideas either gain support or fade with time
- 

Expert Roles (continued)

- ▶ *Technical Integrator* [Level 3]: small team that serves as an evaluator for the technical assessments
 - ▶ Structures and documents information exchanges
 - ▶ Stages effective debates and interactions in critical areas
 - ▶ Responsible for capturing views of larger technical community and considering them in the evaluation process
 - ▶ Responsible for documentation
- 

CEUS SSC Task Schedule

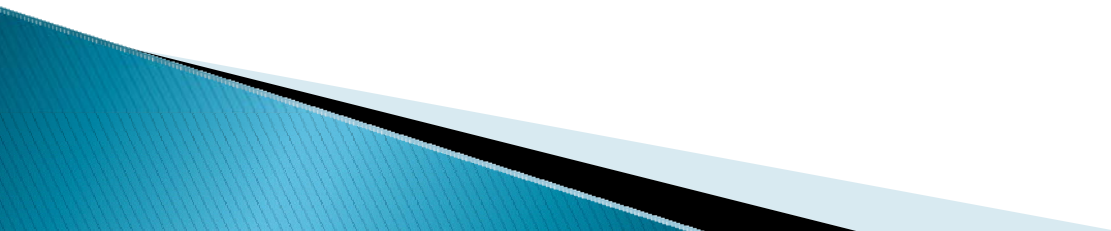
Task	Schedule
Retain Participatory Peer Review Panel	April – May 2008
Database Development	April 2008 – May 2009
Seismicity Catalog	April 2008 – May 2009
Assessment of Hazard-Significant Issues	April - July 2008
Workshop 1 Significant Issues and Databases	July 2008
Workshop 2 Alternative Interpretations	February 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	July 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

Ground Rules for Workshop

- ▶ Workshops are an opportunity for the TI Team to:
 - Exchange data
 - Understand viewpoints of technical community
 - Challenge and defend technical hypotheses
 - Gain information on the project
 - Interact and ask questions
- ▶ Therefore, the focus of this workshop is the TI Team.

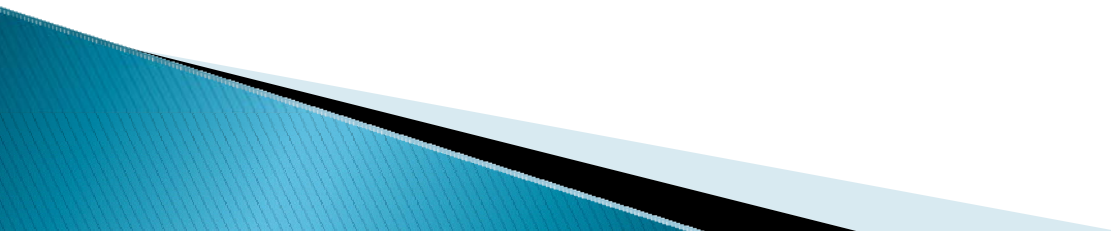
Ground Rules for Workshops

(continued)

- ▶ Conduct of the technical discussions at the workshops will be at the highest professional level.
 - ▶ Discussions will be among the TI team and the presenters; all others will be considered observers
 - ▶ Observers will be provided with opportunities for comments at the end of each day
 - ▶ The TI team runs the workshop and is responsible for keeping to the schedule, logistics, etc.
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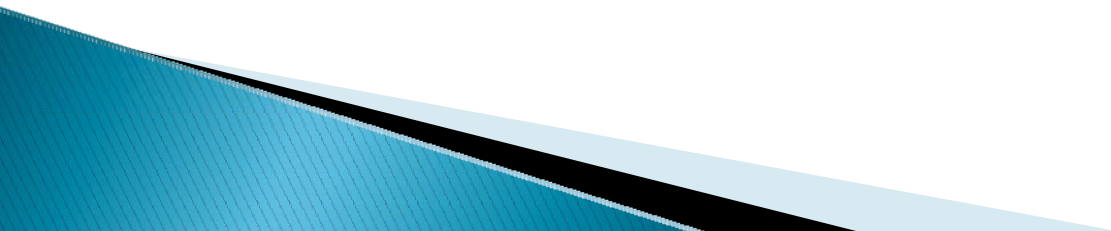
Workshop 2 Alternative Interpretations

Goals of the Workshop

- ▶ To review the project SSHAC Level 3 methodology
 - ▶ To provide an opportunity for the TI team to understand proponent views regarding important technical issues
 - ▶ To discuss the range of alternative views and uncertainties within the larger technical community
 - ▶ To discuss the path forward for the CEUS SSC project
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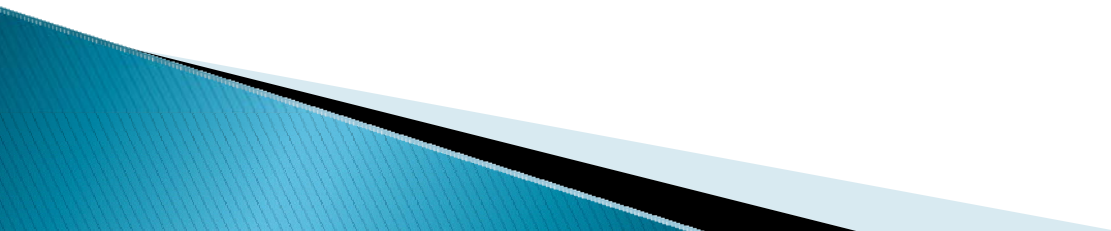
Workshop #2 Alternative Interpretations

Workshop Process

- ▶ TI team has begun to develop a preliminary seismic source model; this workshop will provide valuable information on views of technical community
 - ▶ Resource experts have been asked to provide their views regarding certain key technical issues, including a discussion of the uncertainties associated with those views
 - Key questions/issues have been posed to each presenter
 - TI team is charged with capturing the knowledge and uncertainties within the larger informed technical community
 - This workshop is an important opportunity to directly probe the experts regarding the technical bases for their interpretations
- 

Workshop #2 Alternative Interpretations

Workshop Process (continued)

- ▶ To the extent practical, presentations have been arranged topically to encourage focus on pertinent issues
 - ▶ Ample time has been provided for discussion
 - ▶ PPRP members are observers; will meet with TI team leads on Friday after the workshop
 - ▶ PPRP written comments to follow
- 

Strain (and Stress) Constraints on Seismicity in the St. Lawrence Valley

Stephane Mazzotti

Geological Survey of Canada, Natural Resources Canada,
Sidney BC, Canada

EPRI CEUS Seismic Source Characterization Project
Palo Alto, Feb. 18 2009



Natural Resources
Canada

Ressources naturelles
Canada

Strain (and Stress) Constraints on Seismicity in the St. Lawrence Valley

Outline

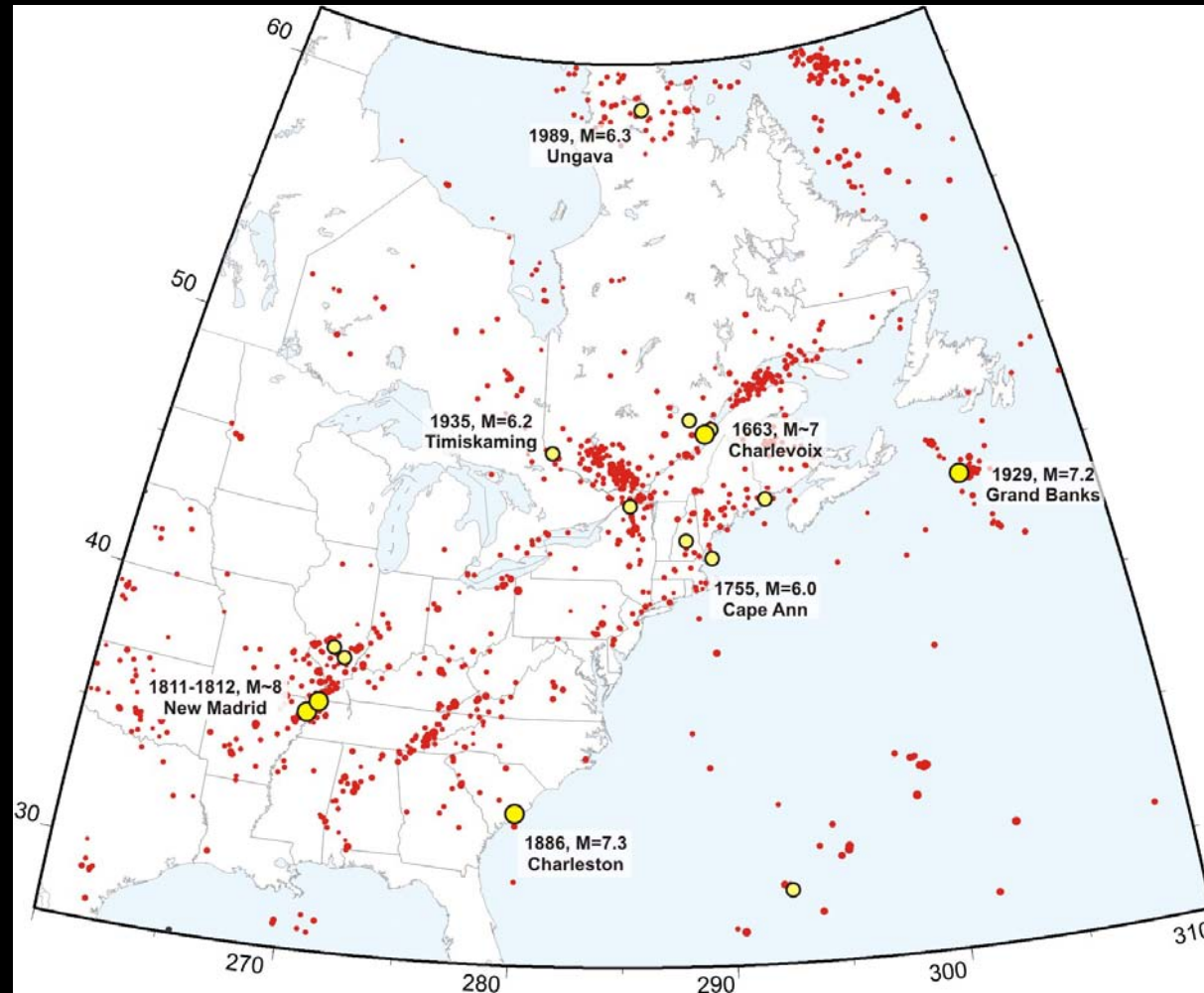
- 1) Distribution of earthquakes & definition of seismic zones
- 2) GPS observations: coverage, uncertainties, rates
- 3) Relationship between GPS, seismicity, and “long-term” strain rates
- 4) Potential role of GIA processes
- 5) Issues & limitations with using GPS for seismicity rates and source zones

1) Seismicity & Seismic Source Zones

Central-eastern US & Canada seismicity

~15 $M > 6$ since ~1600

Concentrations in “hot spots”, e.g. St. Lawrence Valley, Charlevoix (5 $M > 6$ since 1650)



1) Seismicity & Seismic Source Zones

Relationship to geology

Concentrations along
Iapetus rifted margin
and grabens (~600 Ma)

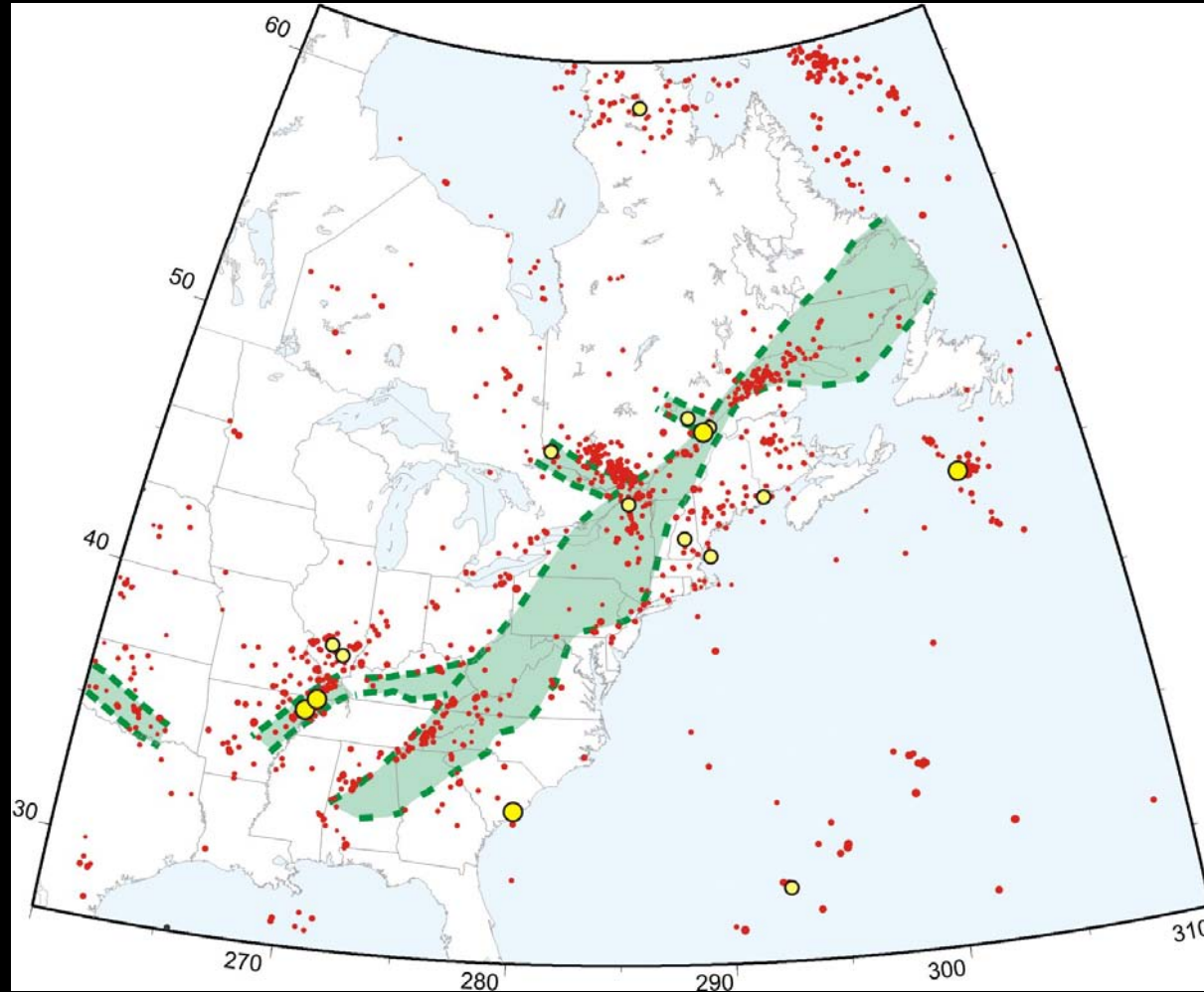
Eastern Canada $M > 6.5$
frequency:

~1/200 years in

Iapetus Rift

~1/5000 years in

Canadian Shield

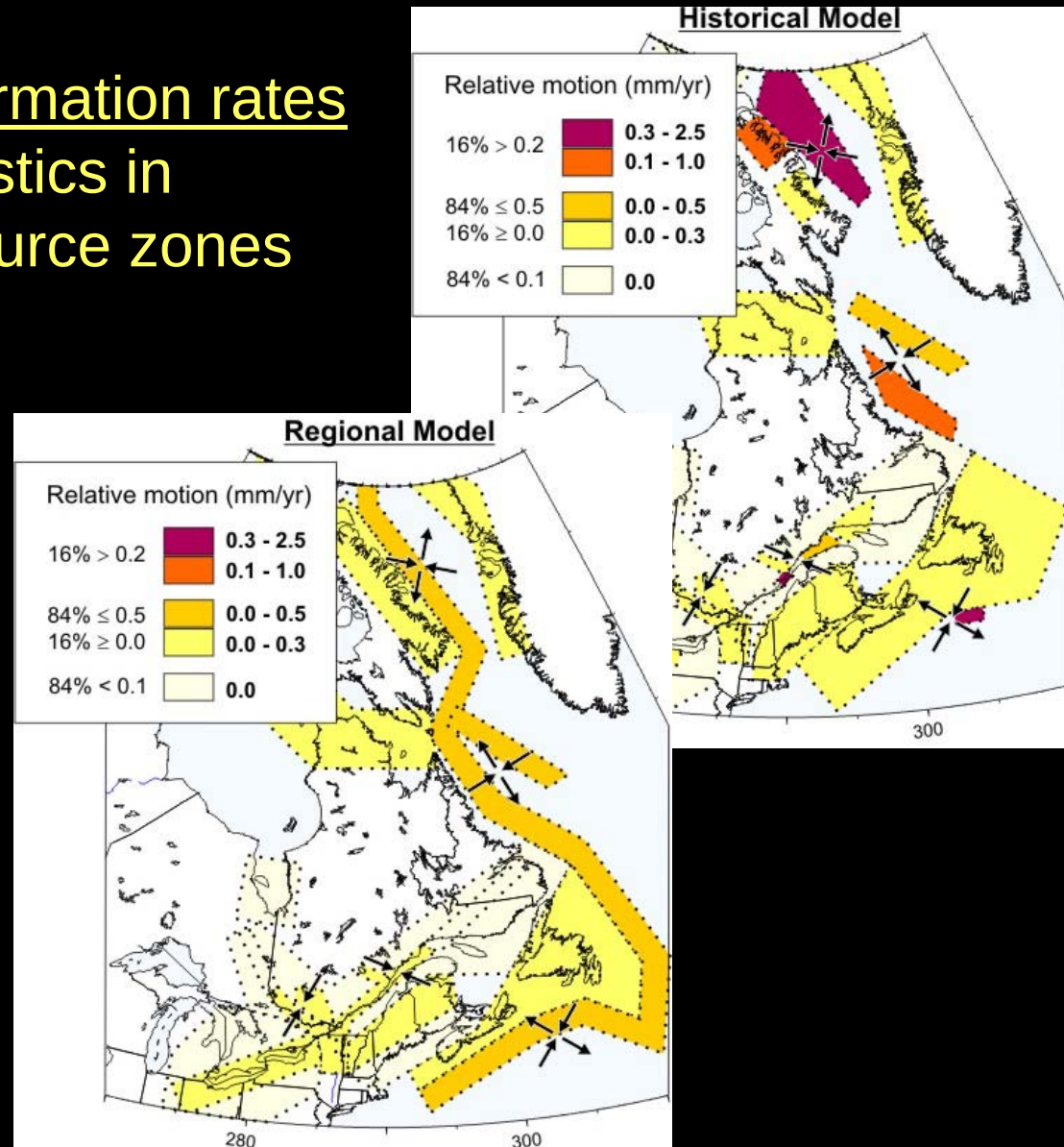


1) Seismicity & Seismic Source Zones

Seismic moment and deformation rates
based on earthquake statistics in
historical vs. geological source zones

Historical source zones:
very heterogeneous
few high strain zones
0.0 – 2.5 mm/yr

Geological source zones:
homogeneous
no high strain zone
0.0 – 0.5 mm/yr



2) GPS Observations

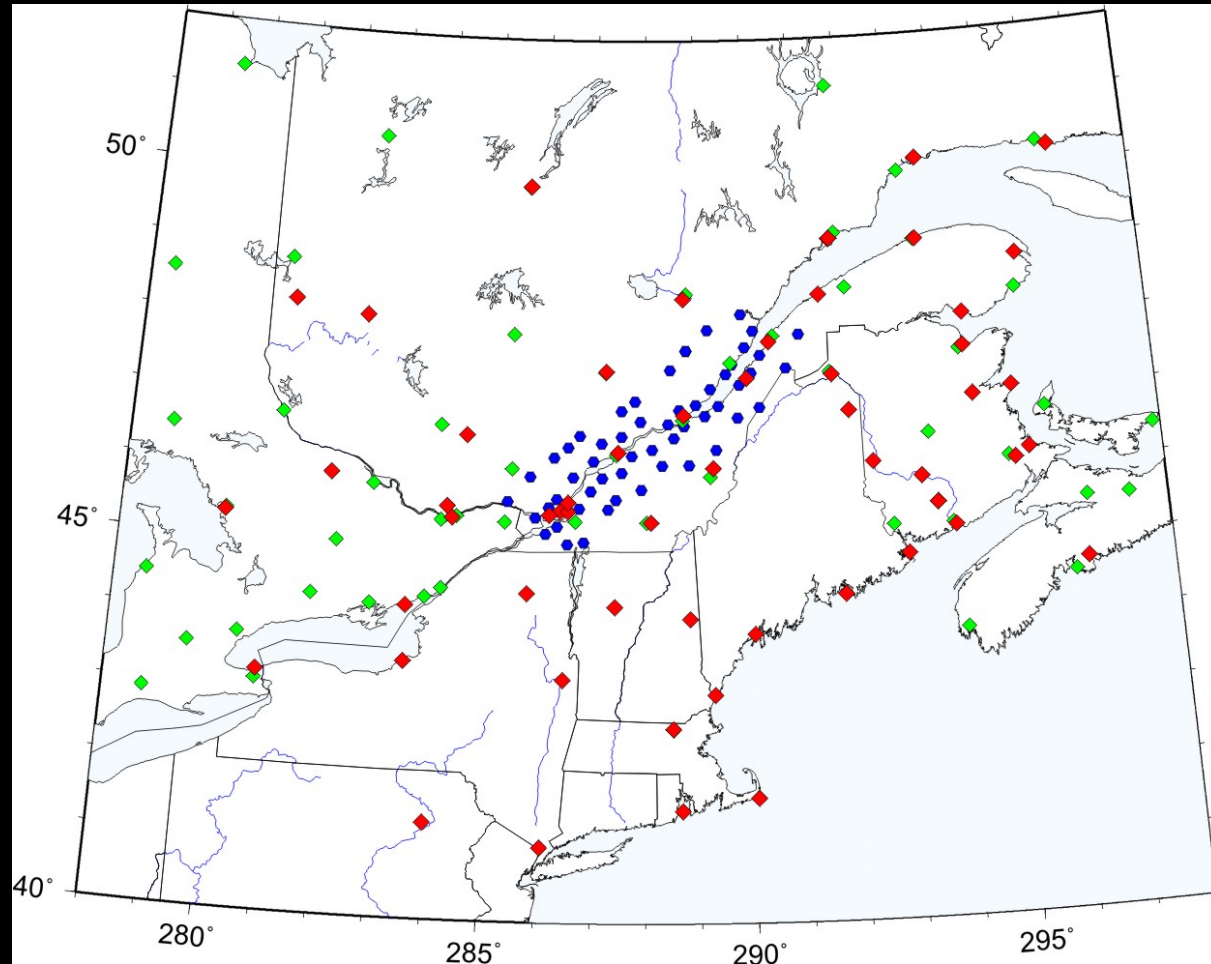
GPS Networks

Regional:

- Backbone of ~50 continuous stations (since 2001 / 2008)
- Densification of ~45 campaign stations (since 1994 / 1999)

Upper St. Lawrence:

- Network of 55 campaign stations (since 2005)



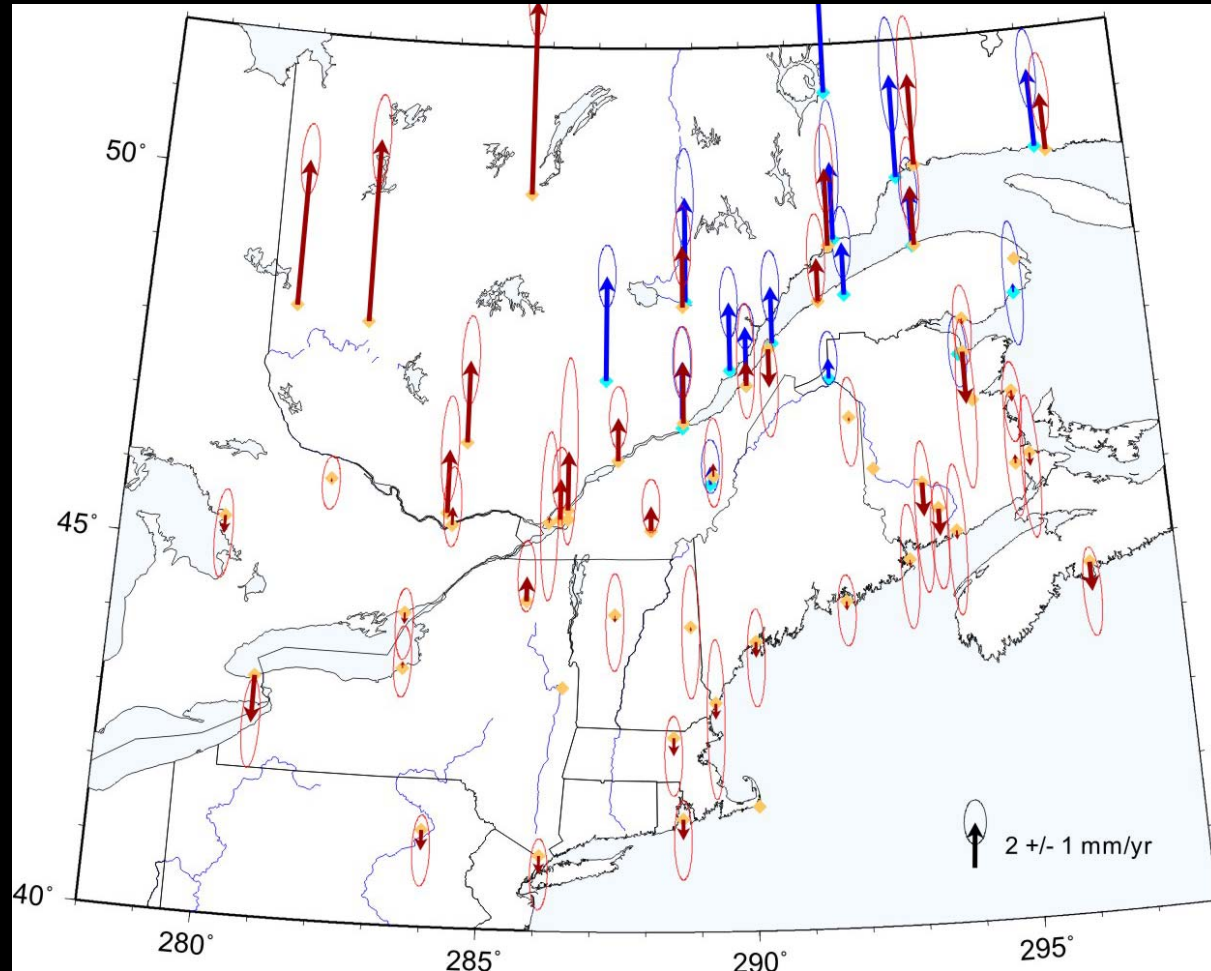
2) GPS Observations

Vertical velocities

Continuous and
campaign regional
networks

ITRF2000

- NW-SE gradient of 7-8 mm/yr
- Hinge line close to Quebec/Maine border
- Consistent with GIA models



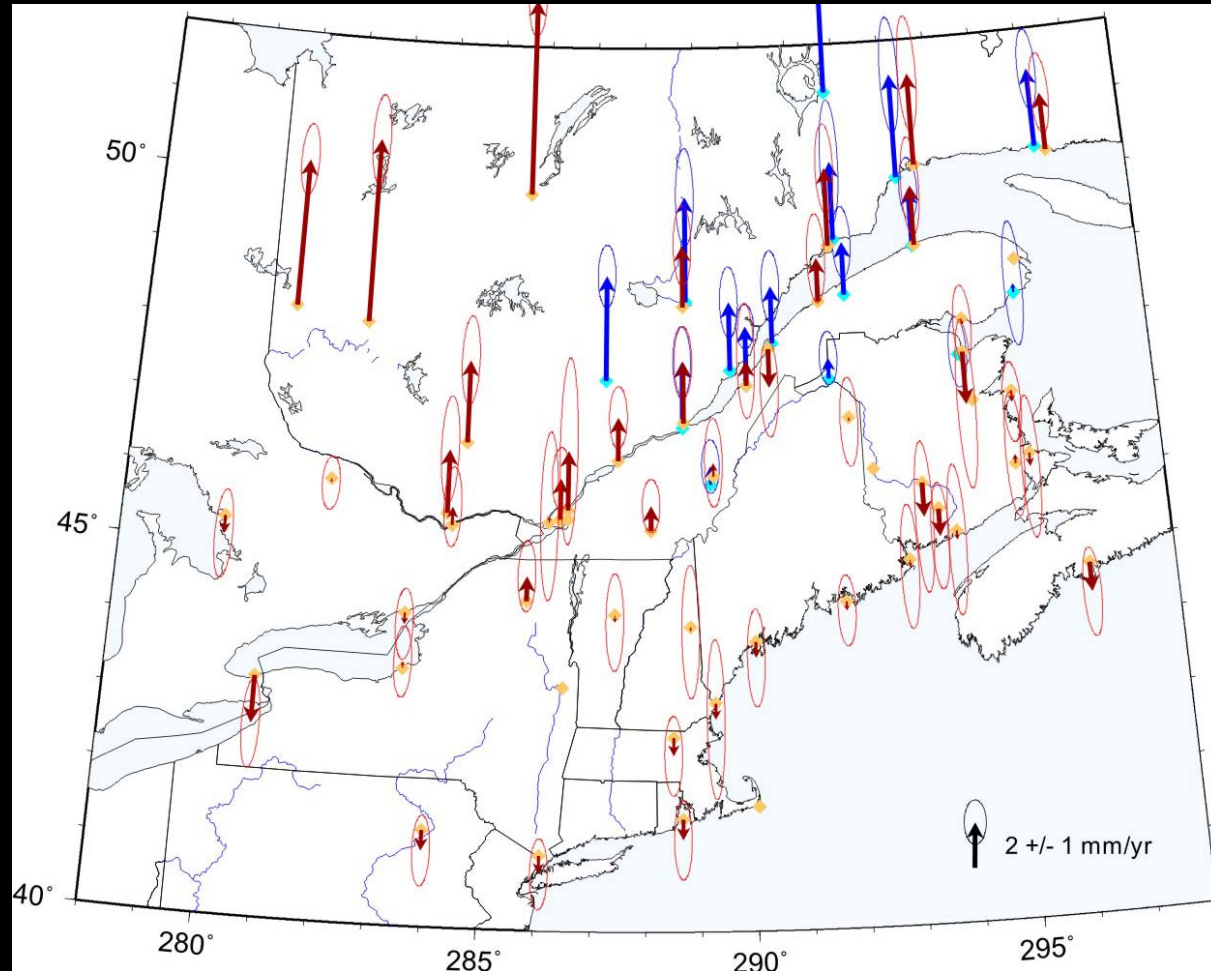
2) GPS Observations

Vertical velocities

Continuous and
campaign regional
networks

ITRF2000

- Good agreement between continuous (3-6 yrs) and campaign (7-9 yrs)
- Uncertainties 1.0-2.0 mm/yr standard error



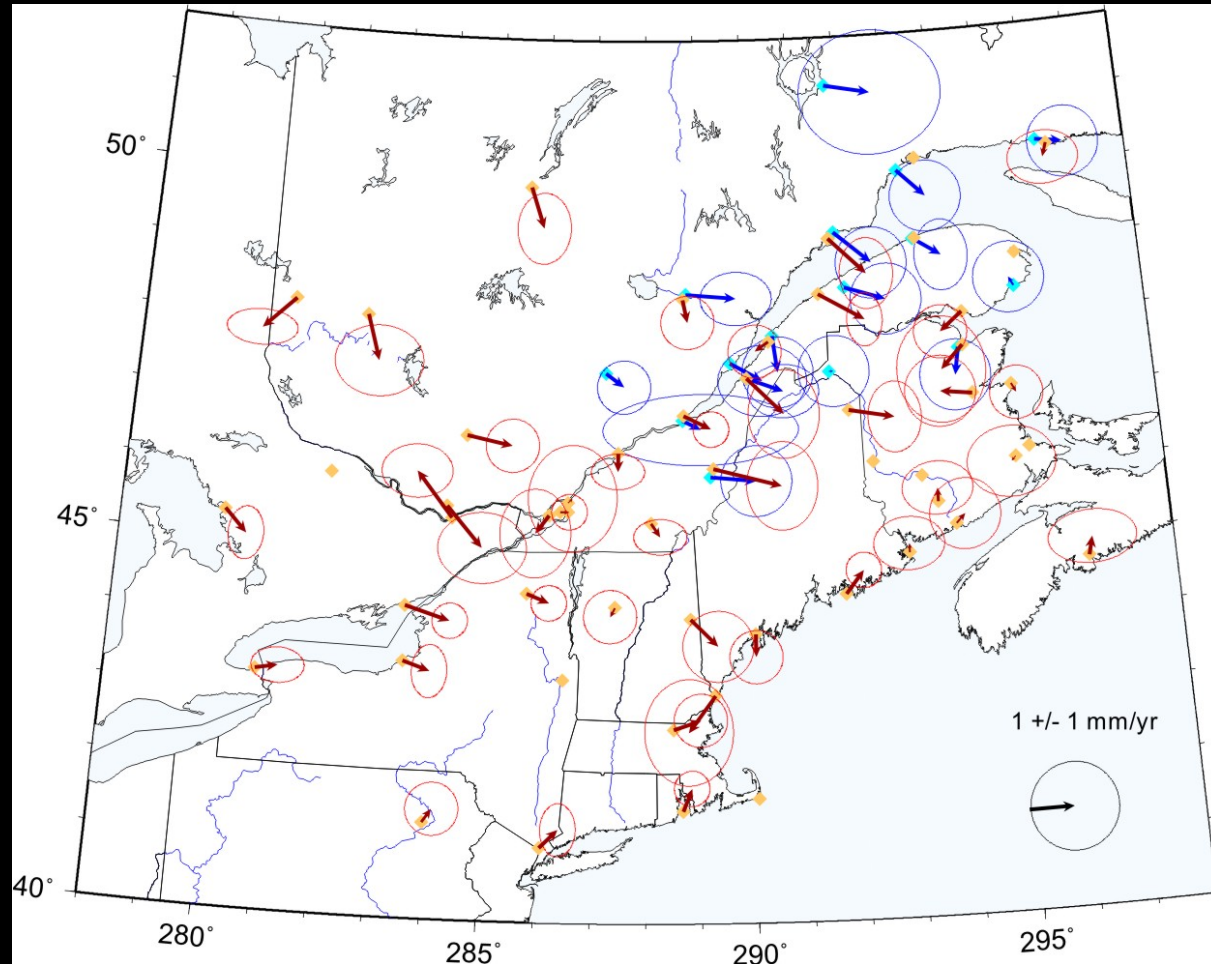
2) GPS Observations

Horizontal velocities

Continuous and
campaign regional
networks

ITRF2000 – North
America

- Eastward velocity
NW-SE gradient of ~ 1
mm/yr
- Consistent with GIA
models



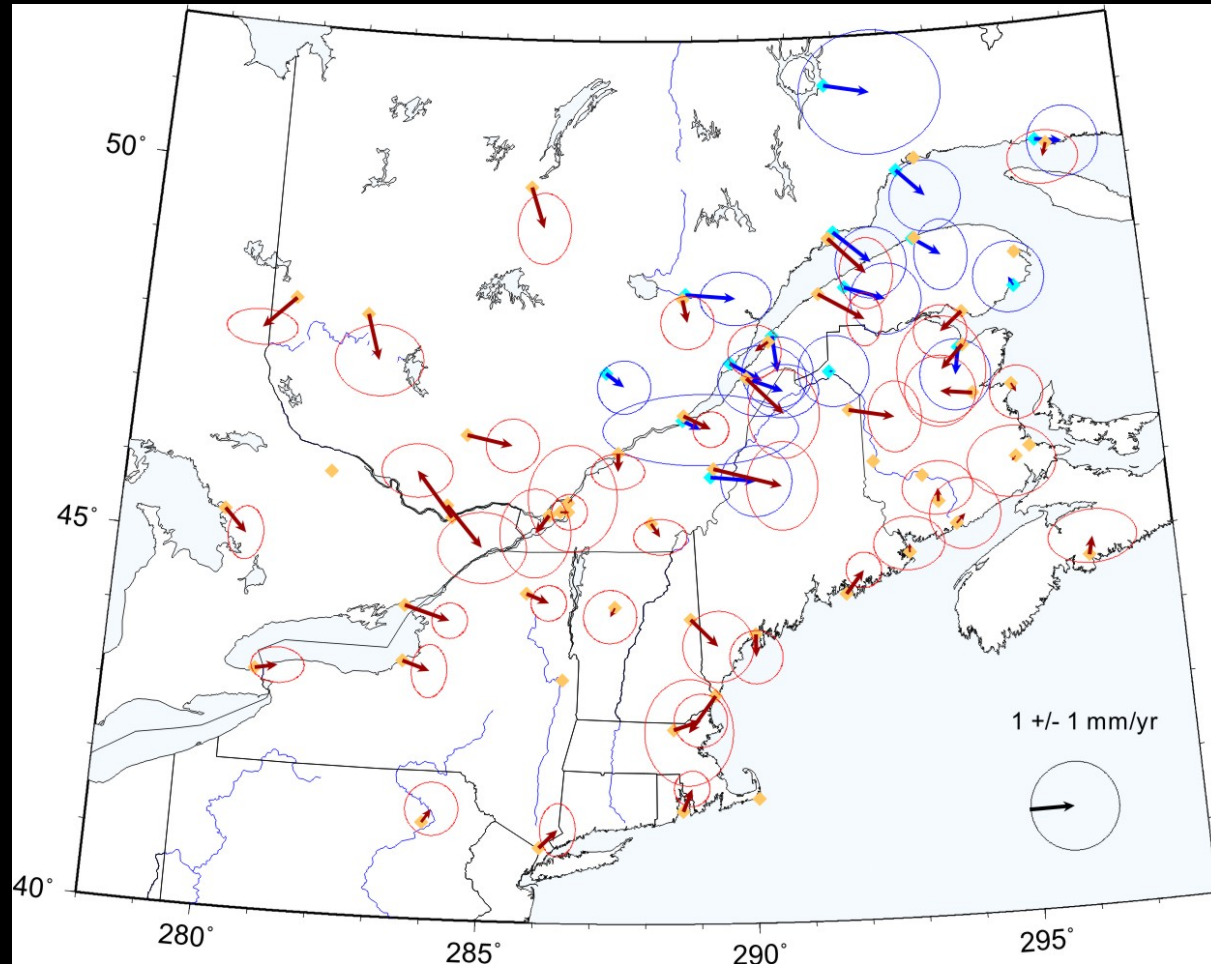
2) GPS Observations

Horizontal velocities

Continuous and
campaign regional
networks

ITRF2000 – North
America

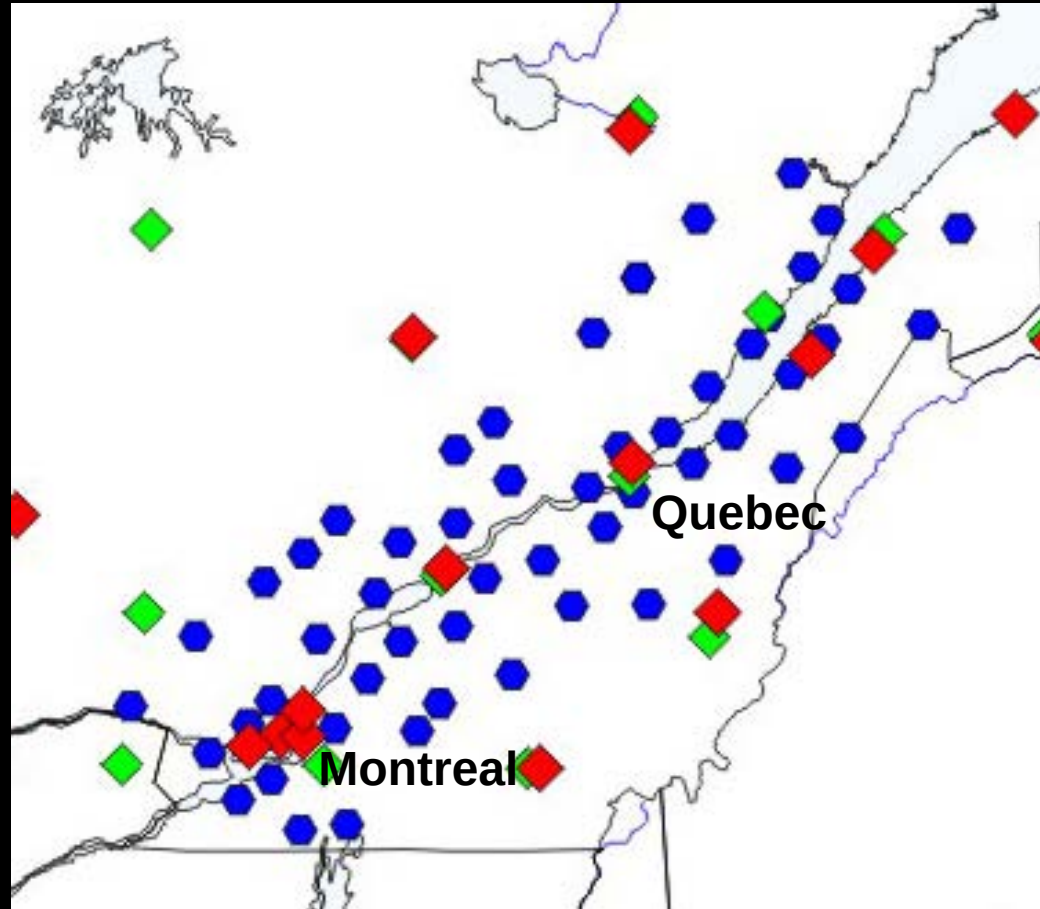
- Good agreement between continuous (3-6 yrs) and campaign (7-9 yrs)
- Uncertainties 0.5-1.0 mm/yr standard error



2) GPS Observations

High-resolution Upper St. Lawrence campaign network

- In progress, first survey in 2005
- Spans high and low seismicity zones from Charlevoix to Montreal
- 55 campaign GPS sites surveyed every 2 years
- Results expected by 2010-2015



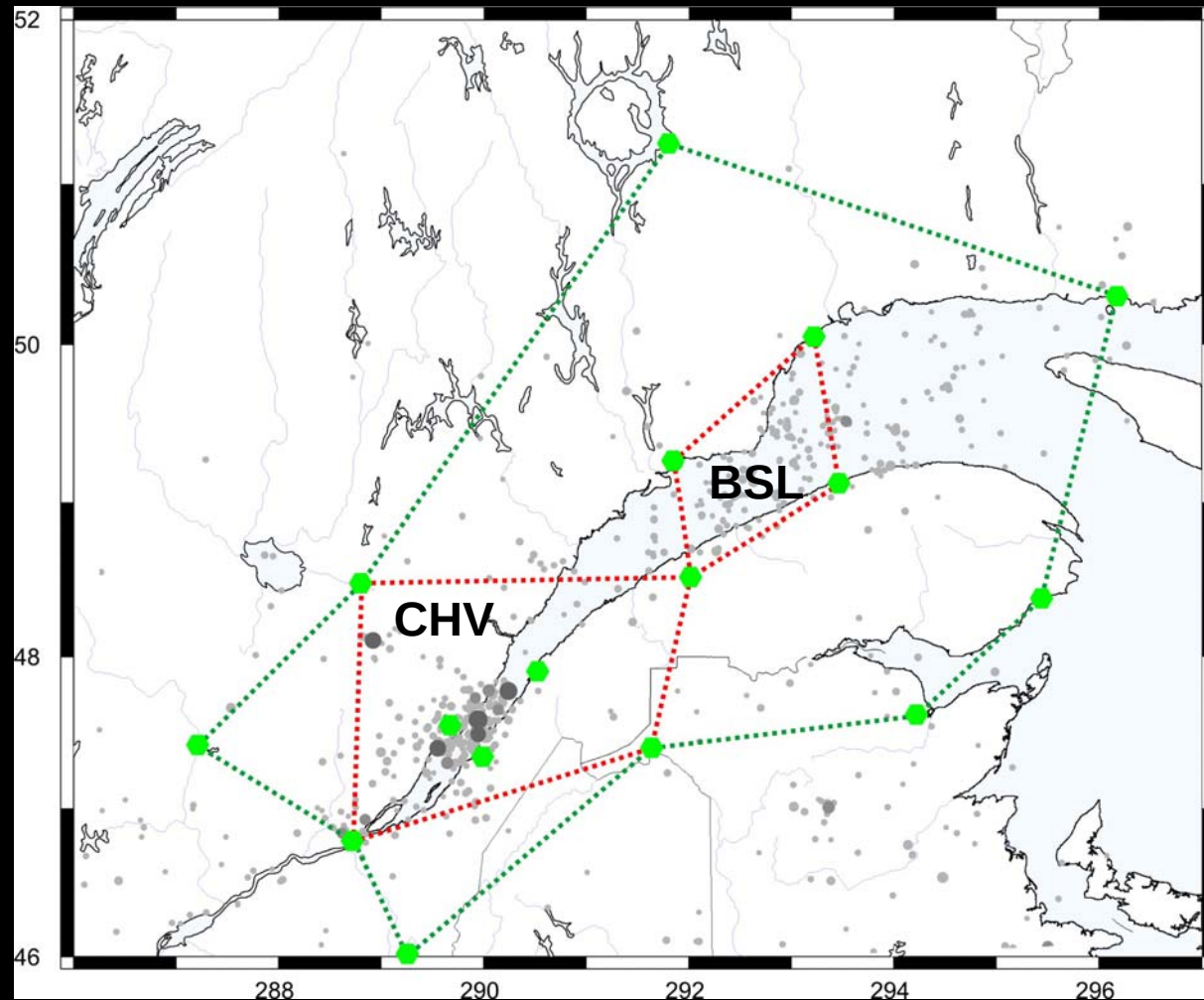
3) GPS, Seismicity & Long-Term Strain Rates

Lower St. Lawrence

16 campaign sites
(Canadian Base
Network)

4-5 occupations
between 1994-1996
and 2003

Subnets around
Charlevoix (CHV) and
Lower St. Lawrence
(BSL) seismic zones



3) GPS, Seismicity & Long-Term Strain Rates

Horizontal strain rates
from 1994-2003 CBN

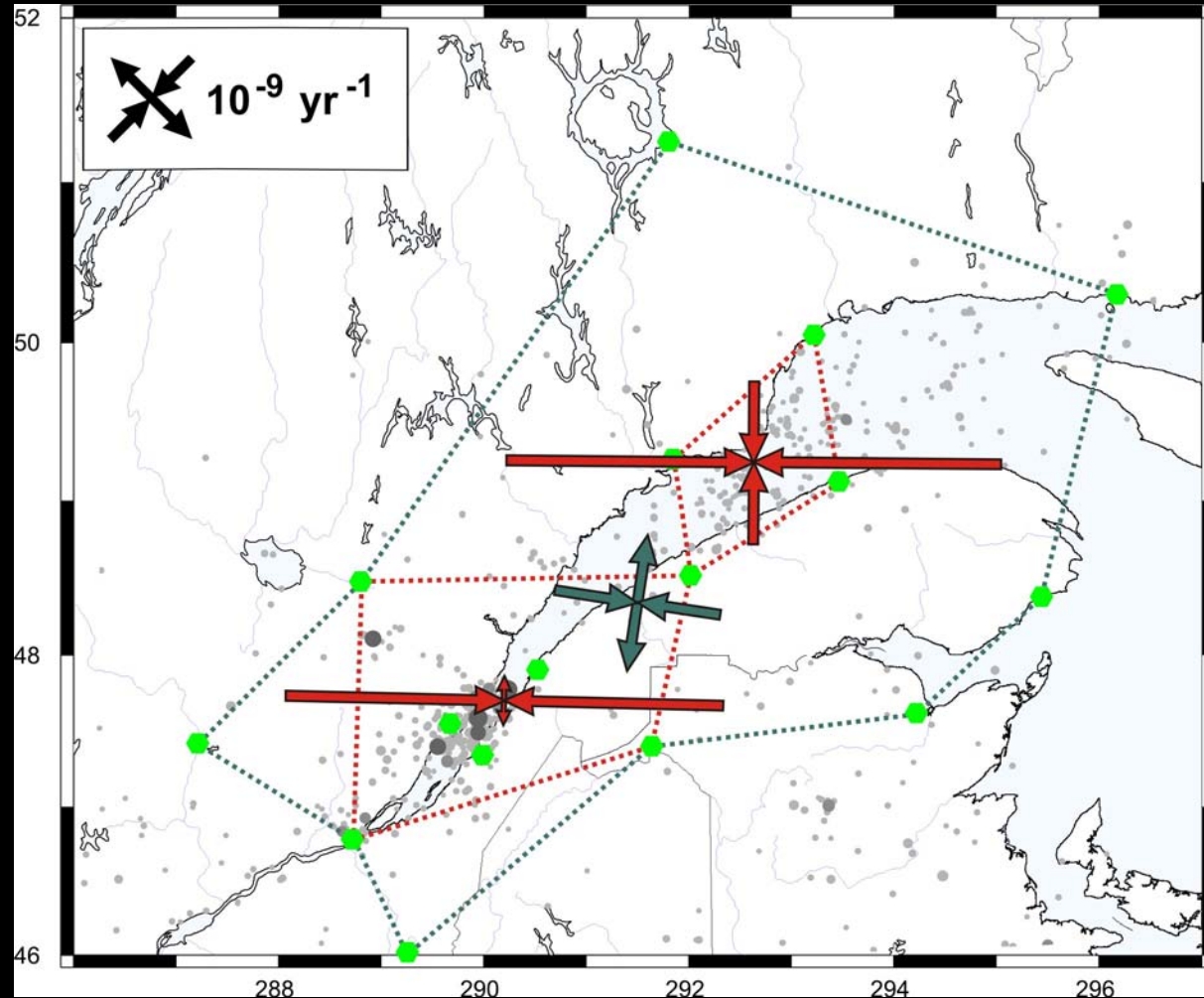
E-W shortening (10^{-9}
 yr^{-1})

Regional: 1.4 ± 1.3

CHV: 3.8 ± 2.3

BSL: 4.3 ± 4.2

Suggestion of higher
strain rates in high
seismicity zones



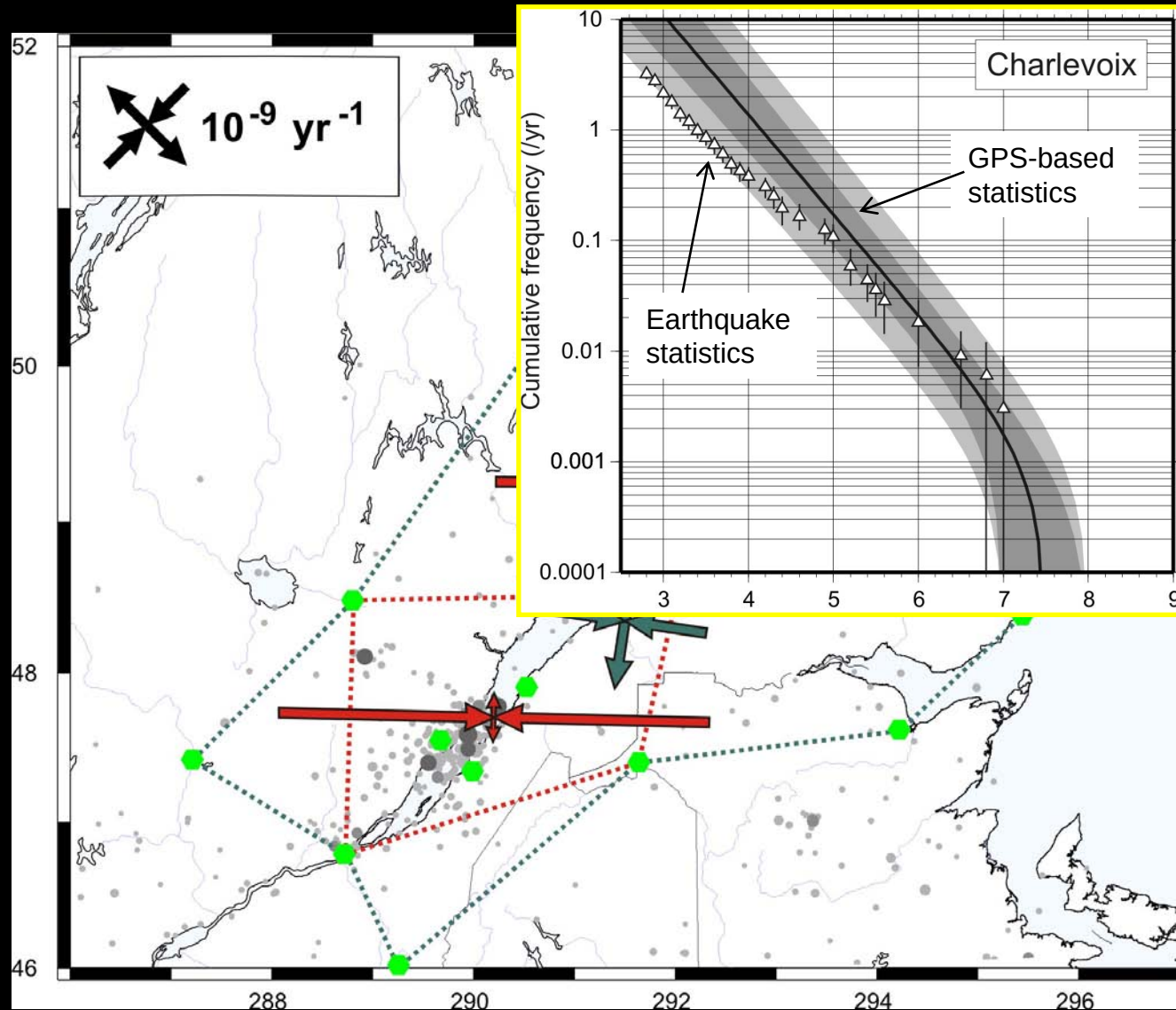
3) GPS, Seismicity & Long-Term Strain Rates

Charlevoix GPS vs. seismicity rates

$$3.8 \pm 2.3 \times 10^{-9} \text{ yr}^{-1}$$

$$0.7 \pm 0.4 \text{ mm/yr}$$

- GPS-based and catalog statistics agree for $M > 6$



3) GPS, Seismicity & Long-Term Strain Rates

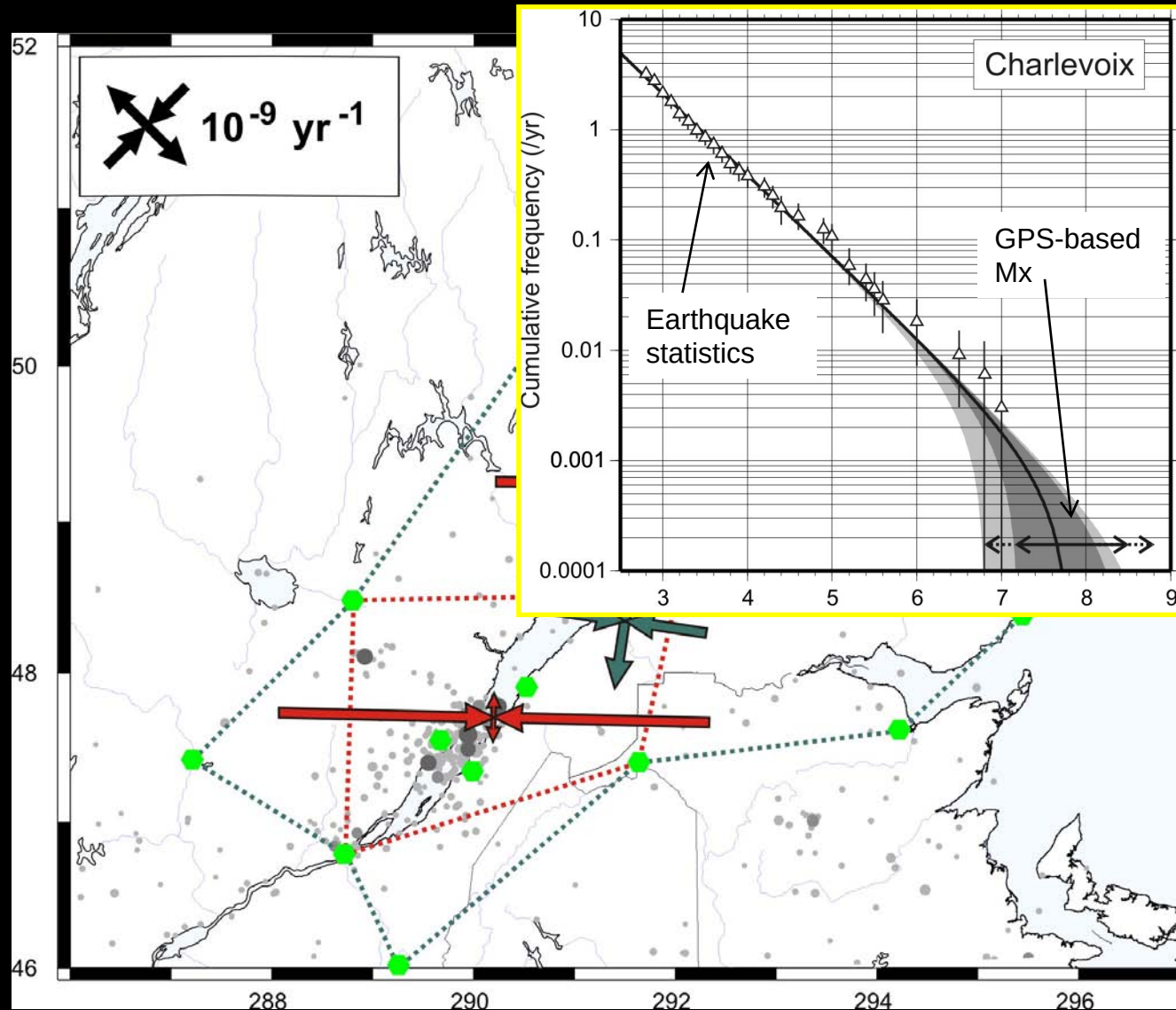
Charlevoix GPS vs. seismicity rates

$$3.8 \pm 2.3 \times 10^{-9} \text{ yr}^{-1}$$

$$0.7 \pm 0.4 \text{ mm/yr}$$

- GPS-based and catalog statistics agree for $M > 6$

- Assuming catalog statistics, GPS strain constrains $M_x = 7.8 \pm 0.6$



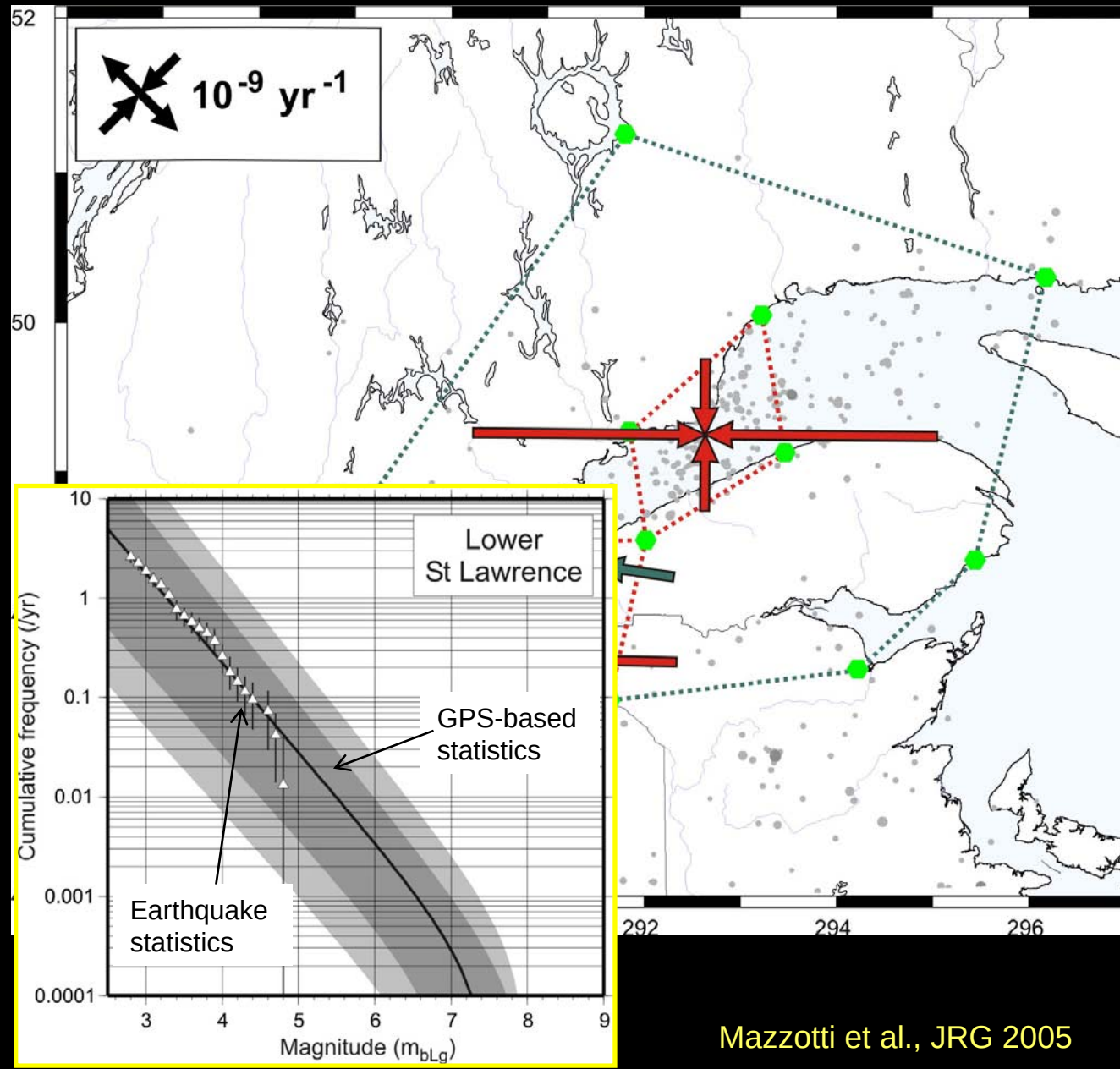
3) GPS, Seismicity & Long-Term Strain Rates

BSL GPS vs.
seismicity rates

$4.3 \pm 4.2 \times 10^{-9} \text{ yr}^{-1}$

$0.2 \pm 0.6 \text{ mm/yr}$

- GPS-based and
catalog statistics
agree for $M < 4.5$



3) GPS, Seismicity & Long-Term Strain Rates

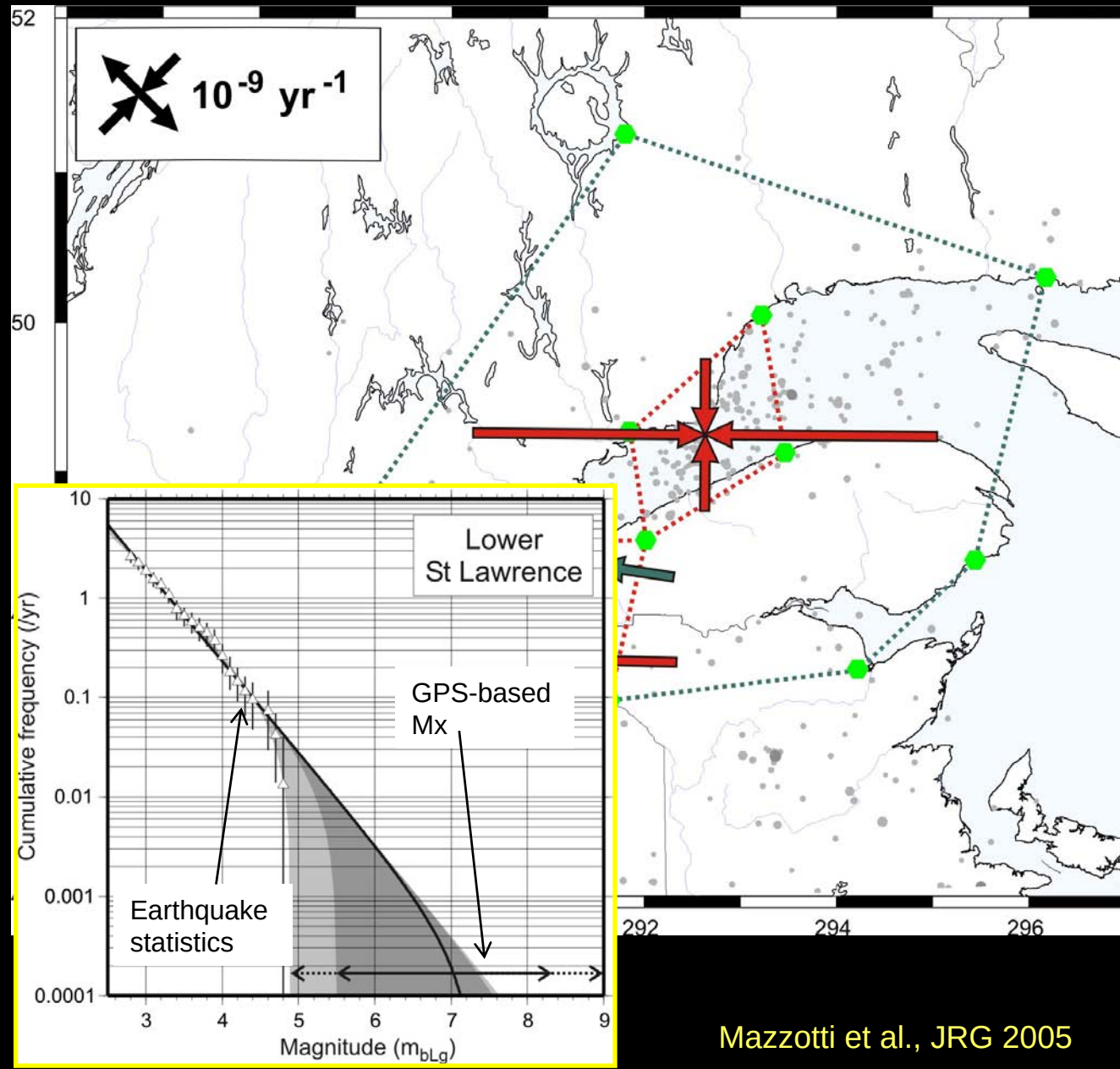
BSL GPS vs. seismicity rates

$$4.3 \pm 4.2 \times 10^{-9} \text{ yr}^{-1}$$

$$0.2 \pm 0.6 \text{ mm/yr}$$

- GPS-based and
catalog statistics
agree for $M < 4.5$

- Assuming catalog
statistics, GPS
strain constrains
 $M_x = 7.3 \pm 1$



3) GPS, Seismicity & Long-Term Strain Rates

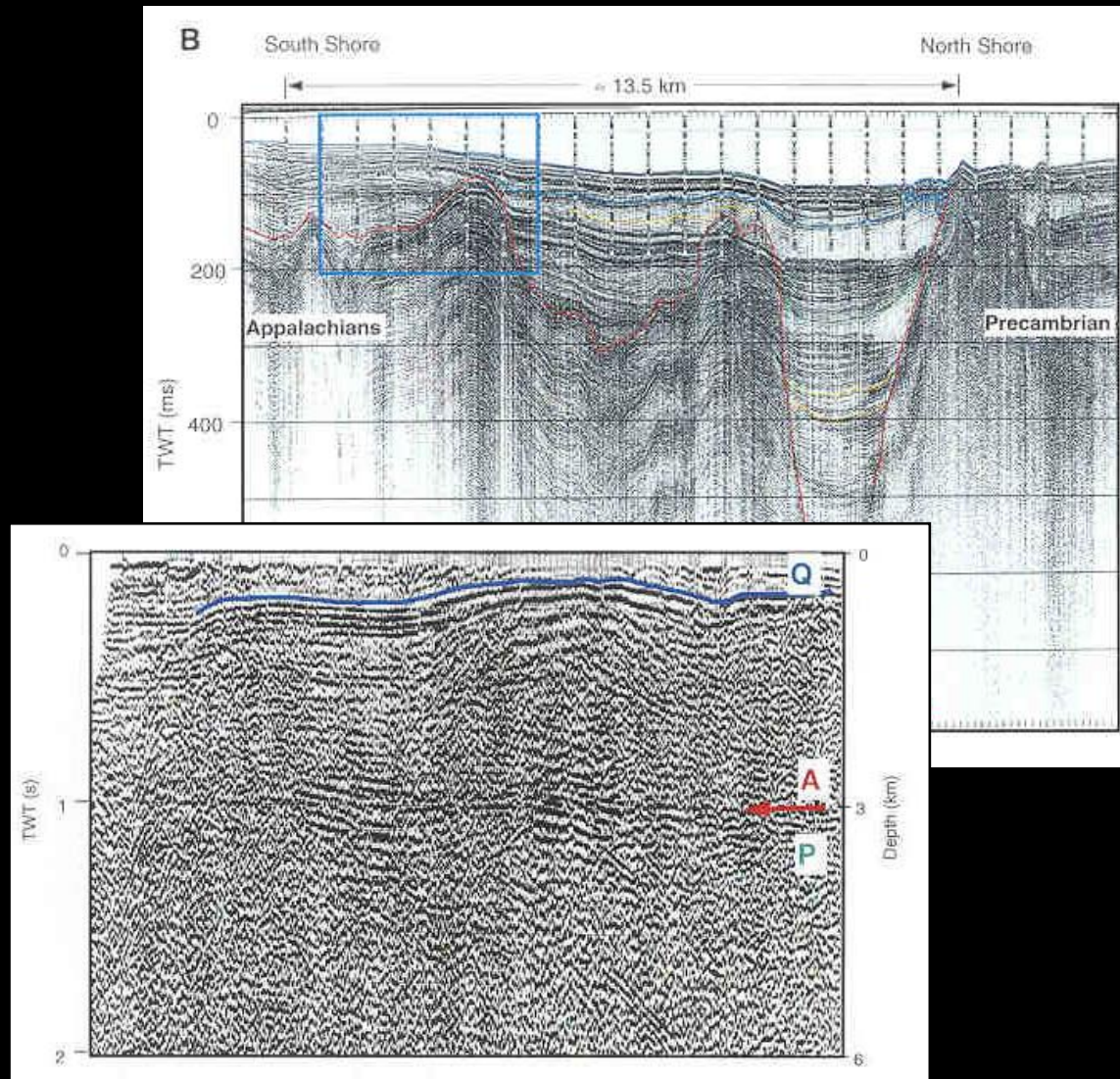
Charlevoix GPS vs.
“long-term” rates

0.7 ± 0.4 mm/yr

300 – 1100 m / Myr

No offset (< 2-5 m) of
Appalachian or
Mesozoic units in
seismic reflection lines

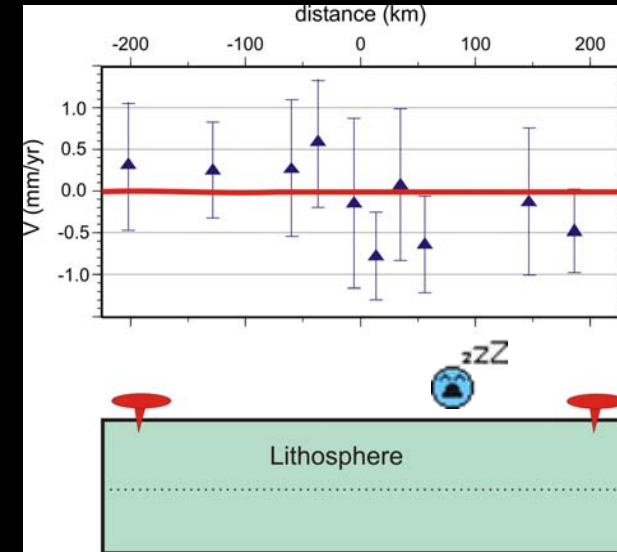
Current strain rates
and seismicity are not
steady-state on Myr
timescale



3) GPS, Seismicity & Long-Term Strain Rates

Within a resolution of ~ 1 mm/yr at 95%, we cannot discriminate between various models

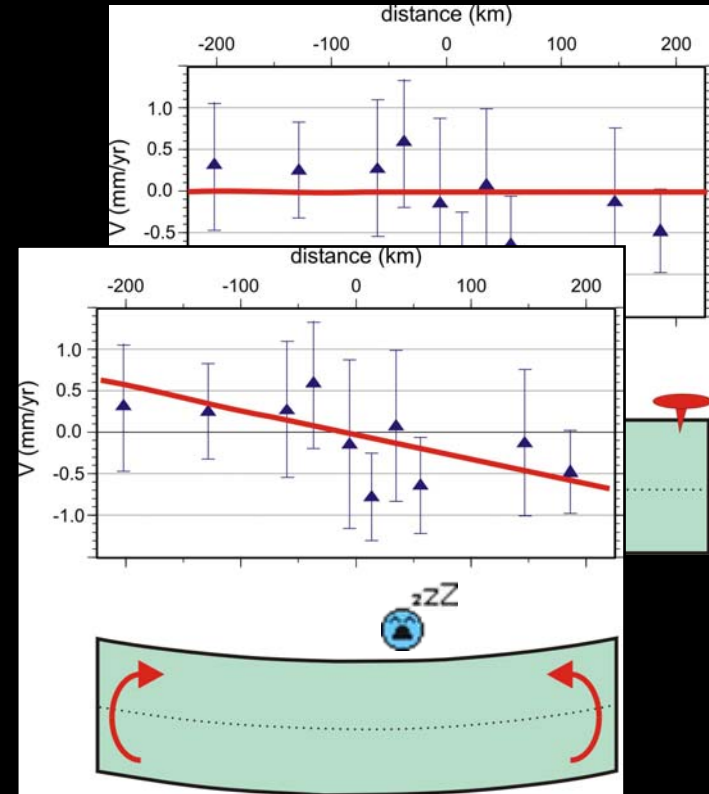
- No strain (no seismicity)



3) GPS, Seismicity & Long-Term Strain Rates

Within a resolution of ~ 1 mm/yr at 95%, we cannot discriminate between strain/earthquake models

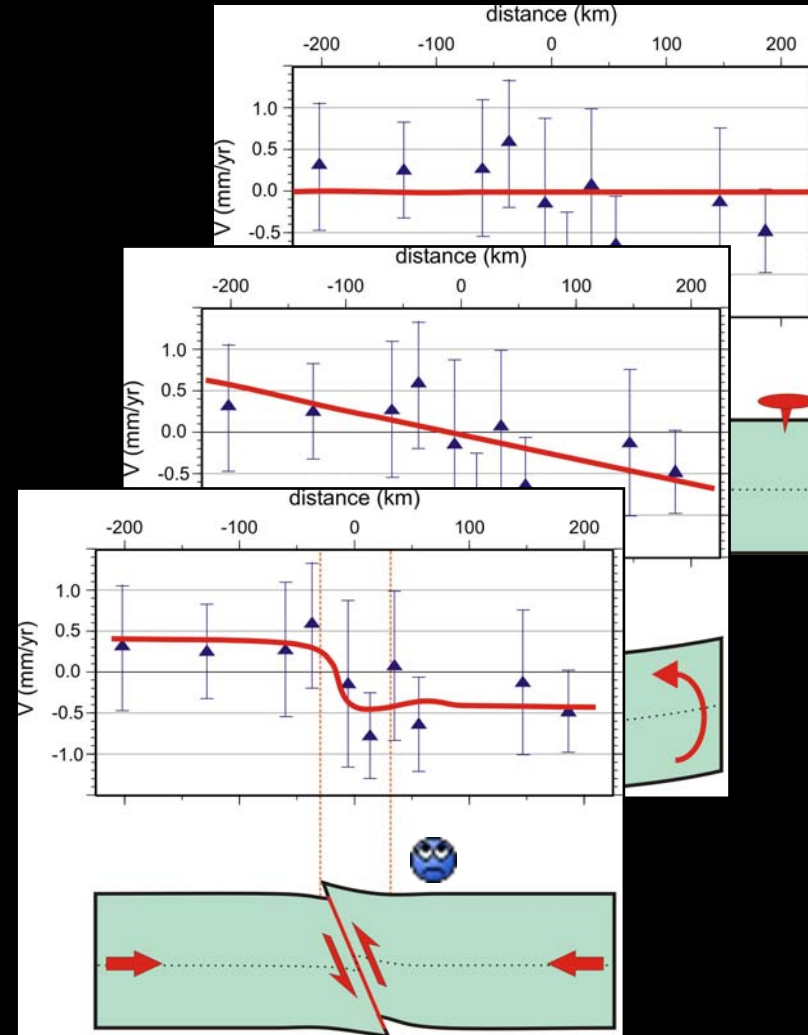
- No strain (no seismicity)
- Elastic GIA strain (no seismicity)



3) GPS, Seismicity & Long-Term Strain Rates

Within a resolution of ~ 1 mm/yr at 95%, we cannot discriminate between strain/earthquake models

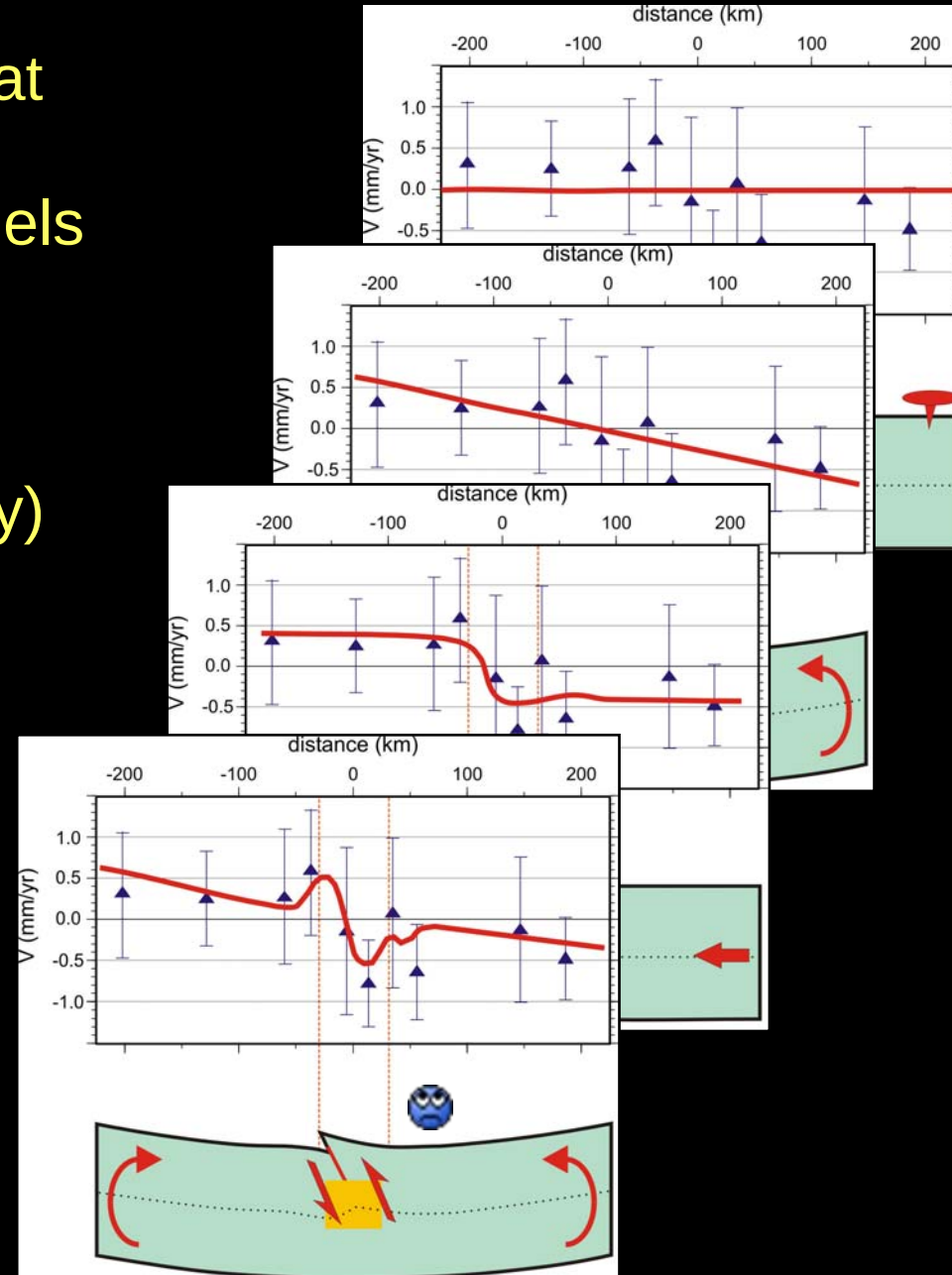
- No strain (no seismicity)
- Elastic GIA strain (no seismicity)
- “Plate-boundary type” strain loading of seismic faults from far-field (steady-state)



3) GPS, Seismicity & Long-Term Strain Rates

Within a resolution of ~ 1 mm/yr at 95%, we cannot discriminate between strain/earthquake models

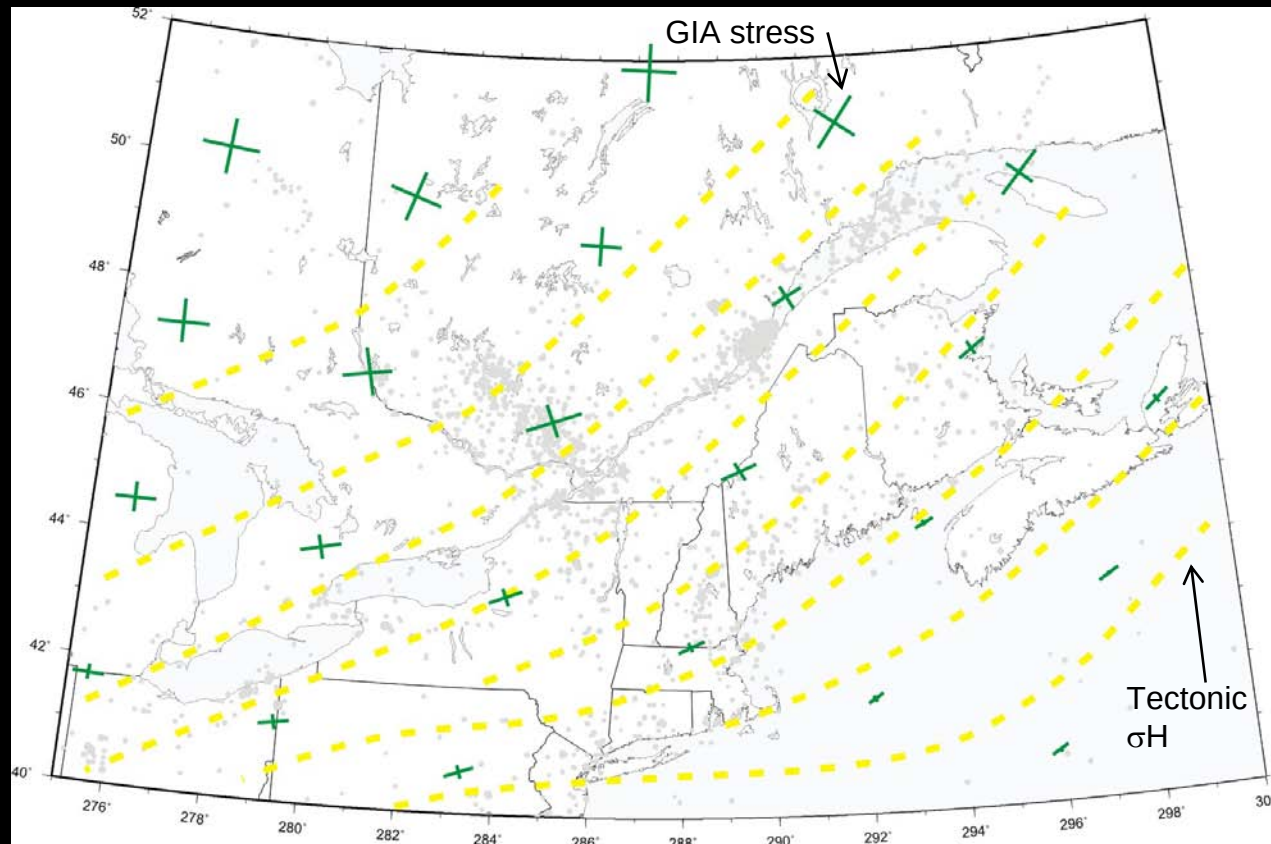
- No strain (no seismicity)
- Elastic GIA strain (no seismicity)
- “Plate-boundary type” strain loading of seismic faults from far-field (steady-state)
- Elastic GIA strain and loading of seismic fault from “local strain concentrators”



4) Potential Role of GIA Processes

Reference GIA model - 1D rheology

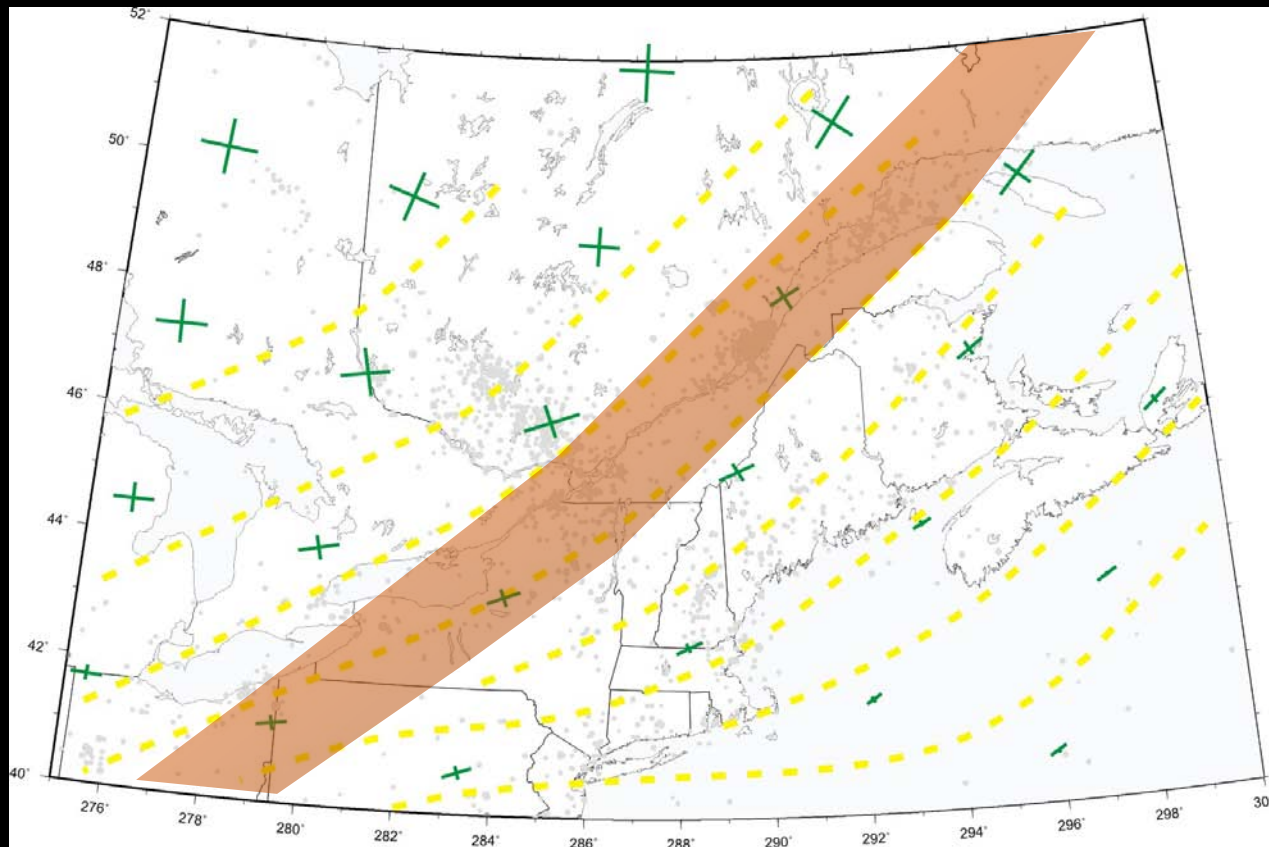
- High elastic strain rates (10^{-9} – 10^{-8} yr $^{-1}$)
- Small stress (few Mpa max.)
- σ_H sub-parallel to tectonic stress (NE-SW)



4) Potential Role of GIA Processes

Impact of “weak zone” on GIA stress & strain

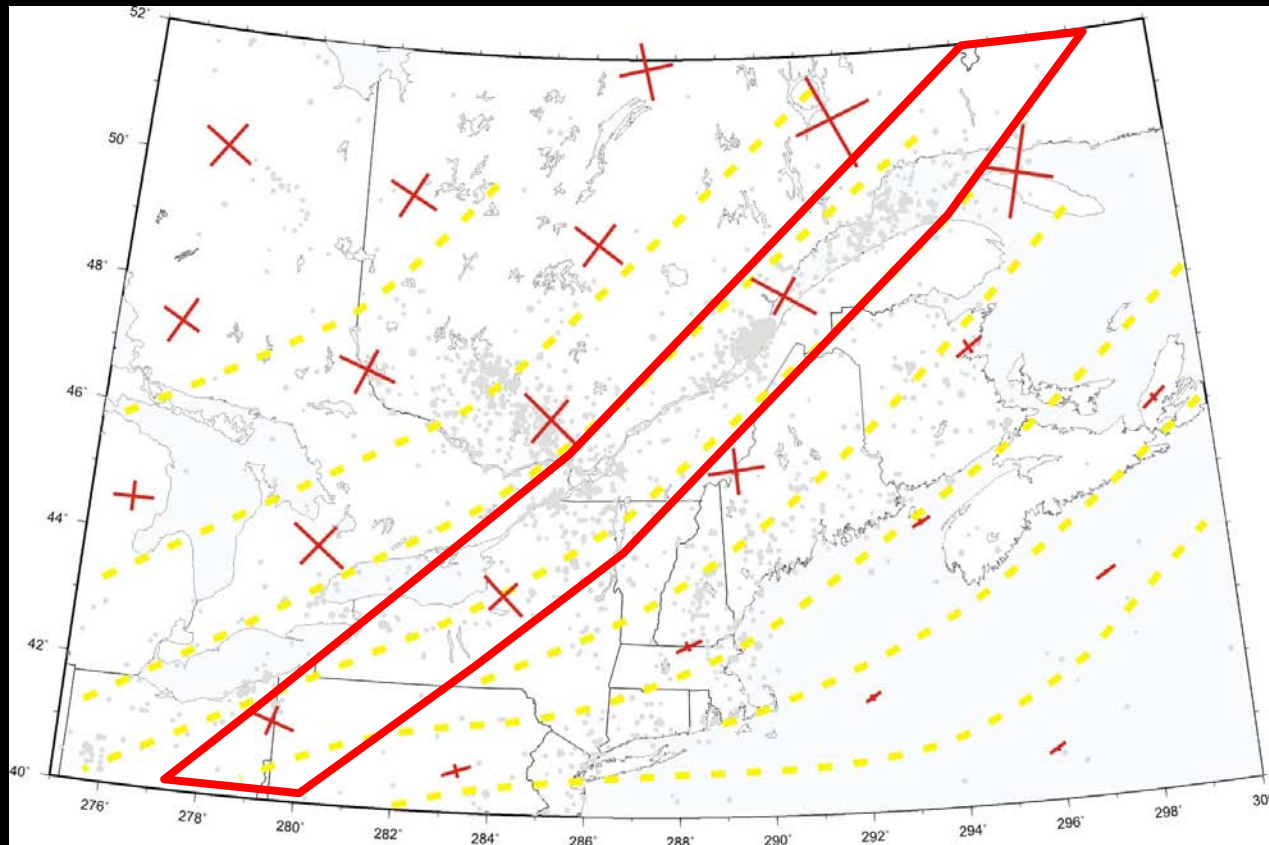
Introduction of low viscosity (10^{20} Pas) lower lithosphere (25-125 km) along the Iapetus Rift



4) Potential Role of GIA Processes

Impact of “weak zone” on GIA stress & strain

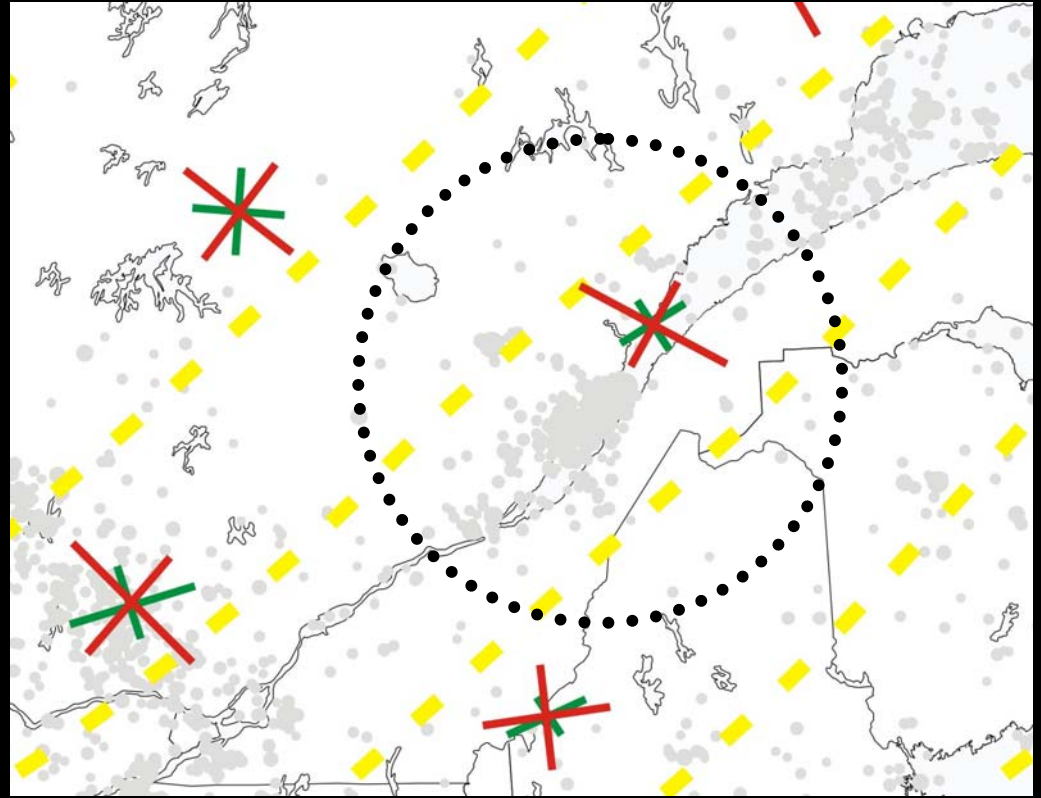
- Stress & strain concentration
- Rotation of σ_H ~50° ckw.



4) Potential Role of GIA Processes

Impact of “weak zone” on GIA stress & strain

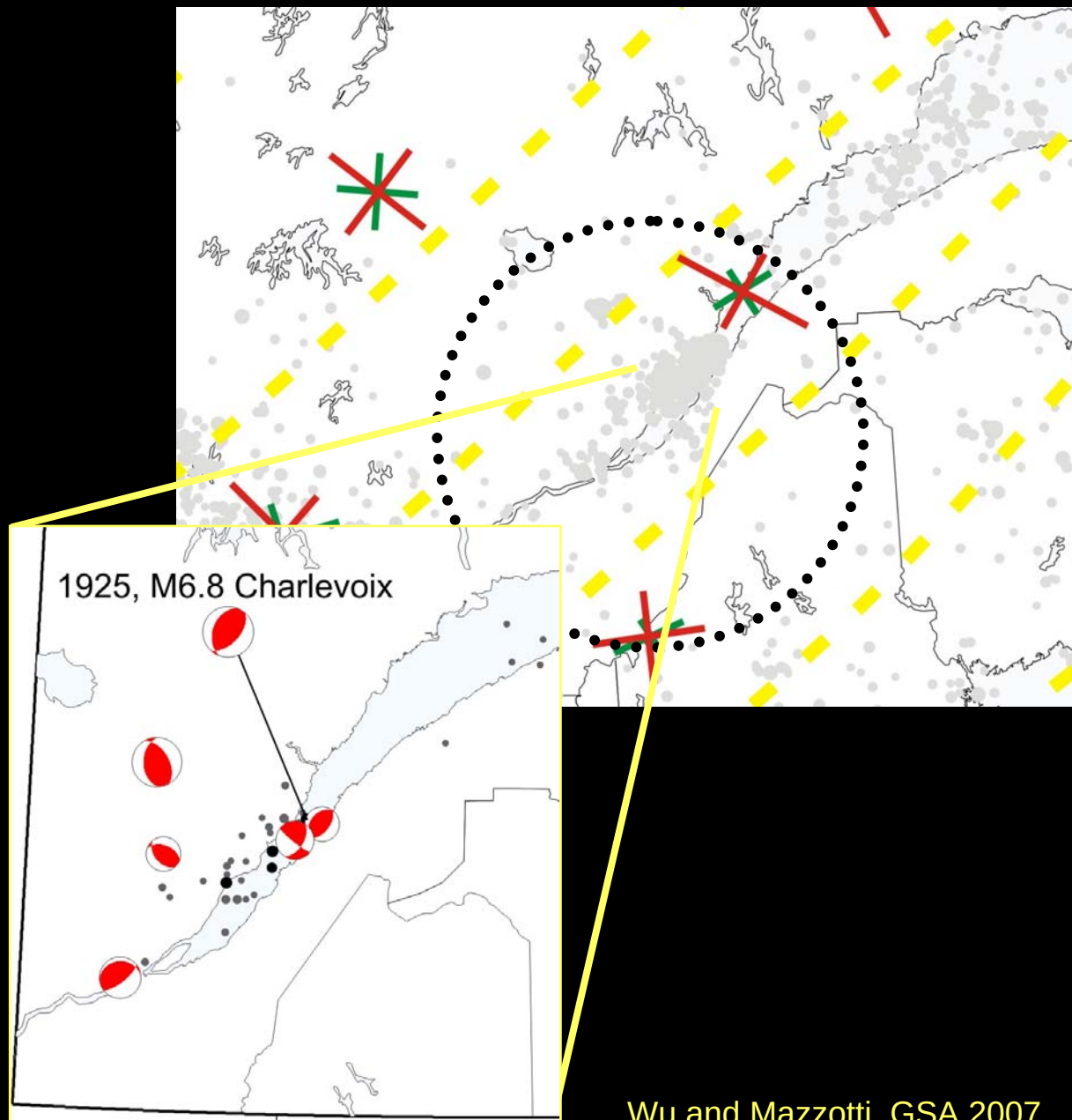
- Increase of stress magnitude by x 2-5
- Rotation of $\sigma_H \sim 50^\circ$ ckw., perpendicular to Iapetus Faults



4) Potential Role of GIA Processes

Impact of “weak zone” on GIA stress & strain

- Rotation of $\sigma_H \sim 50^\circ$ ckw., perpendicular to Iapetus Faults
- Compatible with NW-SE shortening from large earthquakes (1925 M=6.8 Charlevoix)

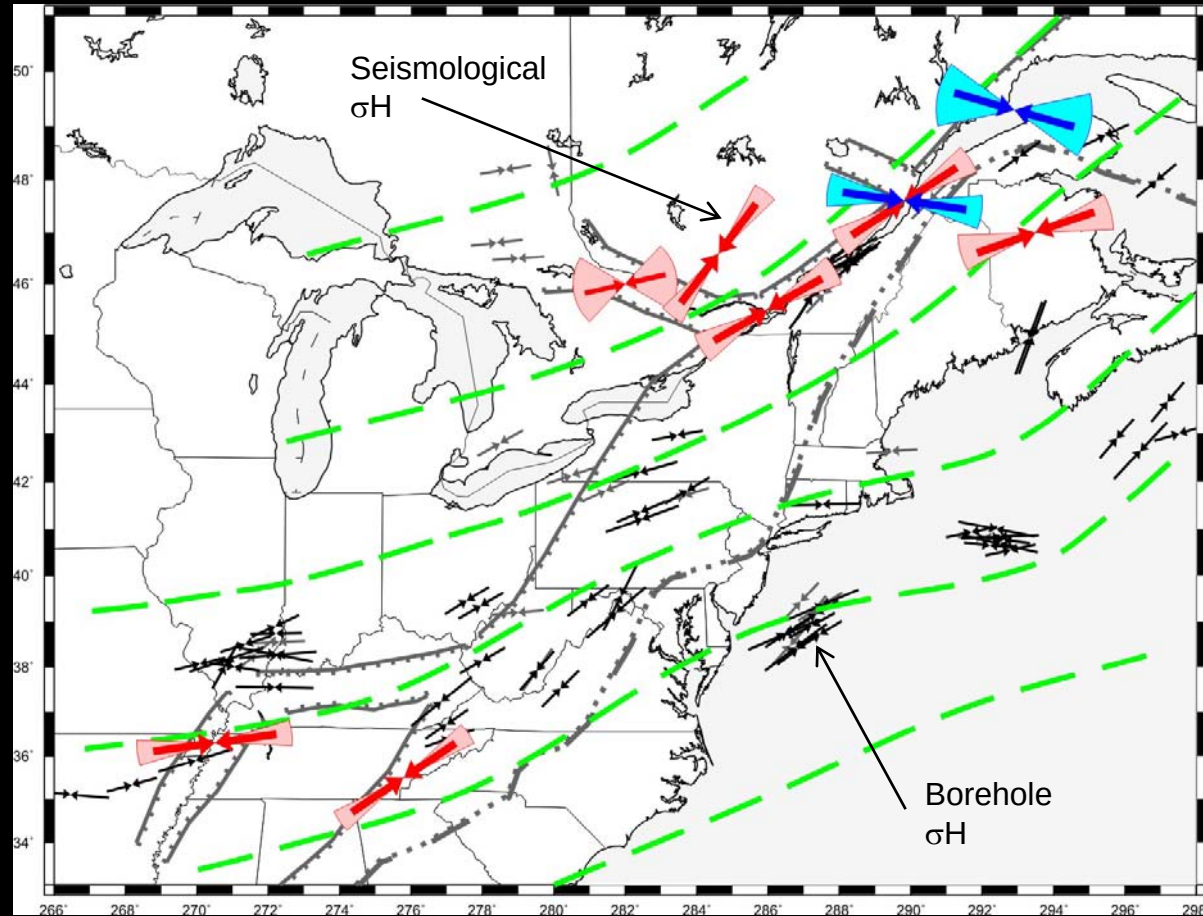


4) Potential Role of GIA Processes

Most seismic zones:
seismological σ_H sub-parallel to borehole σ_H

E. Charlevoix & Low.
St. Lawrence: 40-50°
ckw. rotation

Similar to “weak zone”
GIA model &
GPS strain rates



Points to significant role of GIA & local weak rheology
in seismicity in some seismic zones?

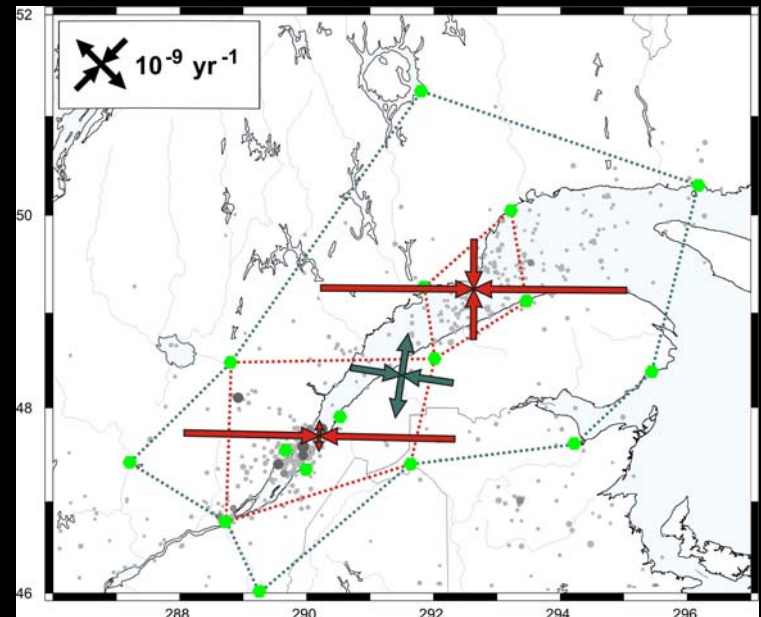
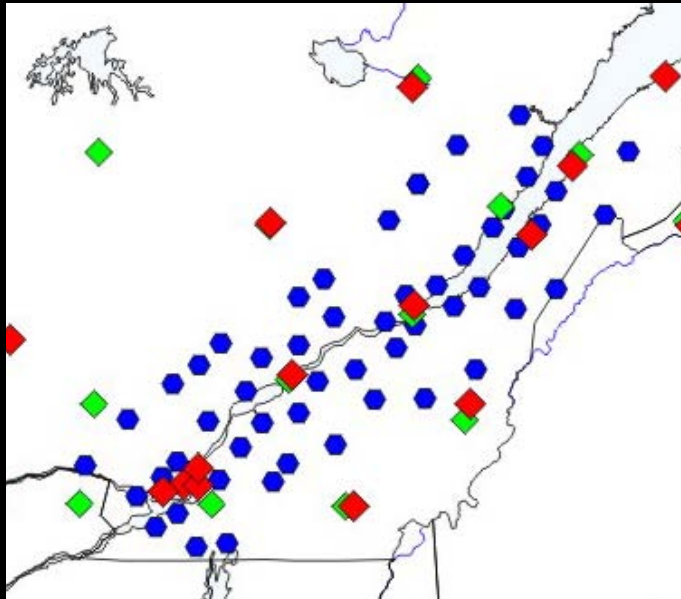
5) Issues and Limitations with GPS Constraints

Resolution of GPS measurements

- Seismic strain signal ($< 1 \text{ mm/yr}$) at the limit of GPS precision

AND

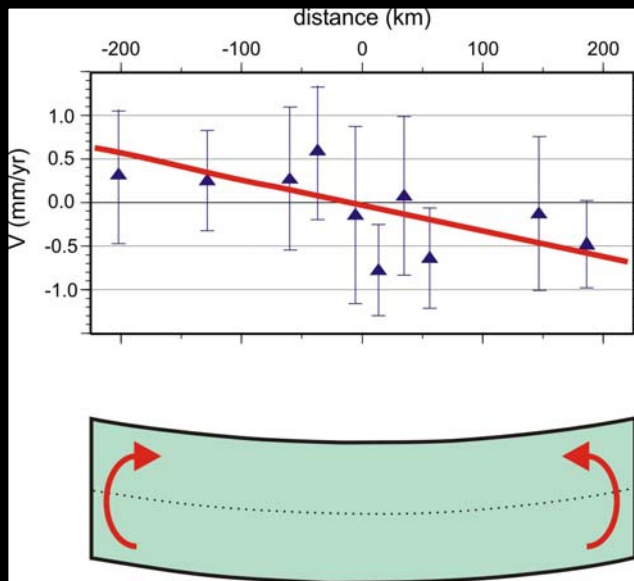
- High spatial resolution required to discriminate between models



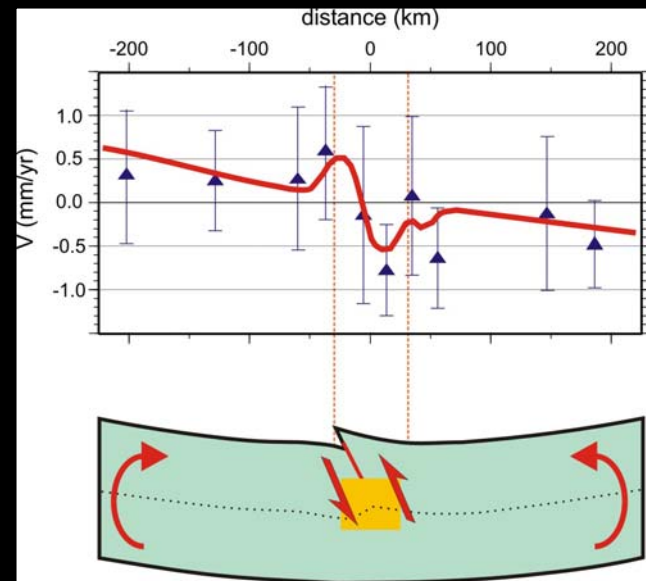
5) Issues and Limitations with GPS Constraints

Interpretation of GPS strain rates based on a geodynamic model

- Role of local weak zones in strain (& seismicity) concentration
- Percentage of elastic vs. plastic vs. seismic deformation



vs.



5) Issues and Limitations with GPS Constraints

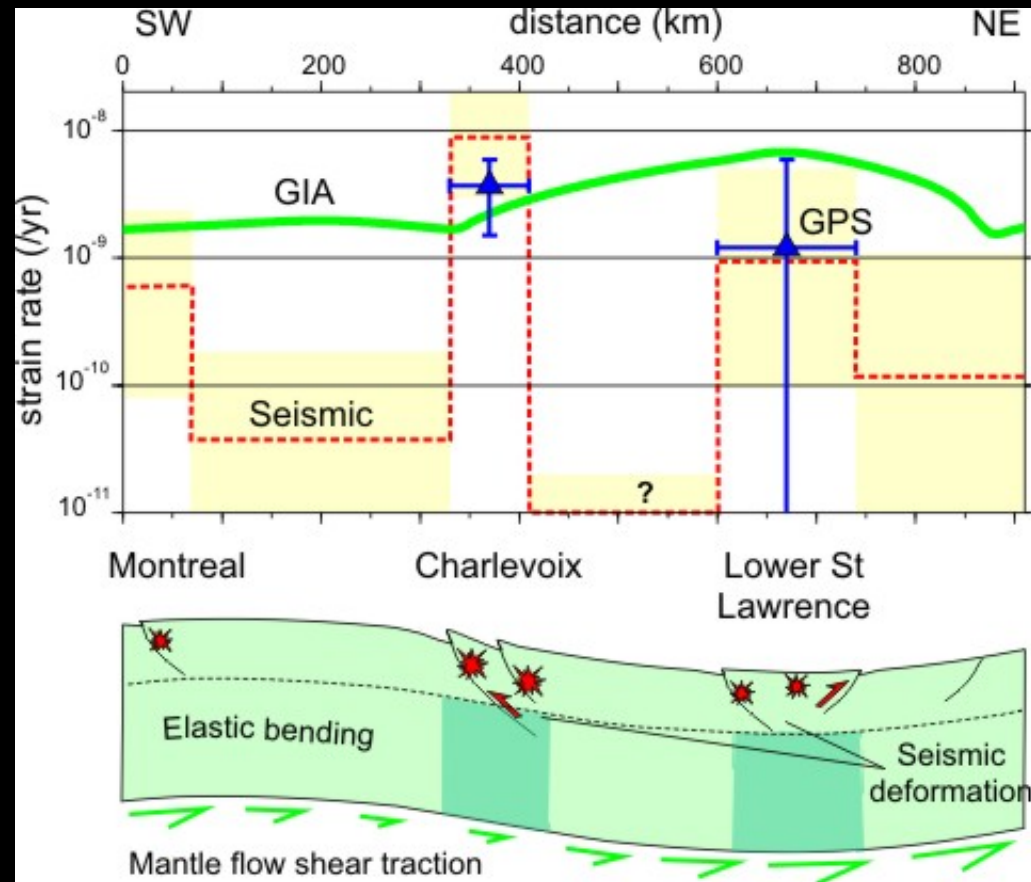
Interpretation of GPS strain rates based on a geodynamic model

E.g., St. Lawrence Valley strain model

- High GIA elastic strain
- Converted to seismic strain in “weak” zones

Is it steady-state (local weak zones) ?

Is there migration over 1000-10,000 year timescale (regional weak zones) ?



Strain and stress constraints on seismicity in the St. Lawrence Valley

- GPS strain rates & seismicity are in good agreement in Charlevoix (and Lower St. Lawrence) seismic zone
- Suggestion of higher GPS strain rates in high seismic zones

However, GPS data cannot yet resolve whether 100-300 years of seismicity represent earthquake hazard over the next 500-5000 years (steady-state vs. migration models)

GPS strain rates should be used in conjunction with rheology, structure and historical seismicity to define seismic source zones (and rates) once a robust integrative geodynamic model is developed

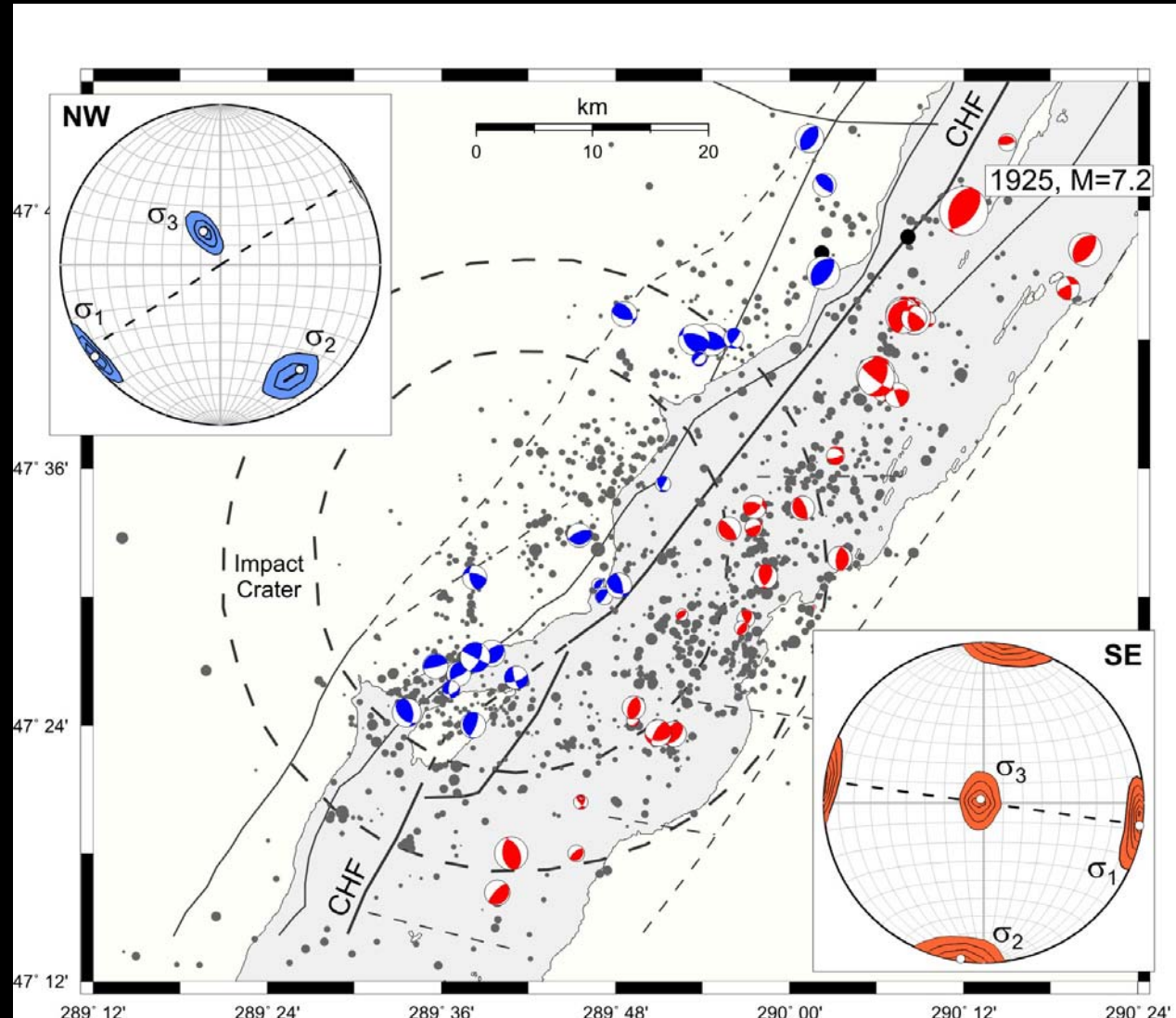
Charlevoix Seismic Zone

NW cluster:

Seismological σ_H
parallel to
borehole σ_H

SE cluster:

Seismological σ_H
rotated $\sim 45^\circ$ ckw.



Mmax for Eastern North America: An Examination of the 1663 Charlevoix Earthquake

Prof. John E. Ebel

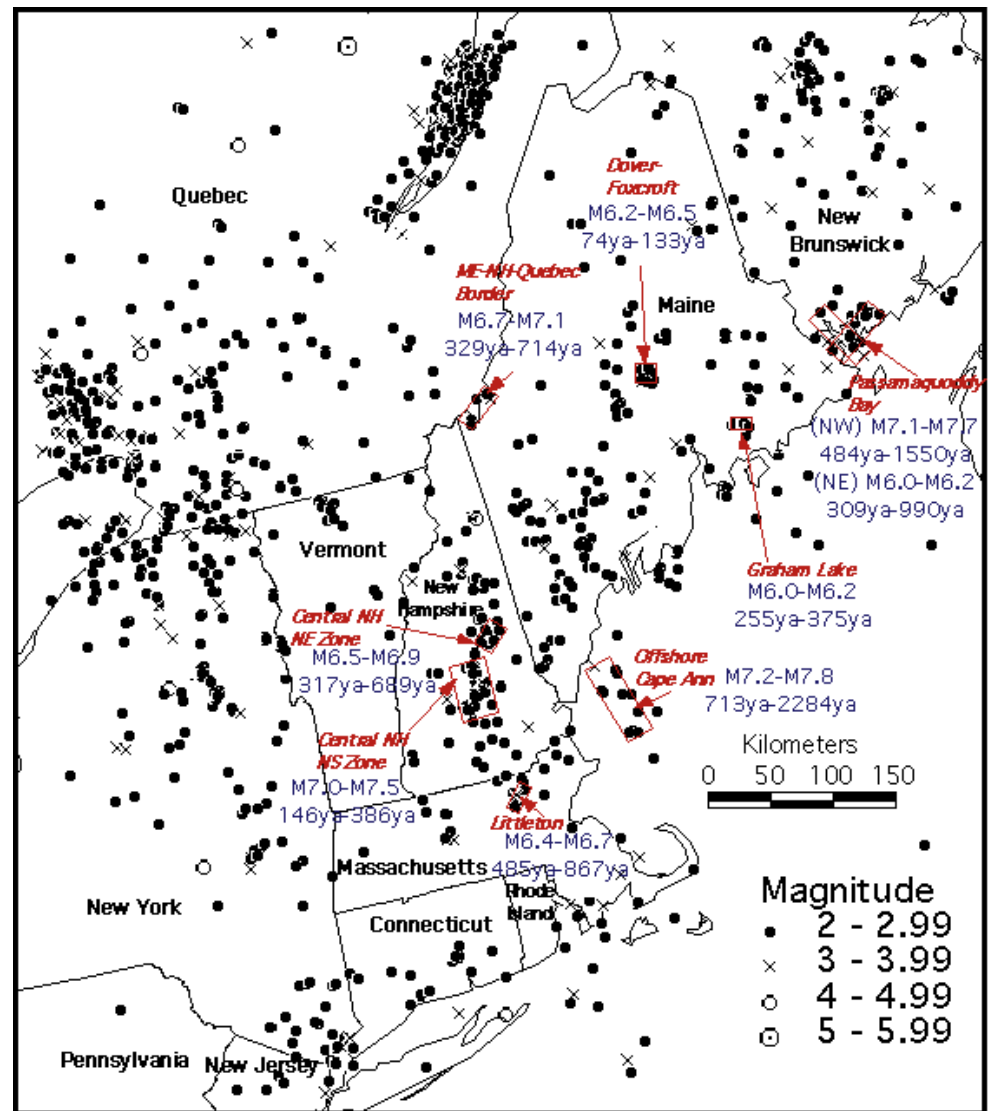
Director, Weston Observatory of Boston College

Department of Geology and Geophysics, Boston
College

“There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact.”

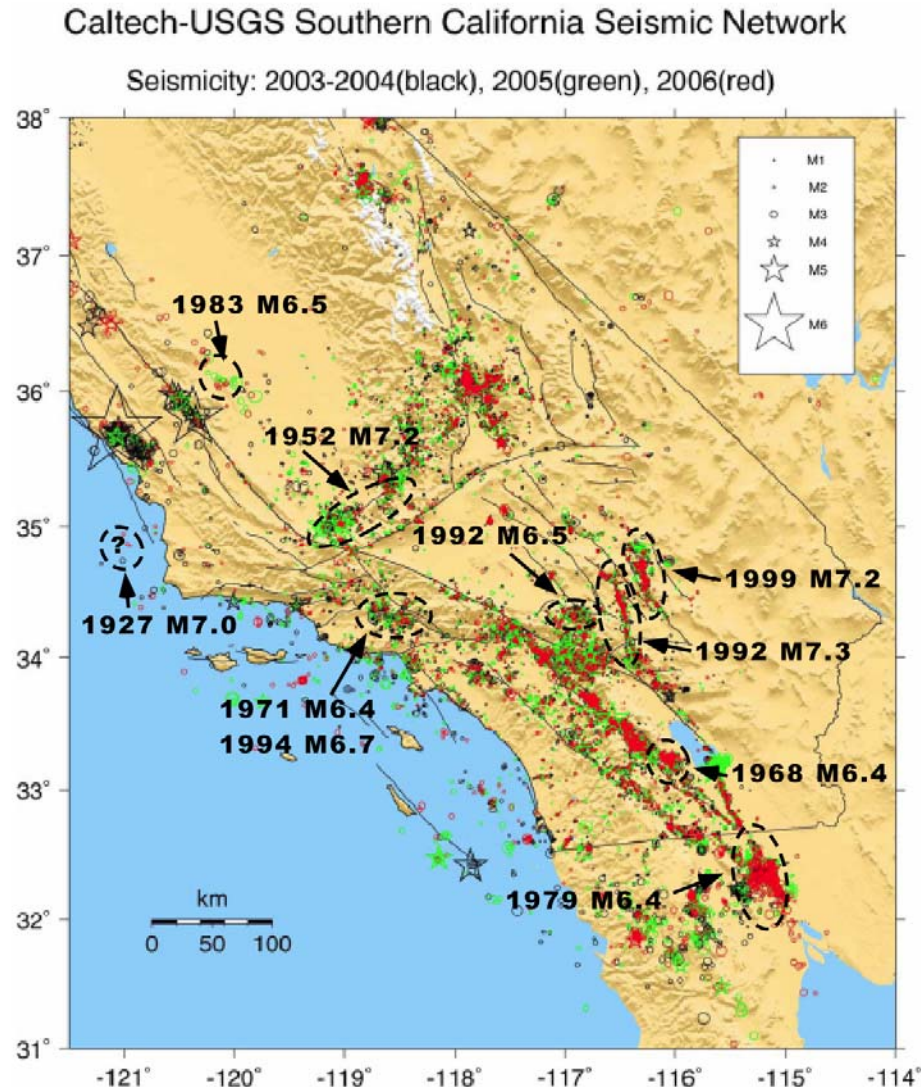
Mark Twain

Many of the small earthquakes in our region may be very late aftershocks of strong earthquakes that took place hundreds or thousands of years ago. Under this “paleoseismicity” hypothesis, the spatial extents and activity rates of clusters of earthquakes can be used to estimate the magnitudes and times before present of past strong earthquakes (from *Ebel, Bonjer and Oncescu, Seism. Res. Lett., 2000*). Documenting persistent earthquake clusters throughout the historic record may help identify the locations of past strong earthquakes.



The Charlevoix seismic zone is between 560 km and 640 km from Boston.

How Long Do Aftershocks Last?



In California, aftershock zones can be active for decades after a main shock.

Estimating the Magnitude of the 1663 Earthquake at Charlevoix, Quebec

- Magnitude from the MMI at Boston, MA
- Magnitude from comparisons with the isoseismal maps of the 1811-1812 New Madrid earthquakes
- Magnitude from the length of the “aftershock” zone
- Magnitude from the observation of chimney damage at Roxbury, MA

The 1663 Earthquake at Charlevoix, Quebec

This earthquake was felt strongly in Canada, and caused major ground deformations (landslides, sandblows, etc.) in what is today the Charlevoix seismic zone. Aftershocks were reported for many months after the mainshock.

Felt Effects at Roxbury and Boston, MA

Felt Report at Boston of the 1663 Earthquake

This earthquake caused some minor chimney damage in Boston at a distance of about 600 km. Several aftershocks were also felt in Boston. Rev. Danforth in Roxbury, Massachusetts wrote:

"1662 Jan. 26 (O.S.) about 6 o'clock at night there happened an earthquake, wch shook mens houses and caused many to run out of their houses into the streets, and ye tops of 2 or 3 chimnyes fell off, or some part ym." (Danforth, 1880).

This appears to be MMI V to VII shaking (See *Ebel, Seism. Res. Lett., 1996*). Sue Hough would probably rate this report MMI VI to VII.

Possible Damage Report at Boston Due to the 1663 Earthquake

The “Ship Tavern” at Ship (North) and Clark Streets in Boston, was originally built as a private residence. It was torn down about 1867. A description in *Rambles in Old Boston* by Edward G. Porter (1887) reads:

“It was originally two stories high, and built of English brick, laid with shell and clay mortar. There was an old crack in the front wall, said to have been caused by an earthquake in 1663, “which made all New England tremble.””

This appears to be MMI V to VII shaking. Sue Hough would probably rate this report MMI V to VI.

Estimating the Magnitude of the 1663 Earthquake at Charlevoix, Quebec

- Magnitude from the MMI at Boston, MA
- Magnitude from comparisons with the isoseismal maps of the 1811-1812 New Madrid earthquakes
- Magnitude from the length of the “aftershock” zone
- Magnitude from the observation of chimney damage at Roxbury, MA

Magnitude Estimate of the 1663 Earthquake due to the MMI Value at Boston

Assuming an epicentral distance of 560 km:

	MMI V at Boston	MMI VI at Boston	MMI VI.5 at Boston
Klimkiewicz and Pulli (1983)	7.0 (mb)	7.5 (mb)	7.8 (mb)
Bakun et al. (2003)	6.7 (Mw)	7.3 (Mw)	7.6 (Mw)

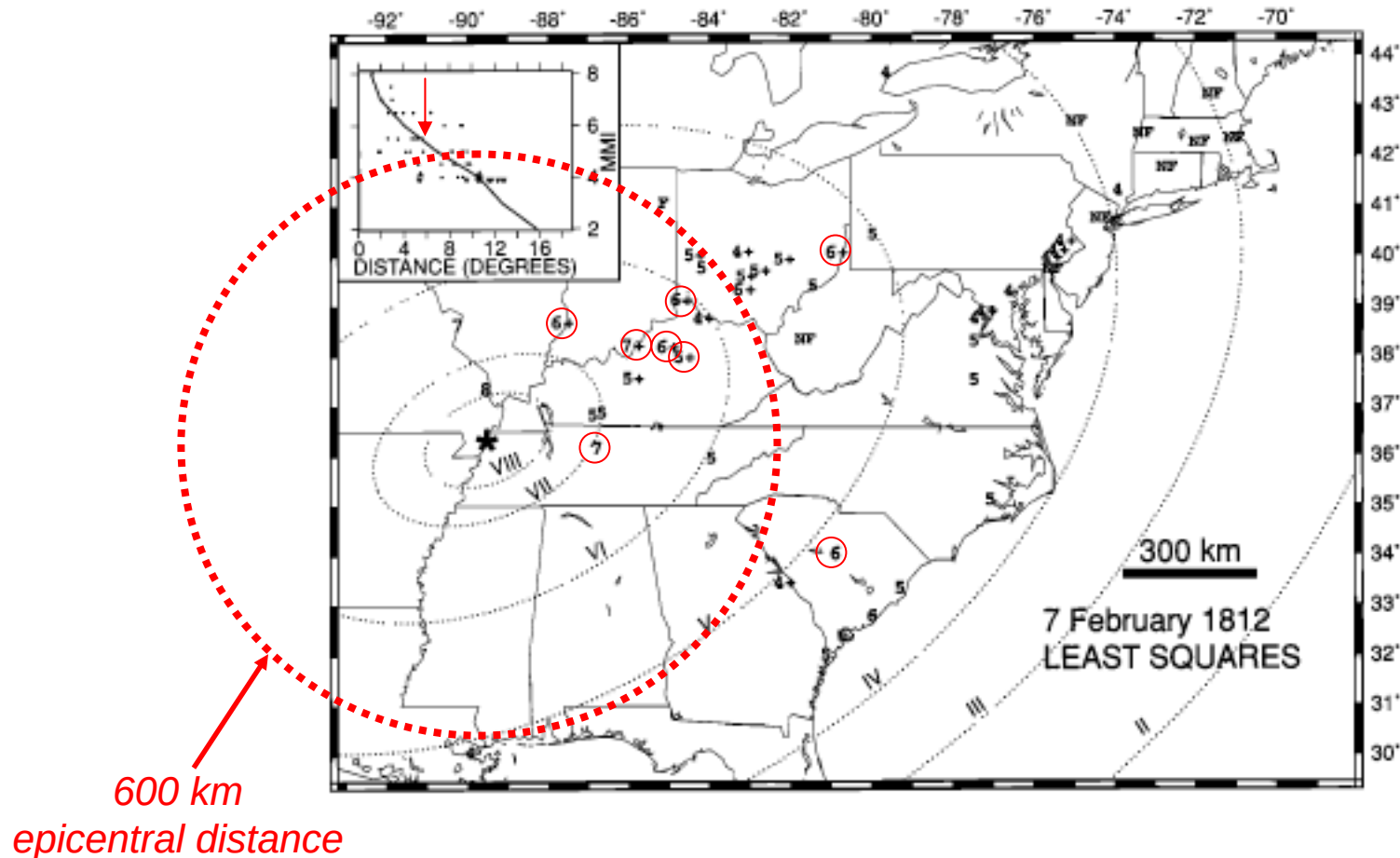
Assuming an epicentral distance of 600 km:

	MMI V at Boston	MMI VI at Boston	MMI VI.5 at Boston
Klimkiewicz and Pulli (1983)	7.0 (mb)	7.5 (mb)	7.9 (mb)
Bakun et al. (2003)	6.8 (Mw)	7.3 (Mw)	7.7 (Mw)

Estimating the Magnitude of the 1663 Earthquake at Charlevoix, Quebec

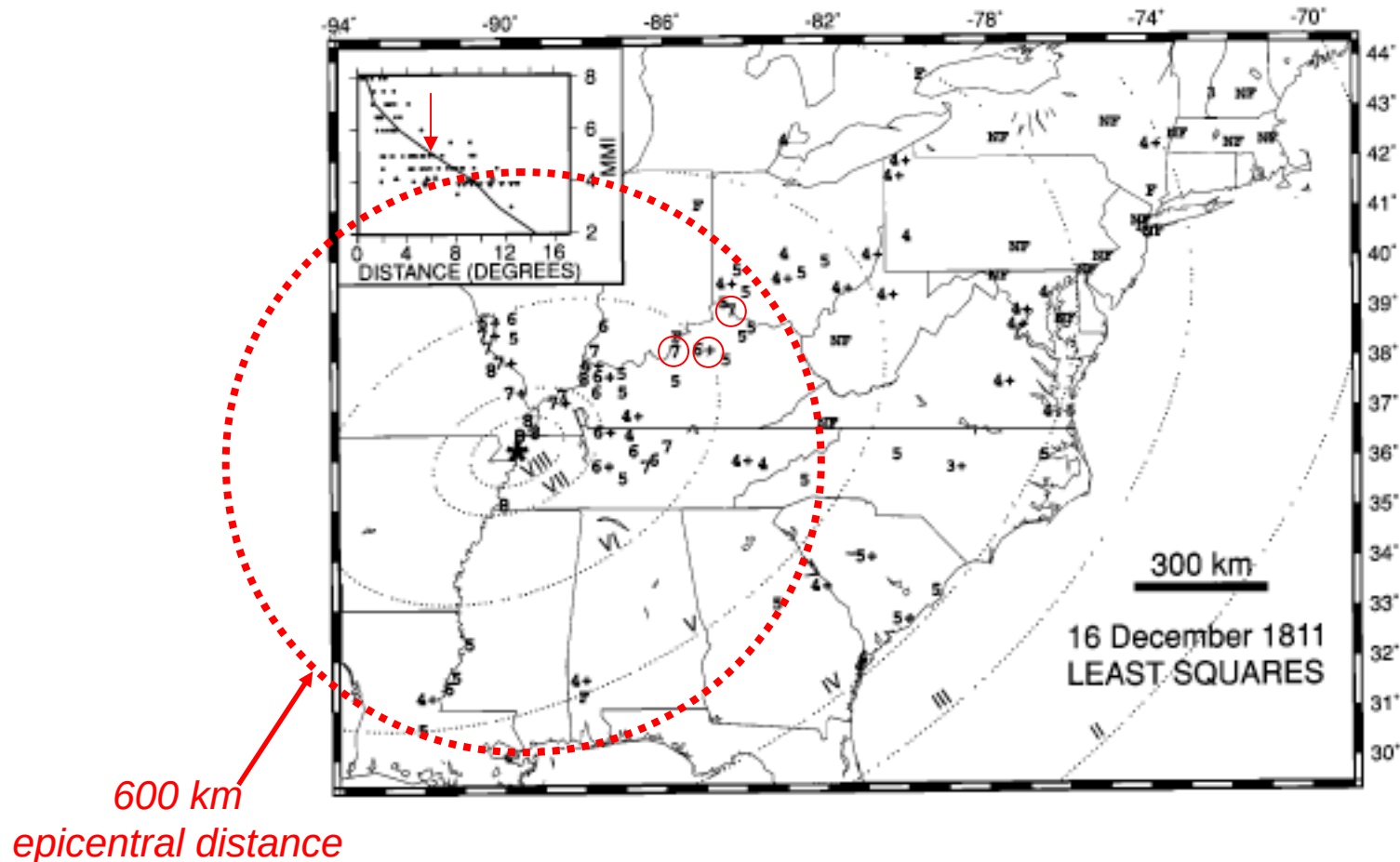
- Magnitude from the MMI at Boston, MA
- Magnitude from comparisons with the isoseismal maps of the 1811-1812 New Madrid earthquakes
- Magnitude from the length of the “aftershock” zone
- Magnitude from the observation of chimney damage at Roxbury, MA

Comparison of the Mw 7.5 February 7, 1812 Iseismal Map with the 1663 Damage Report at Boston (MMI VI at 600 km)



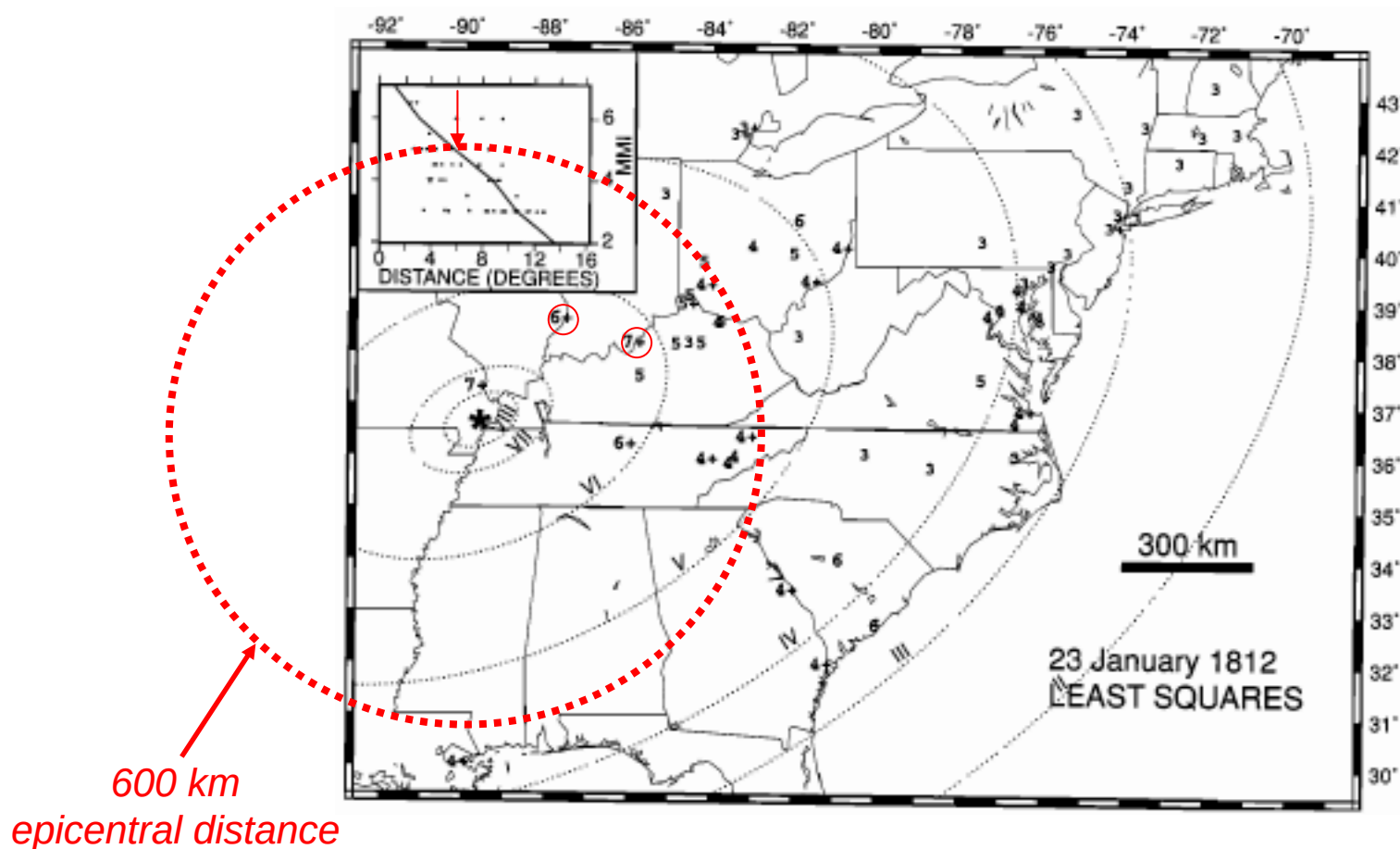
Locations with chimney damage are circled in red.

Comparison of the Mw 7.3 December 16, 1811 Iseismal Map with the 1663 Damage Report at Boston (MMI VI at 600 km)



Locations with chimney damage are circled in red.

Comparison of the Mw 7.0 January 23, 1812 Iseismal Map with the 1663 Damage Report at Boston (MMI VI at 600 km)

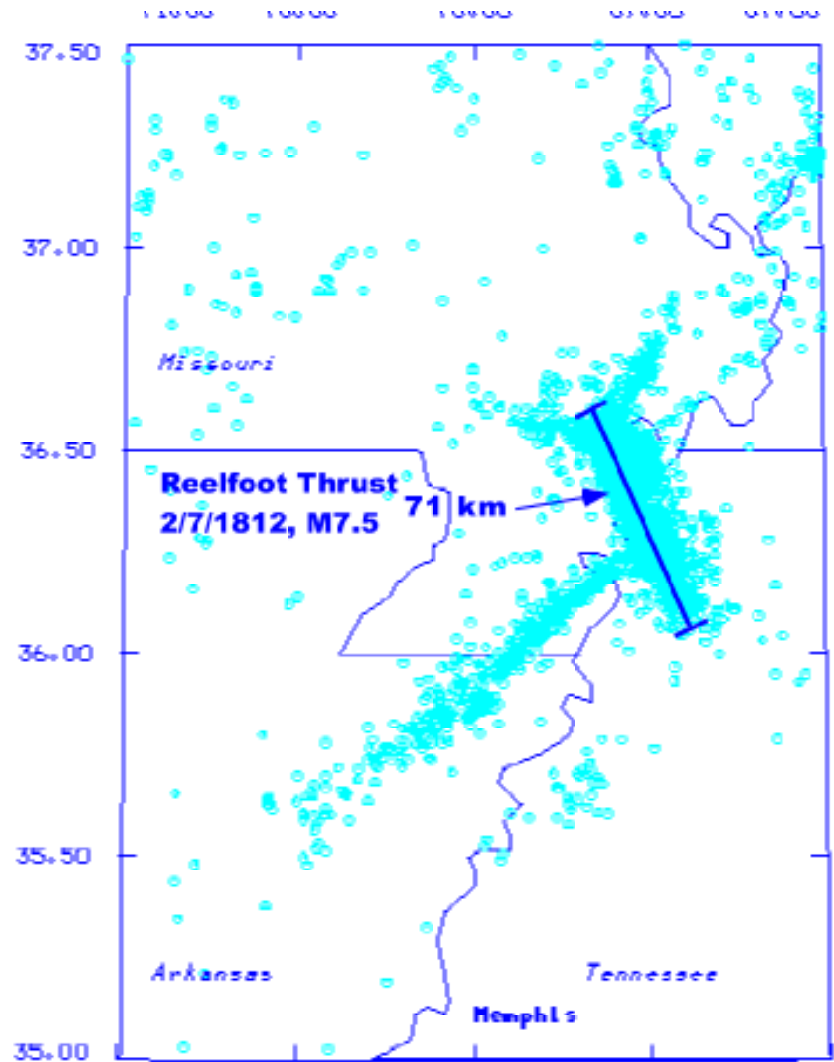
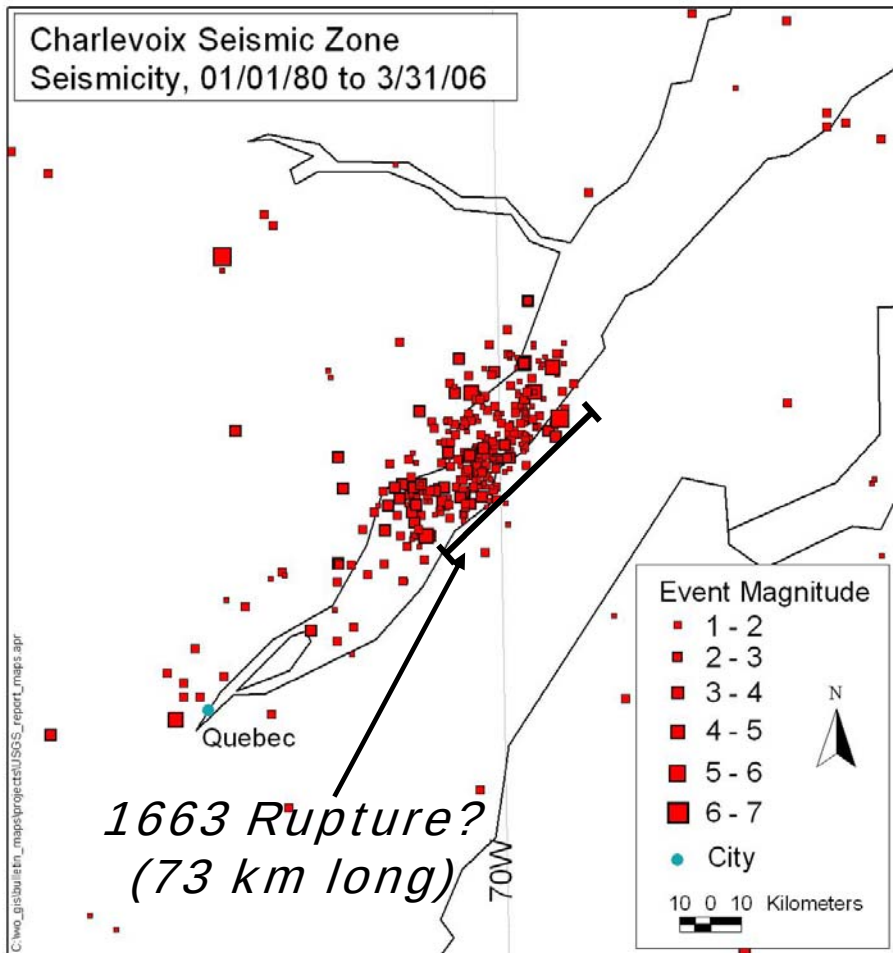


Locations with chimney damage are circled in red.

Estimating the Magnitude of the 1663 Earthquake at Charlevoix, Quebec

- Magnitude from the MMI at Boston, MA
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- Magnitude from the length of the “aftershock” zone
- Magnitude from the observation of chimney damage at Roxbury, MA

1663 Charlevoix vs. 1812 New Madrid



Both were probably reverse faulting earthquakes.

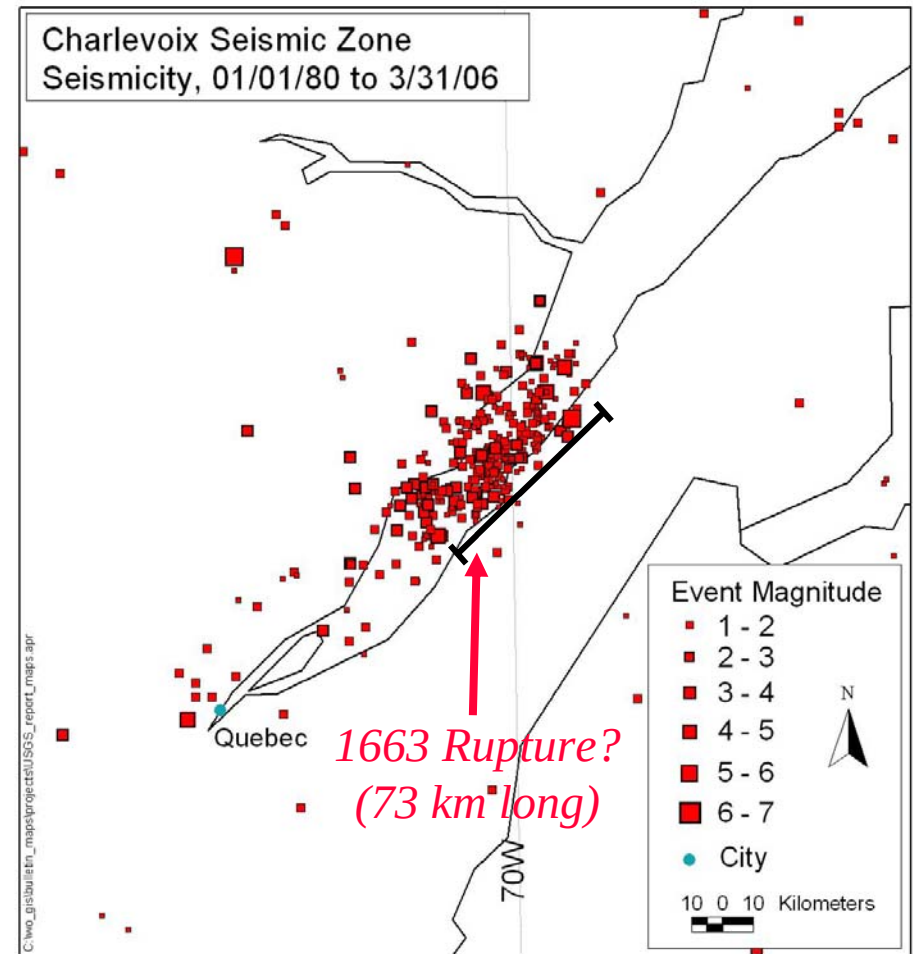
The 1663 Earthquake at Charlevoix, Quebec

If the modern seismicity at Charlevoix is aftershocks of the 1663 event, then its rupture length must have been about 70 km. Using Wells and Coppersmith (1994), a fault length of 73 km, and a fault width of 25 km, the moment magnitude (M_w) estimates are:

(from surf. rup. len.) = 7.3

(from subsurf. rup. len.) = 7.3

(from rup. area) = 7.3



Estimating the Magnitude of the 1663 Earthquake at Charlevoix, Quebec

- Magnitude from the MMI at Boston, MA
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- Magnitude from the observation of chimney damage at Roxbury, MA

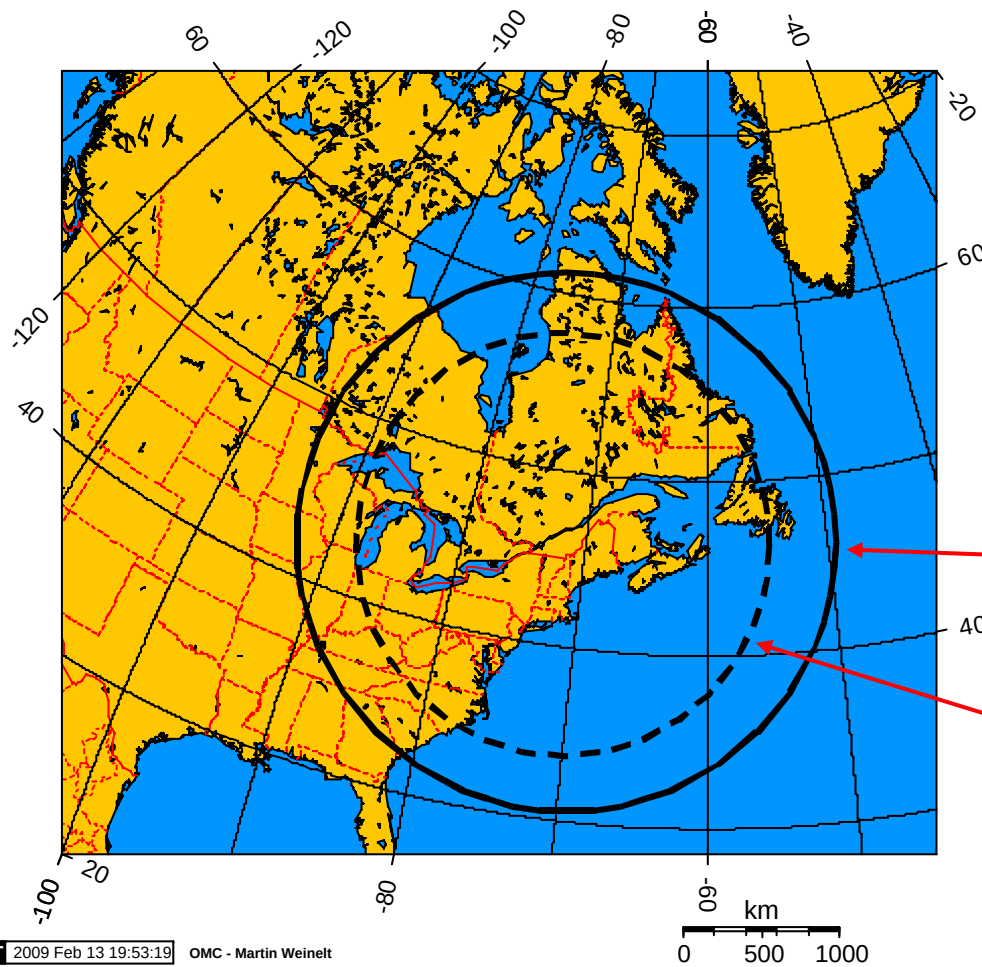
Estimated 1663 Ground Motions at Roxbury, Massachusetts Based on Chimney Damage

	SA at 0.3 sec (g)		
	Soil Site Conditions		
<i>Magnitude (Mw)</i>	7	7.3	7.6
Atkinson and Boore (2006)	0.020	0.026	0.033
Campbell (2003)	0.008	0.011	0.015
Somerville et al. (2001) Rift	0.006	0.011	0.019
Tavakoli and Pezeshk (2005)	0.019	0.027	0.037
<i>Threshold for Chimney Damage = .03g</i>			
	pga (g)		
	Soil Site Conditions		
<i>Magnitude (Mw)</i>	7	7.3	7.6
Atkinson and Boore (2006)	0.008	0.011	0.015
Campbell (2003)	0.008	0.011	0.014
Somerville et al. (2001) Rift	0.006	0.009	0.014
Tavakoli and Pezeshk (2005)	0.010	0.014	0.019
<i>Threshold for Chimney Damage = .01g</i>			

The chimney damage at Roxbury in 1663 suggests that this earthquake was ~ M 7.0-7.6. $SA_{0.3}$ favors the larger values of this range.

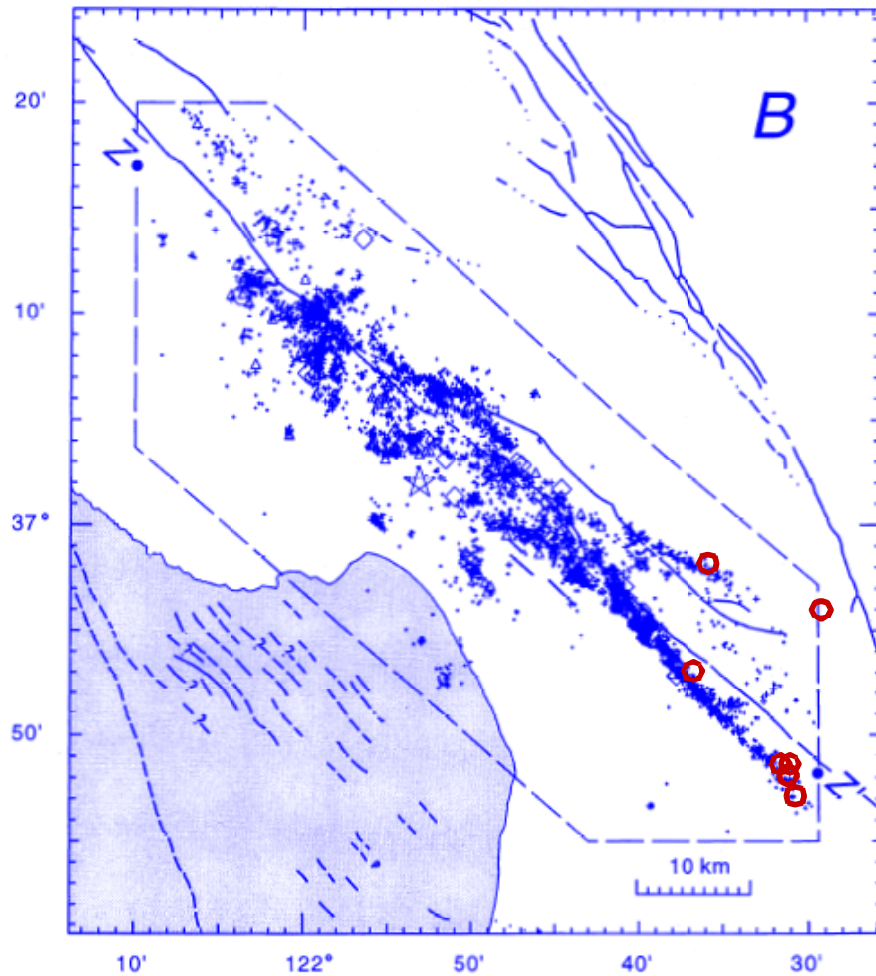
Conclusion: Estimated Magnitude of the 1663 Earthquake

The best estimate of the magnitude of the 1663 Charlevoix earthquake from this study is $M_w \sim 7.3-7.5$.



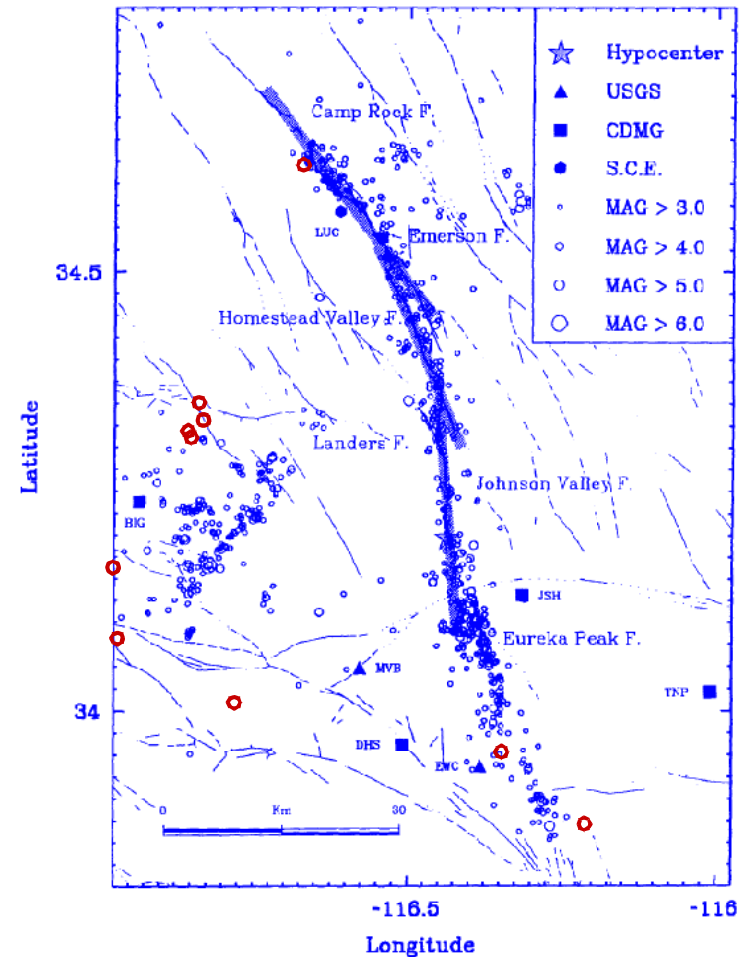
Speculation on Large Events at the Ends of the Aftershock Zones of Large Ruptures

1989 Loma Prieta Aftershocks



Red circles: $M \geq 4$ events 2001-2008

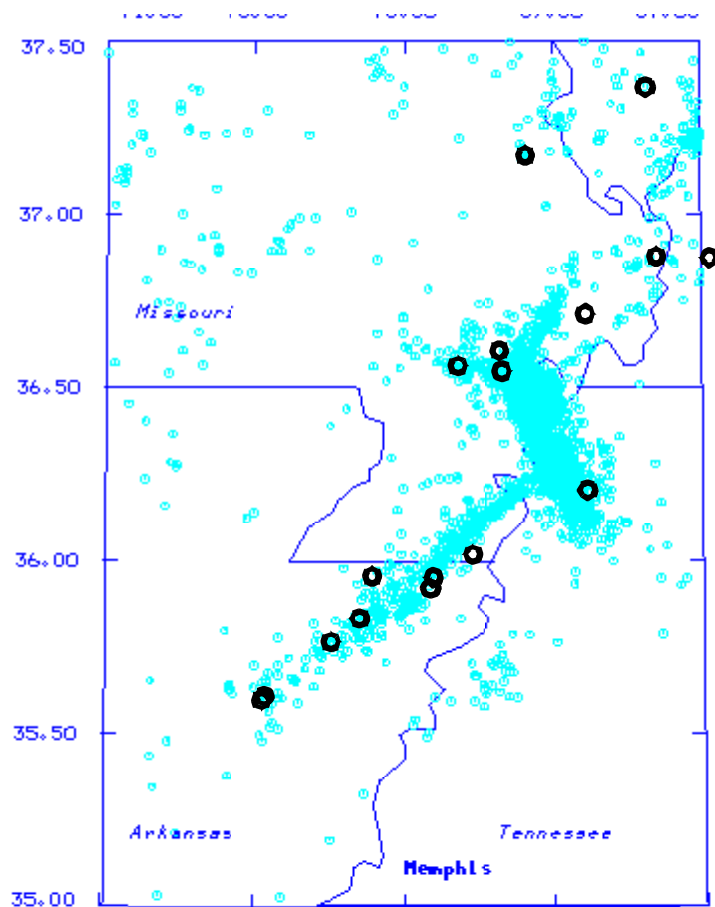
1992 Landers Aftershocks



Red circles: $M \geq 4$ events 2003-2008

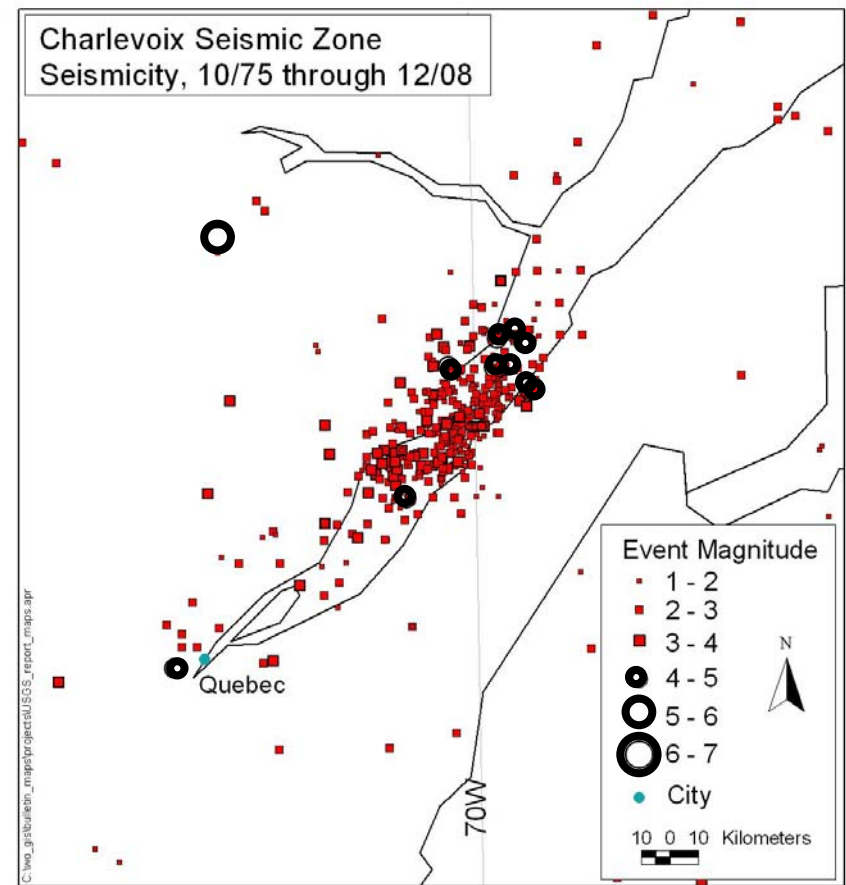
Speculation: Late, larger “aftershocks” concentrate at the edges of an earlier earthquake rupture due to stress concentration at the crack tip. These larger, late “aftershocks” can help delineate where past ruptures took place.

New Madrid Seismic Zone



Black circles: $M \geq 4$ events 1960-2008

Charlevoix Seismic Zone

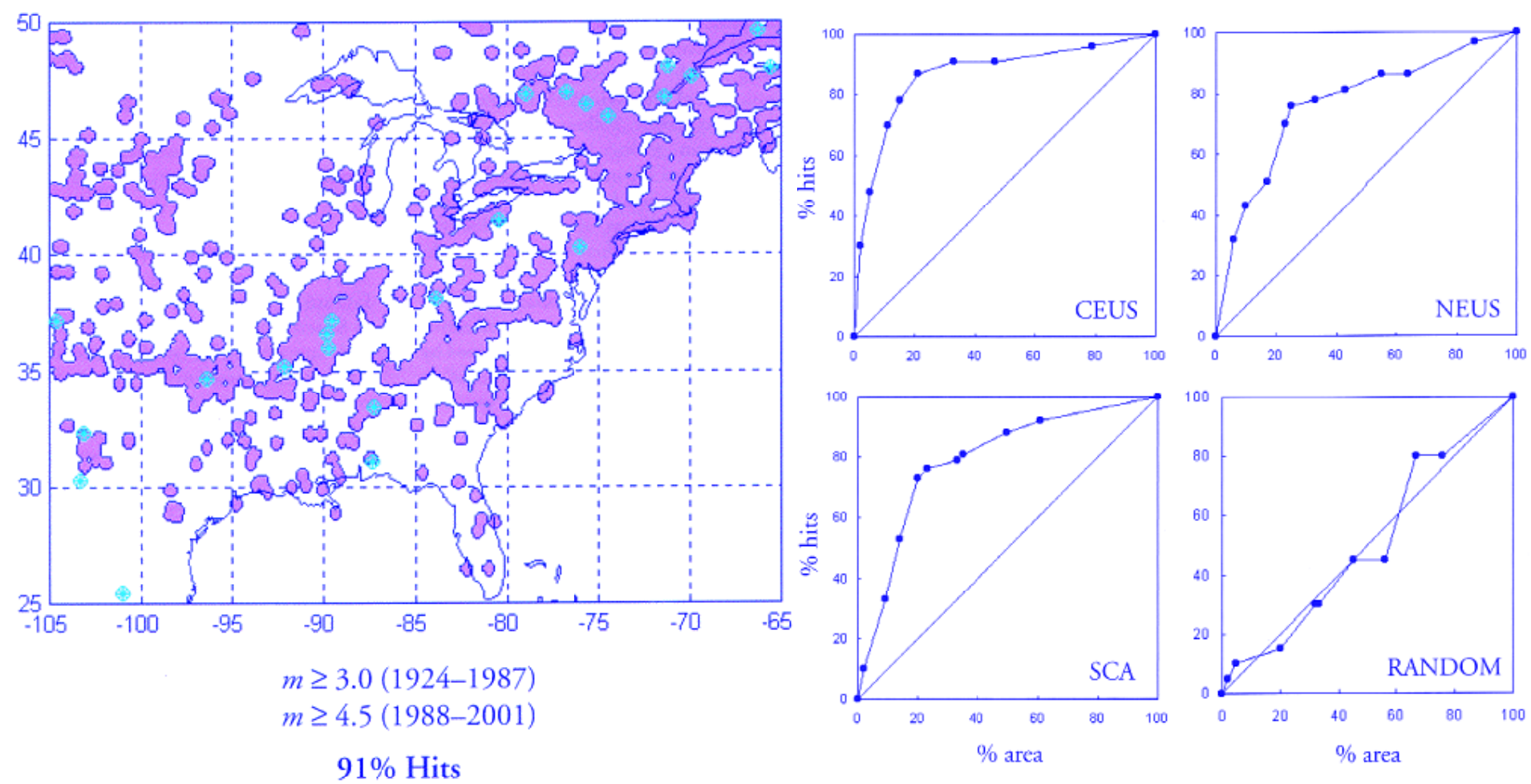


Black circles: $M \geq 4$ events 1975-2008

Speculation: Perhaps the larger events in these two seismic zones show the ends of the ruptures associated with the 1811-1812 and 1663 earthquakes.

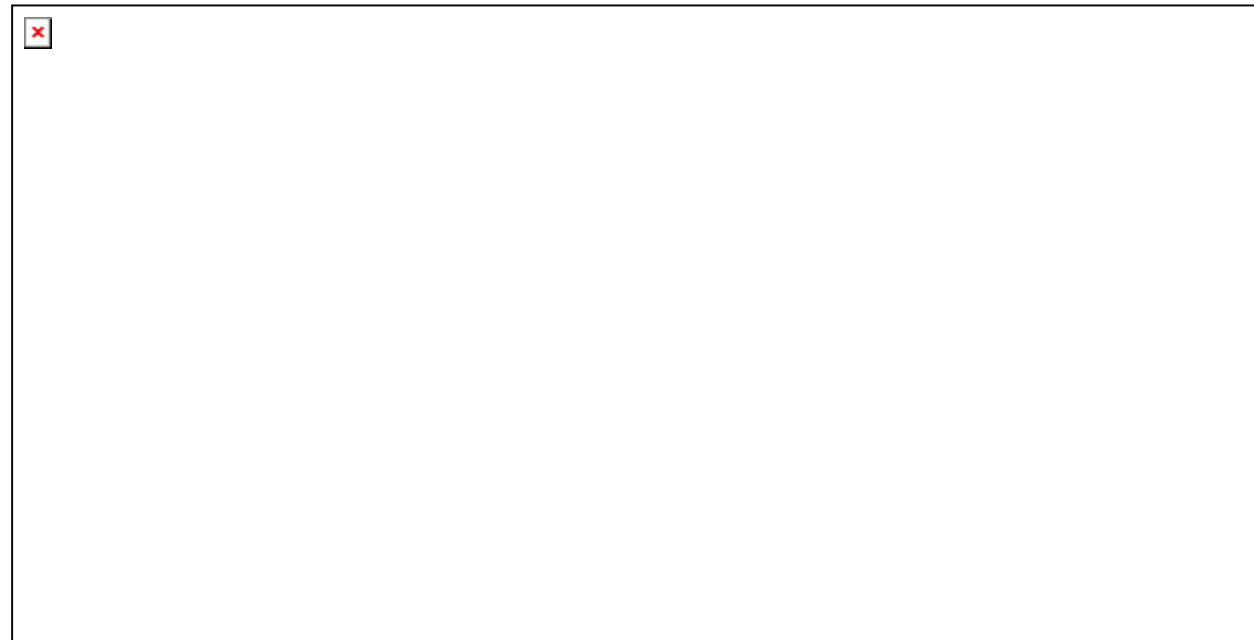
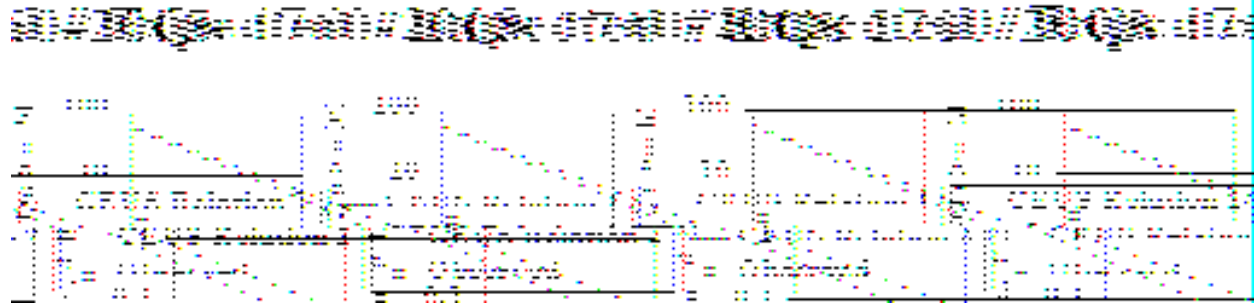
Speculation on How Many Intraplate Earthquakes May Be Aftershocks of Past Large Earthquakes

From Alan Kafka's "cellular seismology" work, most recent earthquakes occur near locations where past earthquakes were located. If this is indicative of repetitive aftershock activity, then most earthquakes in eastern North America may be aftershocks of past strong earthquakes.



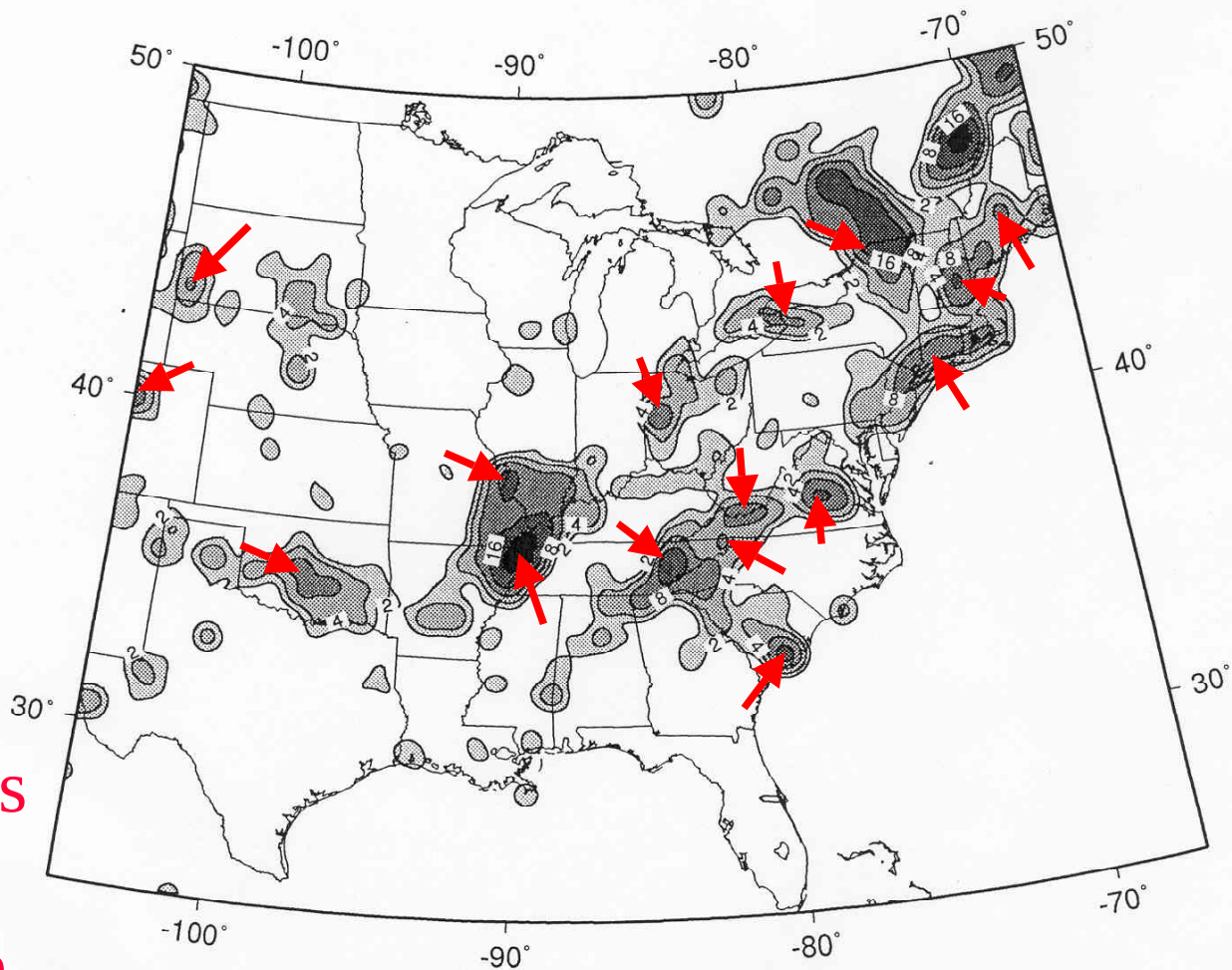
Speculation on the Rates of $M \geq 7$ Earthquakes in the CEUS

For the CEUS and for ENA, the observed rate of $M > \sim 7$ earthquakes is greater than expected from extrapolations of the Gutenberg-Richter curves from the smaller earthquake activity in these regions (*Nishenko and Bollinger, Science, 1990*).



CEUS - Central and Eastern U.S.
ENA - Eastern North America

Building on the paleoseismicity idea that localized clusters of earthquakes in the CEUS delimit aftershock zones of past strong earthquakes, we can take the smaller earthquake activity and postulate locations where $M > \sim 7$ earthquakes may have taken place in the past few thousand years.



The red arrows show areas of enhanced, localized seismicity rates where the estimated rate of $M=0$ earthquakes per 60 years is greater than 8 (modified from *Frankel, Seism. Res. Lett., 1995*).

M>~7 Seismicity Rates Underestimated for the CEUS?

If all of the CEUS modern seismicity clusters show locations of M>~7 during the past 2000 or so years, then the rate of M>~7 earthquakes is approximately 2 to 3 times greater than that found from extrapolations of the smaller seismicity to larger magnitudes.

Paleoseismicity Cluster Analysis Results
Main shocks between M7.0 and M7.5 H ave Equ al Rates

Rate of M=0 Earthquakes in 60 Years	Time of Analysis (years)	Nishenko & Bollinger (1990) Relation 1 Recurrence Curve Prediction	Nishenko & Bollinger (1990) Relation 2 Recurrence Curve Prediction	Nishenko & Bollinger (1990) Relation 1 Cluster Analysis Prediction	Nishenko & Bollinger (1990) Relation 2 Cluster Analysis Prediction
16 or more	1118	3.0	1.7	8	8
8 or more	2124	5.7	3.1	15	15

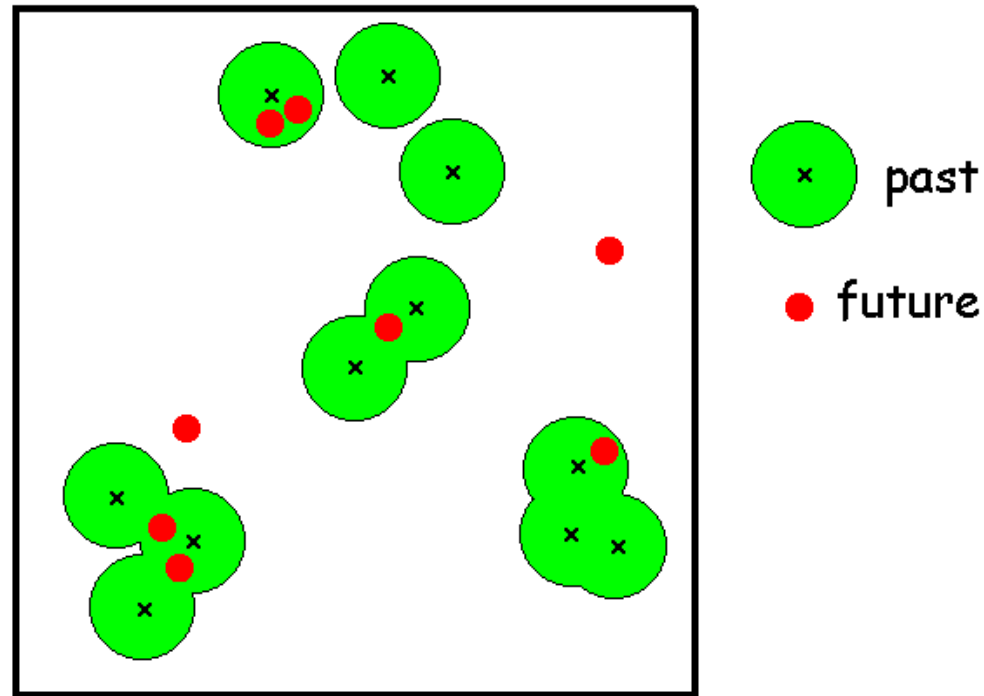
Table 2b
Paleoseismicity Cluster Analysis Results
Main shocks between M7.0 and M7.5 H ave Gutenberg-Richter Distribution

Rate of M=0 Earthquakes in 60 Years	Time of Analysis (years)	Nishenko & Bollinger (1990) Relation 1 Recurrence Curve Prediction	Nishenko & Bollinger (1990) Relation 2 Recurrence Curve Prediction	Nishenko & Bollinger (1990) Relation 1 Cluster Analysis Prediction	Nishenko & Bollinger (1990) Relation 2 Cluster Analysis Prediction
16 or more	1118	3.0	1.7	6	4
8 or more	2124	5.7	3.1	13	7

Gutenberg-Richter
Extrapolation

Paleoseismicity
Extrapolation

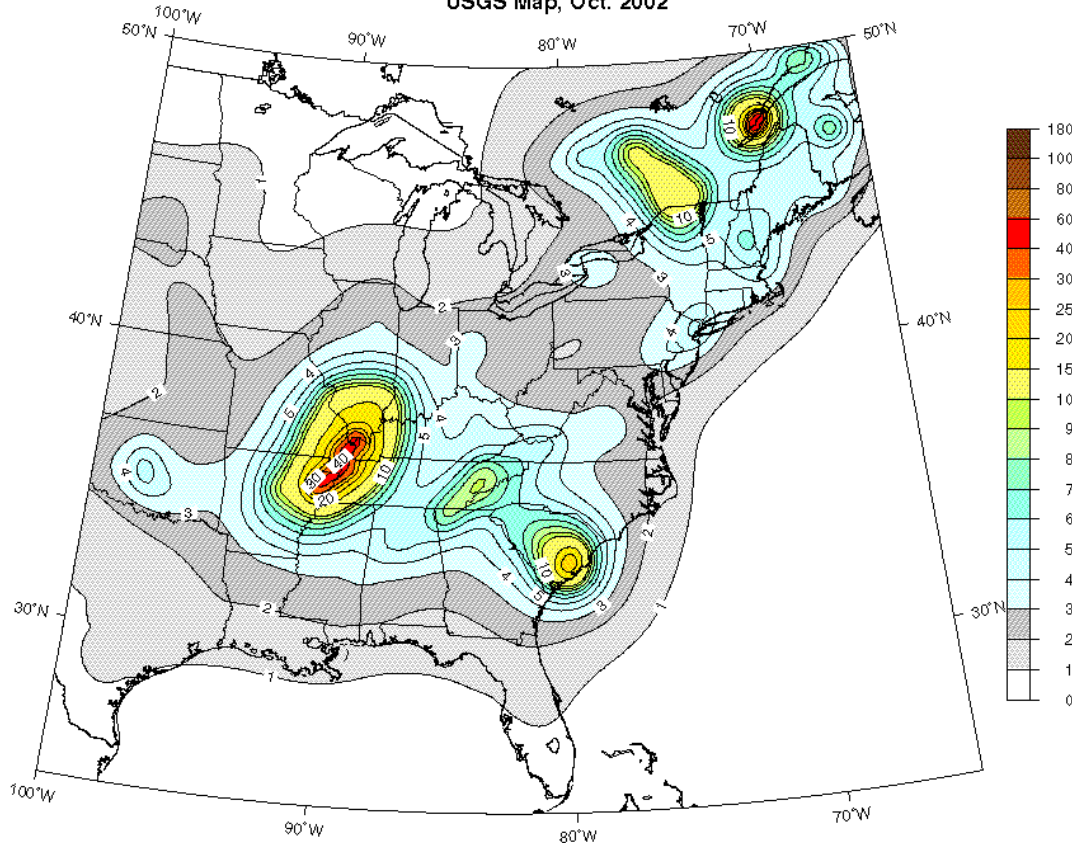
USE OF SEISMICITY TO DEFINE SEISMIC SOURCES: APPLICATION TO EASTERN NORTH AMERICA



“Cellular Seismology”

Alan L. Kafka
Weston Observatory
Boston College

Peak Acceleration (%g) with 10% Probability of Exceedance in 50 Years
USGS Map, Oct. 2002



Questions:

(1) Is the "tendency for future earthquakes to occur near past earthquakes" a real, measurable, physical phenomenon?

(2) Do we have samples that are representative of this phenomenon?

(3) Can we measure it?

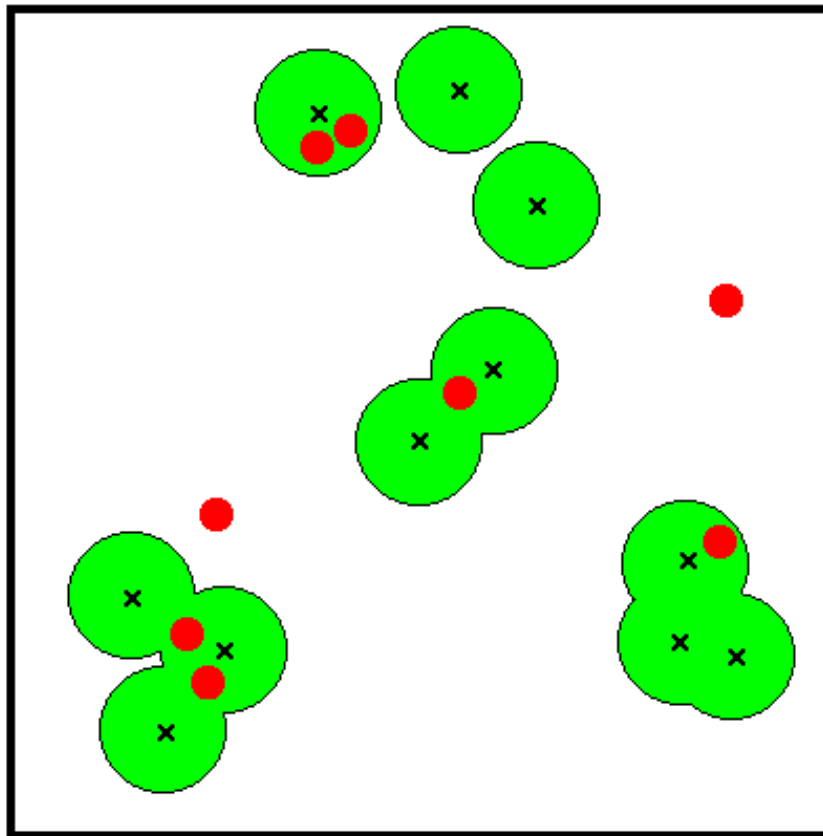
USGS National Seismic Hazard Maps

Past Seismicity → Future Earthquakes

"If you can't measure it, it isn't science."
- Lord Kelvin

“Cellular Seismology”

(analogous to a cellular phone system)



past
(before)



future
(after)

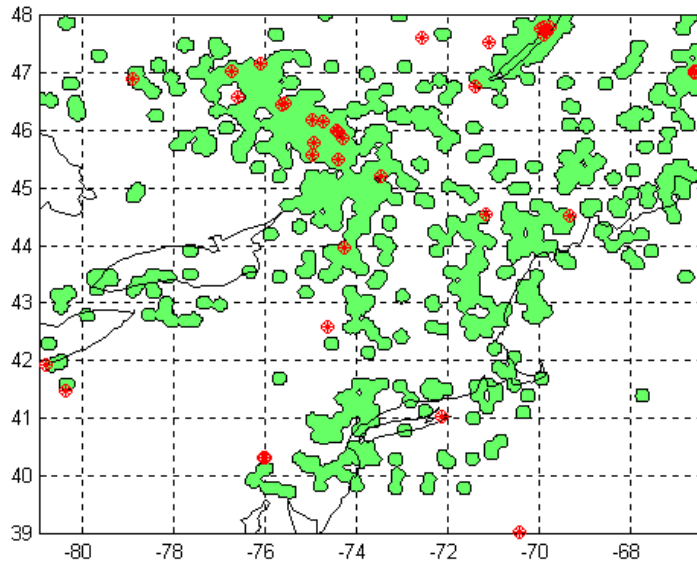
Choose a radius such that circles fill **P** percentage of map area.

$\hat{\rho} = 6/8 = 75\% =$ sample of binomial random variable, ρ .

$\rho =$ Probability(“success”)

success = **red circle** occurs within one of the **green circles**.

Northeastern United States



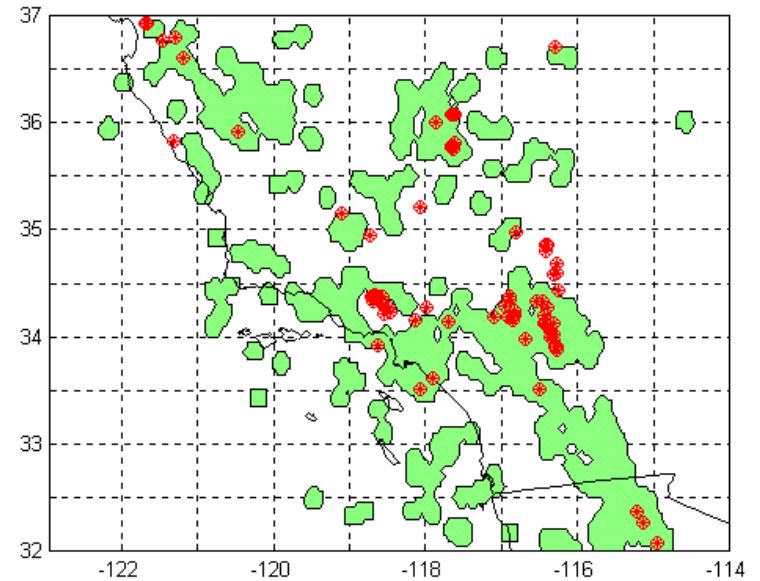
$M \geq 2.0$ (1975-1987)

$M \geq 4.0$ (1988-2001)

78% Hits

33% Map Area

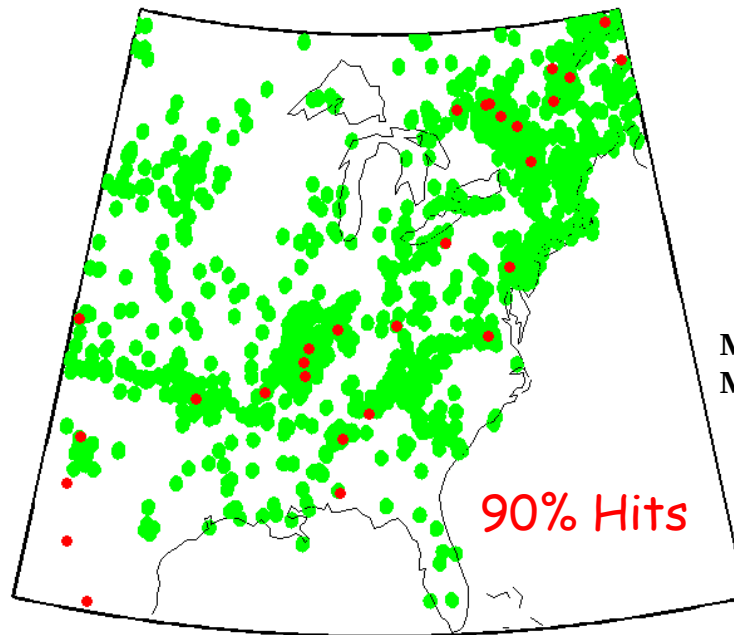
Southern California



$M \geq 3.0$ (1984-1987)

$M \geq 5.0$ (1988-2001)

79% Hits



$M \geq 3.0$ (1924-1987)

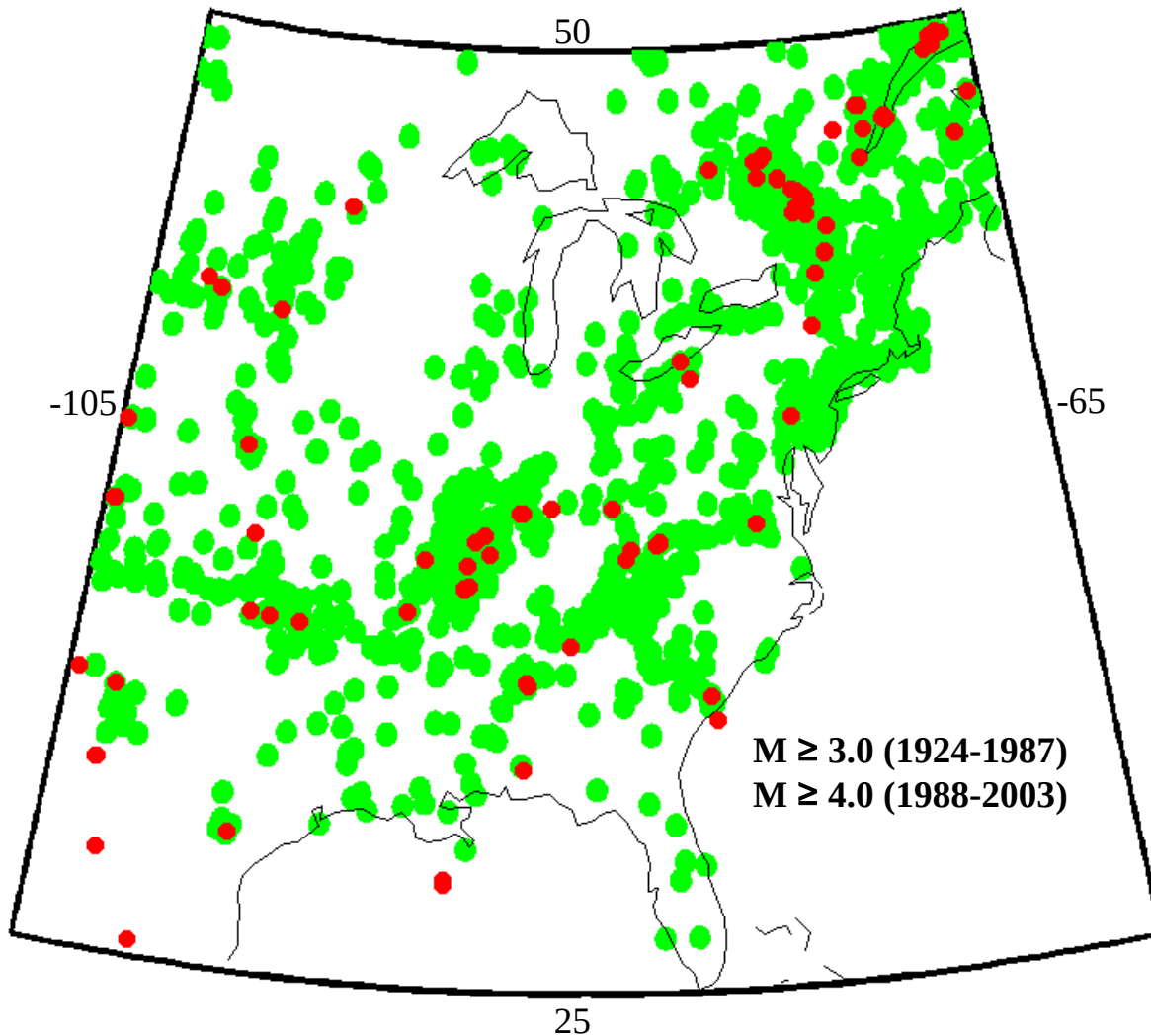
$M \geq 4.5$ (1988-2003)

90% Hits

Central and Eastern United States

Kafka (2002, 2007)

Central and Eastern United States



green zones = 33% map area

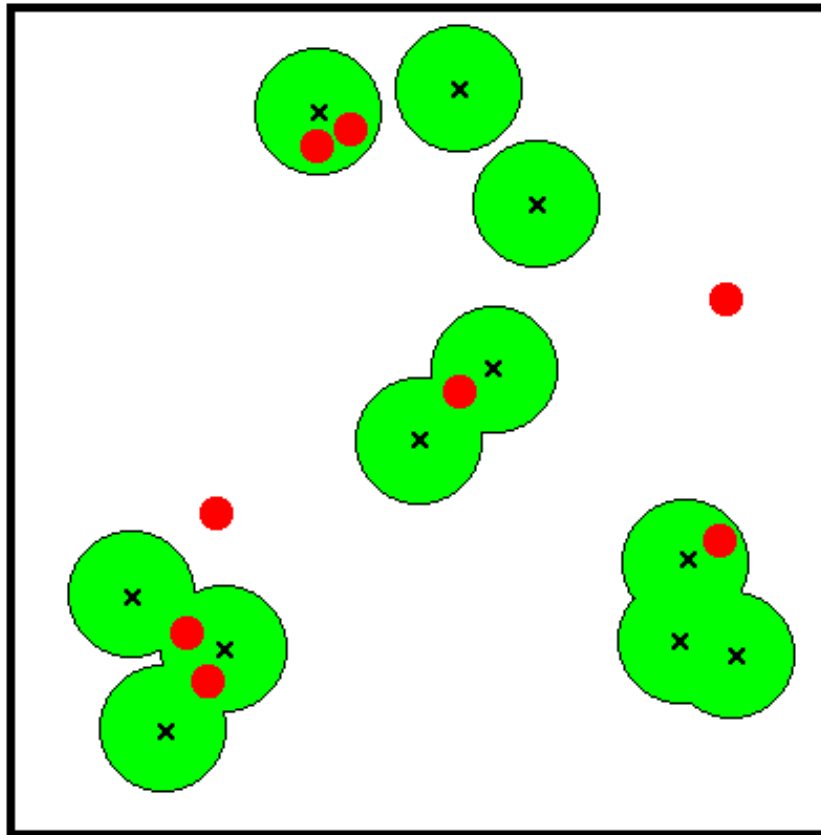
Future large earthquakes in the CEUS have about 86% probability of occurring within 36 km of past earthquakes.

- Kafka (2007)

95% Confidence Interval

79% ← 86% → 93%

“Cellular Seismology”



past
(before)



future
(after)

$\hat{\rho}$ = sample of binomial random variable, ρ .

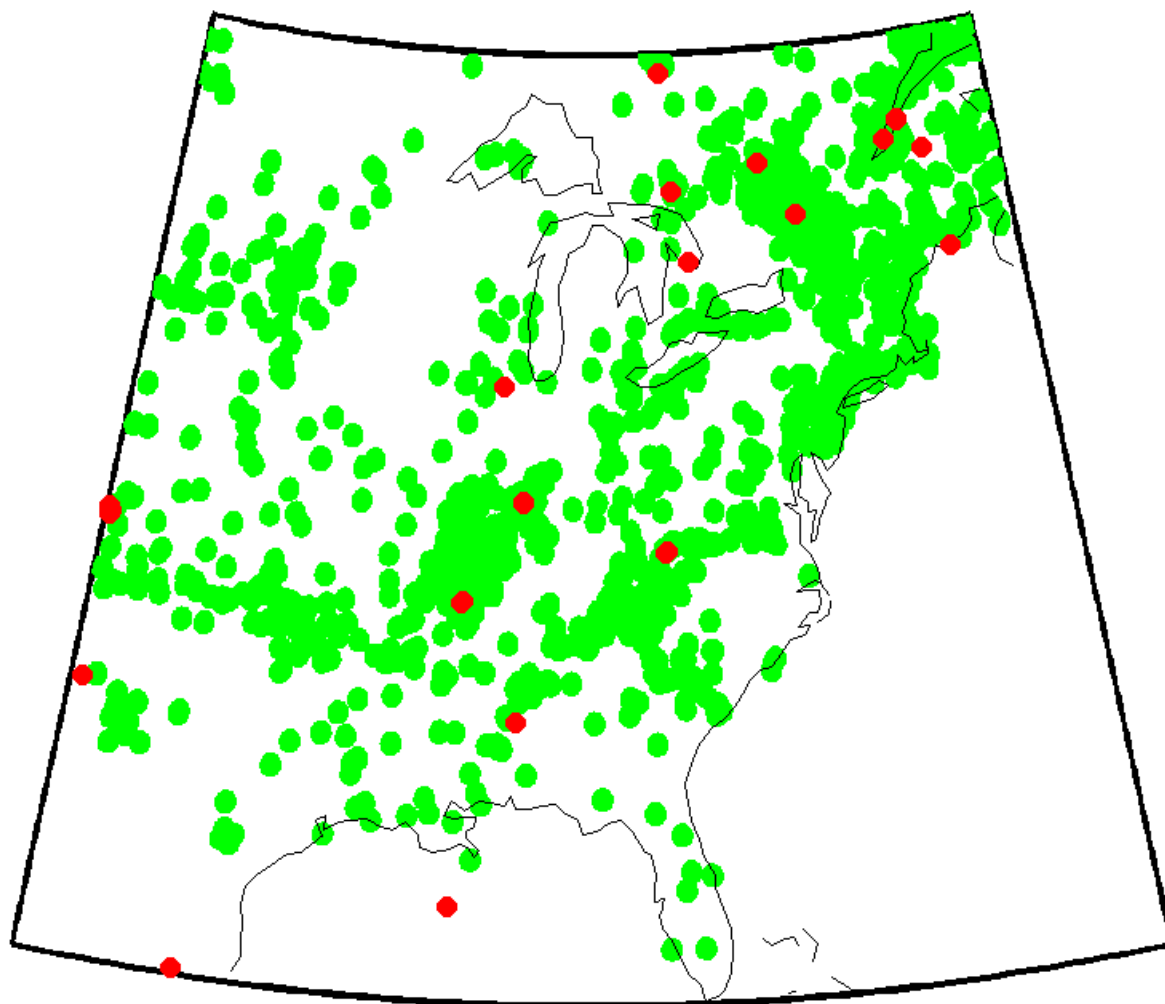
ρ = Probability(“success”)

success = red circle occurs within one of the green circles.

$$\rho = \hat{\rho} \pm 1.96 \sqrt{\frac{\hat{\rho}(1 - \hat{\rho})}{n}}$$

**95% Confidence Interval
(given n “after” earthquakes)**

Central and Eastern United States



$M \geq 3.0$ (1924-1987)

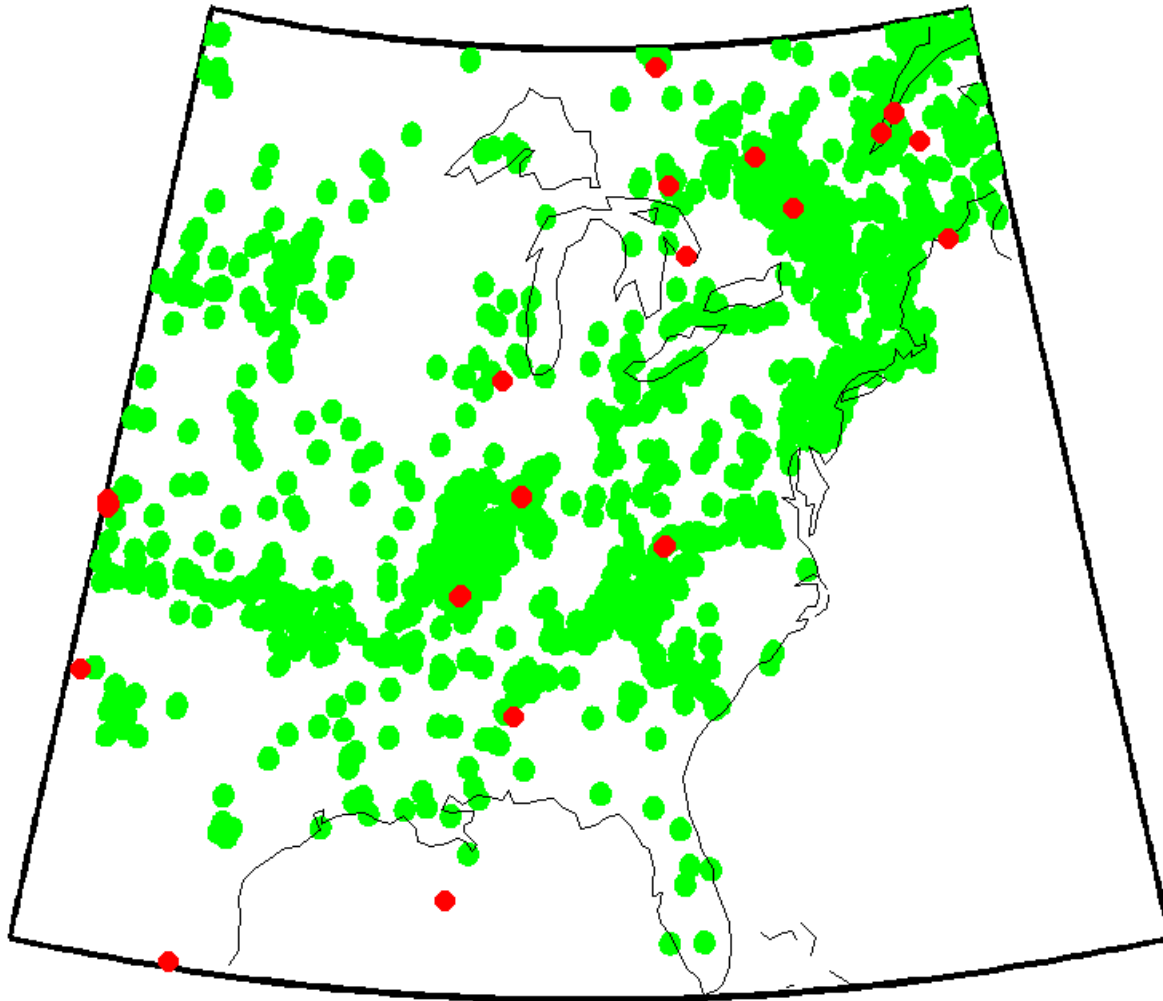
$M \geq 4.0$ (2004-2008)

95% Confidence Interval
(from previous slide)

79% $\leftarrow$ 86% $\rightarrow$ 93%

green zones = 33% map area

Central and Eastern United States



$M \geq 3.0$ (1924-1987)

$M \geq 4.0$ (2004-2008)

95% Confidence Interval
(from previous slide)

79% ← 86% → 93%

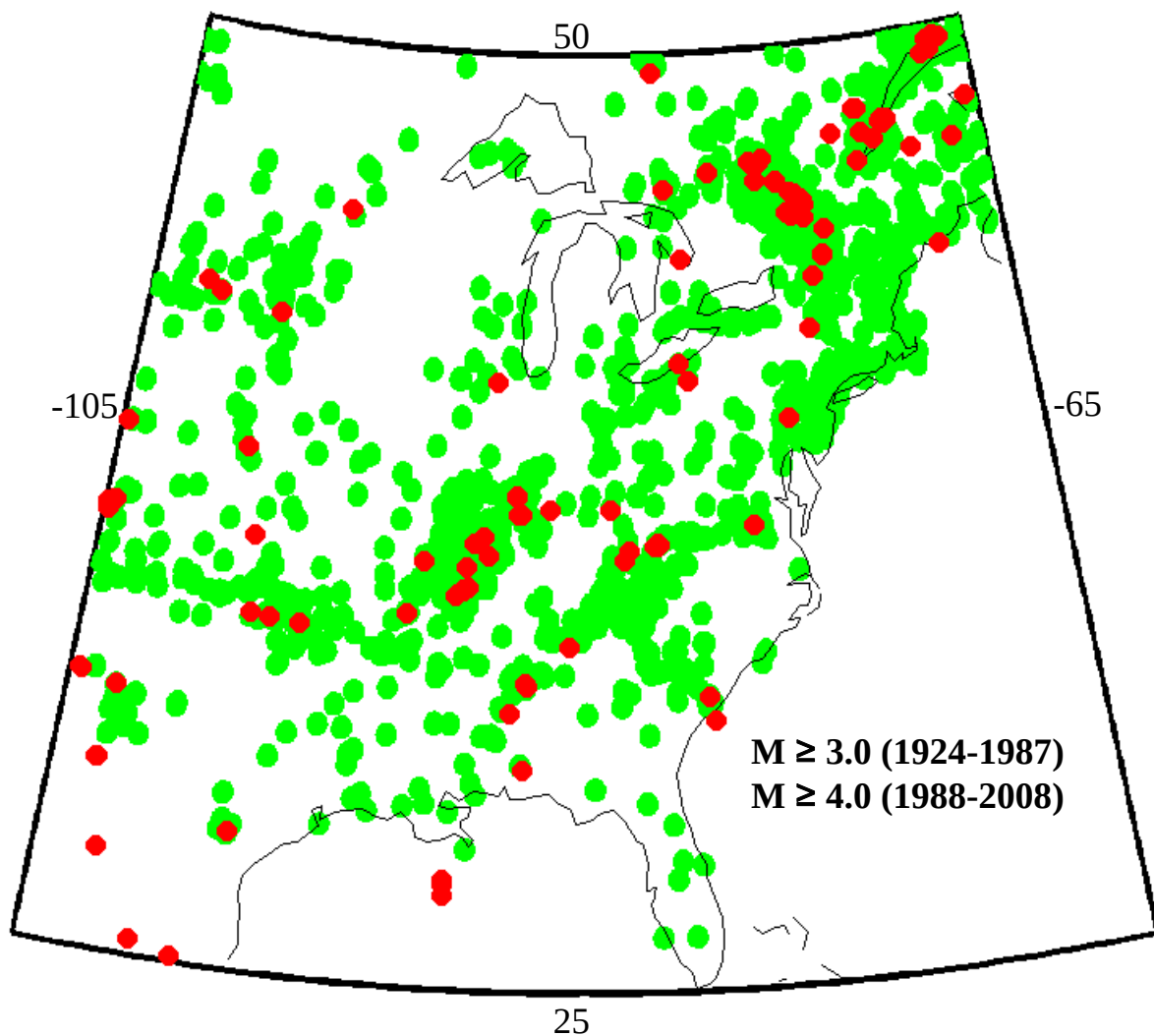
**“Market gurus predict
stock rebound but won’t
rule out extreme move
up - or down.”**

- USA Today, January 2, 2009

green zones = 33% map area →

67% hits

Central and Eastern United States

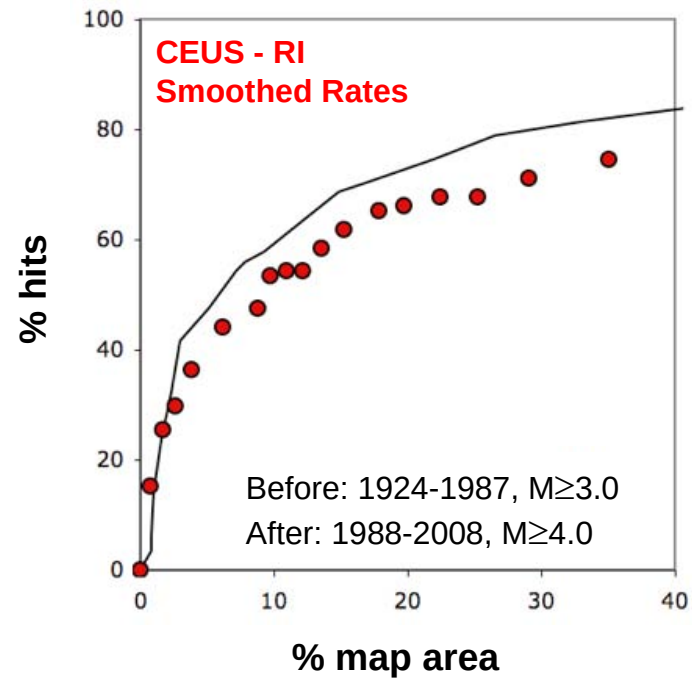
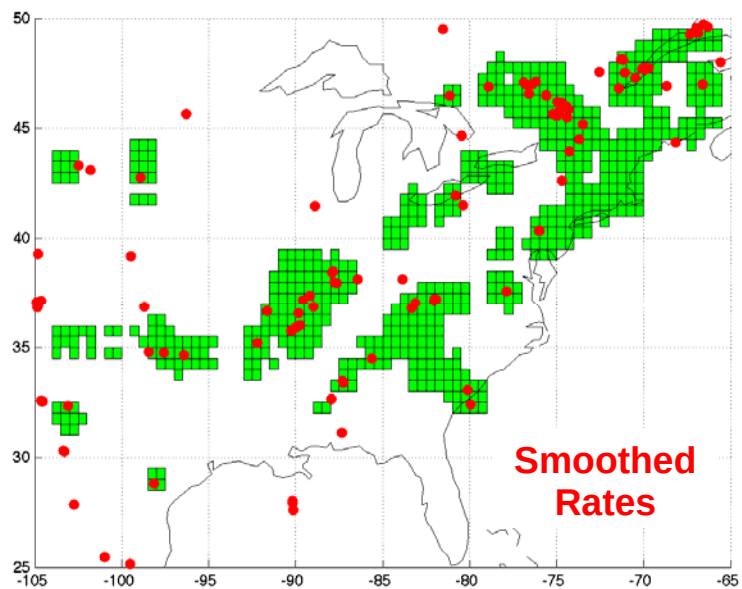
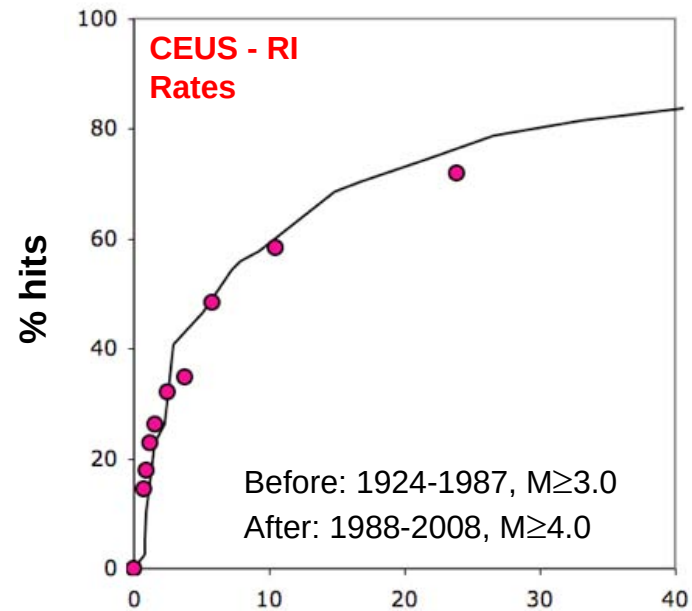
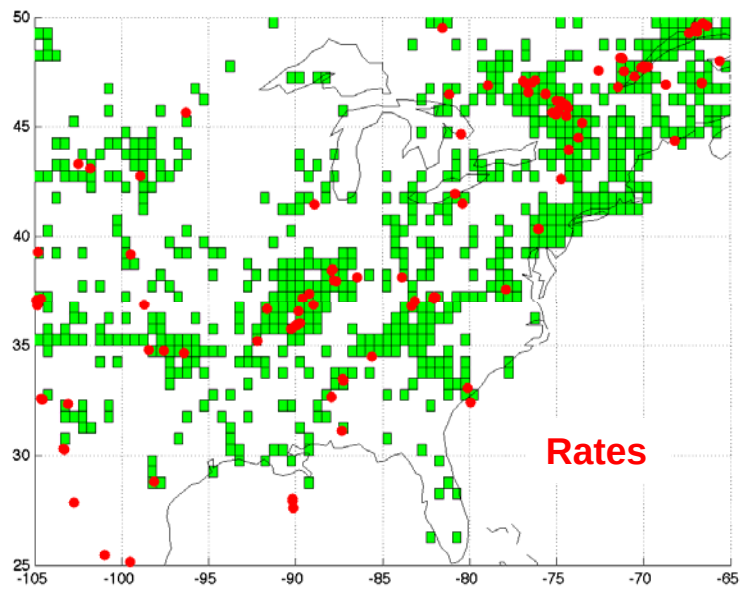


95% Confidence Interval

74% $\leftarrow$ 81% $\rightarrow$ 88%

Updated Forecast

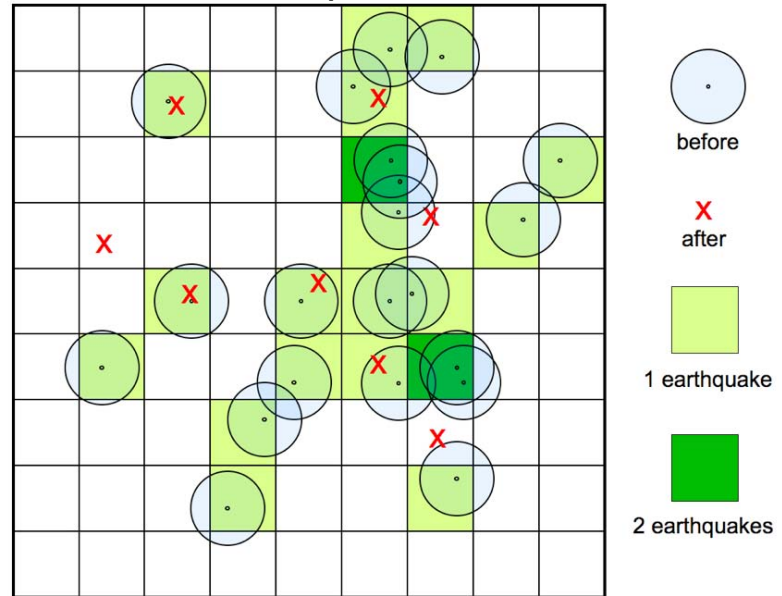
green zones = 33% map area



Cellular Seismology: 6/8 Hits

Rates: 5/8 Hits

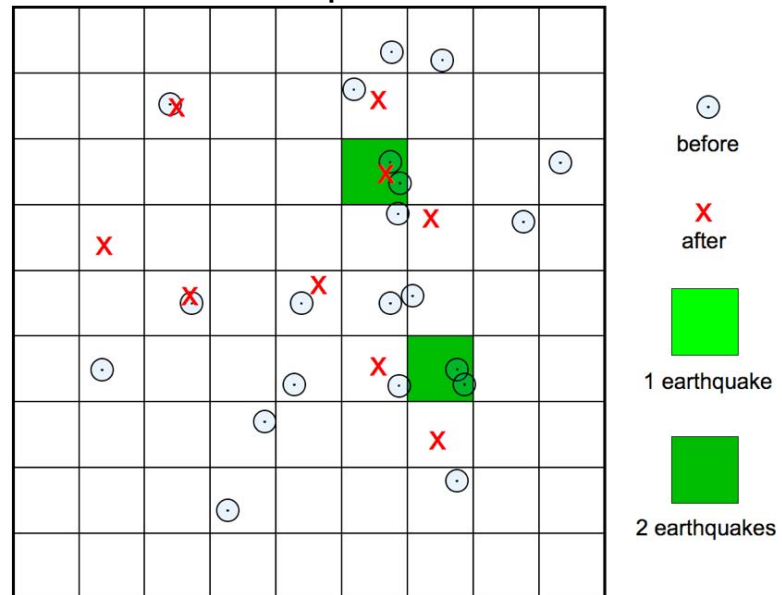
23% Map Area



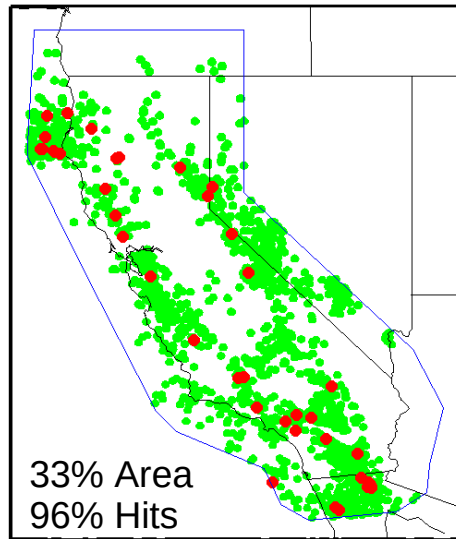
Cellular Seismology: 2/8 Hits

Rates: 1/8 Hits

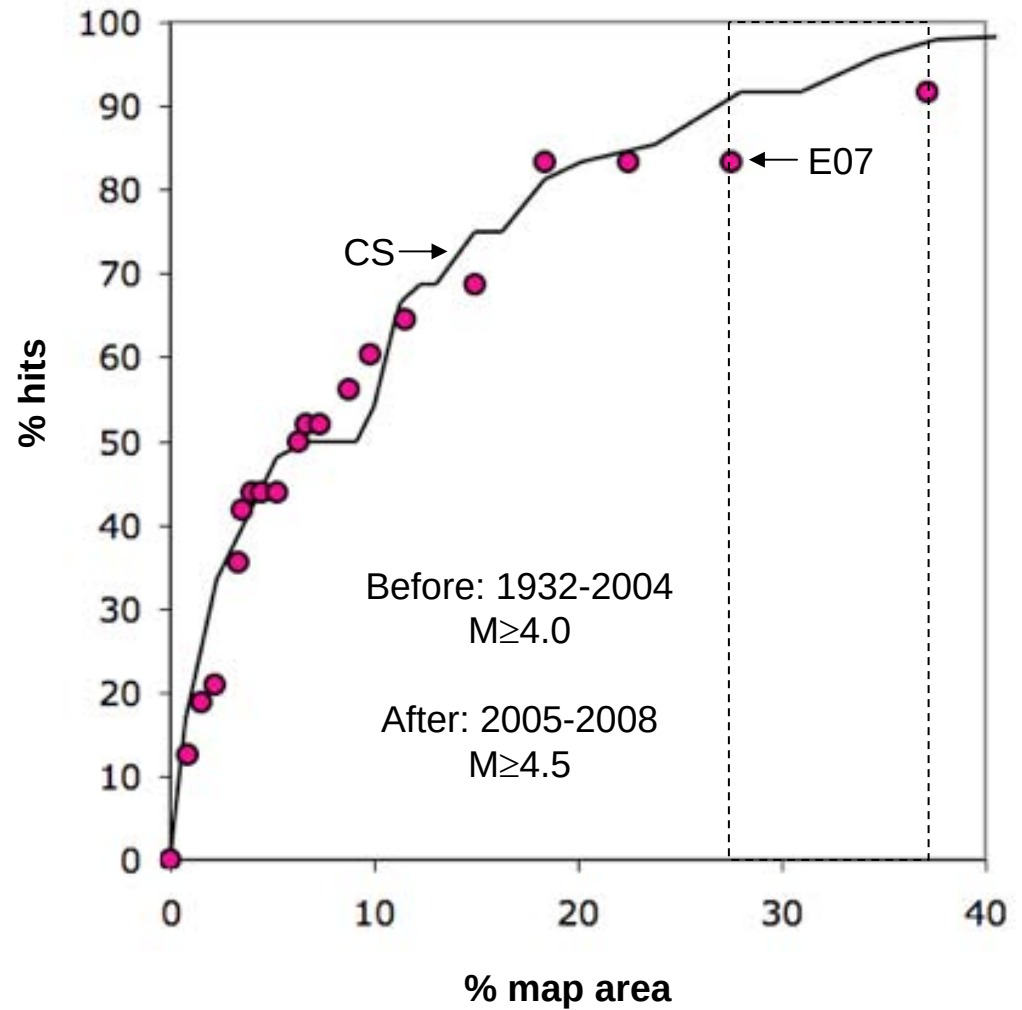
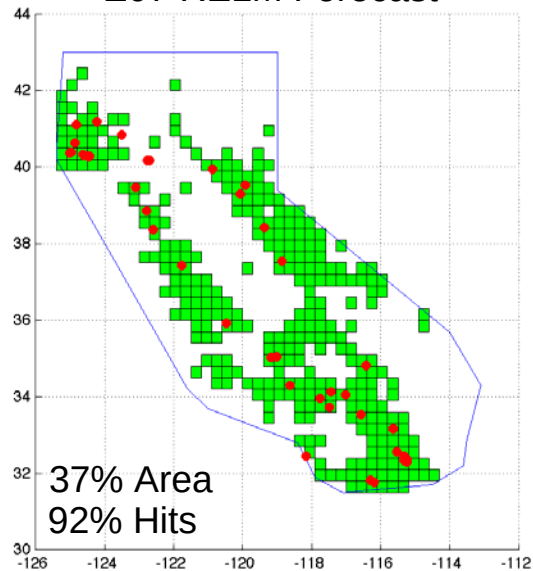
2% Map Area



Cellular Seismology (CS)



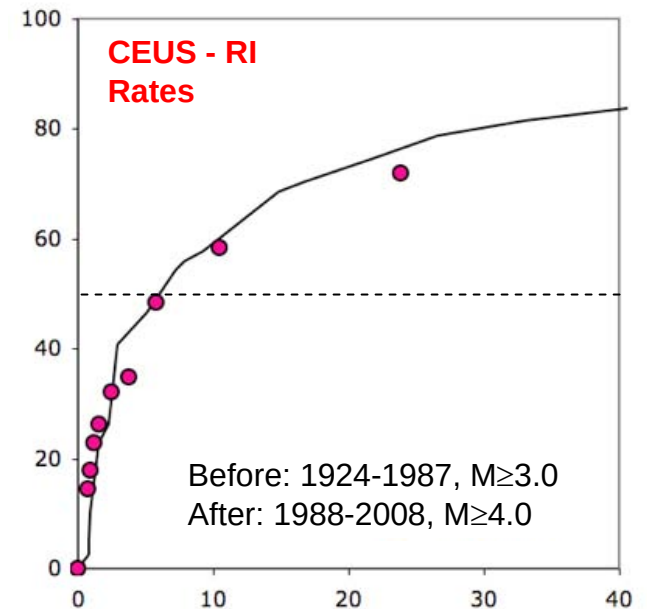
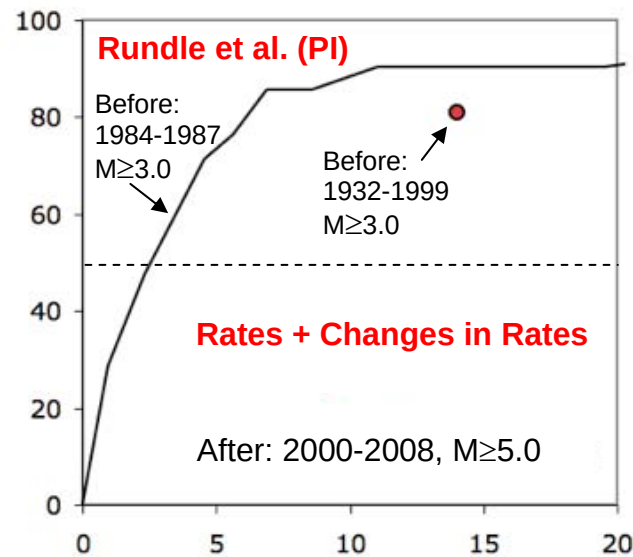
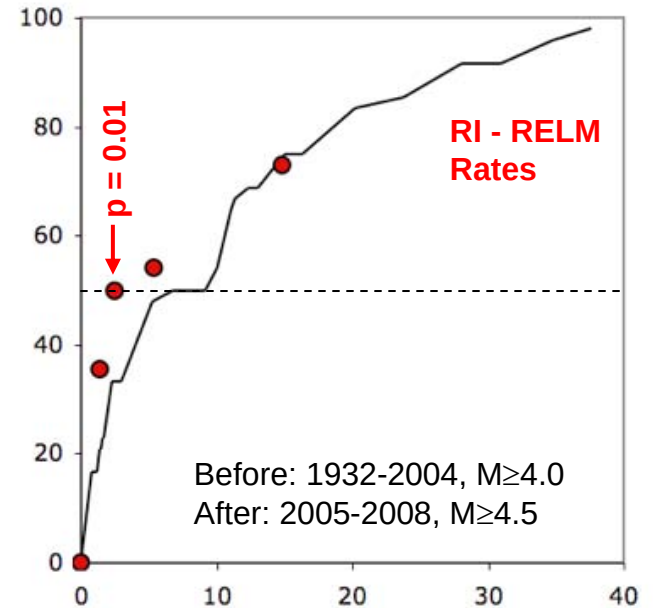
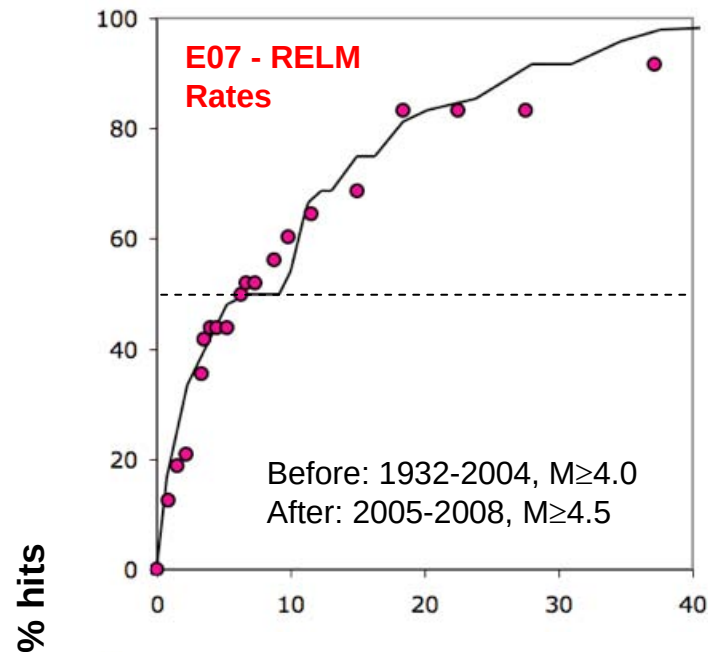
E07 RELM Forecast



E07 = RELM Forecast of Ebel, Chambers, Kafka and Baglivo (2007), based on rates of activity in cells.

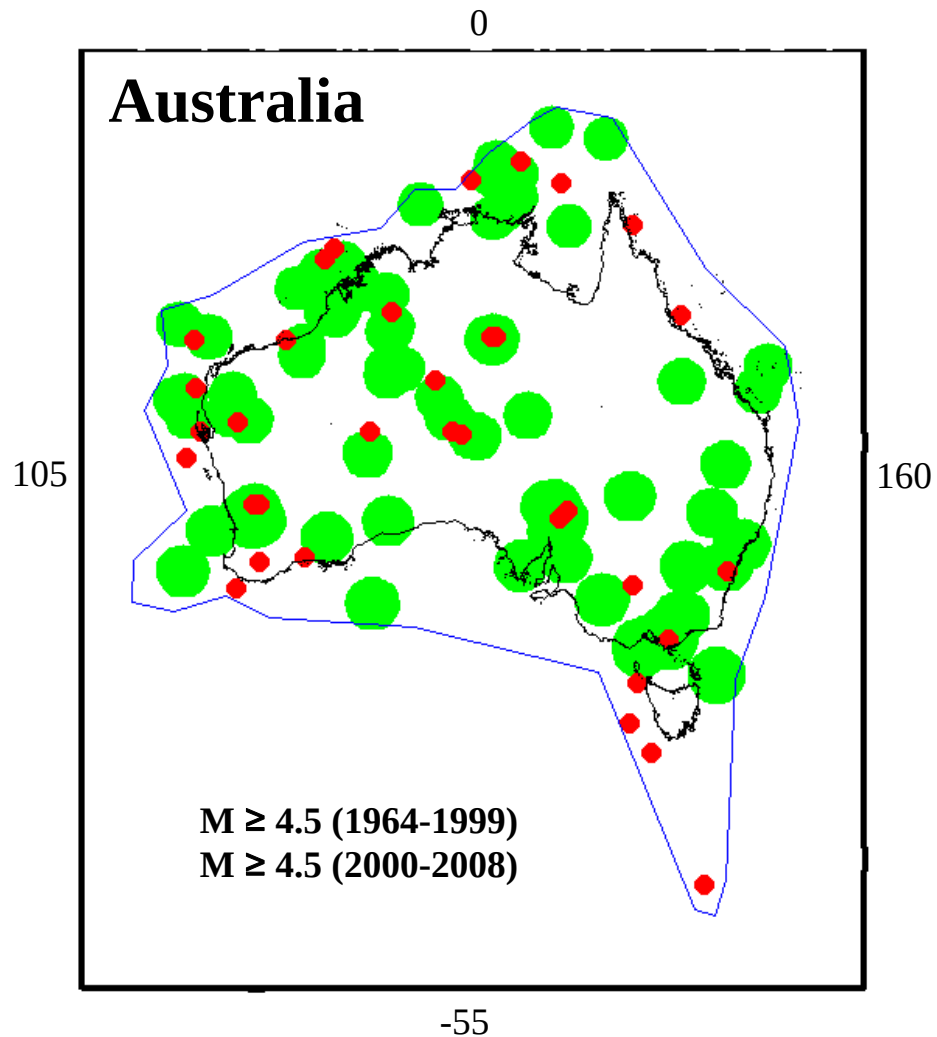
Cellular Seismology

Other Methods



From: Kafka and Ebel (2008), manuscript in preparation.

% area

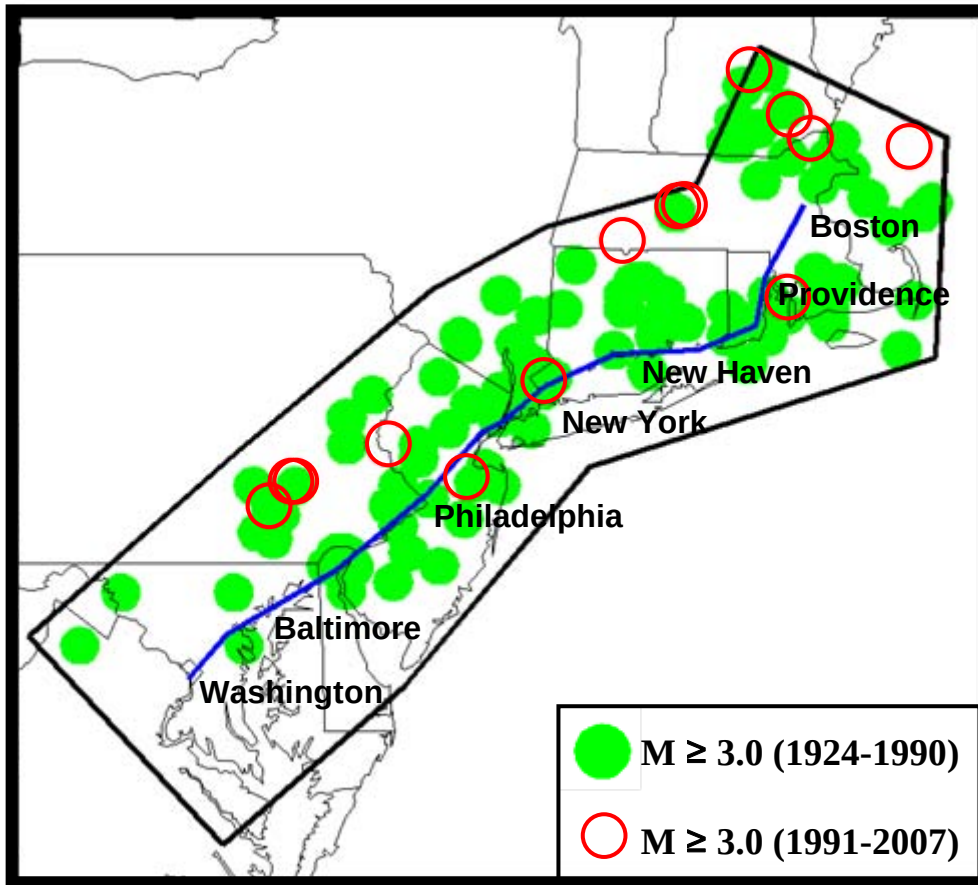


95% Confidence Interval

54% ← 68% → 83%

green zones = 33% map area

Cellular Seismology Forecast for the Northeast Corridor of the United States



Forecast Issued on October 2, 2008

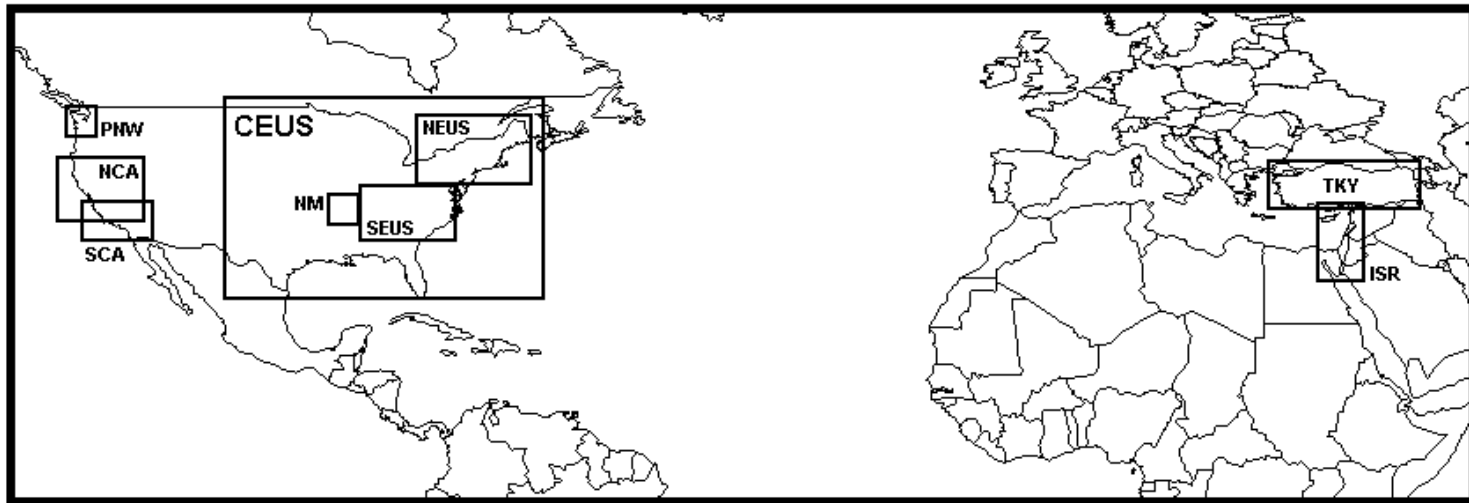
Based on this forecast:

Future earthquakes inside this polygon have a 67% probability of occurring within the green zones shown here. Those green zones cover 33% of the area enclosed by the polygon.

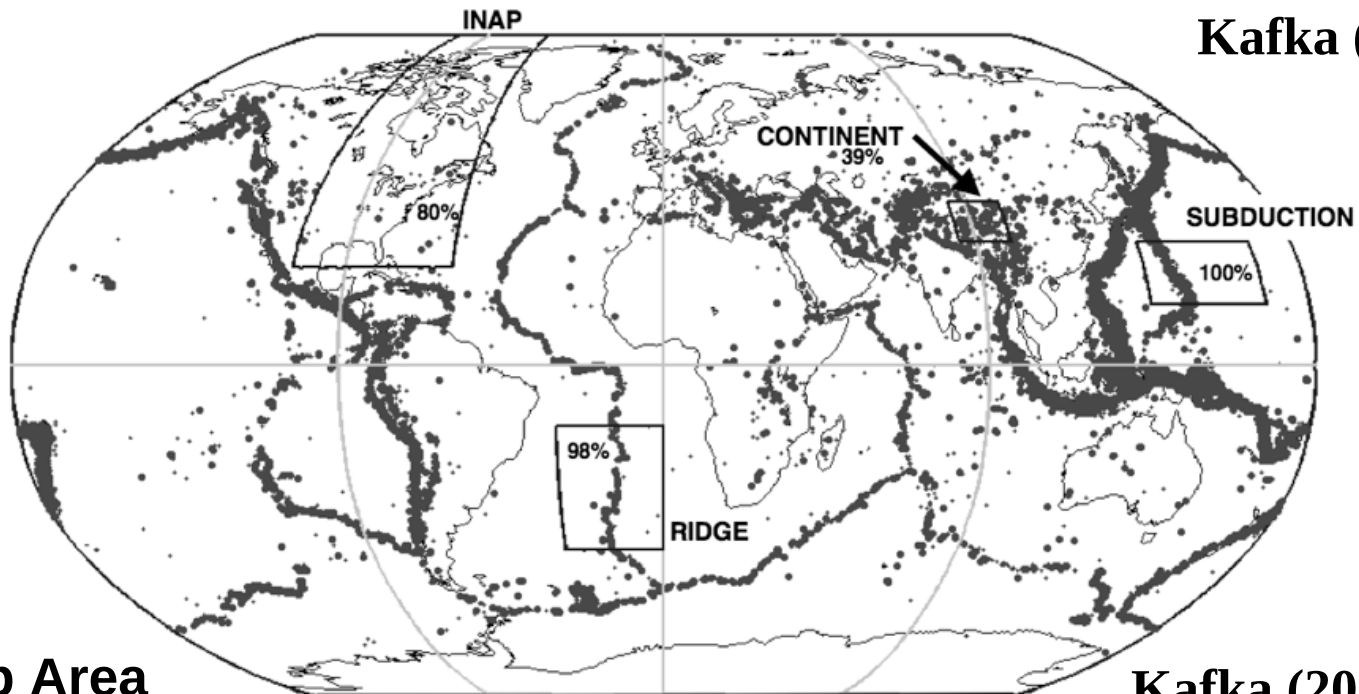
95% Confidence Interval

43% ← 67% → 91%

Tectonic Regions Studied



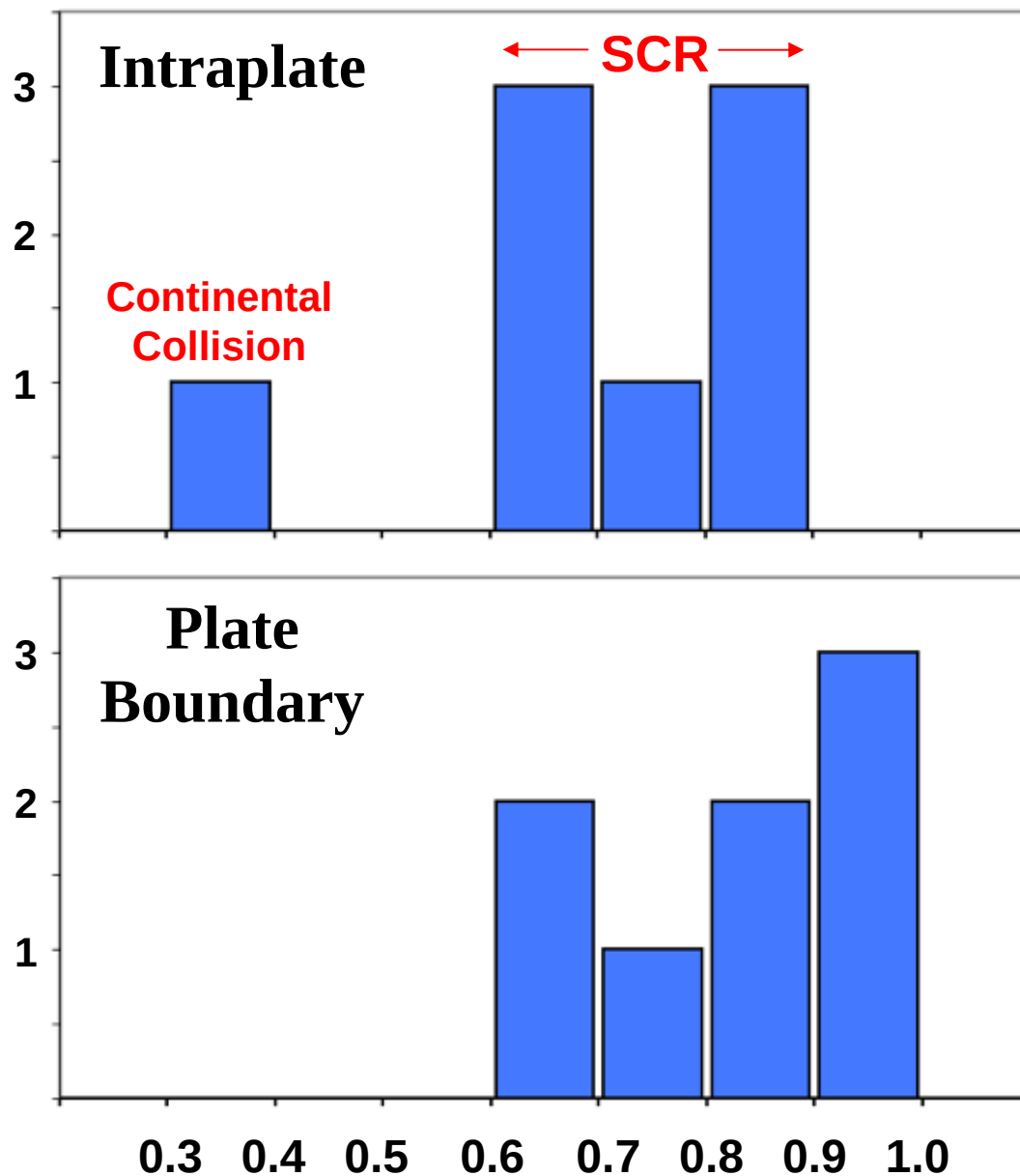
Kafka (2002)



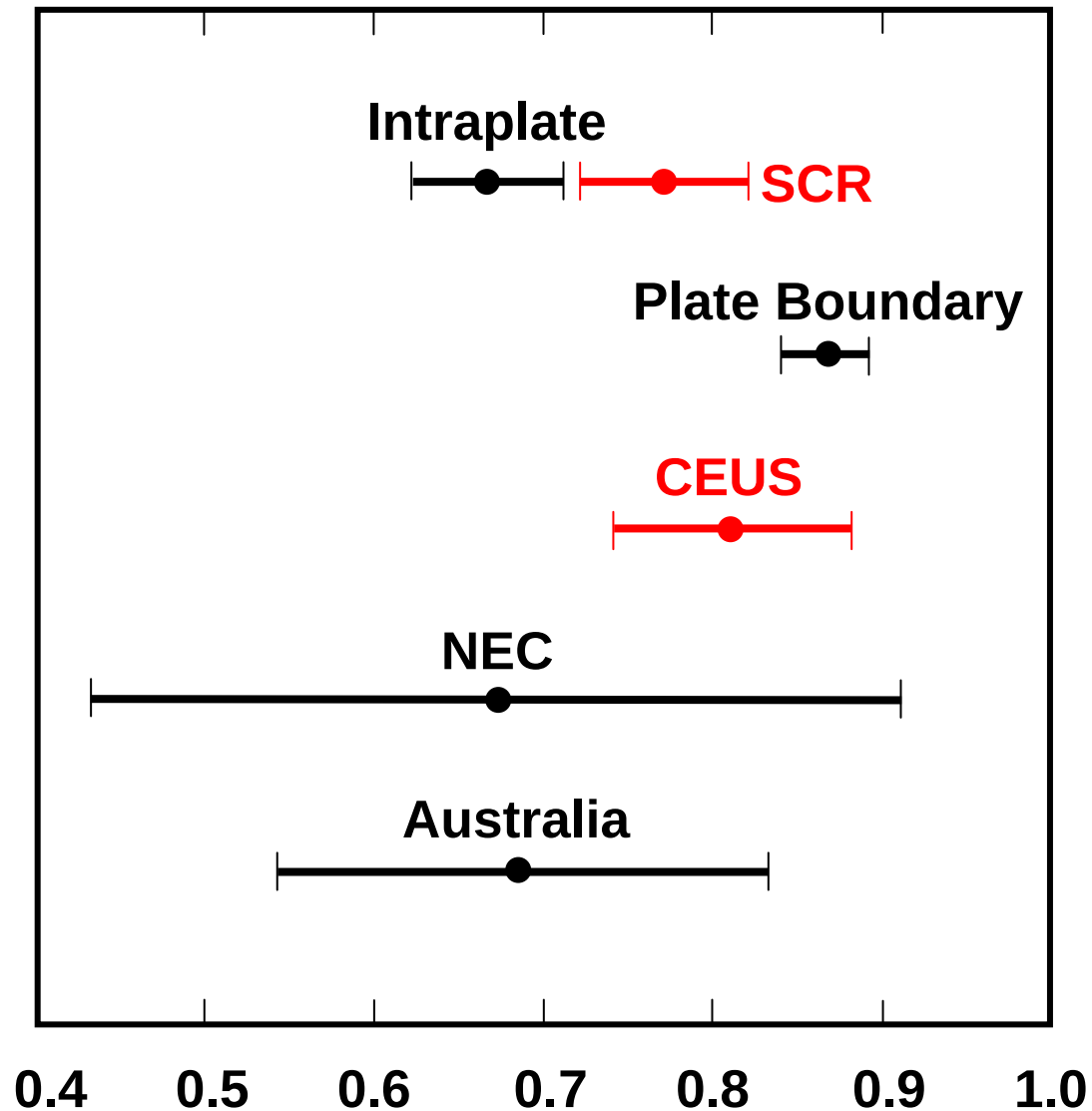
33% Map Area

Kafka (2007)

**Observed %Hits
(33% Map Area) for
the Different
Tectonic Regions
Analyzed**

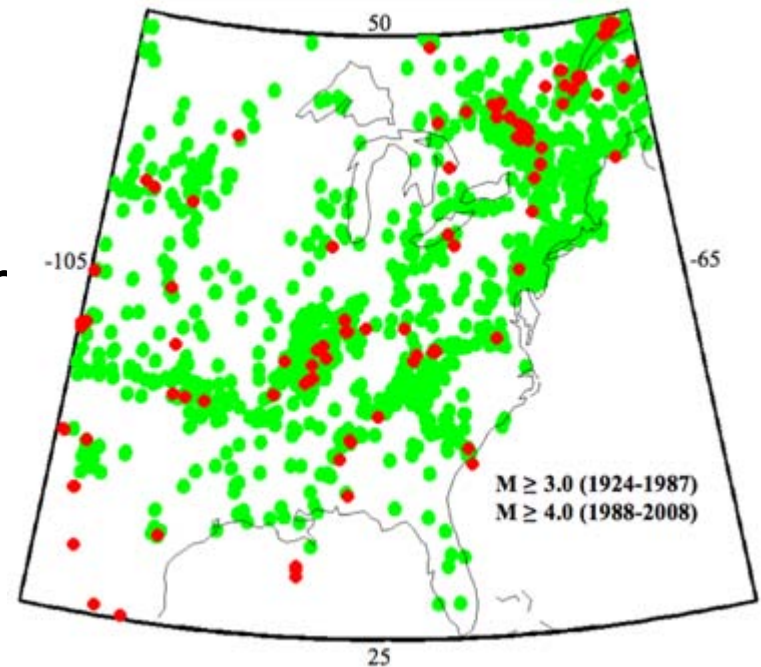


Confidence Intervals for %Hits



CONCLUSIONS

1. I have yet to find any other method of forecasting locations of future earthquakes that performs better than Cellular Seismology. Still searching...
2. CS forecast for CEUS:
81±7% probability that future earthquakes will occur within these CS zones covering 33% of map area.
3. CS forecast probabilities lower for intraplate regions than for plate boundary regions?



Eastern Canadian experience with Geological Source Zones and Mmax

John Adams

Presentation for EPRI meeting Palo Alto 2009 02 18

3rd Generation seismic hazard model

Basham and Berry

Developed ~1979-1982

Implemented in 1985 code

4th Generation seismic hazard model

Developed ~1994-1997

Finalized 2003

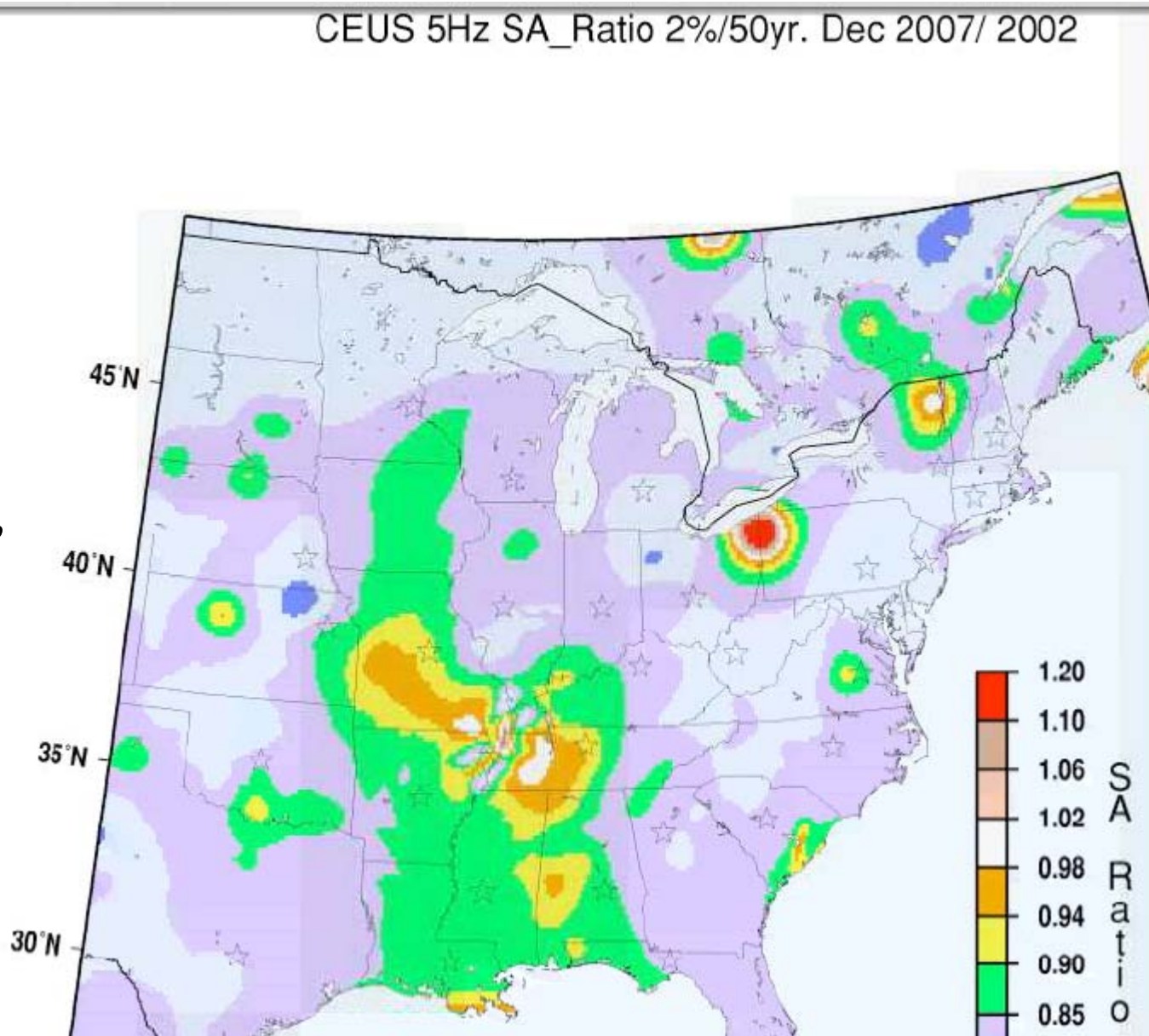
Implemented in 2005 code

Smoothed seismicity is interesting, but not enough

- Counter-Example: Saguenay earthquake M5.9, had no prior activity $m_N > 3$ for more than 50 years prior; would not have shown up
- Counter-Hypothesis: Contemporary earthquake clusters represent locations of past large earthquakes; activity rate is for aftershocks, not the large initiator.

Smoothed seismicity is interesting, but not enough

Estimates are not very stable, anyway
(USGS difference map: Mark Petersen, NGA meeting May 2008)



Geological sources were proposed in Canada in 1983
for the passive continental margin (Adams/Basham)

Geological sources were established for US (early
nineties, Rus Wheeler) but not used by USGS for
NEHRP

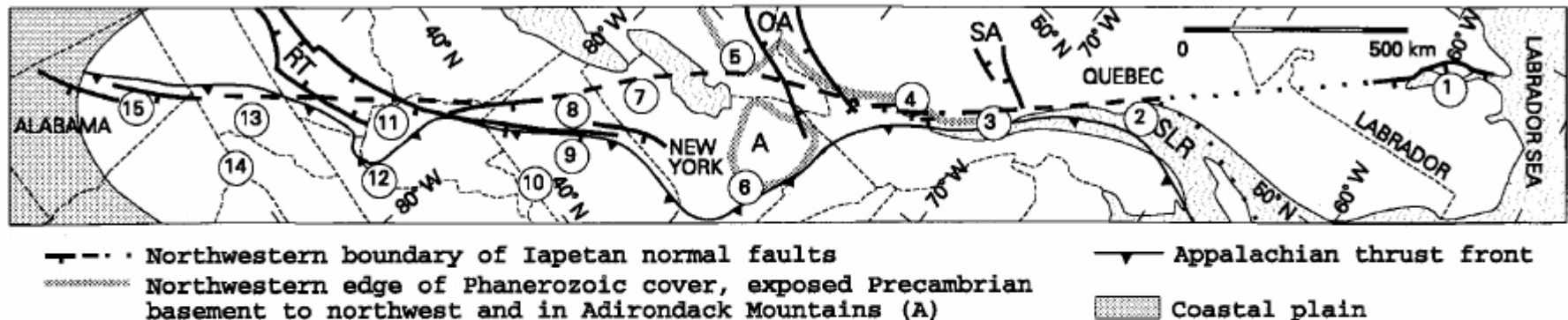
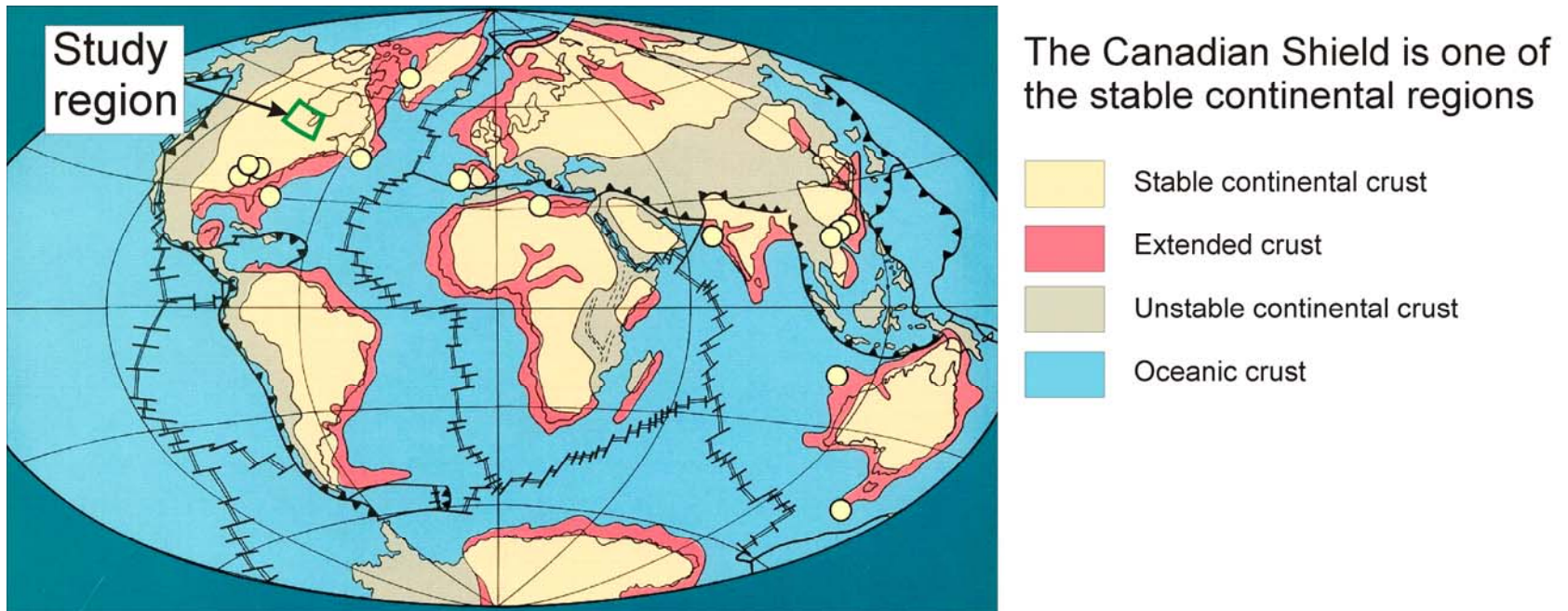


Figure 2. Northwest boundary of Iapetan normal faults. Circled numbers locate known and probable Iapetan faults, keyed to entries in Table 1. Local seismograph networks are installed at localities 2, 3, 7, 12, and 13 (Table 1). Faults at localities 1, 4, 8, 9, 11, and 15 are large enough to show selected individual faults here. Northwest boundary is dashed where inferred between known faults; two speculative extremes are dotted in eastern Quebec and Labrador, where geologic mapping is sparse (C. F. Gower, P. S. Kumarapelli, 1992, oral and written commun.), and in lower St. Lawrence River (SLR). For reasons discussed, northwest boundary is drawn to ignore Iapetan faults of Saguenay aulacogen (SA; DuBerger et al., 1991), Ottawa aulacogen (OA; Forsyth, 1981), Rome trough in Kentucky (RT; Harris, 1978; Webb, 1980; Cable and Beardsley, 1983), and Southern Oklahoma and Reelfoot aulacogens west of map area.

They did feed into the Mmax

EPRI- SCR

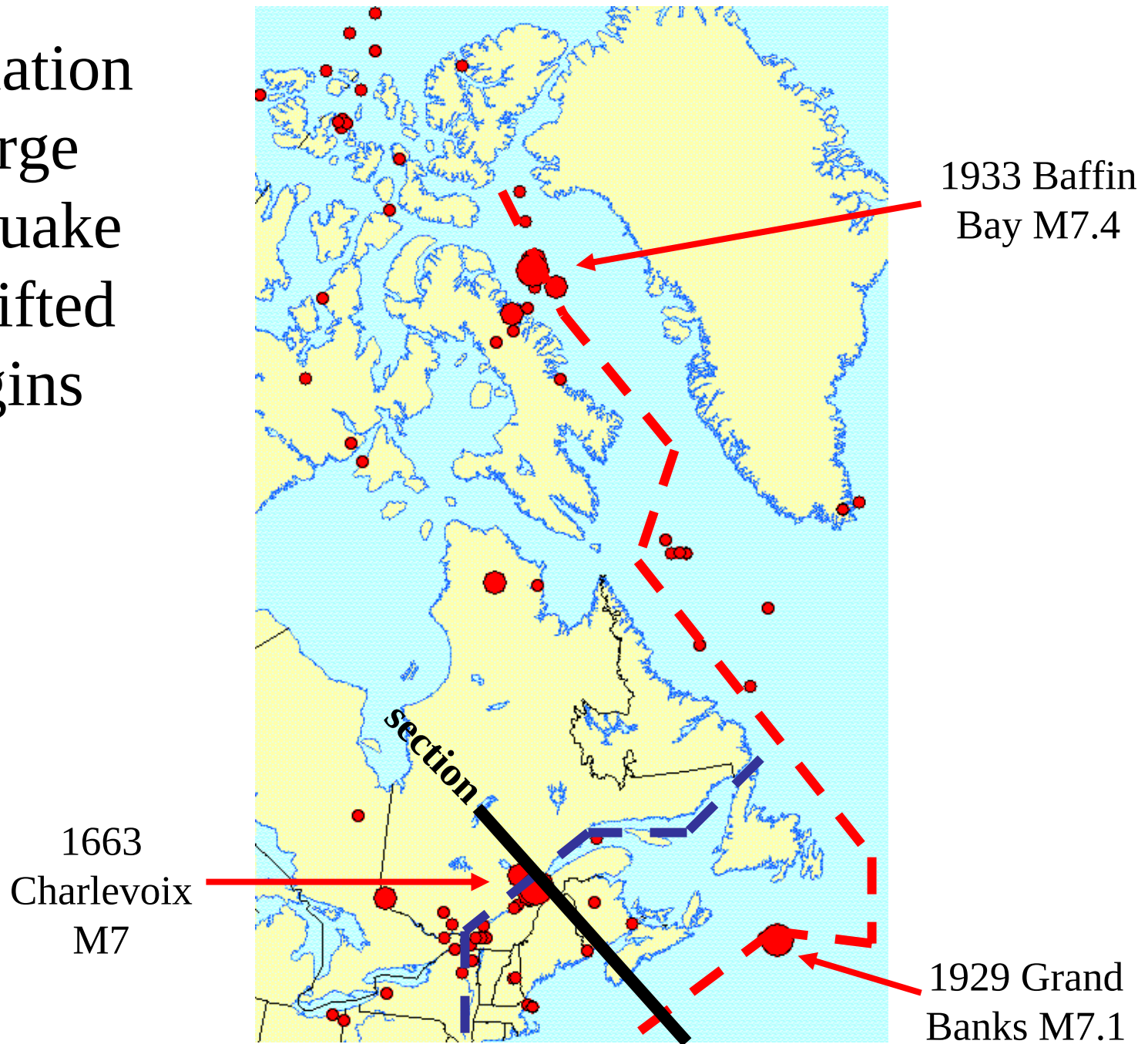
Phanerozoic rift zones generate more (& larger earthquakes than unrifted continental crust.



Examples from Canada

What are the appropriate analogs?

Association of large earthquake with rifted margins

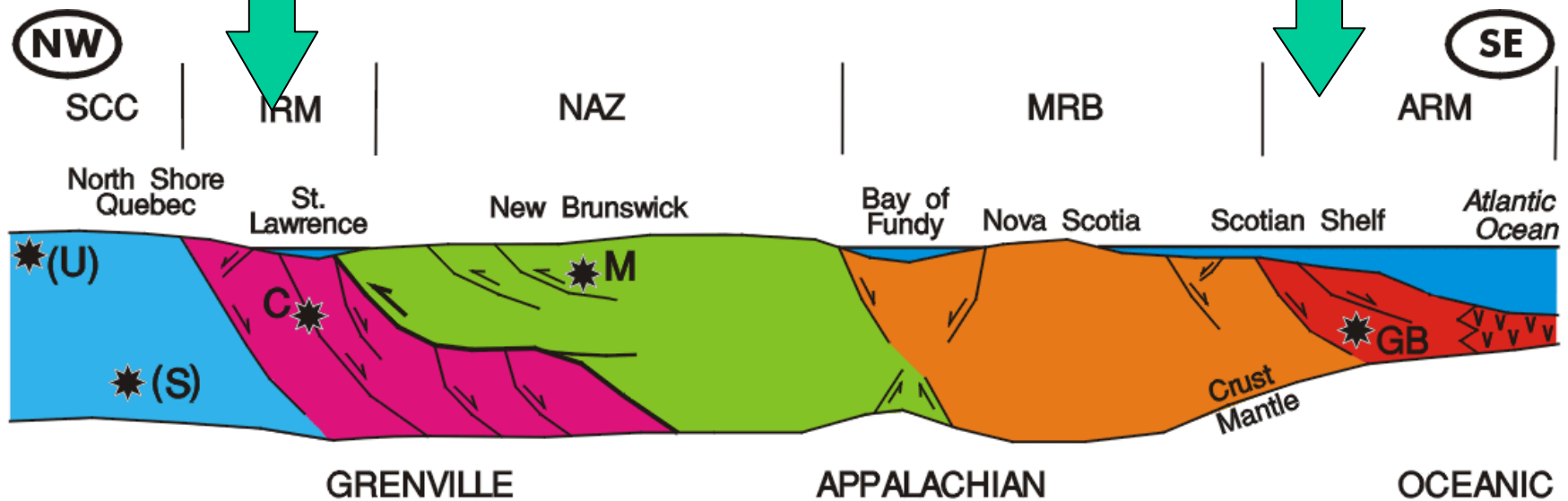


Ancient
rifted margin

Modern rifted
margin

Shield

Appalachians



Legend of representative earthquakes

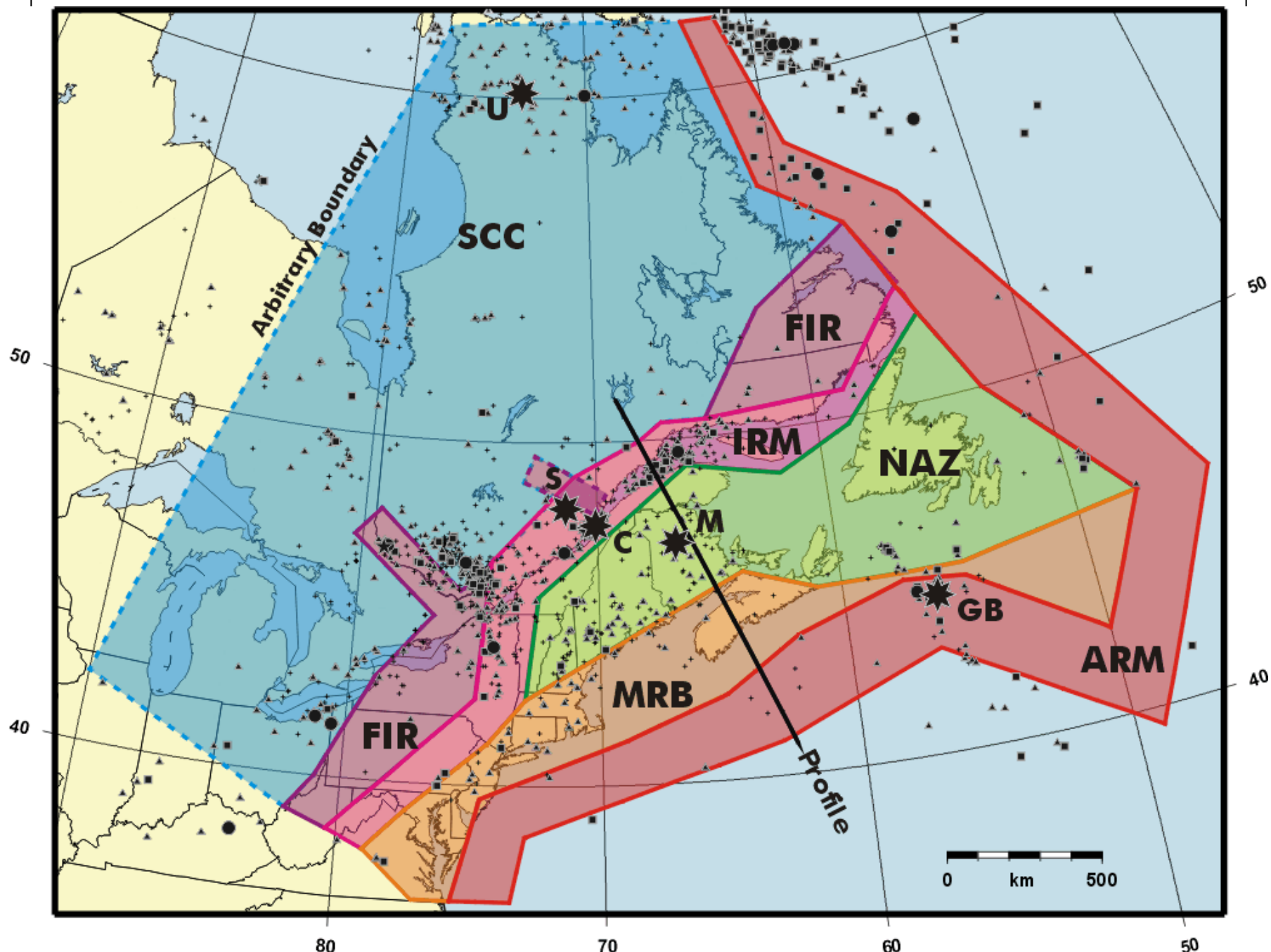
U - 1989, 6.3, Ungava Peninsula, Quebec

S - 1988, 5.9, Saguenay, Quebec

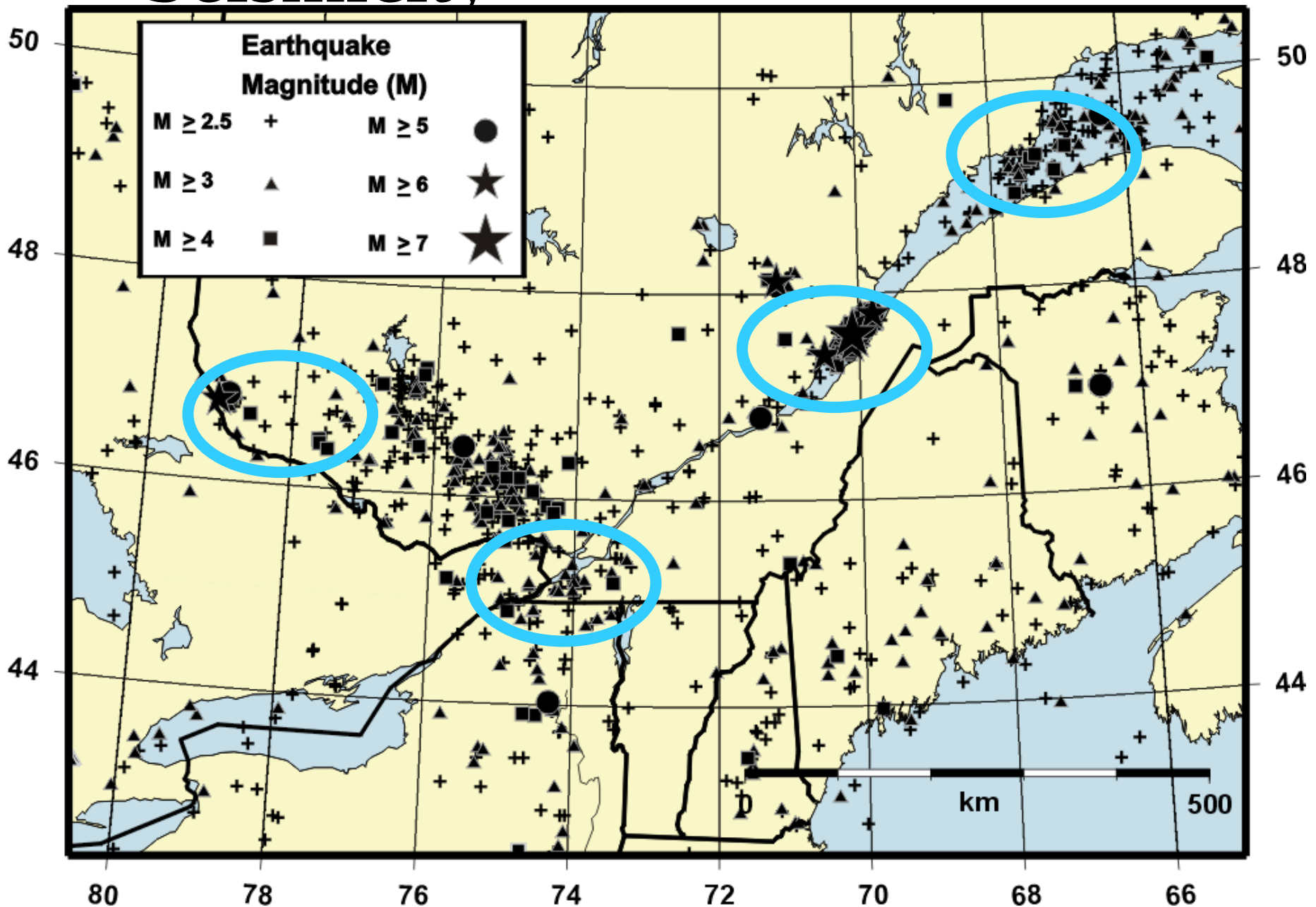
C - 1925, 6.2, Charlevoix-Kamouraska region, Quebec

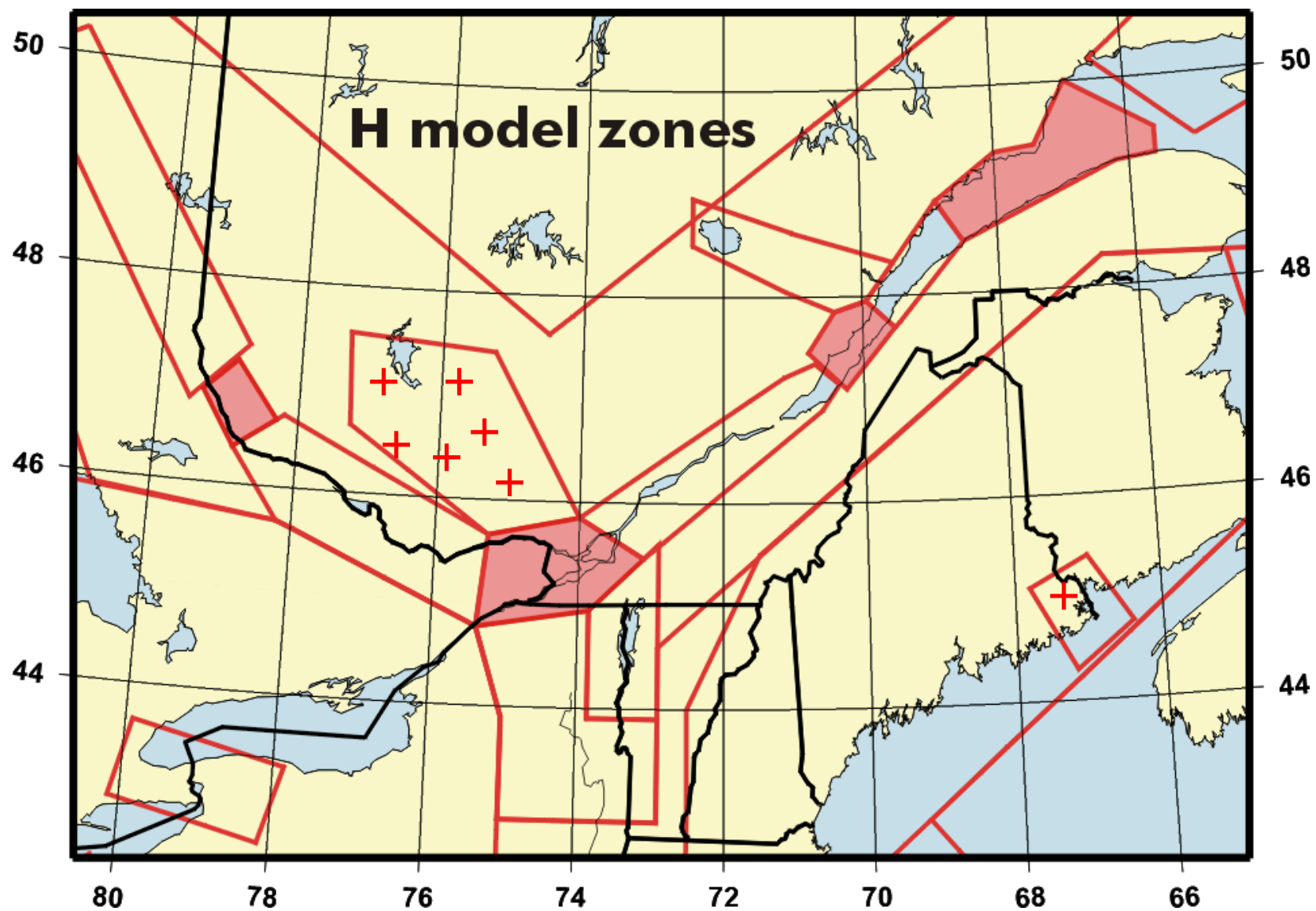
M - 1982, 5.7 and 5.4, Miramichi region, New Brunswick

GB - 1929, 7.2, Grand Banks, Atlantic Ocean, south of Newfoundland

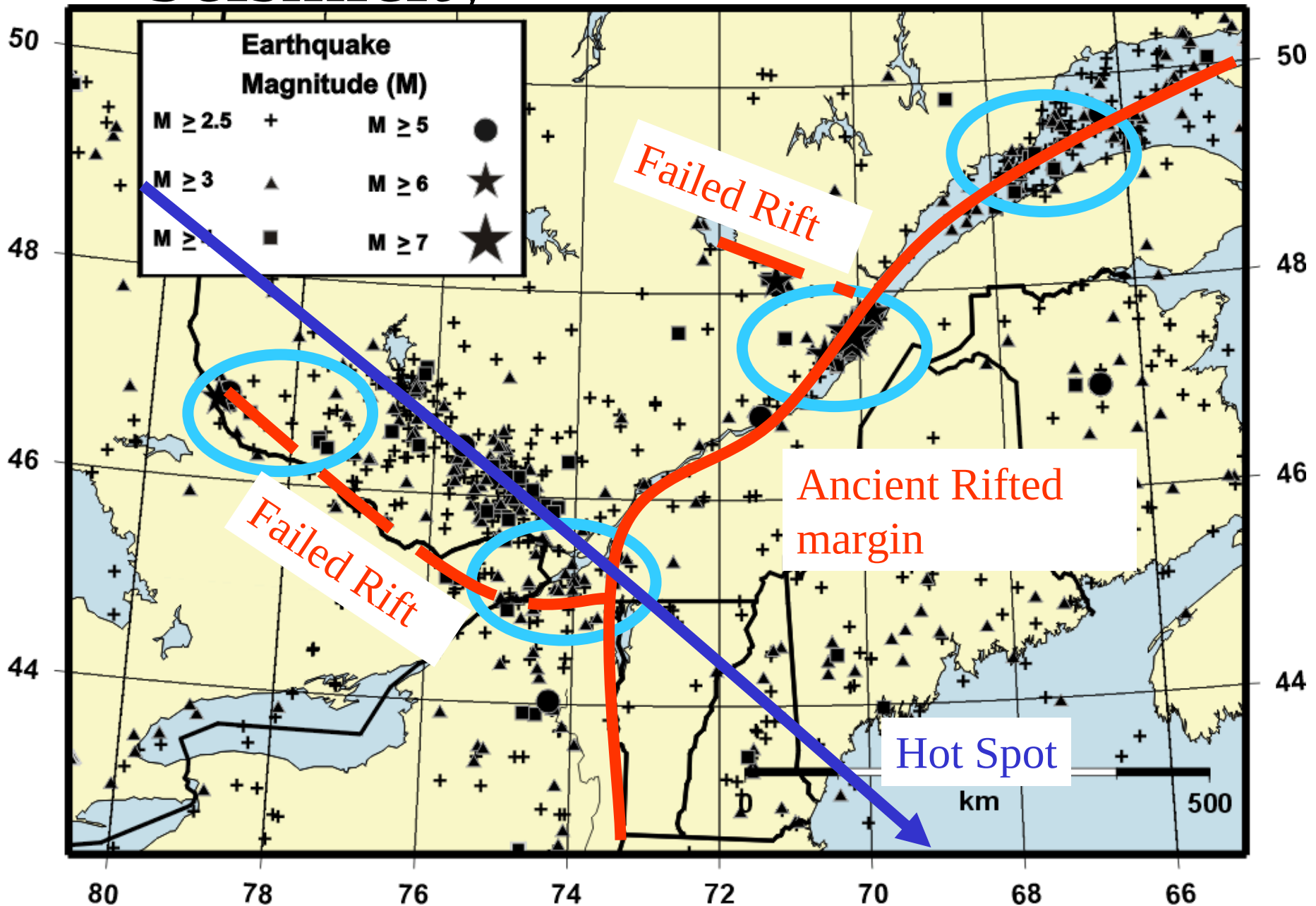


Seismicity

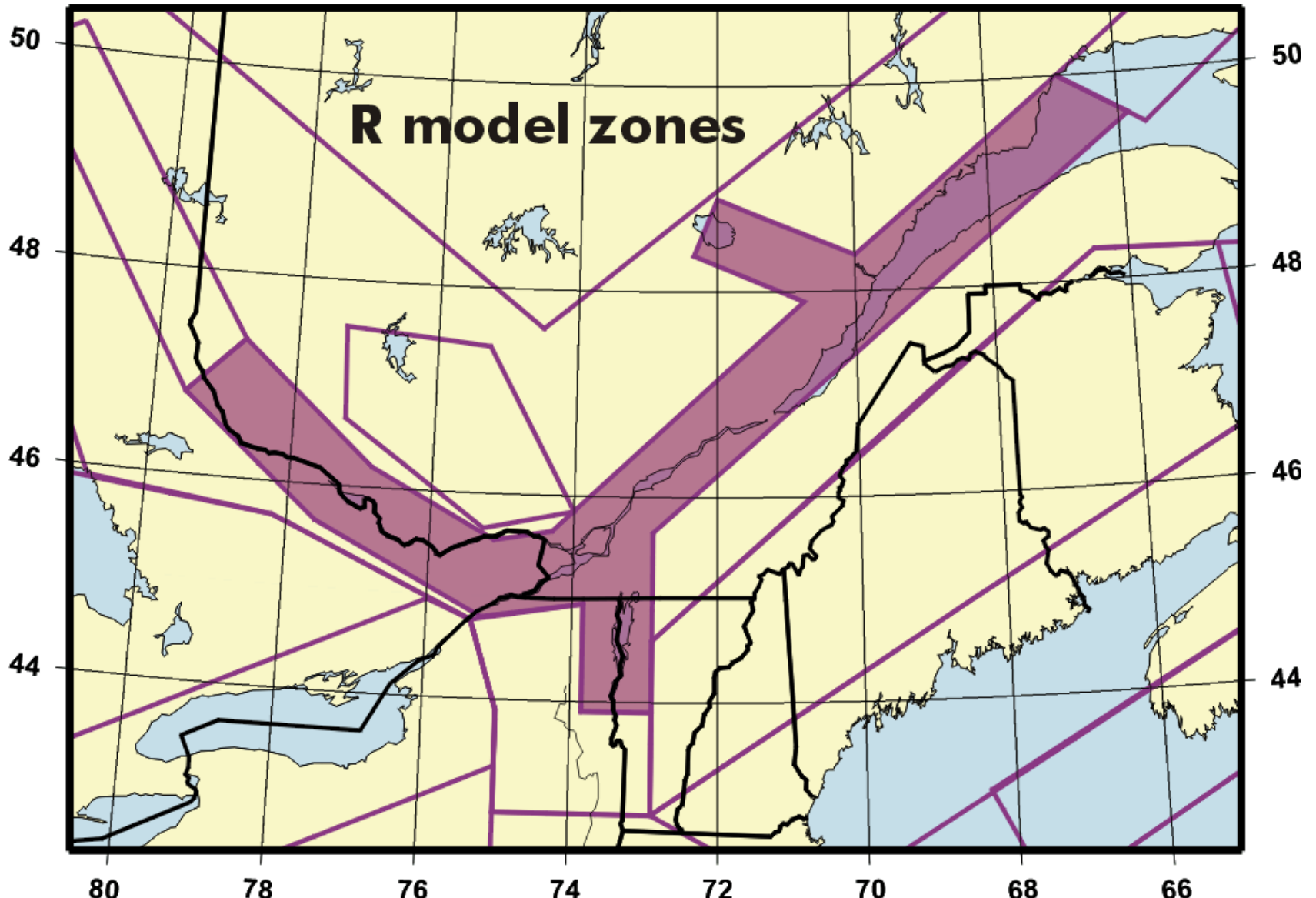


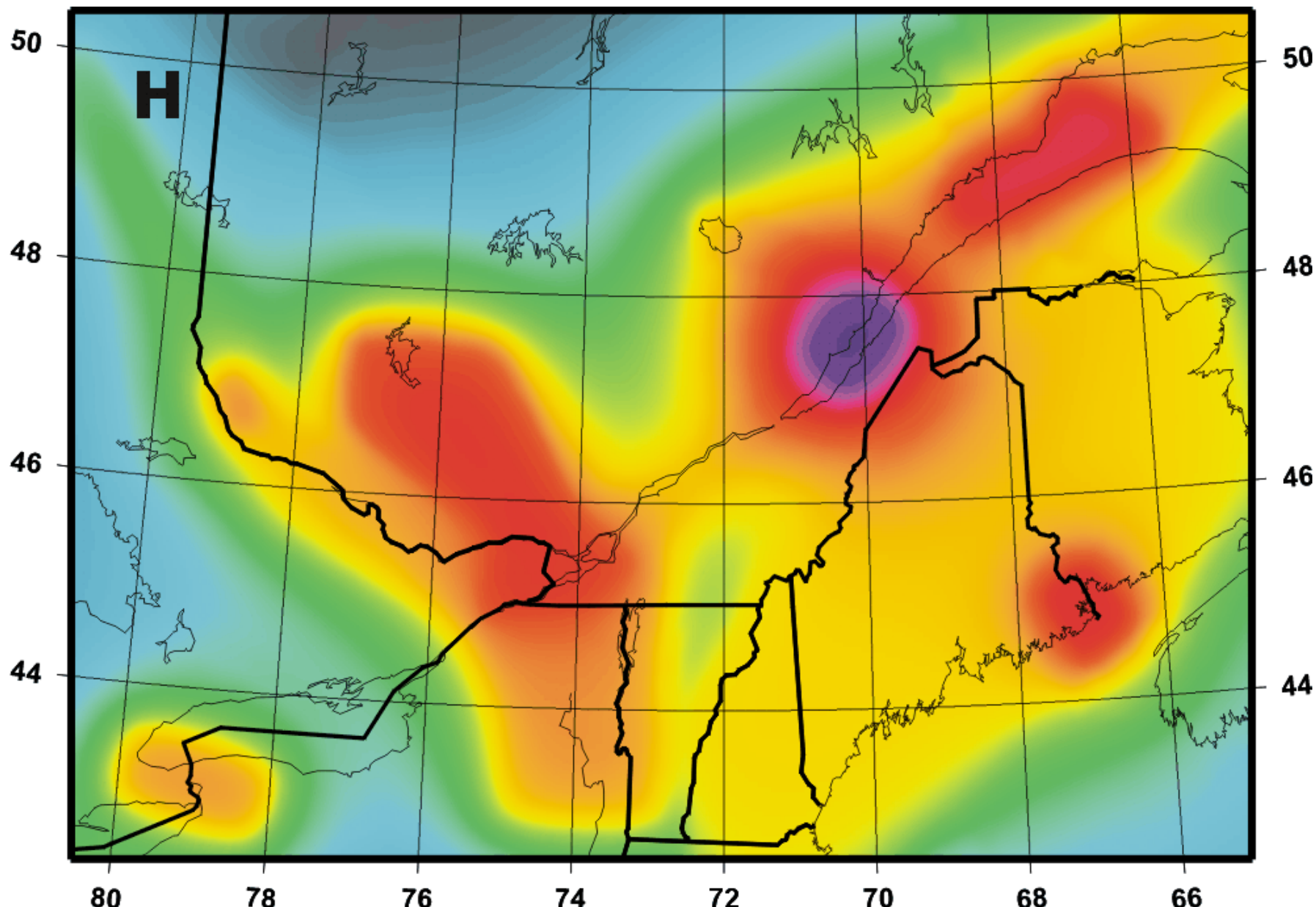


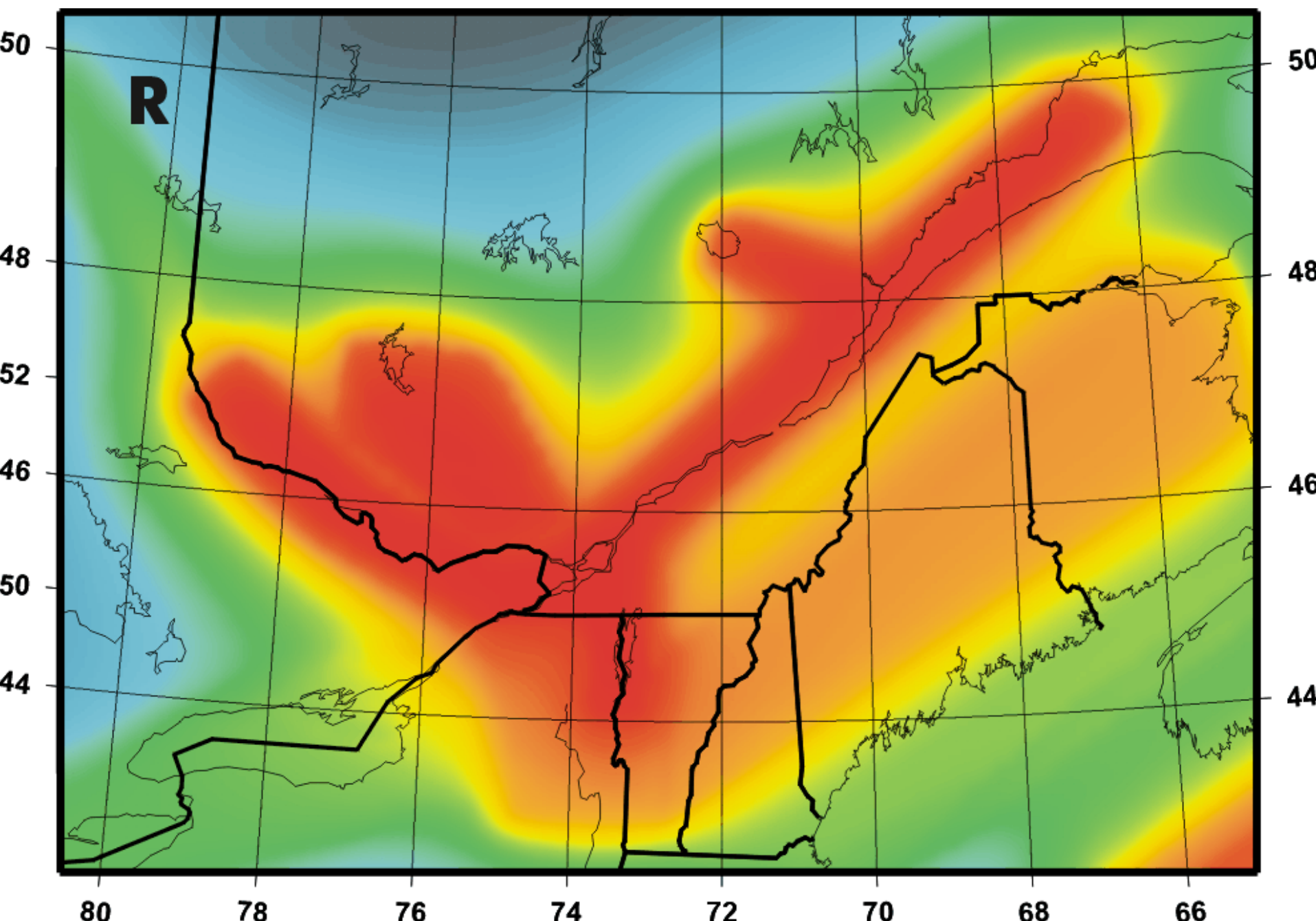
Seismicity



R = regional source

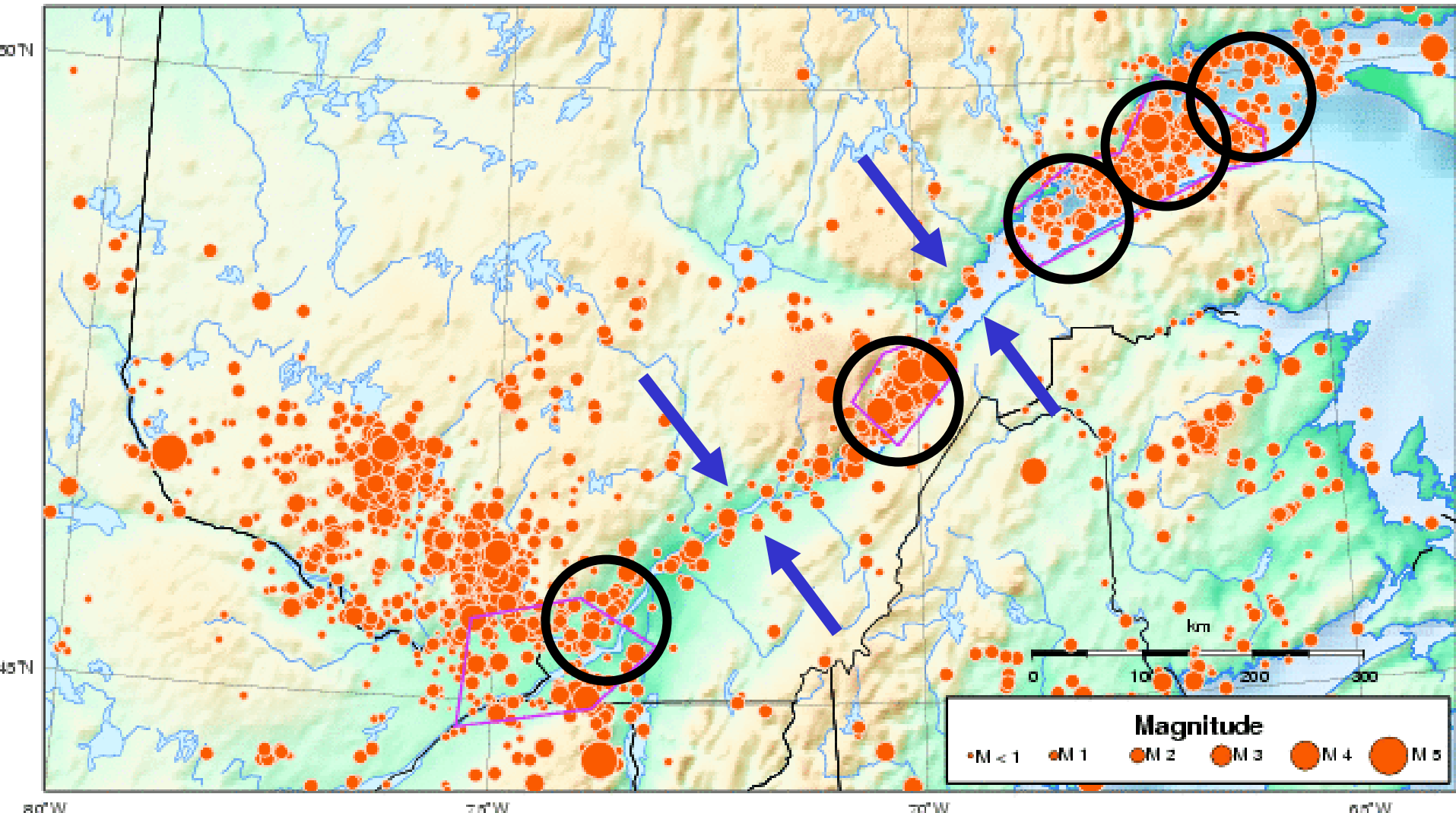




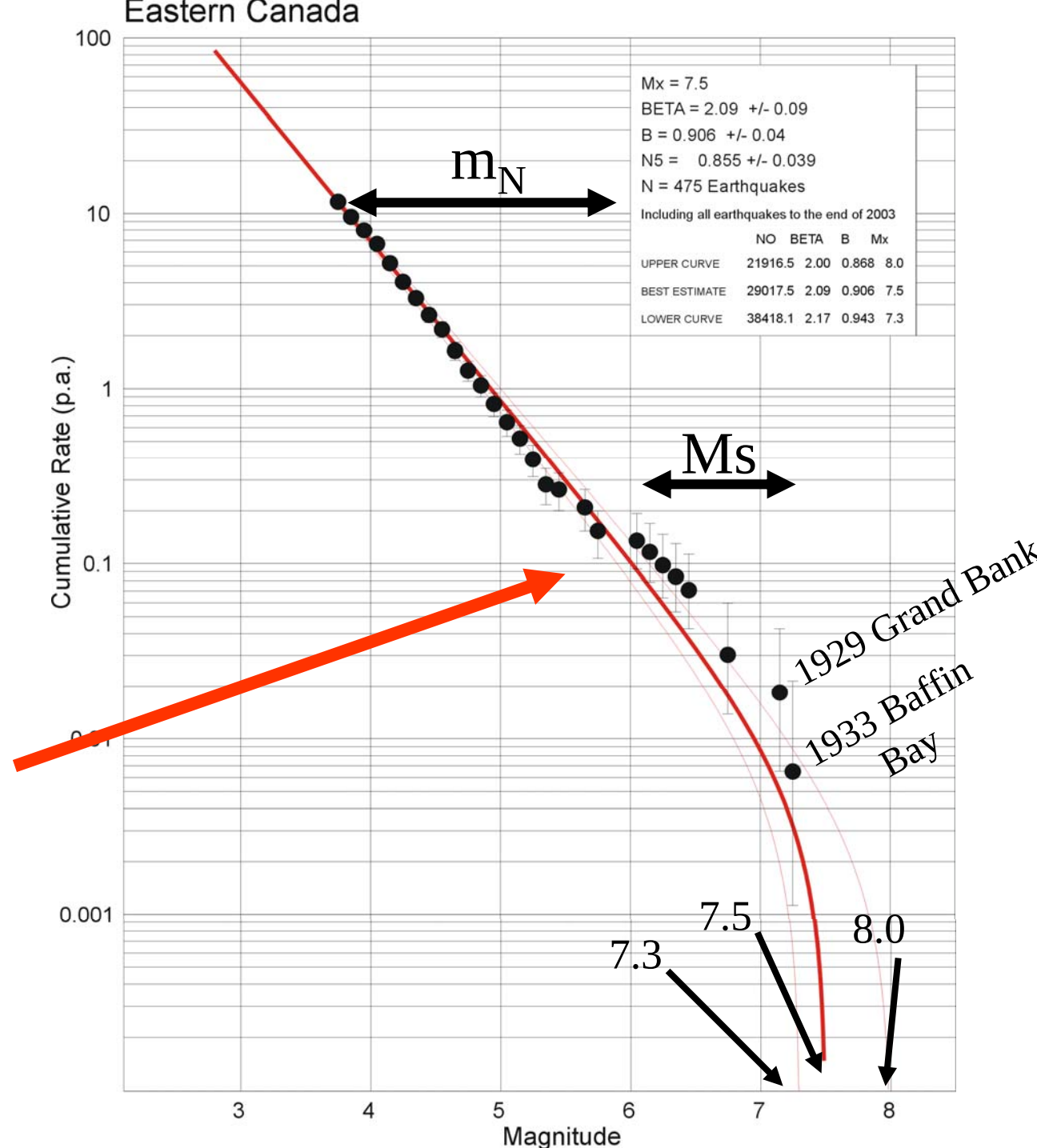
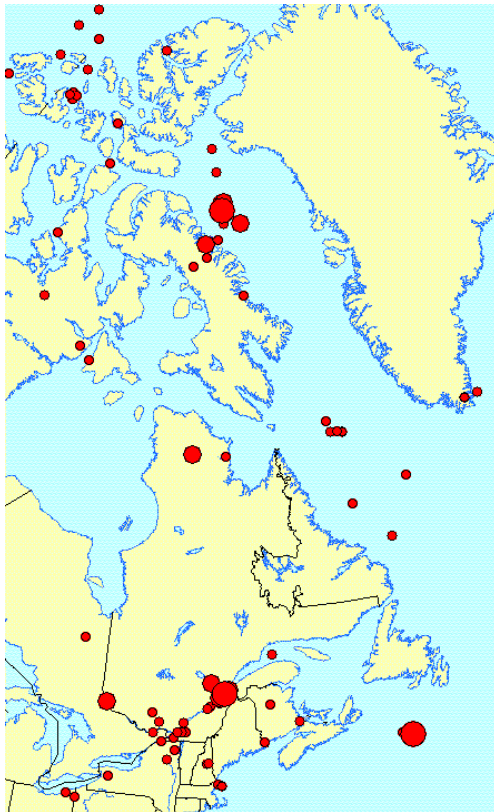


Geological structures/source zones form a way of
“filling in” between historical clusters

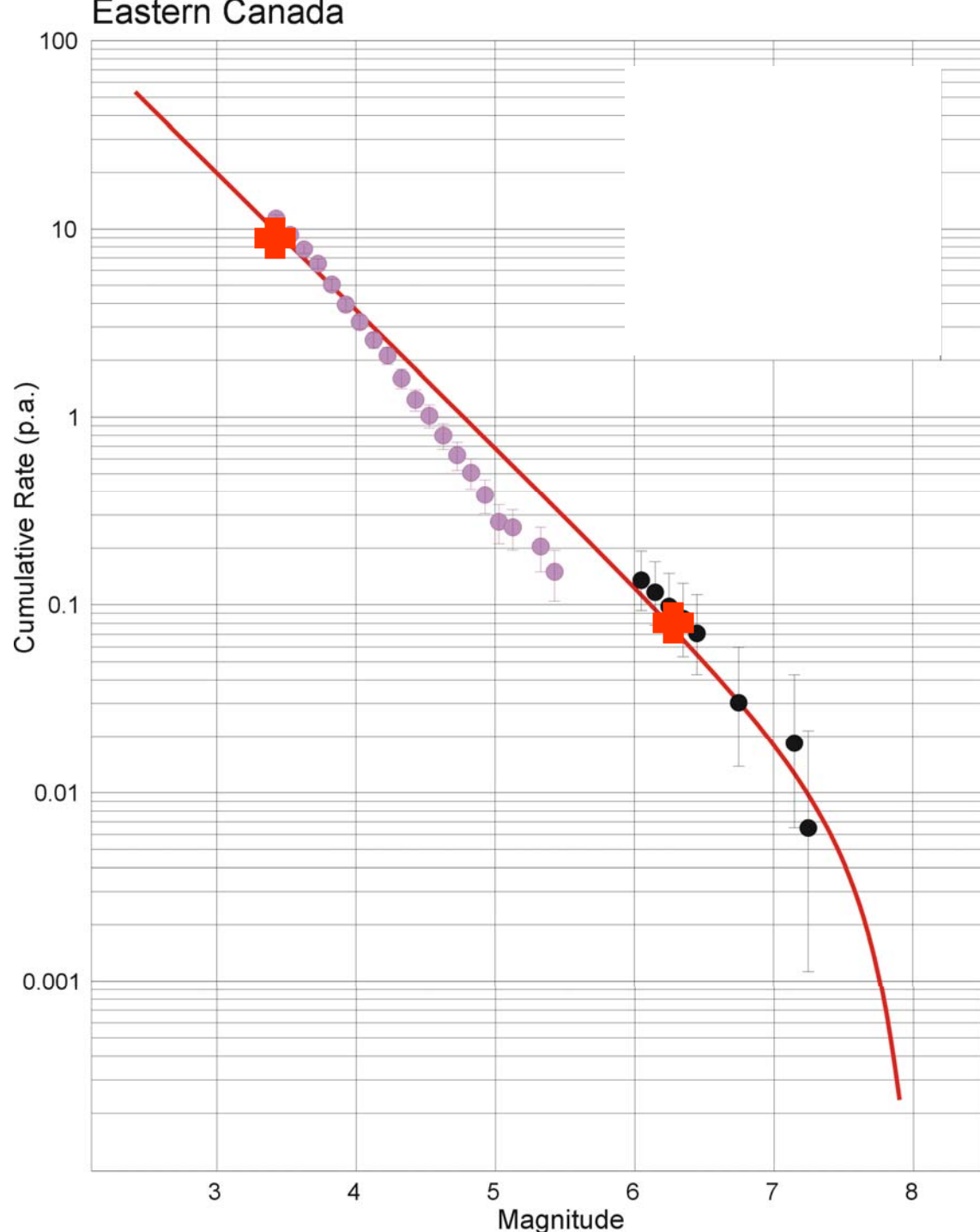
Hypothesis being supported by smaller earthquakes
2000-2006



Magnitude-recurrence for eastern Canada



Need to adjust for
mN scale used for
smaller events →
Possible revised fit
through M3, M6



Eastern Canadian experience with Mmax

Probabilistic seismic hazard is computed by integration over a range of magnitudes

from $M_{\min}$, the minimum considered event,

to $M_{\max}$, the largest considered

$M_{\max}$ cannot be smaller than the largest observed event, but otherwise there are few universally-agreed rules

Often there is a conflict between those approaching the problem from below and those approaching the problem from above



Natural Resources
Canada

Ressources naturelles
Canada

Significant
Earthquakes

1982 - 2001

Mmax: 3rd Generation Canadian Experience

Was 6.0
Got 6.6, 6.9

Nahanni 1985

Was 5.0 or 6.5

Got 6.2

Ungava 1989

Saguenay 1988

Miramichi 1982

Nisqually 2001

Was 5.0

Got 5.9

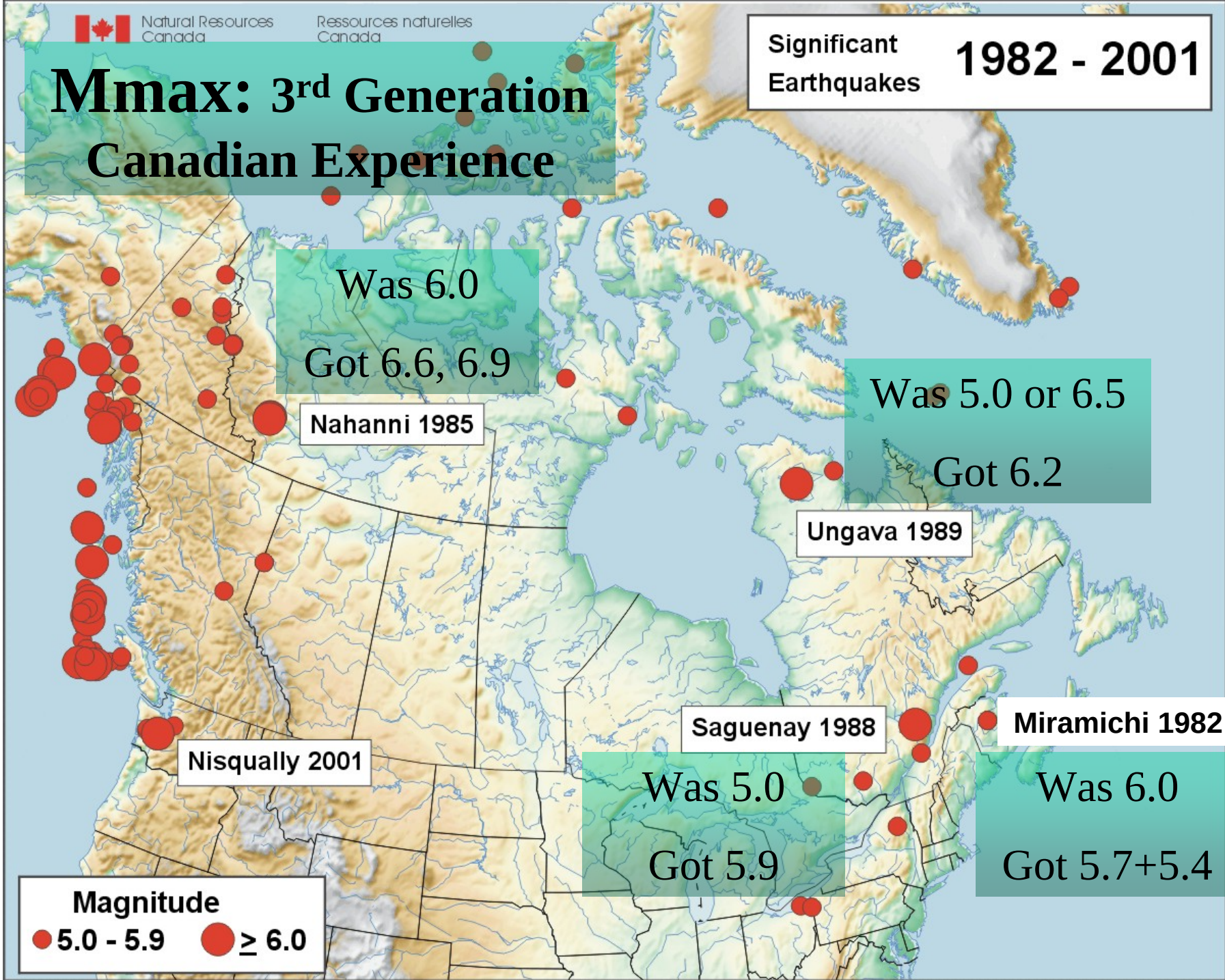
Was 6.0

Got 5.7+5.4

Magnitude

● 5.0 - 5.9

● ≥ 6.0



So **Mmax** for the 4th Generation

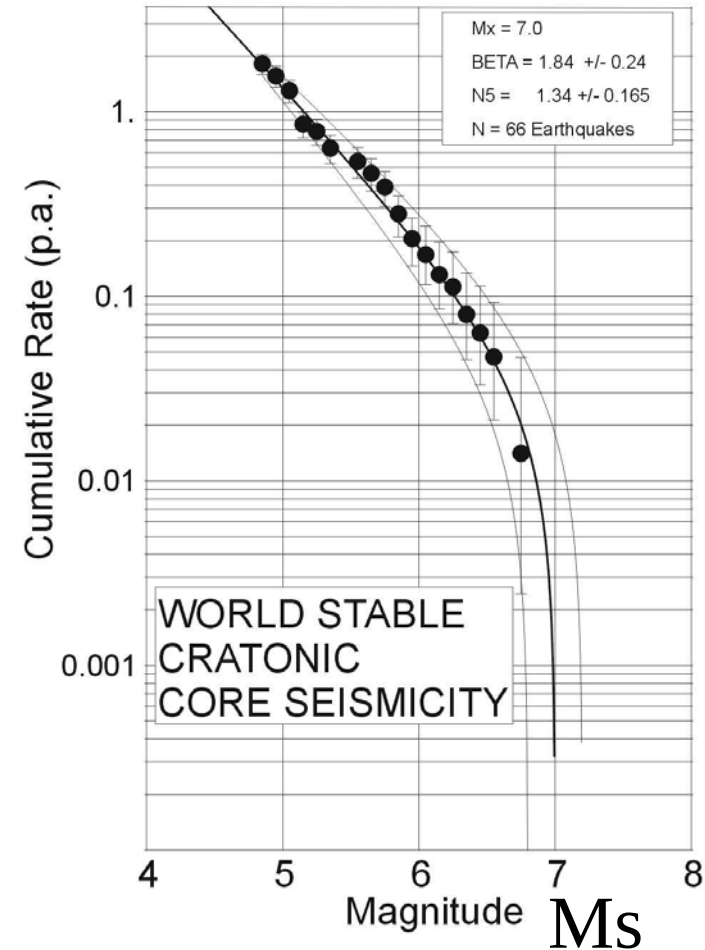
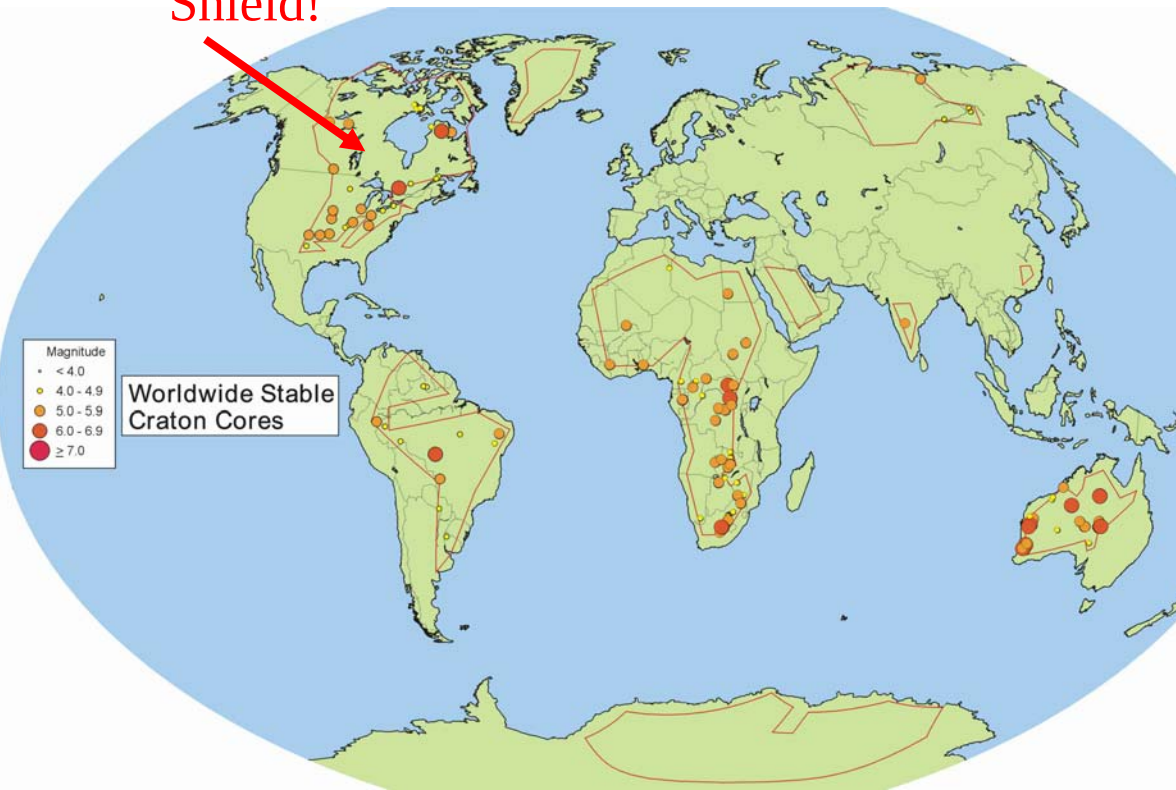
- chosen to be larger
- based on continent-scale and global analogs
- methods similar to the early 1990's EPRI study of stable continental regions
- used some geophysical constraints (e.g. thin seismogenic crust) in a few regions.

The **smallest Mmax** were taken to be the largest events from the most stable cores of the continents (7.0 ± 0.2) - could be larger given recent paleoseismic work from Australia (& South Africa- Kango Fault?).

Stable Craton Core (SCC) rates and M_{max}

Fenton and Adams, 1997; Fenton et al 2006

Places like Canadian
Shield!



Reconciling neotectonic and seismic recurrence rates in SW Western Australia.

Mark Leonard and Dan Clark

Australian Earthquake Engineering Society 2006

http://www.aees.org.au/Proceedings/2006_Papers/019_Leonard_Clark.pdf

Précised by John Adams for EPRI workshop, Palo Alto 2009 Feb 18

In all the recurrence analyses an **Mmax of 7.6** has been used. Several of the fault scarps identified on the DEMs in SW WA consistent with M7.4-7.5 earthquakes. The long period of time (100ka or more) for which it is likely that the neotectonic catalogue is complete for earthquakes >M7 make it likely that there has been several earthquakes close to Mmax.

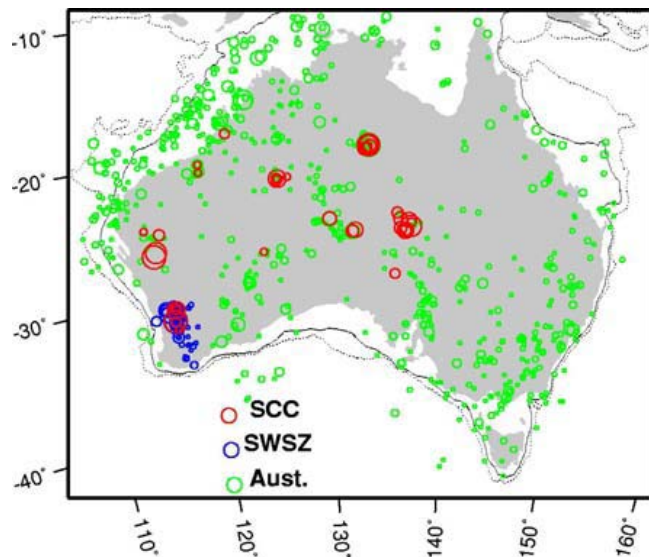
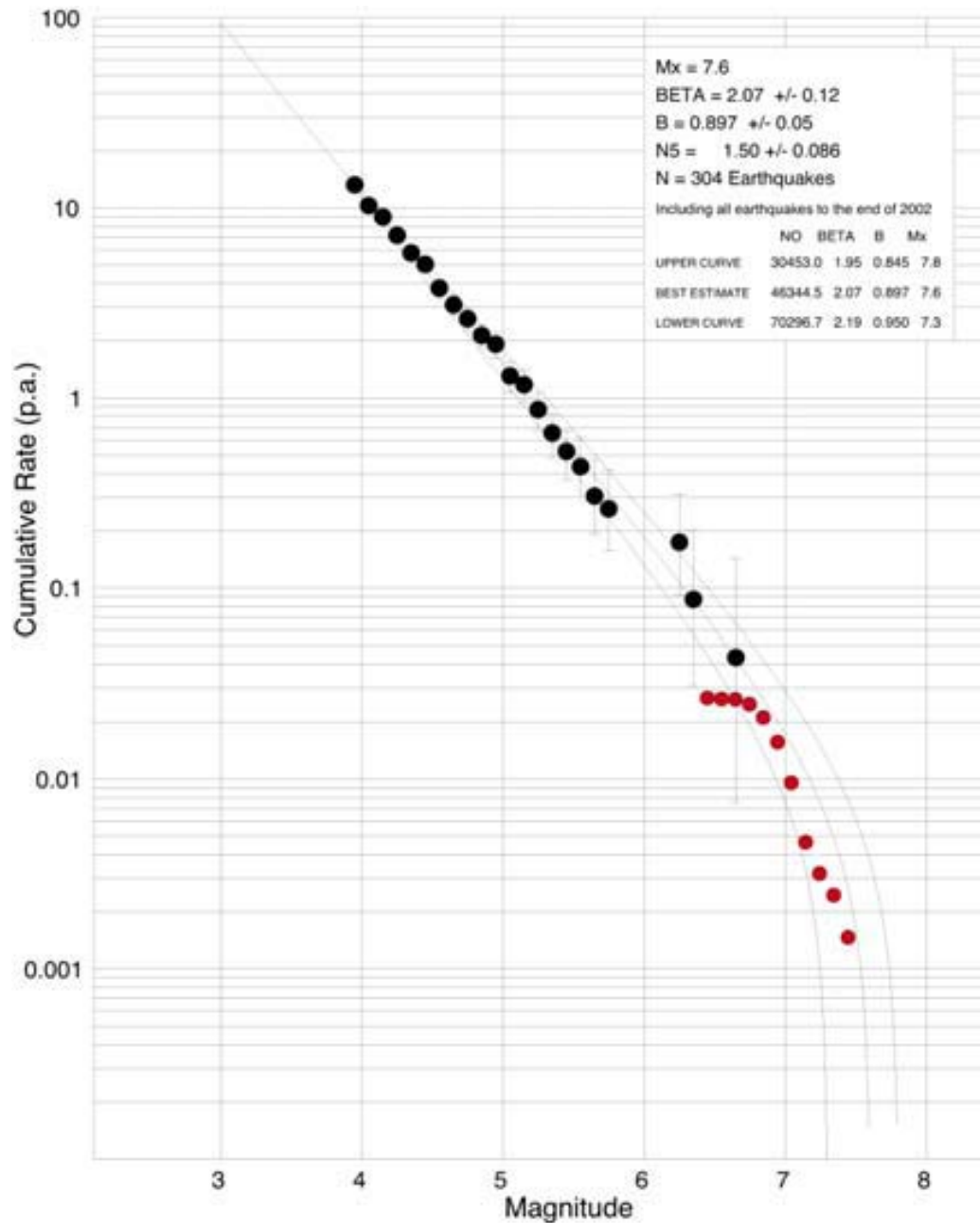


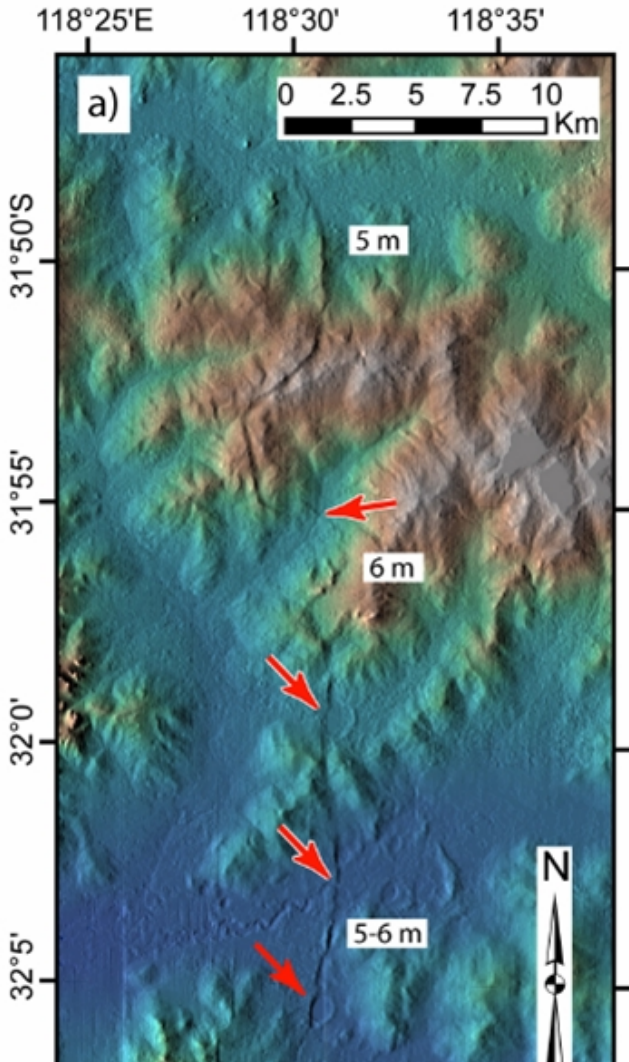
Figure 4. The recurrence rate for the Australian continent and the scaled neotectonic catalogue



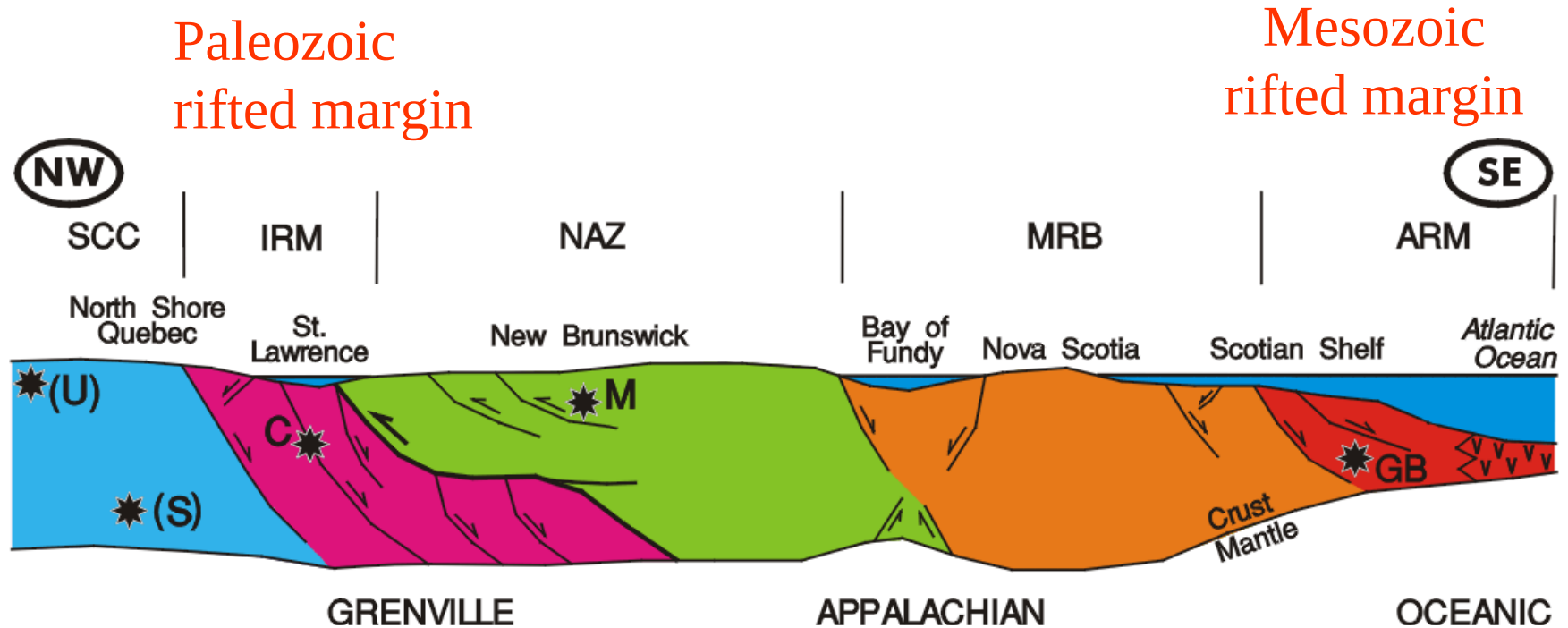
Conclusions of Leonard and Clark

At present only about $\frac{1}{4}$ of the features of have had field investigation. All those inferred scarps that were checked in the field were verified to be actual earthquake scarps. This suggests the method of identifying scarps from DEMs is valid.

1. Under the right geological and climatological conditions fault scarps can be preserved for 100ka or more for scarps from $\geq M7.3$ earthquakes.
2. Mmax stable continental crust is perhaps more like M7.5 than M7.0-7.2.
3. The recurrence rate for the neotectonic catalogue and historical earthquakes in the SCC of Australia are similar.



Mmax choices for E. Canada rifted crust



Note: The following examples are intended to be illustrative, not definitive. Complications arise because some magnitudes are Nuttli and others are Mw

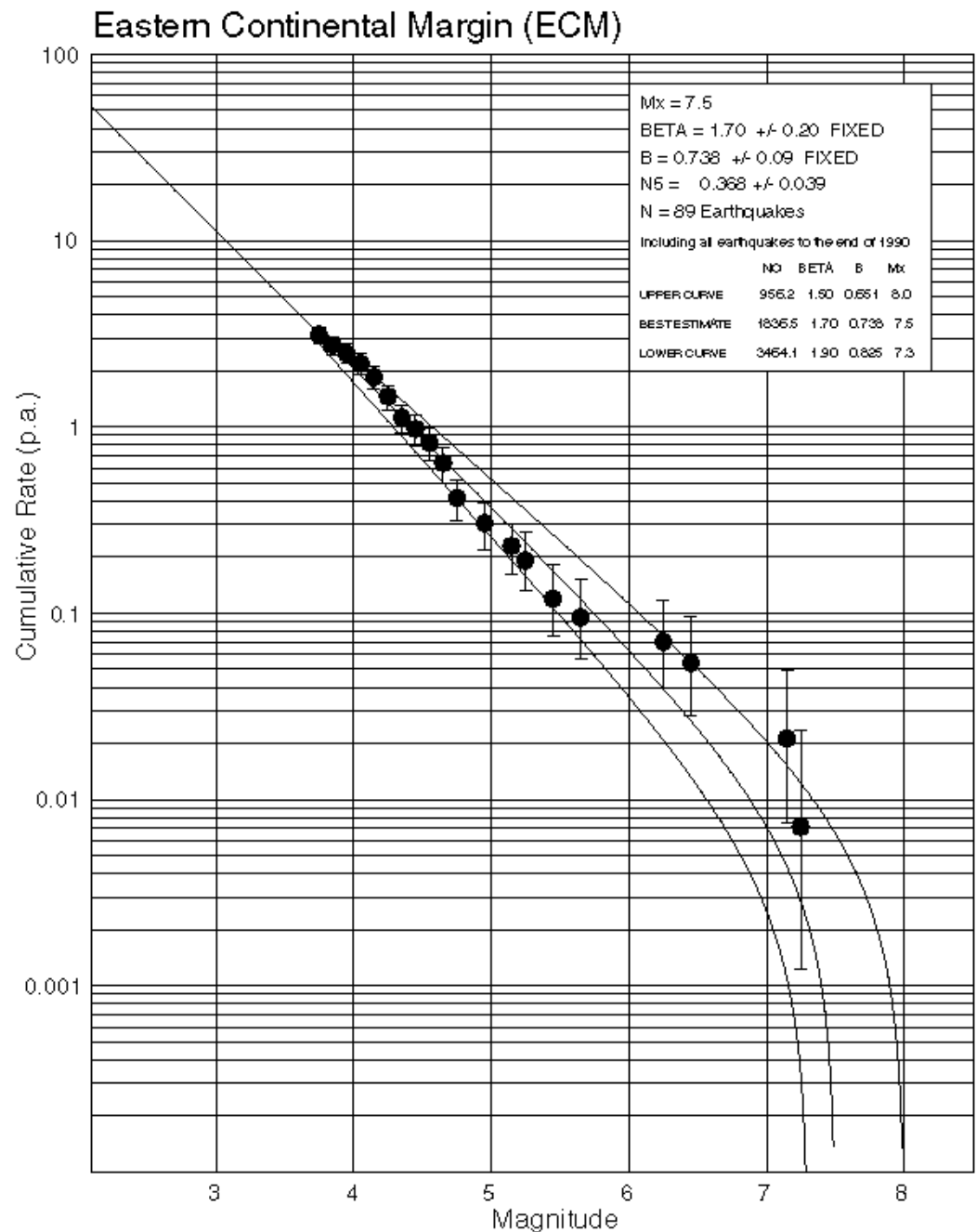
Mesozoic rifted margin

$M_{obs} \sim 7.3$

Weighted branches
best, upper, lower

7.5	8.0	7.3
0.68	0.16	0.16

Plenty of potential
large faults $\rightarrow M8$



Paleozoic rifted margin (1)

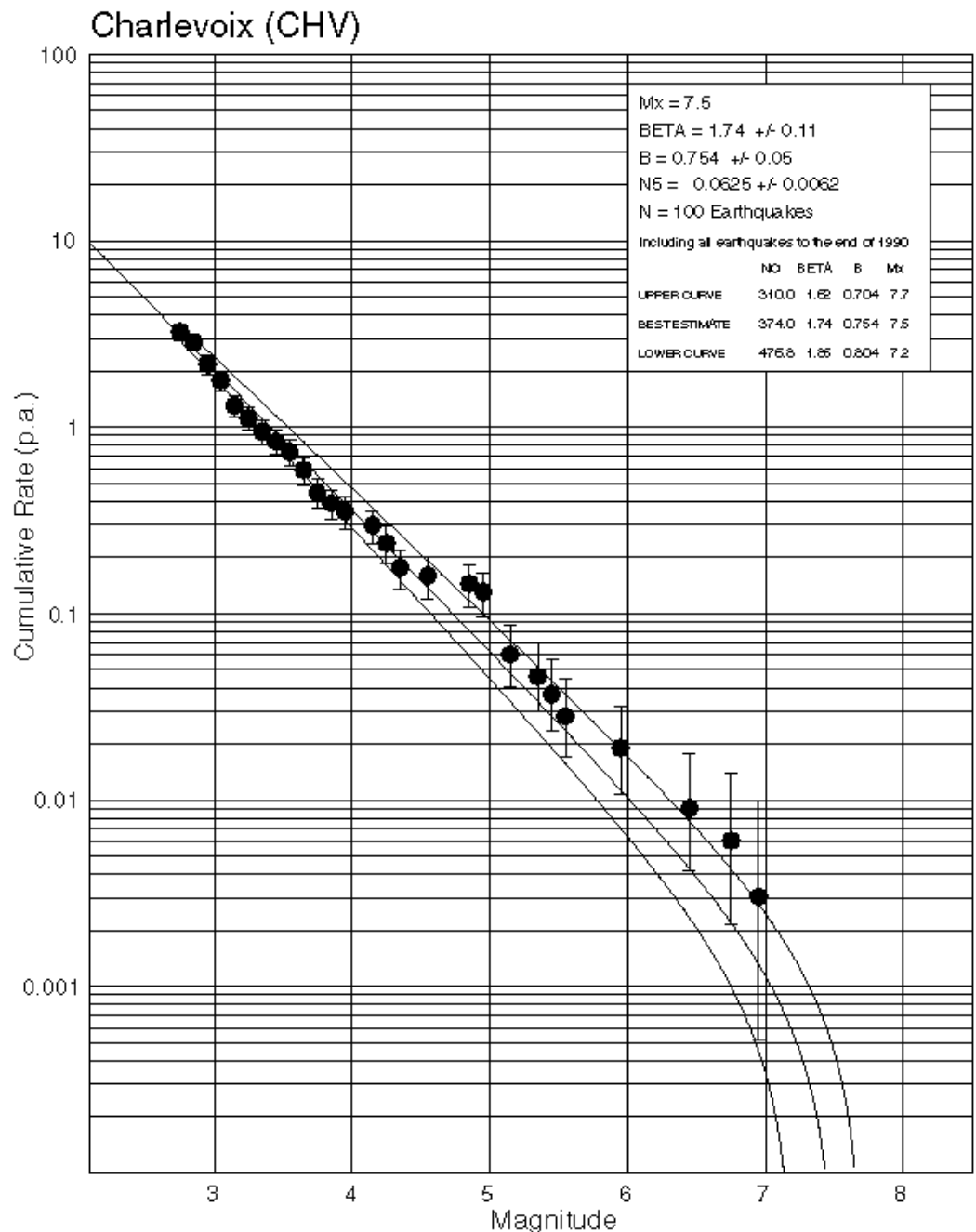
Mobs ~ 7.0

Weighted branches
best, upper, lower

7.5	7.7	7.2
0.68	0.16	0.16

Enough potential large
faults

Not large enough? (why
not $\geq$ New Madrid)



Interior
?slightly extended

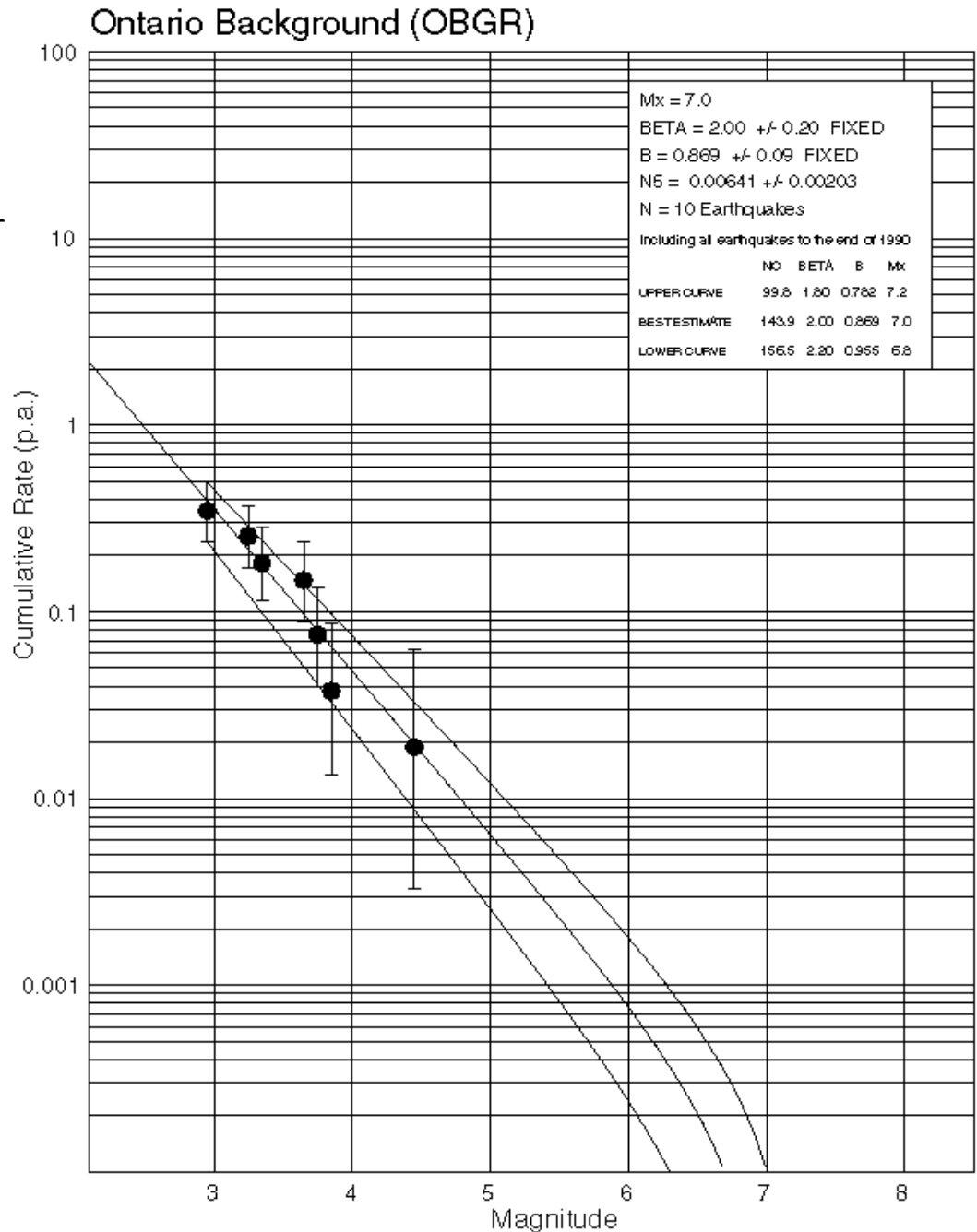
Mobs < 5.0

Weighted branches
best, upper, lower

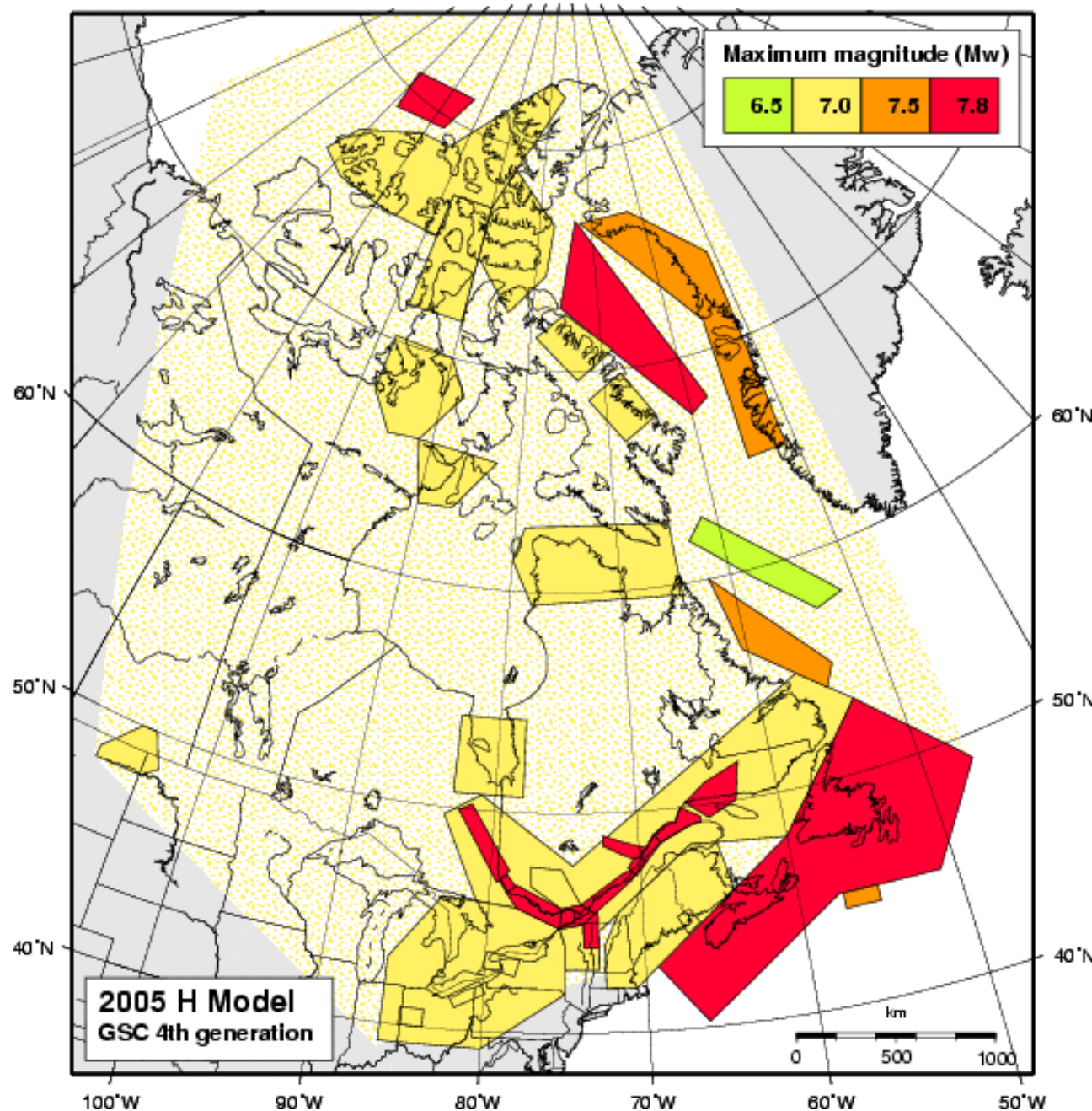
7.0	7.2	6.8
0.68	0.16	0.16

potential large faults?

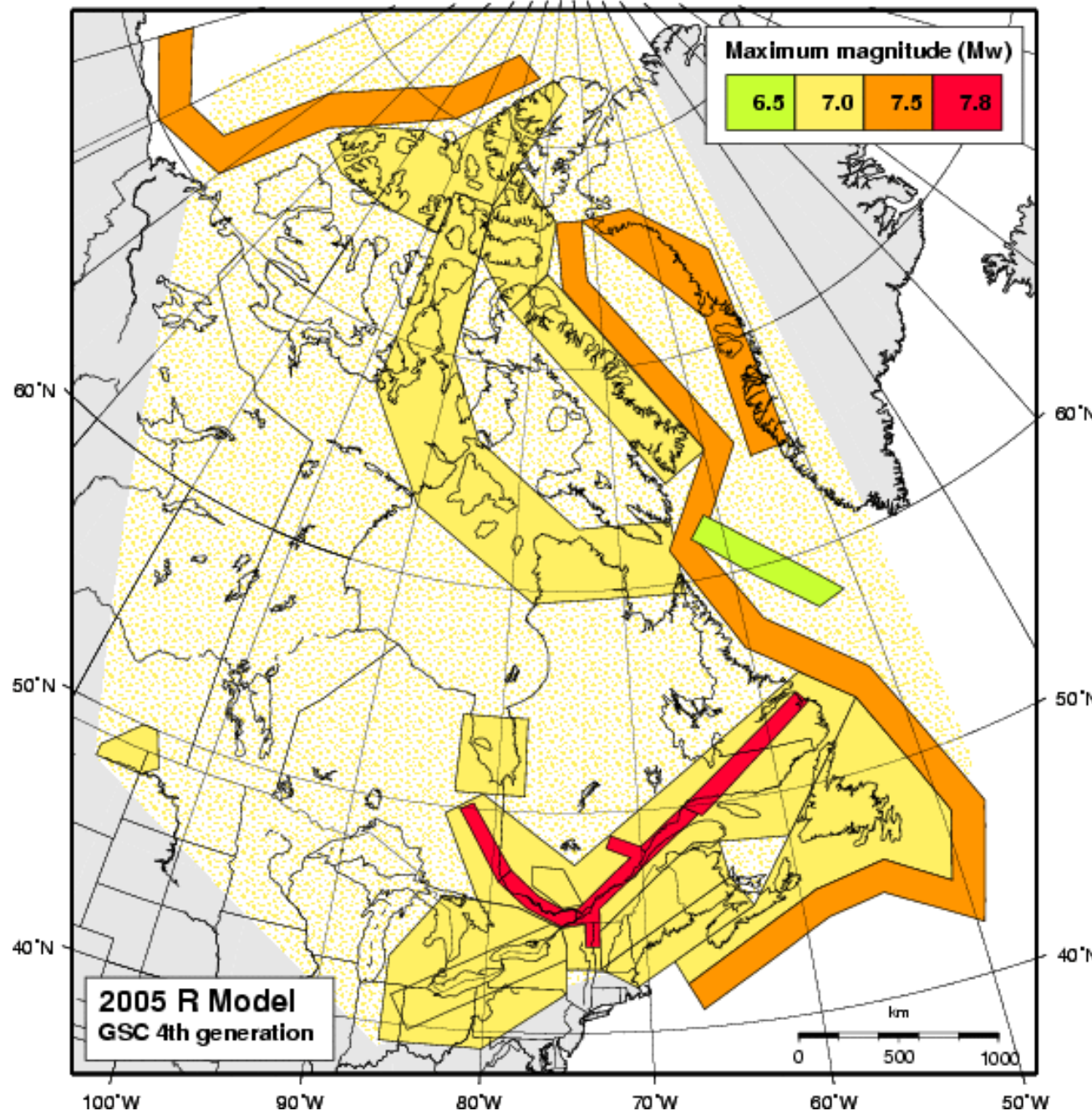
consistent with SCC



2005 as-
implemented
for
“Historical
clusters”
model

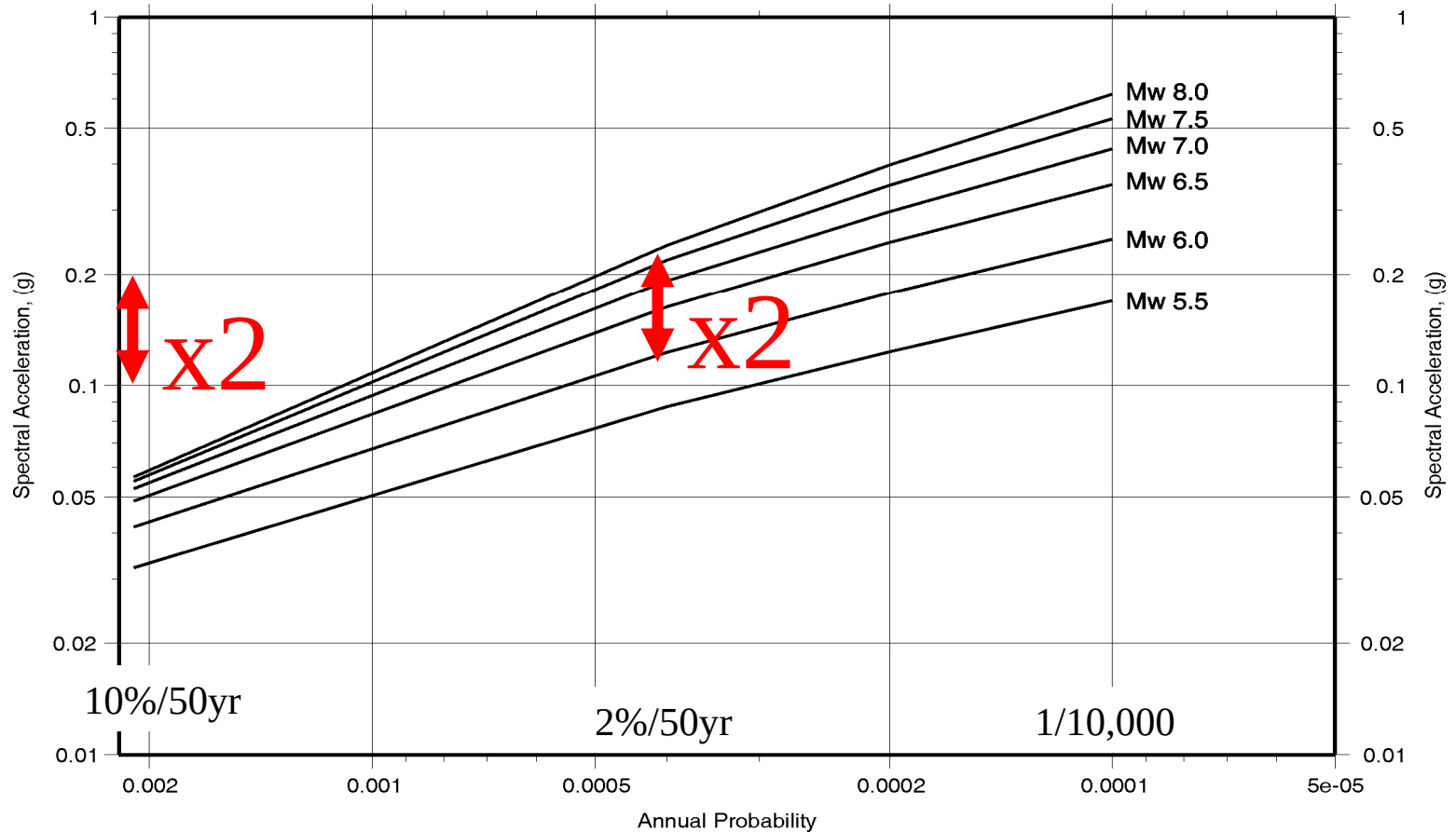


2005 as-
implemented
for
“Geological
sources”
model



Mmax can matter

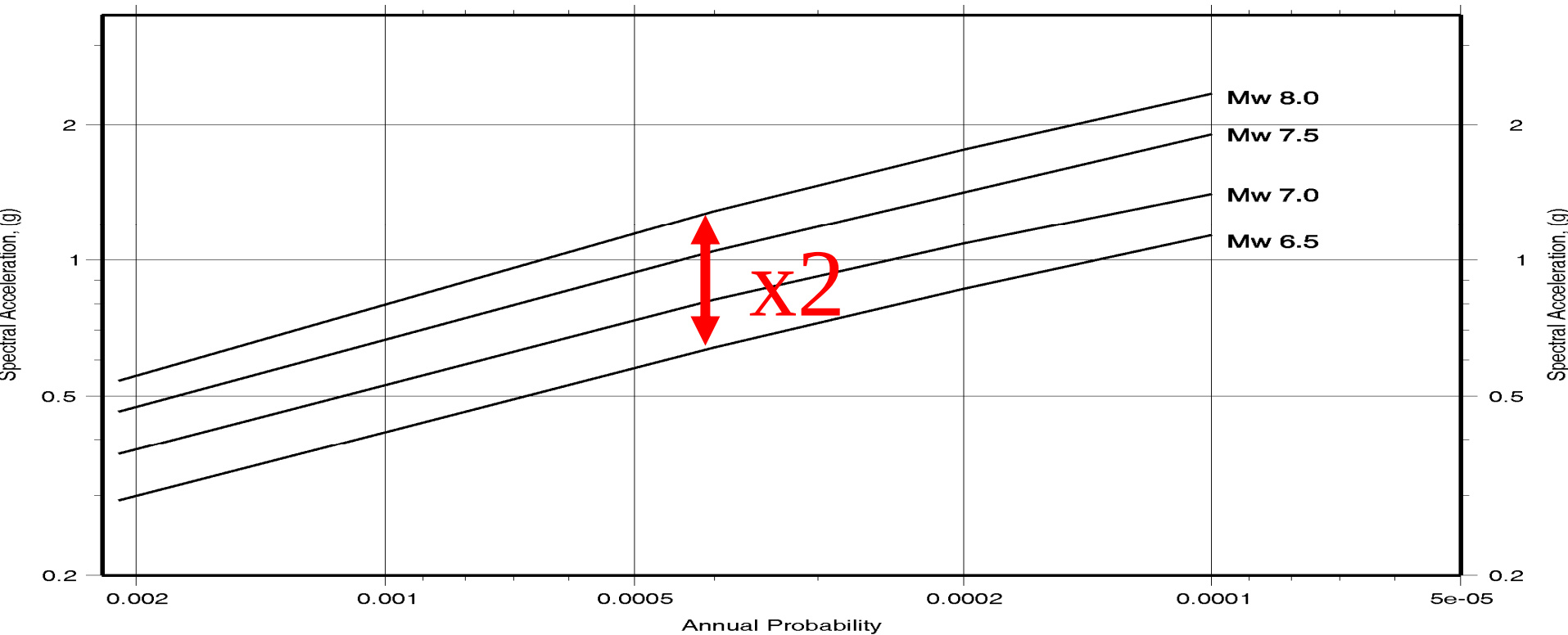
Hazard curves for low-seismicity source (Niagara)



Sa(0.5) second hazard curves for test site in centre of NAT zone

Mmax can matter

Hazard curves for high-seismicity source (Charlevoix)



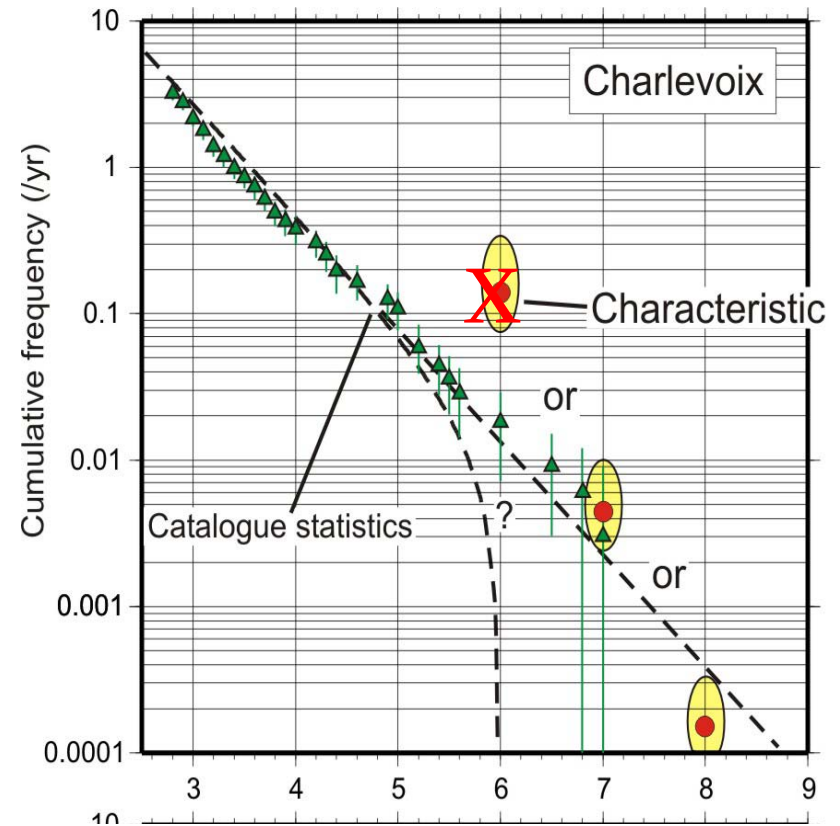
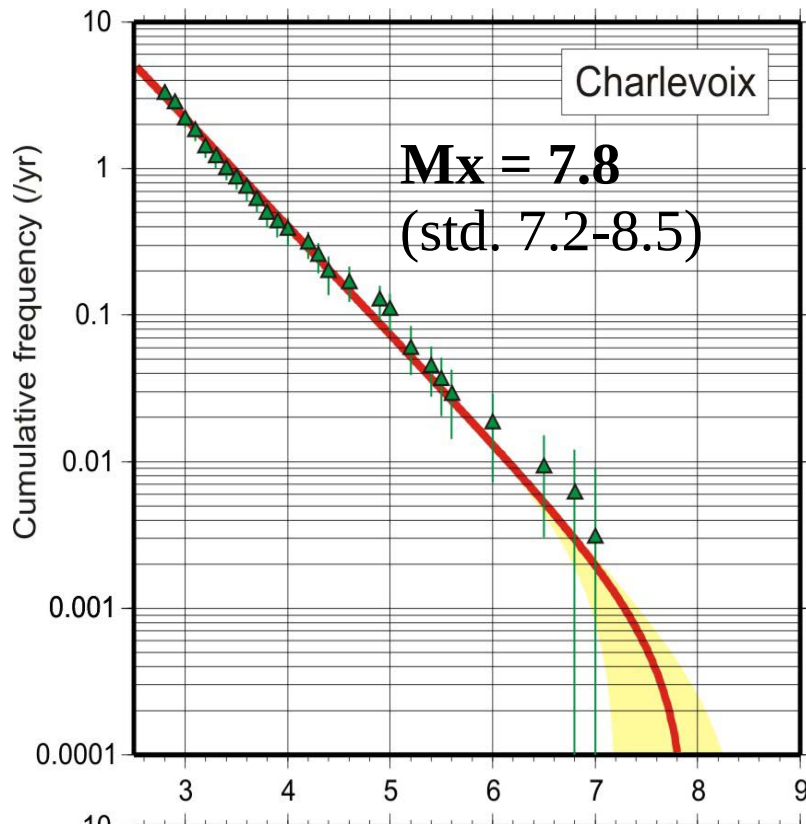
Sa(0.5) second hazard curves for test site in centre of CHV zone

GPS & Seismic Hazard

GPS convergence rate: $\sim 0.7 \pm 0.4$ mm/yr

Mazzotti's work using GPS

- Places uncertain upper limits on $M_{\max}$
- May provide additional constraints as longer time series are evaluated

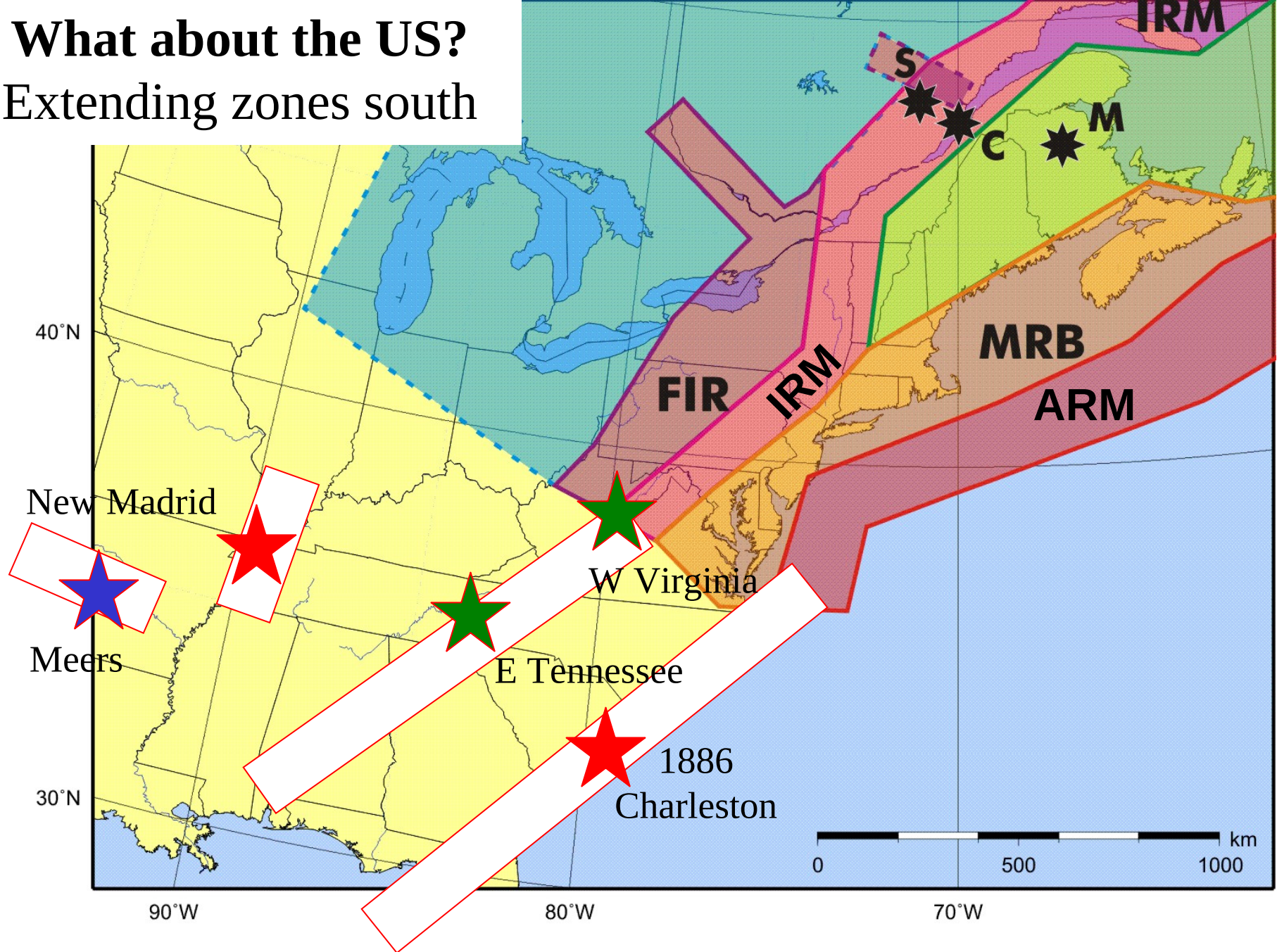


Thoughts

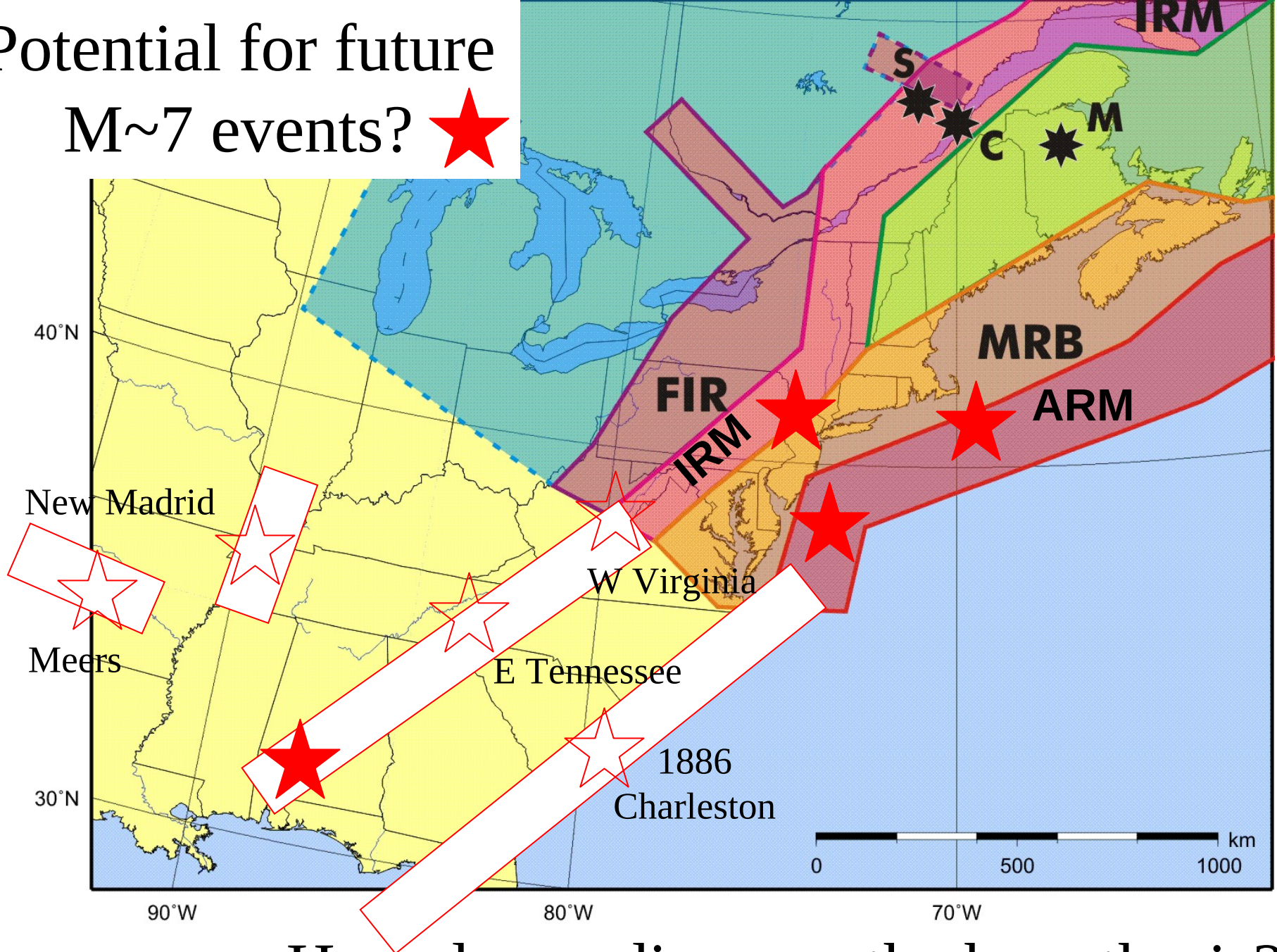
- Cannot rule out large earthquakes anywhere
- Certainly $M_{\max} \sim 7.0 M_w$ everywhere, probabilities will be very low in many SCR areas
- Phanerozoic rifted crust contains enough long and deep faults (or fault systems) that $M_{\max} \sim 8.0 M_w$ seem plausible
- Hazard is sensitive to $M_{\max}$, if the adopted range of $M_{\max}$ is large

What about the US?

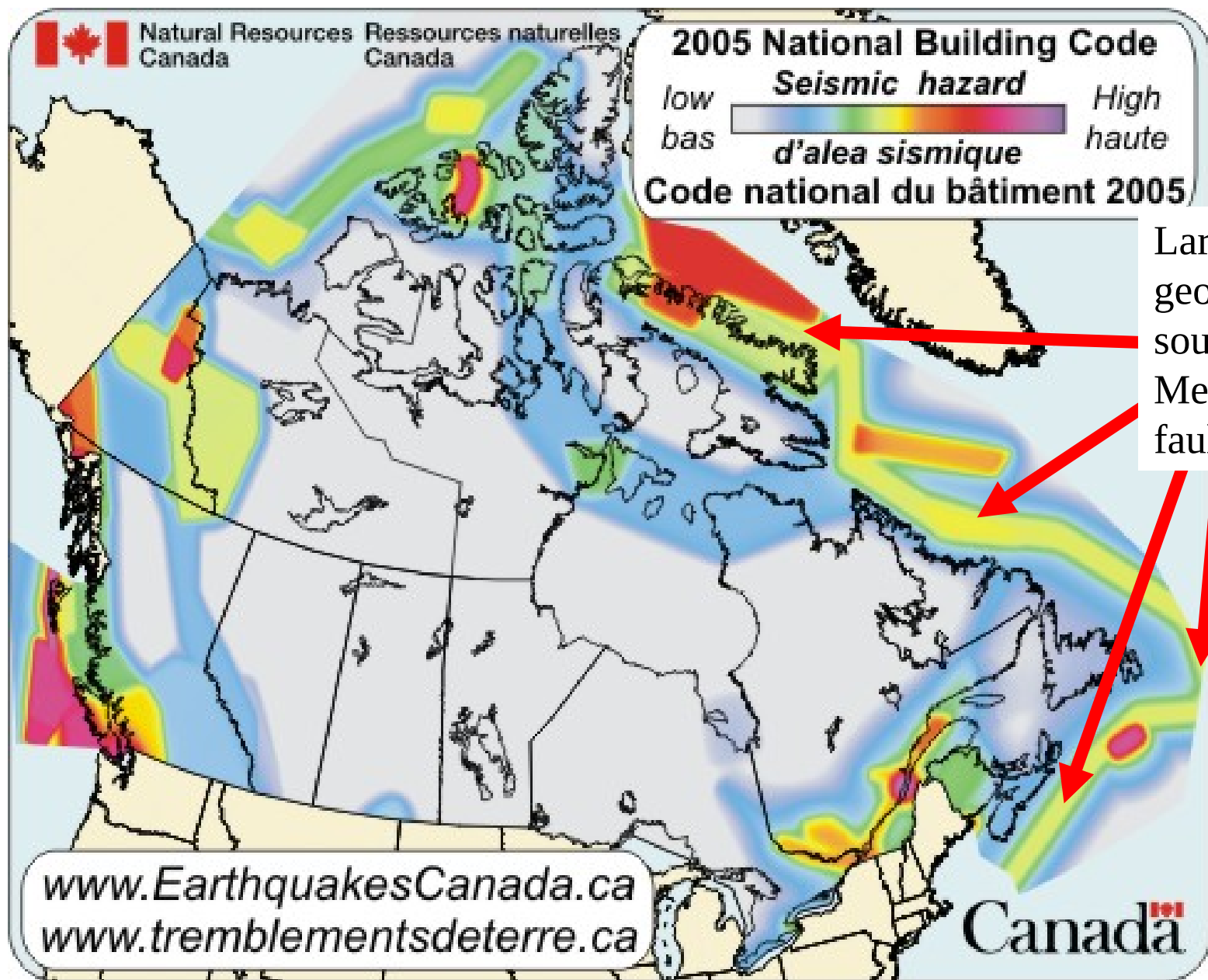
Extending zones south



Potential for future
M~7 events? ★



How do we disprove the hypothesis?

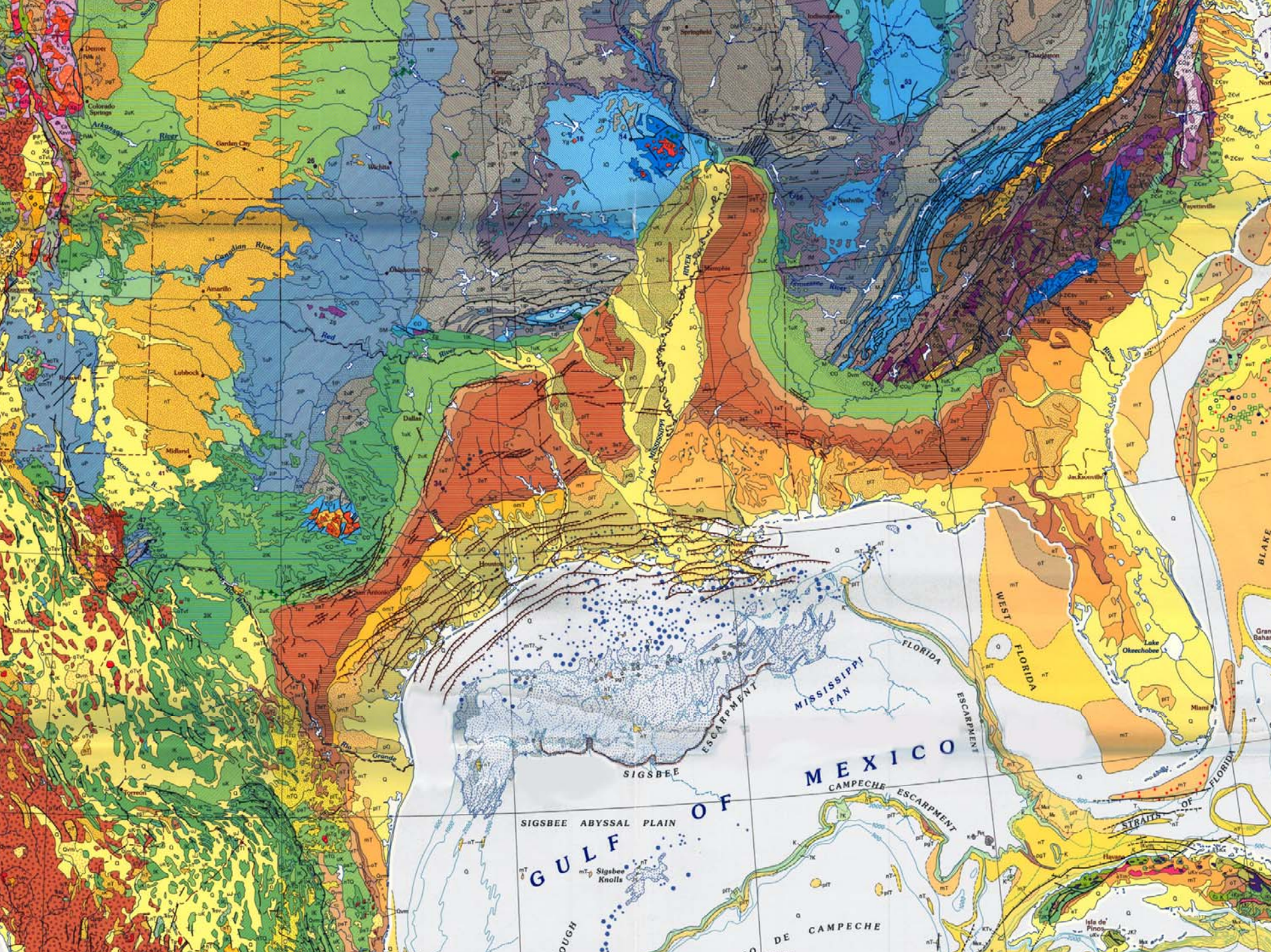


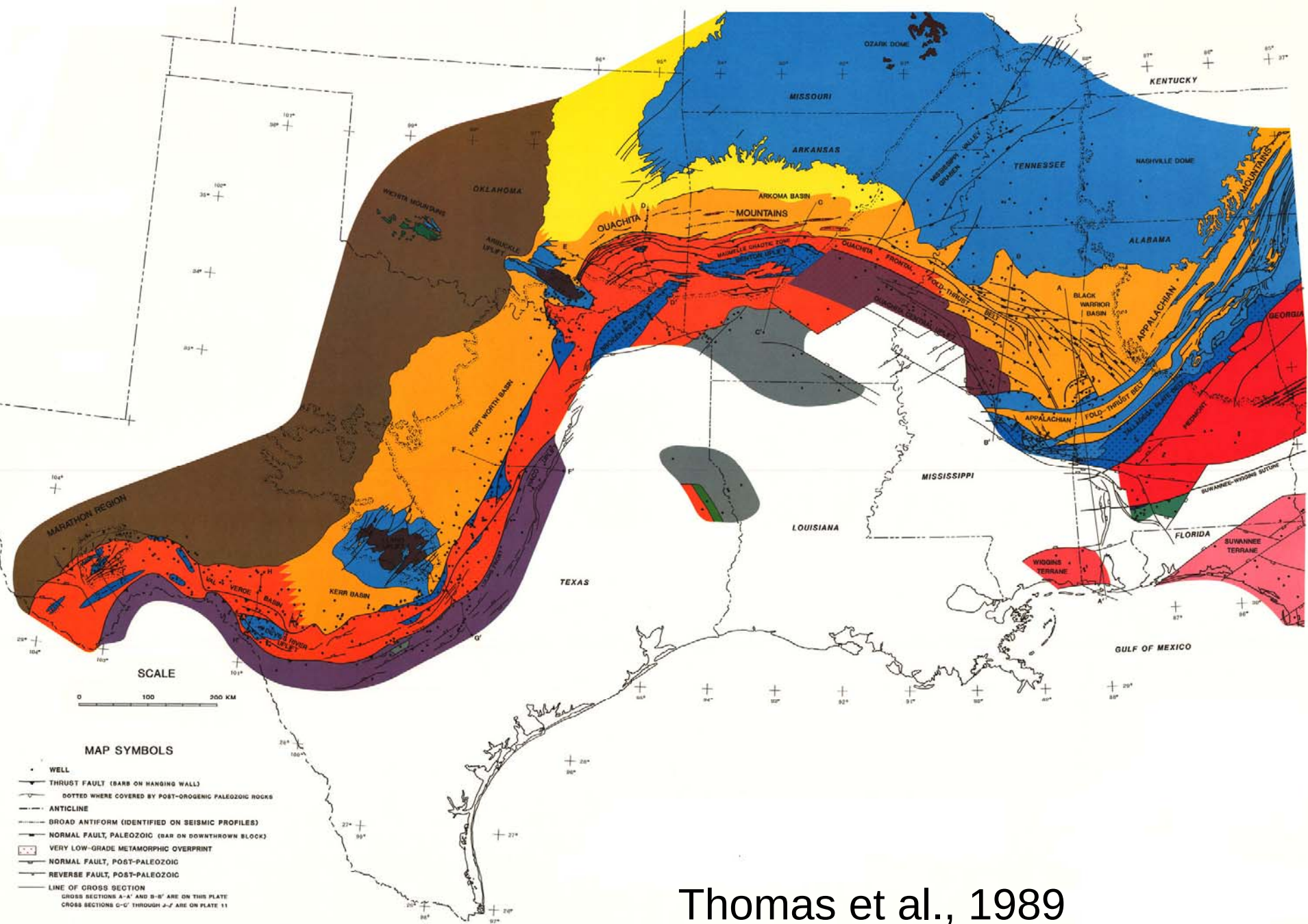
Thank You!

CEUS SEISMIC SOURCE CHARACTERIZATION

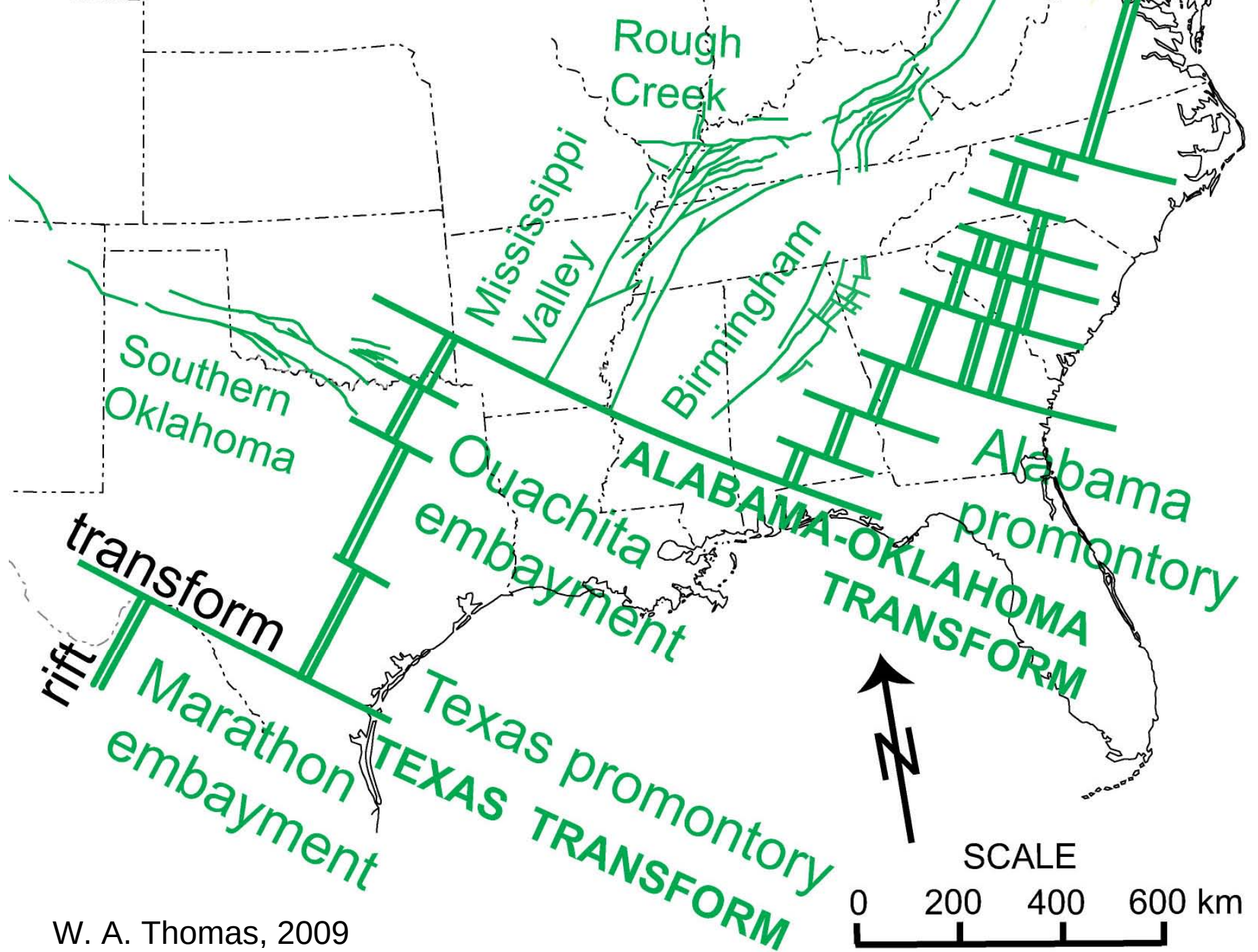
OUACHITA SUB-DETACHMENT STRUCTURES

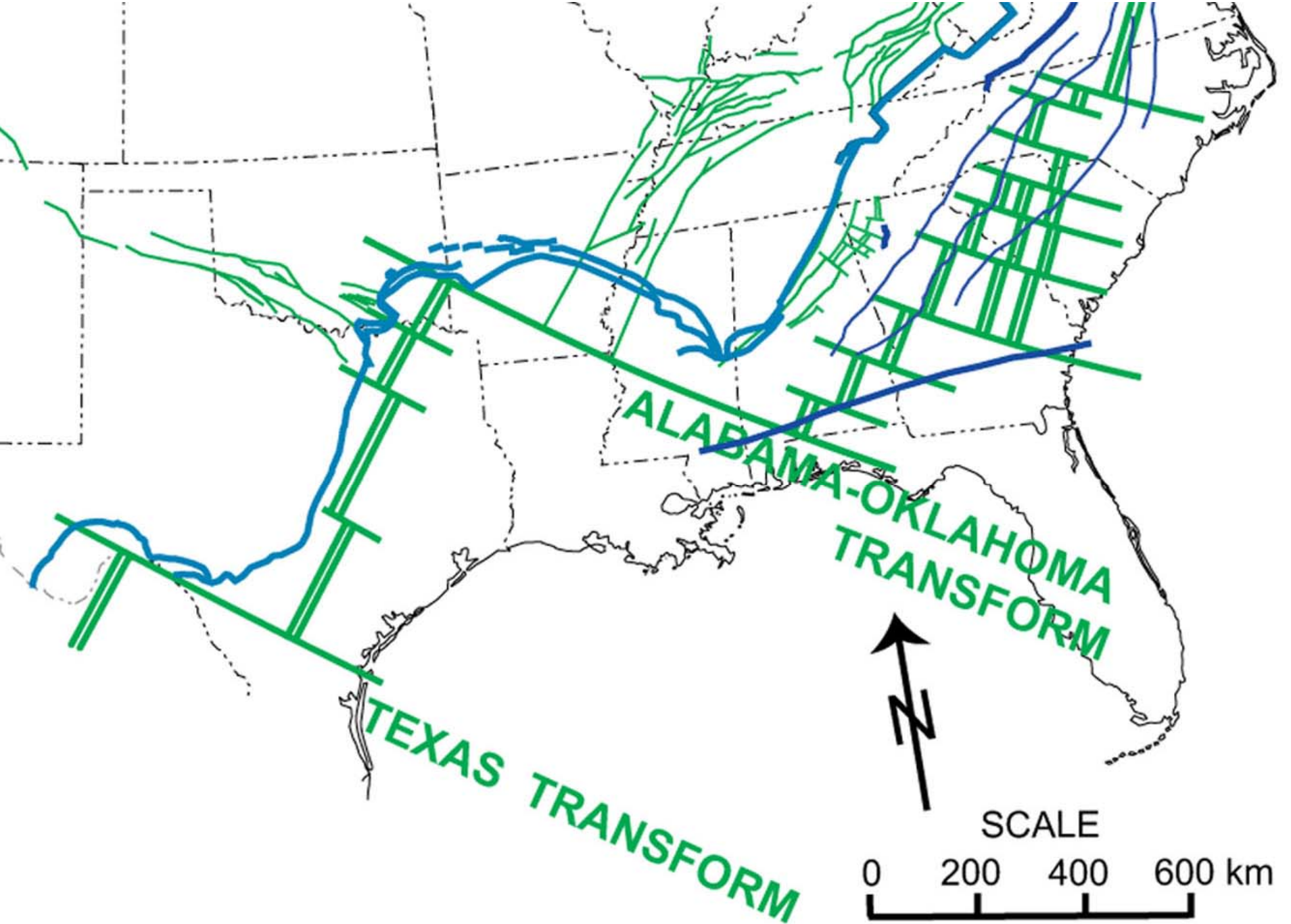
William A. Thomas
University of Kentucky

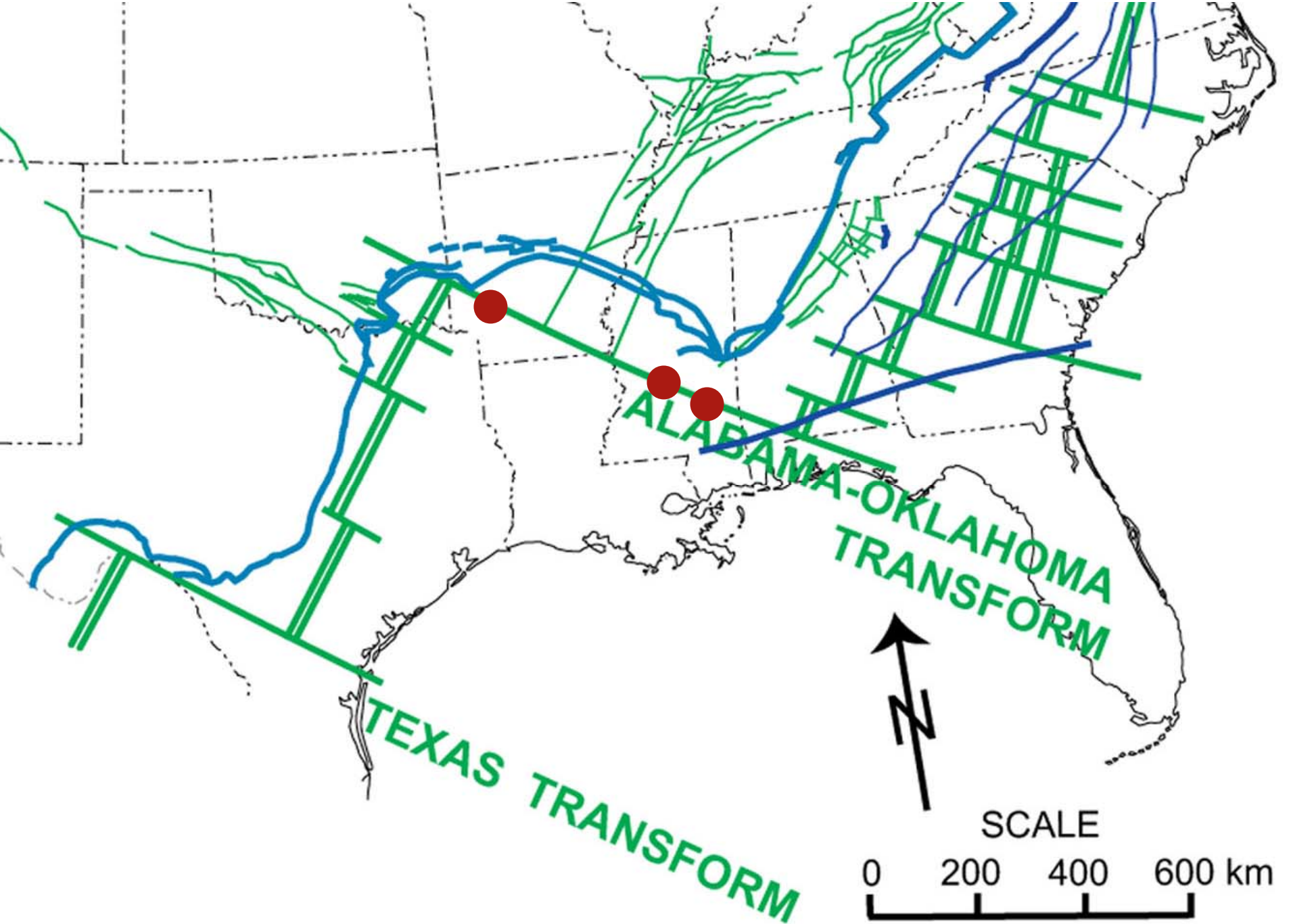


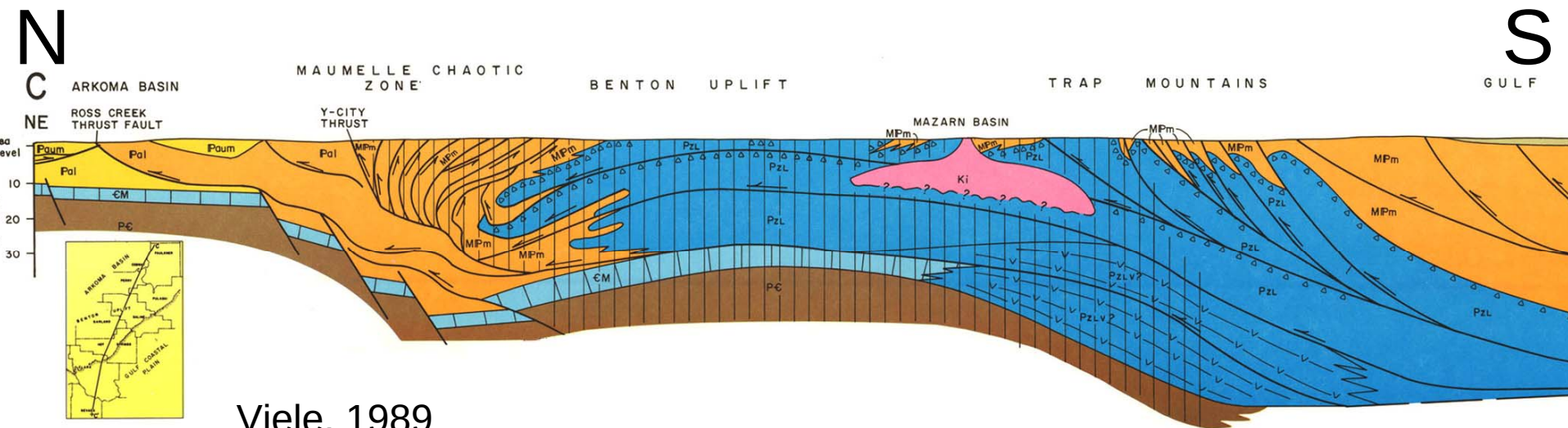


Thomas et al., 1989

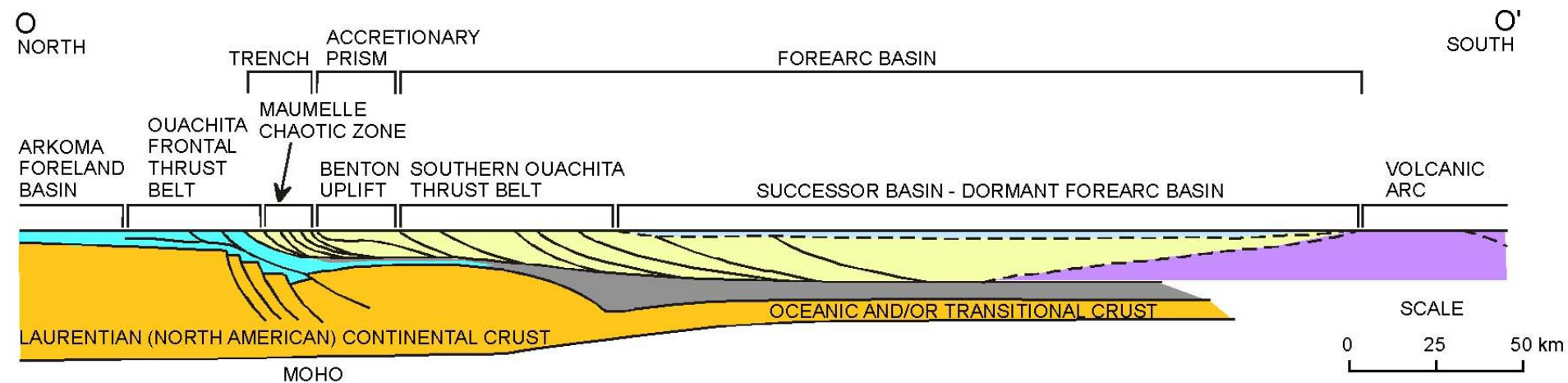




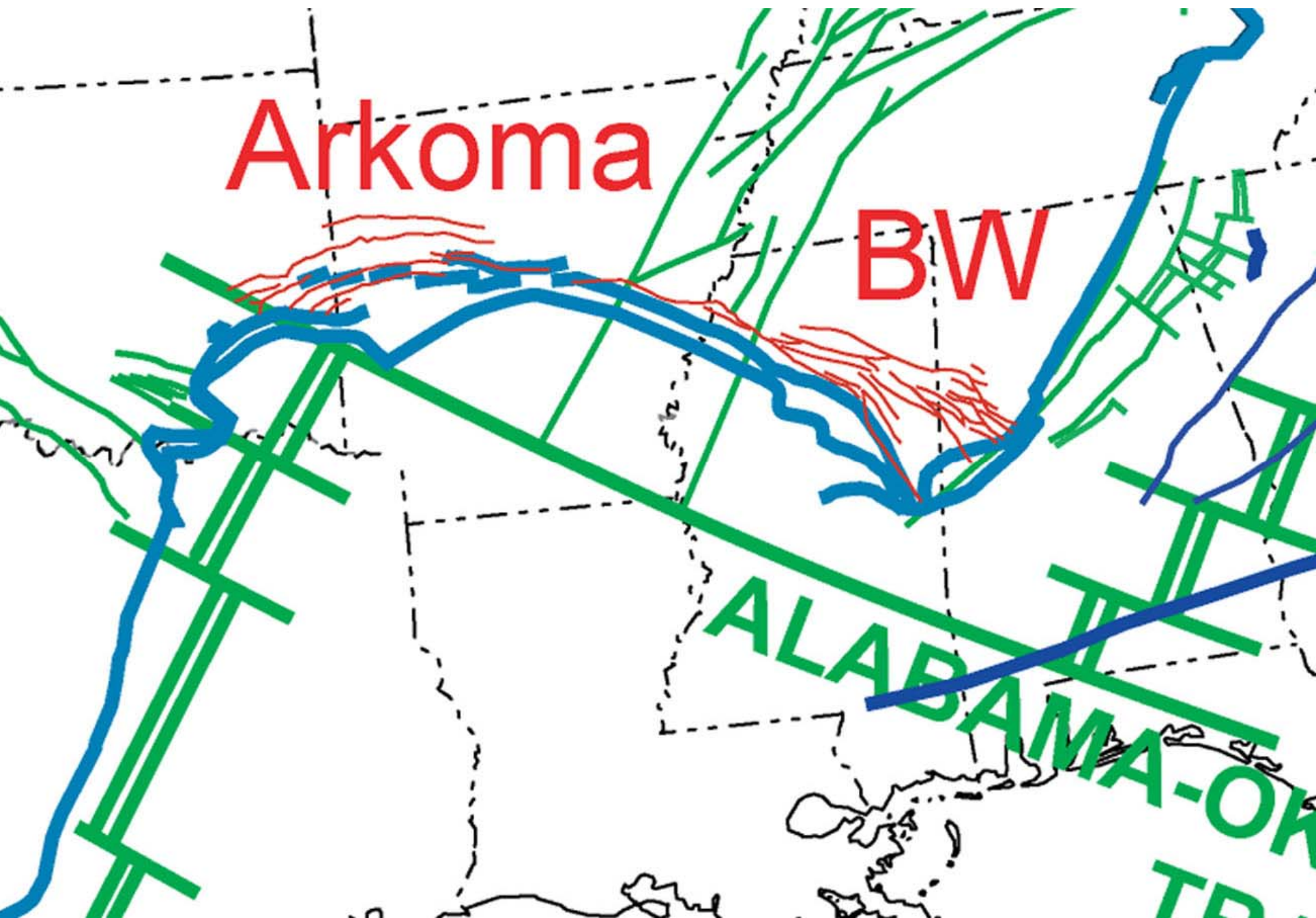


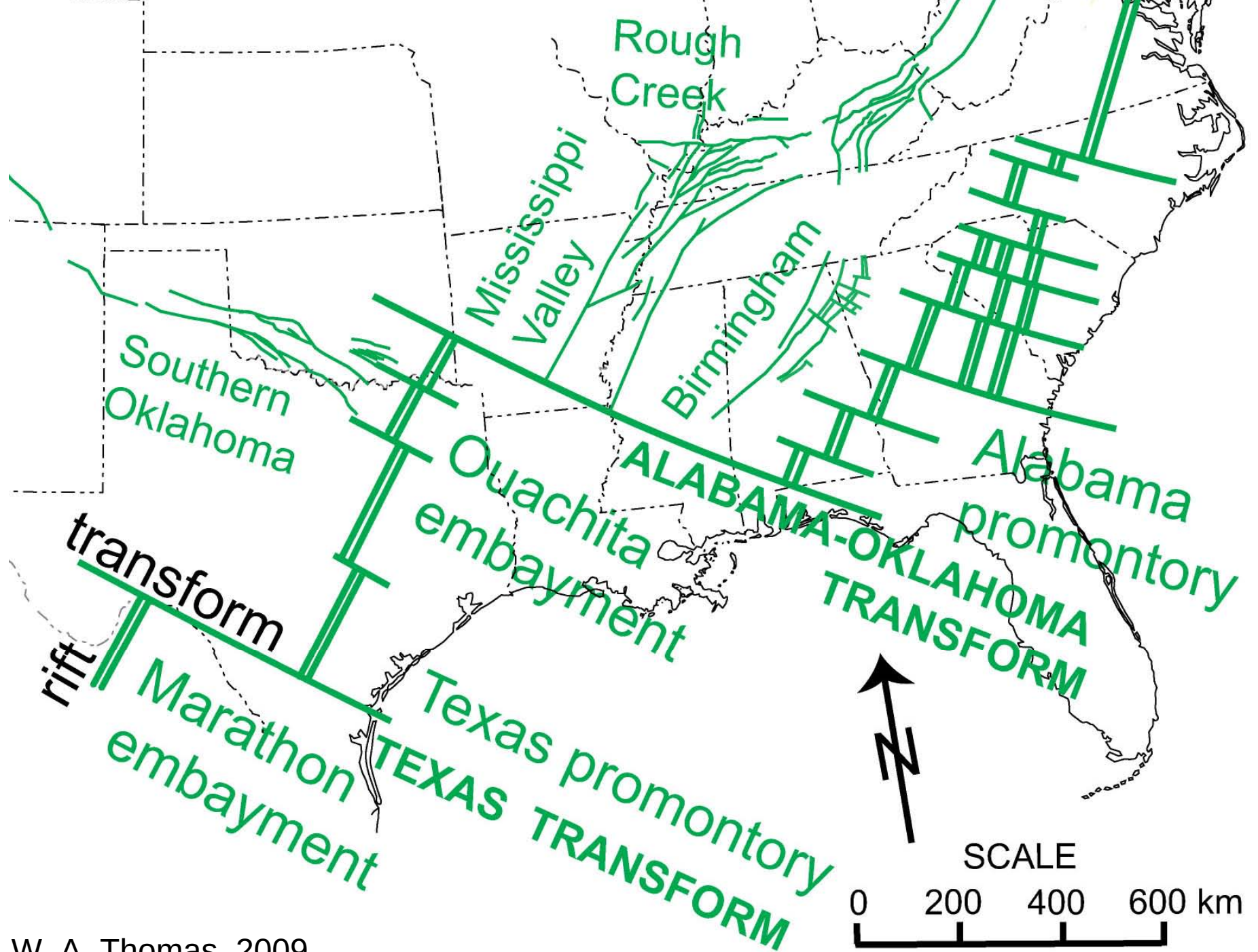


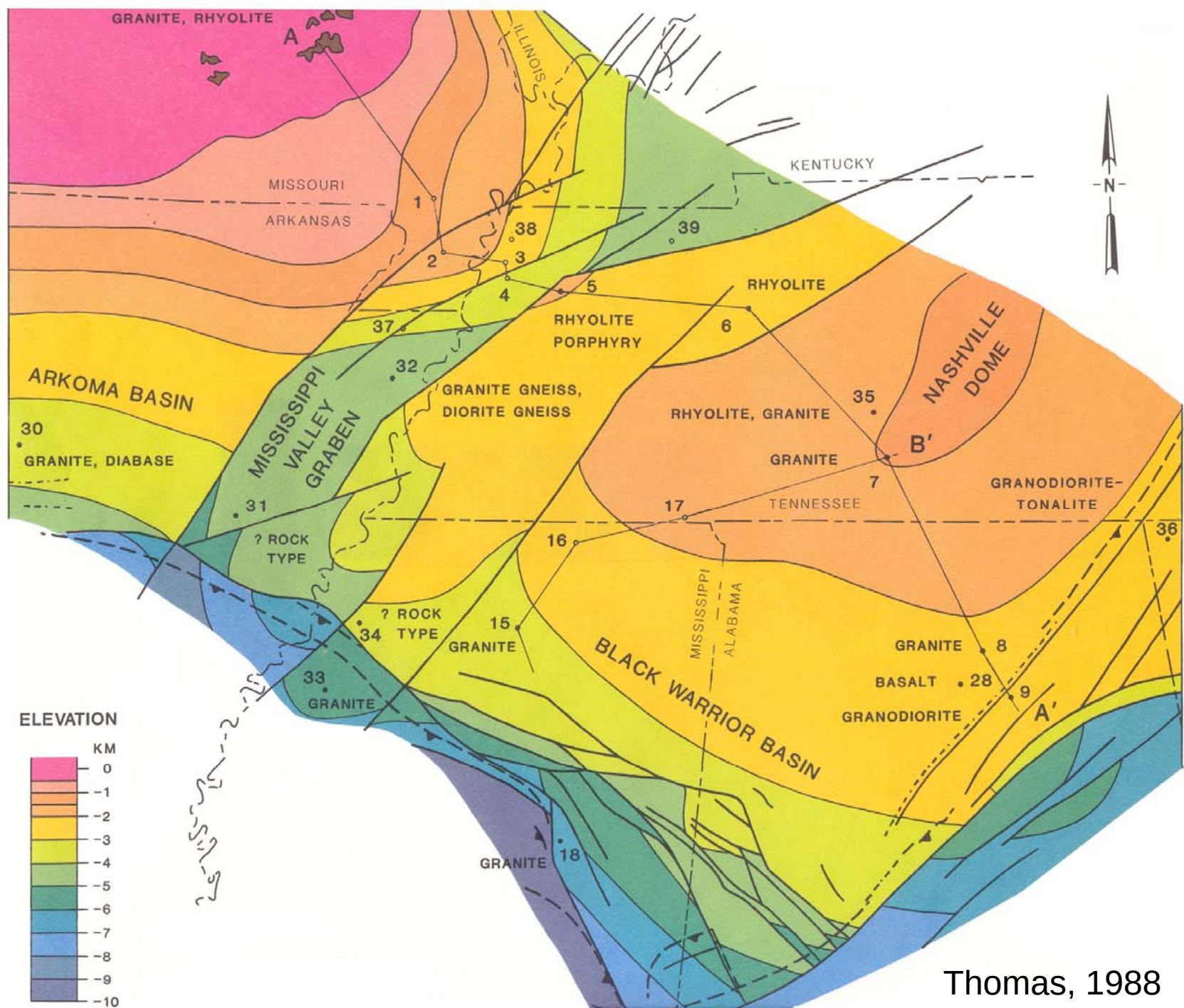
Viele, 1989



W. A. Thomas, 2009







Thomas, 1988

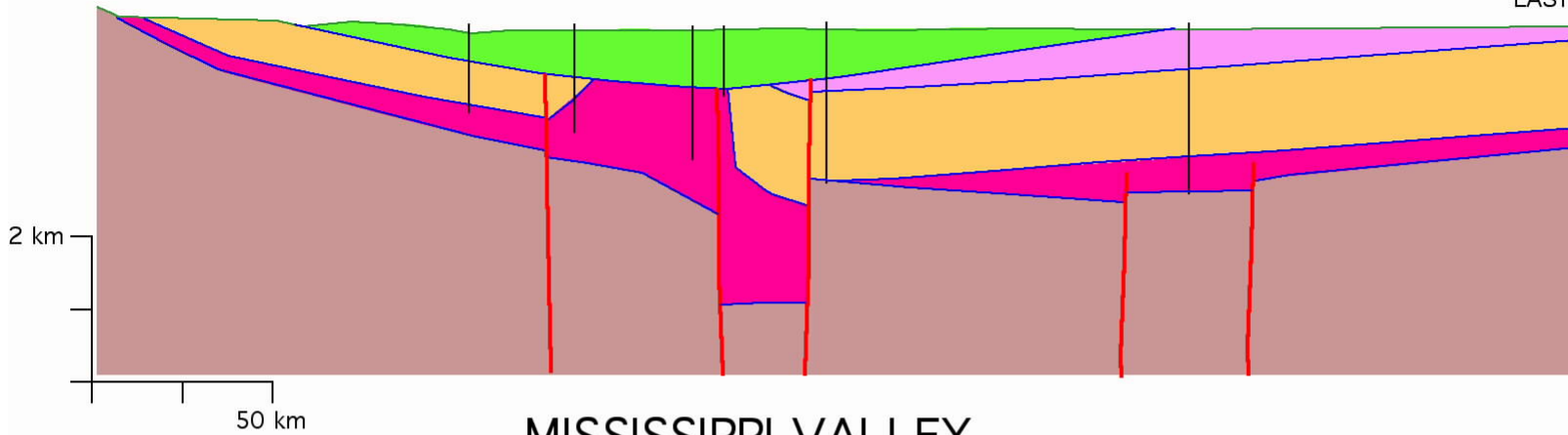
OZARK DOME

MISSISSIPPI EMBAYMENT (MESOZOIC-CENOZOIC)

NASHVILLE DOME

WEST

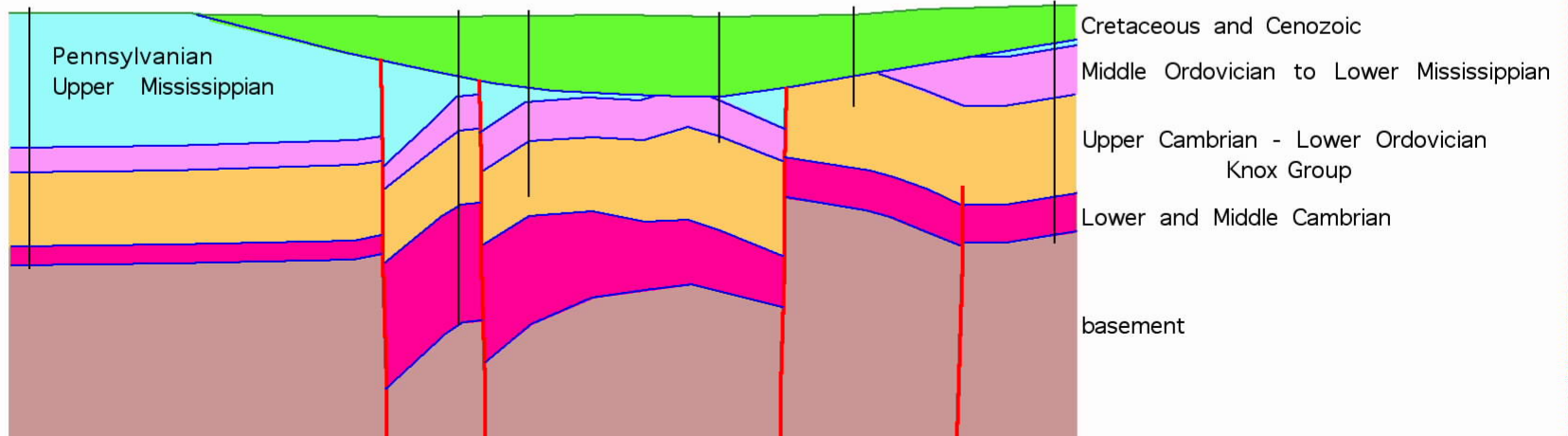
EAST

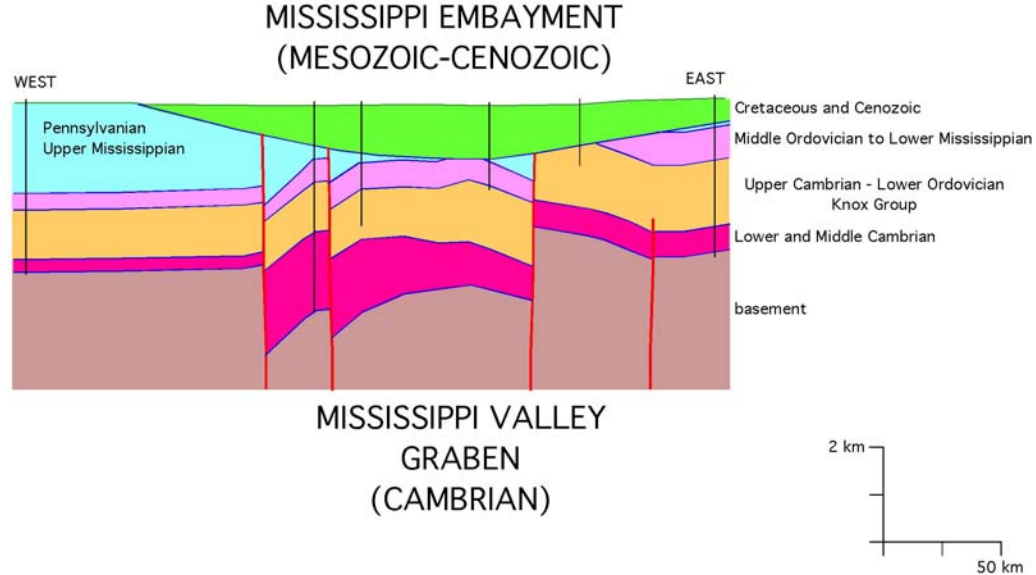


MISSISSIPPI VALLEY GRABEN (CAMBRIAN)

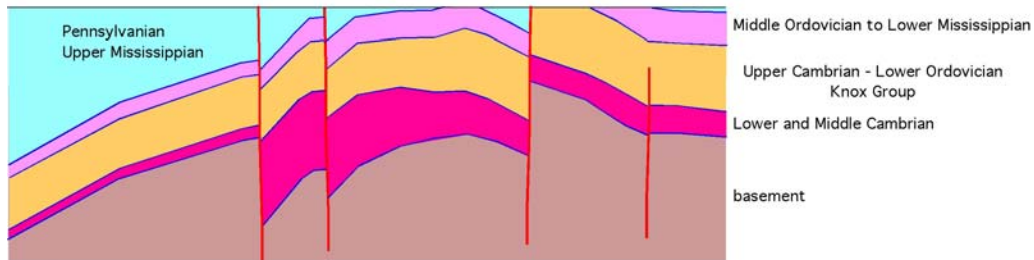
WEST

EAST

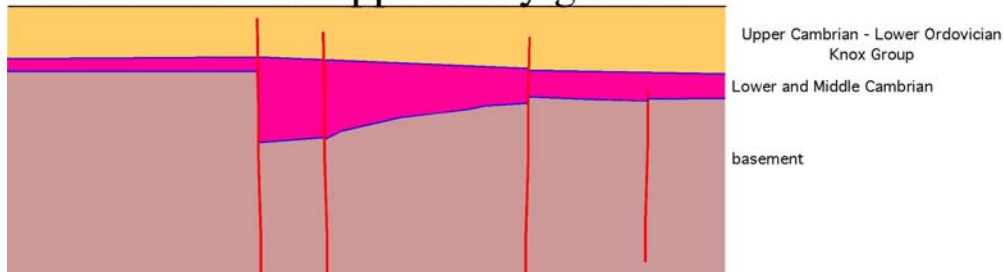


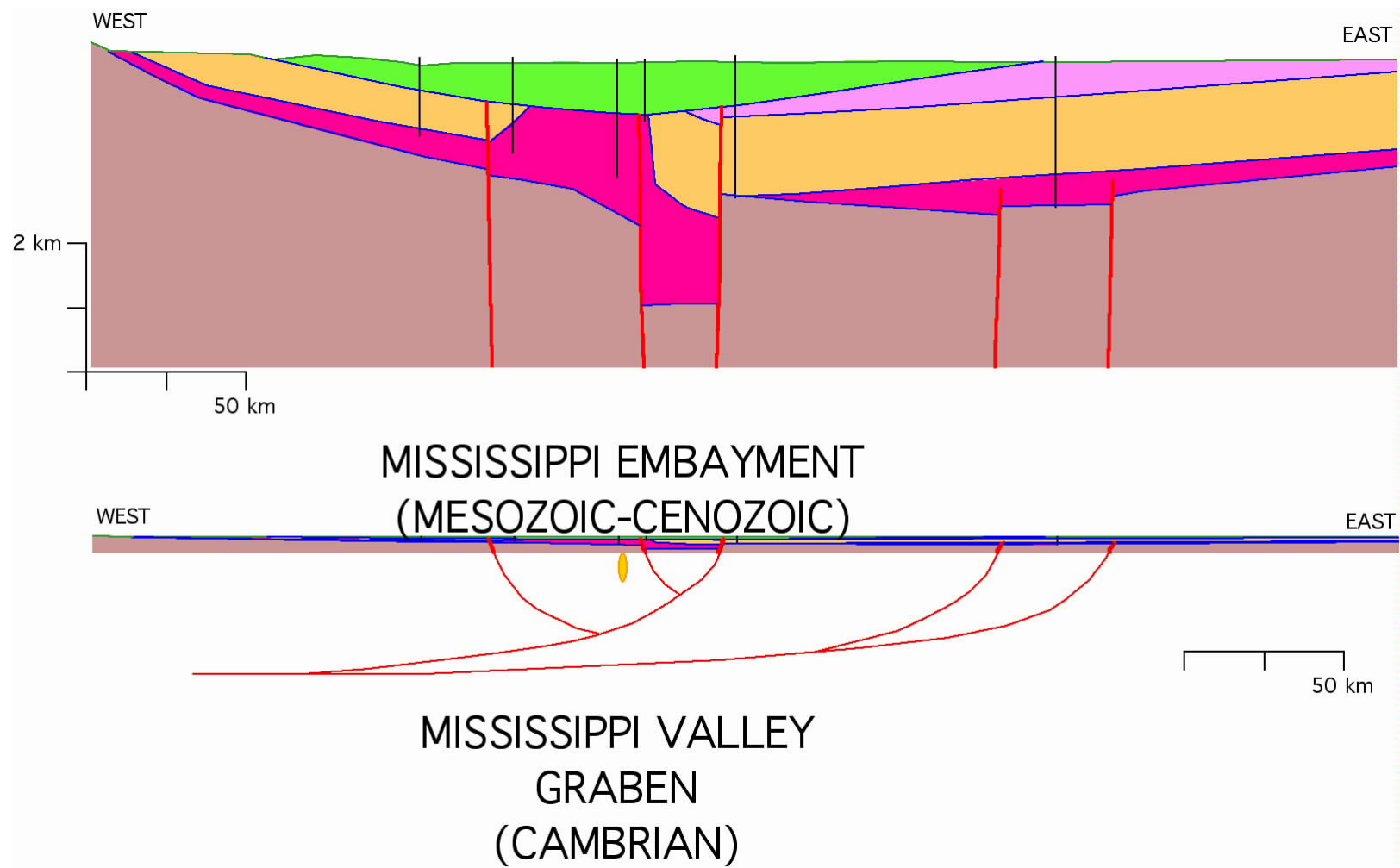


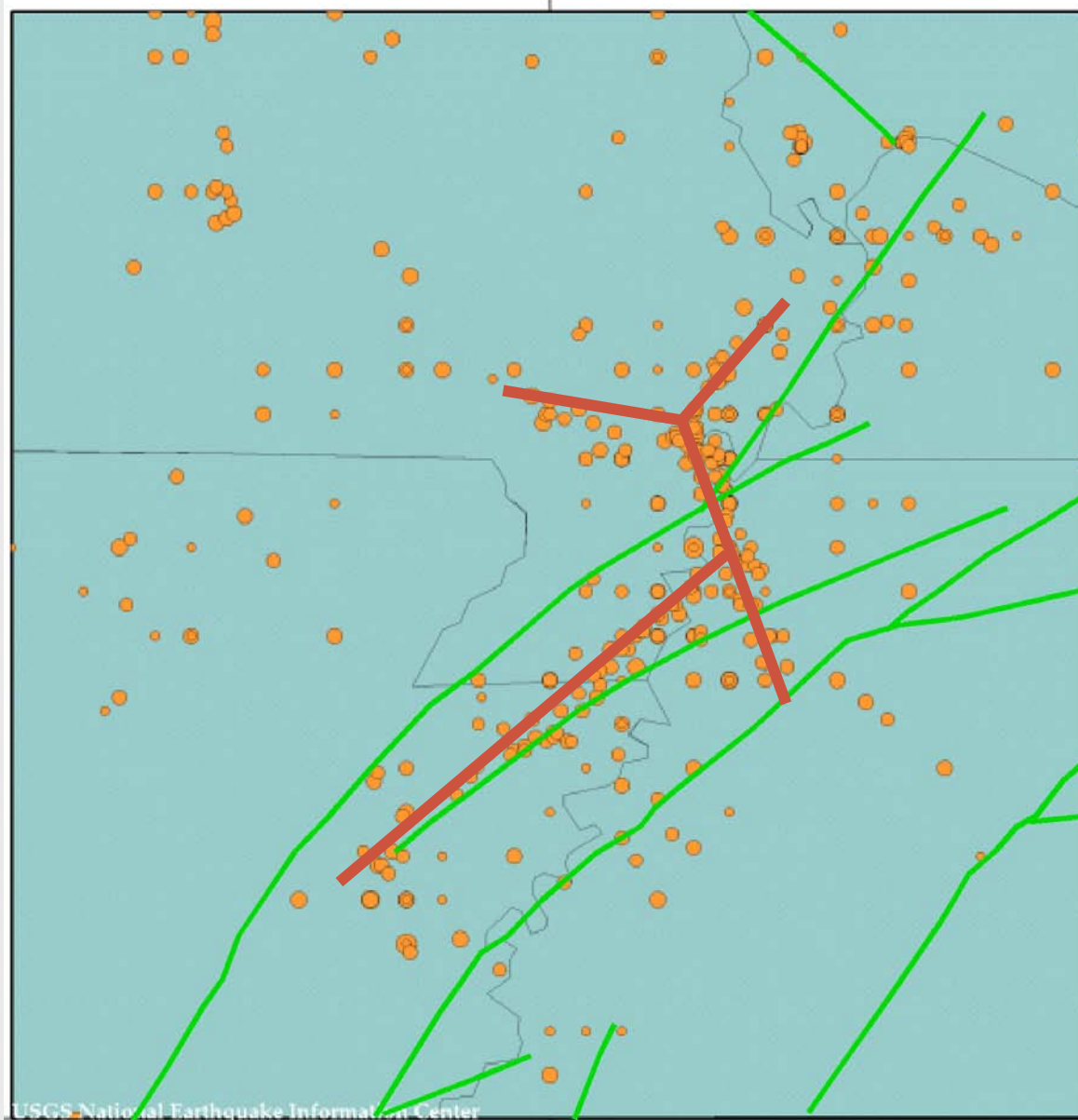
Pennsylvanian-Permian anticline

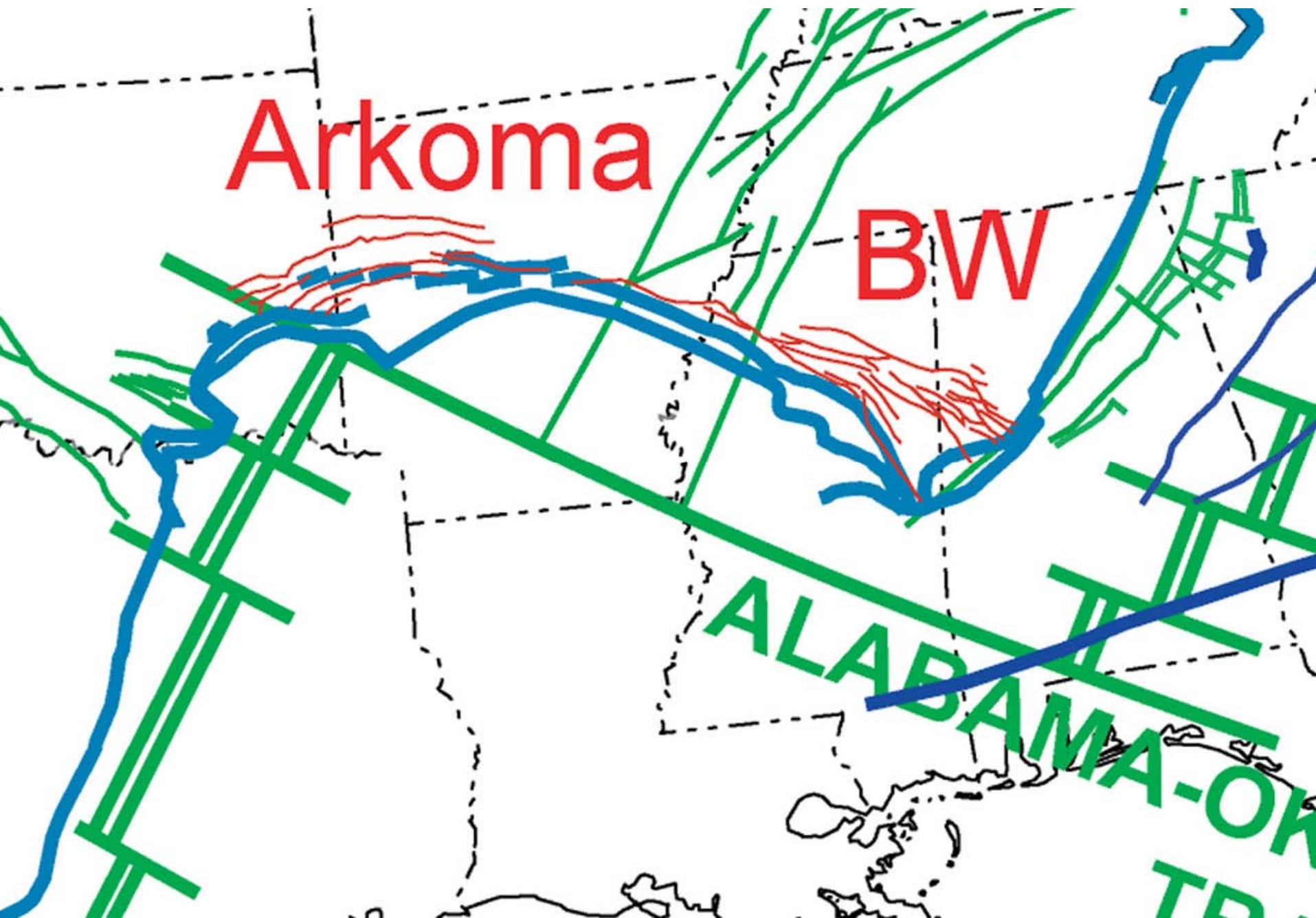


Cambrian Mississippi Valley graben

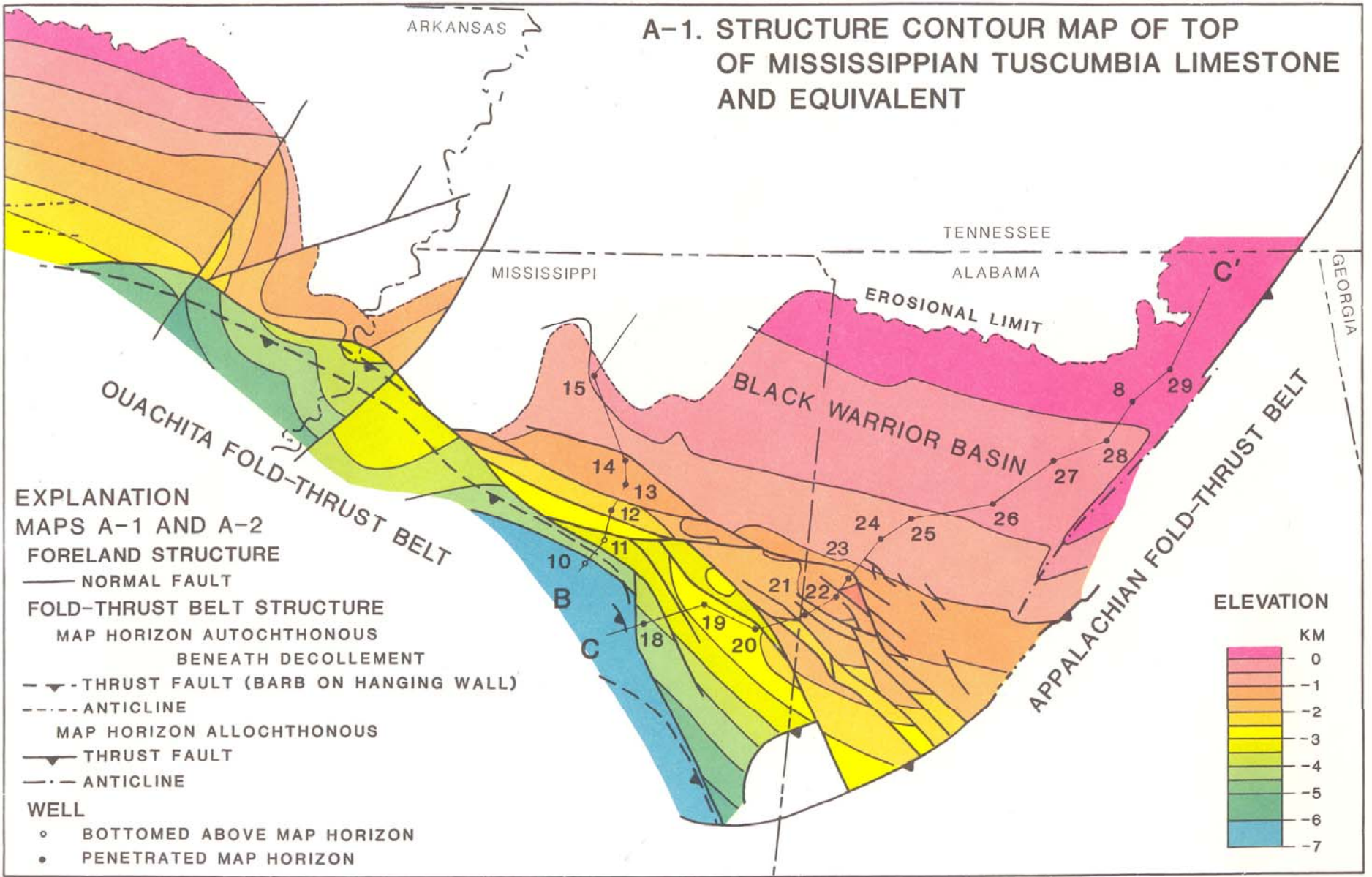




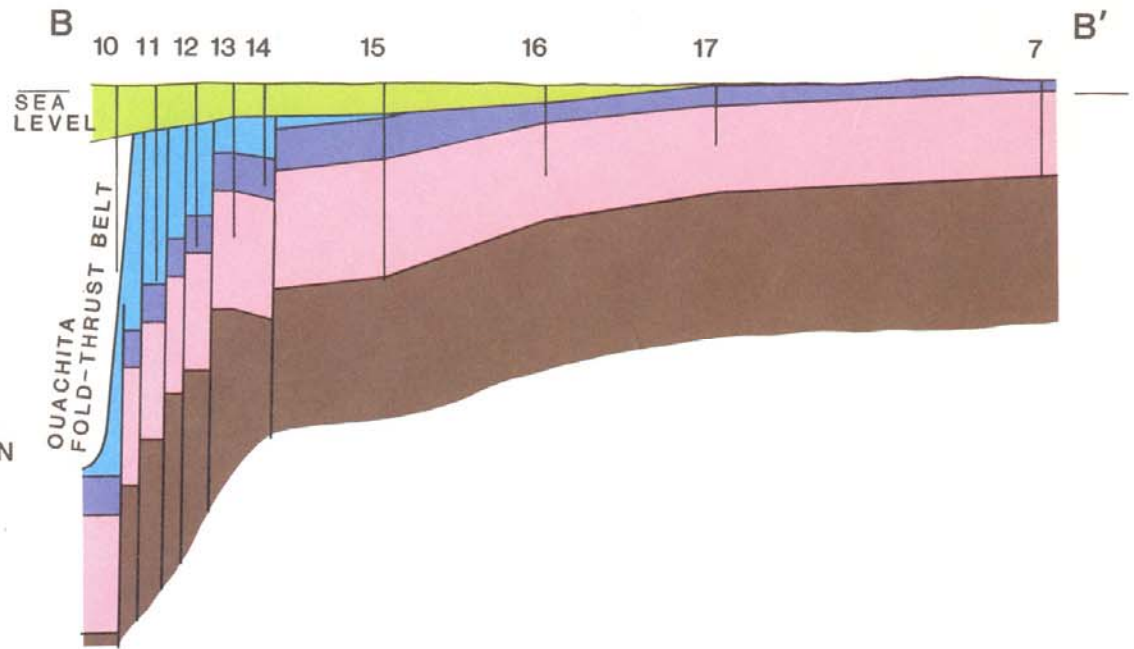
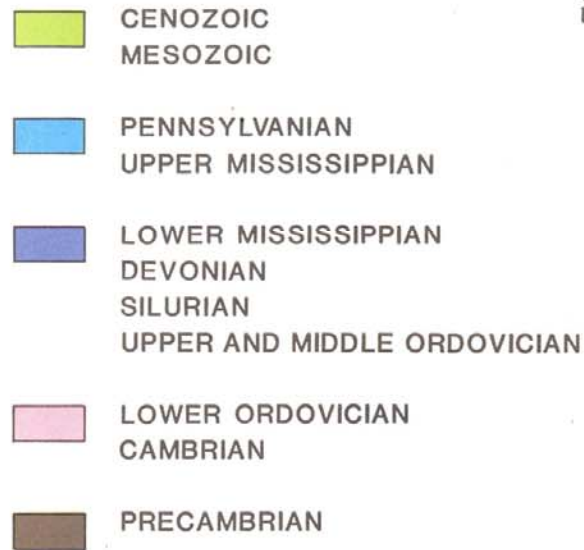




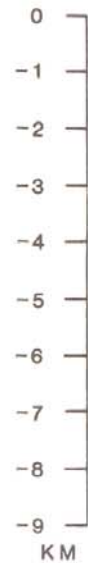
A. STRUCTURAL GEOLOGY



EXPLANATION

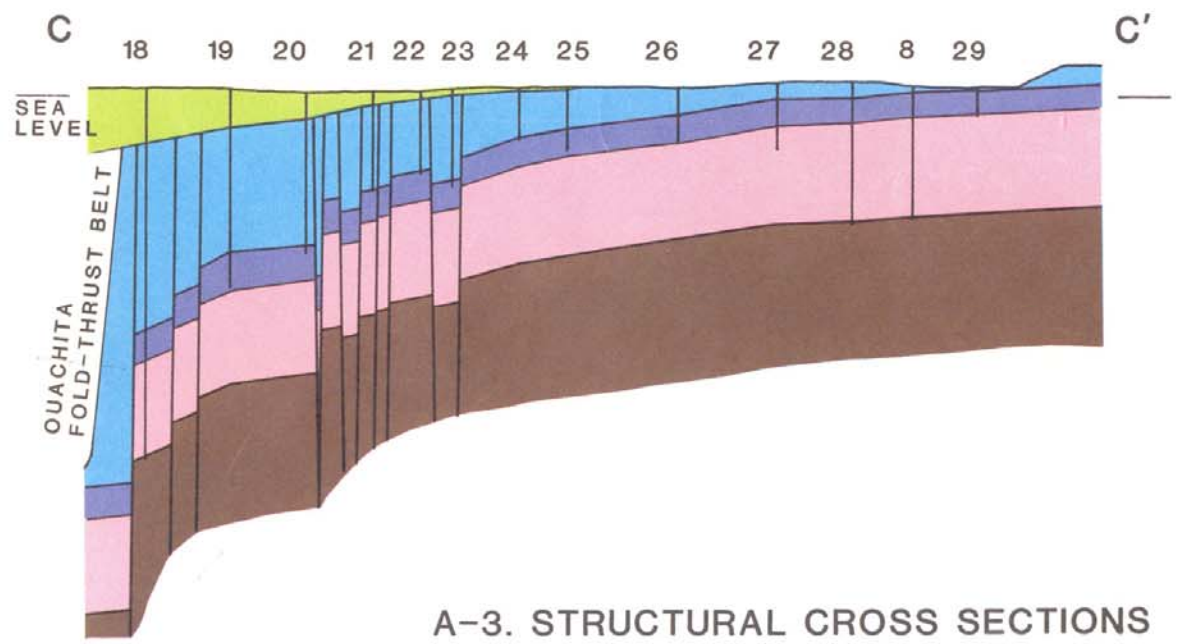


VERTICAL SCALE



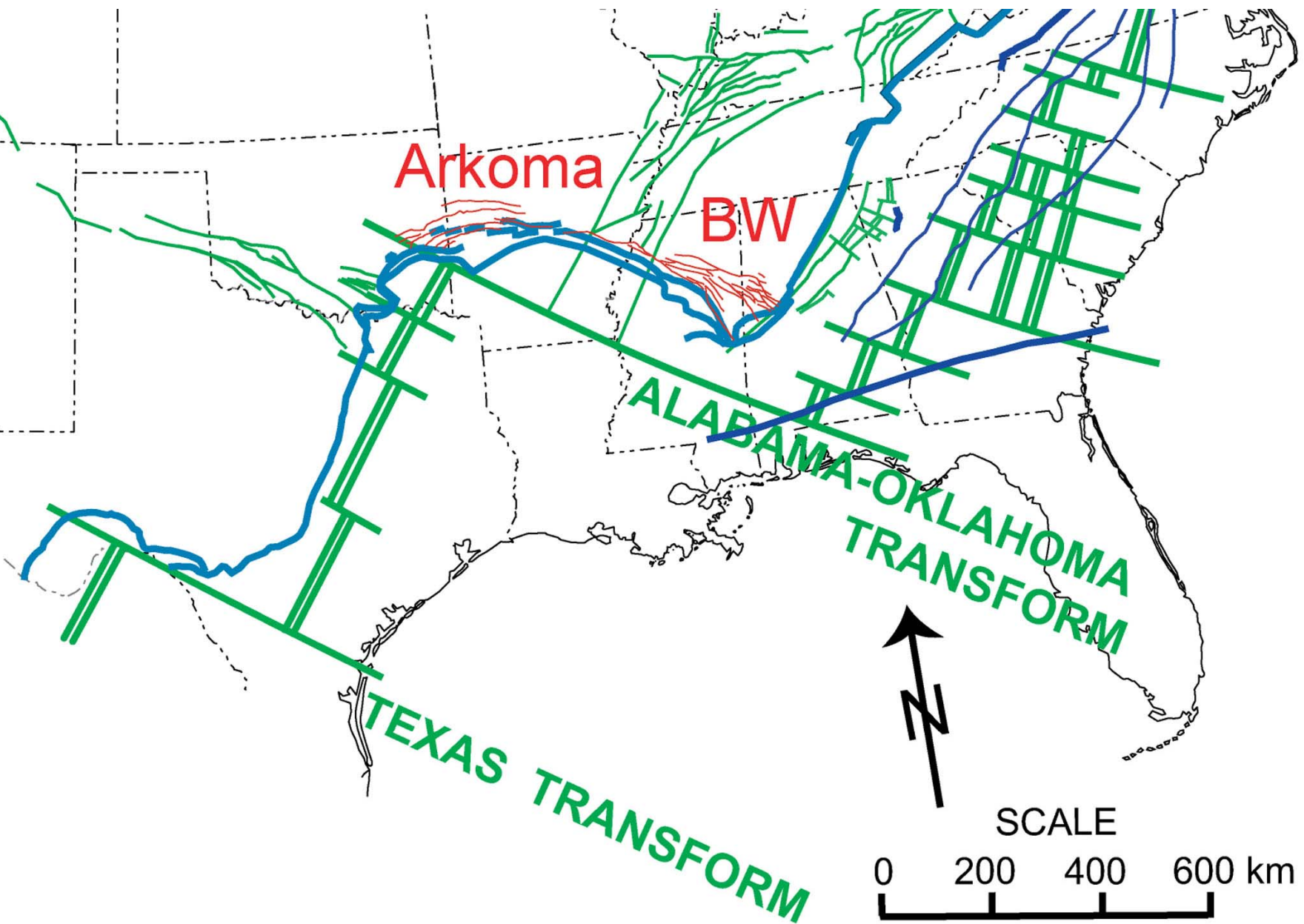
HORIZONTAL SCALE

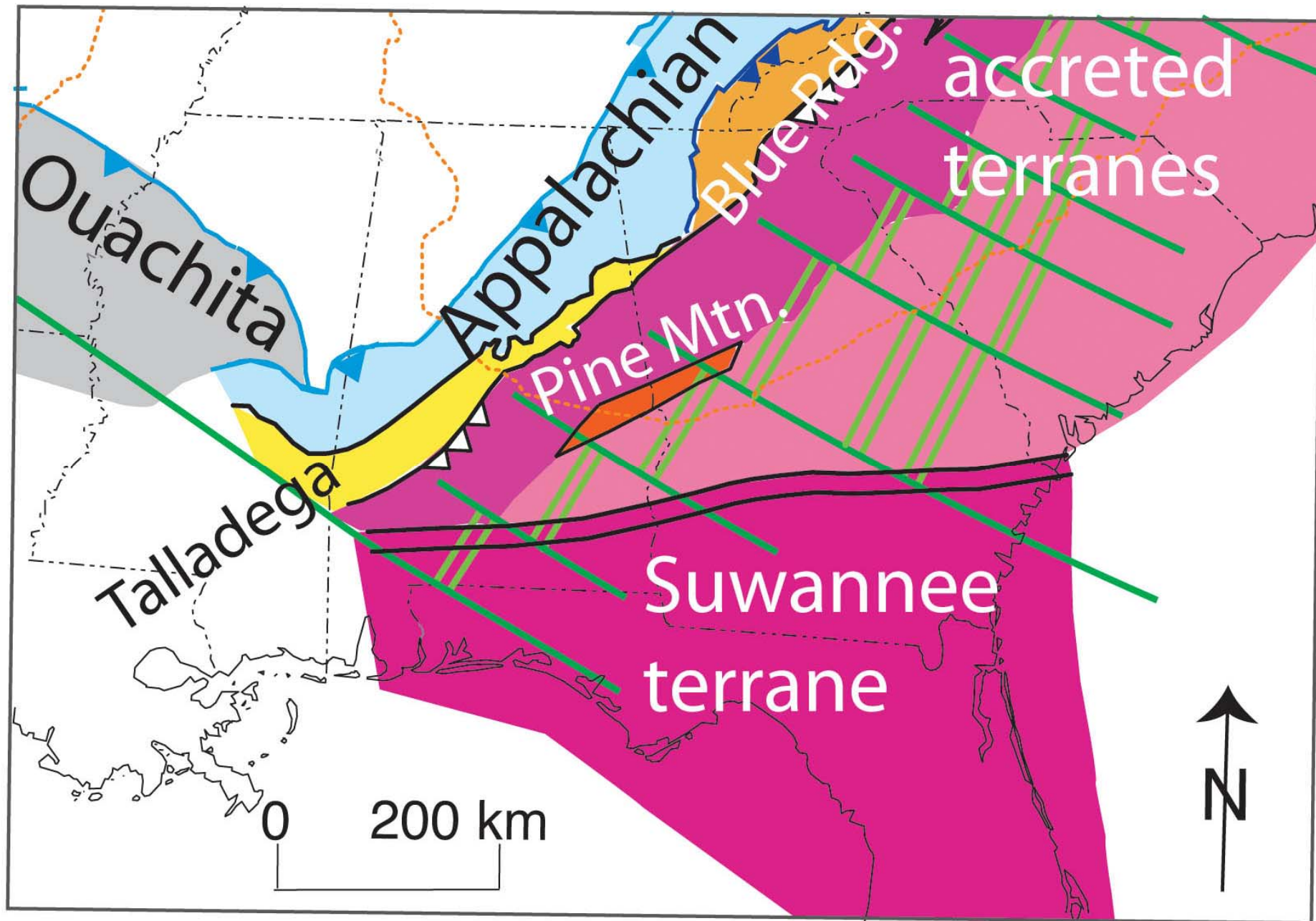
MAPS A-1 AND A-2
AND CROSS SECTIONS

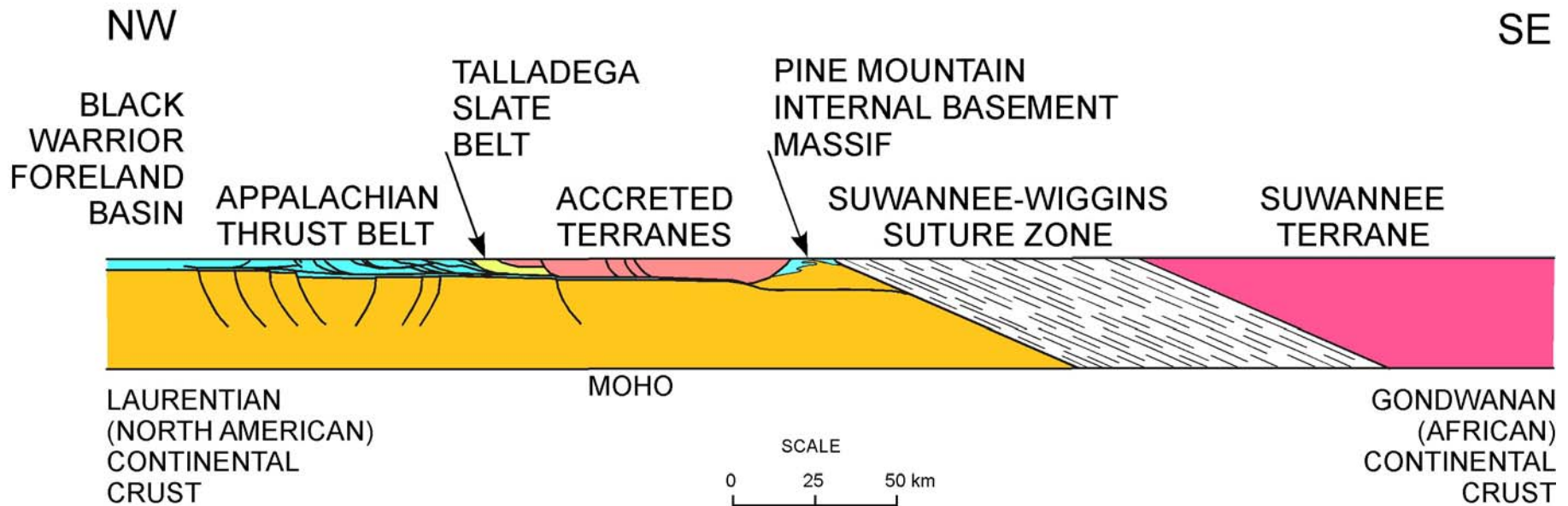


Thomas, 1988

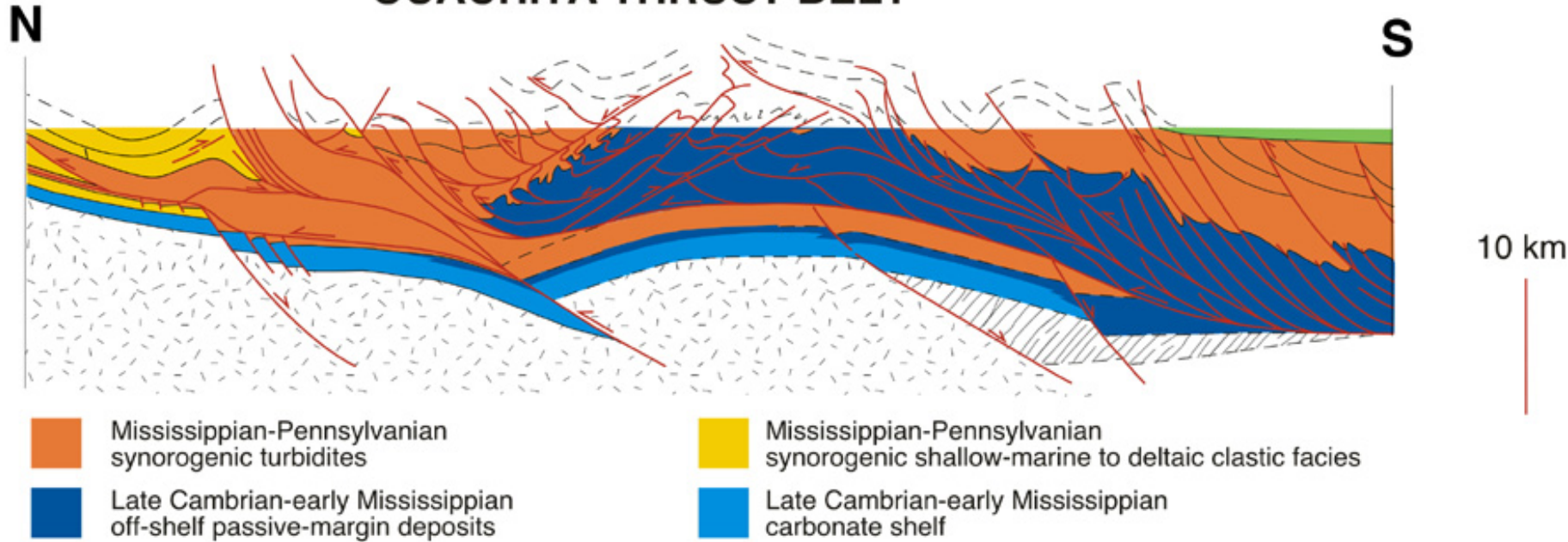
A-3. STRUCTURAL CROSS SECTIONS



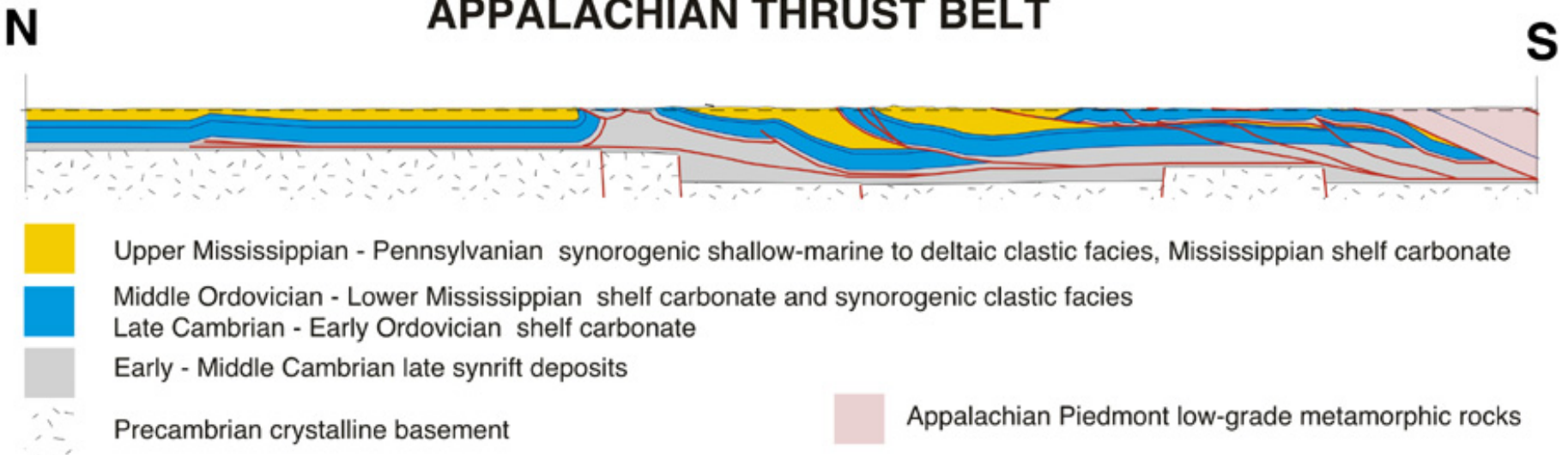


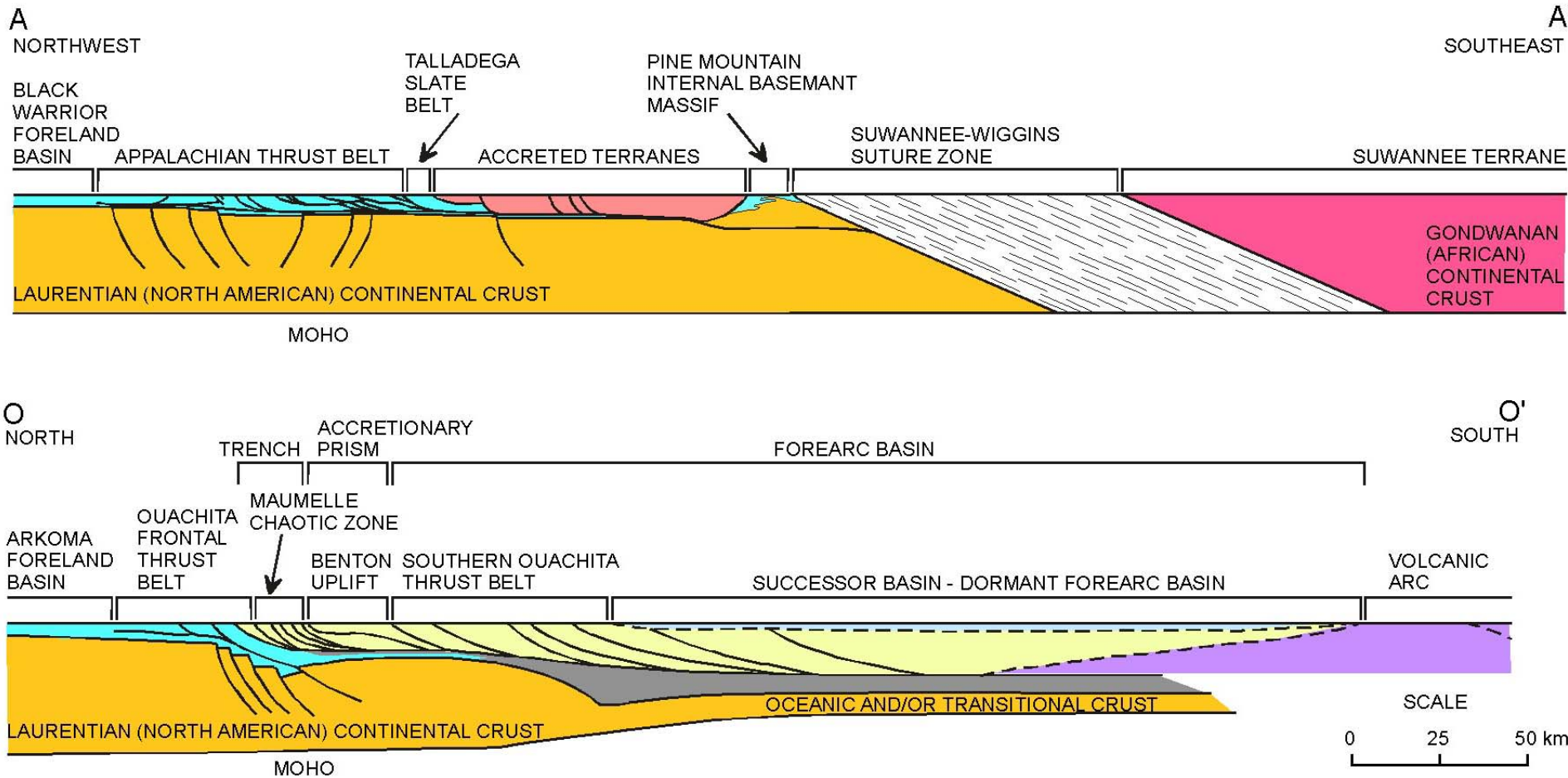


OUACHITA THRUST BELT

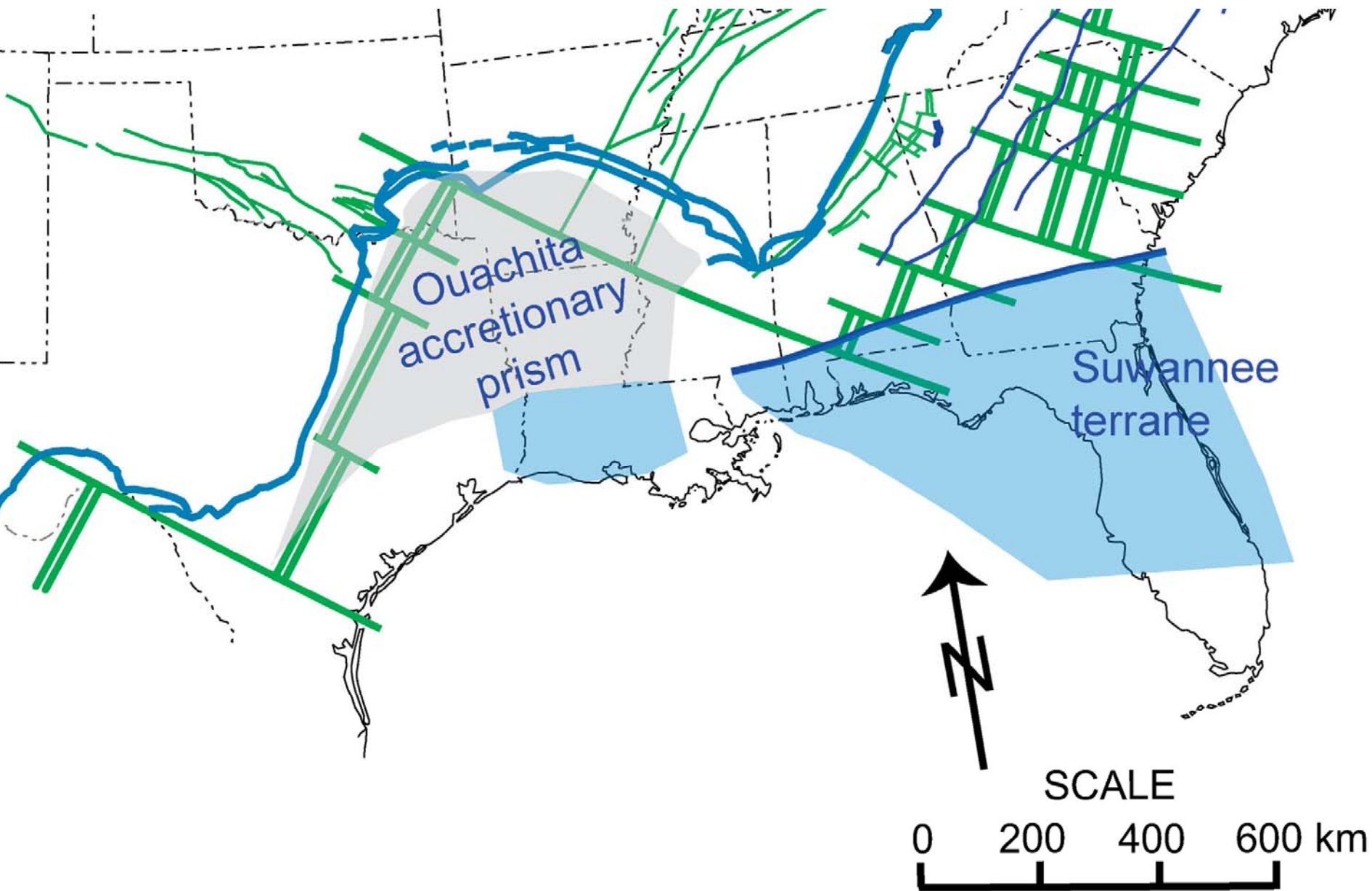


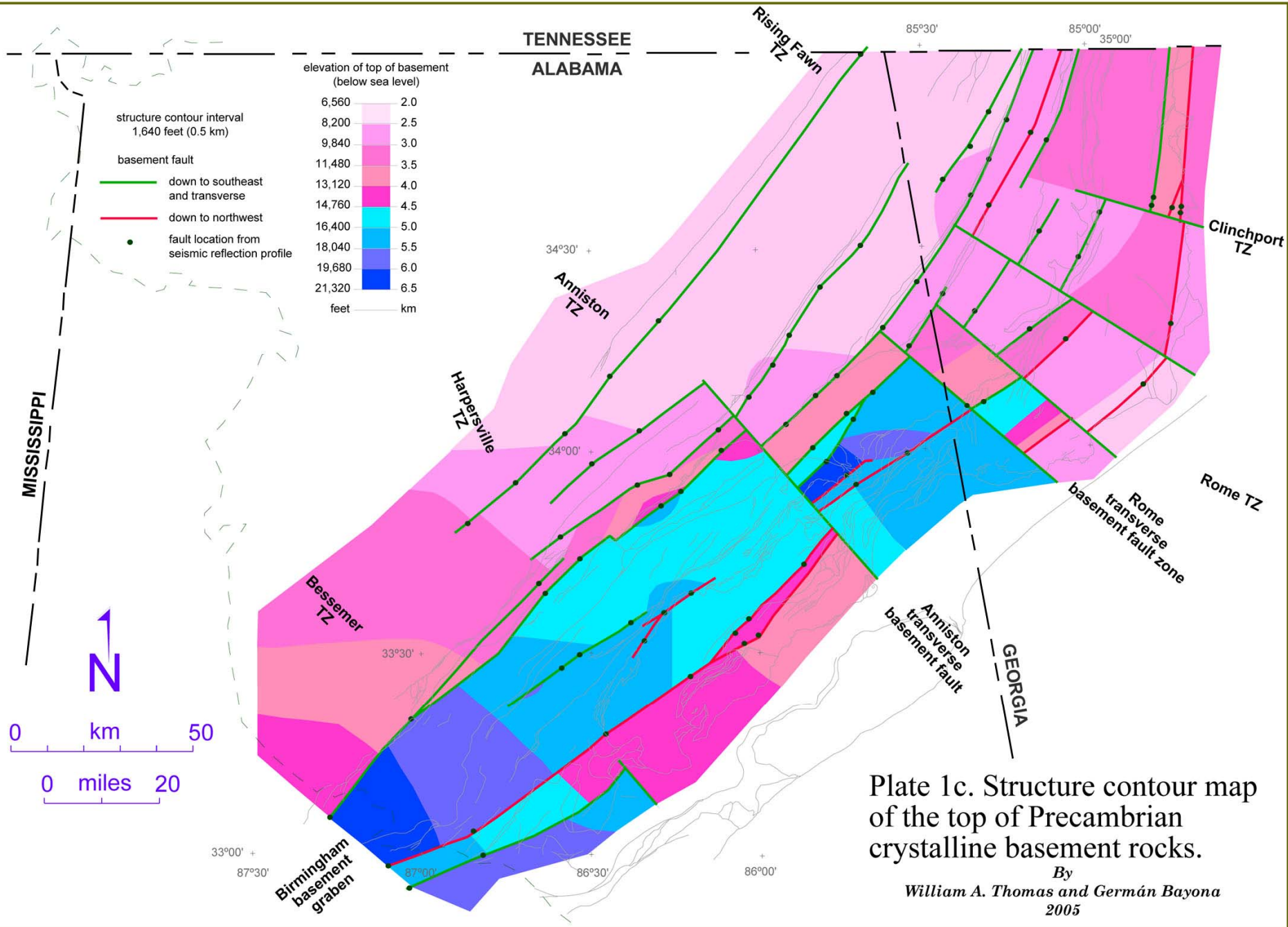
APPALACHIAN THRUST BELT



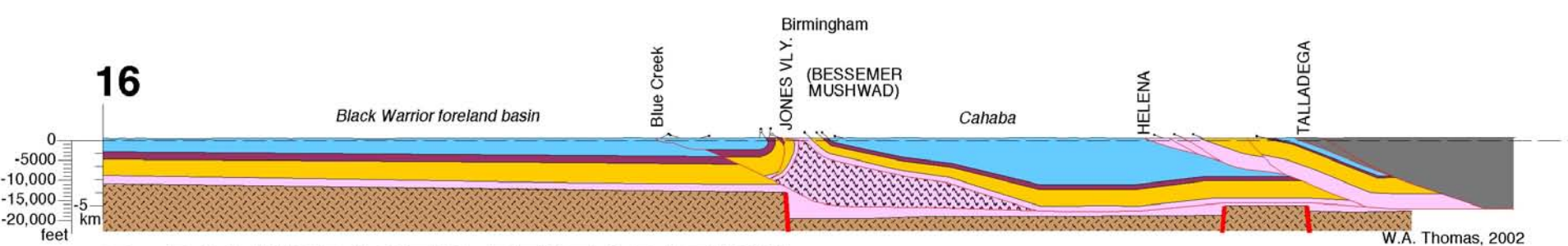


W. A. Thomas, 2009

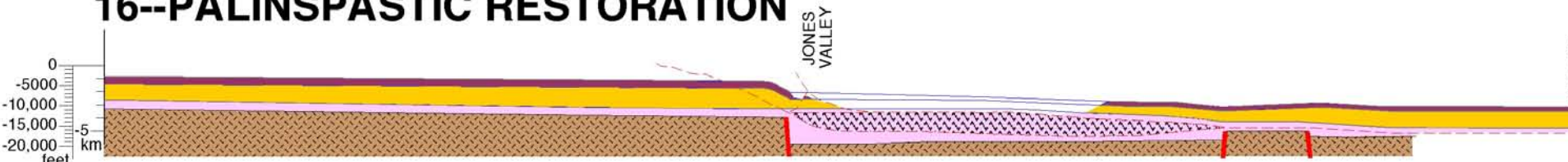




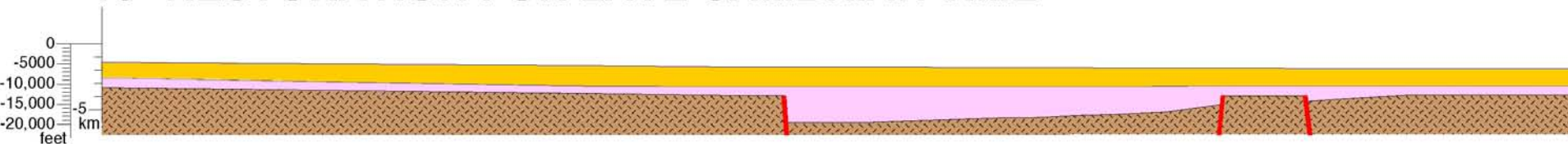
16



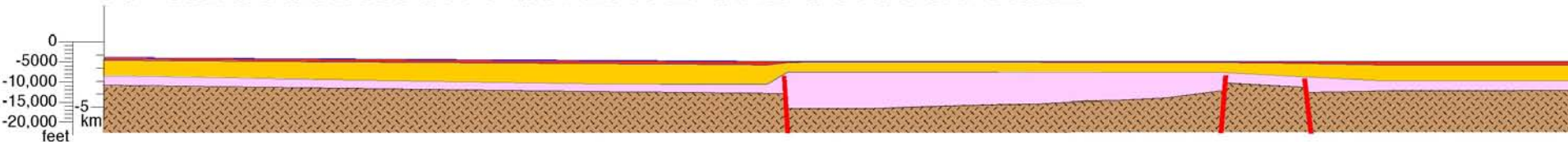
16--PALINOSPASTIC RESTORATION



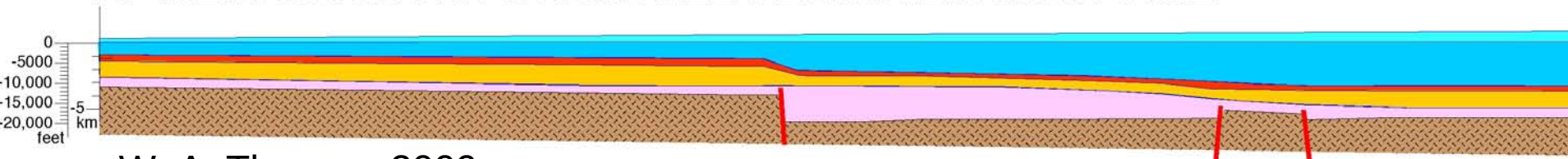
16--RESTORATION FOR LATE CAMBRIAN TIME



16--RESTORATION FOR LATE ORDOVICIAN TIME

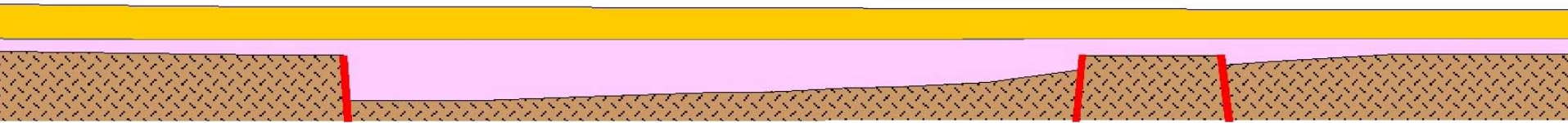


16--RESTORATION FOR MIDDLE PENNSYLVANIAN TIME



W. A. Thomas, 2009

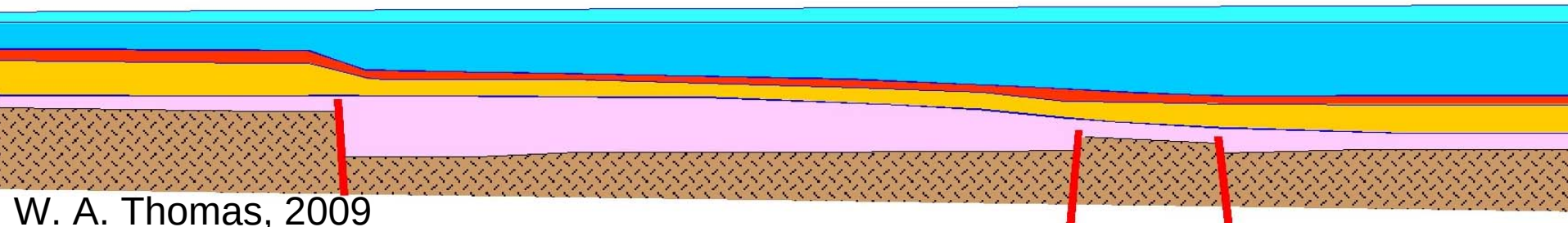
LATE CAMBRIAN TIME

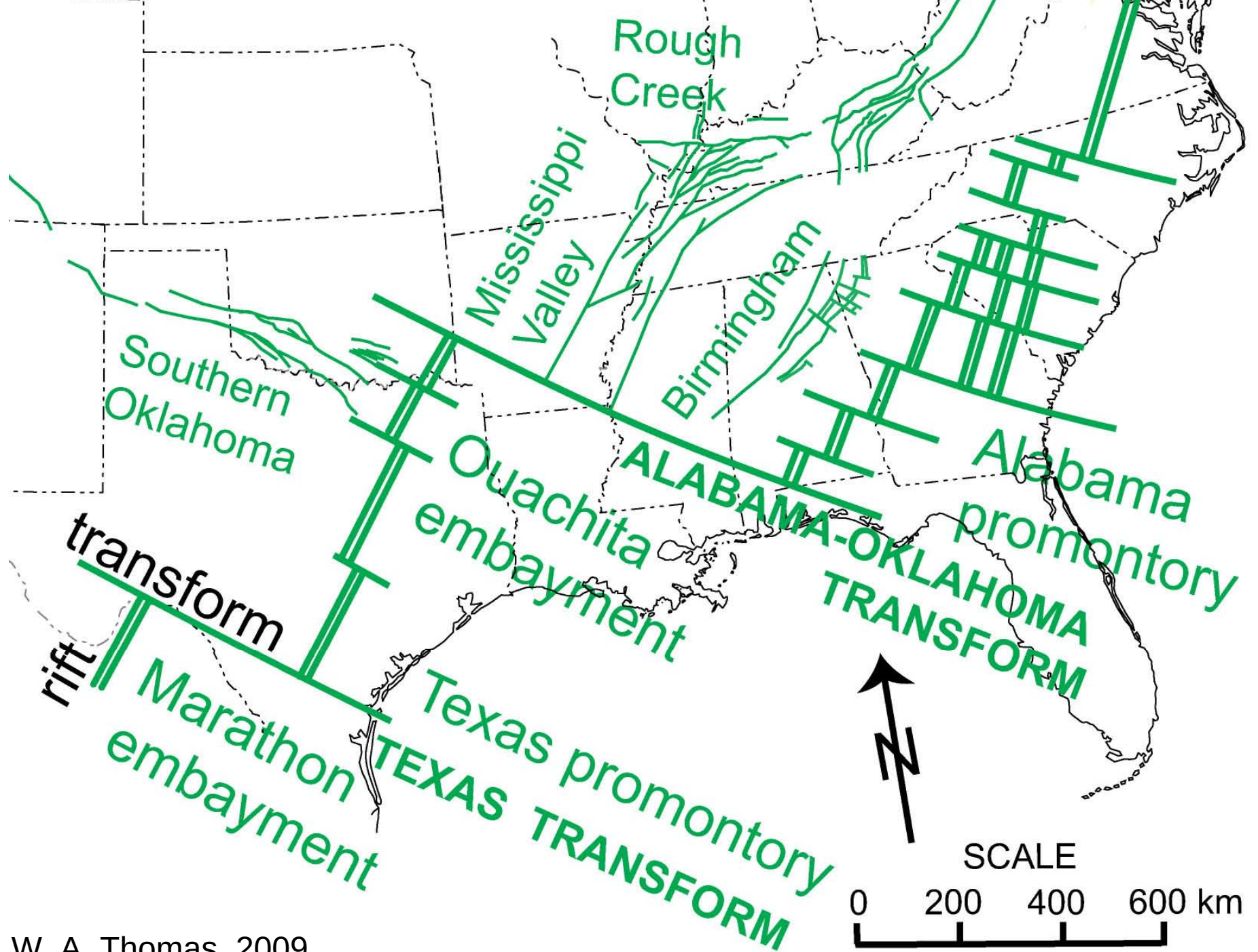


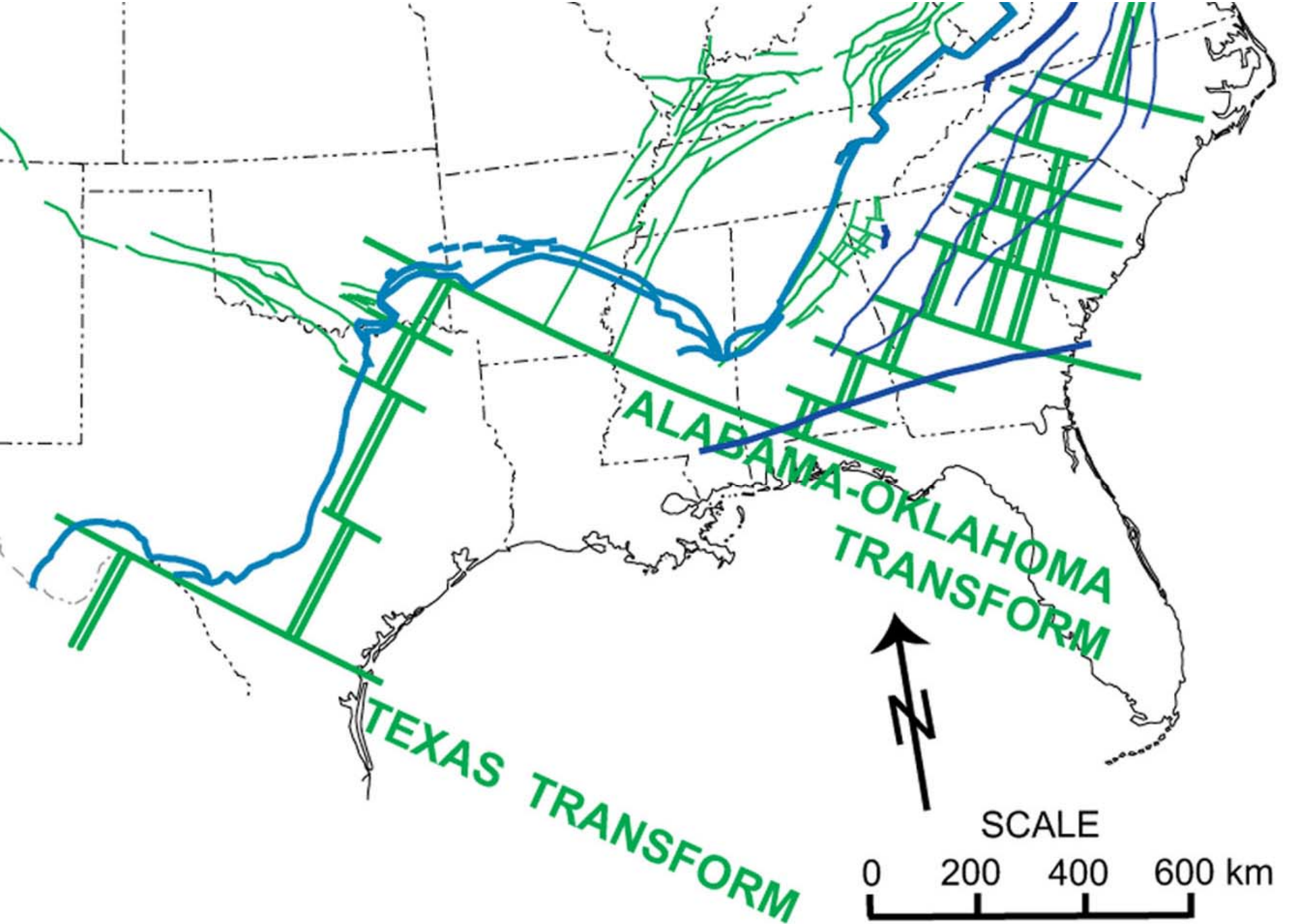
LATE ORDOVICIAN TIME

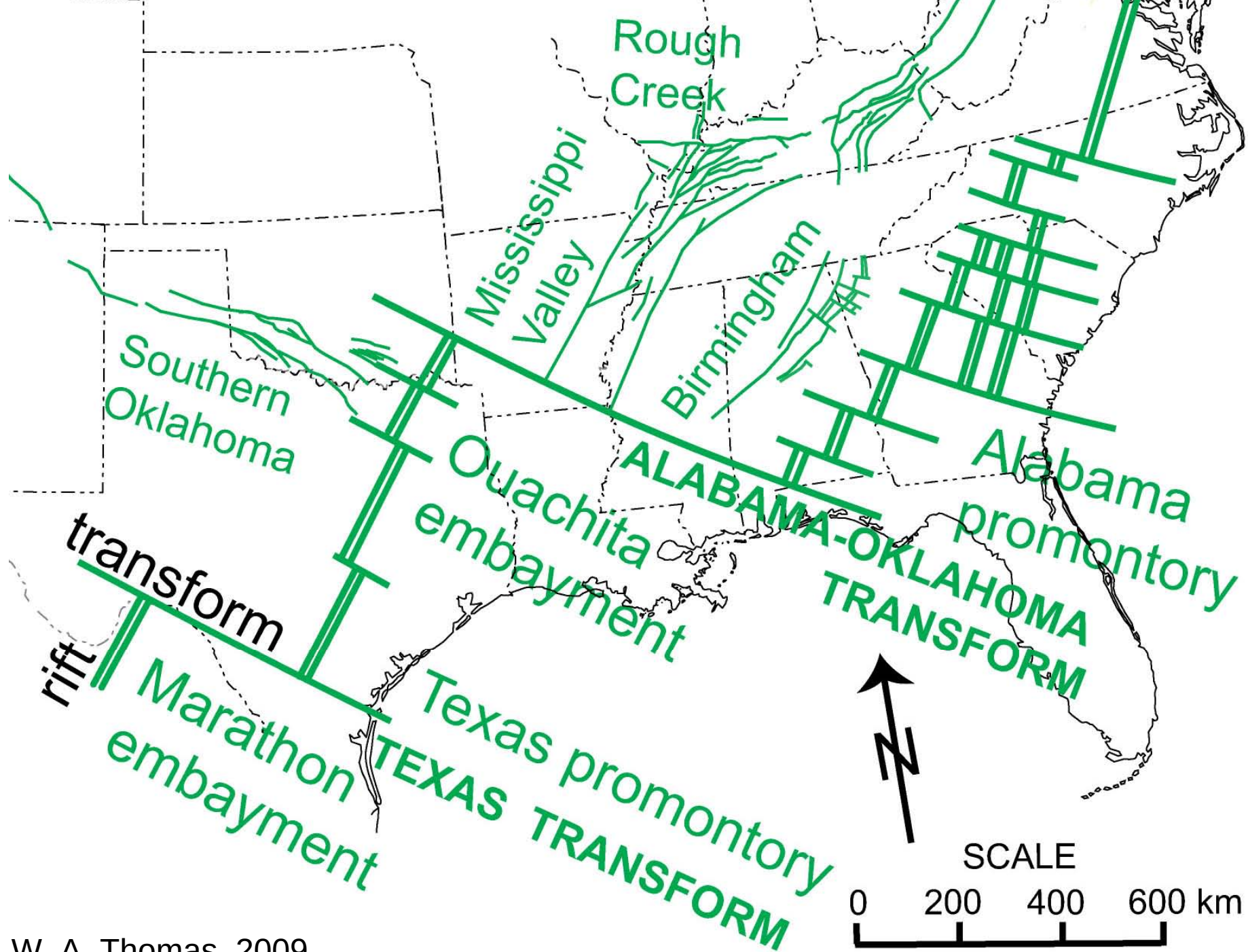


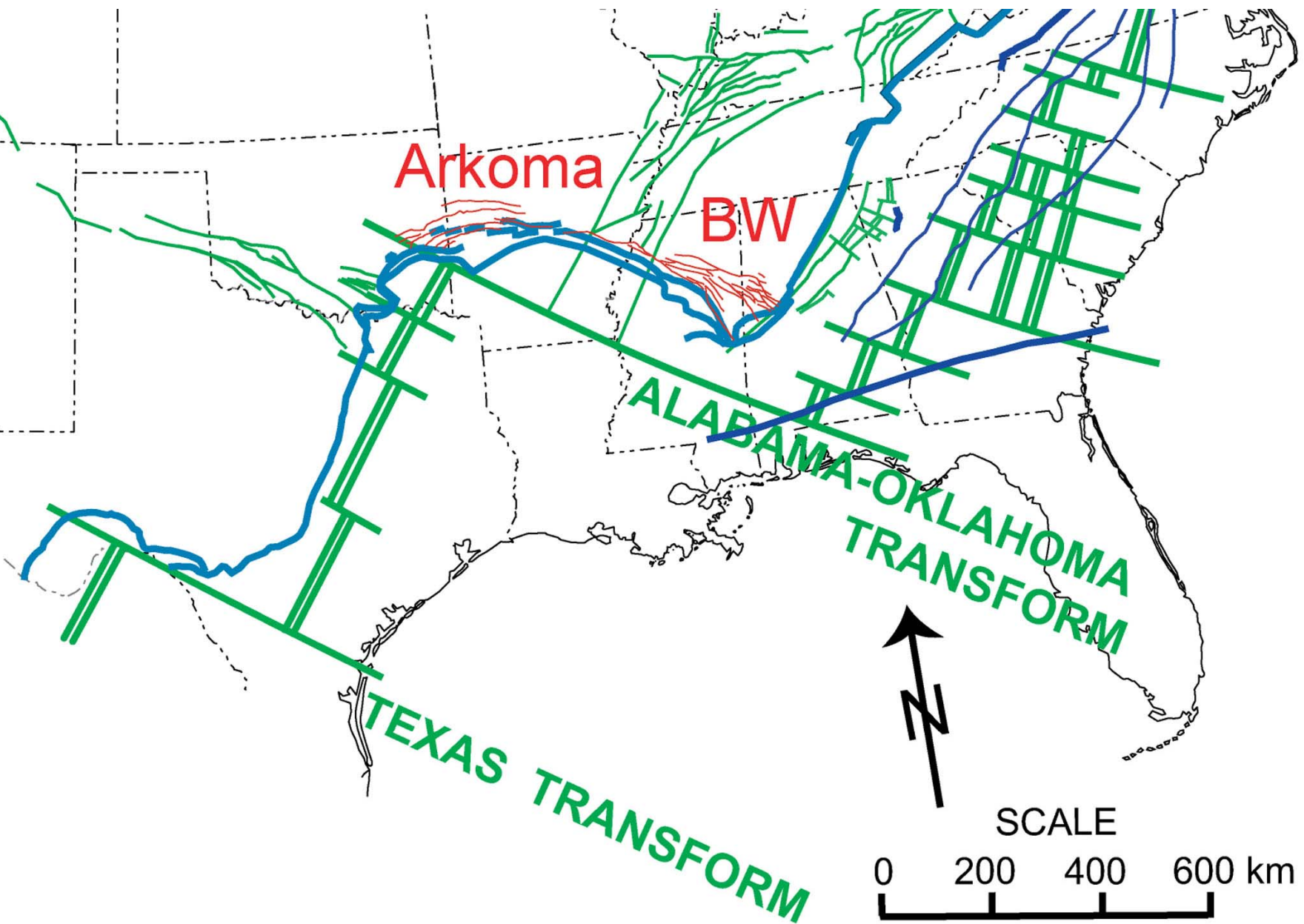
MIDDLE PENNSYLVANIAN TIME

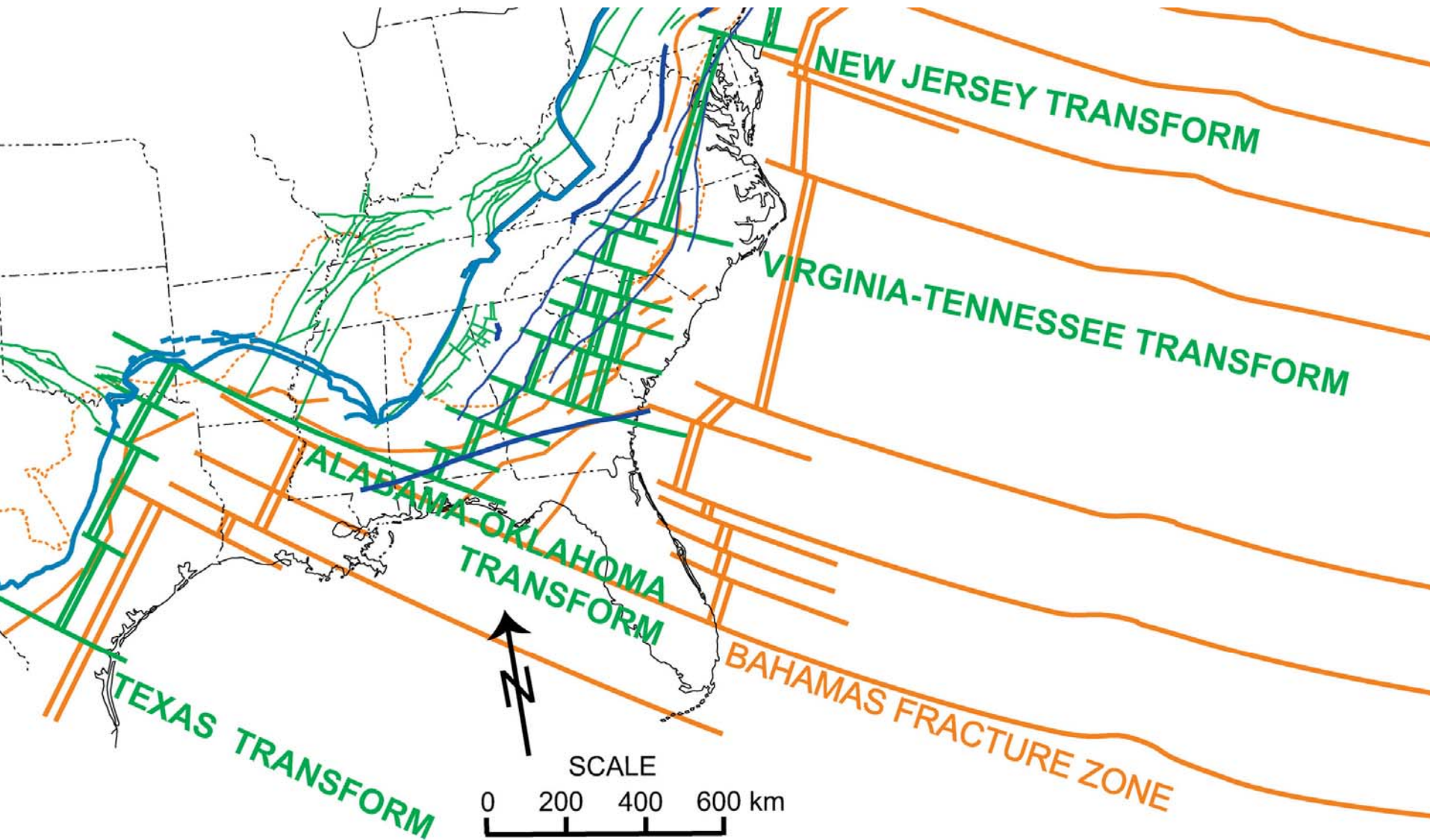












Rifts in the Midcontinent: East Continent Rift Basin, Rough Creek Graben and the Rome Trough

**Central and Eastern United States
Seismic Source Characterization Project
Workshop 2**

Wednesday, February 18, 2009

*James A. Drahovzal
Kentucky Geological Survey
University of Kentucky*



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- SEISCO, Inc.

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- John Rupp, Indiana Geological Survey
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- Tina White, WV Dept. of Environmental Protection

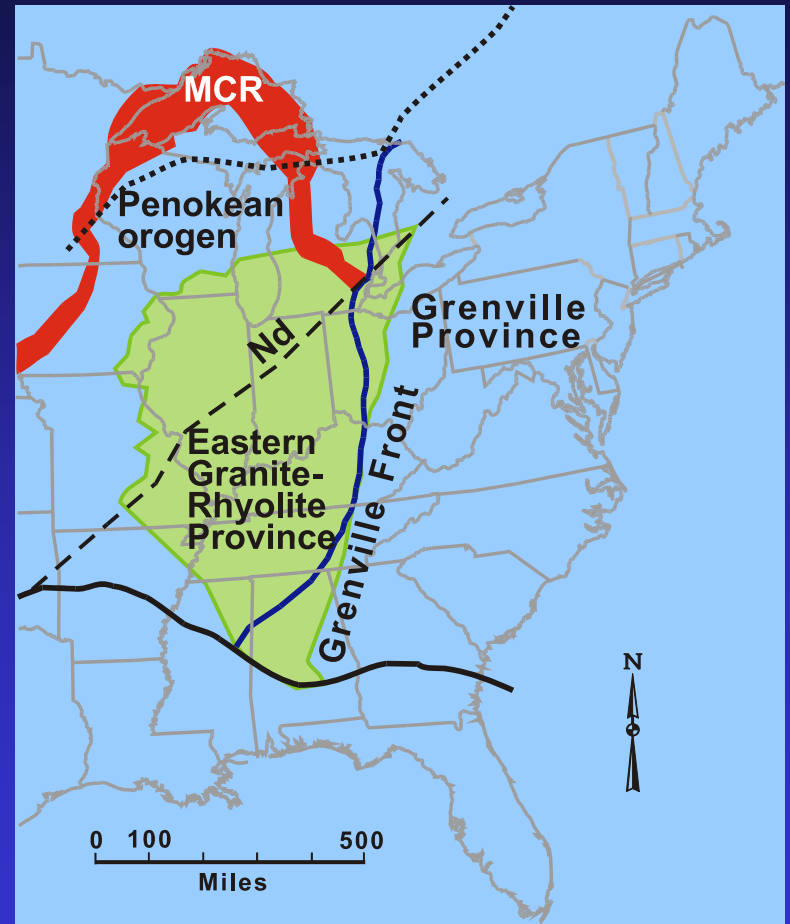


Outline

- **East Continent Rift Basin (ECRB)**
 - Grenville Thrust Belt (GTB)
 - Hoosier Thrust Belt (HTB)
- **Fort Wayne Rift (FWR) and Anna Seismic Zone**
- **Rome Trough (RT)**
 - East Tennessee Seismic Zone (ETSZ)
 - East Continent Gravity High (ECGH)
- **Rough Creek Graben (RCG)**
- **Continuity of the RT and the RCG**

Classical “Basement” Geology

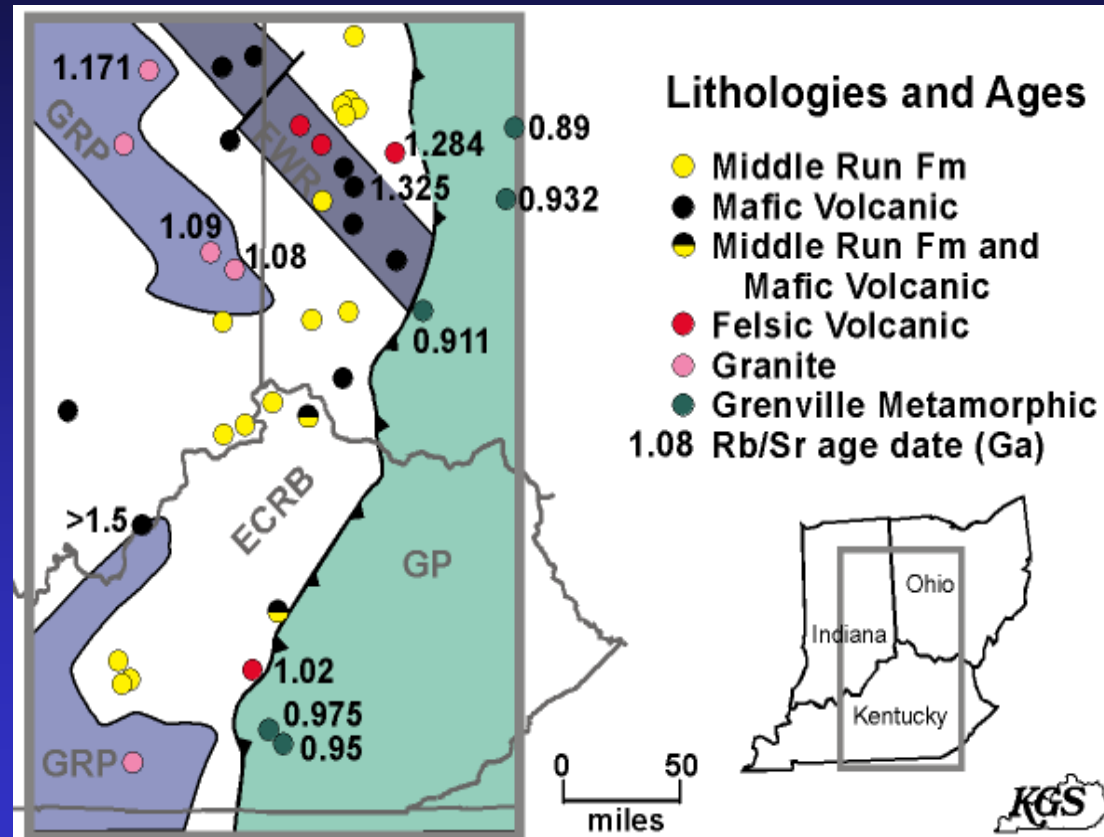
- Crystalline Rock
- Relatively Simple Geology
- Eastern Granite-Rhyolite Province
 - 1.45 - 1.48 Ga
- Grenville Province
 - Emplaced ~ 1.0 Ga



Modified from Denison and others, 1984

Proterozoic Drilling Data in the Eastern Midcontinent Shows a Different Story

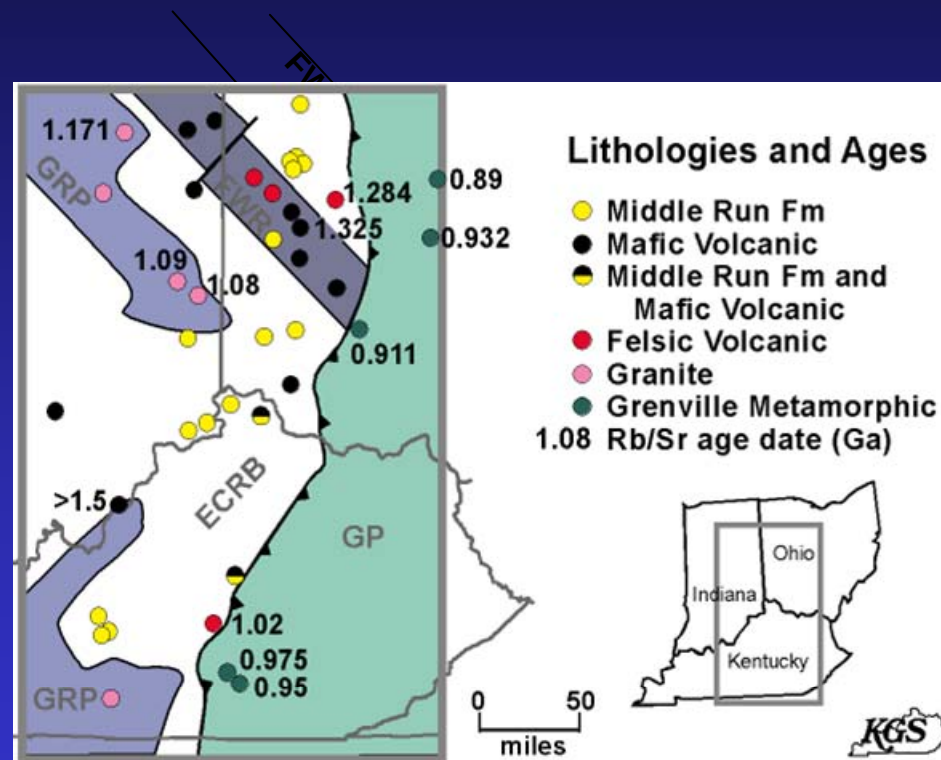
- **East Continent Rift Basin**
 - Largely sedimentary rocks
 - Lithic arenite (Middle Run Fm)
 - Interbedded with mafic volcanic rocks
 - Also felsic intrusions
 - Thick sequence—rift basin
- **Granite-Rhyolite Province to West is distinct and older**
 - Fort Wayne Rift Zone –an early rift center
 - Louisville basalt (also an early rift center?)
 - Younger granite intrusions in this area
- **Grenville Province to East**
 - Thrust over ECRB



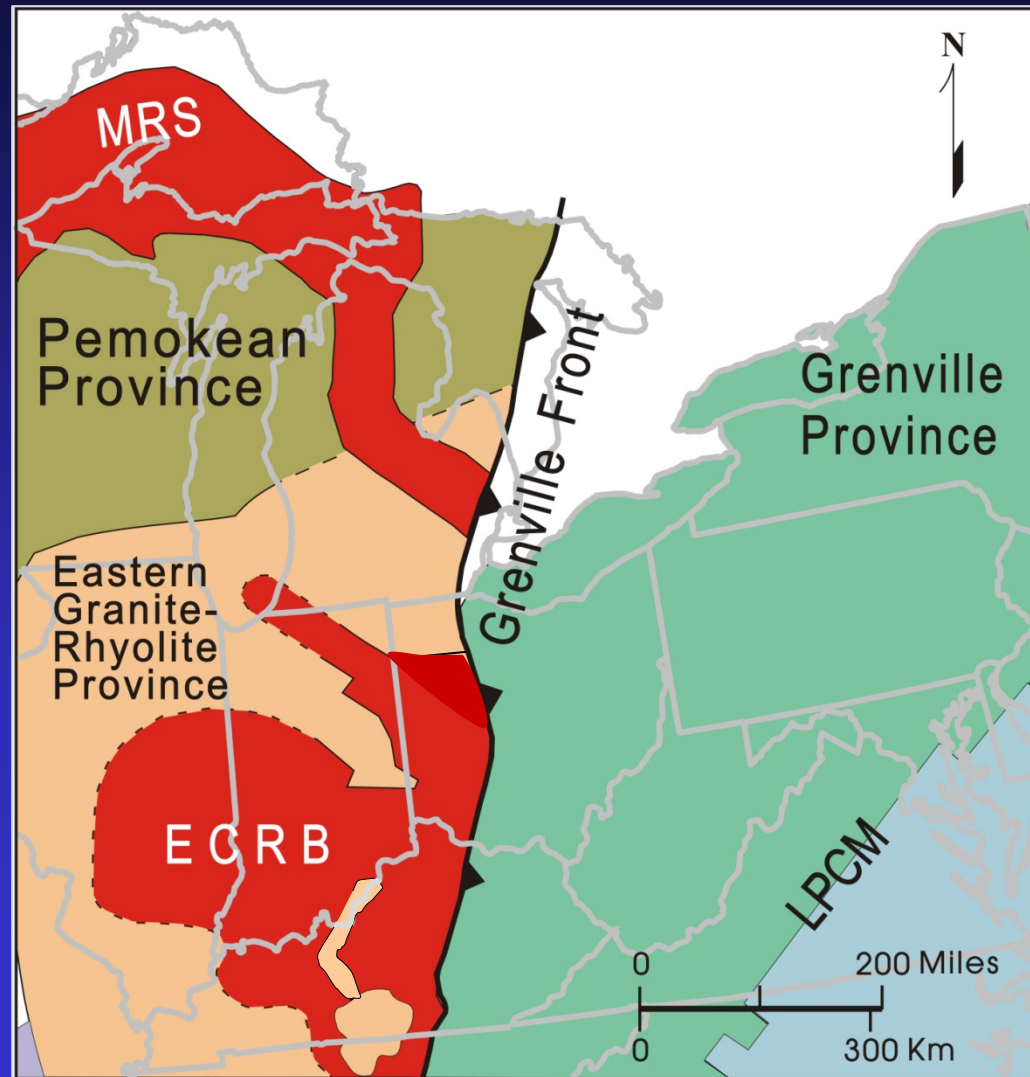
Modified from Drahovzal and others, 1991
Based on Bass, written comm. 1969; Hoppe and others, 1983;
Denison and others, 1984; Lucius and von Frese, 1988; Collata and
others, 1990; Drahovzal and others, 1991; Harris, 1991a, 1991b

Revised “Basement”/Proterozoic Geology

- Geology more complex
- Eastern Granite-Rhyolite Province
 - Classically 1.45 - 1.48 Ga
 - Includes the Ft. Wayne Rift 1.325 Ga
 - Uplifted basalt at Louisville >1.5 Ga
 - Granite intrusions 1.08-1.171 Ga
- Sedimentary/Volcanic Province (East Continent Rift Basin--ECRB)
 - 1.02 – 0.95 (?) Ga
 - Late Foreland basin fill 0.6? Ga
 - Rift basin overprinted with compressional structures
 - Folds and thrust faults
 - Evidence of later wrench and extensional structures
- Grenville Province
 - Emplaced ~ 1.0 Ga in OH, KY, TN
 - Young metamorphic and thrusting ages (0.89-0.98 Ga)
 - Older petrolioth ages in part (1.457 Ga)

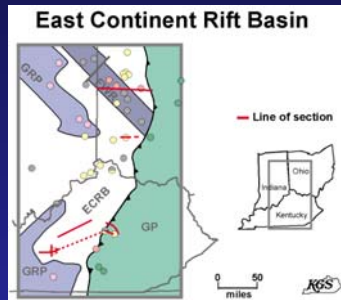


Possible Areal Extent of the ECRB based largely on seismic reflection data



Modified from Drahovzal, 1994a

Southwest Ohio Drill and Seismic Data



- **Definition of Middle Run Fm in well**

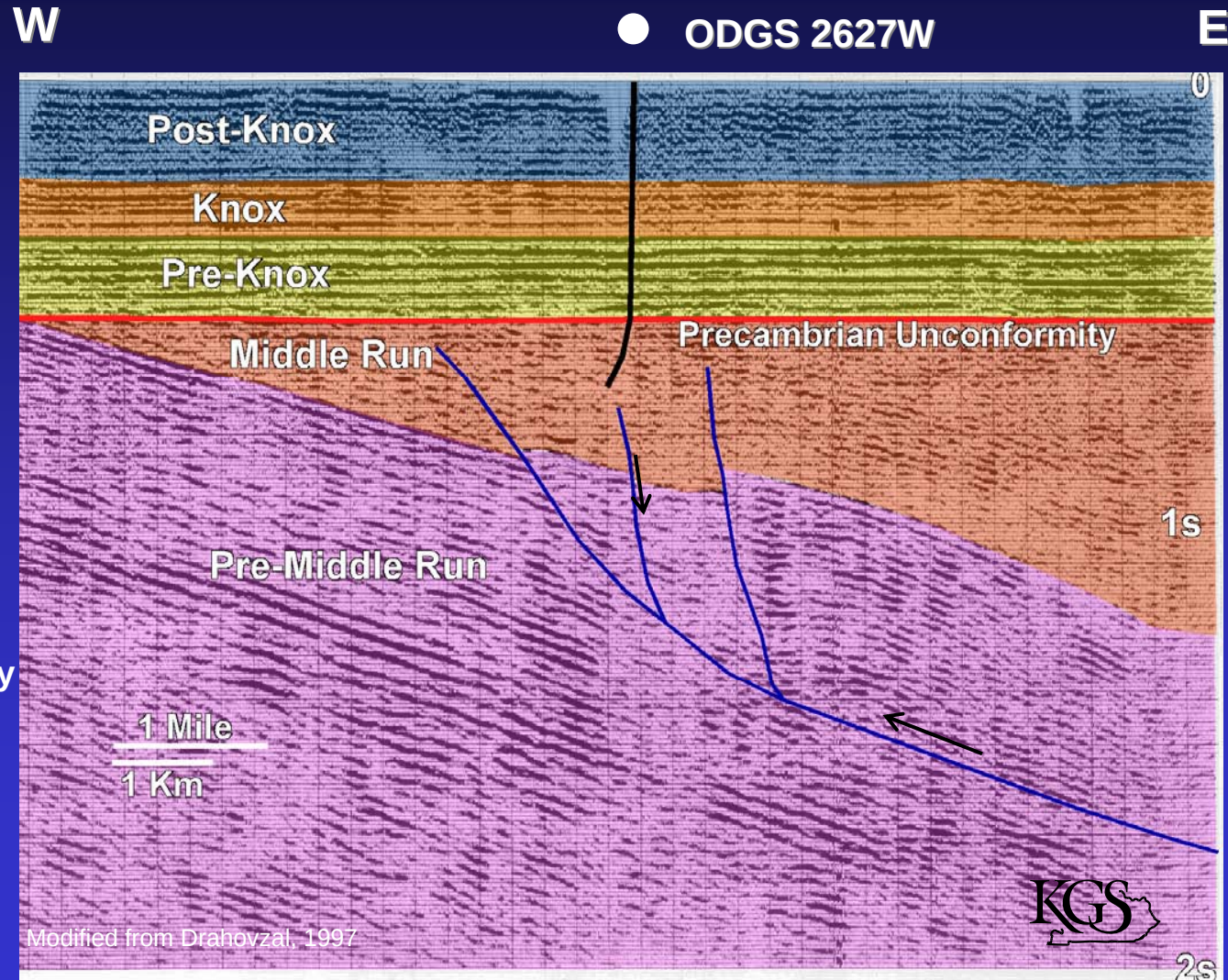
- Mesoproterozoic

- **Seismic data:**

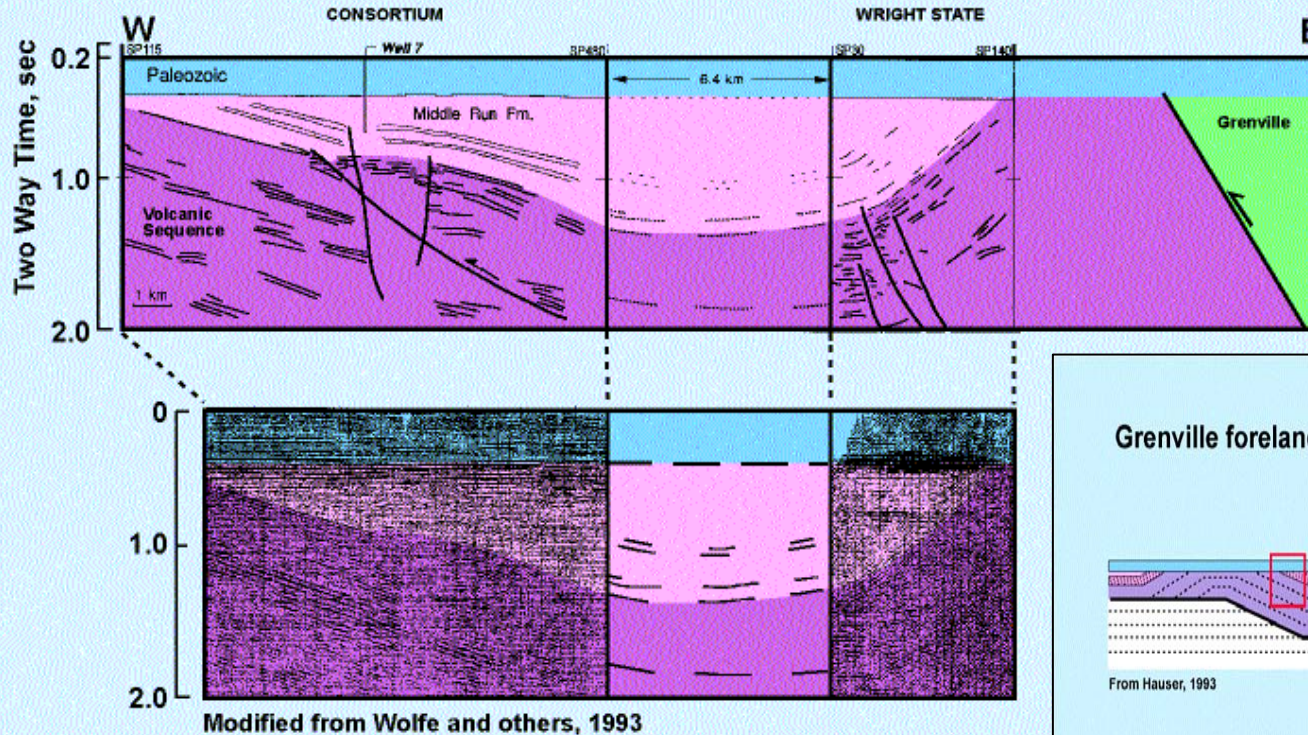
- East dipping
- angular unconformity
 - ~ 0.5 Ga
- Pre-Middle Run

- **Folding and thrusting**

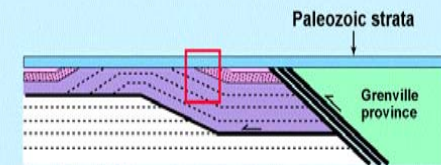
- Also extensional faulting



Broader View Southwest Ohio



Grenville foreland thrust belt model

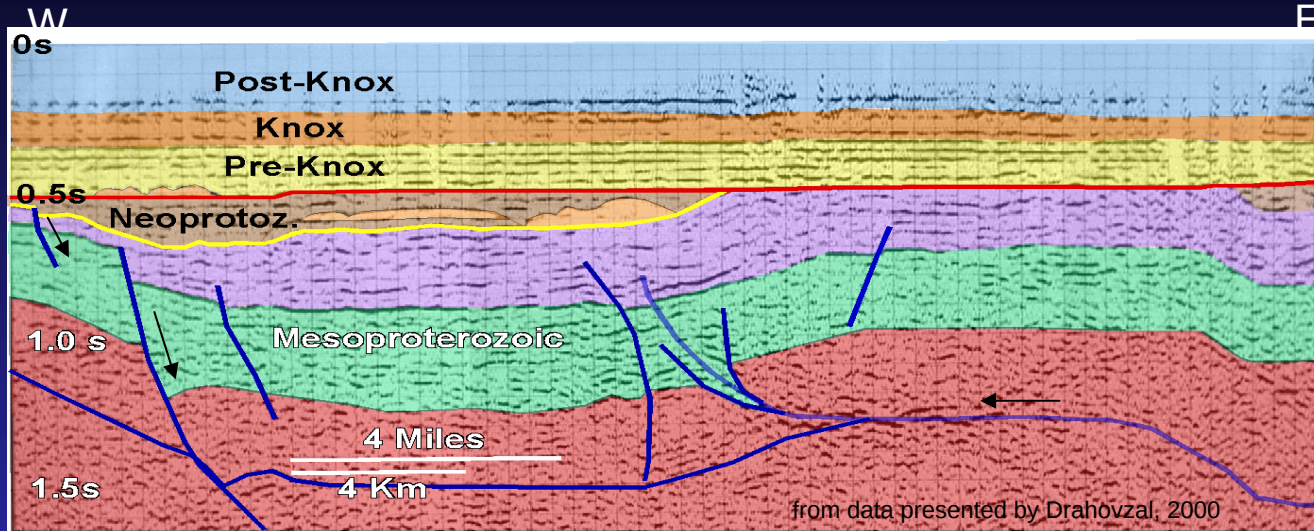


From Hauser, 1993

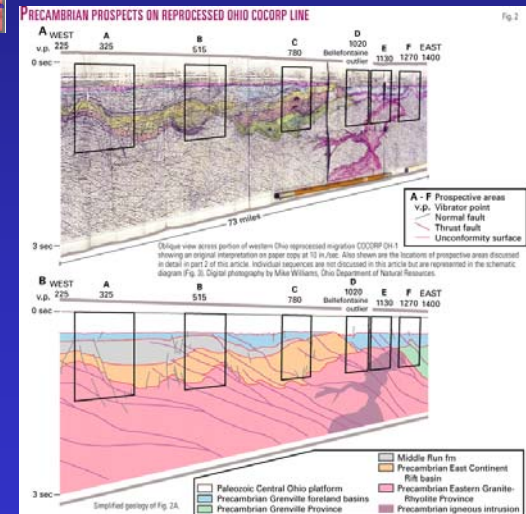
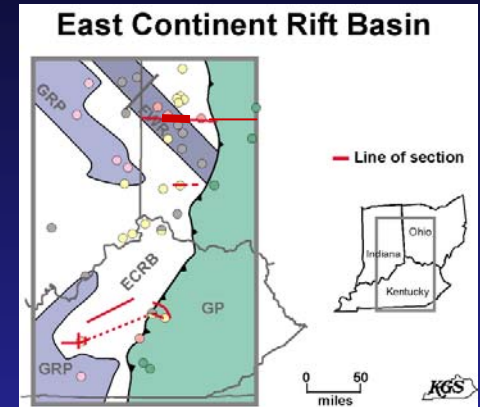


- West-vergent Fold and Thrust Belt

Eastern Ft. Wayne Rift, W. Ohio



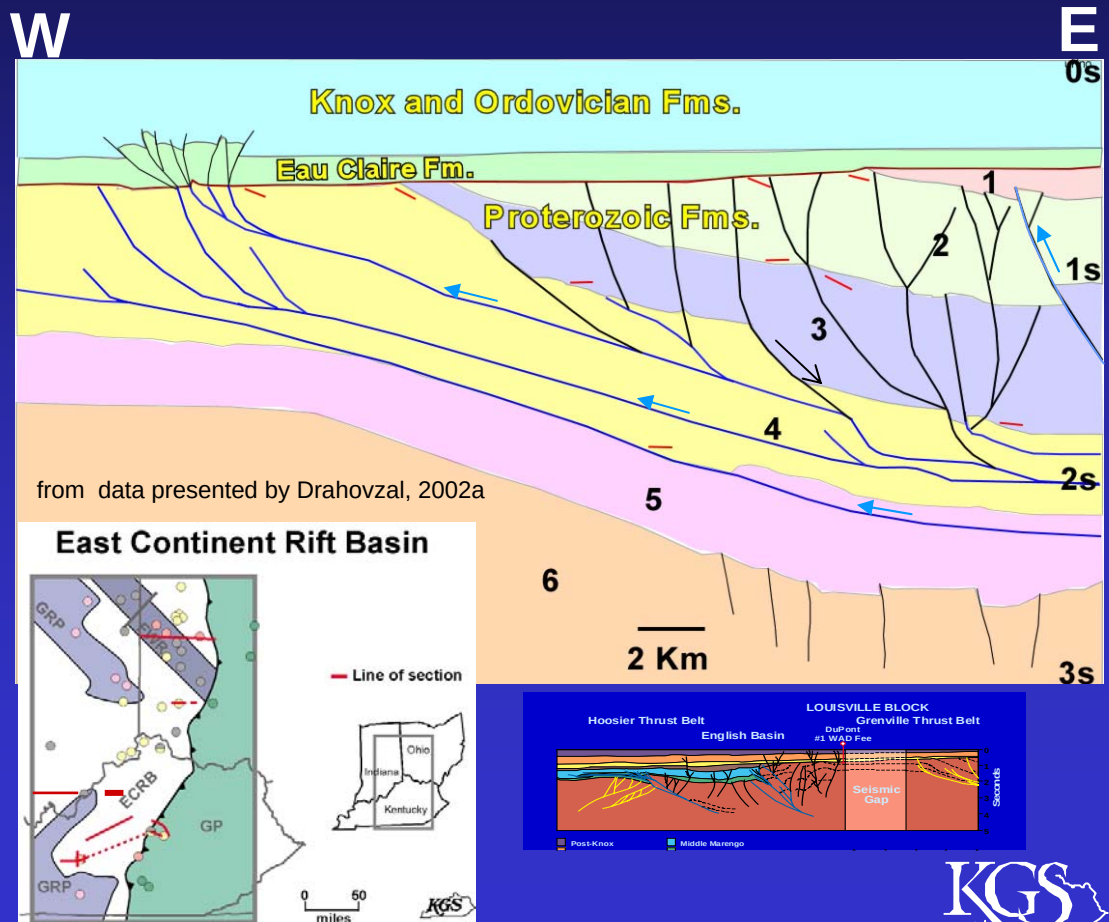
- Layered reflectors below unconformity
 - Lithic arenites, basalts, and rhyolites in nearby wells
- Mesoproterozoic rocks are folded and faulted
 - West-vergent fold and thrust belt (Grenville Thrust Belt)
 - Later extensional faults
- Neoproterozoic (?) undeformed
 - Onlaps onto rocks beneath
 - Cut by extensional faults



from Dean and Baranoski, 2002

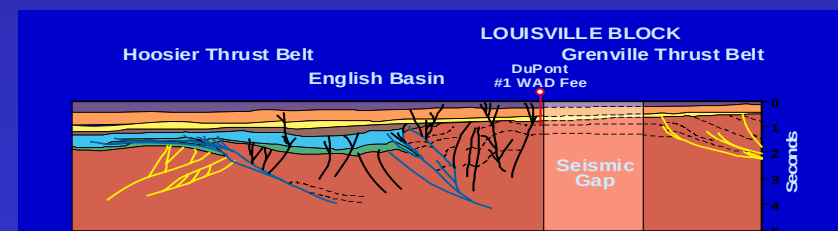
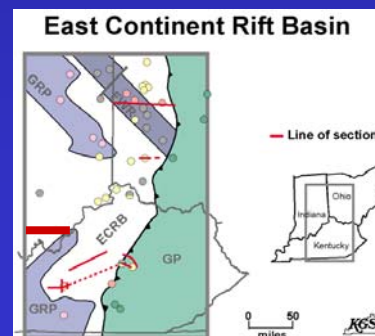
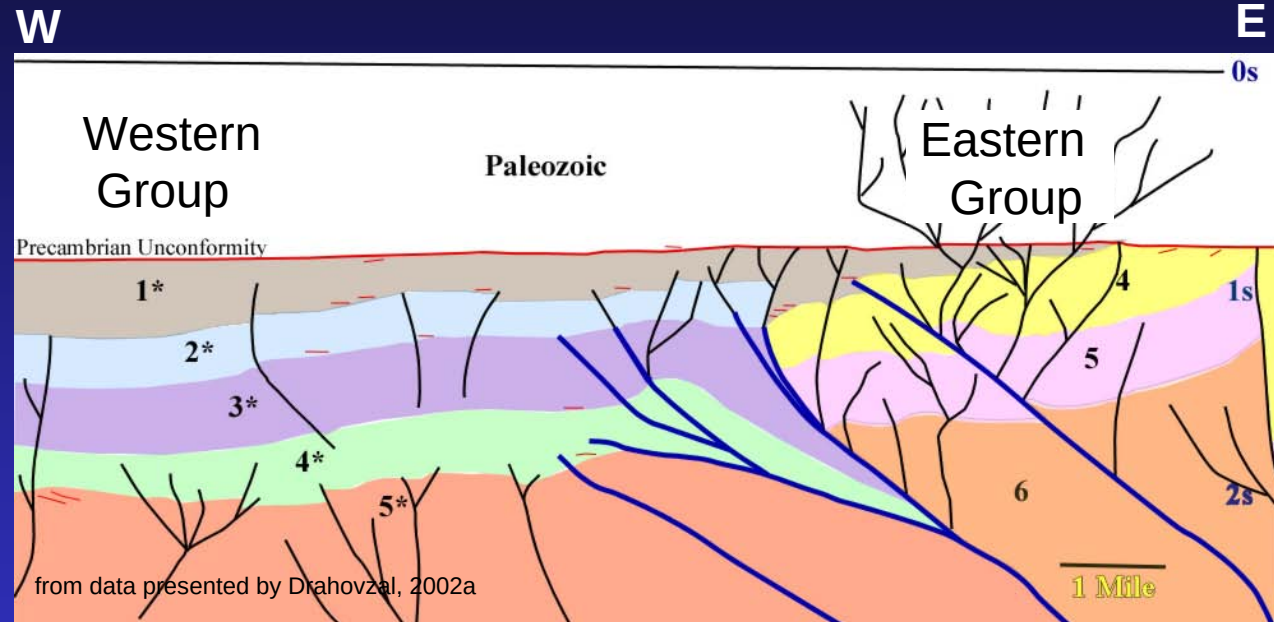
Layered Reflectors in North-Central Kentucky

- Angular unconformity top of Mesoproterozoic
- Thrust- faulted E dipping layered reflectors
 - Six reflector packages labeled 1- 6
 - sequence boundary indicators
 - Truncations, onlap, downlap & toplap
 - 3 and 4 drilled to south—lithic arenite
- Later Proterozoic extensional faulting rooted in the thrust faults
- Some Paleozoic wrench faulting



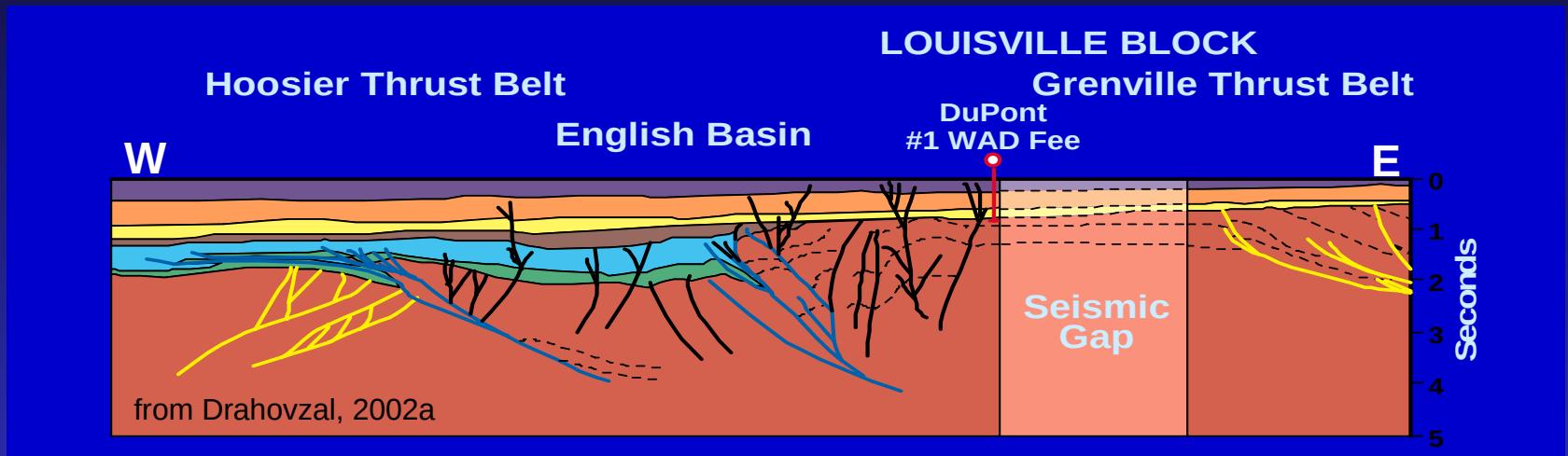
Layered Reflectors in Southwest Indiana

- Angular unconformity top of Mesoproterozoic
- W dipping layered reflectors (Sequences 4-6)
- Sequences in English Basin (Western Group)
 - Five sequence packages labeled 1*- 5*
 - Sequence boundary indicators
 - Not drilled
 - Much of Western Group younger (?) than Eastern Group
 - 1* undeformed
- Late (0.6 Ga) Uplift along reverse faults*
- Extensional faulting
- Some Paleozoic wrench faulting



* Stark, 2002

Cross Section: Northern Kentucky and Southwestern Indiana



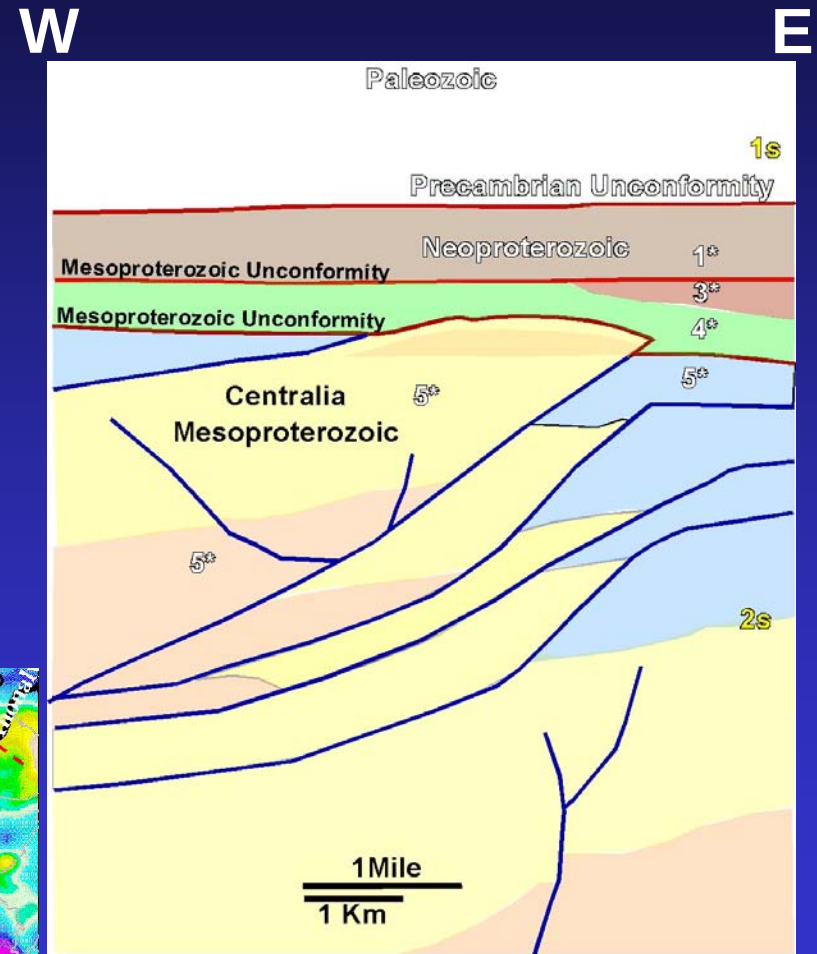
- Louisville Block uplifted 4-8 km 0.6 Ga (based on apatite fission track data, Stark, 2002)
- West vergence to the East
 - Grenville Thrust Belt
 - Faults associated with Louisville Uplift
- East vergence to the West
 - Hoosier Thrust Belt

Thrust Belt in Southern Indiana

- Sequence 5* is deformed by a east-vergent thrust belt
 - Hoosier Thrust Belt
- East-vergent Hoosier Thrust Belt may be age equivalent to the west-vergent Grenville Thrust Belt
- ~12,000 ft to the top of the anticline



from data presented by Stark
and others, 1999

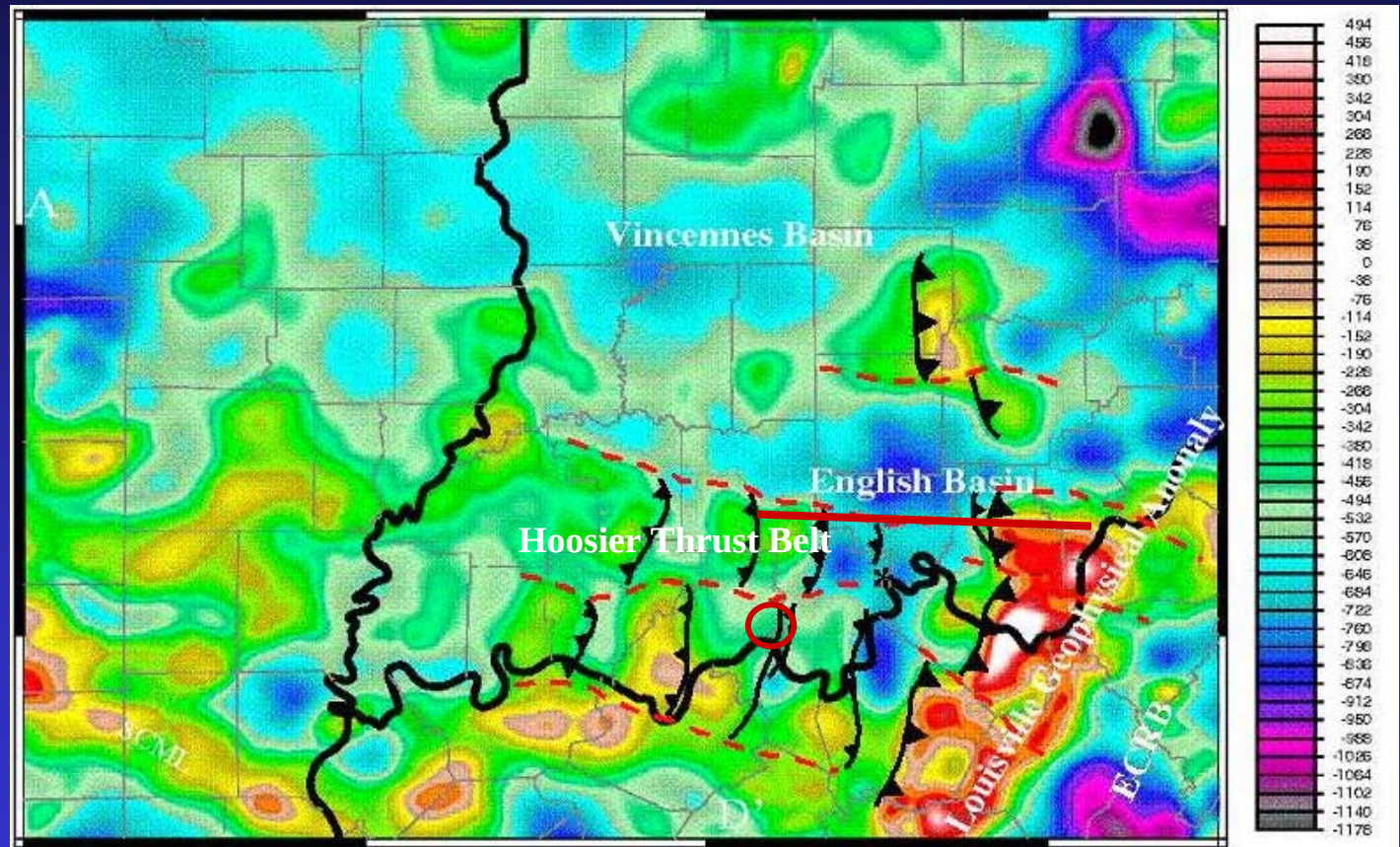


from data presented by Drahovzal, 2002b



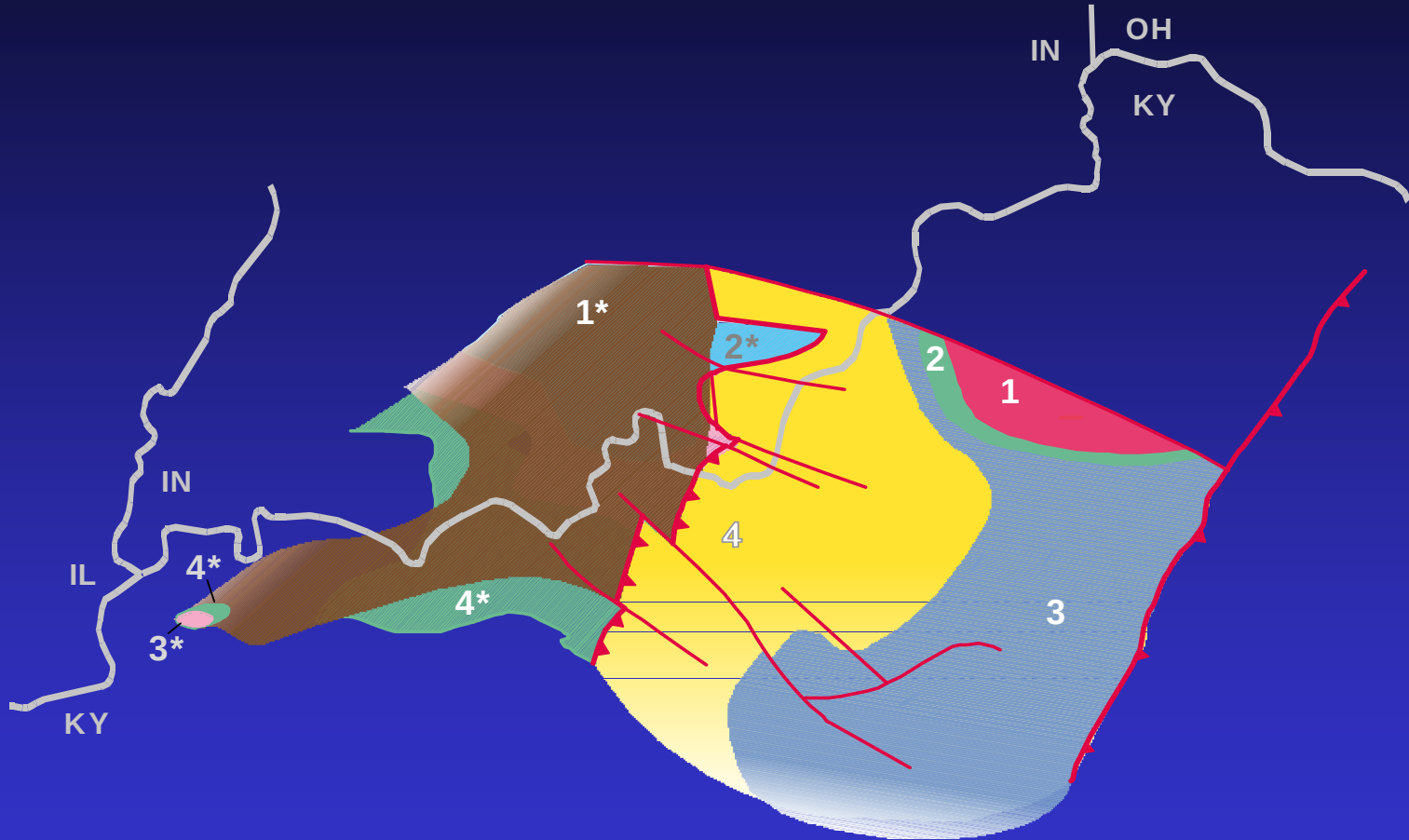
Aeromagnetic Map of the Southeast Midcontinent

- East Continent Rift Basin
- Louisville High and Fault Zone
- English Basin
- Hoosier Thrust Belt

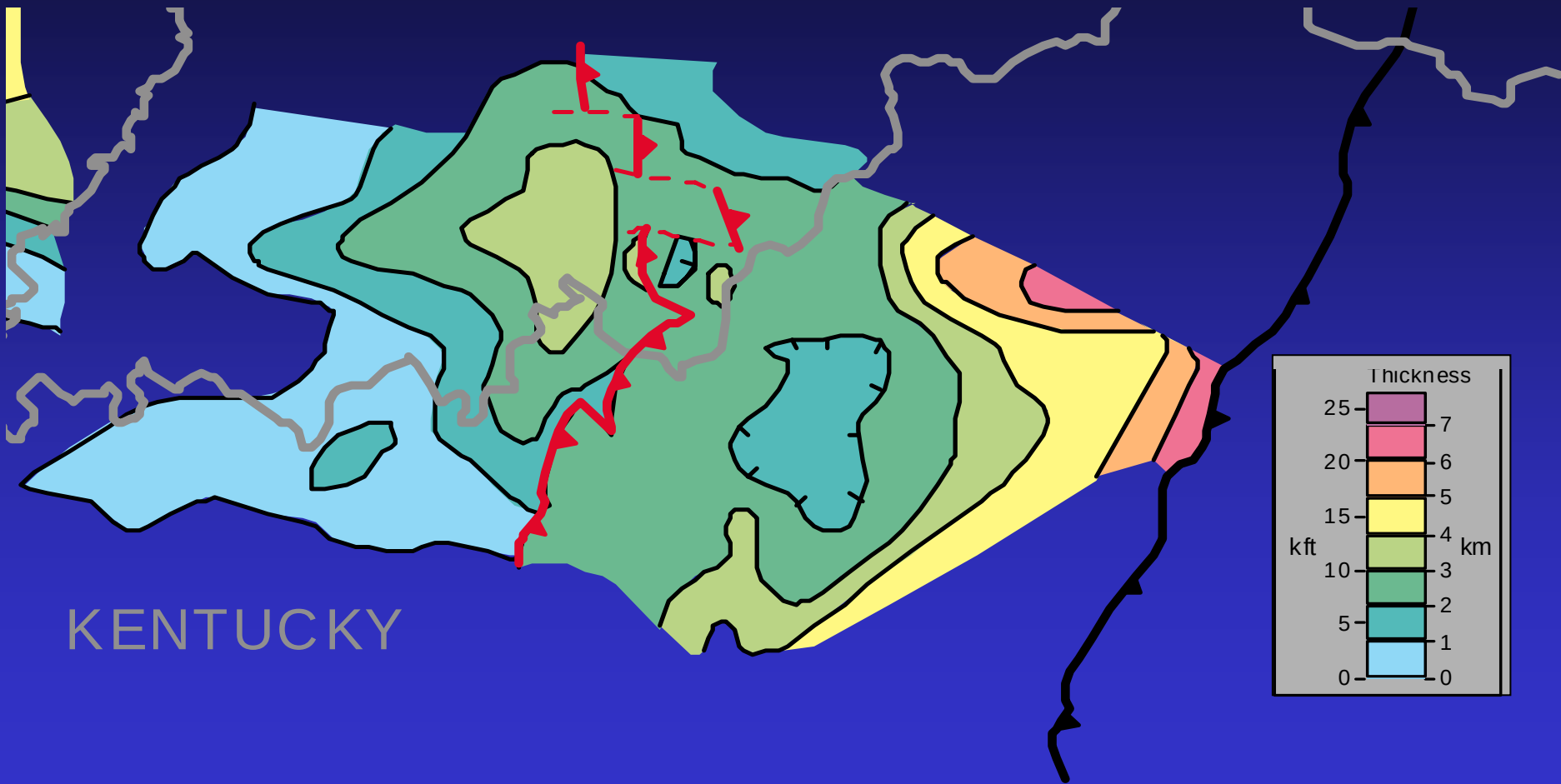


From Stark et al., 1999

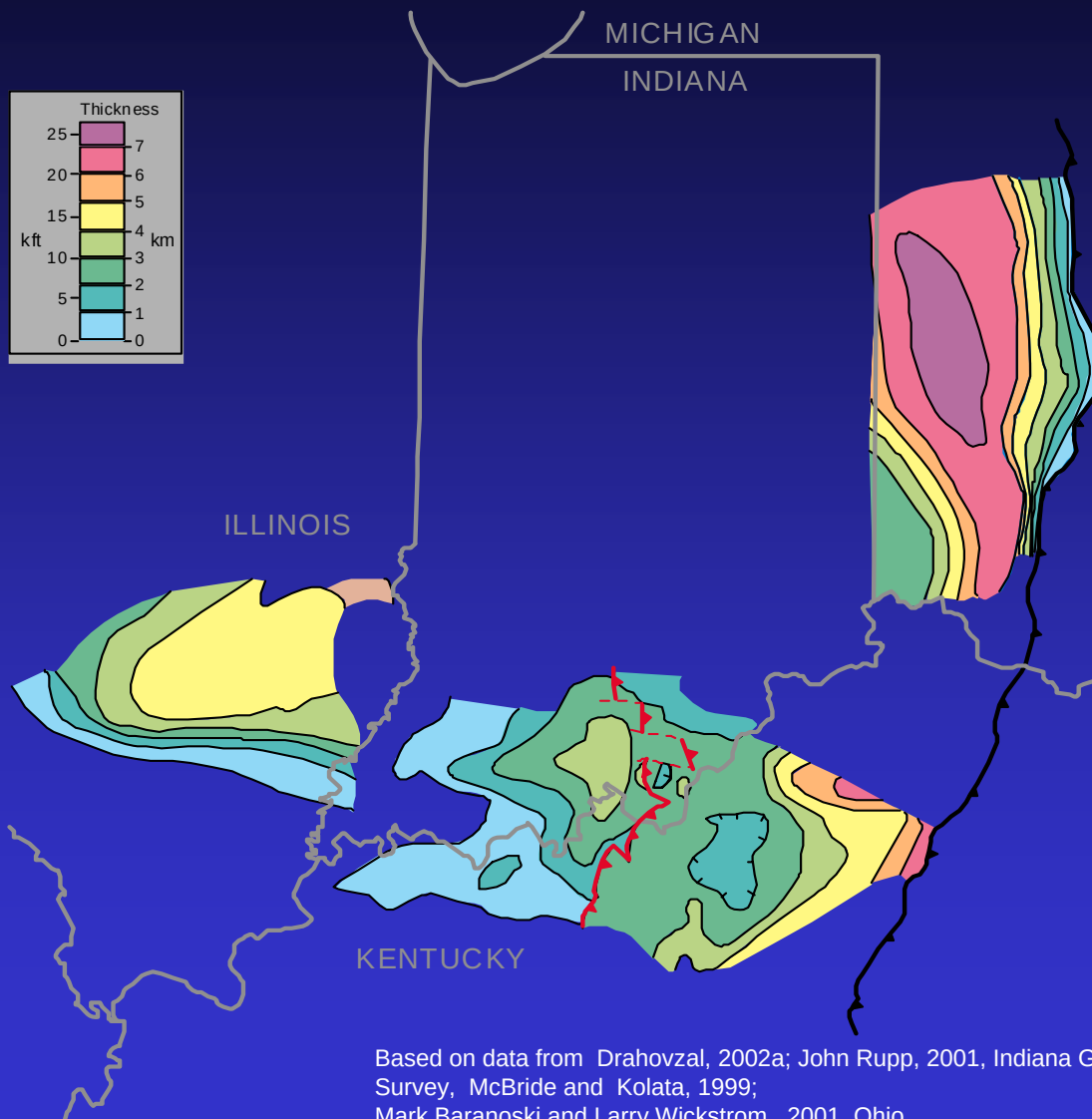
Proterozoic Geologic Map Kentucky and Indiana



Proterozoic Isopach of Map Kentucky and Indiana



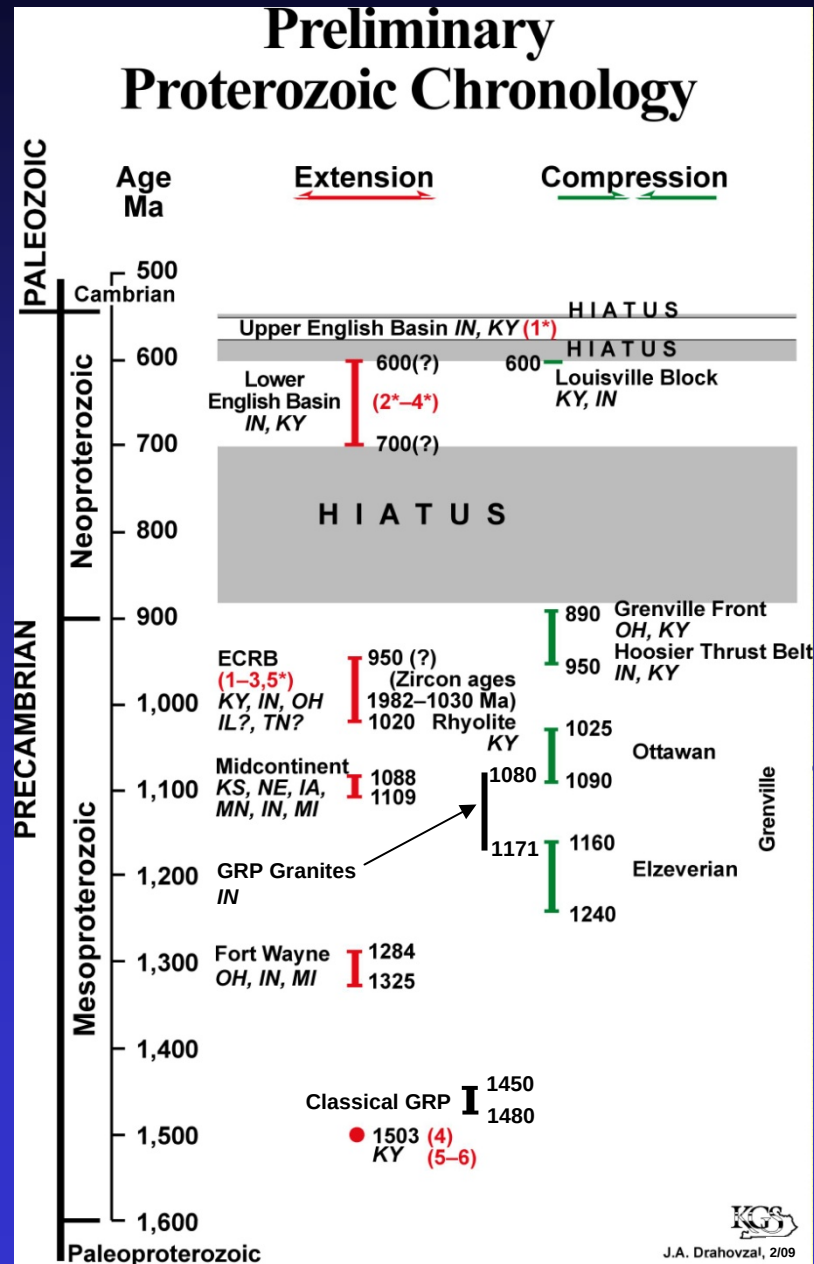
Regional Proterozoic Layered-Reflector Isopach Map

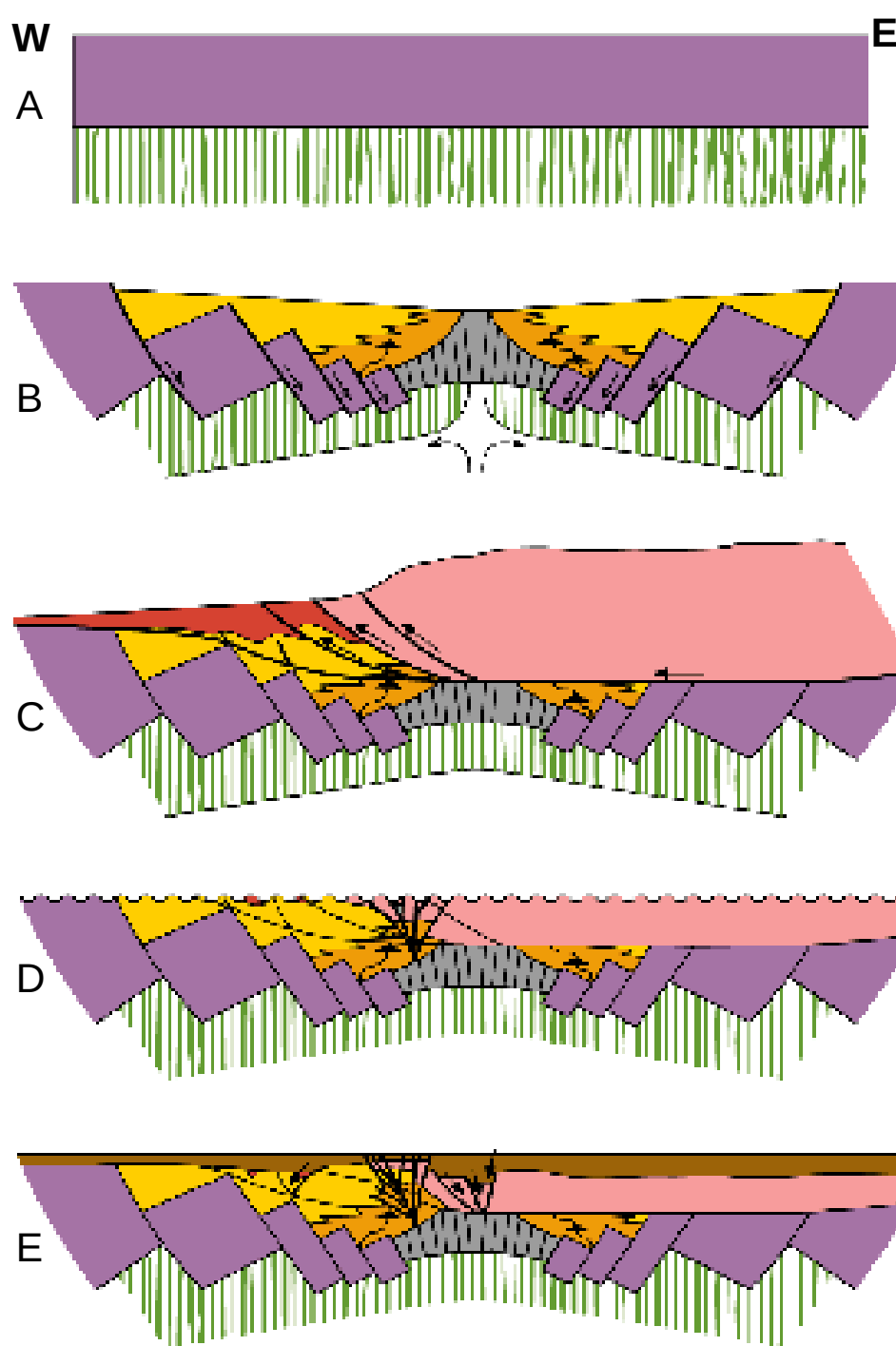


Based on data from Drahovzal, 2002a; John Rupp, 2001, Indiana Geological Survey, McBride and Kolata, 1999; Mark Baranoski and Larry Wickstrom, 2001, Ohio Geological Survey



Preliminary Proterozoic Chronology



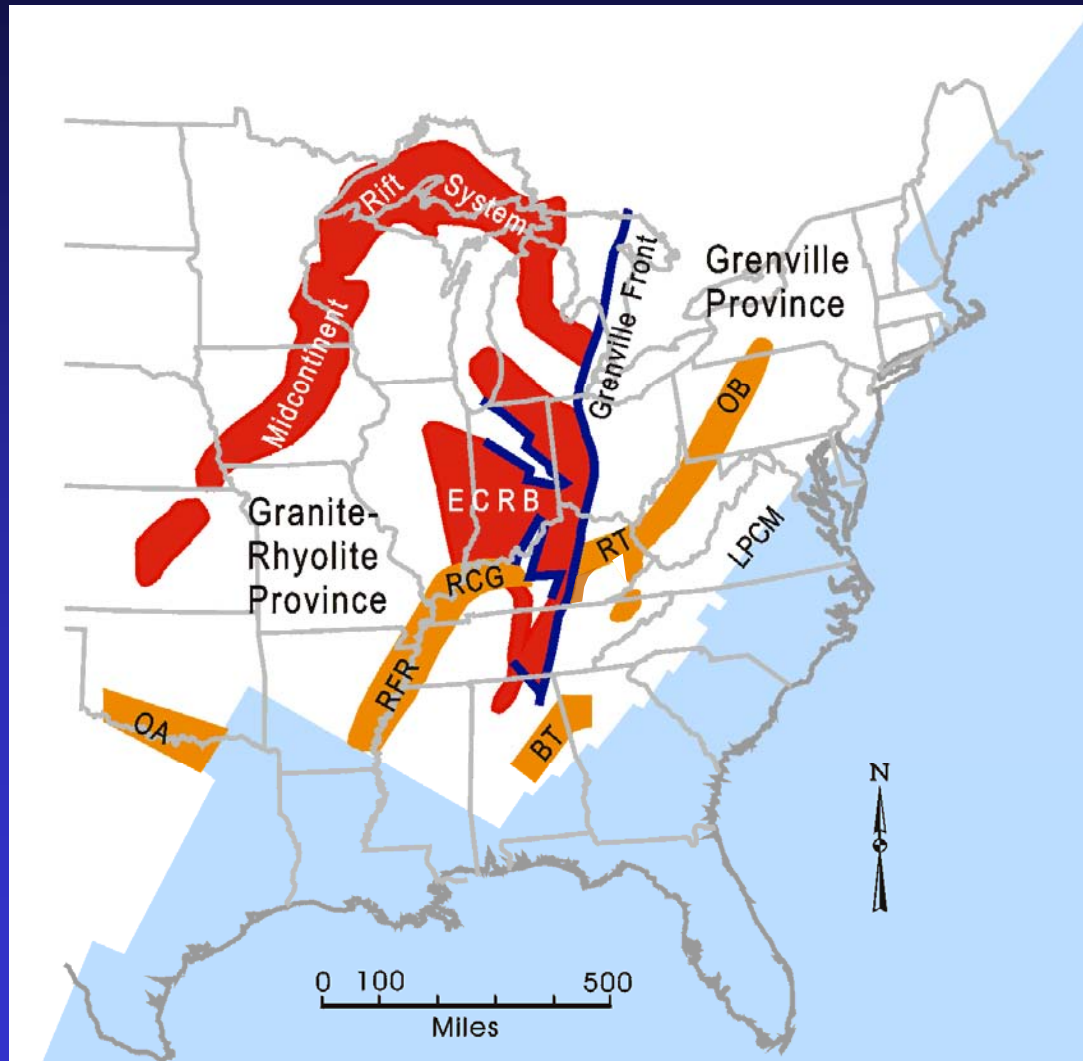


East Continent Rift Basin Development Model

- A. Emplacement of Granite-Rhyolite Province
- B. Extension and emplacement of central mafic plug with attendant basalt flows, felsic intrusions and thick alluvial fan deposits (Middle Run Fm) from eroded fault blocks
- C. Emplacement of Grenville allochthon, folding and faulting in Middle Run Fm. and foreland basin development
- D. Deep erosion; extensional and wrench faulting; uplift of Louisville Block and deposition of undeformed rocks (not shown)
- E. Cambrian “inversion” to W; extension and subsidence to E (Rome Trough) and far W (Rough Creek Graben; not shown)

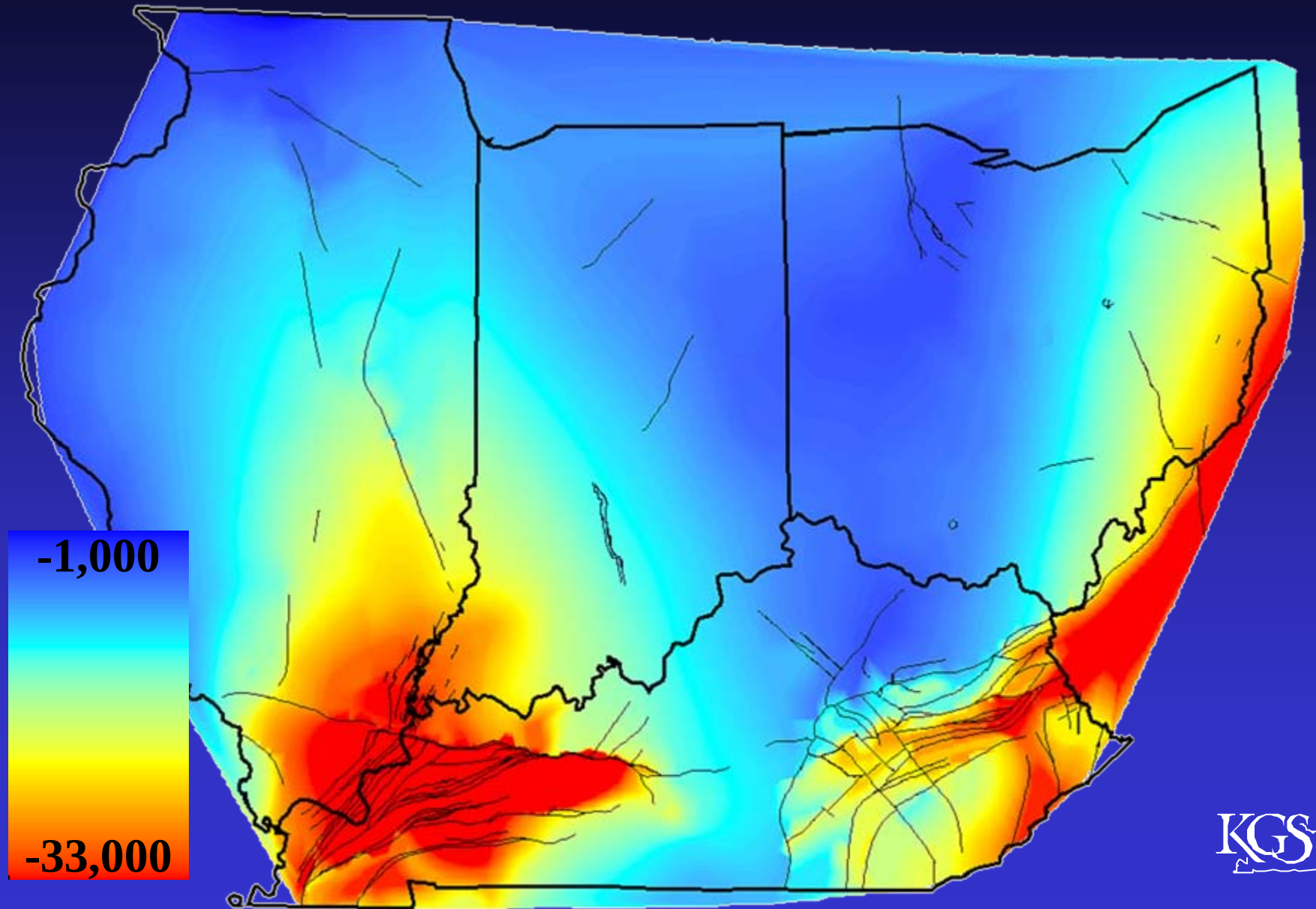
from Drahovzal
and others, 1992

Proterozoic and Cambrian Basins of Eastern US



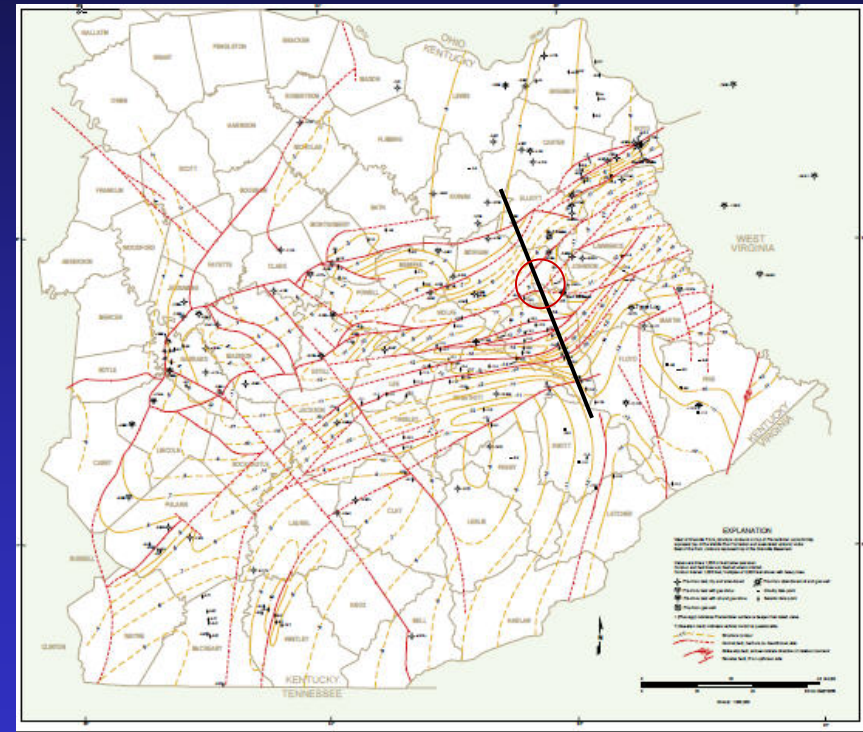
Modified from Drahovzal, 1994a

Structure: Top of Proterozoic



Rome Trough: Eastern Kentucky

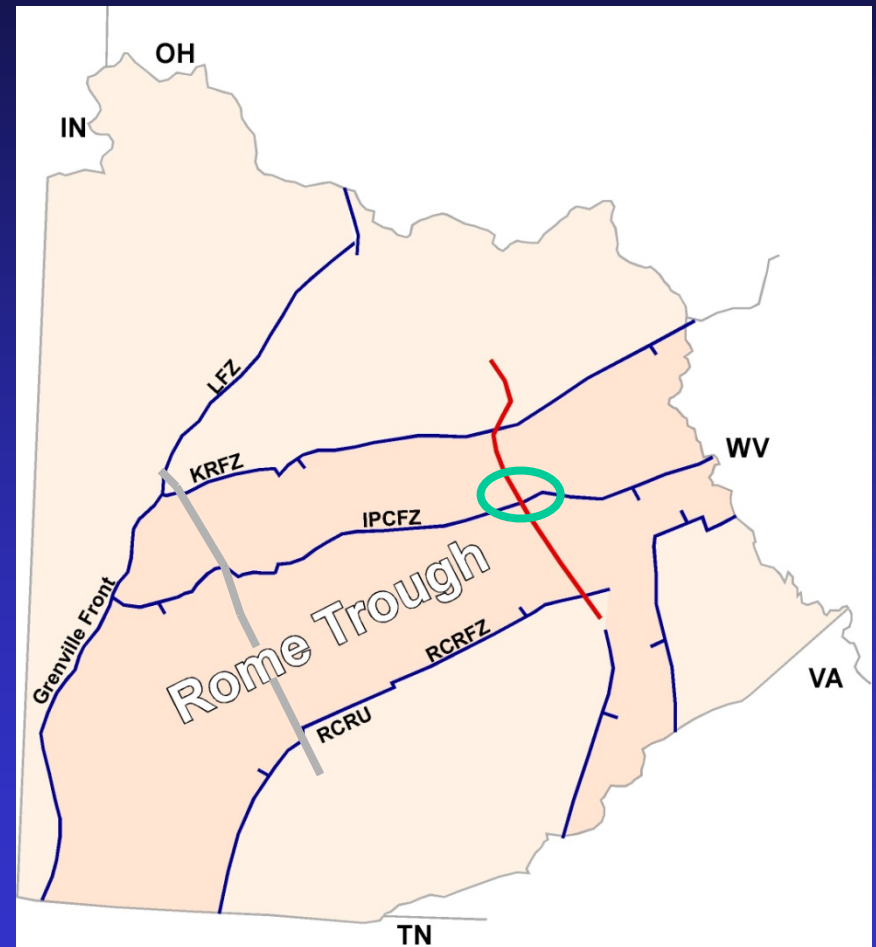
- Symmetrical Cambrian rift basin
- Three major Fault Zone Boundaries
 - N: Kentucky River FZ (KRFZ)
 - S: by Rockcastle River FZ (RRFZ)
 - Medial: Irvine-Paint Creek FZ (IPCFZ)
- Thickening
 - across the KRFZ is 2.5- 5x
 - across the IPCFZ is 2- 4.5x
 - Across the RRFZ is 0- 2x
- Structural relief:
 - ~12,000 ft across the KRFZ to the deepest part of the basin
 - Up to only ~ 7,000 feet across the RRFZ
- Deepens from -5,000 to -7,000 ft along W edge to -10,000 to -17,000 depth at WV line



from Drahovzal and Noger, 1995

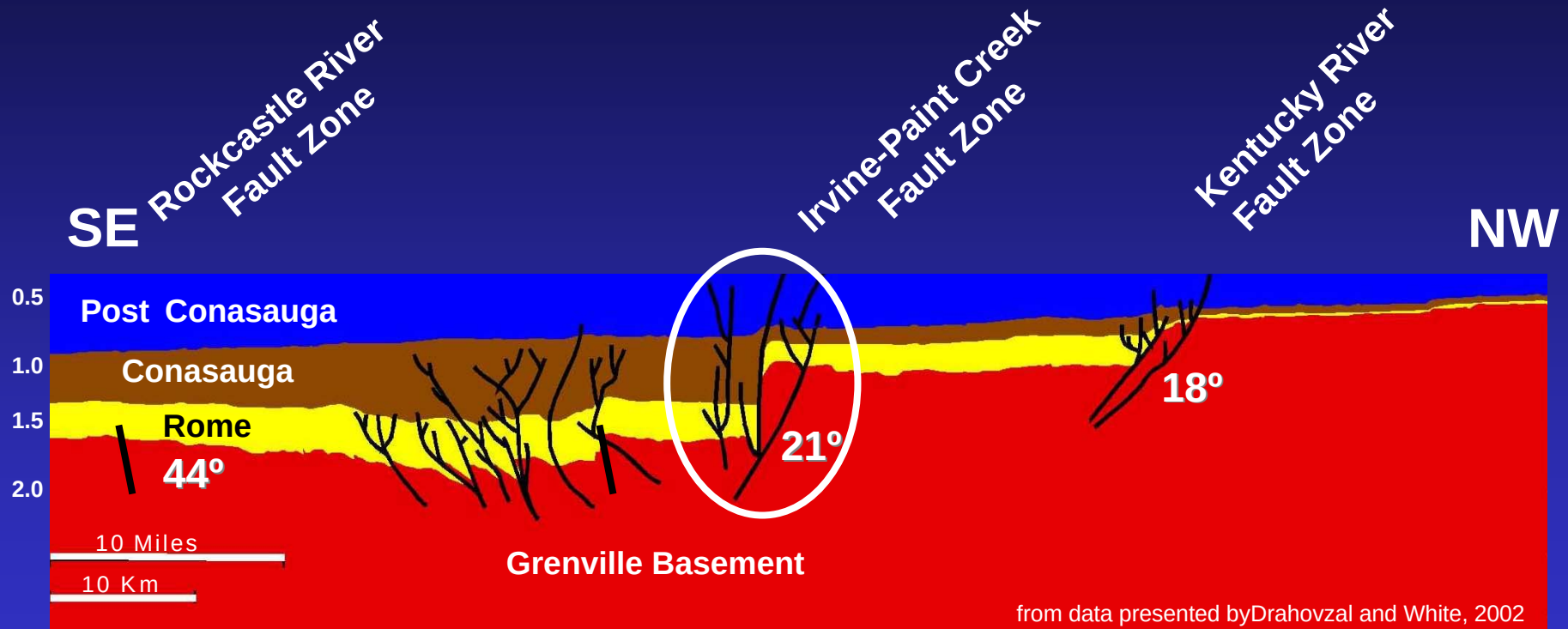
Cross Section of the Rome Trough

- Focus on the eastern part of the Rome Trough
- And on the Irvine-Paint Creek FZ



from data presented by Drahovzal and White, 2002

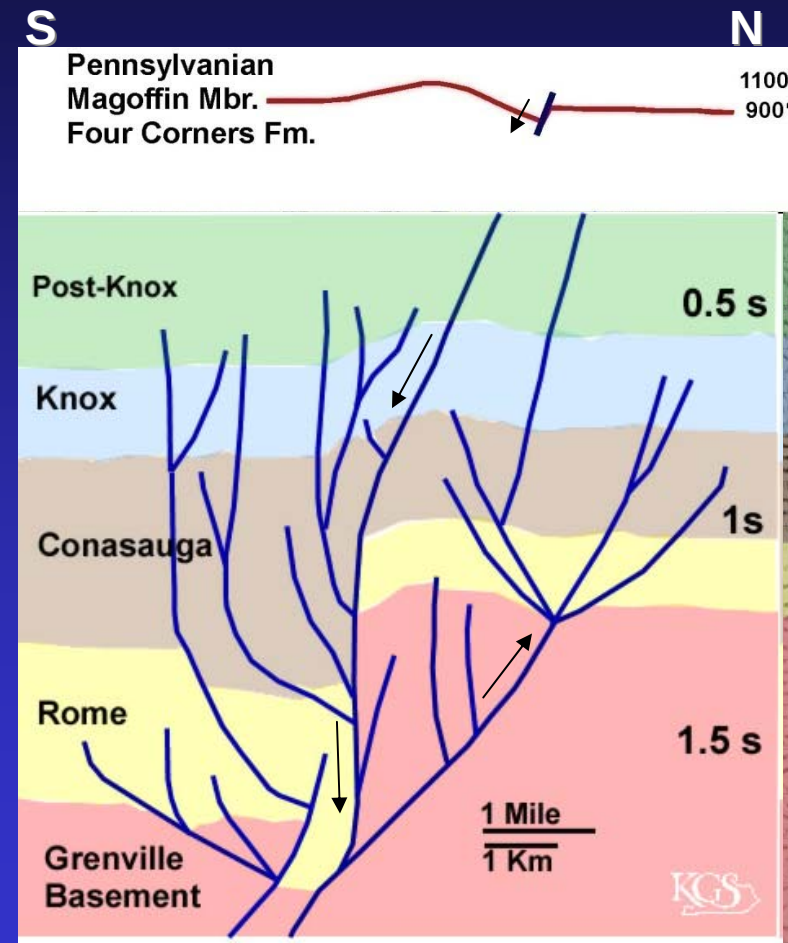
Cross Section of the Rome Trough



- Note thickening across KRFZ and IPCFZ; but little across RRFZ
- Listric faults in the major fault zones; steeper in near surface
- Note low angles of the faults at depth; suggests influence of a compressional event; also apparent reverse faults in basement
- Focus on Irvine-Paint Creek Fault Zone area

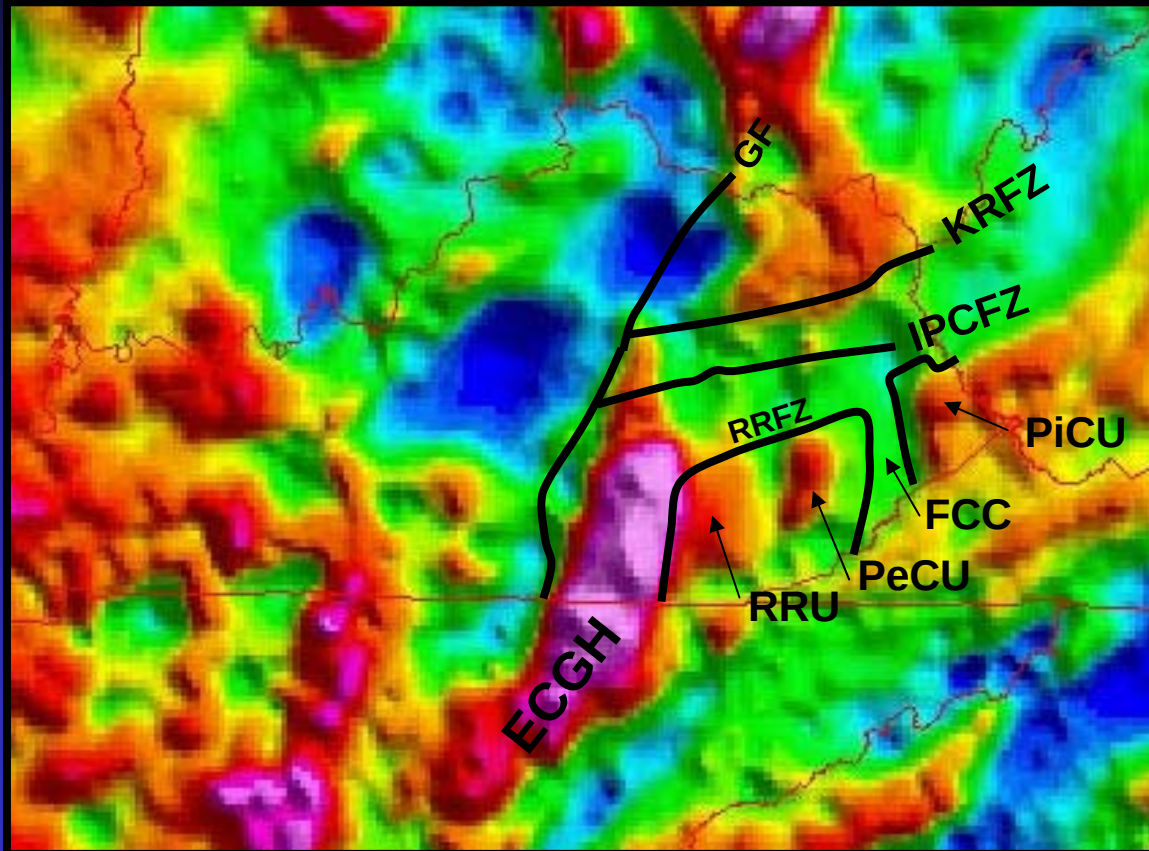
Is there evidence of Mesozoic reactivation in the Rome Trough?

- **Rift Phase: Steep Cambrian extension fault with major Cambrian growth of $>2 \times$**
- **Later, lower-angle reverse faulting folded basement through Pennsylvanian rocks**
 - Note vertically stacked anticlines
 - Likely Alleghanian transpression
- **Down-to-south normal faulting in the Pennsylvanian reactivated the original Cambrian normal fault**
 - Likely due to Triassic-Jurassic regional extension (opening of the Gulf of Mexico?)



from data presented by Drahovzal and White, 2002

What is the relationship between East Continent Gravity High (ECGH) and the Rome Trough (RT)?



Isostatic anomaly gravity from USGS

<http://mrdata.usgs.gov/geophysics/gravity.html>

GF – Grenville Front

KRFZ– Kentucky River Fault Zone

IPCFZ– Irvine-Paint Creek Fault Zone

RRFZ—Rockcastle River Fault Zone

RRU—Rockcastle River Uplift

PeCU– Perry County Uplift

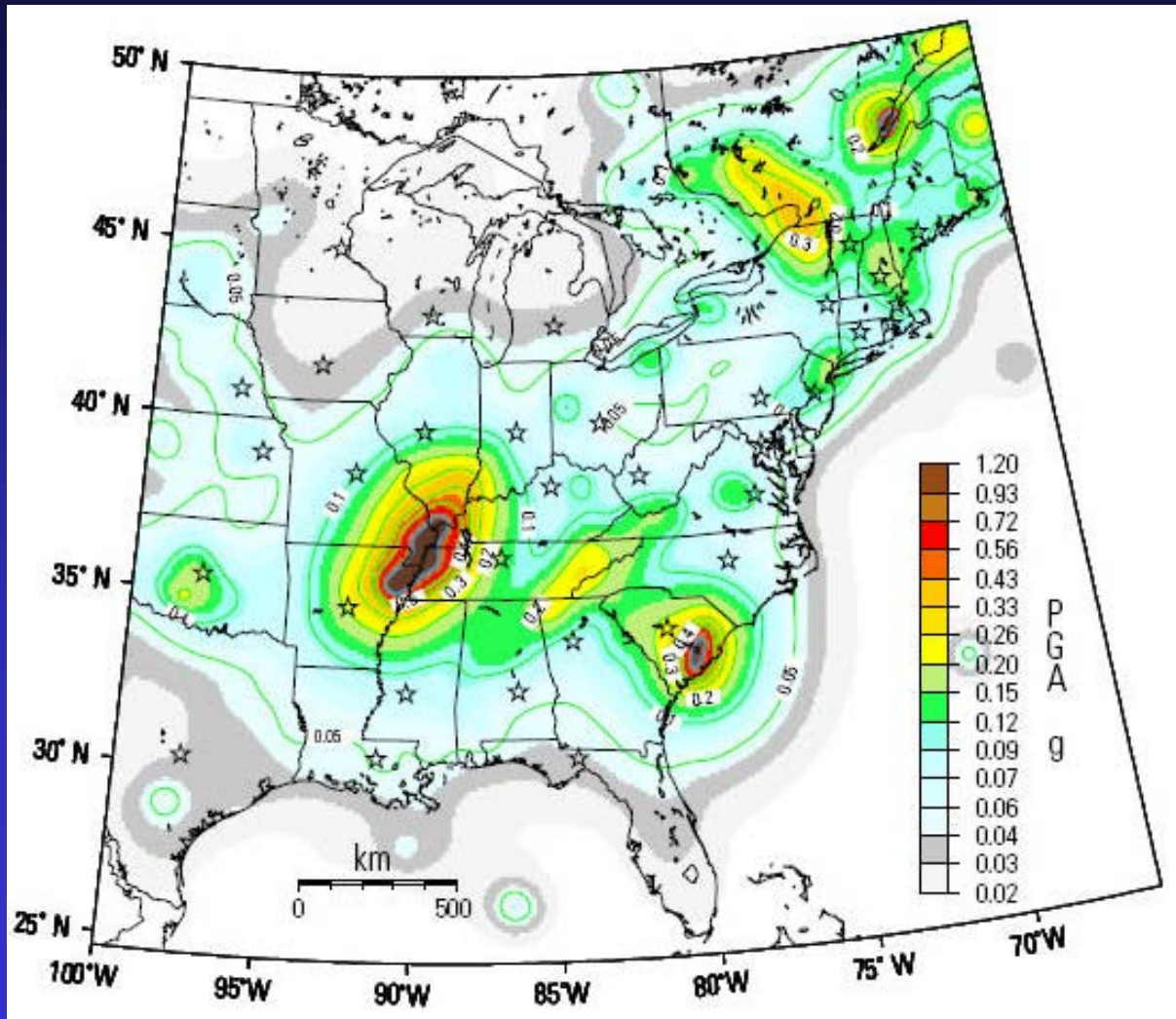
FCC—Floyd County Channel

PiCU—Pike County Uplift

- ECGH lies within SSW extension of RT
 - Bounded on W by Grenville Front; on E by Rockcastle River Fault Zone
 - ECGH “sinker”?
 - Remainder of RT in gravity lows
- N and S boundaries controlled by gravity highs
 - Rockcastle River FZ – Rockcastle River, Perry Co., and Pike Co. Uplifts
 - Kentucky River FZ— high to N
- Irvine-Paint Creek FZ and the Floyd Co. Channel in the Rome Trough

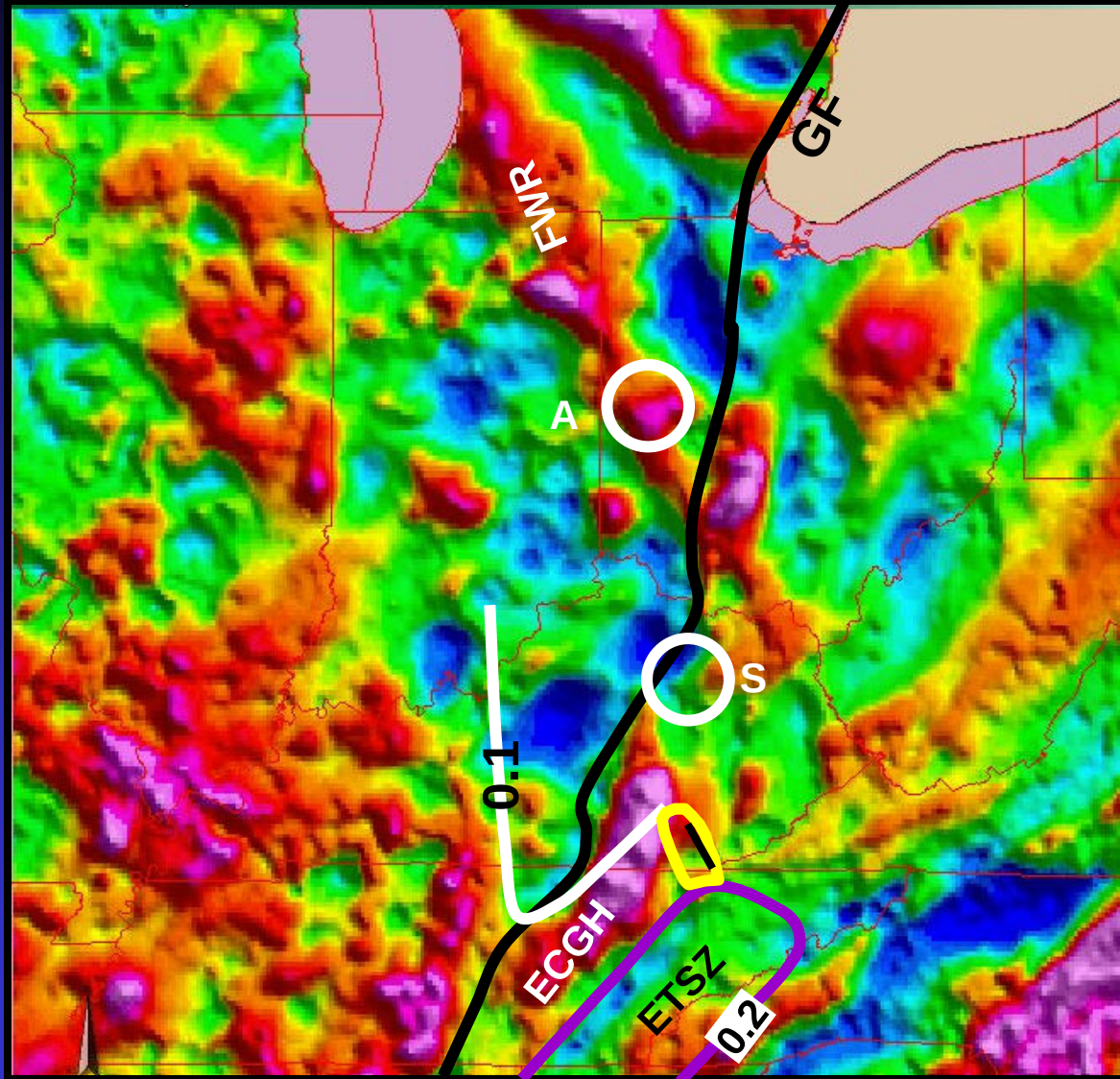


Seismicity: Map of peak ground acceleration (PGA) for 2% probability of exceedance in 50 yrs in std. gravity



USGS 2008

What is the relationship of the East Continent Gravity High (ECGH) and East Tennessee Seismic Zone (ETSZ)?



- **East Tennessee Seismic Zone**
 - SE and parallel to the ECGH
 - Truncated to NE
 - Spur of earthquake activity in SE KY; truncates at ECGH
 - East edge parallel to the Rocky Face & Dorton Branch FZs (black line)
- The Sharpsburg (S) M 5.2 event lies close to the ECGH
- Anna Seismic Zone (A) is coincident with the Ft. Wayne Rift (FWR)
 - FW R is older (1.2-1.3 Ga) than ECGH, cutting across it*
 - ECGH is ECRB rift center

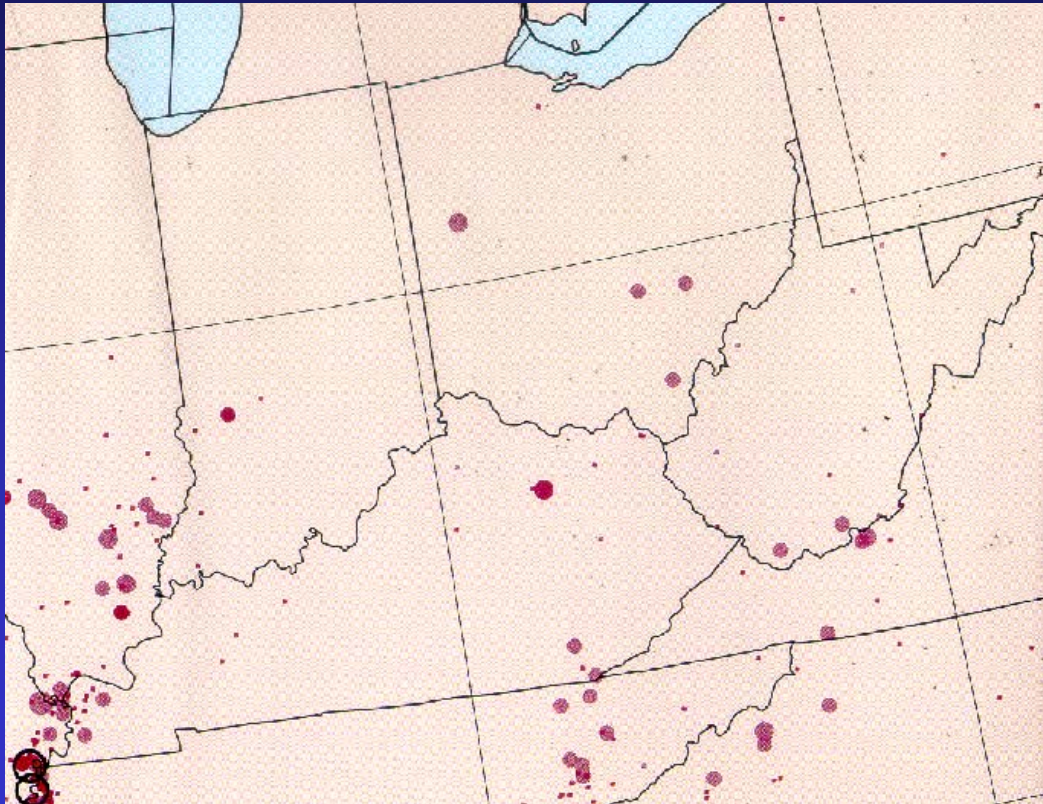
Isostatic anomaly gravity from USGS

<http://mrdata.usgs.gov/geophysics/gravity.html>

*Atekwana, 1996



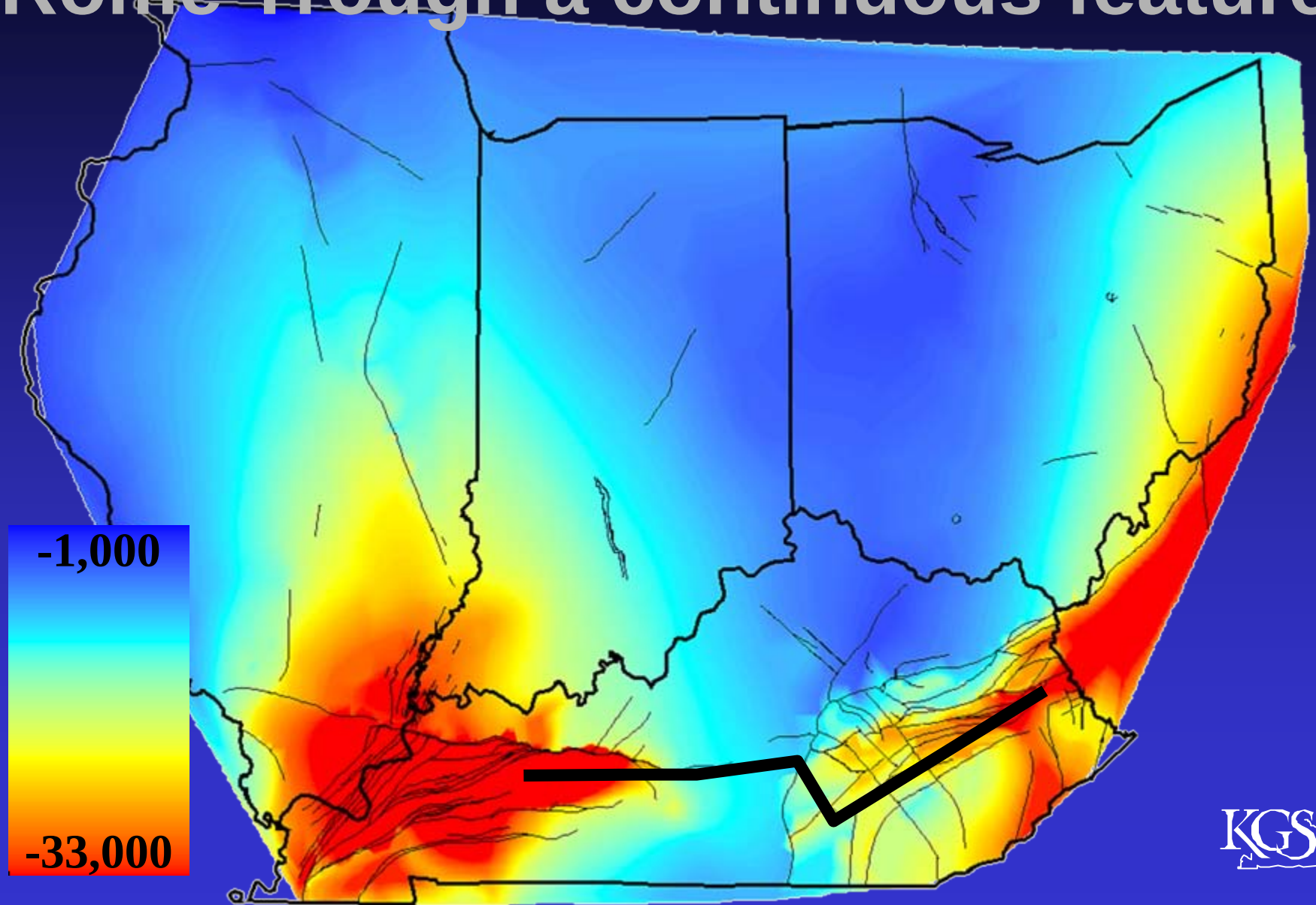
Seismicity in the Eastern Midcontinent



from Geological Society of America, 1988

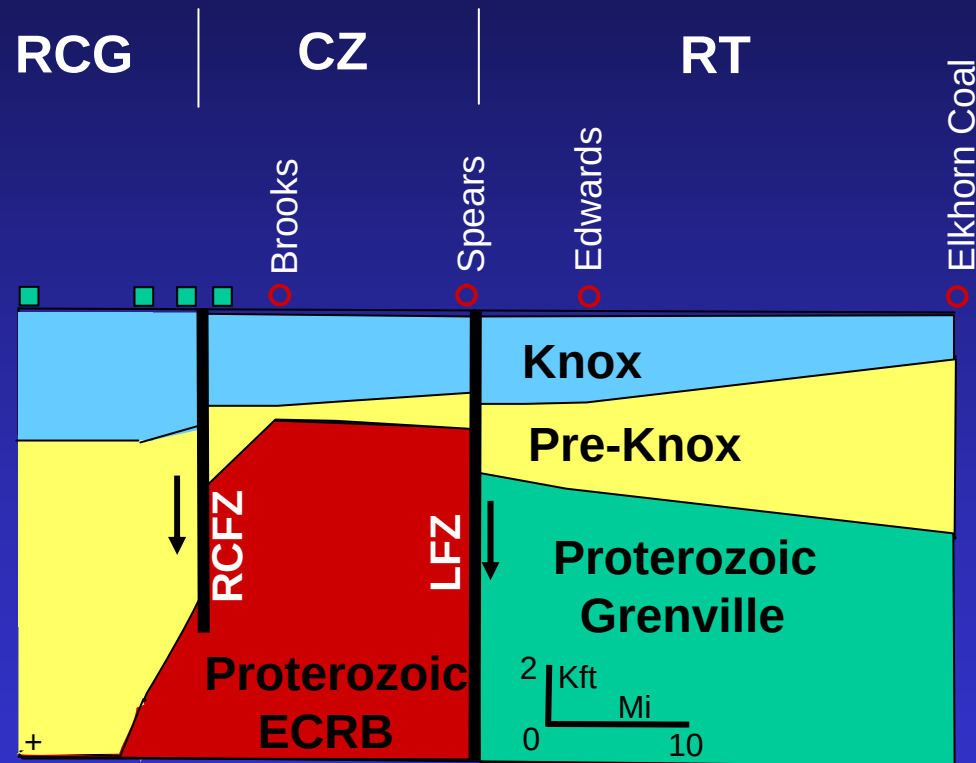
- All M 5 or less earthquakes , except for SW corner
- Aseismic
 - Rough Creek Graben
 - Rome Trough
- East Continent Rift Basin
 - High-level seismicity in southern IL
- Low seismicity on and near ECGH and FWR
 - Anna, Ohio
 - Sharpsburg, KY
 - southeastern KY

Is the Rough Creek Graben and the Rome Trough a continuous feature?



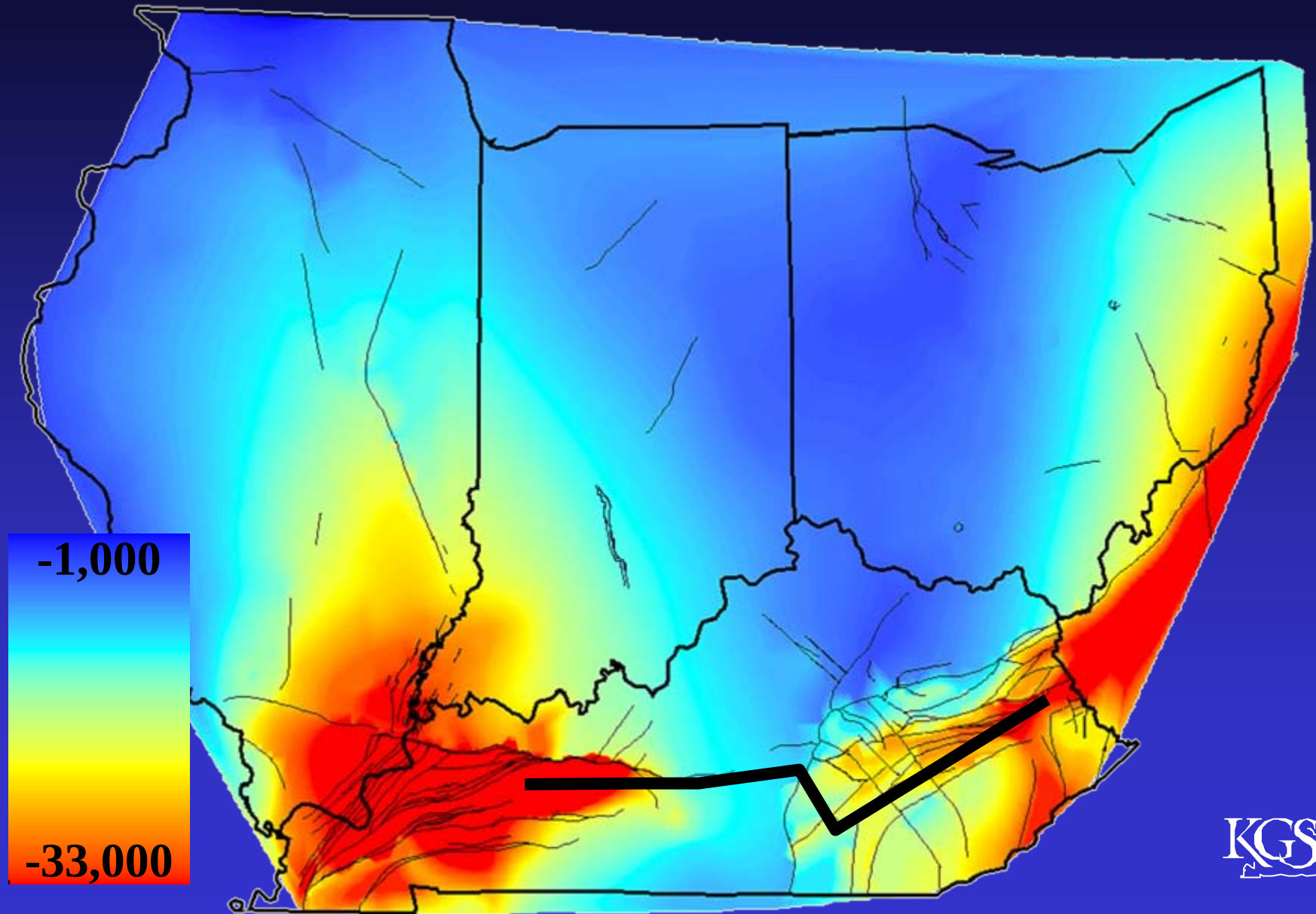
Schematic Cross Section: Rough Creek Graben to Rome Trough, Kentucky

- Cambrian syntectonic deposition (Pre-Knox) in the Rome Trough (RT) & the Rough Creek Graben (RCG)
- Based on available data, cannot demonstrate Cambrian (Pre-Knox) rifting in the central zone (CZ)
 - However, a lack of well and available quality seismic data in south-central Kentucky
- Central zone is coincident with the thickest part of ECRB
 - suggests Cambrian inversion or at least relative stability
 - Conformity of Knox-Pre-Knox boundary suggests non-deposition



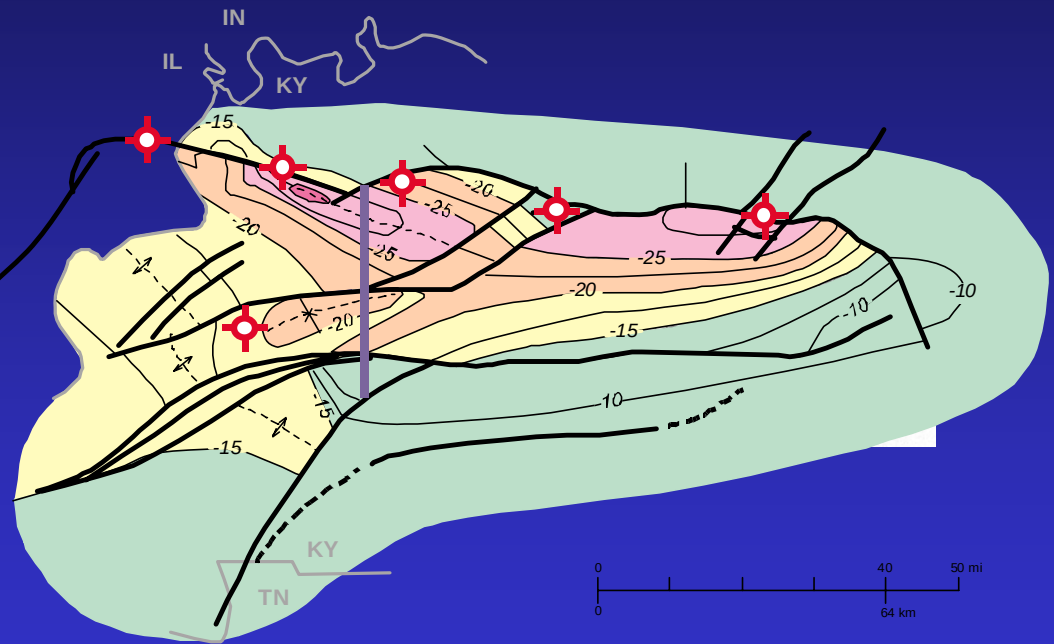
- Proprietary seismic data
- Well data

Structure: Top of Proterozoic



Rough Creek Graben, Western Kentucky

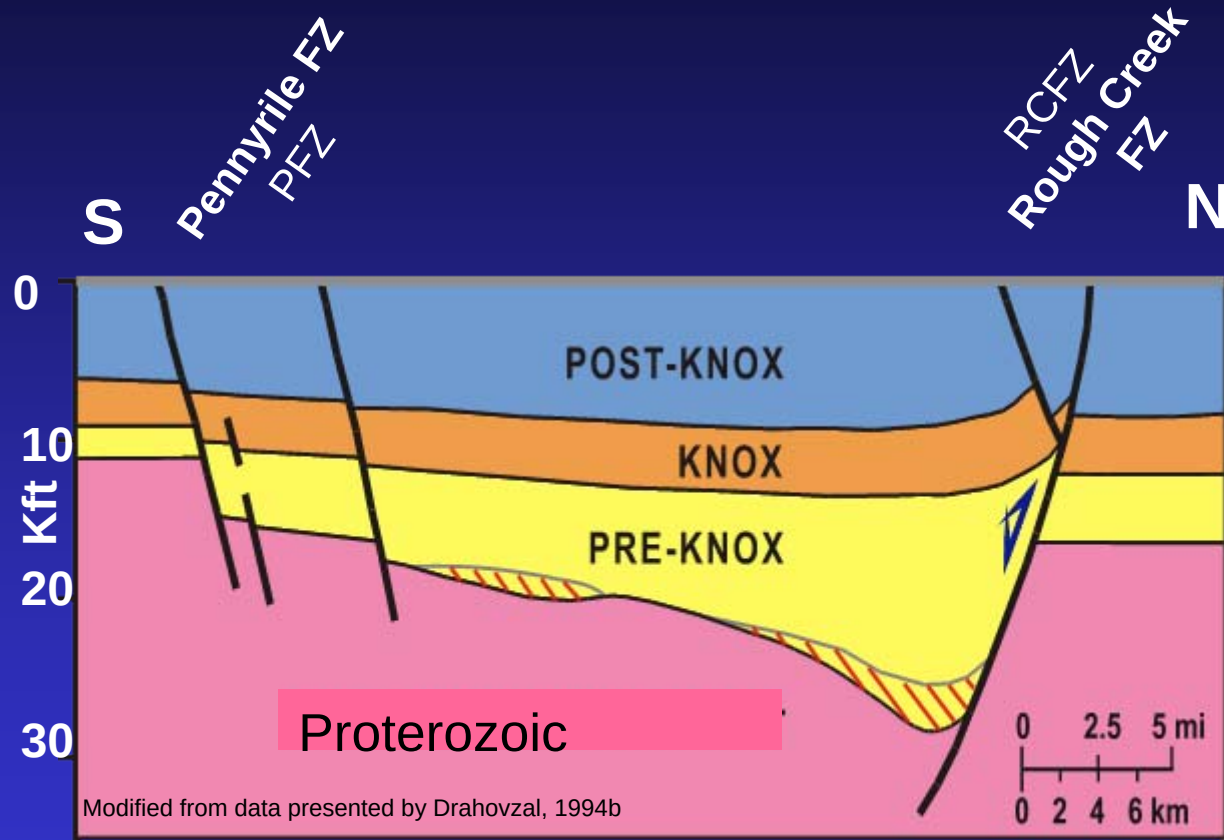
- Cambrian asymmetrical half graben
- Major bounding fault on N side
 - Rough Creek FZ
 - Pennyrile FZ on S edge
- Most deep wells along N edge
 - Known primarily from seismic data
- Changes polarity to SW: more symmetrical Reelfoot Rift (Mississippi Valley Graben)
- Terminates to East on inverted ECRB



Modified from data presented by Drahovzal 1994b

Is there evidence of Mesozoic reactivation of the Rough Creek Graben?

- Deep half-graben > 30,000' depth at deepest part
- Shallows to S and E
- Cambrian thickening on RCFZ up to 8 x
- Up to 15,000' of Pre-Knox Cambrian rocks
- Offset of the Precambrian is up to 17,000'
- Several reactivations
 - Uplift on the S side of RCFZ—transpression during Alleghany Orogeny*
 - subsidence along RCFZ and PFZ—likely regional extension during Triassic-Jurassic**



* Bertagne and Leising, 1991; Kolata and Nelson, 1991

**Strunk, 1984; Bertagne and Leising, 1991;
Kolata and Nelson, 1991

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GEOPHYSICAL CHARACTERIZATION OF FAULTING AND FOLDING IN THE ILLINOIS BASIN AND RELATION TO SEISMICITY

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INTRODUCTION

- ▶ Objectives
- ▶ Problem of fault reactivation
- ▶ General structural setting of Illinois basin, north of the New Madrid seismic zone
- ▶ Limitations imposed by availability of data



Objectives

- ▶ What are the dominant structural styles in the southern Illinois basin at the basement-Paleozoic contact? And how have these structures propagated from depth?
- ▶ What is the expected degree of crustal (i.e., at seismogenic depths) heterogeneity for the area north of the NMSZ?
- ▶ Evaluate idea of pre-existing geologic structures governing seismicity (can we prove it)?
- ▶ And, if so, what is the potential for using structure-hypocenter correlations for constraining seismic hazard estimates (is it practical given the limited data for each)?
- ▶ Can we identify specific “seismic source zones” associated with particular structures, such as the Commerce geophysical lineament, the Fluorspar Area fault complex, the La Salle deformation belt, and the Du Quoin monocline?

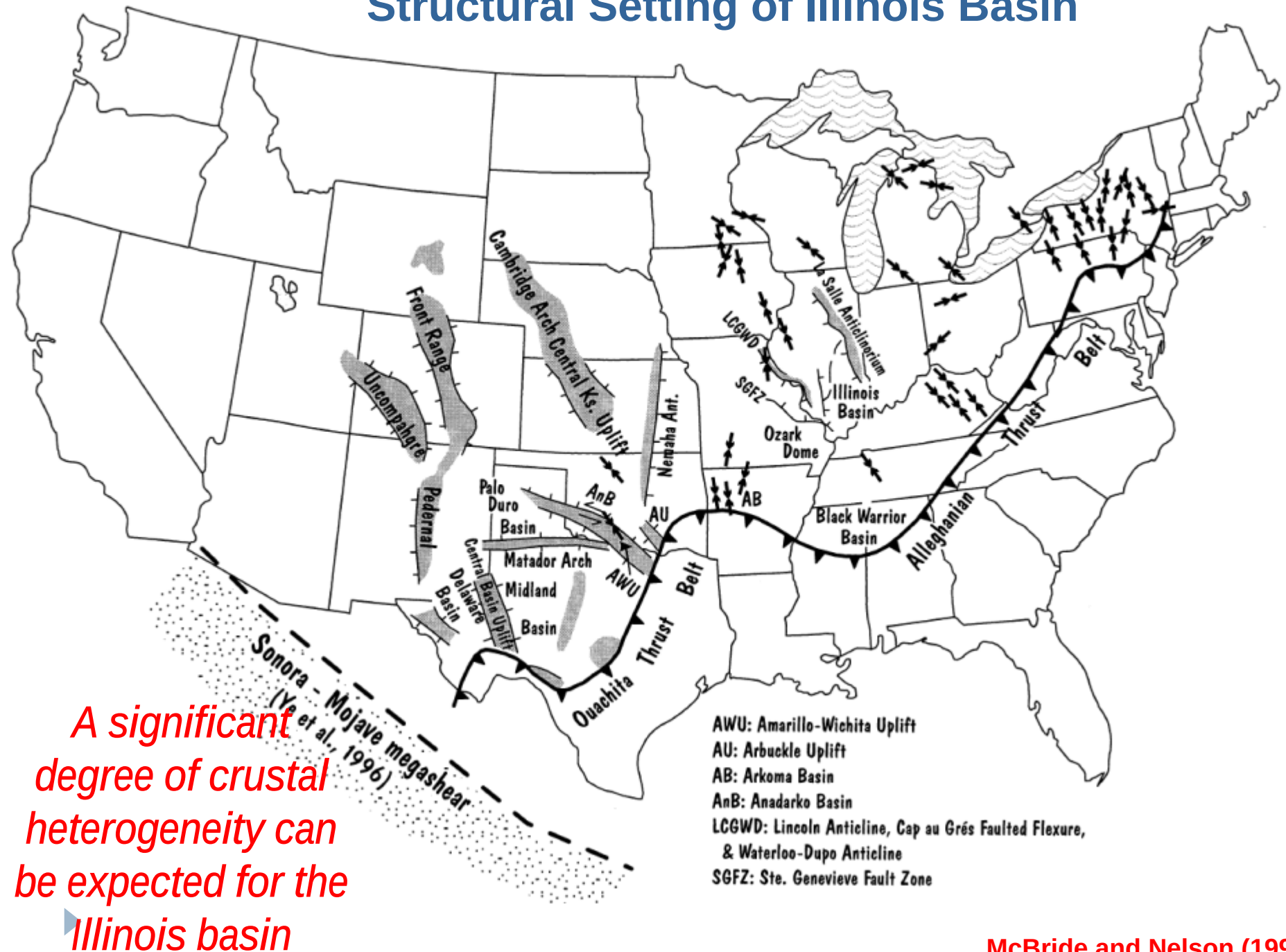


Fundamental question for the “reactivationists”;

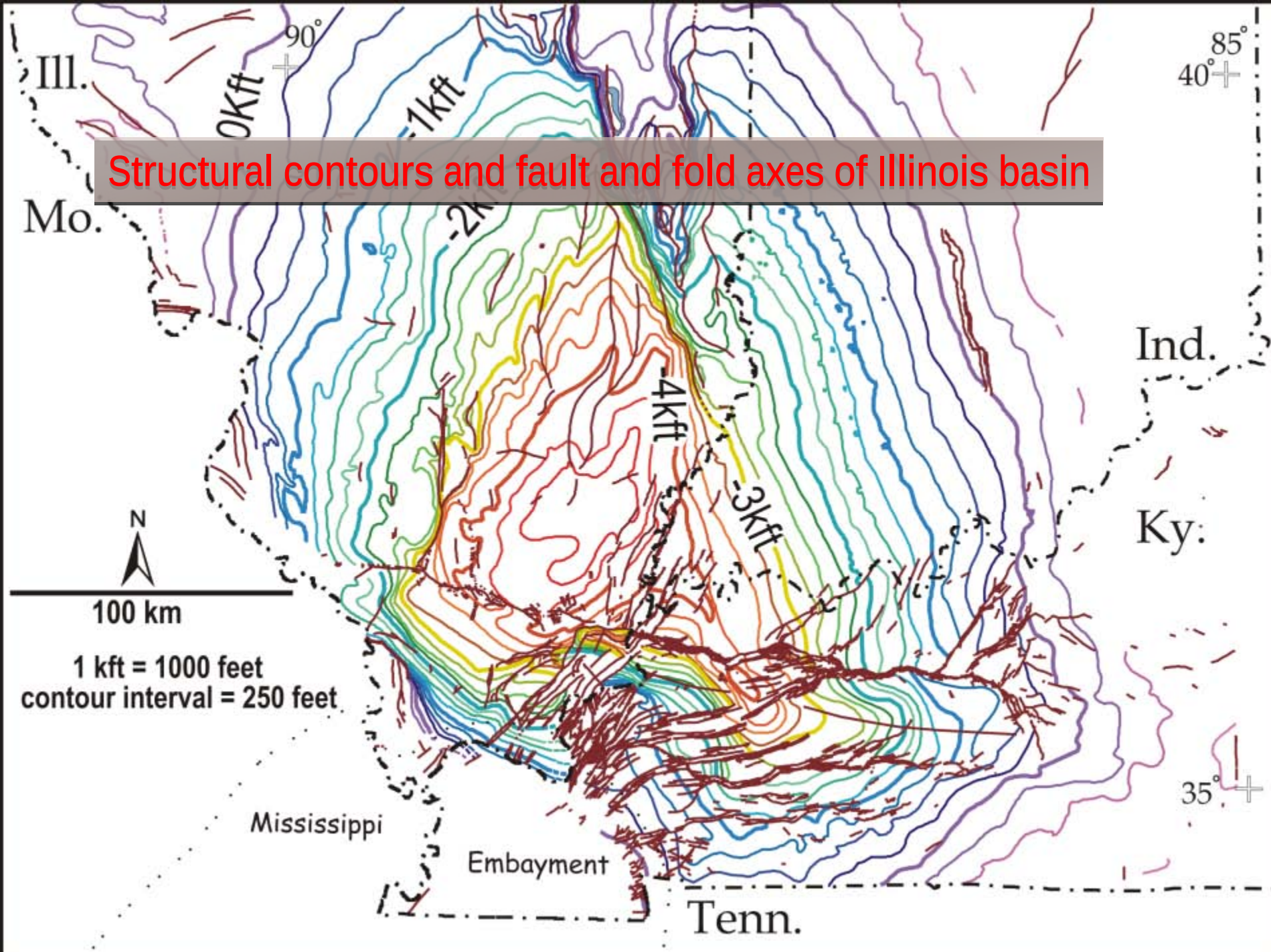
- ▶ Many of us subscribe to the notion that “once a fault, always a fault”, i.e., that reactivation of pre-existing structures by contemporary stress is a valid paradigm.

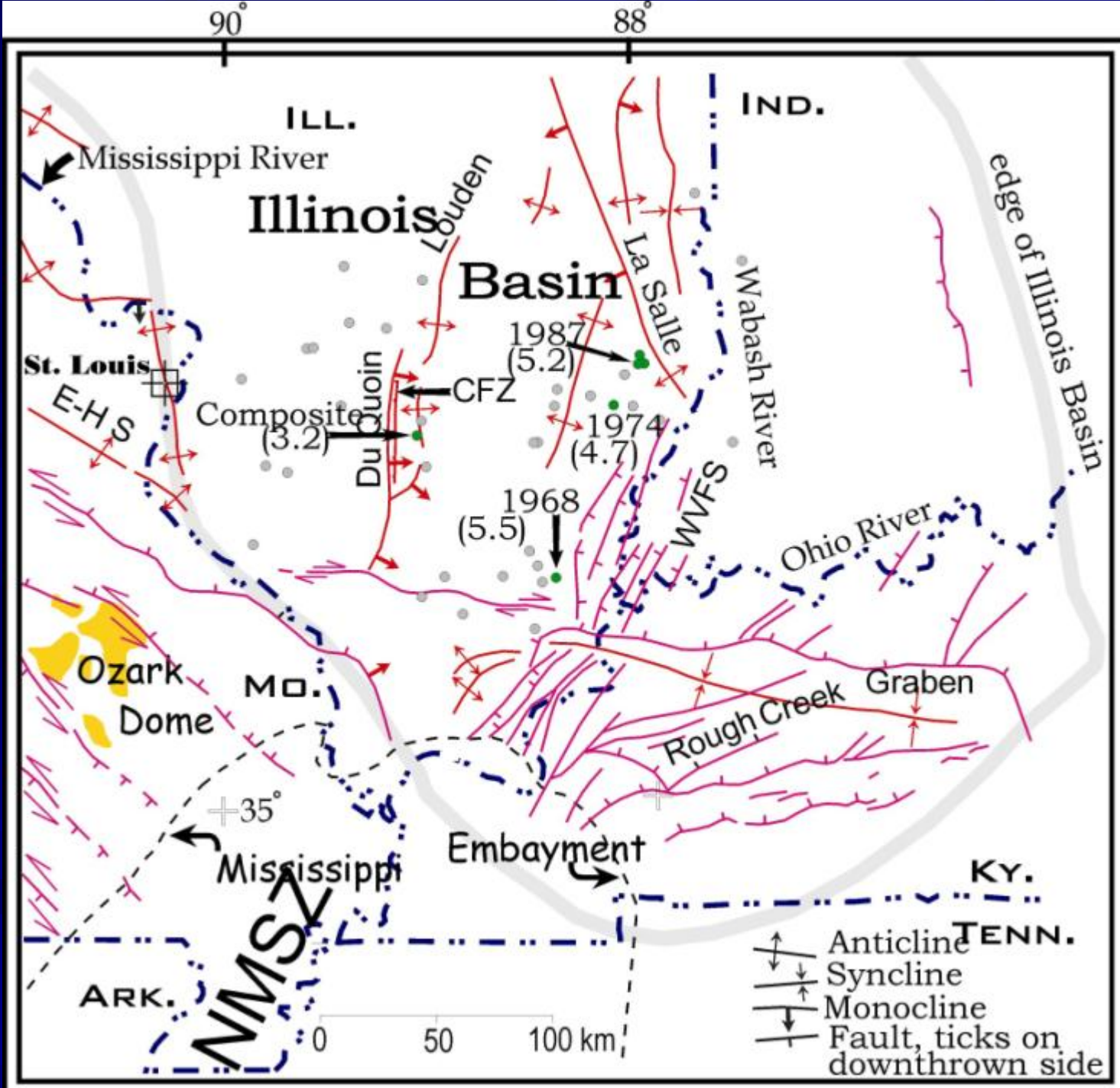


Structural Setting of Illinois Basin



Structural contours and fault and fold axes of Illinois basin





SW

NE

HOUSE SPRINGS ANTICLINE (Missouri)



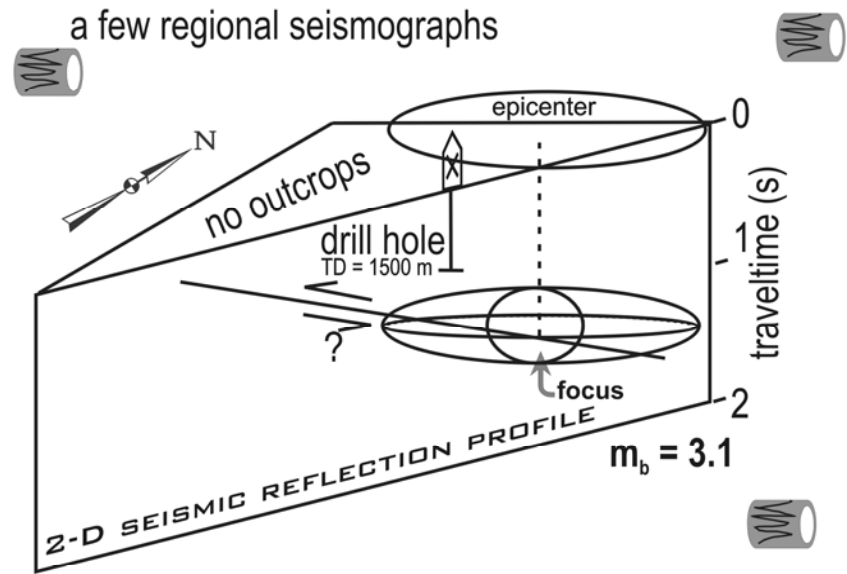
Mississippian System (Burlington &
Fern Glen Limestones)

Outcrops, like this one on the margin of the Illinois basin south of St. Louis, are rare to non-existent in the study area.

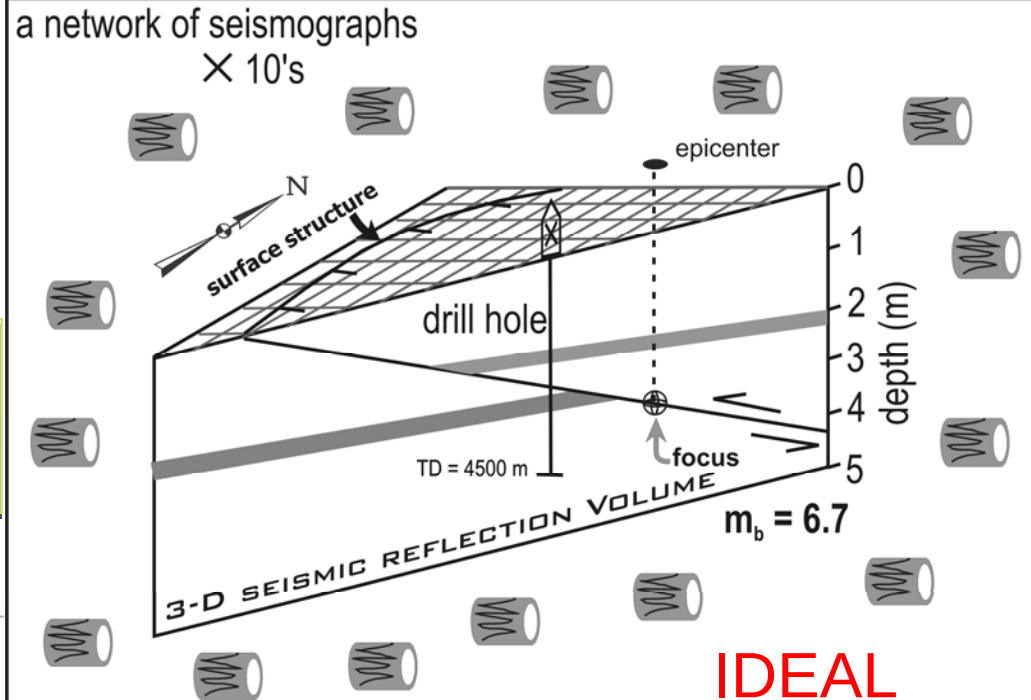
Photo by J. H. McBride.

Problem facing scientists wanting to make an association between seismicity and specific geologic structures in a place like the central Midcontinent (e.g., Illinois basin)

What we would like, in terms of data coverage and access, and what we have.



REALITY

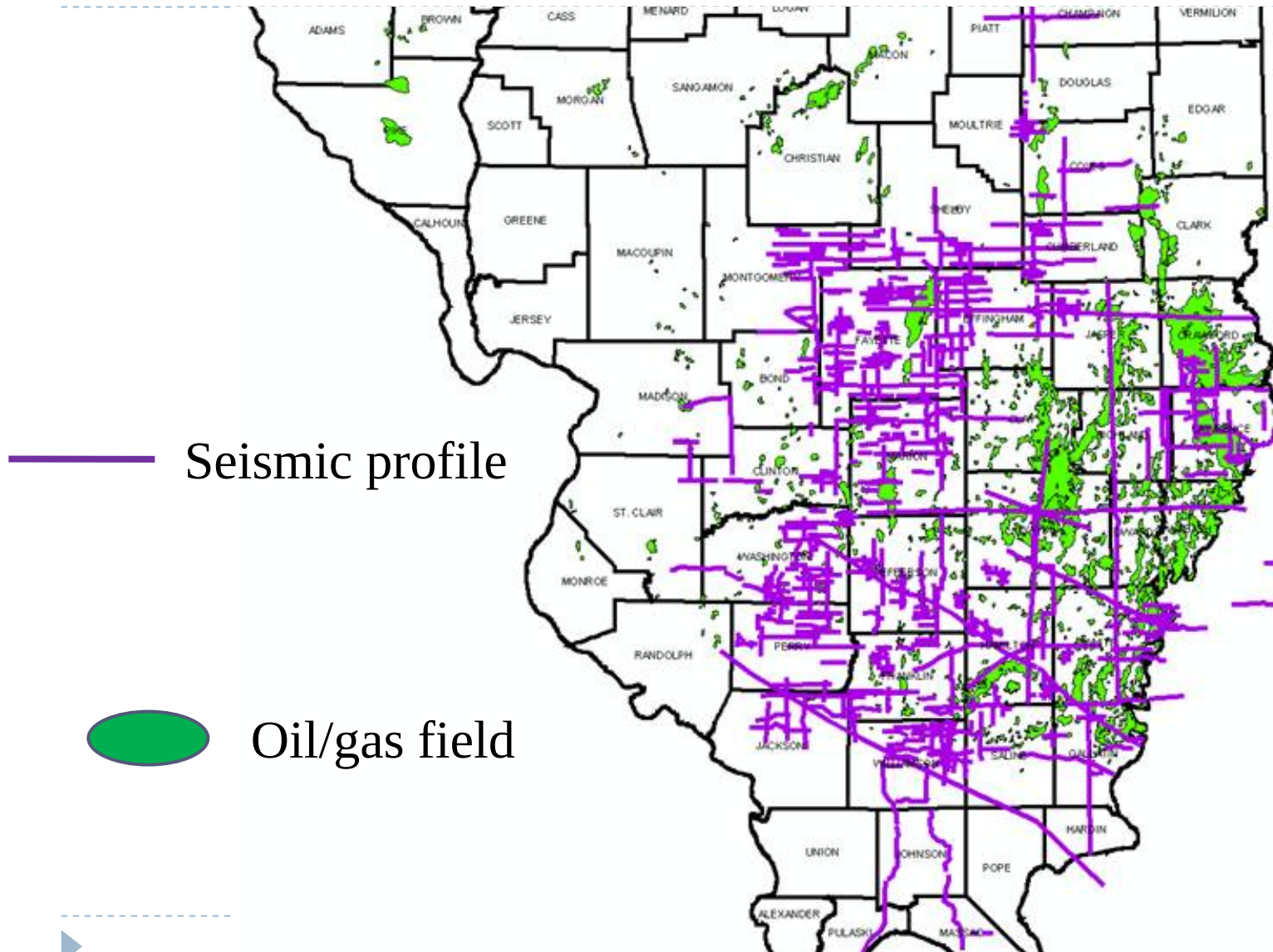


IDEAL

What are our sources of information for the southern Illinois basin?



Excerpt of seismic reflection data base from the Illinois State Geological Survey (courtesy, Dr. Hannes E. Leetaru)



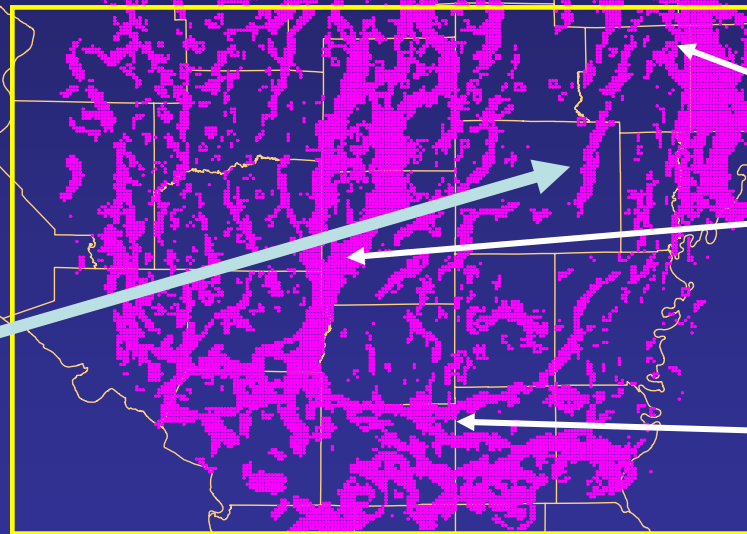
First Derivative
Changes in Slope of
the
Beach Creek Structure
(Mississippian) – a
response to hidden
fault structure at depth
(i.e., at Cambrian and
pC levels).

Linear slope
anomalies are
interpreted as a
response to
deeper (pre-
Miss.) faulting at
Mt Simon levels.

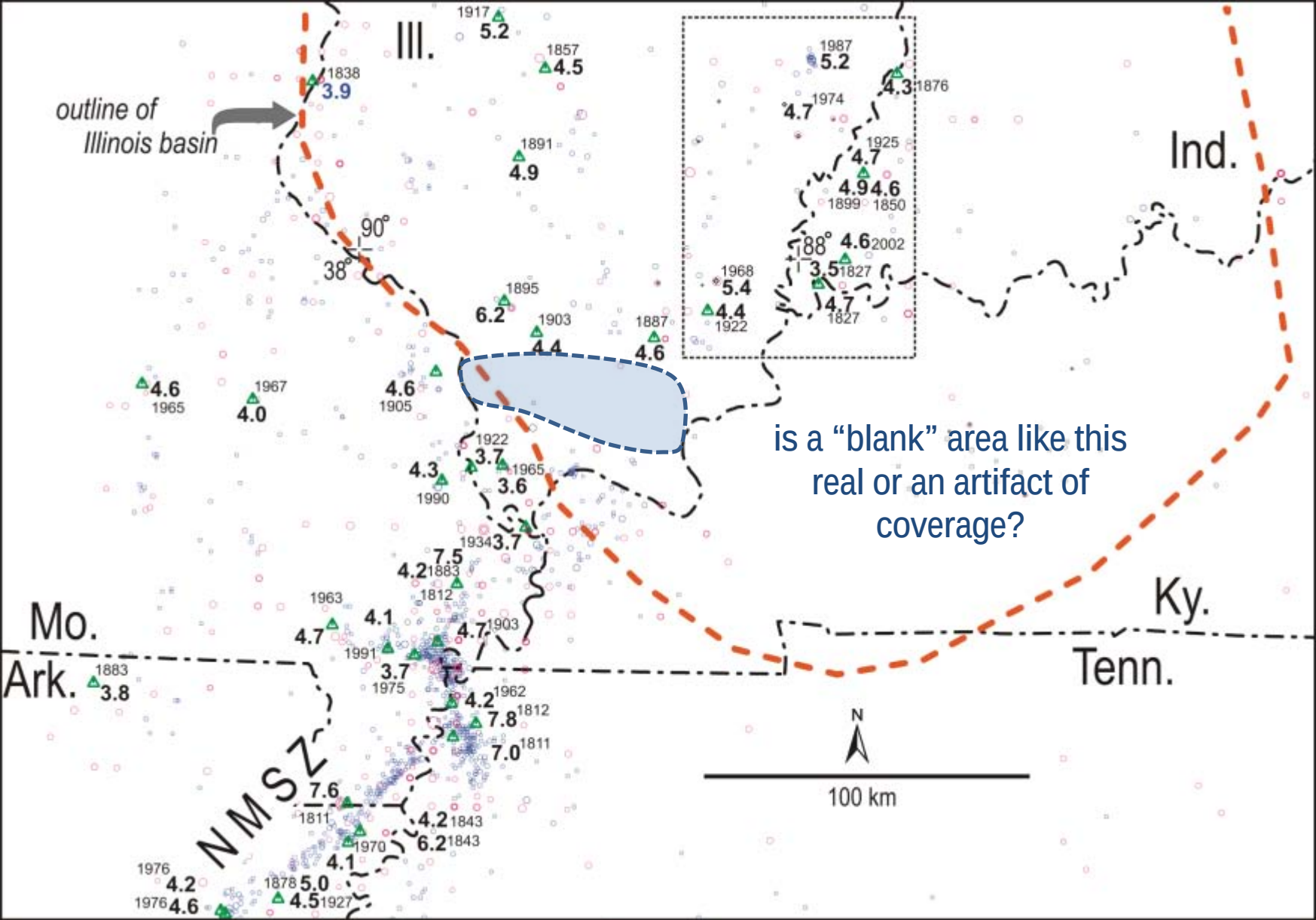
La Salle deformation
Belt

Du Quoin Monocline

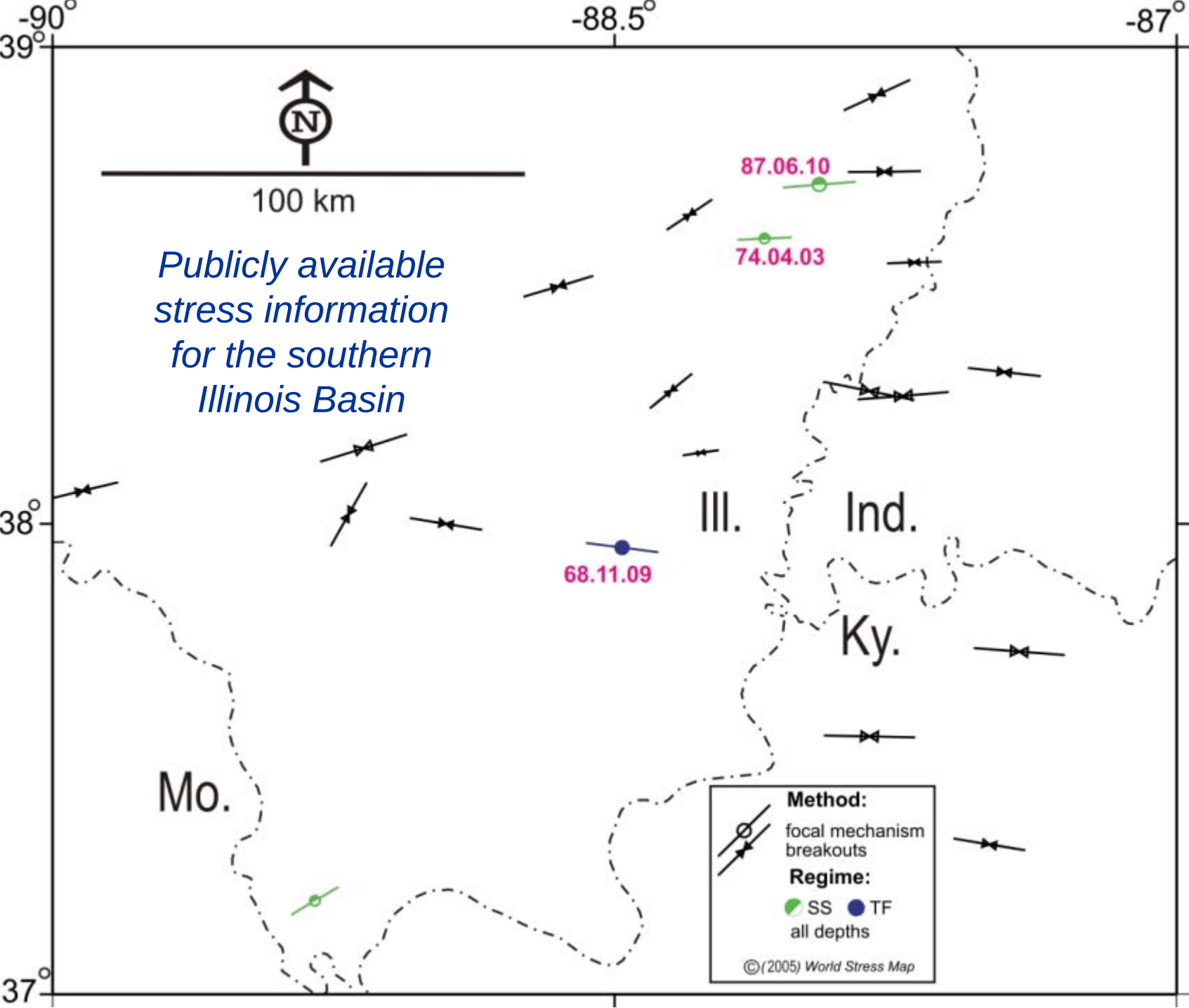
Cottage Grove Fault



Such structural trends can be compared (with caution) with earthquake epicenter patterns.



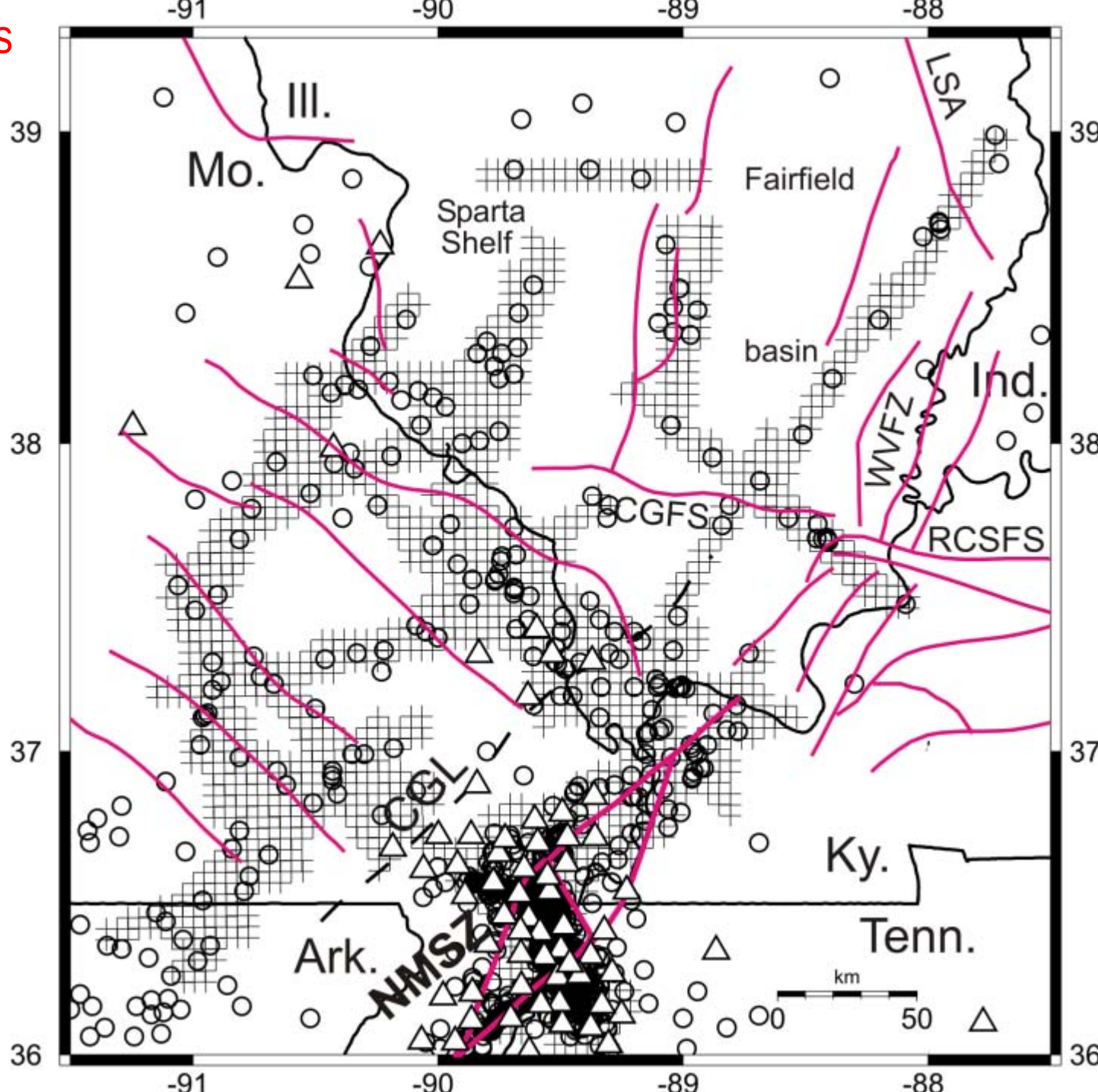
**Central U. S. earthquakes
through 2004**



Statistical studies
relating
earthquake
epicenter
patterns to
geologic
structures yield
mixed results.

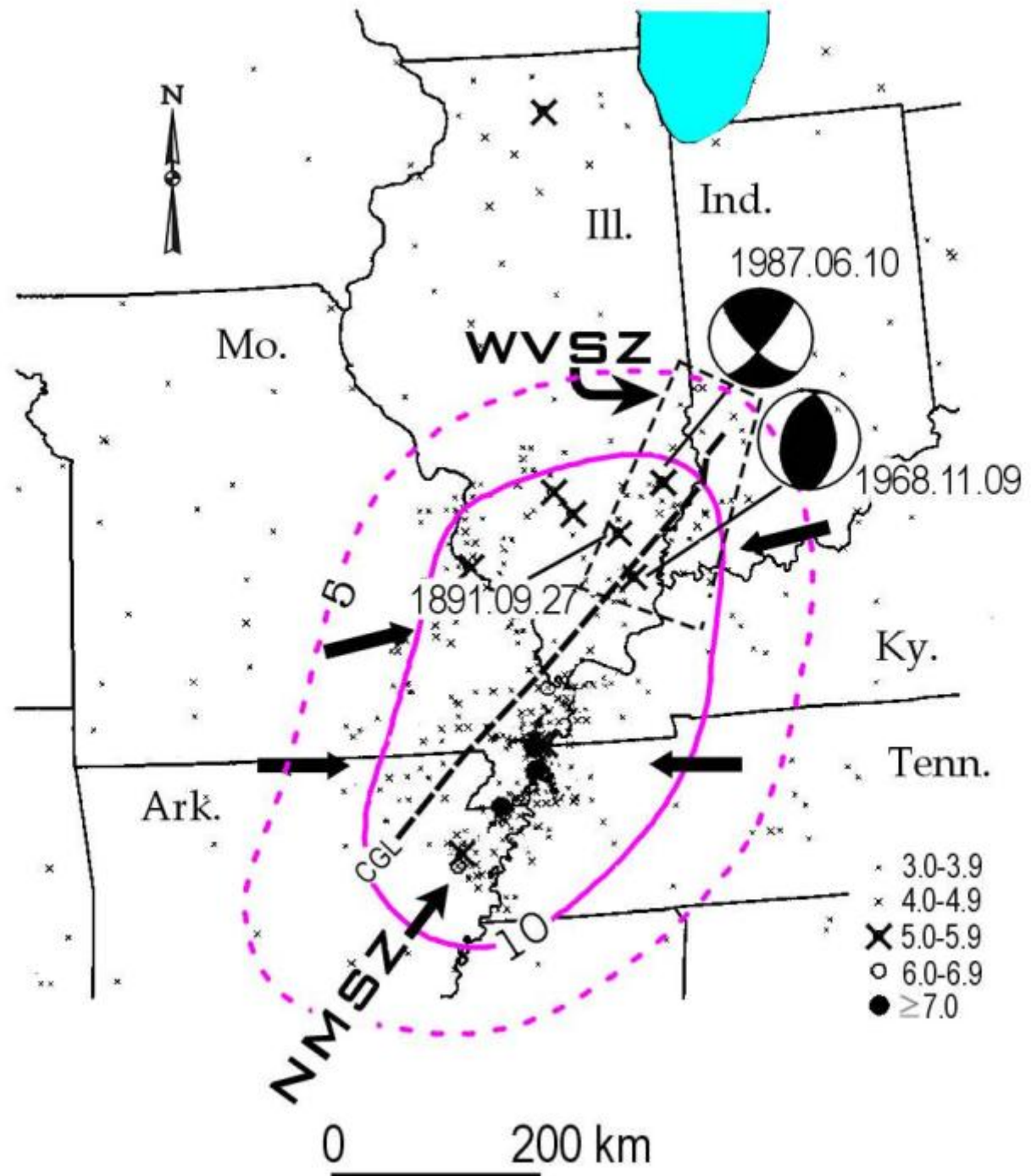
“When using
the Blade
Method, the
Commerce
Geophysical
Lineament does
not seem to be
significantly
seismic.”

Amorèse (2003)



The nature of the northern part of the NMSZ and its possible (if at all) northward continuation remain uncertain.

Although seismicity patterns are poorly constrained in this region, the southeastern Illinois area over the past half-century has hosted several instrumentally recorded events of magnitude 3.0 or greater.



Assessment of Major Structures in the Southern Illinois Basin

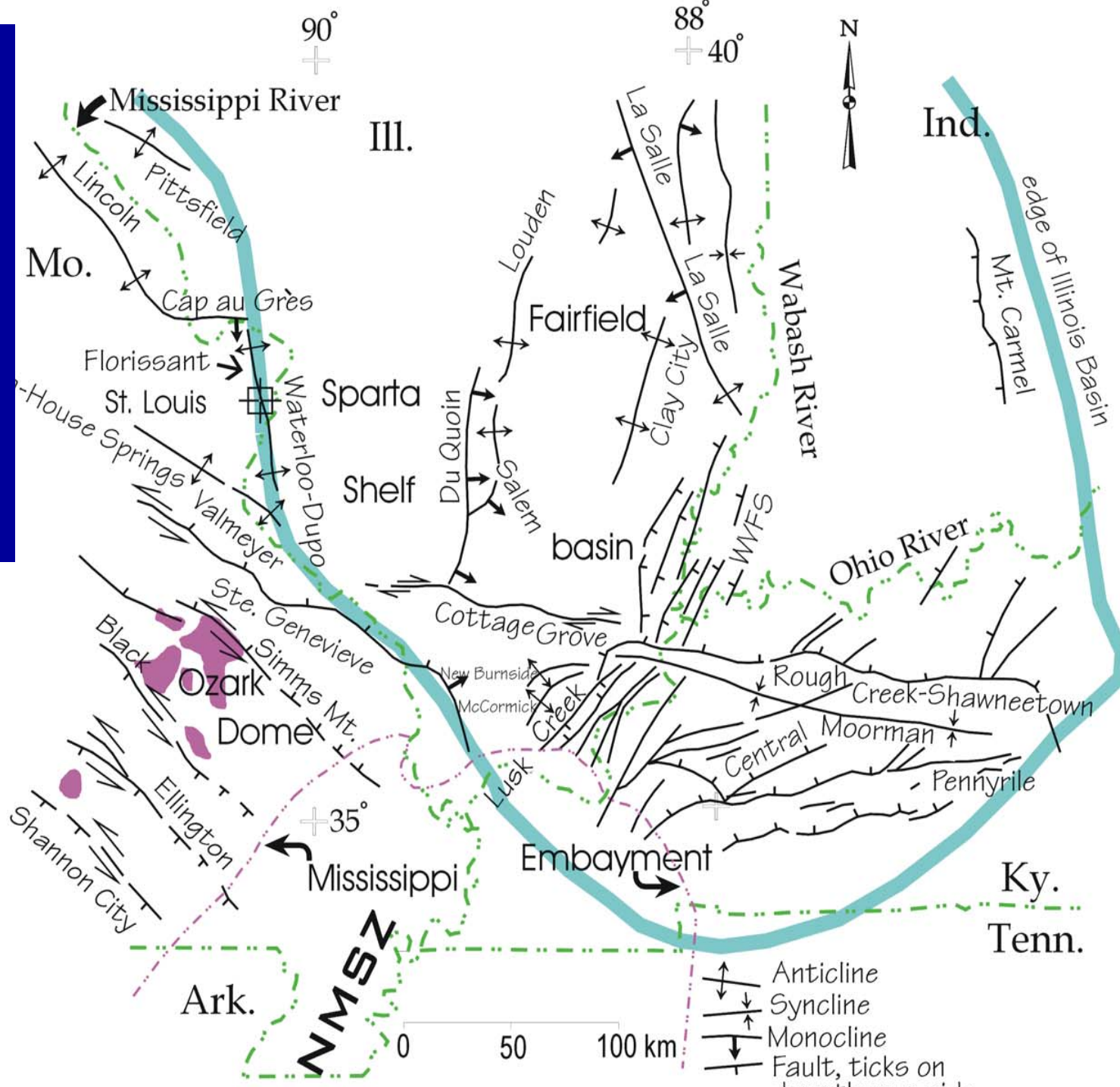
- ▶ La Salle deformation belt and vicinity
- ▶ Fairfield sub-basin (a locally deep portion of the Illinois basin)
- ▶ Area near the Wabash Valley fault system
- ▶ Du Quoin monocline complex
- ▶ Fluorspar Area fault complex and Cottage Grove fault system



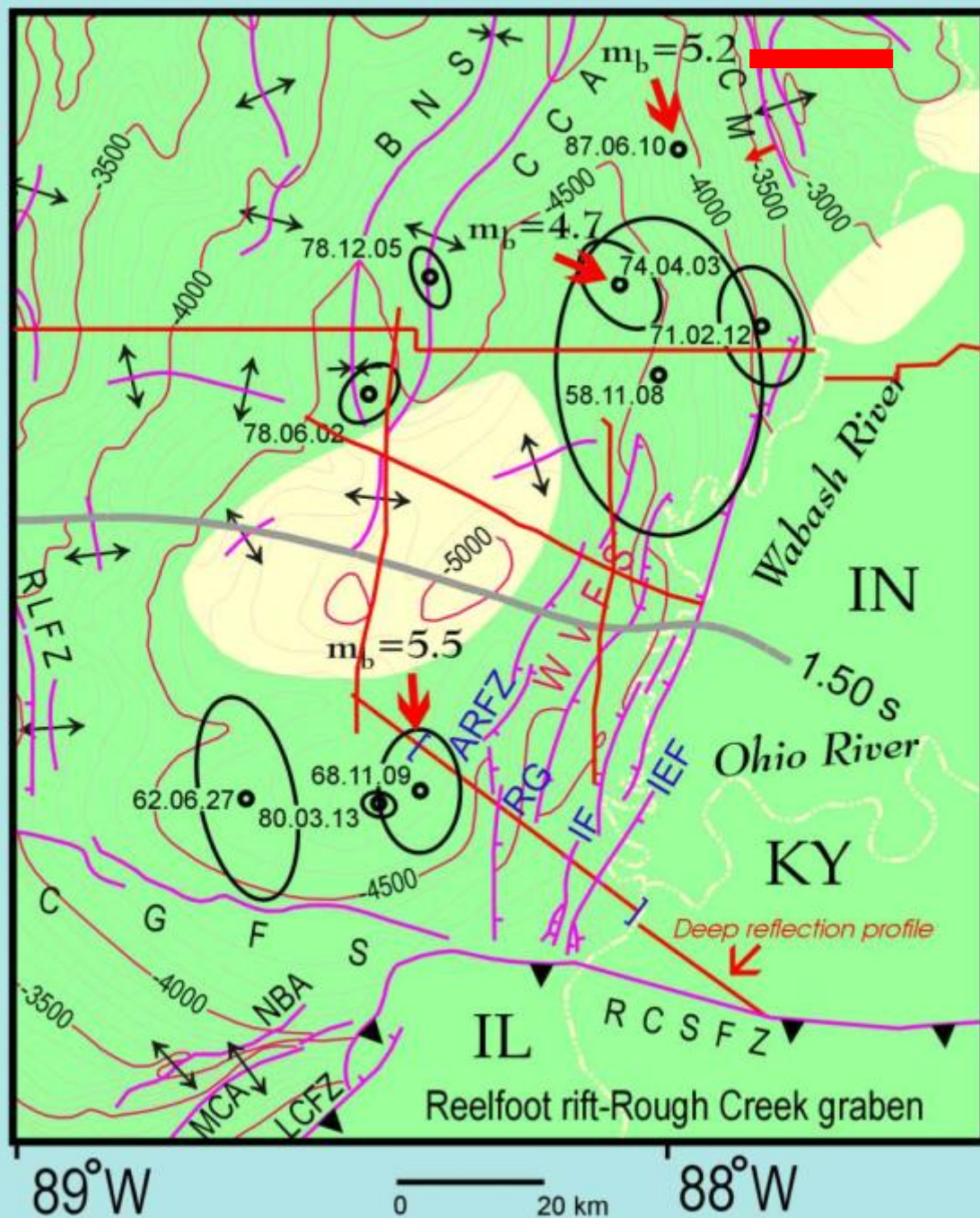
La Salle deformation belt and vicinity



Illinois basin is structurally complex at deeper (Cambrian) levels – Laramide-style fold and fault zones.



COCORP
Profile

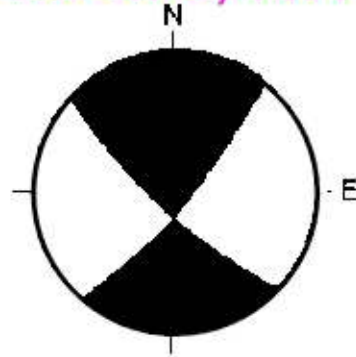


Southern end of
the La Salle
deformation belt

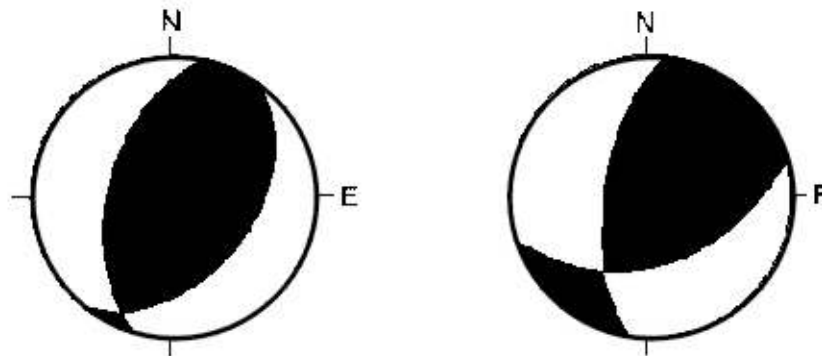


**from
Langer and
Bollinger
[1991]**

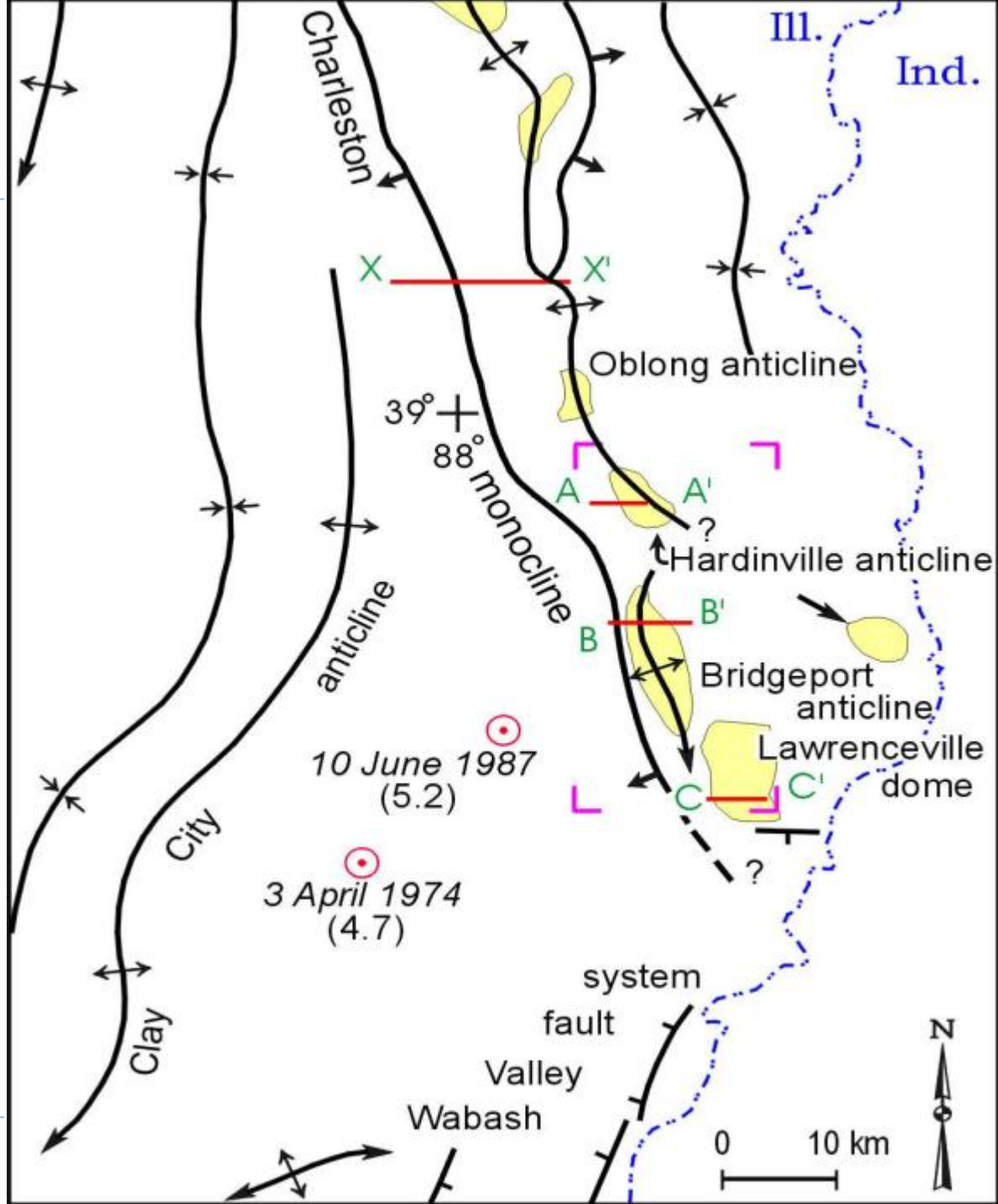
Main Shock
7-11 km hypocentral depth
(~2.3-3.7 s, TWTT)



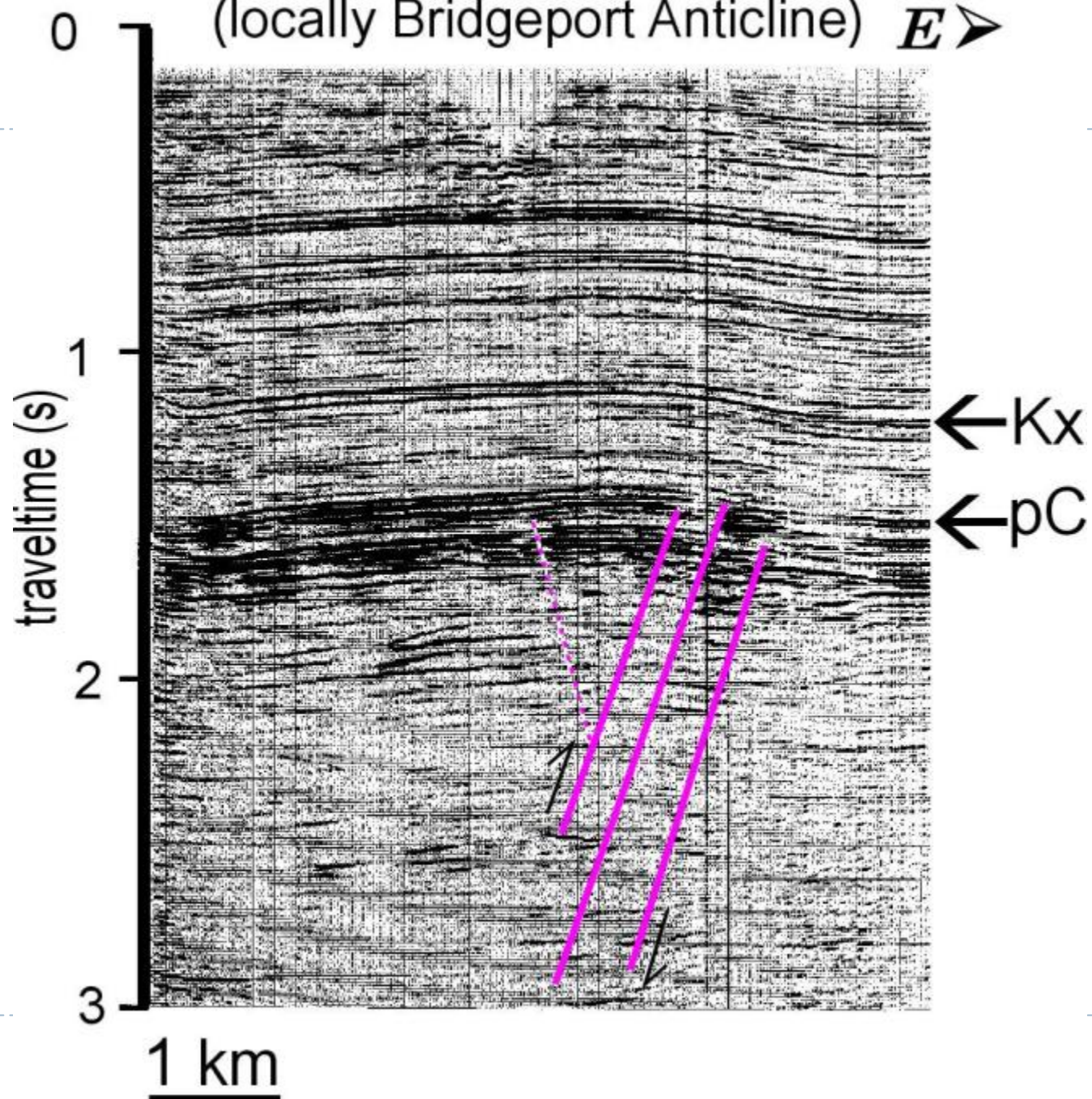
10 June 1987 Events



Aftershock
Composite focal mechanism solutions



La Salle anticline (locally Bridgeport Anticline) $E \rightarrow$



b)

— *A*

Hardinville

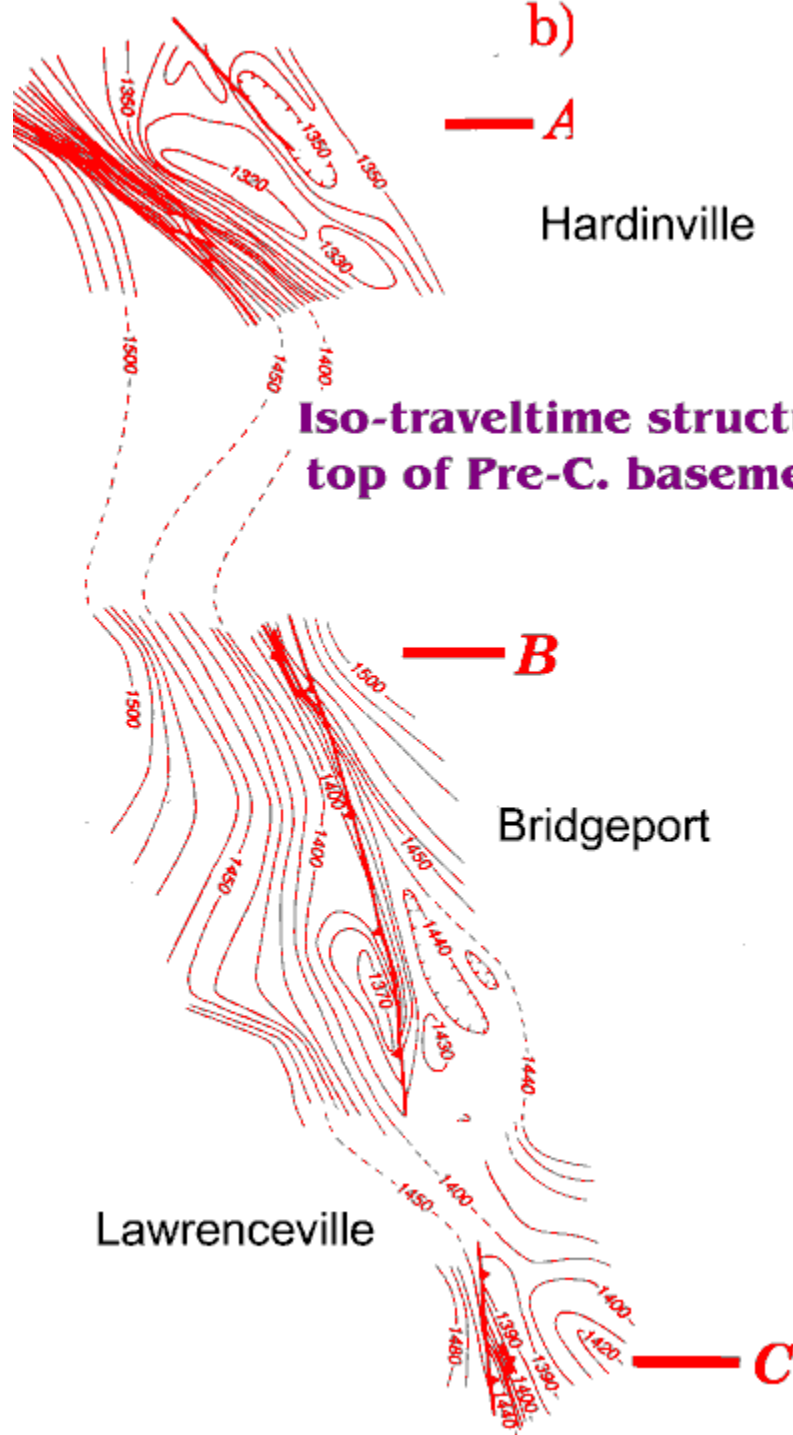
**Iso-traveltime structure
top of Pre-C. basement**

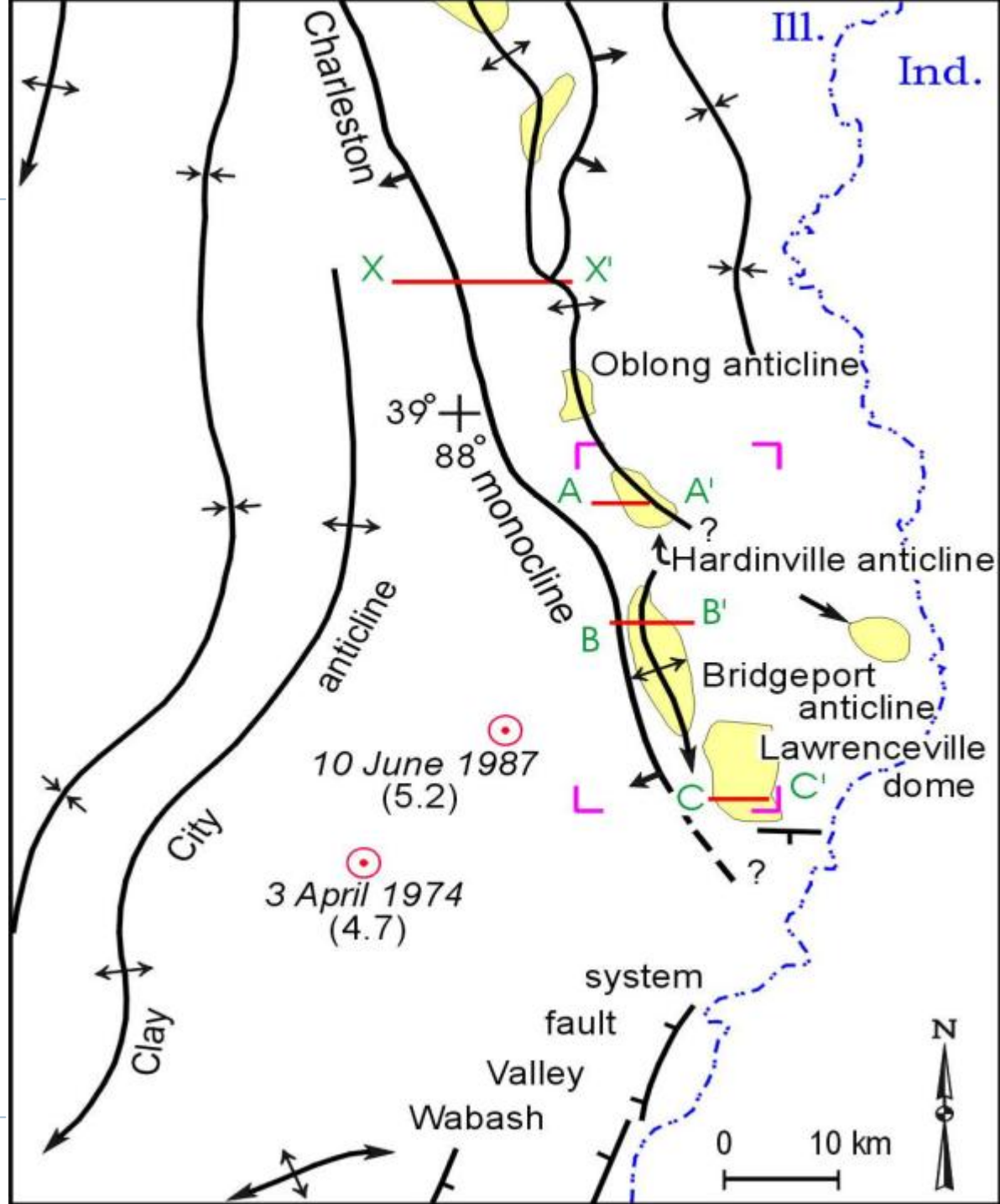
— *B*

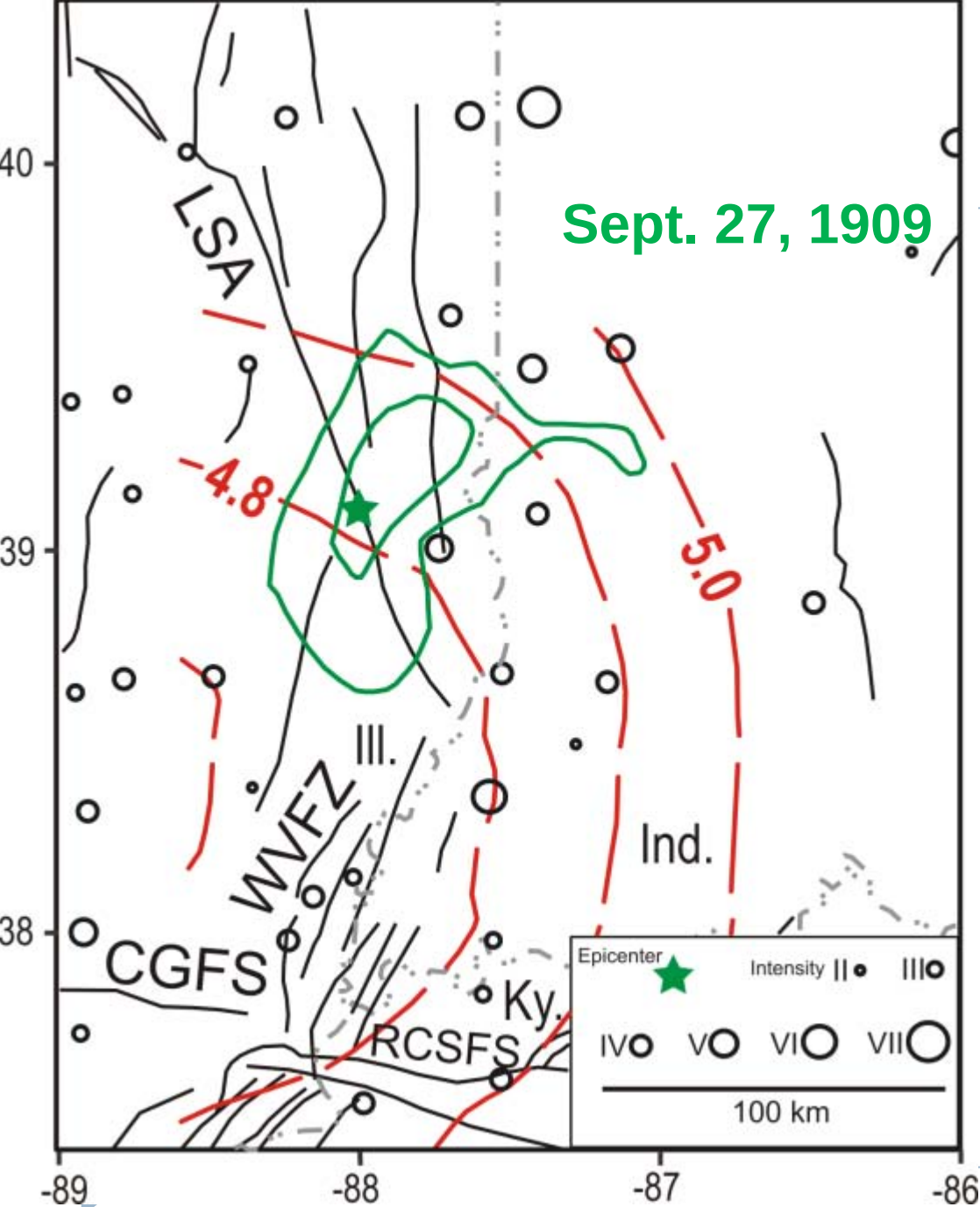
Bridgeport

Lawrenceville

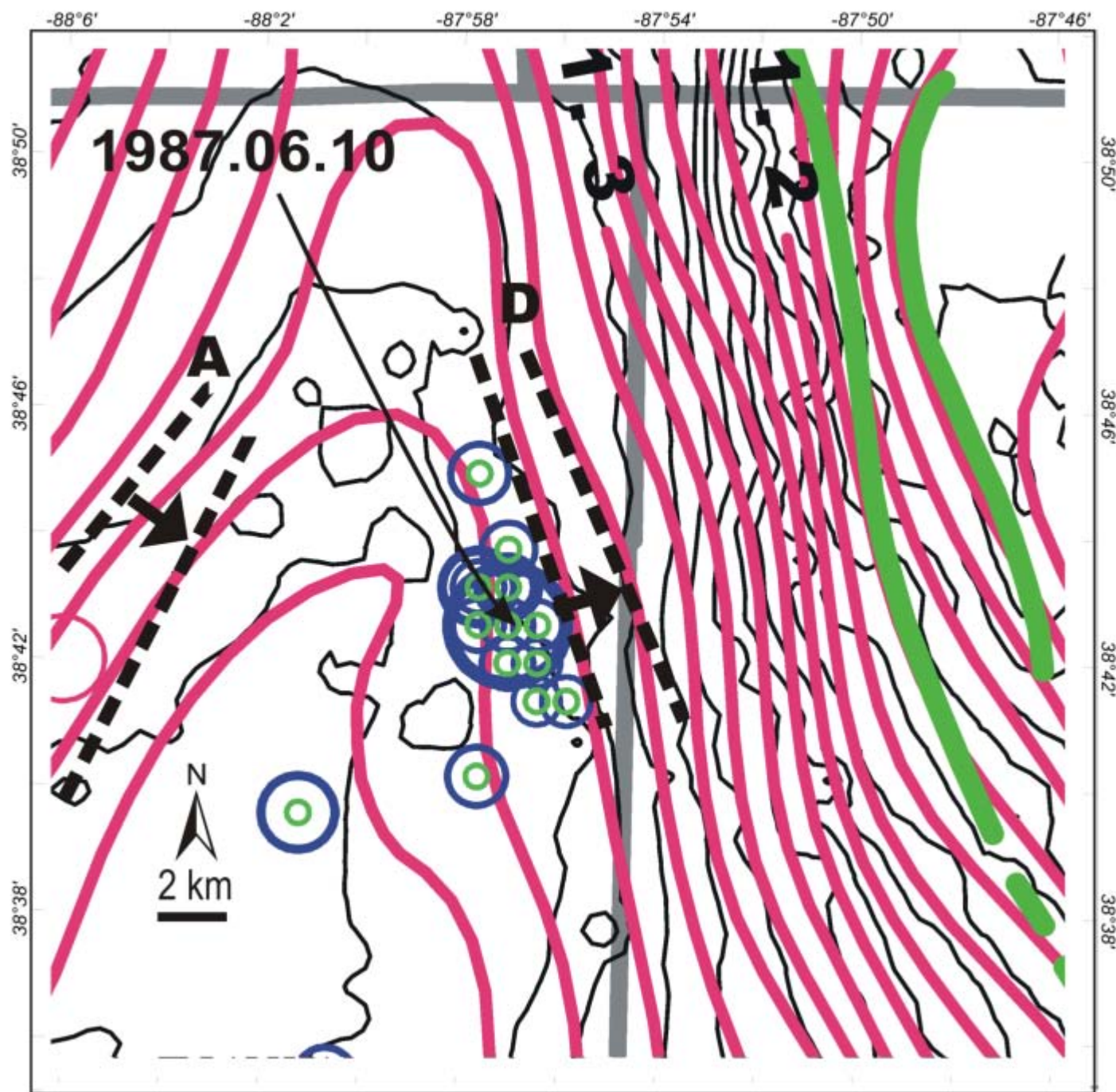
— *C*





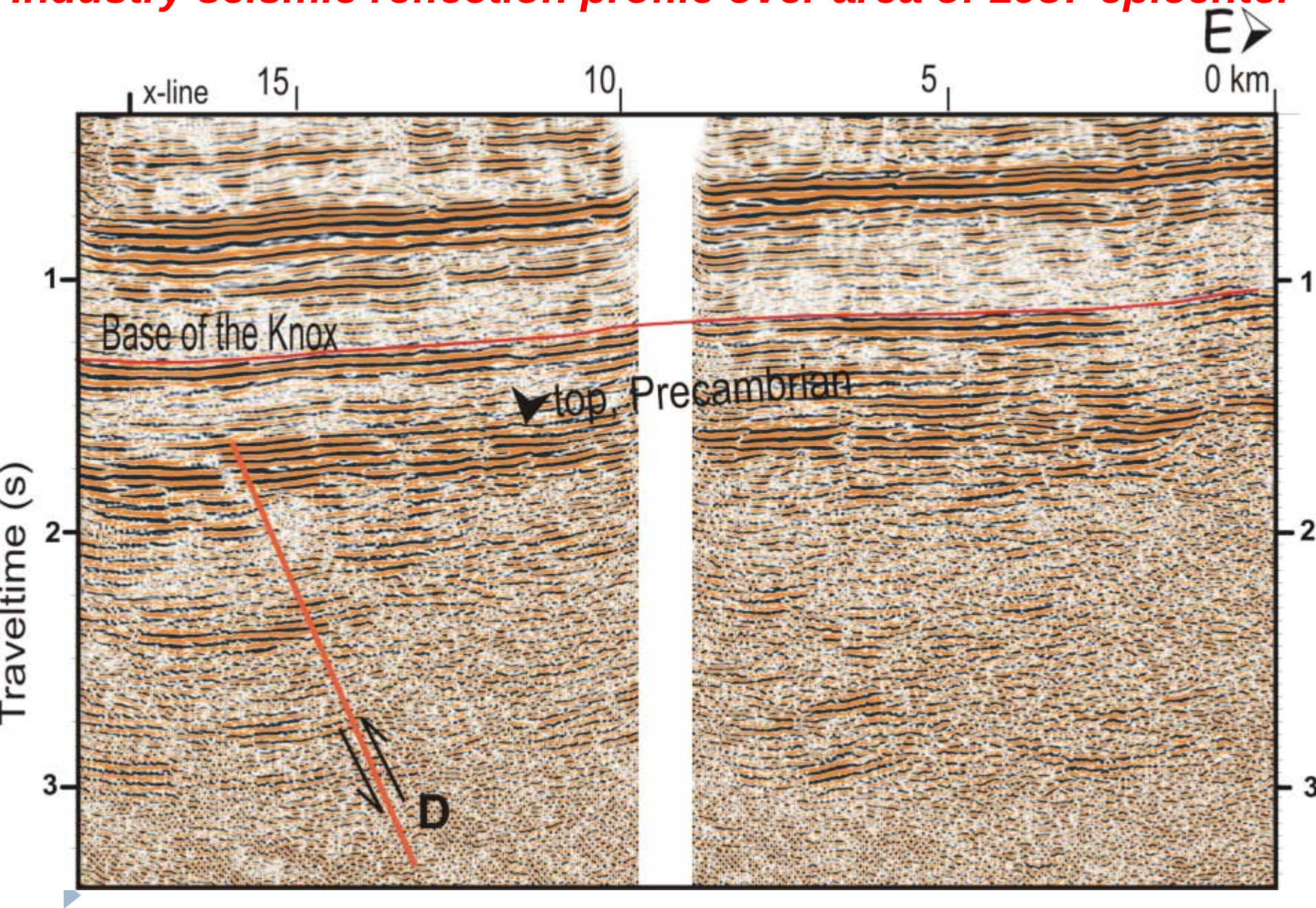


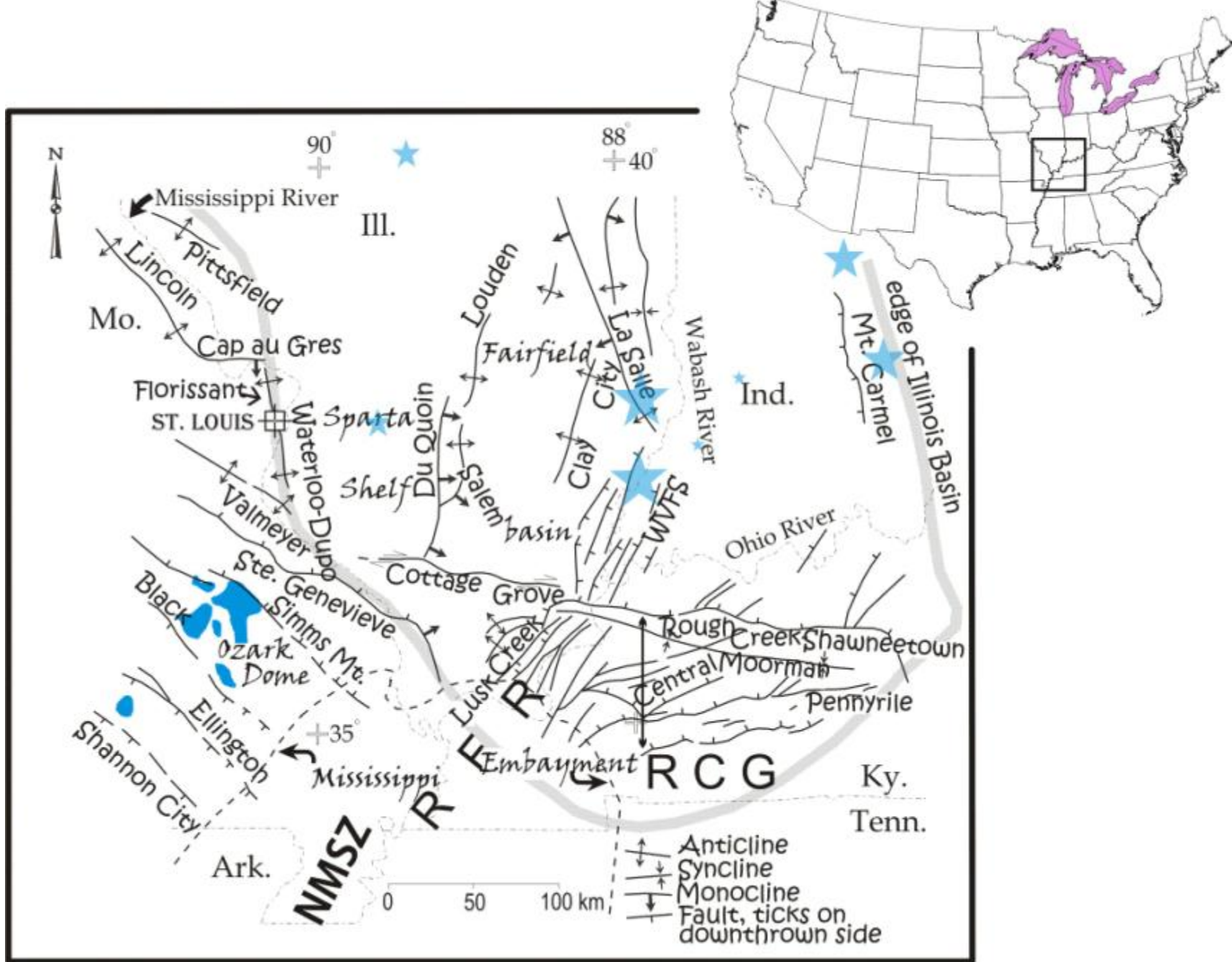
***Example of the results
of a relocation study by
the USGS for historical
earthquakes in the
Illinois Basin region
(Bakun and Hopper,
2004)***



**1987 event
($m_b = 5.2$)
and
aftershocks
and relation
to La Salle
deformation
belt**

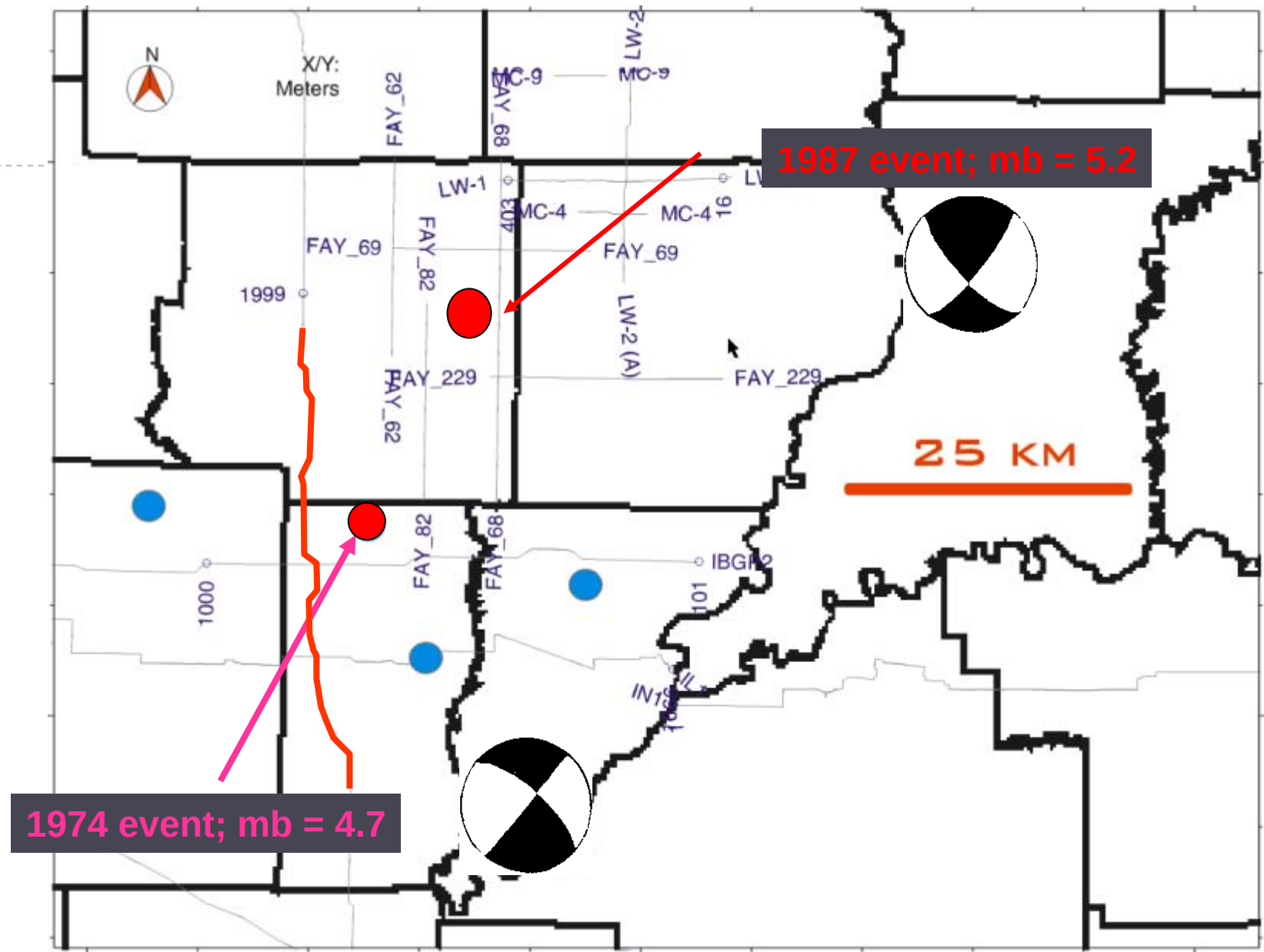
Industry seismic reflection profile over area of 1987 epicenter

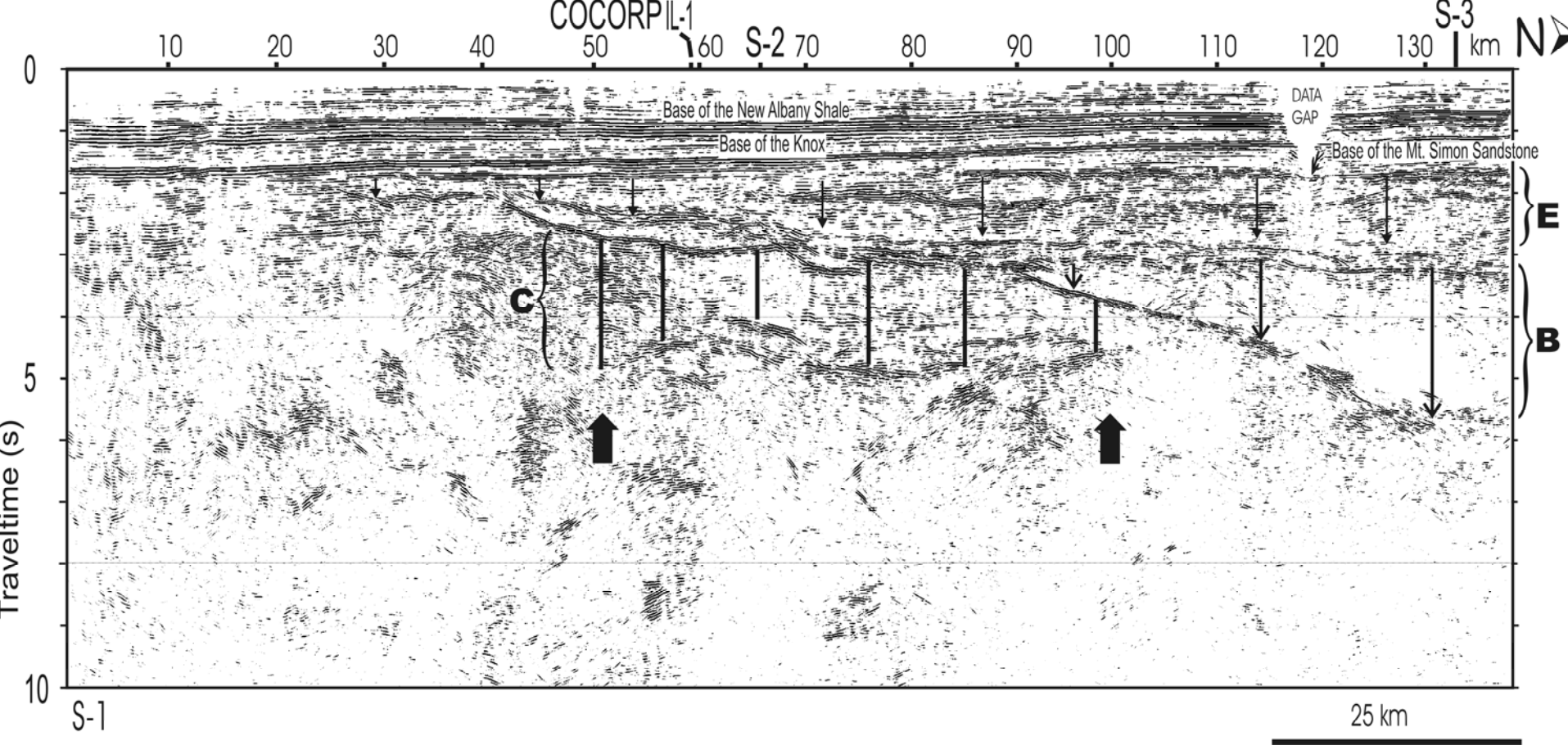




Fairfield Sub-basin

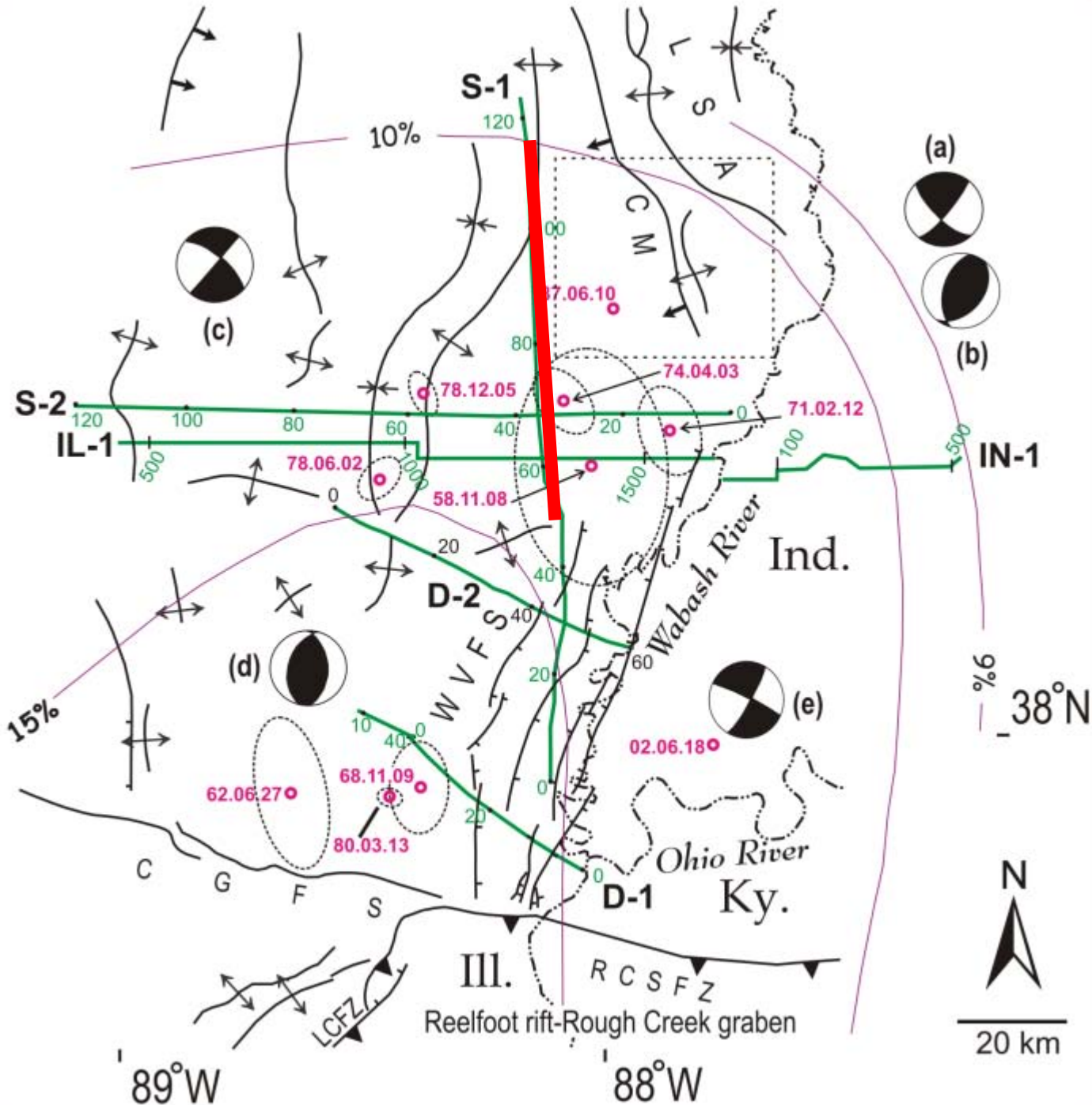




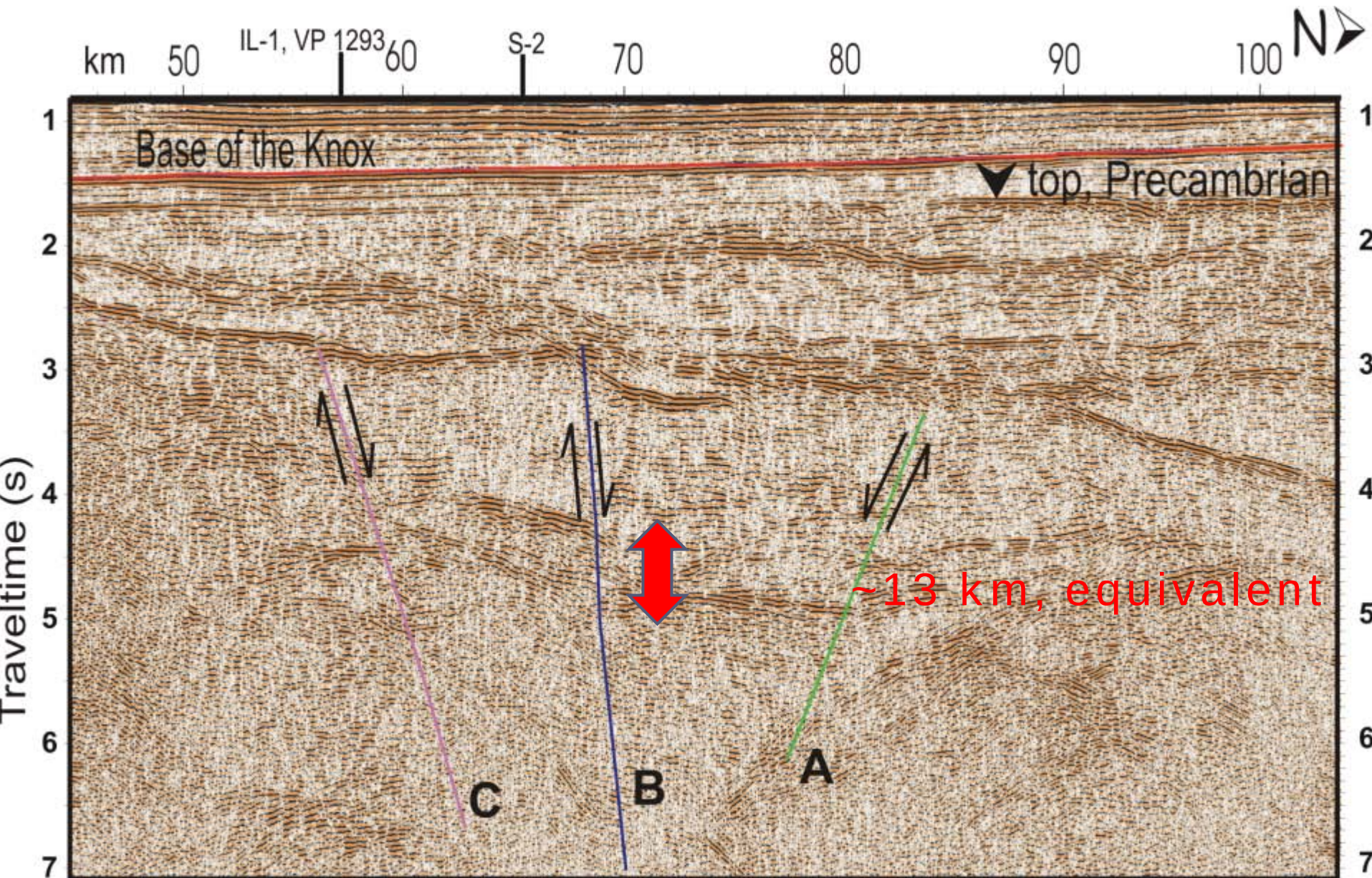


Note strong *heterogeneity* of crust over seismogenic depths (roughly, 2-8 s)

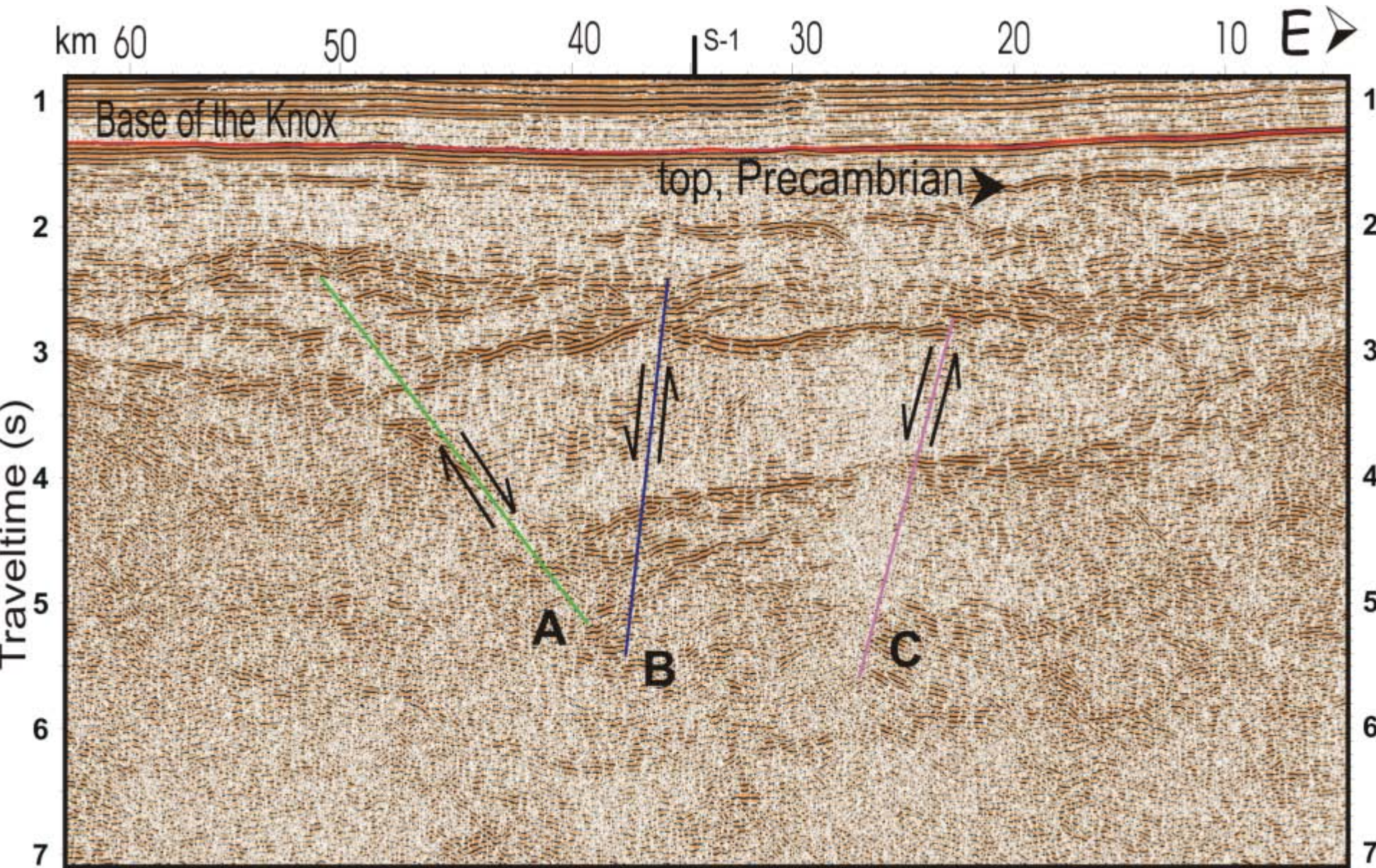
South-to-north deep seismic reflection profile through
Fairfield sub-basin
(locally, a deep part of the Illinois basin).



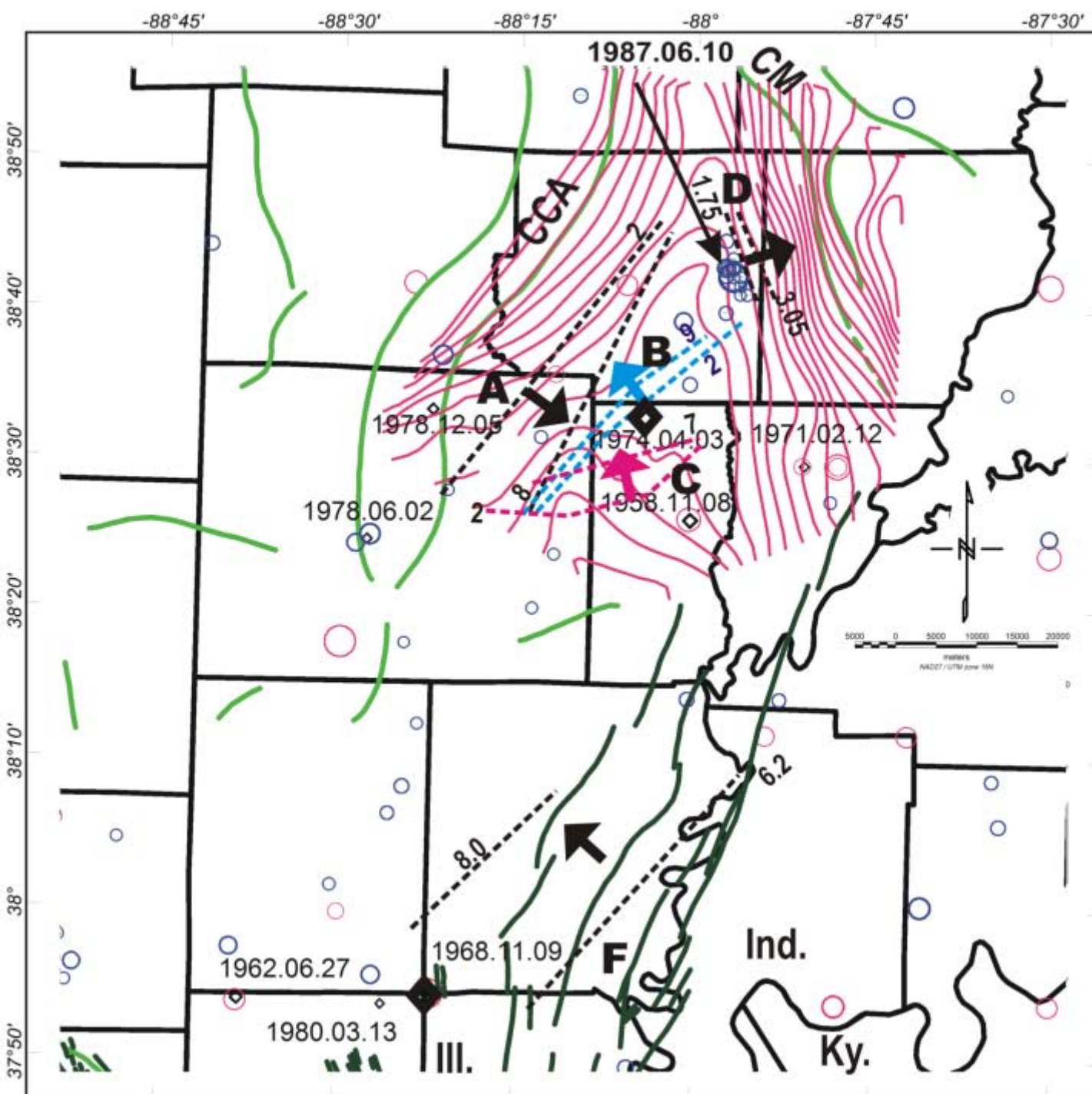
Look at a close-up of the north-south regional deep seismic profile near the 1974 event.



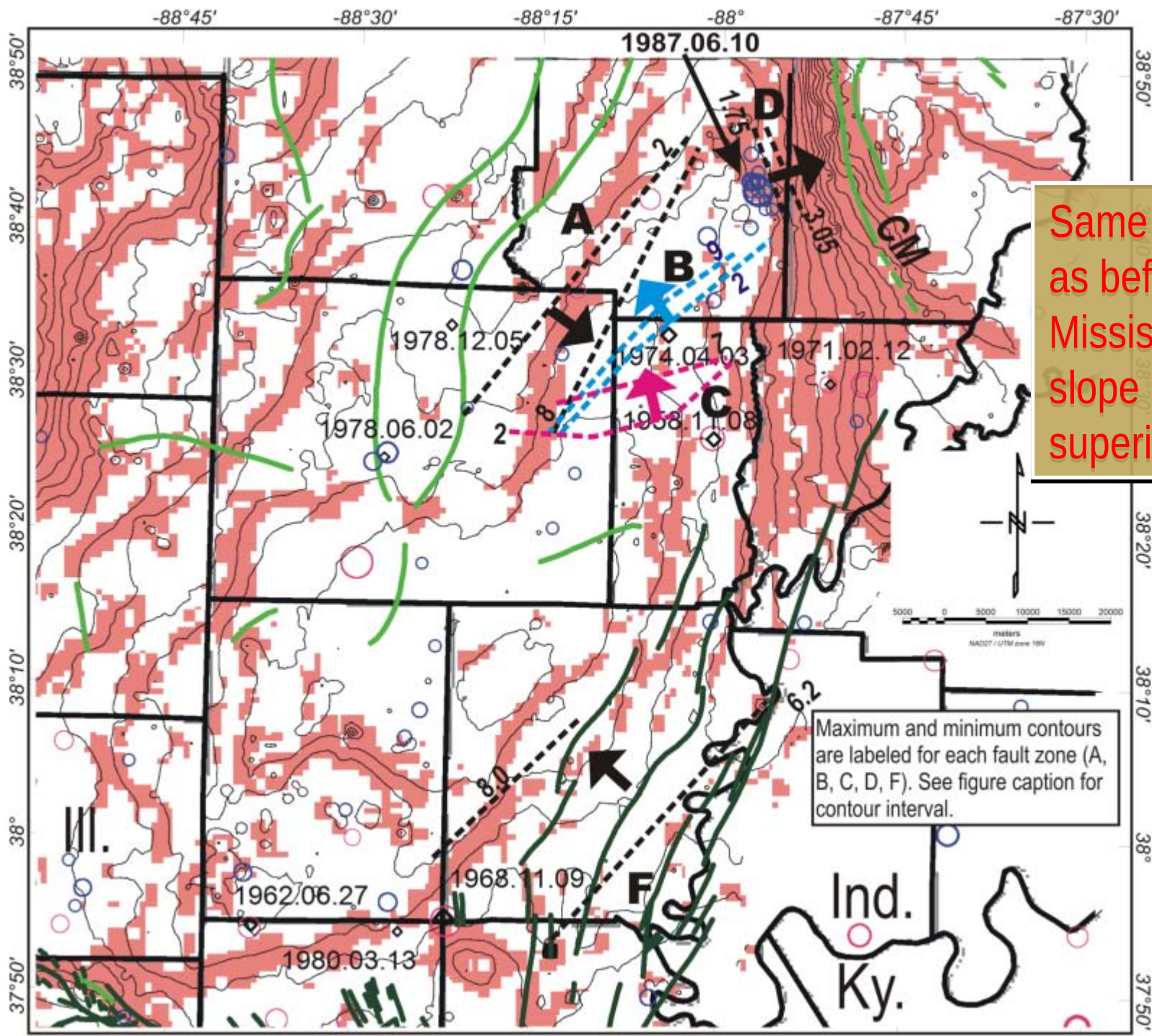
S-1 Apr. 3, 1974 $m_b = 4.7$ strike-slip event projected ~5 from the east

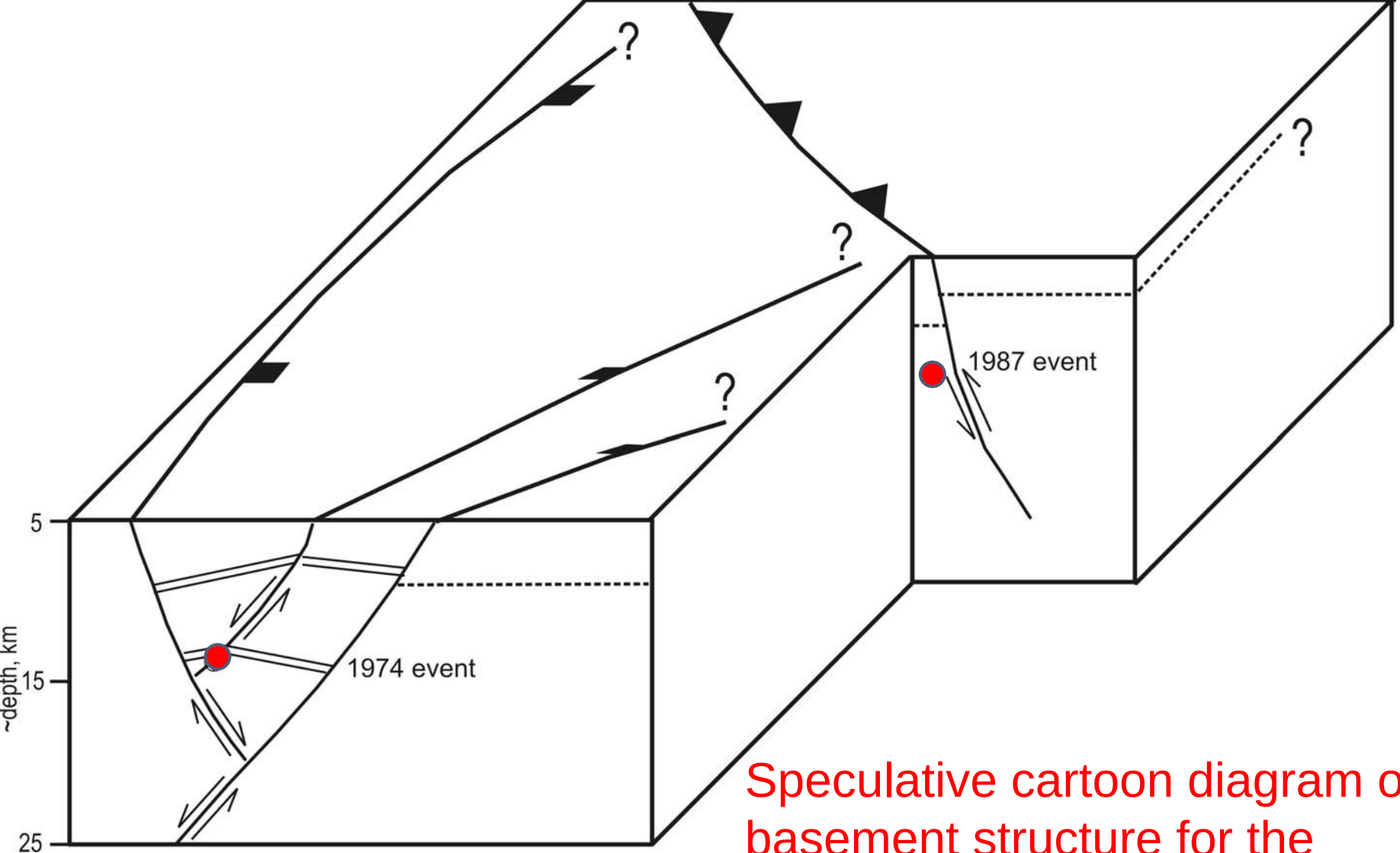


S-2 An orthogonal seismic reflection profile with faults interpreted



Three fault zones mapped from the seismic reflection profiles. Several earthquakes plot within this zone of locally more intense faulting.



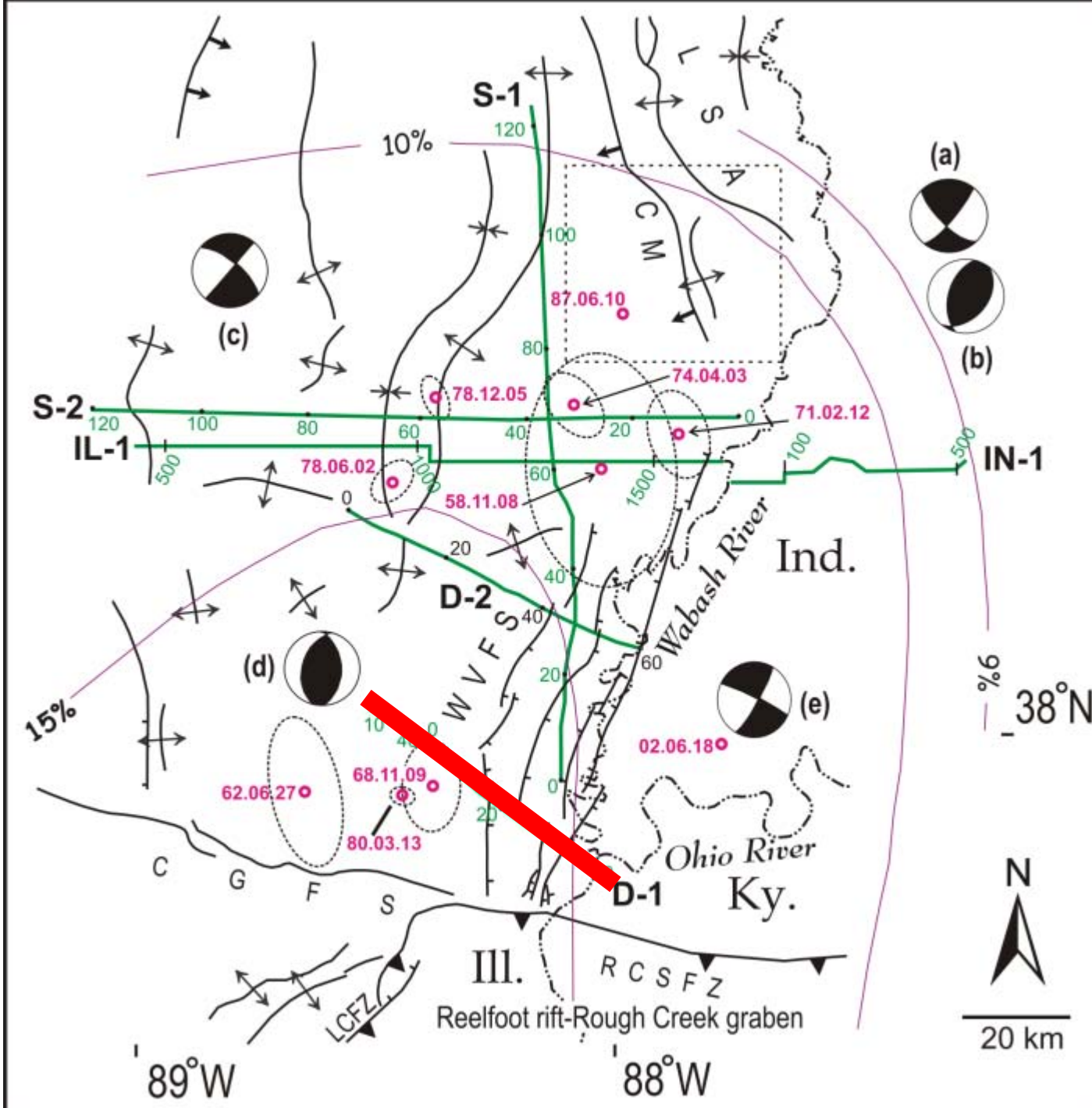


Speculative cartoon diagram of basement structure for the interpreted zone of rifting beneath the Fairfield sub-basin



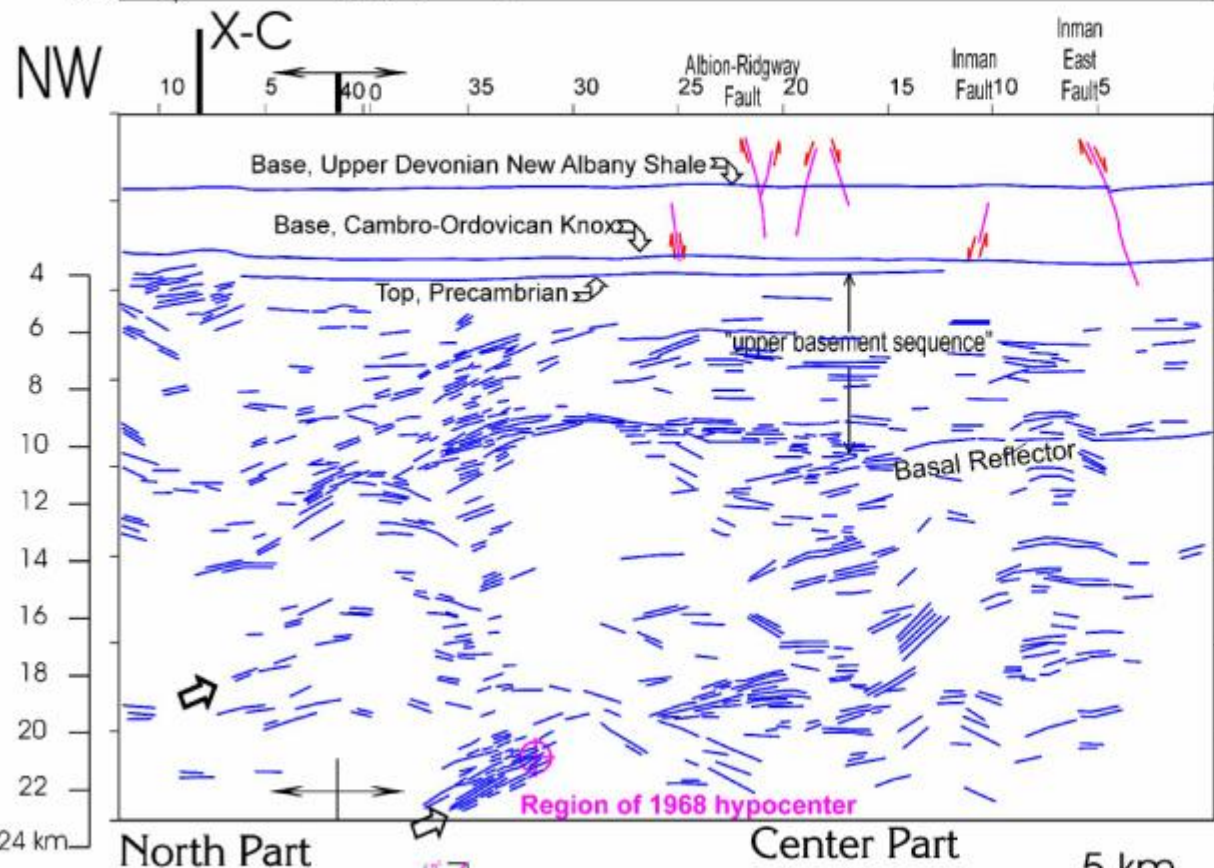
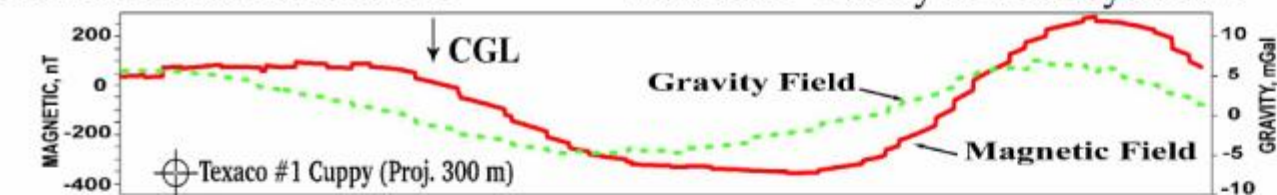
near the Wabash Valley fault system





central Illinois Basin

Wabash Valley Fault System

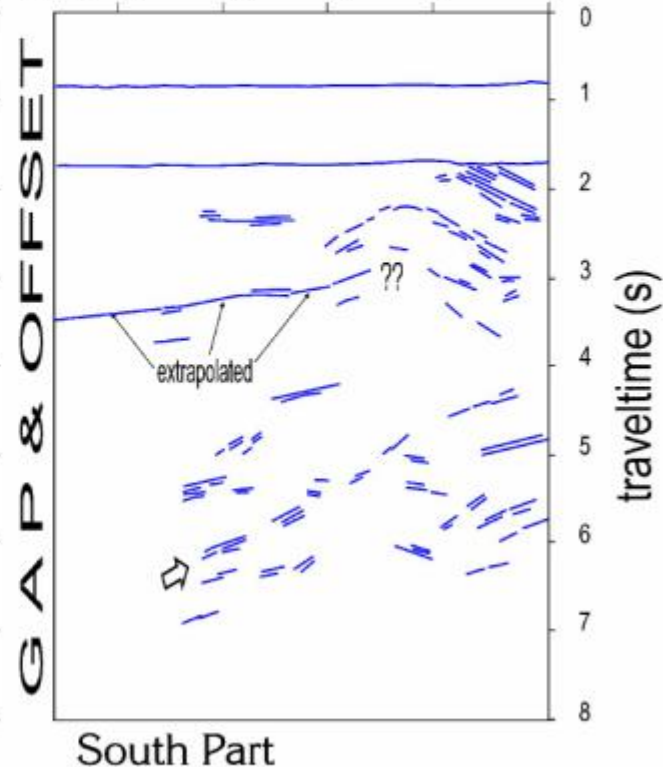


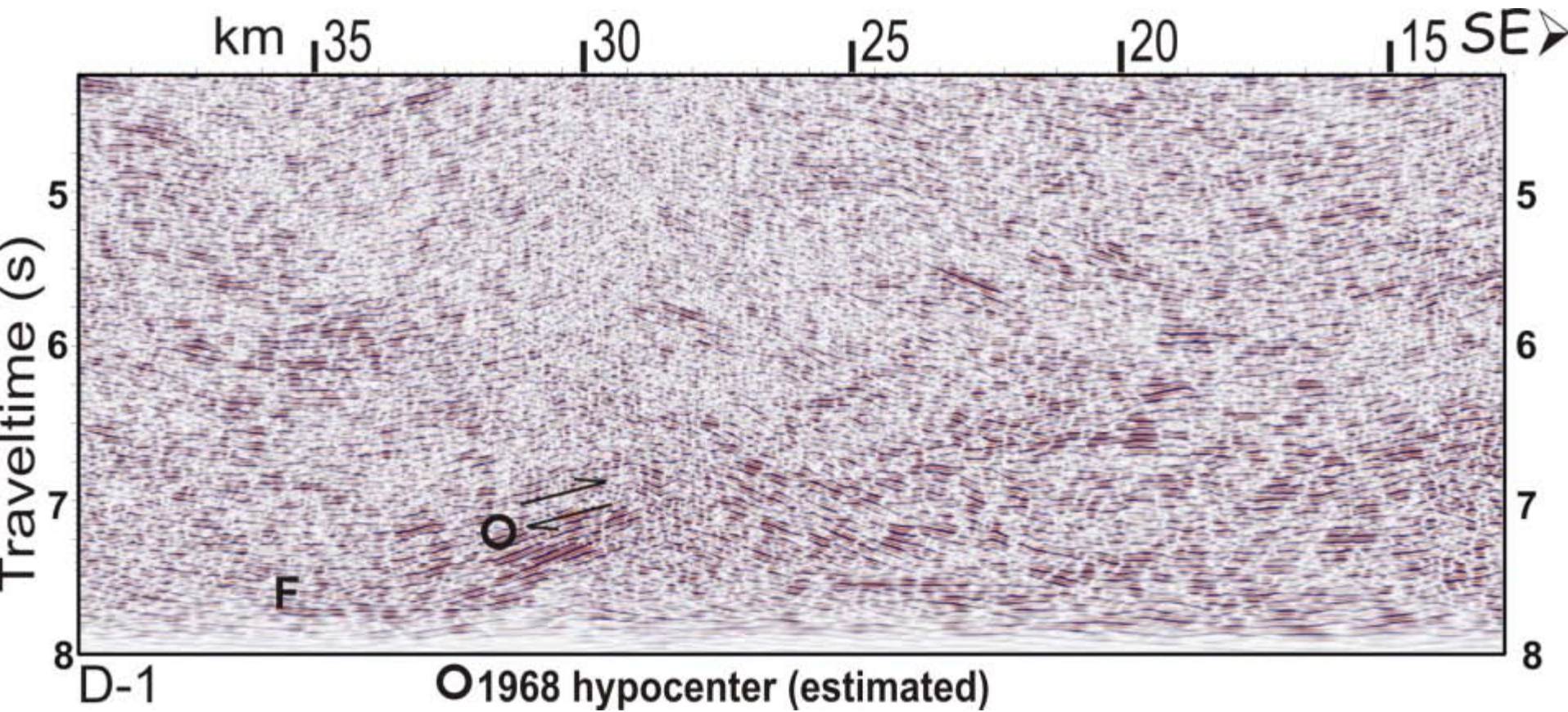
43°
2.9 km
Dip and length of
interpreted fault plane
based on earthquake parameters

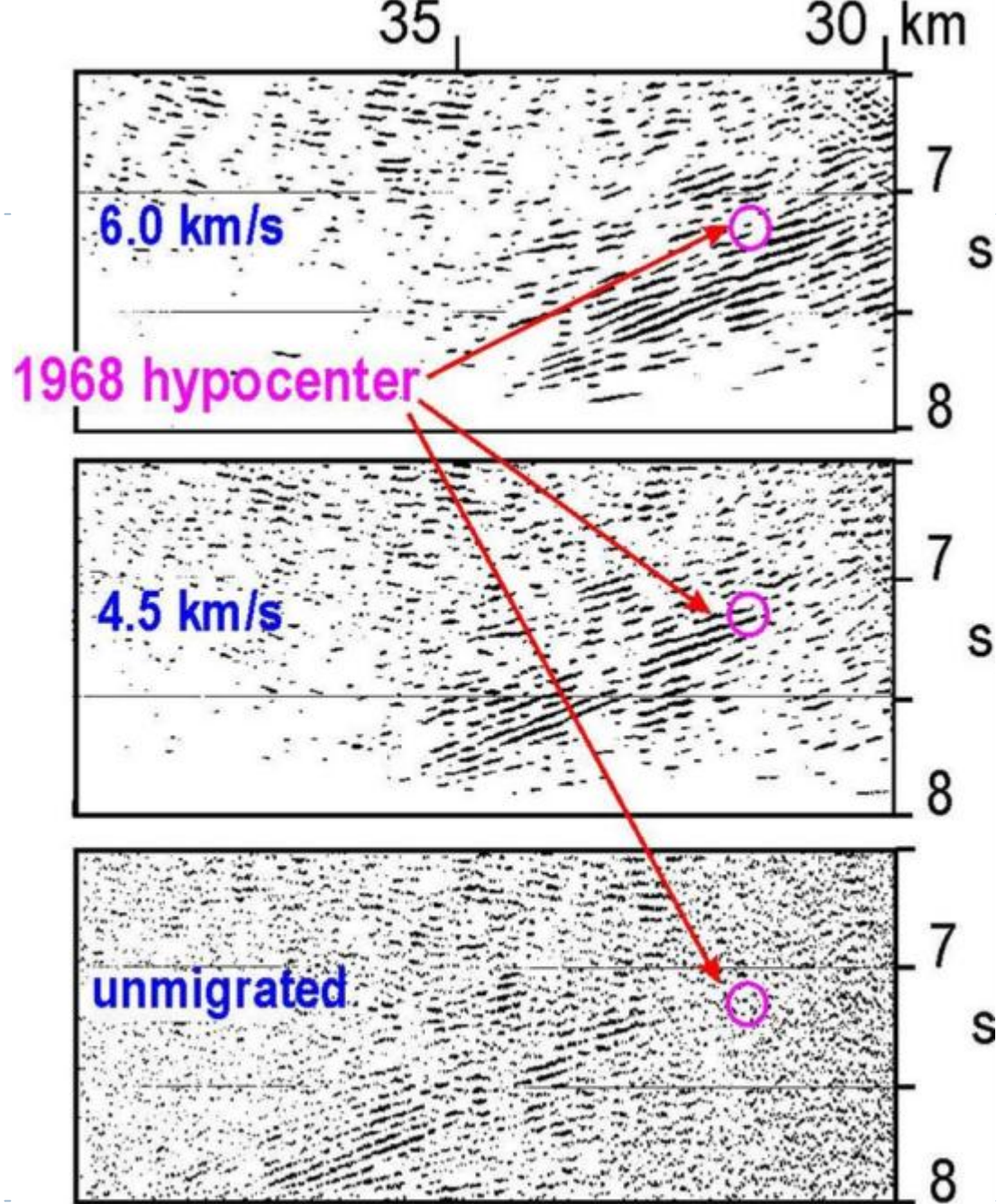
Profile A

Rough Creek Graben

Wabash
River

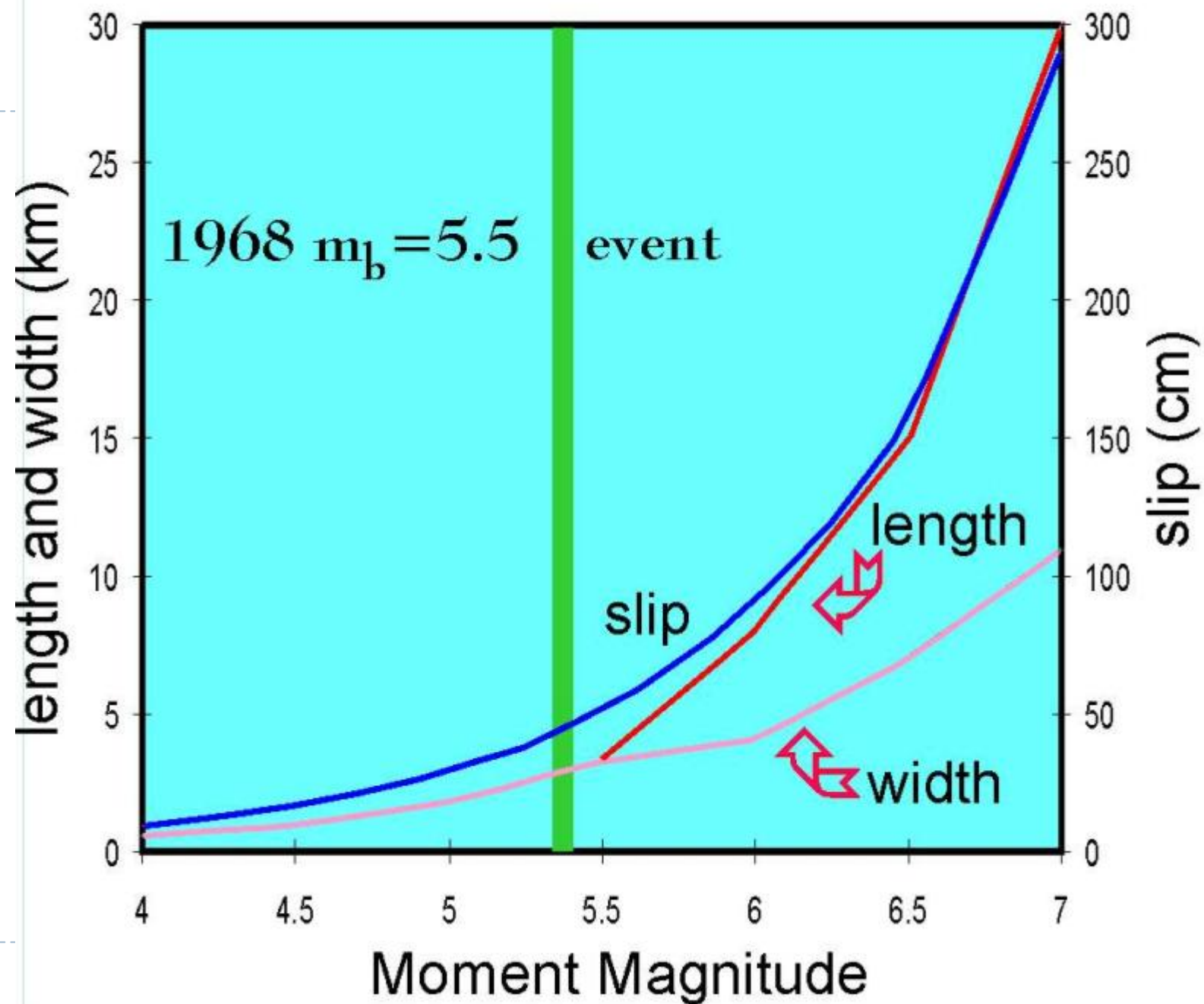


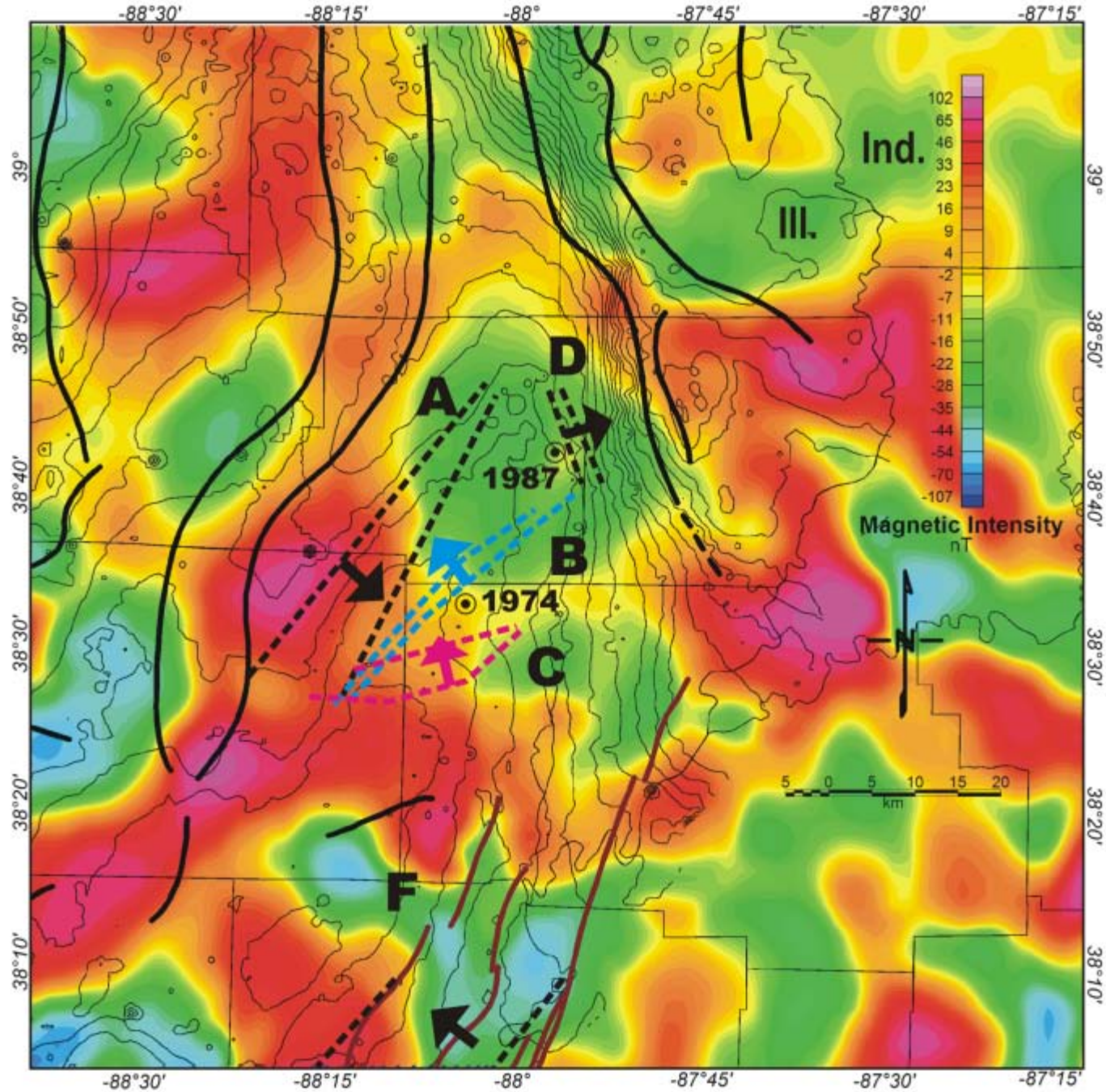


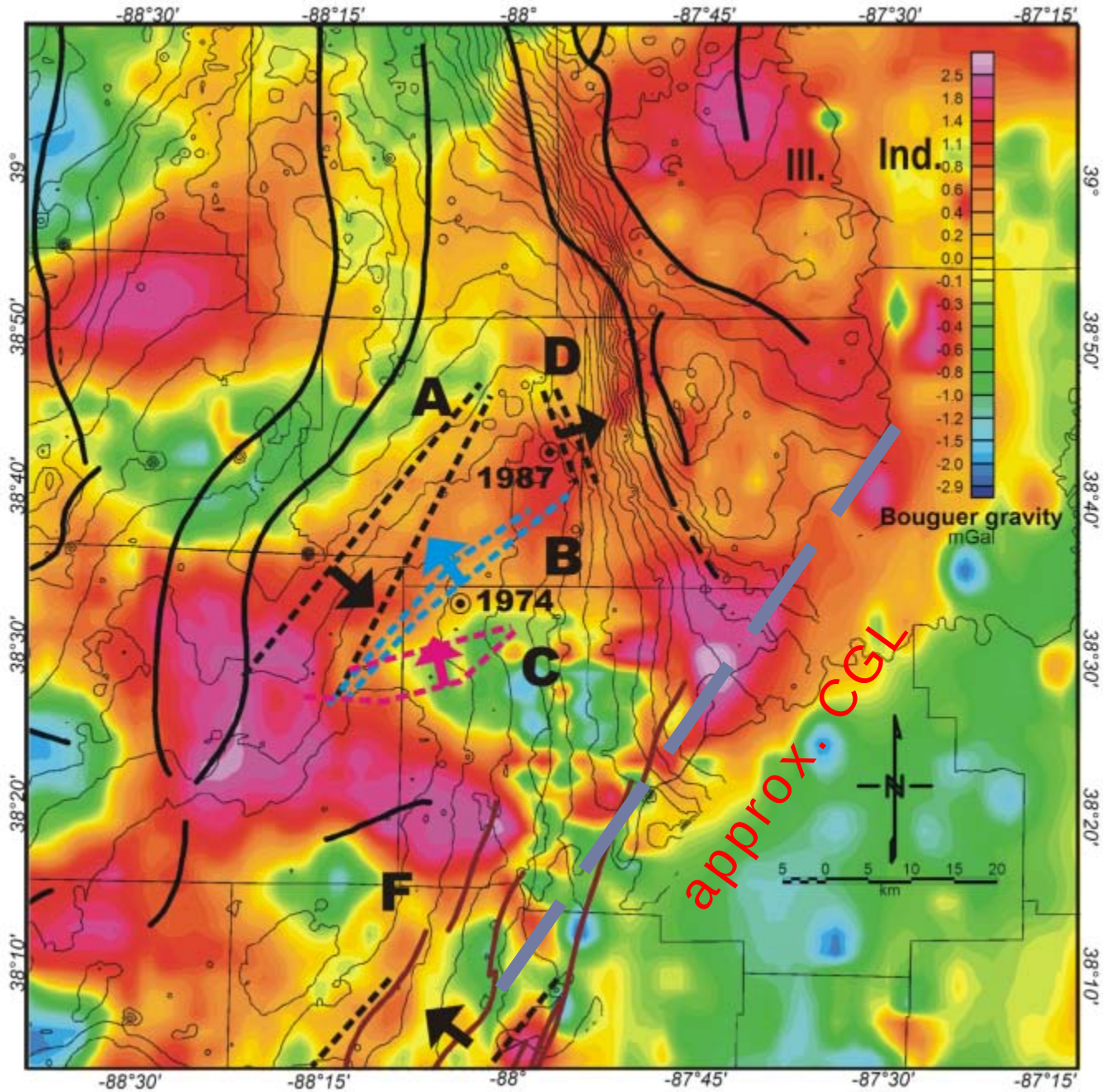


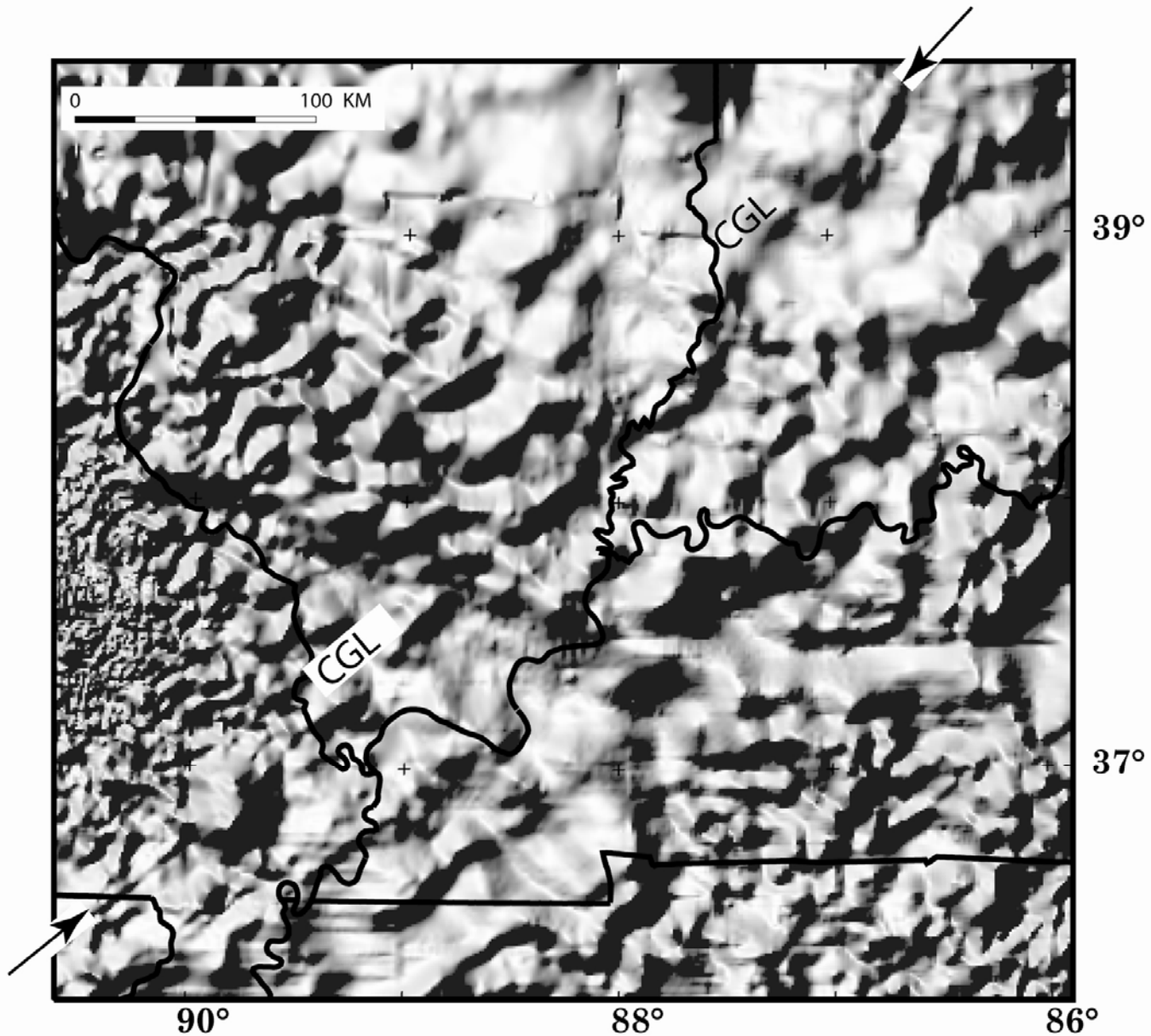
Velocity values have been reduced by 40% in order to reduce over-migration artifacts

Migration spectra





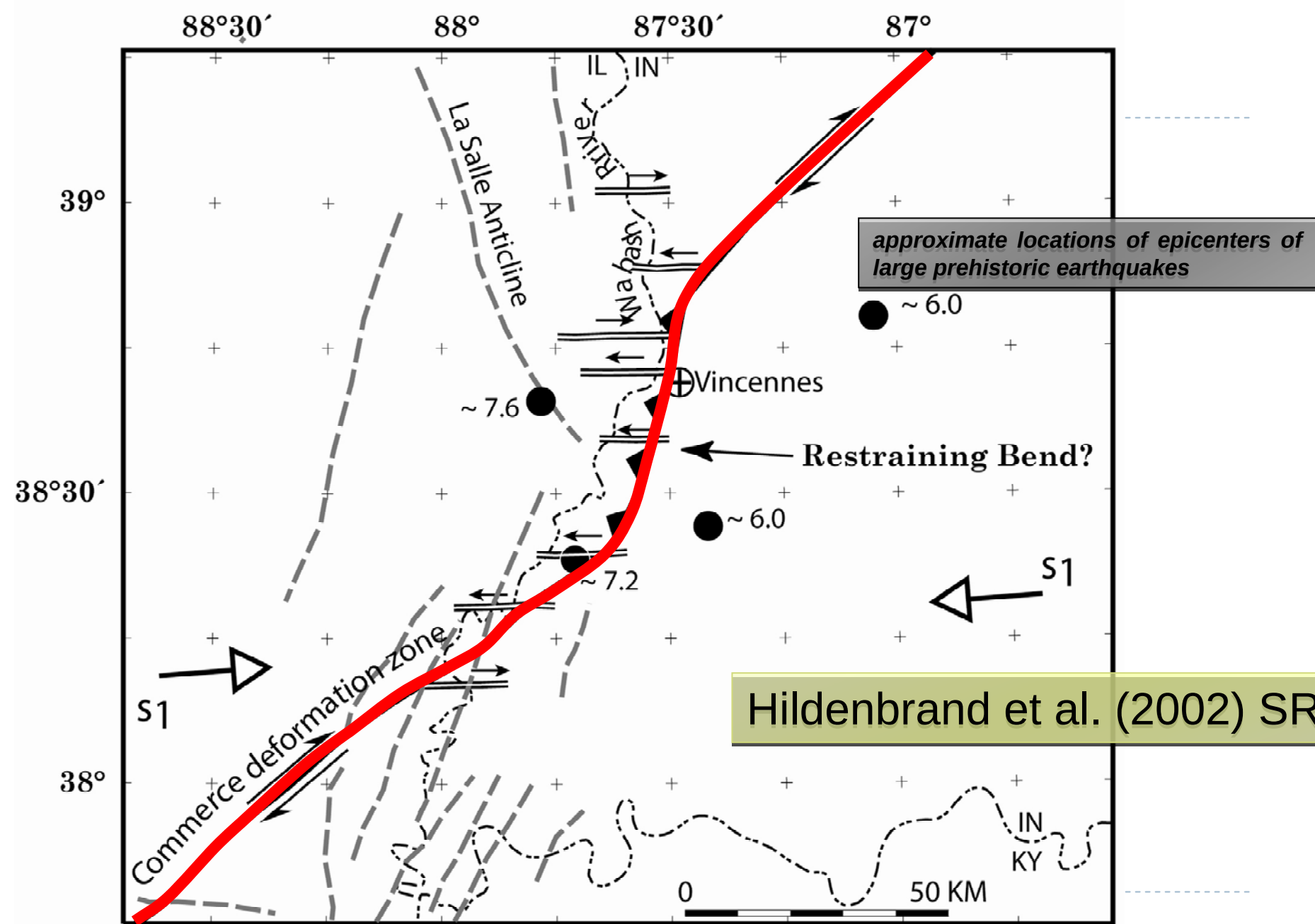




Shaded-relief magnetic field (illumination from the west)

Hildenbrand et al. (2002) SRL

proposed restraining bend or right-step in the Commerce deformation zone



central Illinois Basin

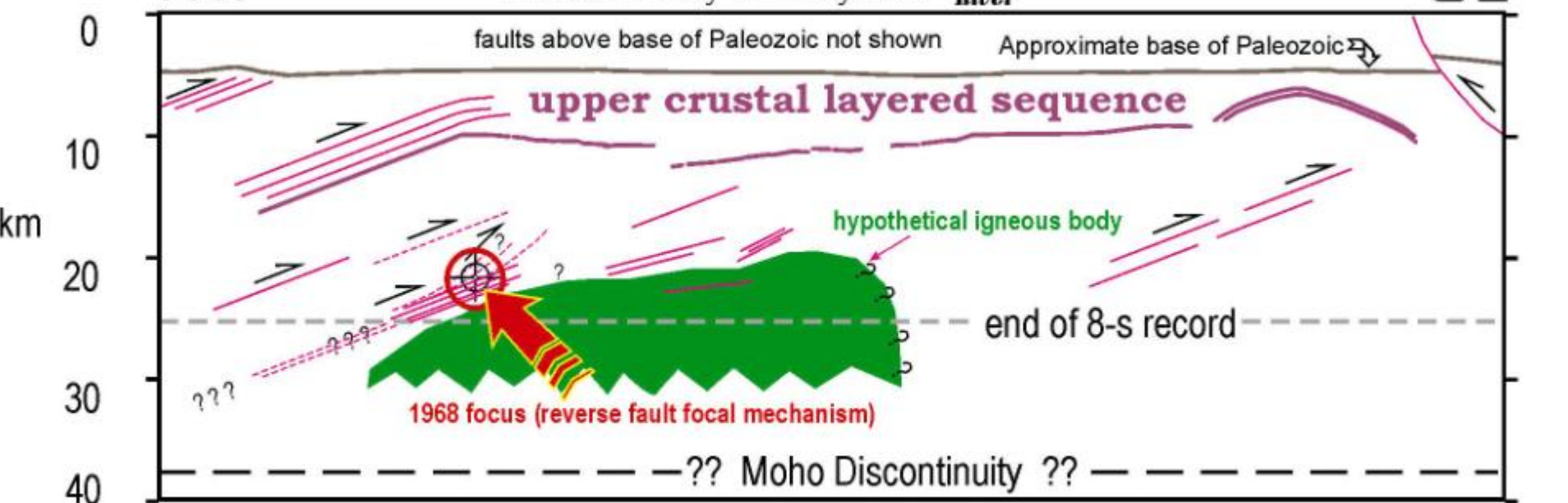
CGL

Wabash Valley Fault System

Wabash River

Rough Creek Graben

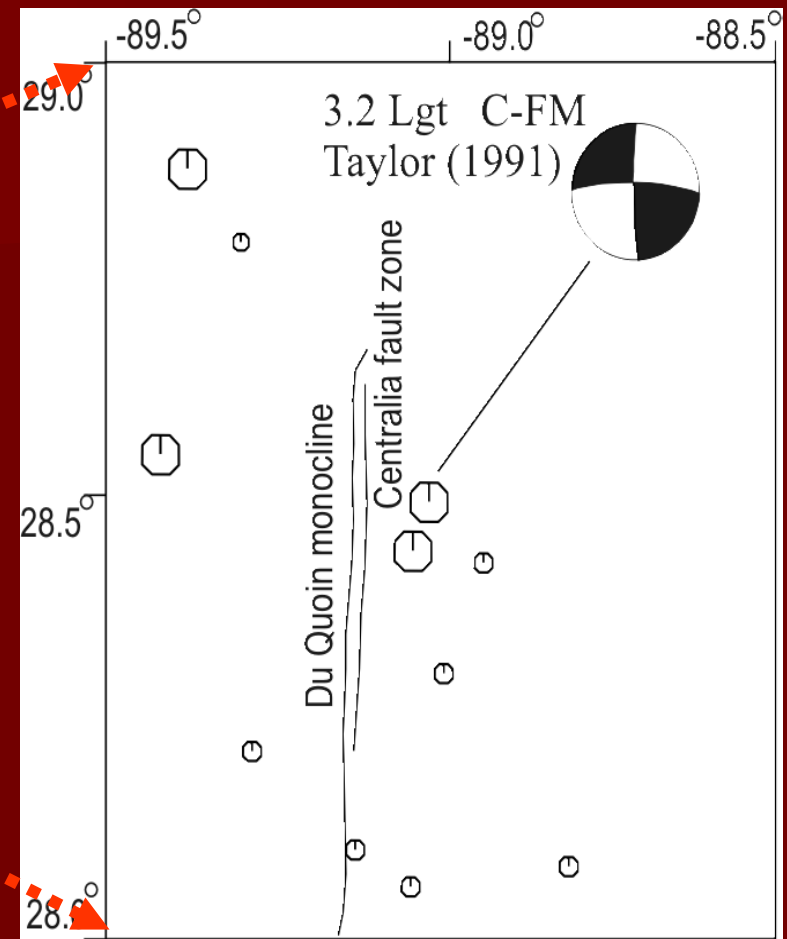
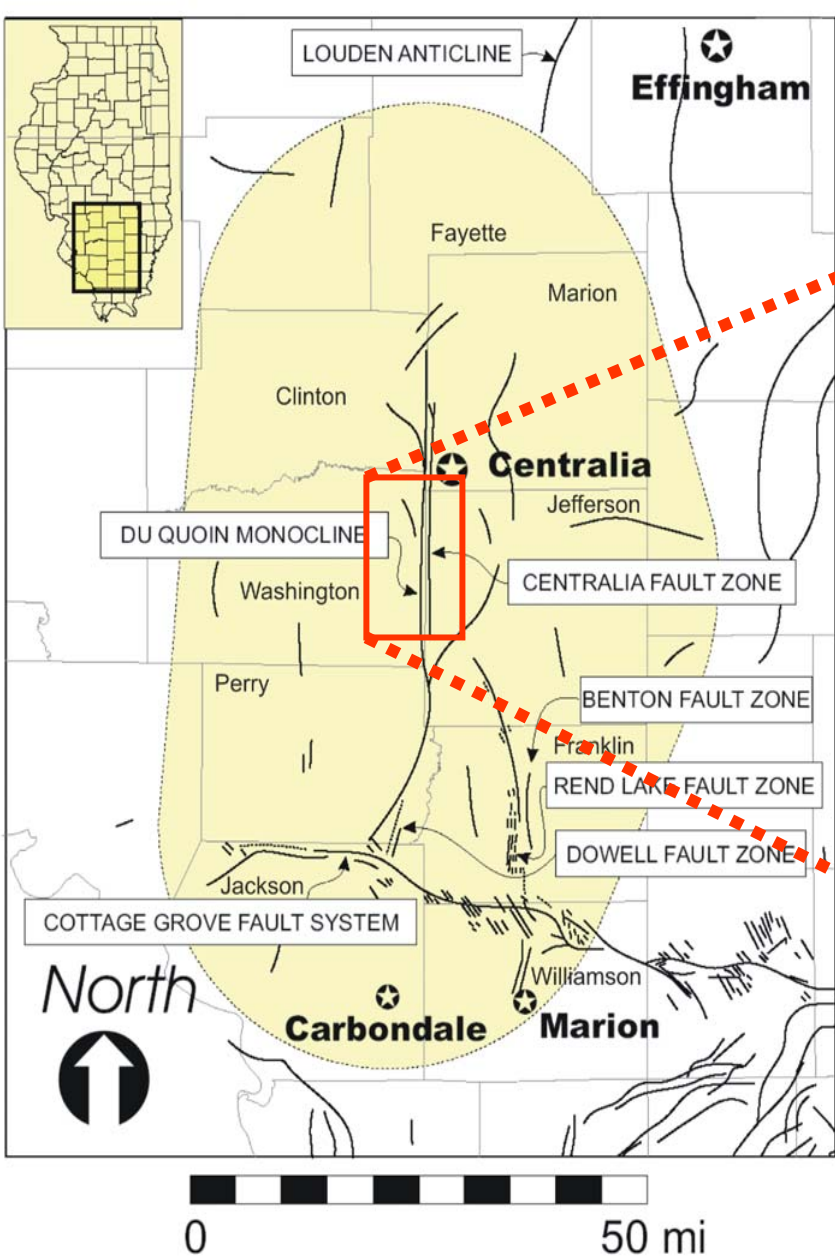
SE



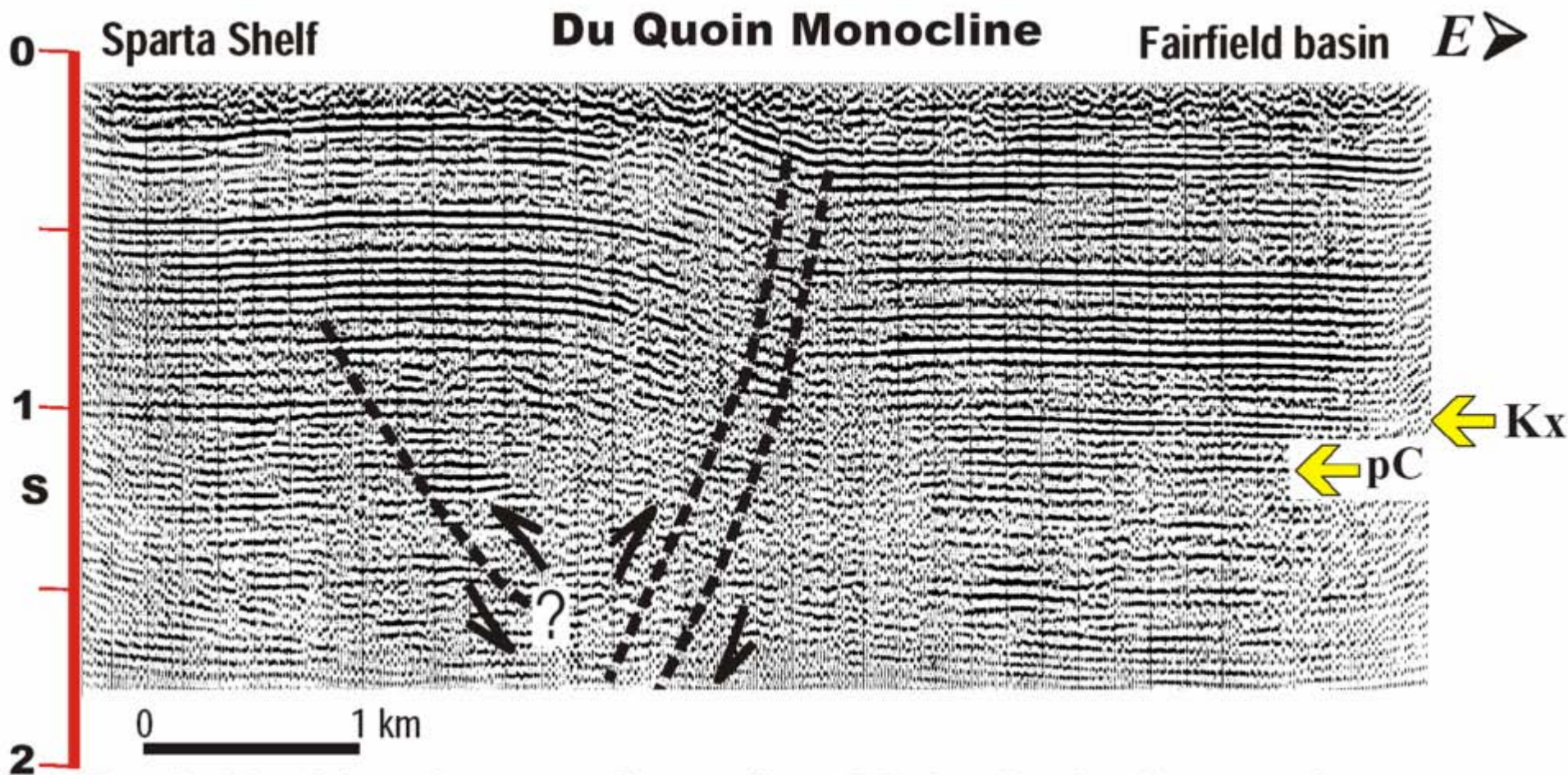
Interpretation of a reprocessed deep seismic reflection profile over the Wabash Valley seismic zone showing the reactivation mechanism for the 1968.11.09 mb = 5.5 thrust-fault earthquake along a pre-existing crustal shear zone localized along an intrusive complex inferred from potential field modeling. The profile also intersects the Commerce Geophysical lineament (CGL), which is thought to represent a significant seismic hazard.

Du Quoin monocline complex

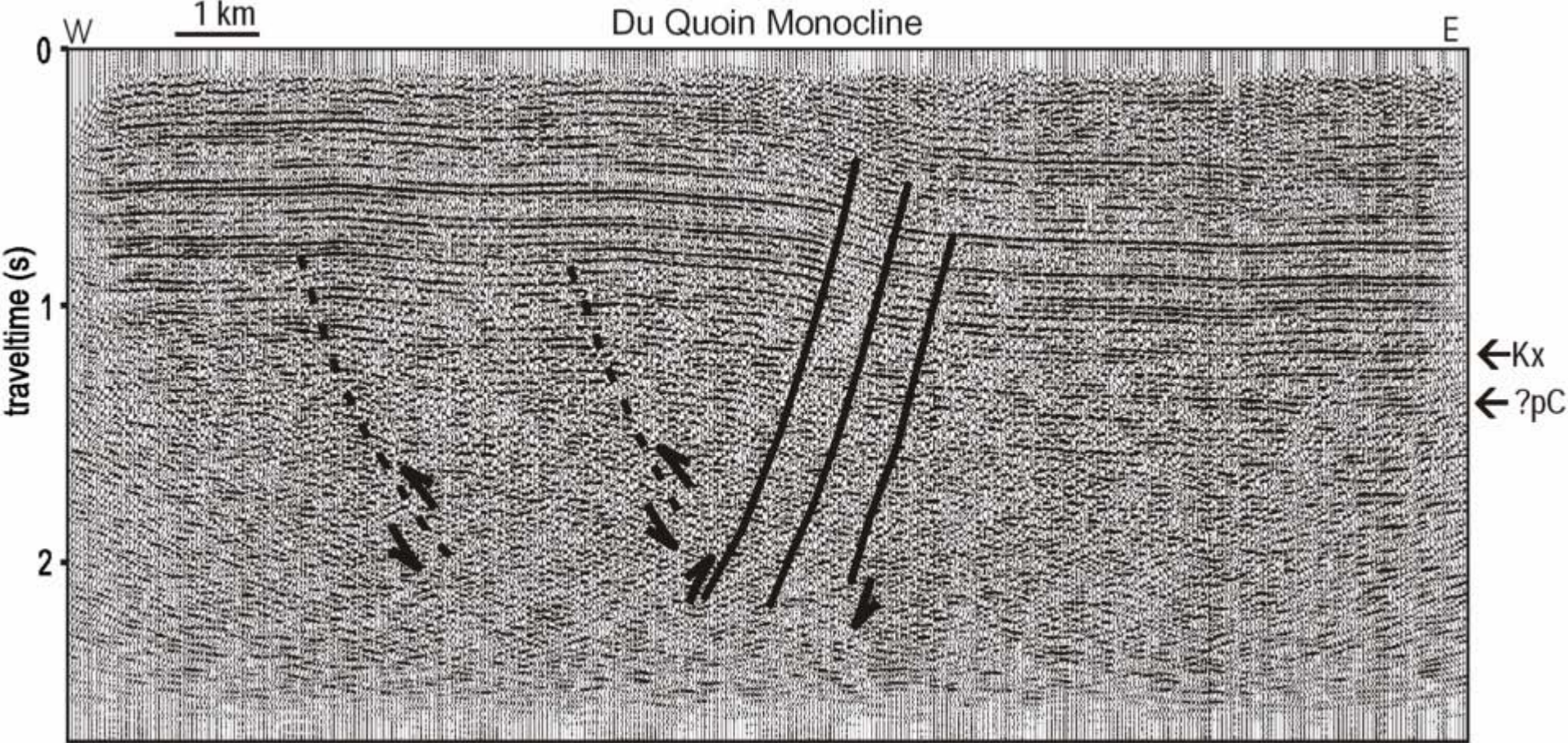




Map of epicenters from Taylor (1991) near Du Quoin Monocline and Centralia Fault Zone. Composite focal mechanism solution.



Some evidence for disruption of Precambrian basement, possibly extending into seismogenic depths; however, evidence of post-Paleozoic deformation is lacking.

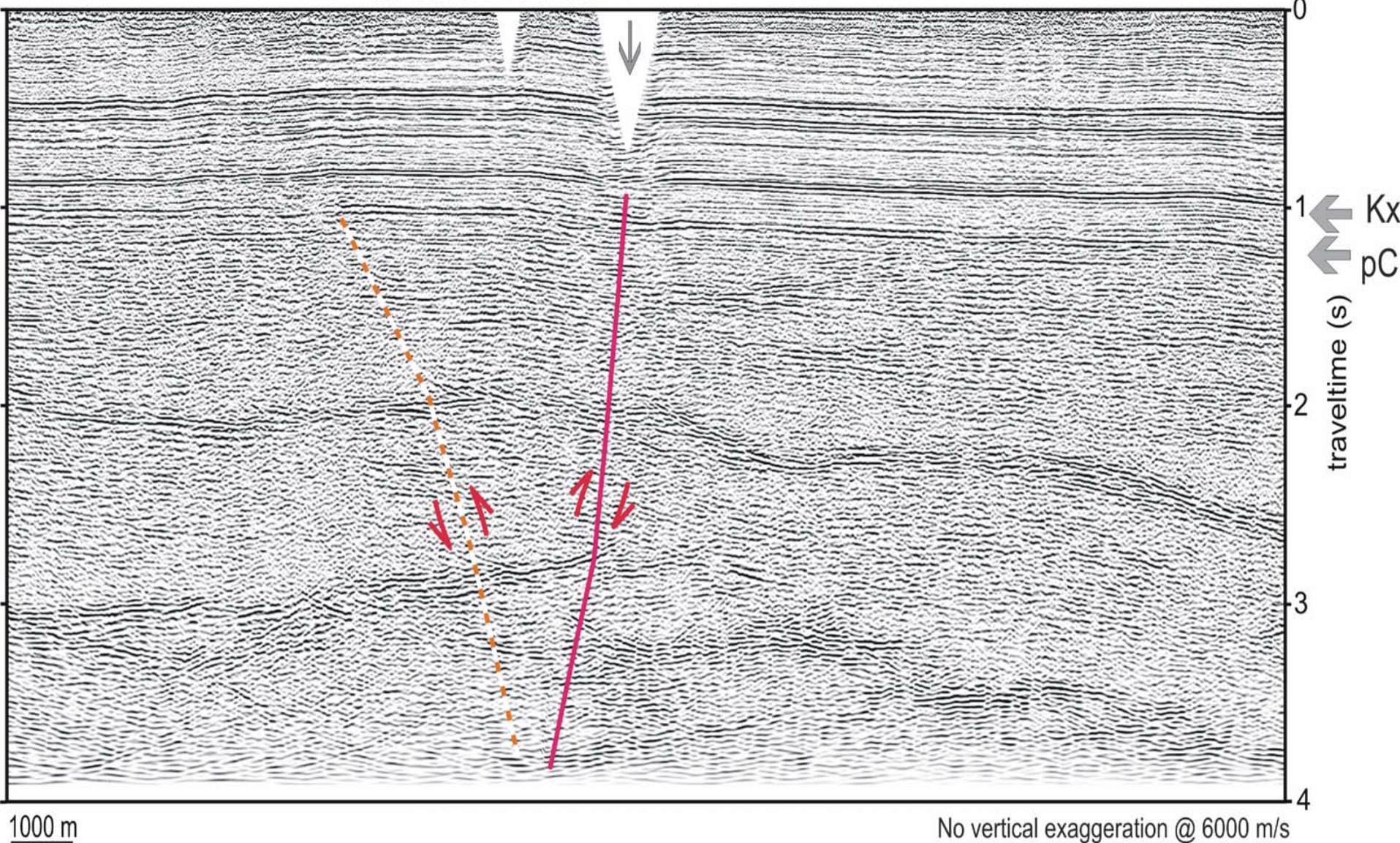


**Migrated seismic reflection profile across Du Quoin monocline.
This seismic reflection line was vectorized and migrated.**

Fault relationships much clearer in Paleozoic sedimentary section.

Louden Anticline

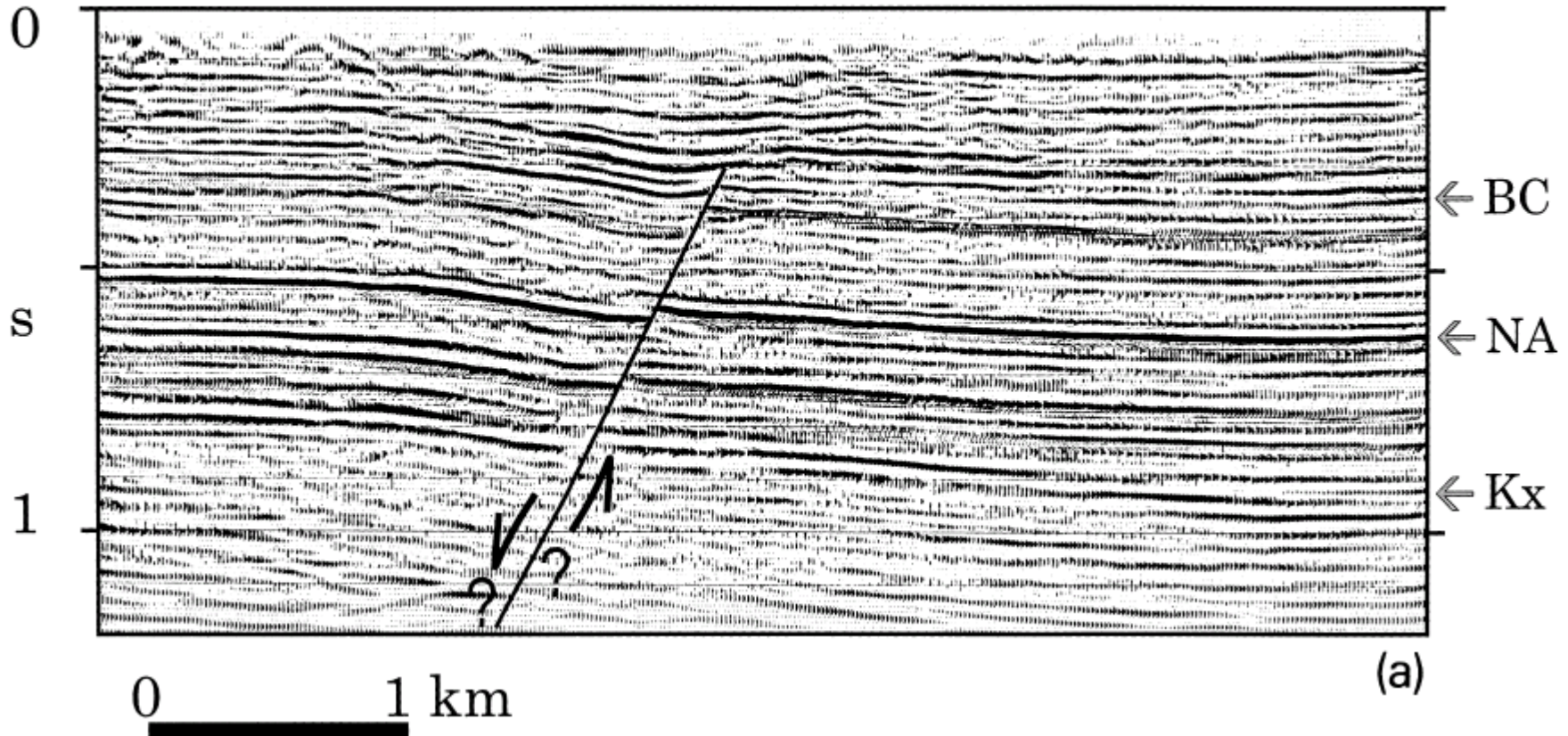
E ➤



Digitally post-stack (& pre-stack) reprocessed regional “deep” industry seismic profile.

East flank of Du Quoin Monocline/Centralia Fault Zone

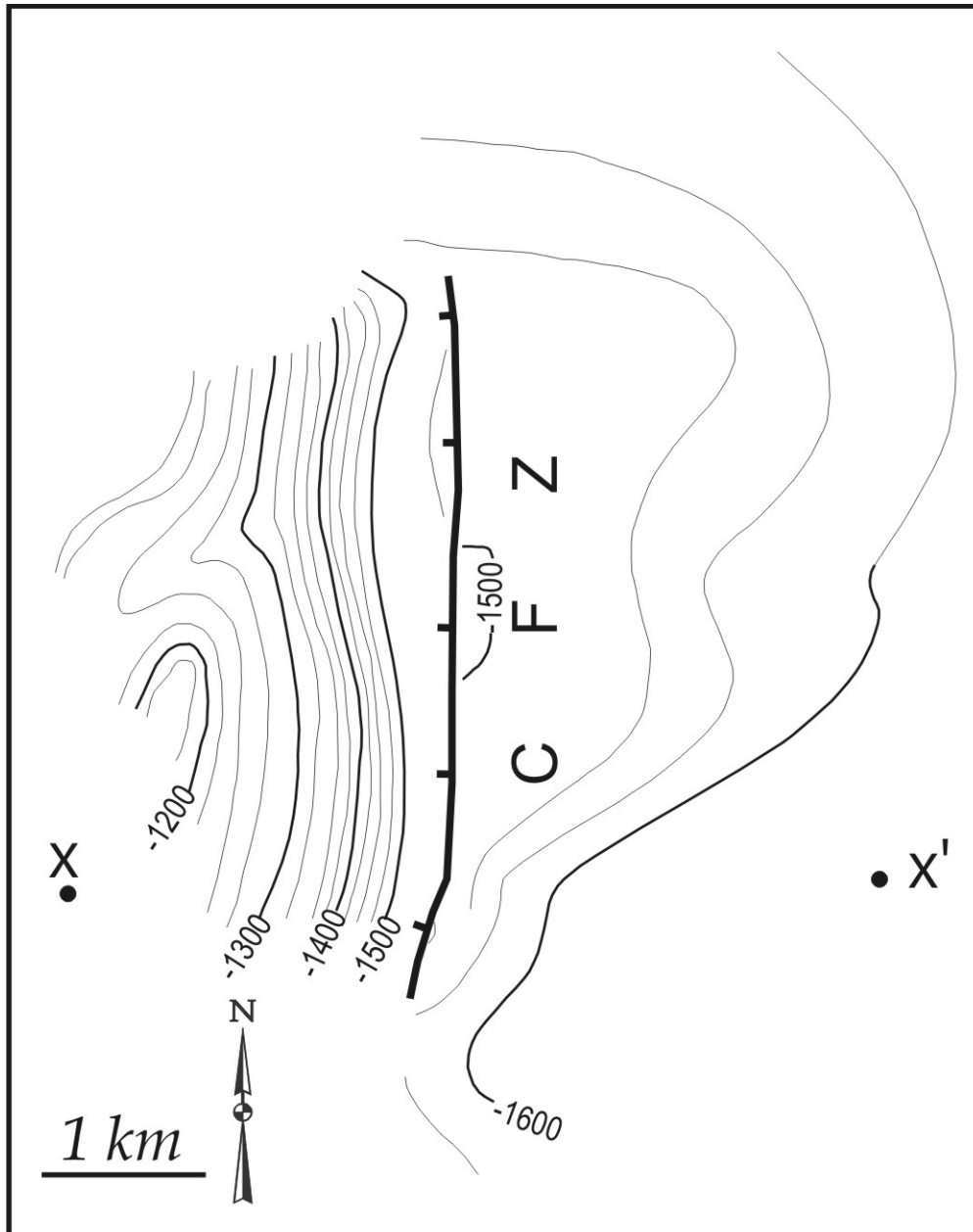
E ➤



(a)

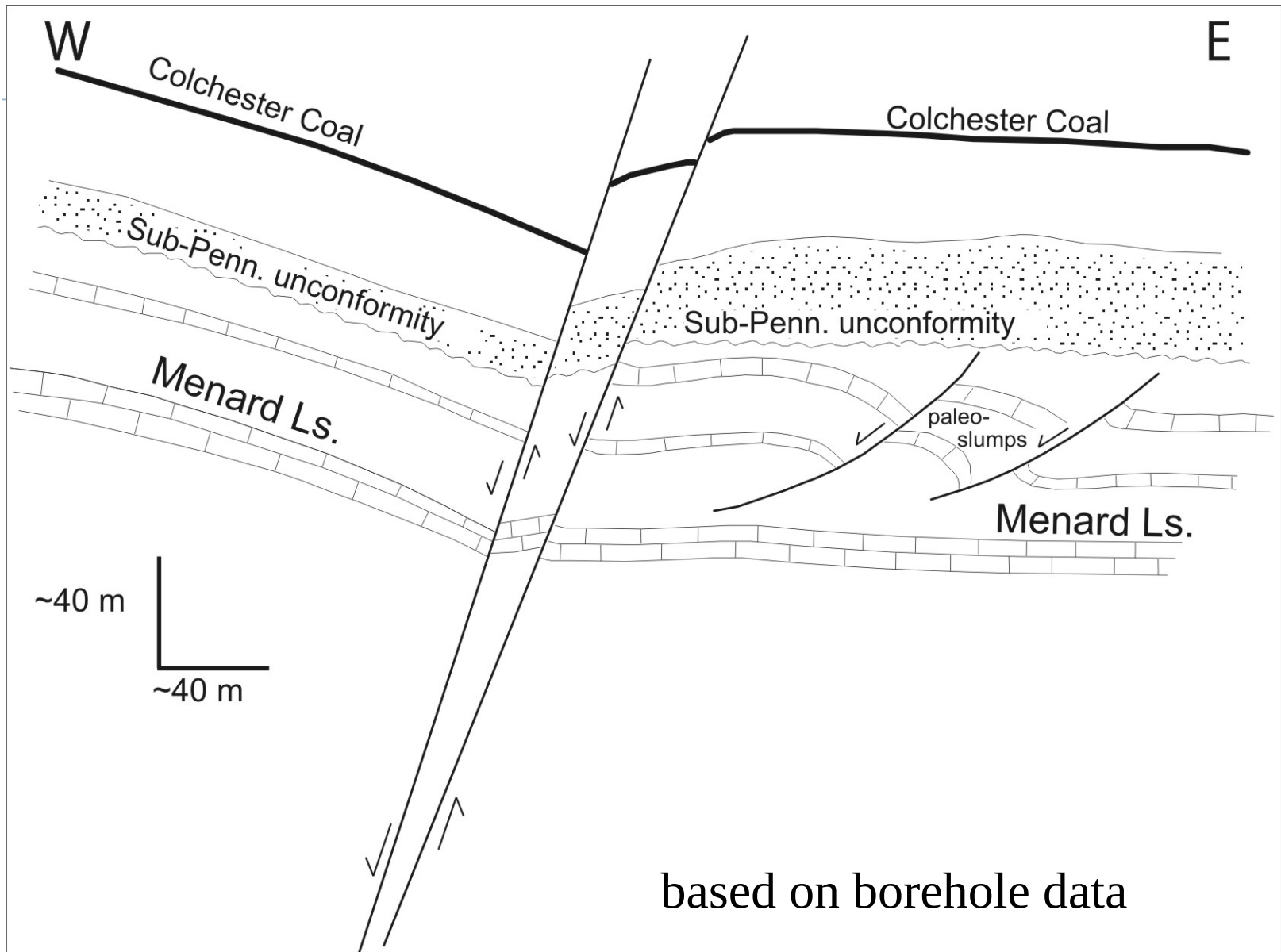
High-resolution migrated seismic profile provides some evidence for reactivation along the older reverse fault.

Structure-contour map of the Beech Creek Limestone over the Centralia Fault Zone.



Structure contours indicate the strong deformation associated with reactivation at Mississippian levels.

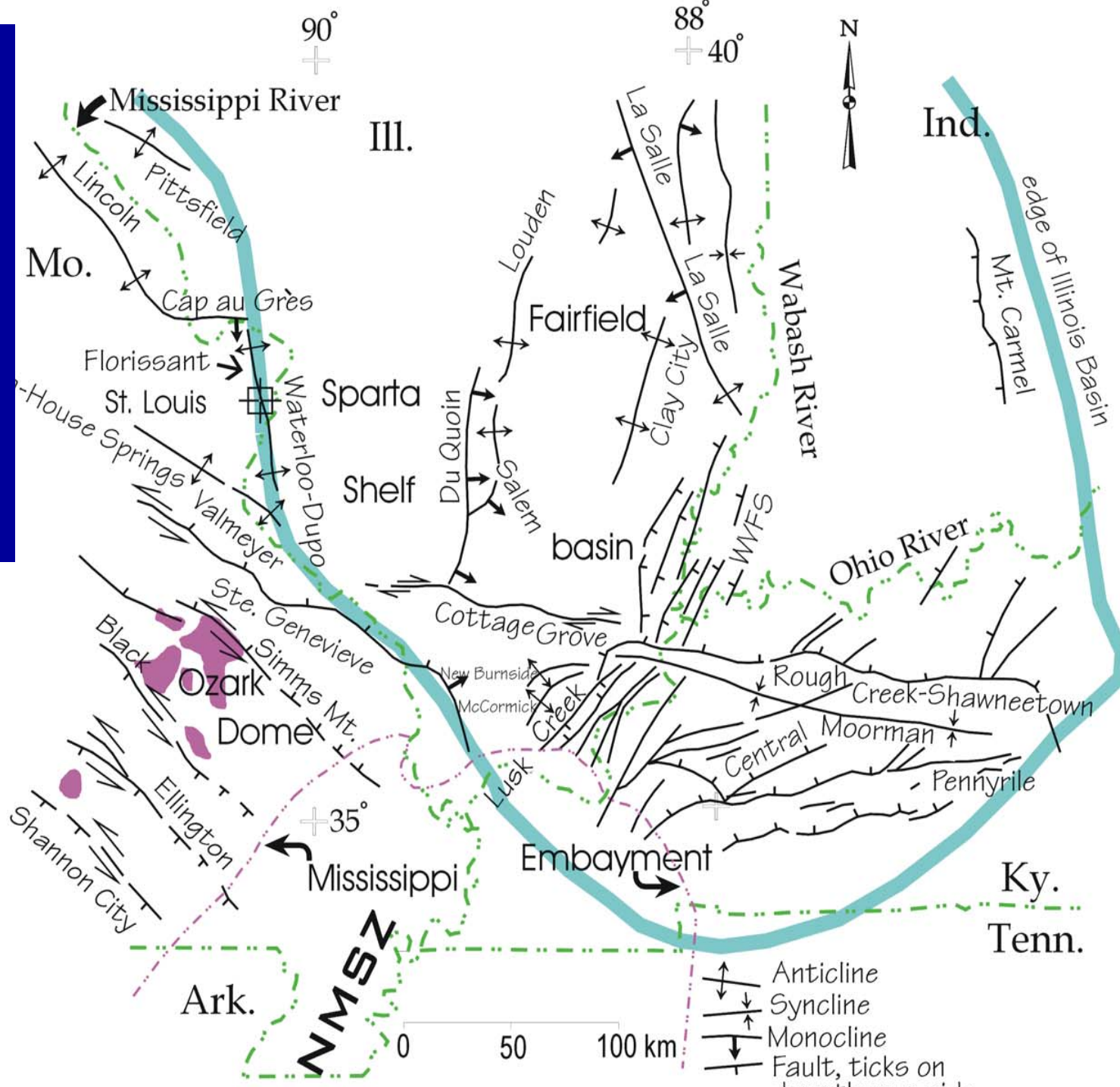
Interpretive cross-section based on borehole data across the Centralia Fault Zone



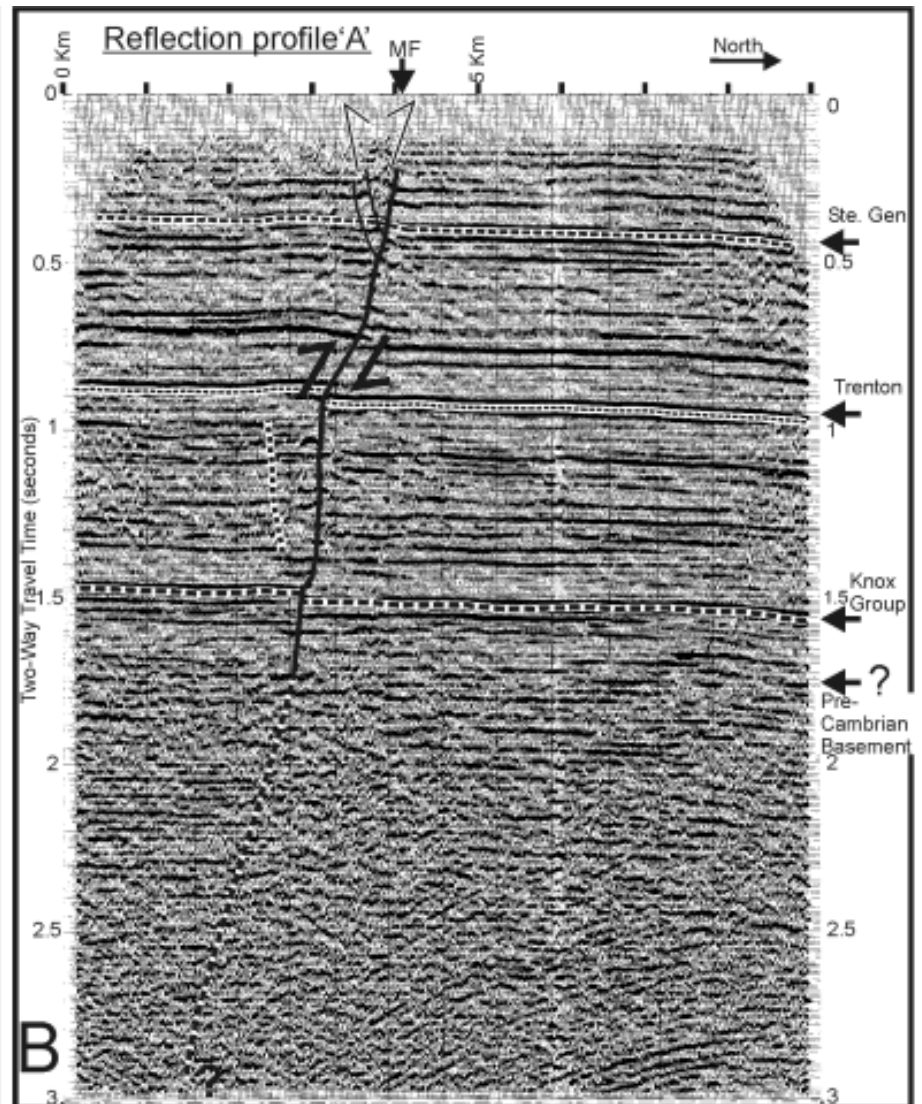
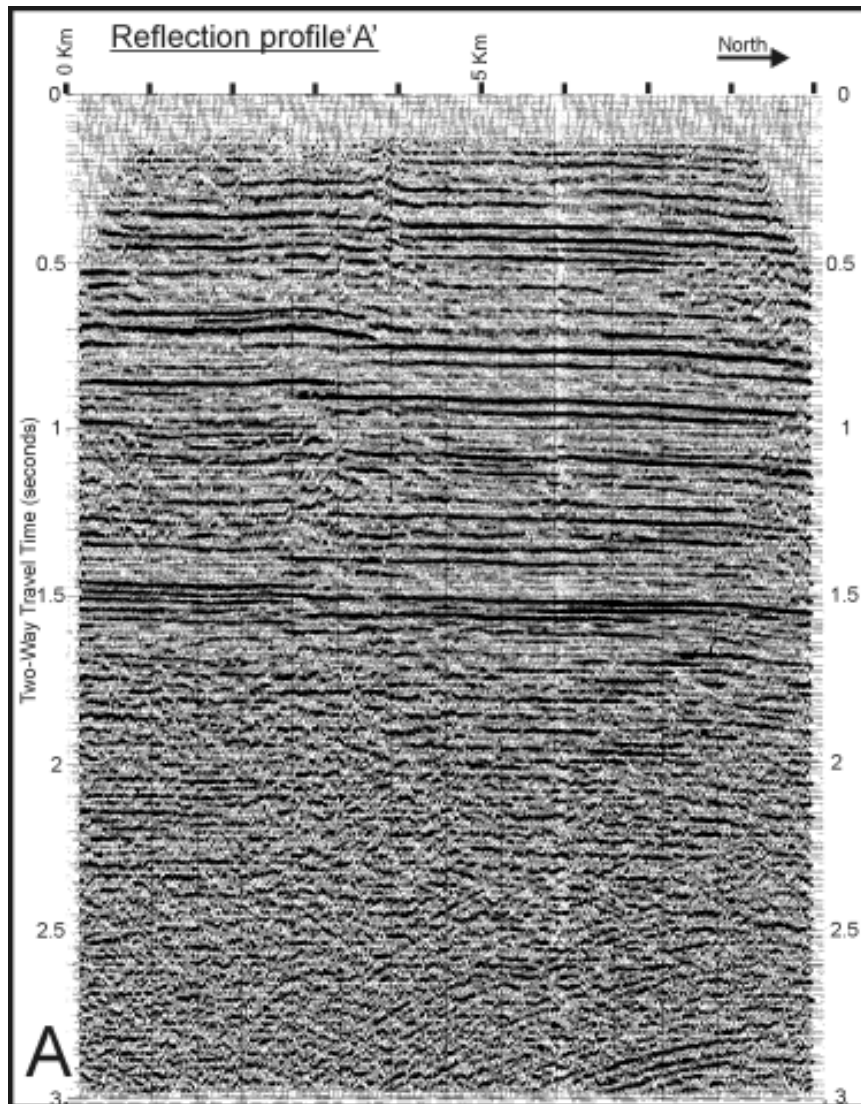
Fluorspar Area fault complex and Cottage Grove fault system



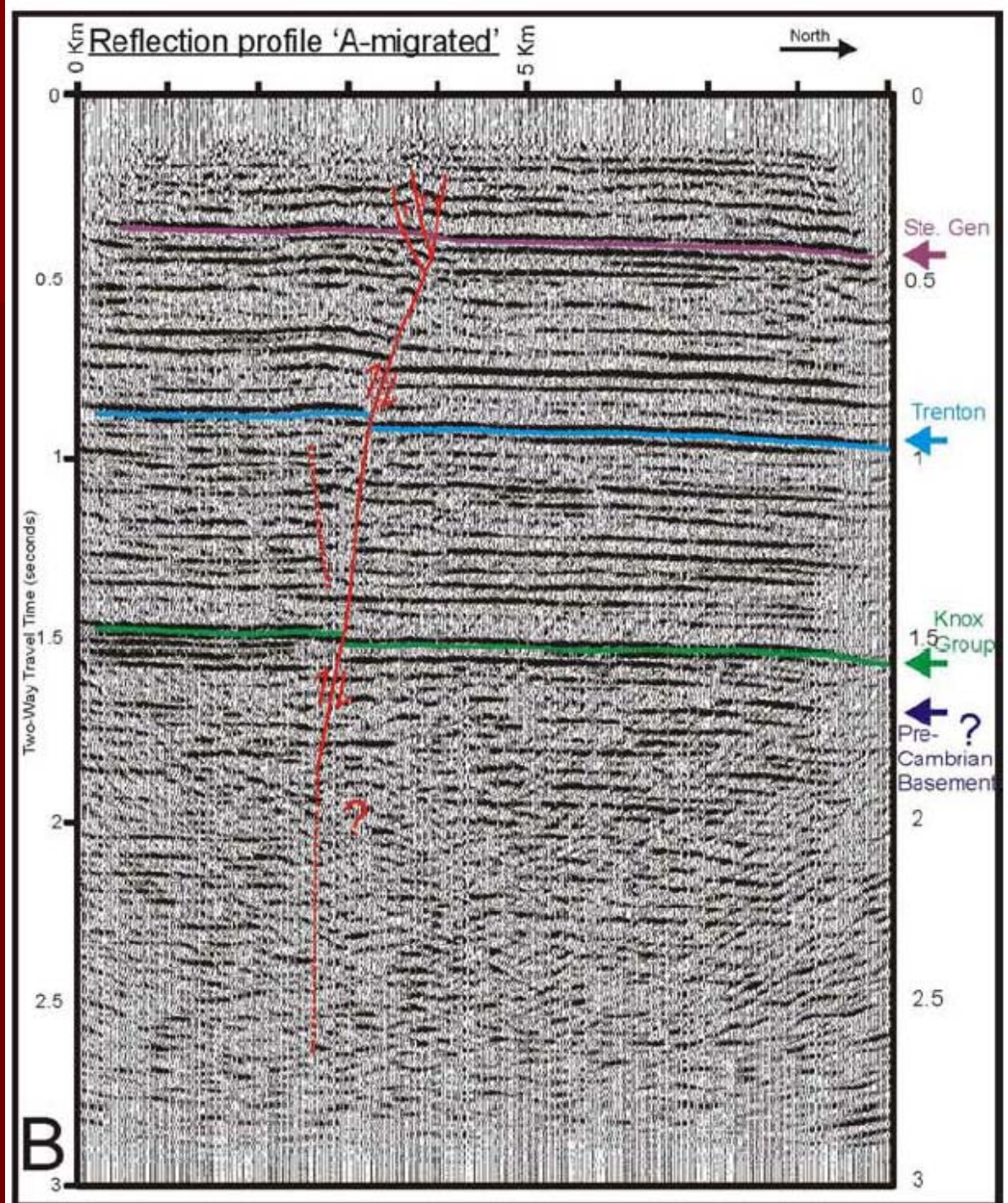
Illinois basin is structurally complex at deeper (Cambrian) levels – Laramide-style fold and fault zones.



Seismic reflection profile across the Cottage Grove fault system showing a small “flower structure” associated with transpression along the fault system.

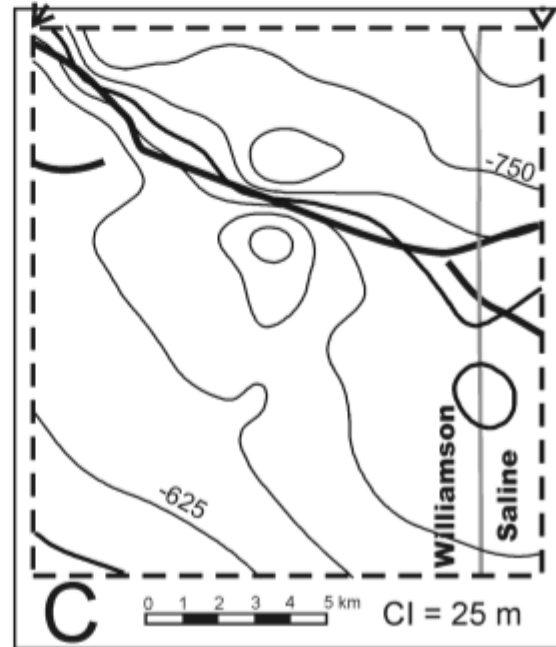
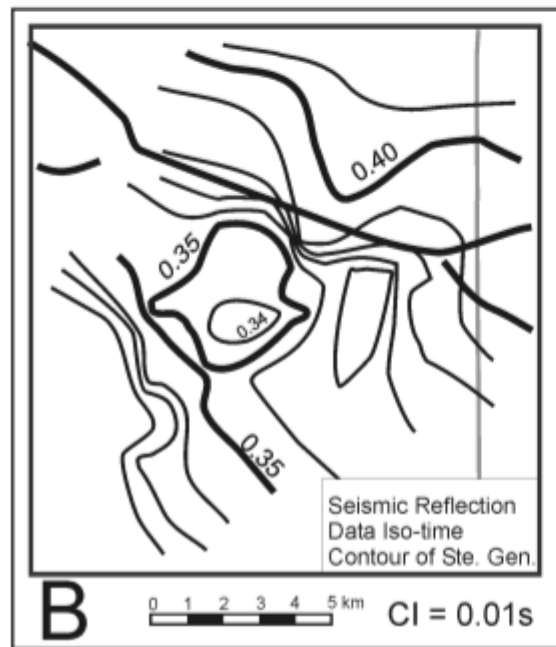
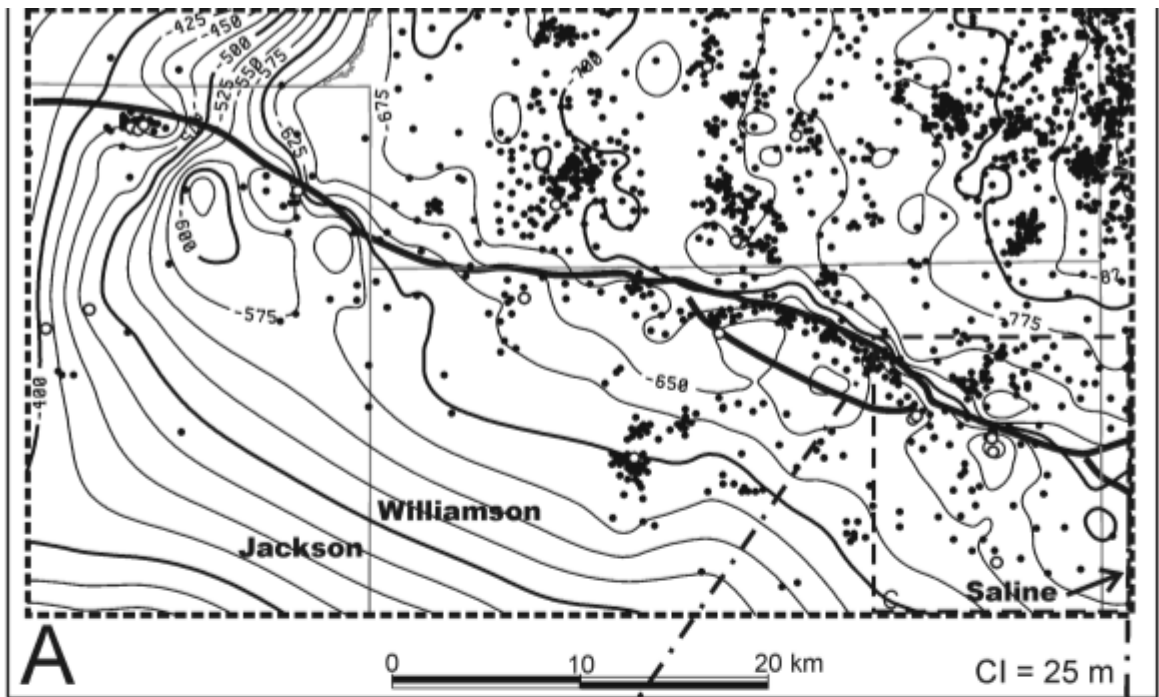


Migrated seismic reflection profile across master fault of Cottage Grove fault system. This seismic reflection line was vectorized and migrated.

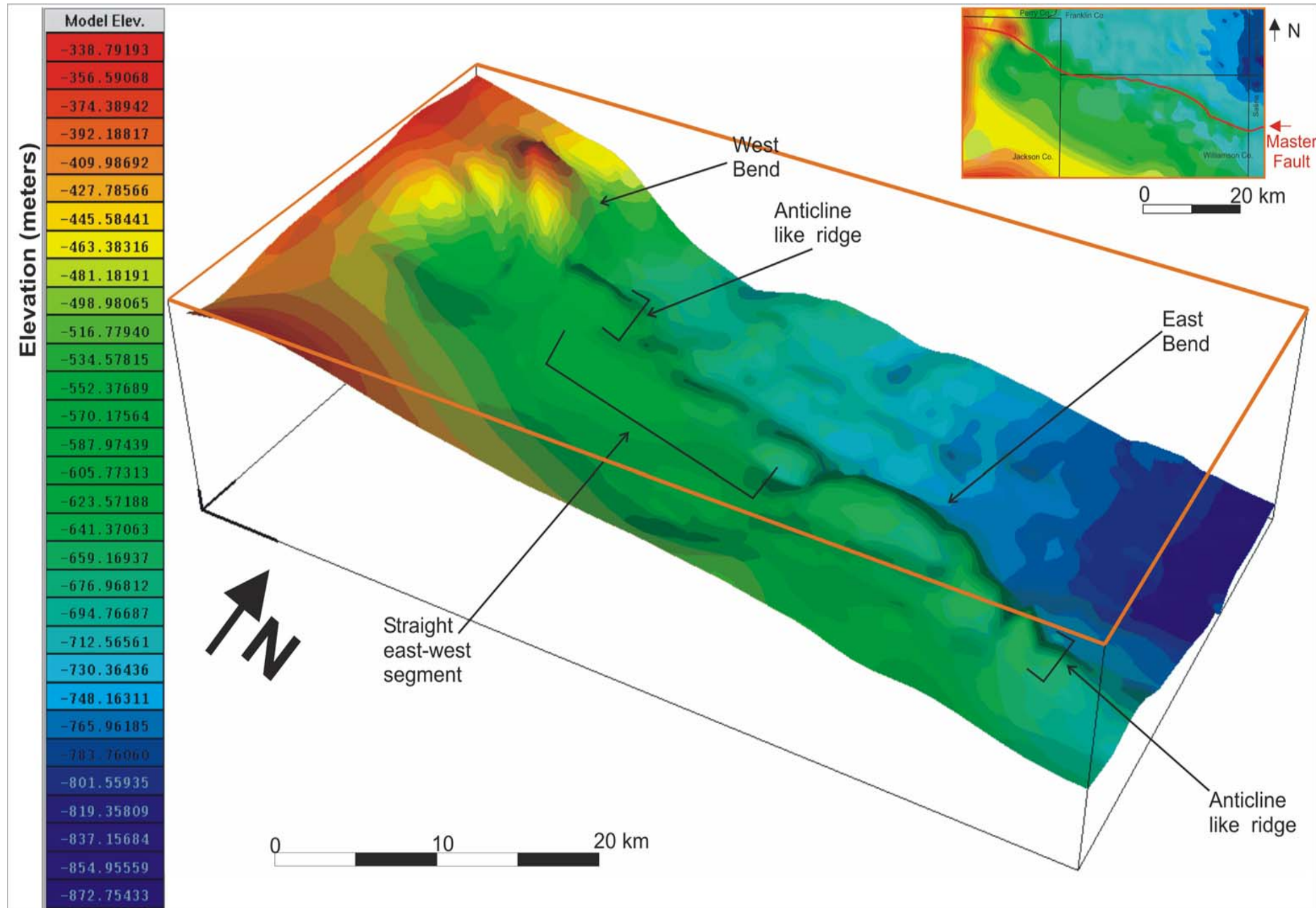


Duchek et al., 2003

Structure contour map of top of Ste. Genevieve Limestone (Mississippian) based on borehole data.

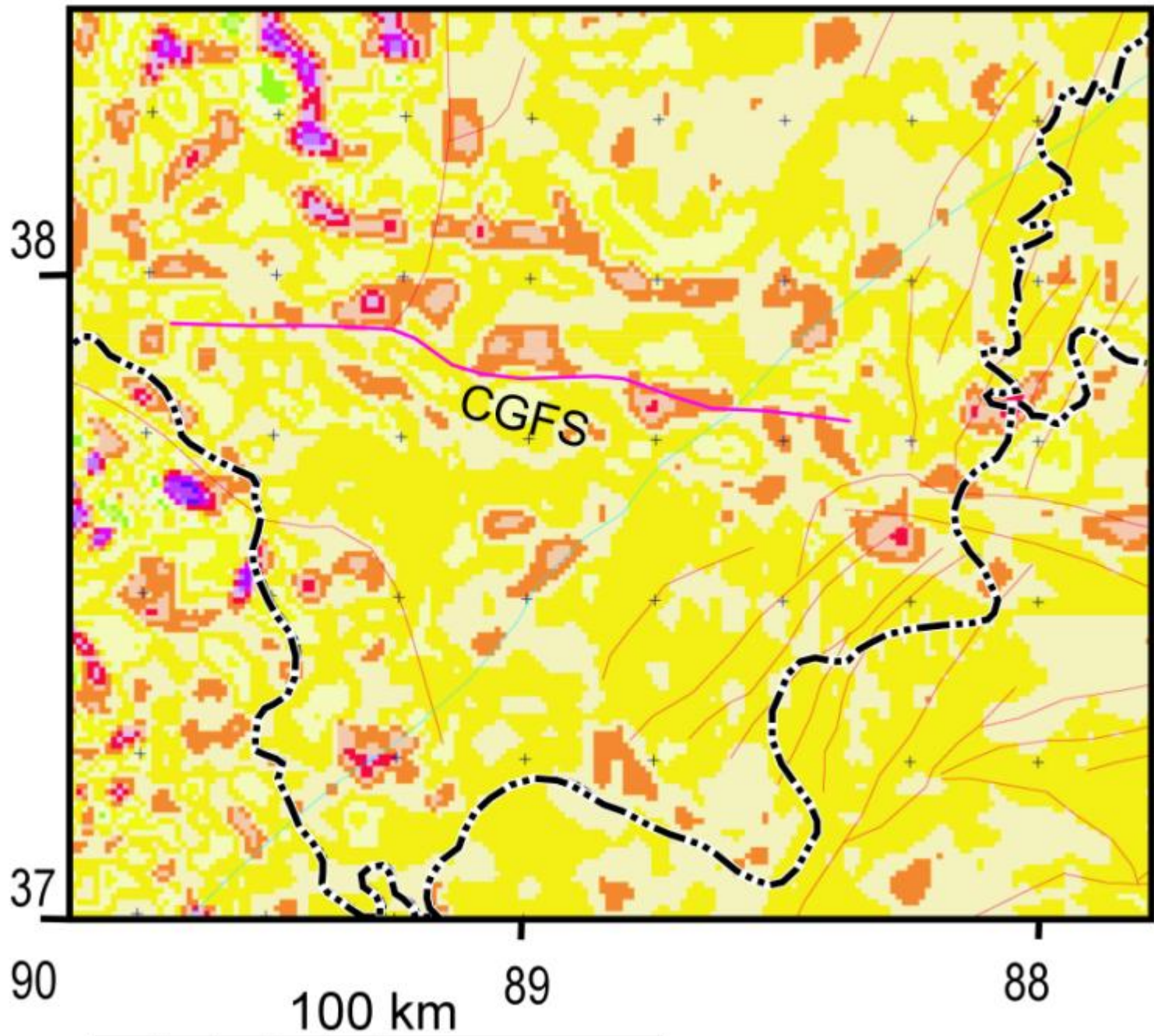


Three-dimensional contour of top of Ste. Genevieve Limestone



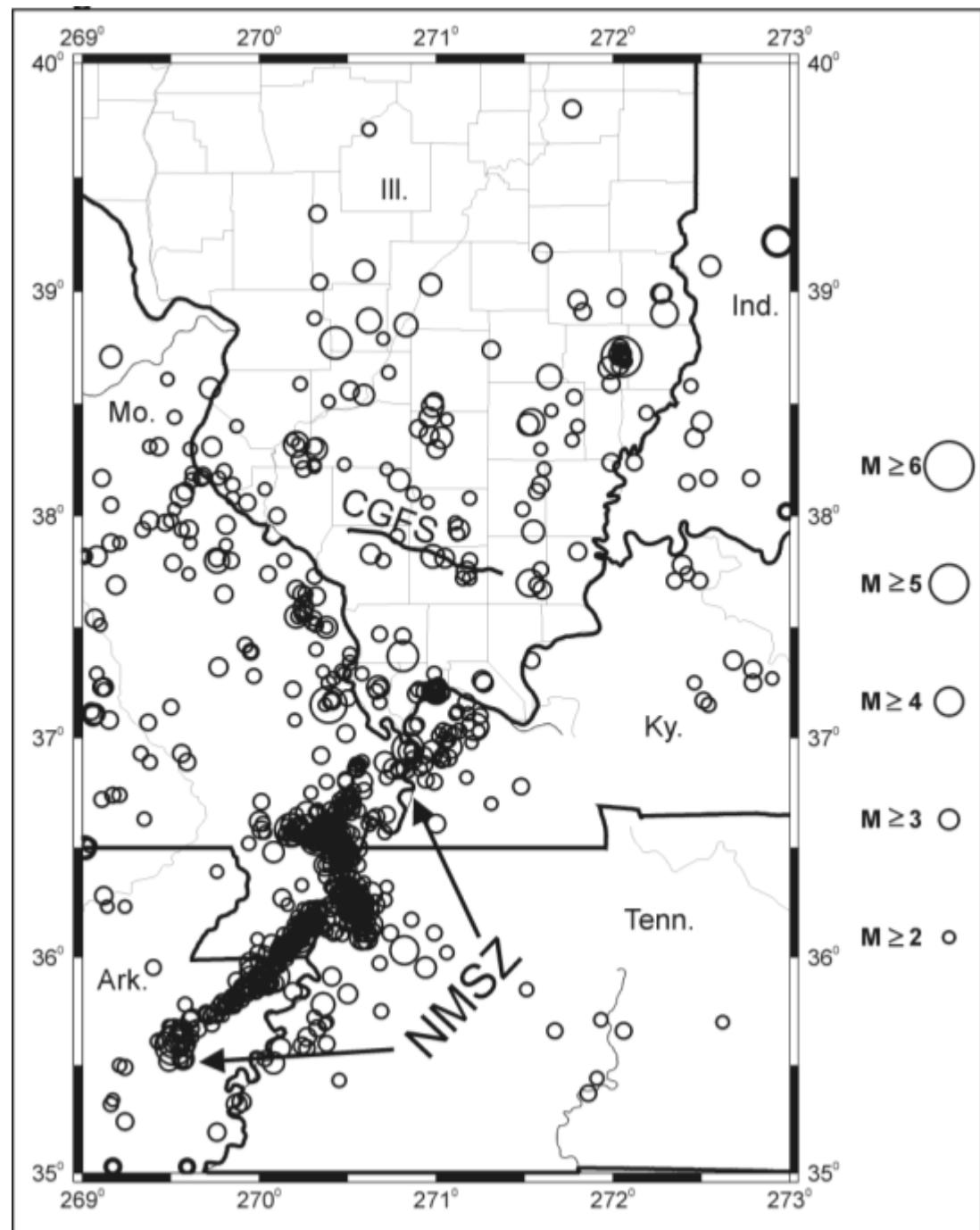
2nd Vertical derivative RTP Magnetic Intensity (Up. Cont. 1000 m)

Note the "stair-step" pattern of anomalies following curves and bends of CGFS



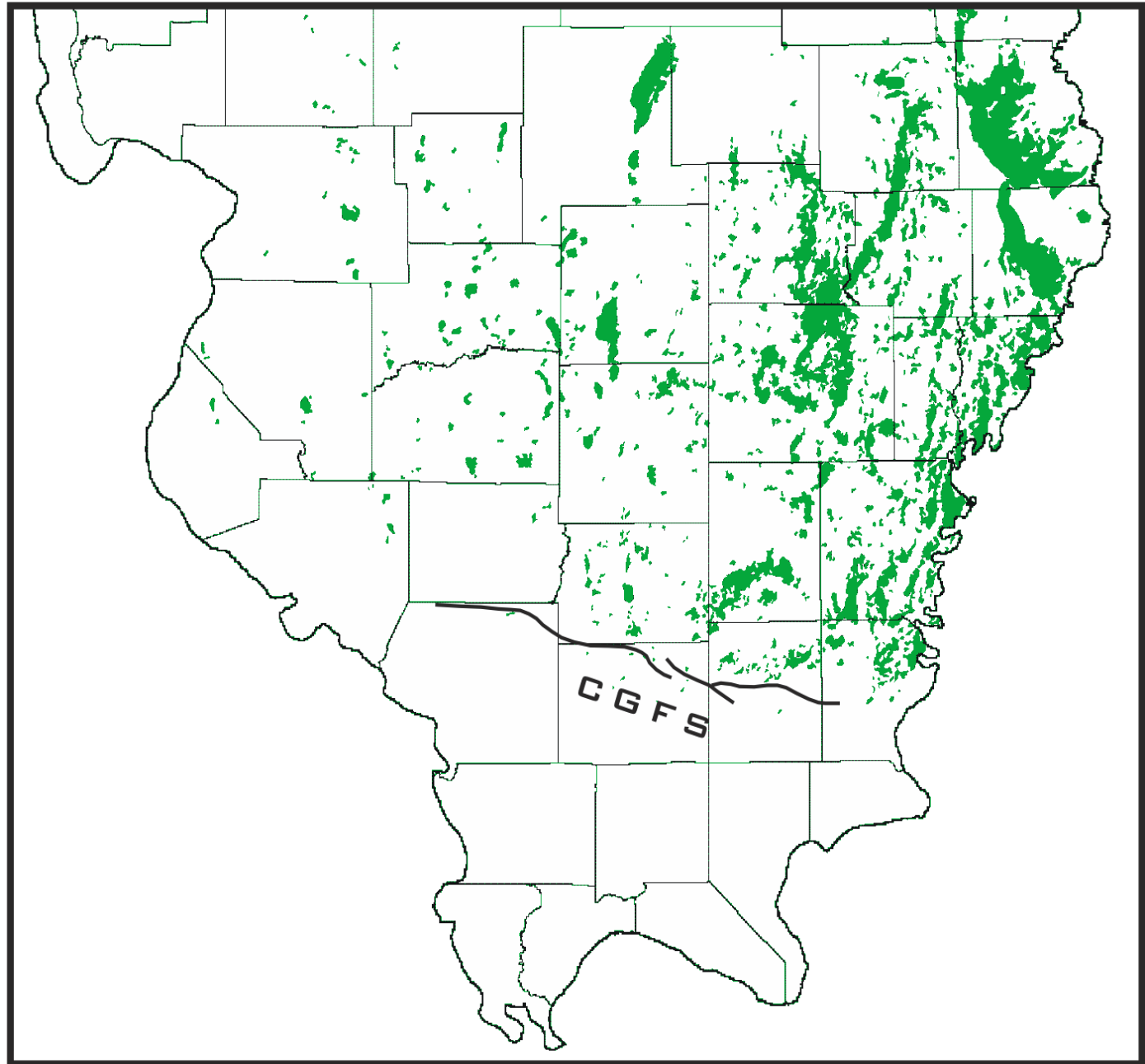
Map of regional seismicity: note the “quiet zone” between CGFS and northern tip of NMSZ:

does this imply a suture zone or some kind of fundamental crustal boundary as proposed by previous workers?

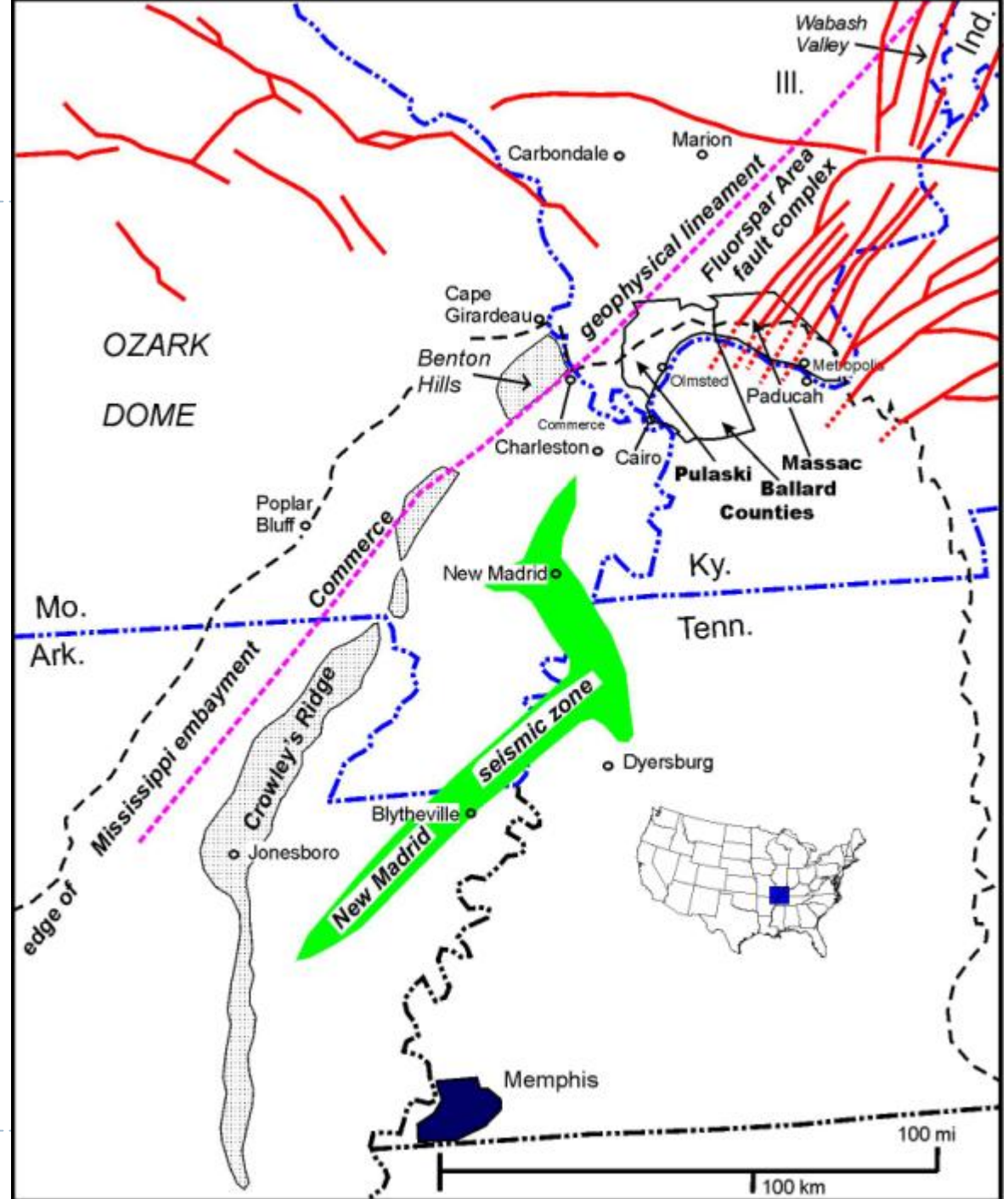


Petroleum production in the Illinois Basin (Illinois portion only)

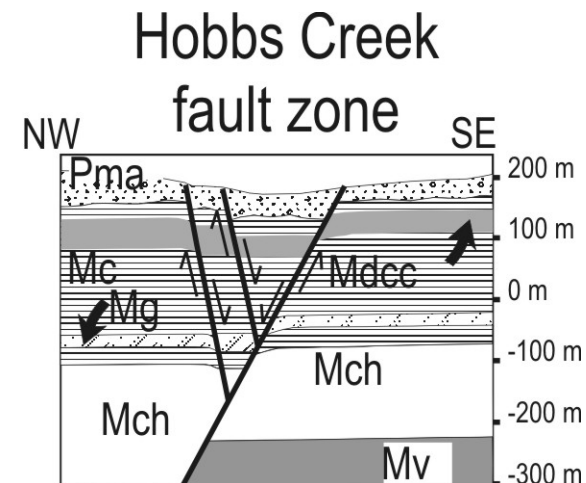
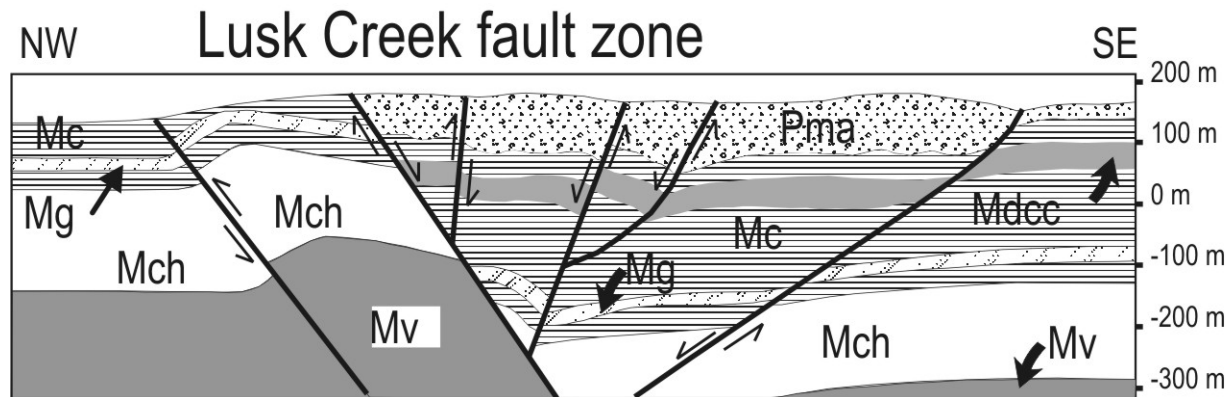
Does the abrupt change in production mimic some effect of structure or deformation that is also related to seismicity?



A key area is at the northern terminus of the NMSZ and the southern mapped limit of the Fluorspar Area fault complex, both with a NE trend.

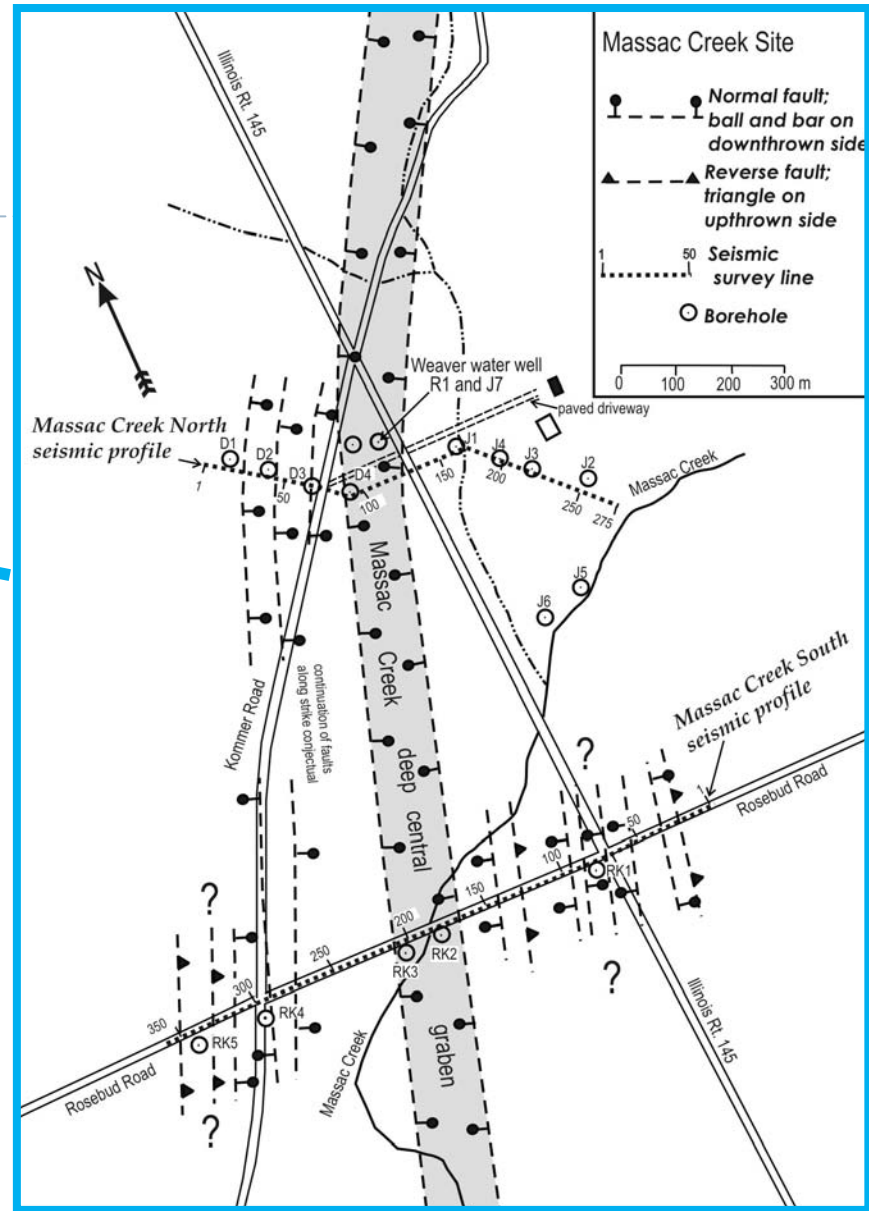
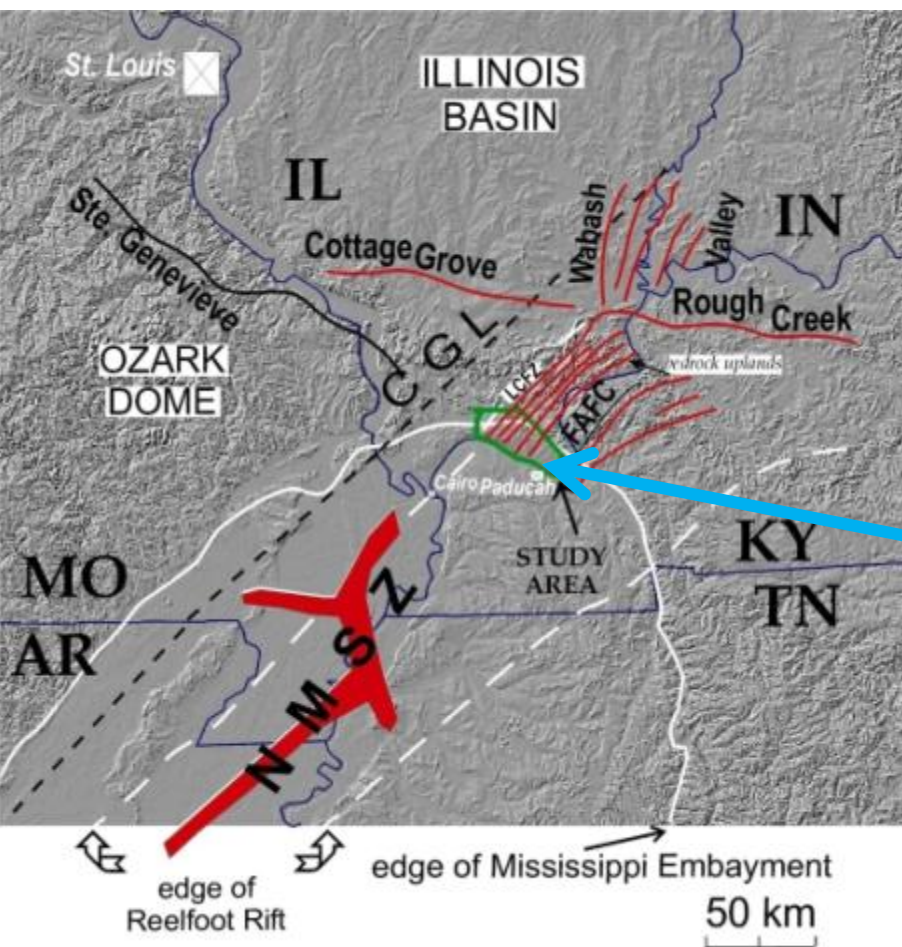


Structural cross sections in the uplands north of Mississippi Embayment (Pope County, Ill.) over portions of FAFC showing strong deformation in Mississippian-Pennsylvanian strata, but no evidence of Cenozoic deformation.



No vertical exaggeration.

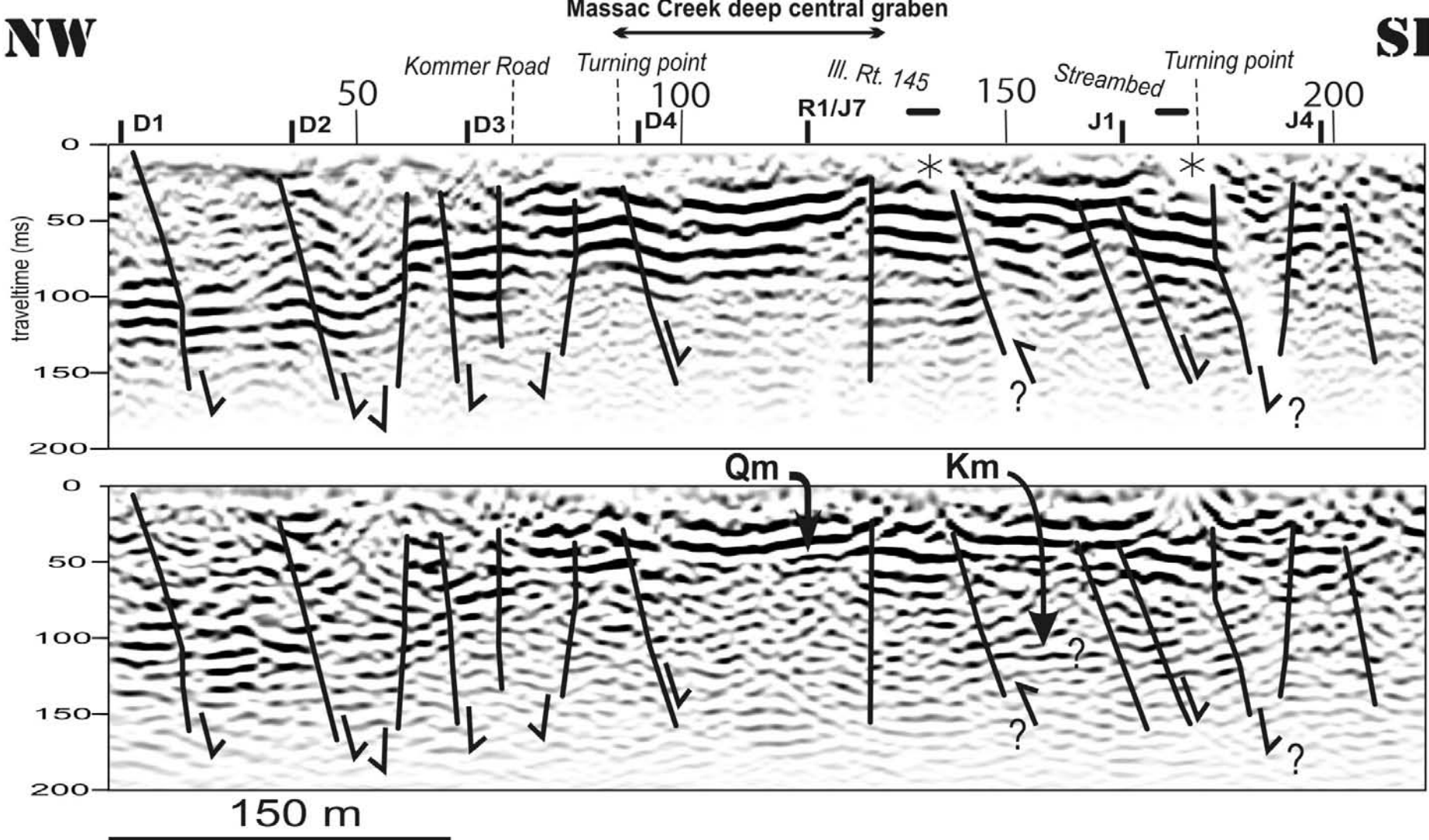




Map of the Massac Creek site showing seismic reflection profiles, drill holes, creeks along which banks were examined for geologic structures, and interpreted faults.

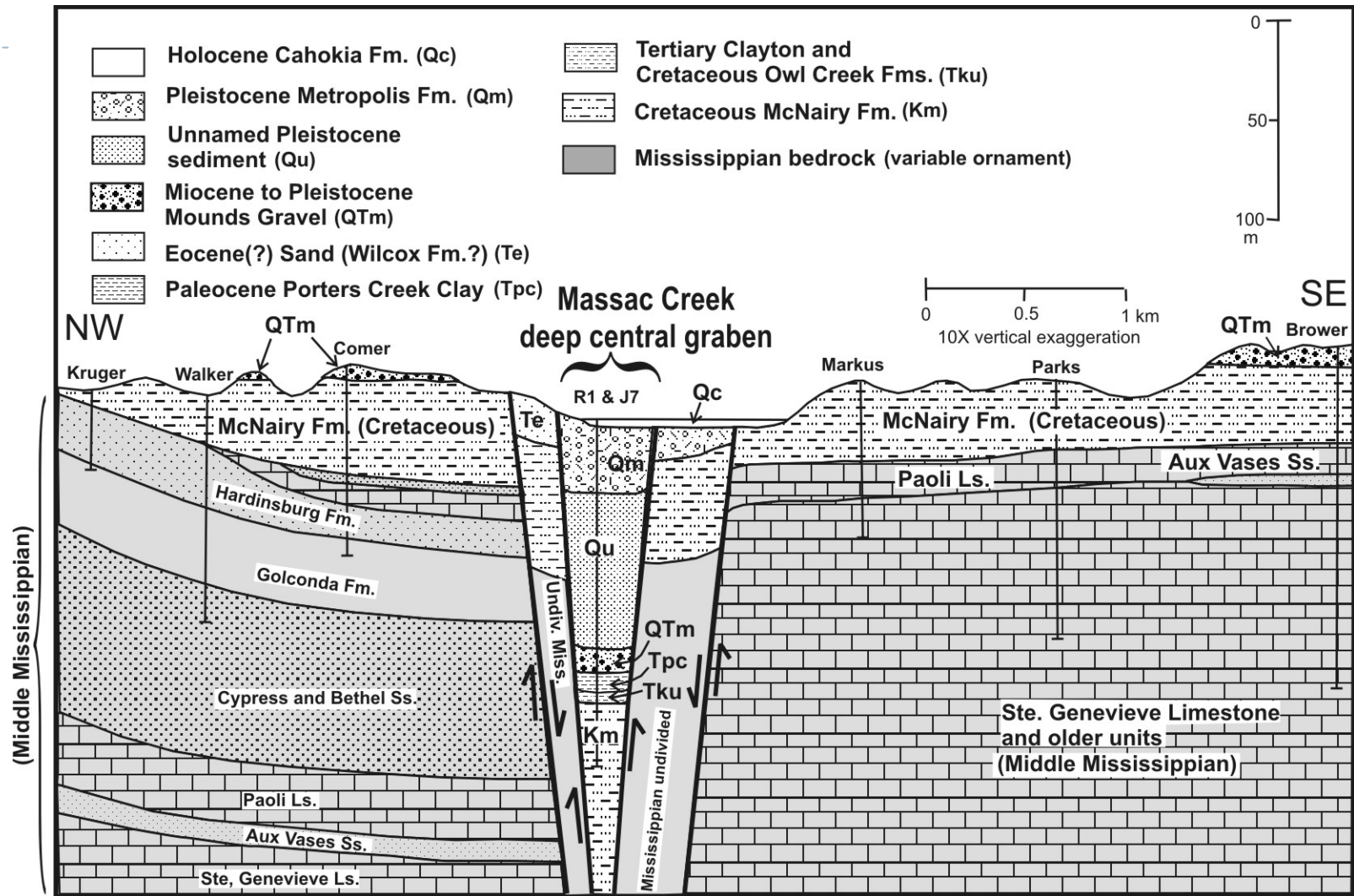
NW

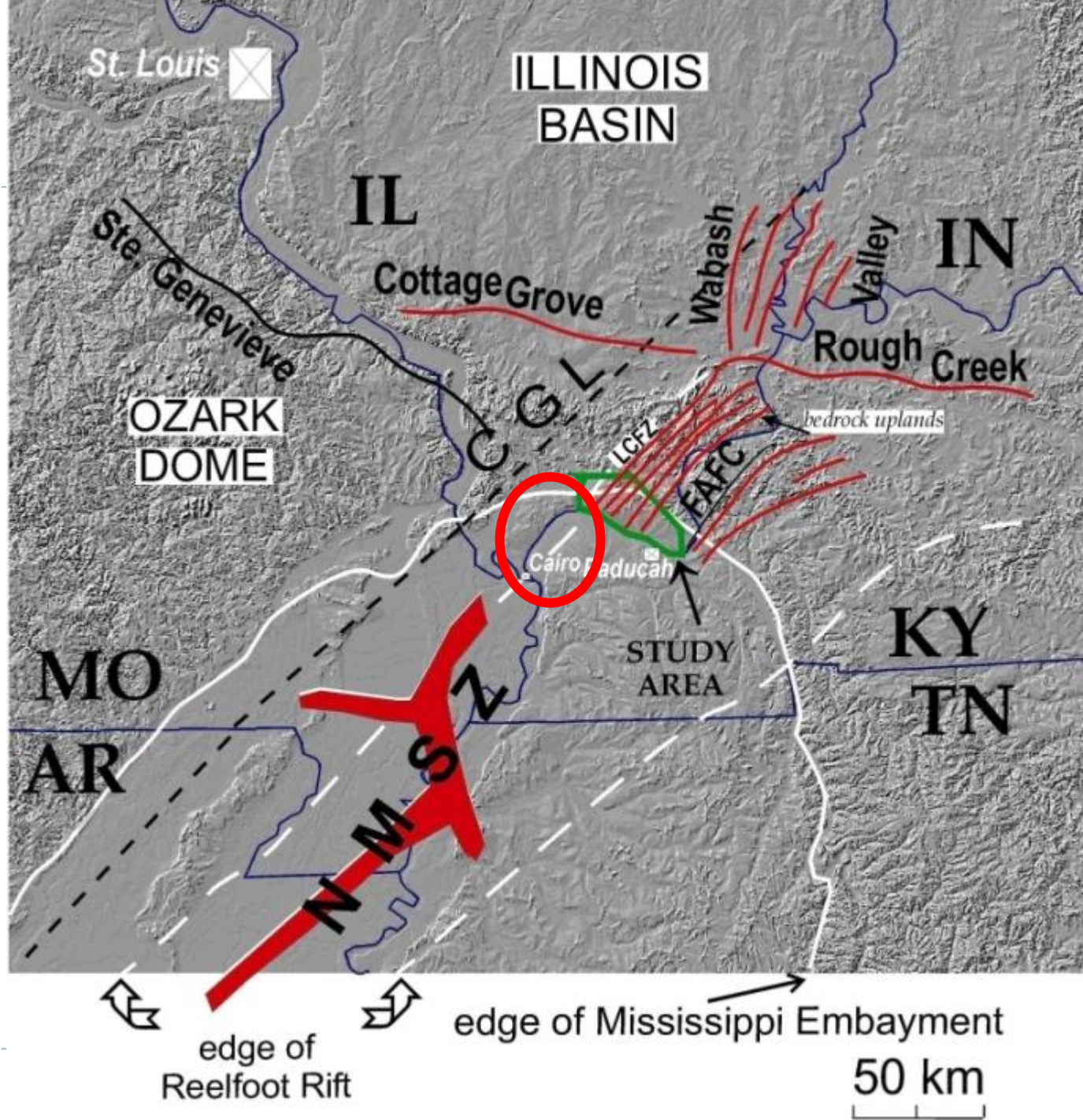
SE

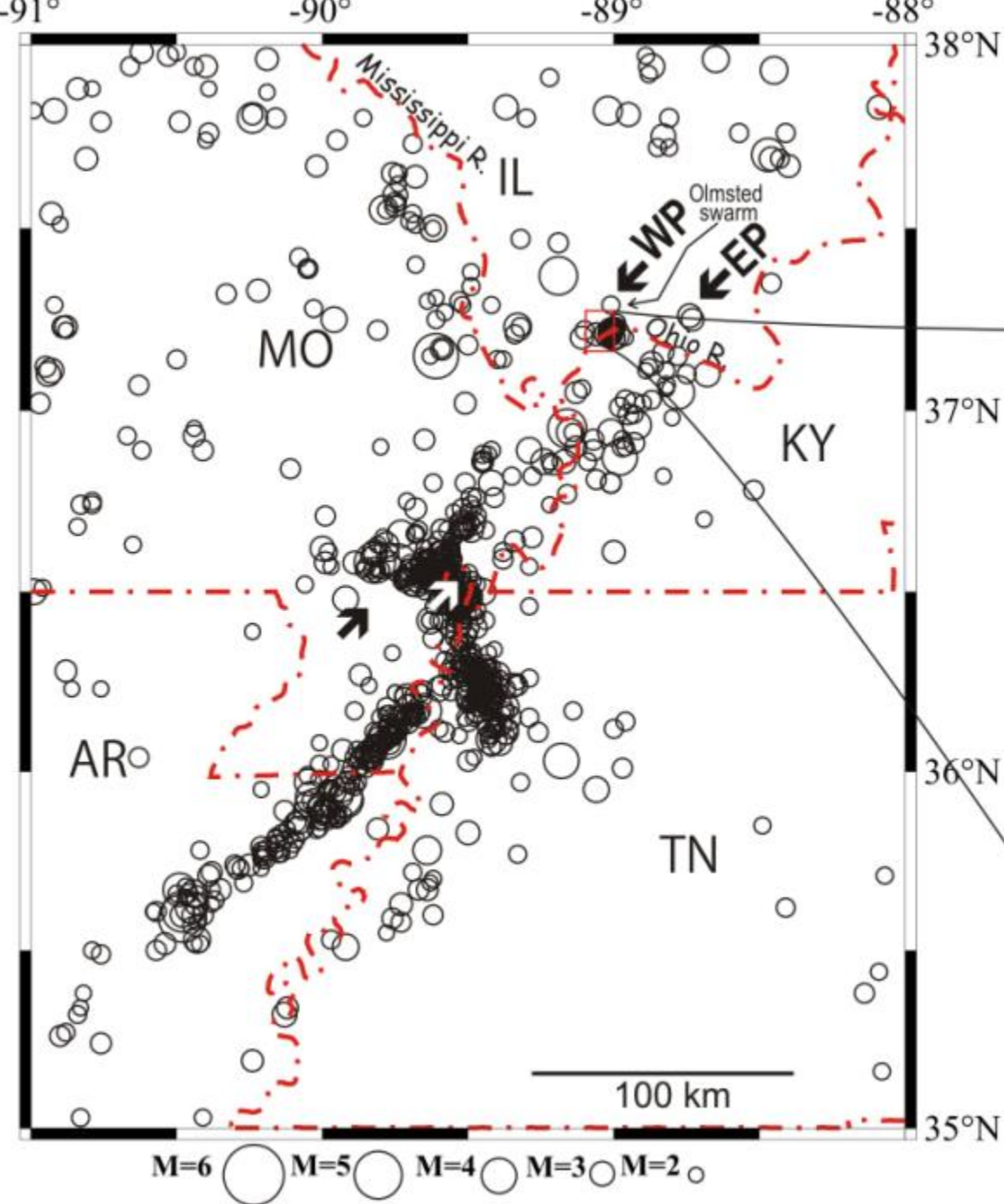


Portion of northern seismic reflection profile at the Massac Creek site (shown centered over Massac Creek deep central graben)

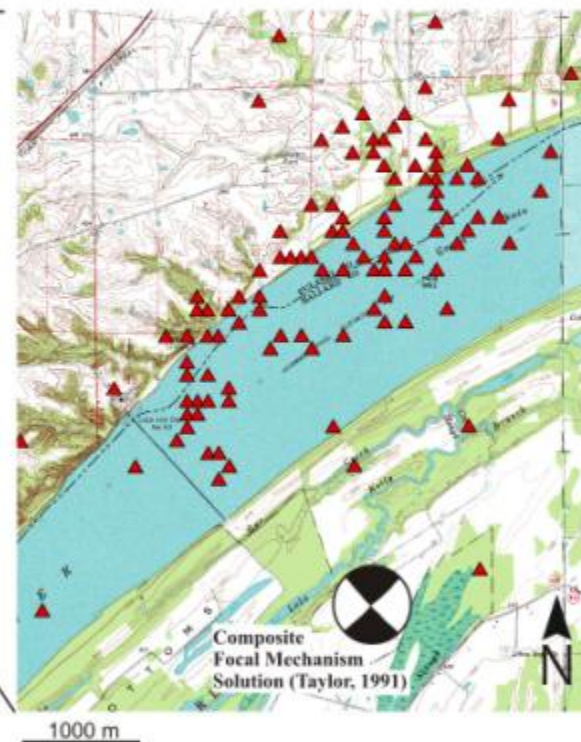
Generalized regional cross section of Massac Creek graben, mainly based on available well data and limited outcrops.







February 1984 Earthquake Swarm
Data from St. Louis University Earthquake Center



Conclusions

- ▶ Hypocenters near disrupted structure (e.g., fault offsets) on reflection profiles (e.g., 1974 event).
- ▶ Spatial correlation between blind-thrust mechanism events (e.g., 1968) and dipping reflector structure in the middle crust.
- ▶ Slope maps based on stratal markers suggest possible influence of Paleozoic deformation by Precambrian structures -- “pathways” for seismic reactivation.
- ▶ The area where the LSA and WVFS meet seems to have the highest expectation for fault reactivation.
- ▶ The Du Quoin monocline/Centralia fault zone may be an overlooked possible seismic source.
- ▶ Commerce geophysical lineament corresponds in places (from this study, most likely SE Illinois area) to disrupted structure that may be seismogenic.
- ▶ The Cottage Grove fault system corresponds to a major crustal boundary, south of which seismicity seems to abruptly cease before re-emerging as the NMSZ.
- ▶ It is difficult to associate the Fluorspar Area fault complex with a seismicity pattern, but evidence exists to suggest a relation to the NMSZ.



Acknowledgments

- ▶ The author gratefully acknowledges software grants from the Landmark (Halliburton) University Grant Program (GeoProbe™, SeisWorks3D™, and ProMAX2D™) and from Seismic Micro-Technology (The Kingdom Suite™).

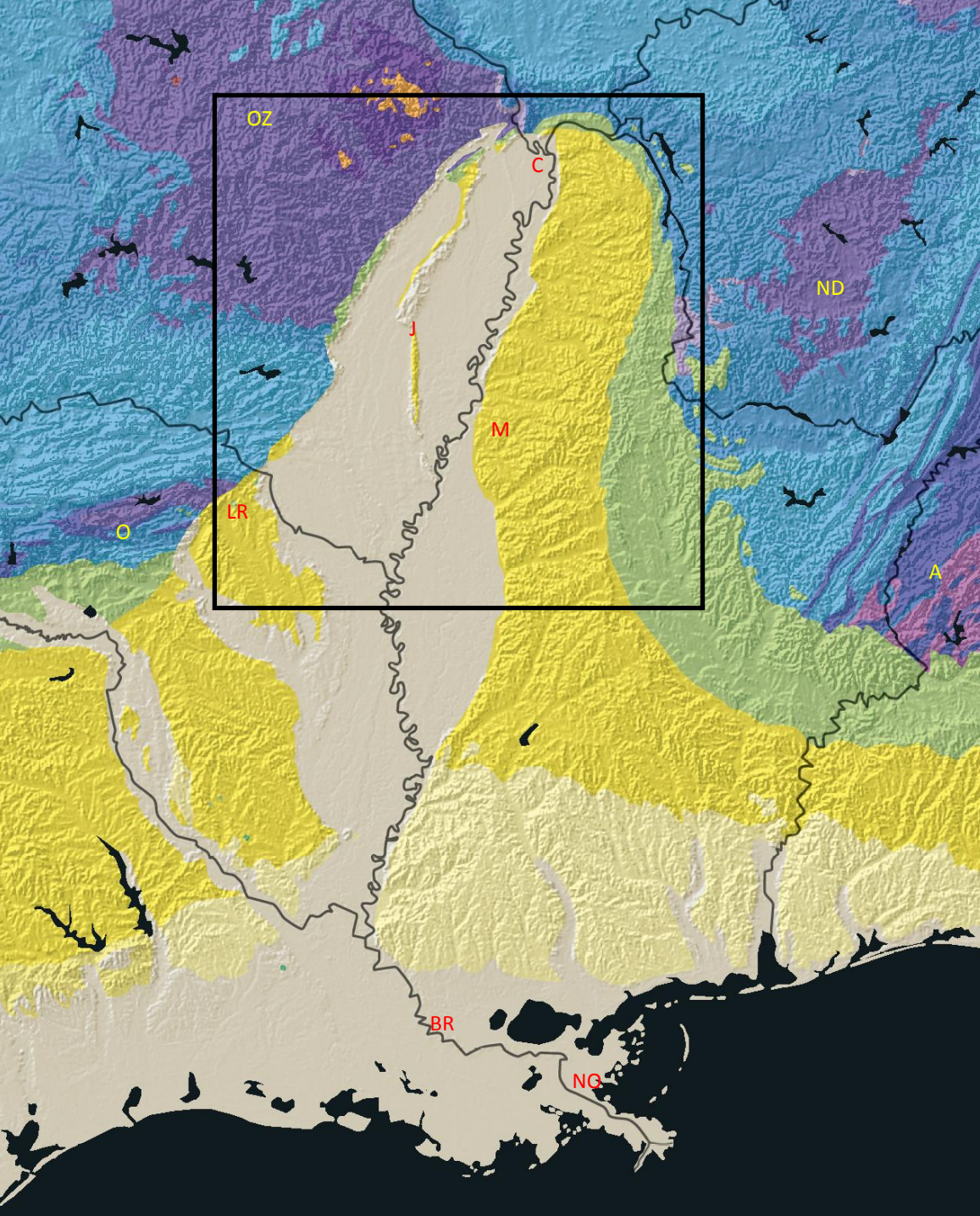


-
- ▶ The author has made every effort to ensure high-quality results and interpretations as represented in this report. The author makes no warranty, expressed or implied, regarding the suitability of any findings arising from the report for a particular purpose. Brigham Young University and/or the author shall not be liable under any circumstances for any direct, indirect, incidental, or consequential damages with respect to claims by users of any findings arising from or contained in this report

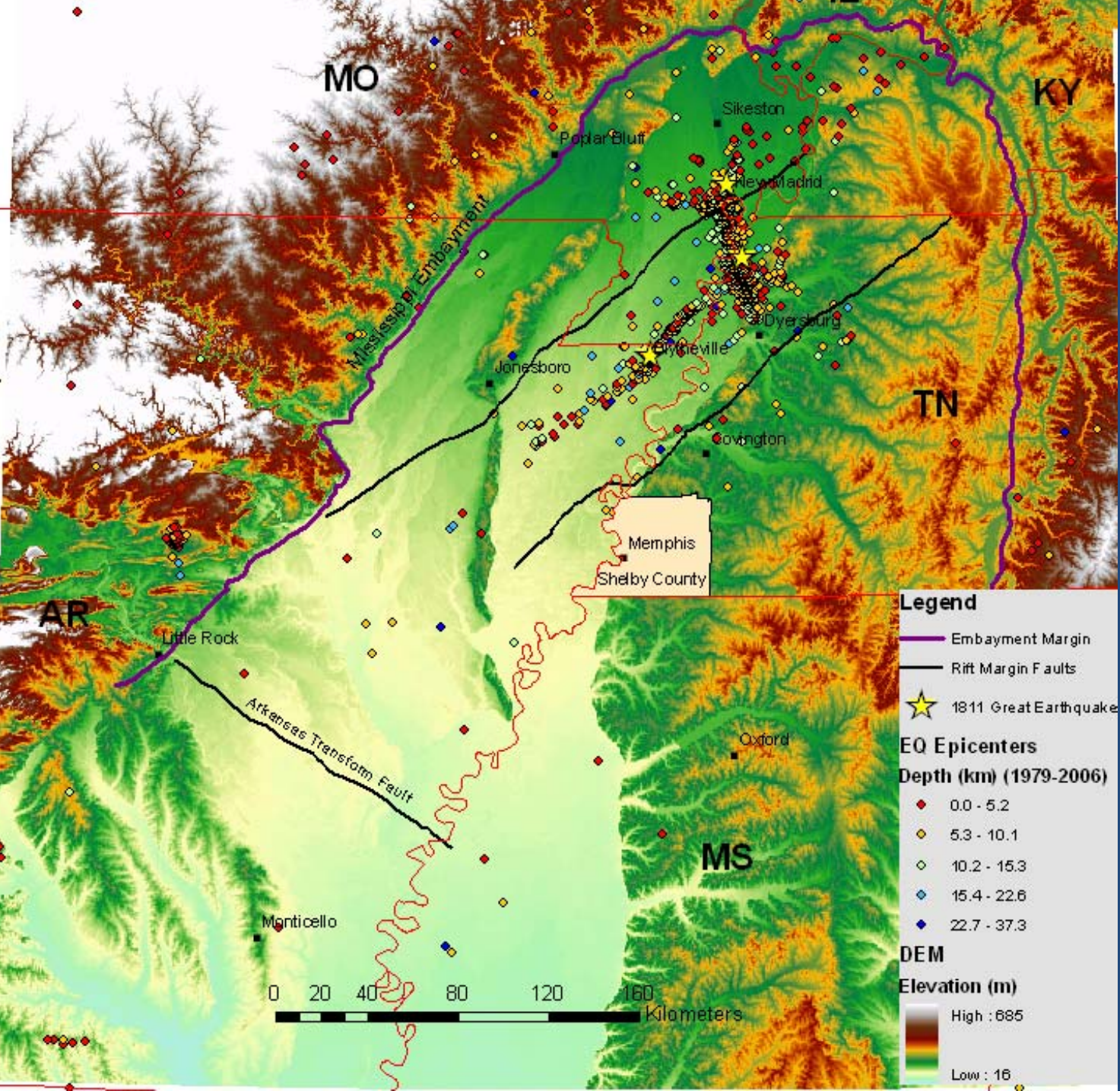


Quaternary Deformation within the Reelfoot Rift, Rome Trough,
and Wabash Valley Fault System

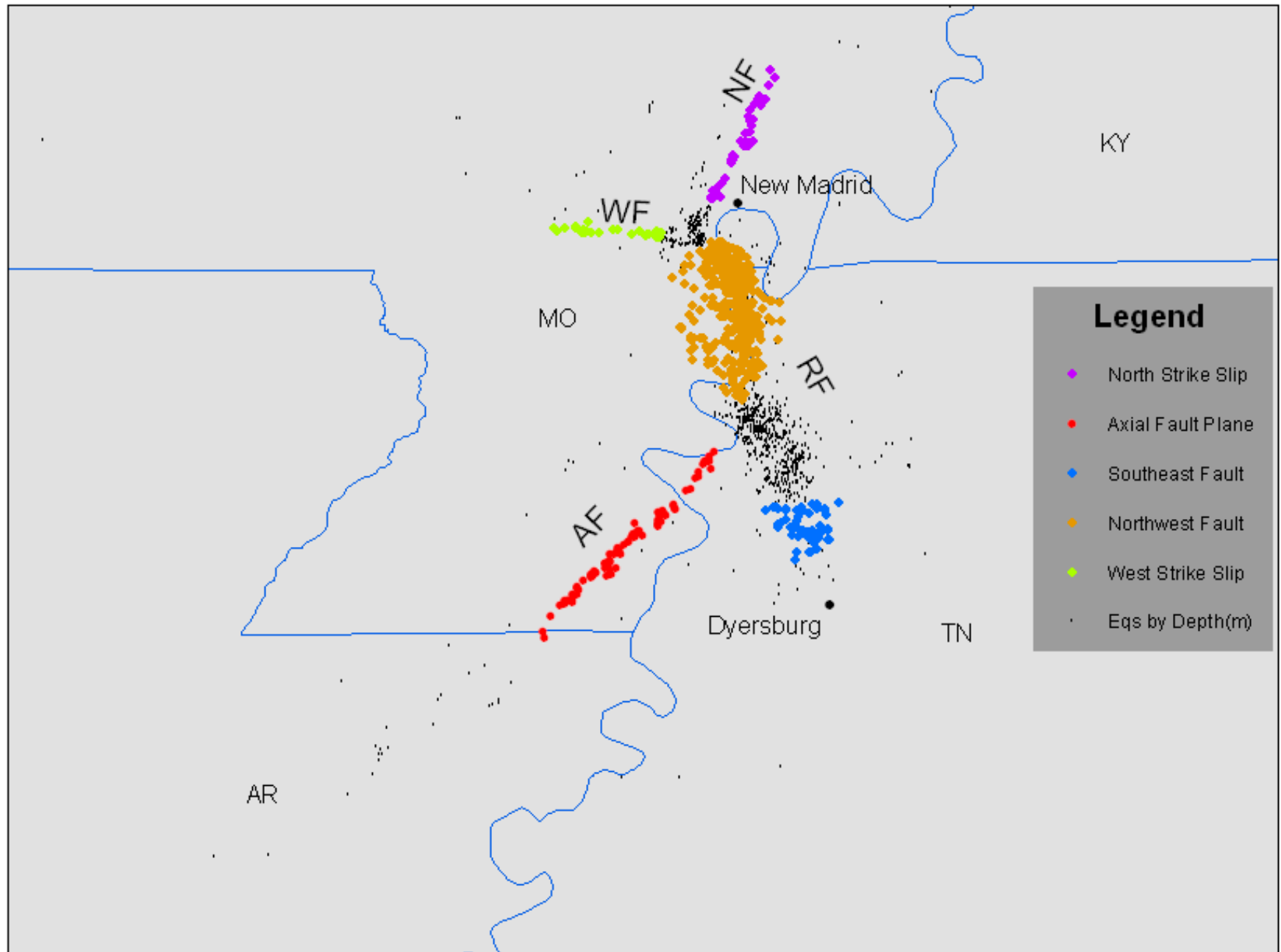
Roy Van Arsdale
Department of Earth Sciences
The University of Memphis



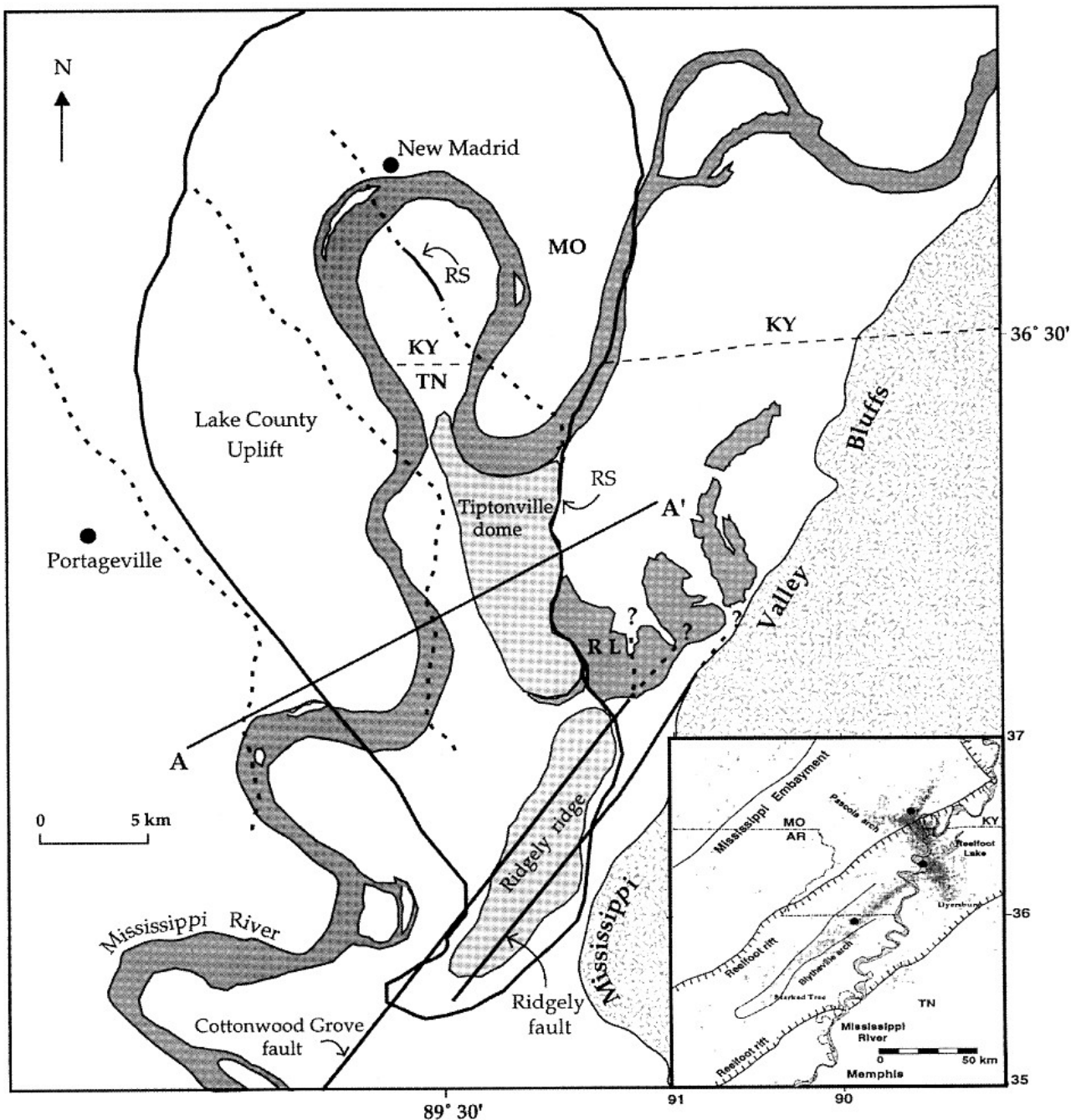
The Mississippi embayment.
M = Memphis, LR = Little Rock,
J= Jonesboro, C = Cairo



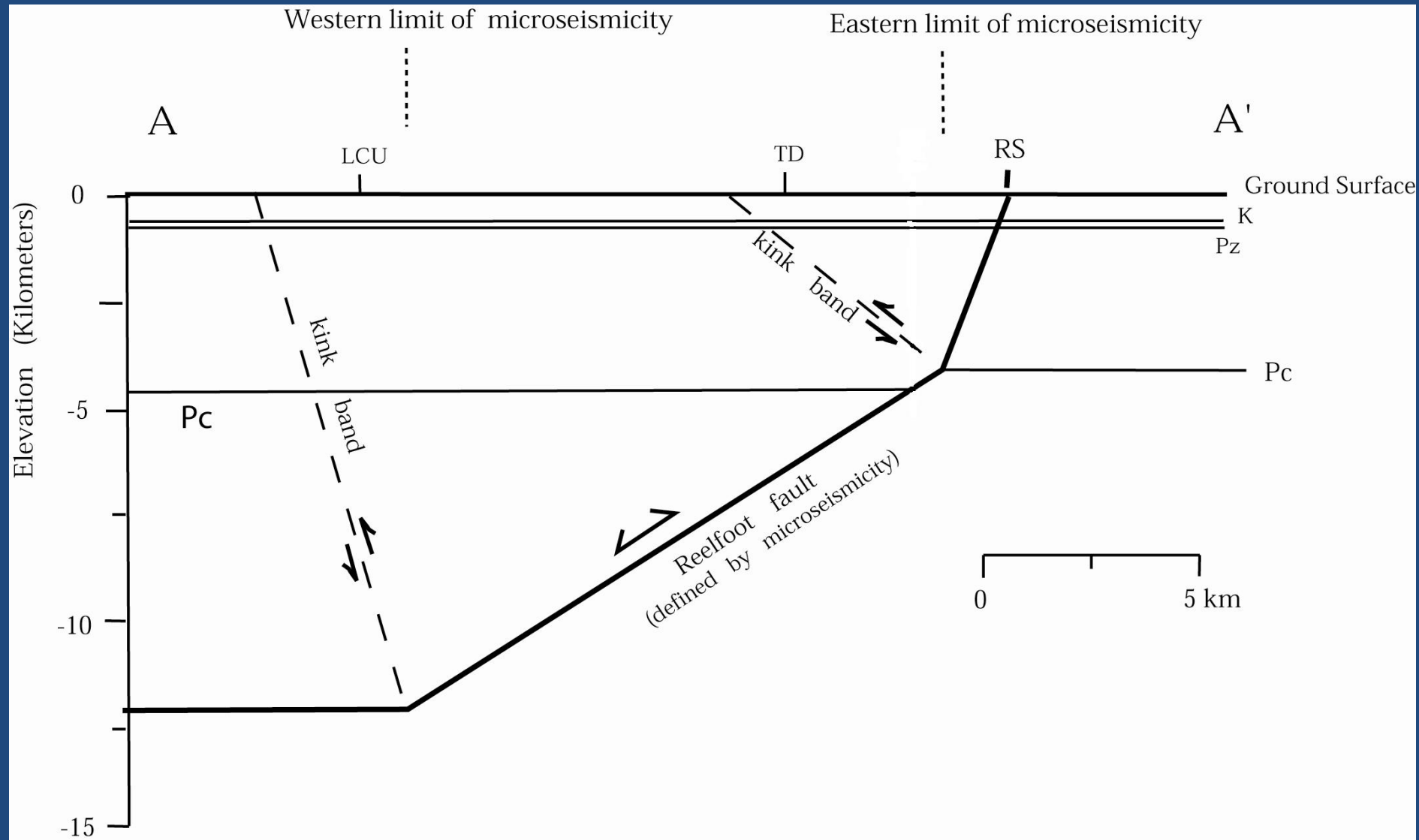
New Madrid seismic zone in northern Mississippi embayment . Stars are large earthquakes of 1811-1812 (from Csontos and Van Arsdale, 2008).



Discrete faults within the New Madrid seismic zone (from Csonotos and Van Arsdale, 2008).



The Lake County uplift and vicinity. The solid line marks the boundary of the Lake County uplift as defined by Russ (1982), and the dotted lines are kink bands (back thrusts) on the west side of the Tiptonville dome and Lake County uplift. Line A-A' is the line of cross section in following figure . The inset represents the microseismicity epicenters (pluses) within the New Madrid seismic zone. RS = Reelfoot scarp; RL = Reelfoot Lake (from Purser and Van Arsdale, 1998).

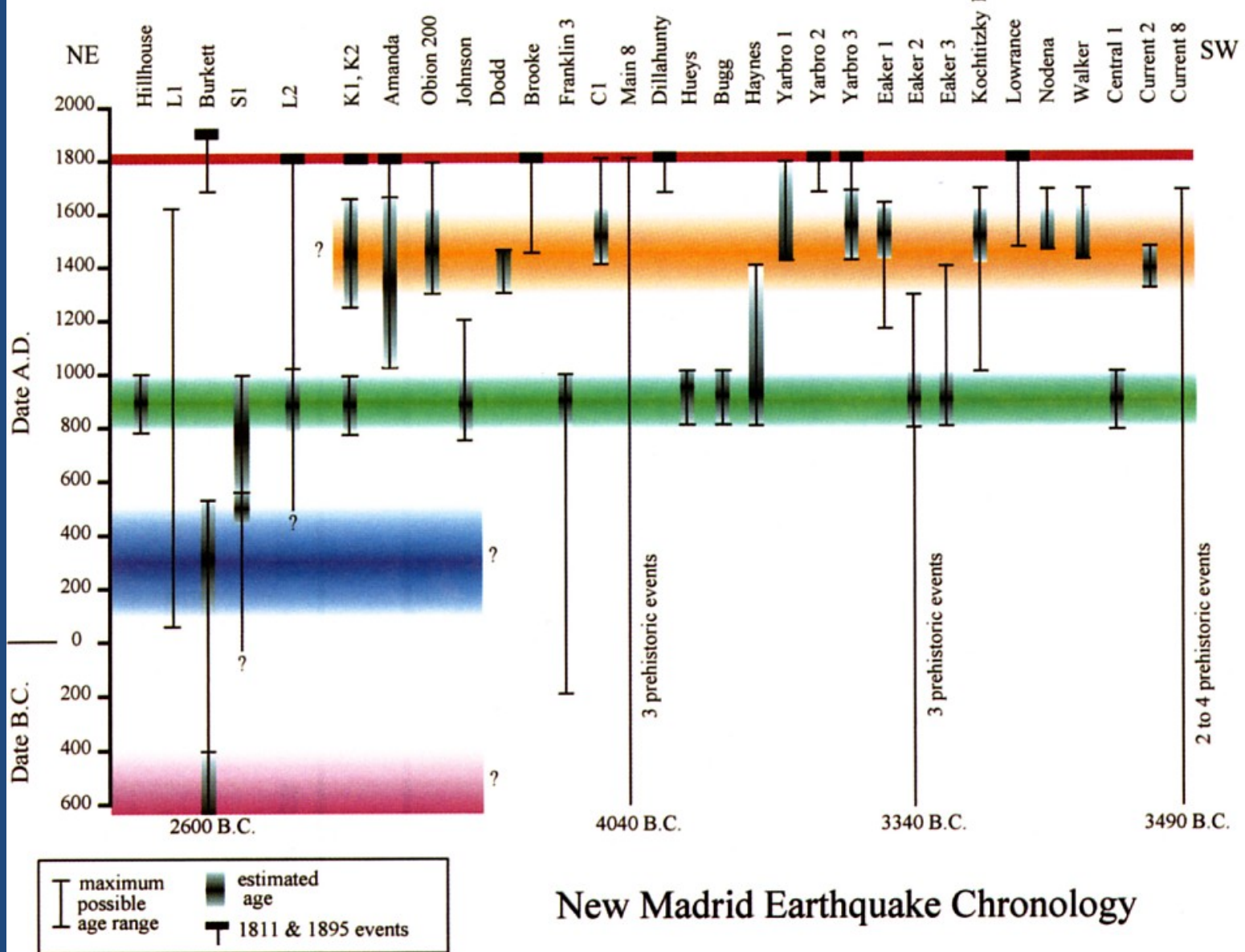


Cross section of the Reelfoot fault with its kink bands (back thrusts). K = top of Cretaceous; Pz = top of Paleozoic, Pc = top of Precambrian, LCU = Lake County uplift western margin, TD = Tiptonville dome western margin, RS = Reelfoot scarp (modified from Van Arsdale, 2000). No vertical exaggeration.



Reelfoot fault scarp looking west at the upthrown side and Reelfoot scarp trench excavation to determine faulting history (Kelson et al., 1996).

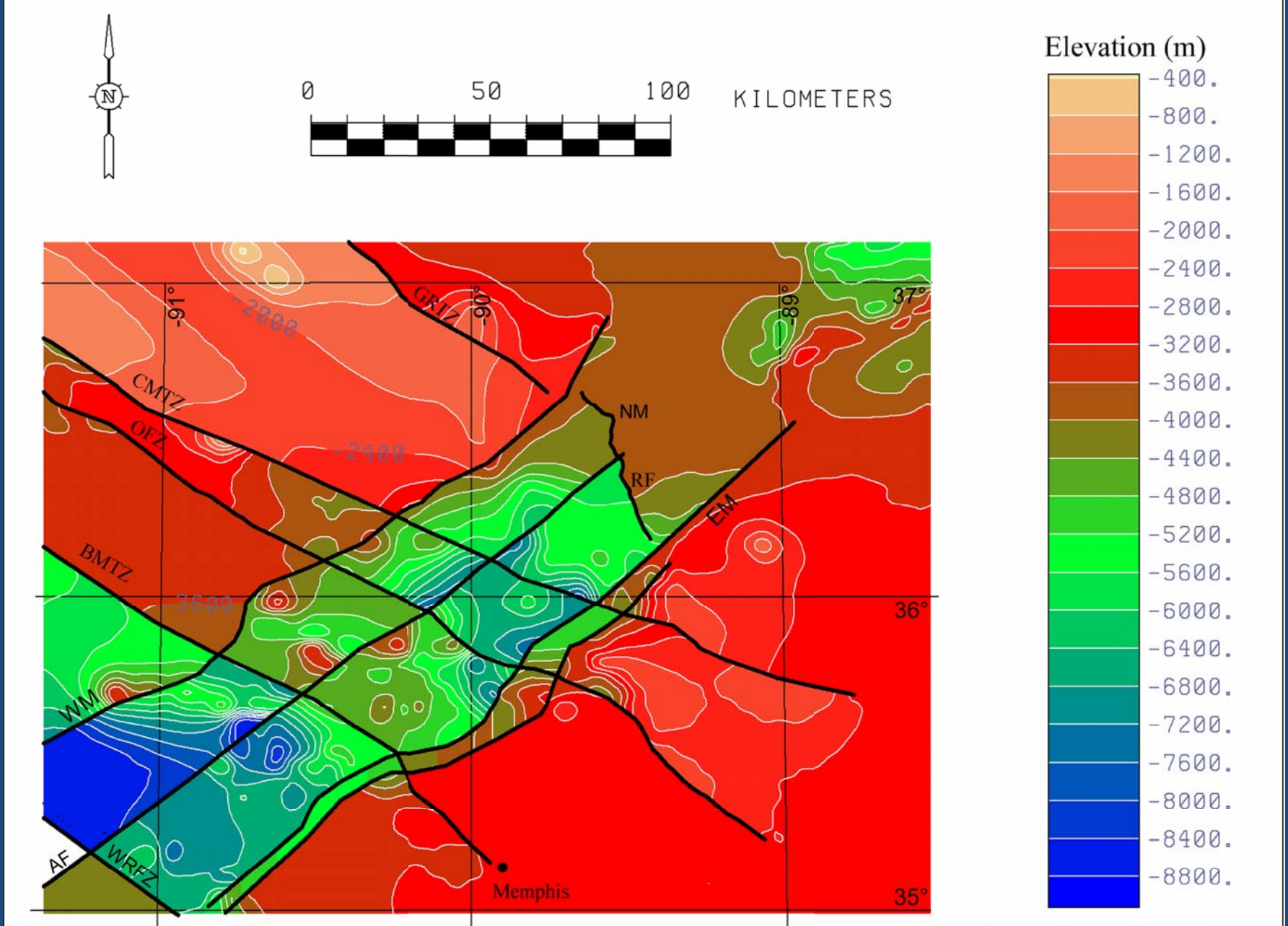




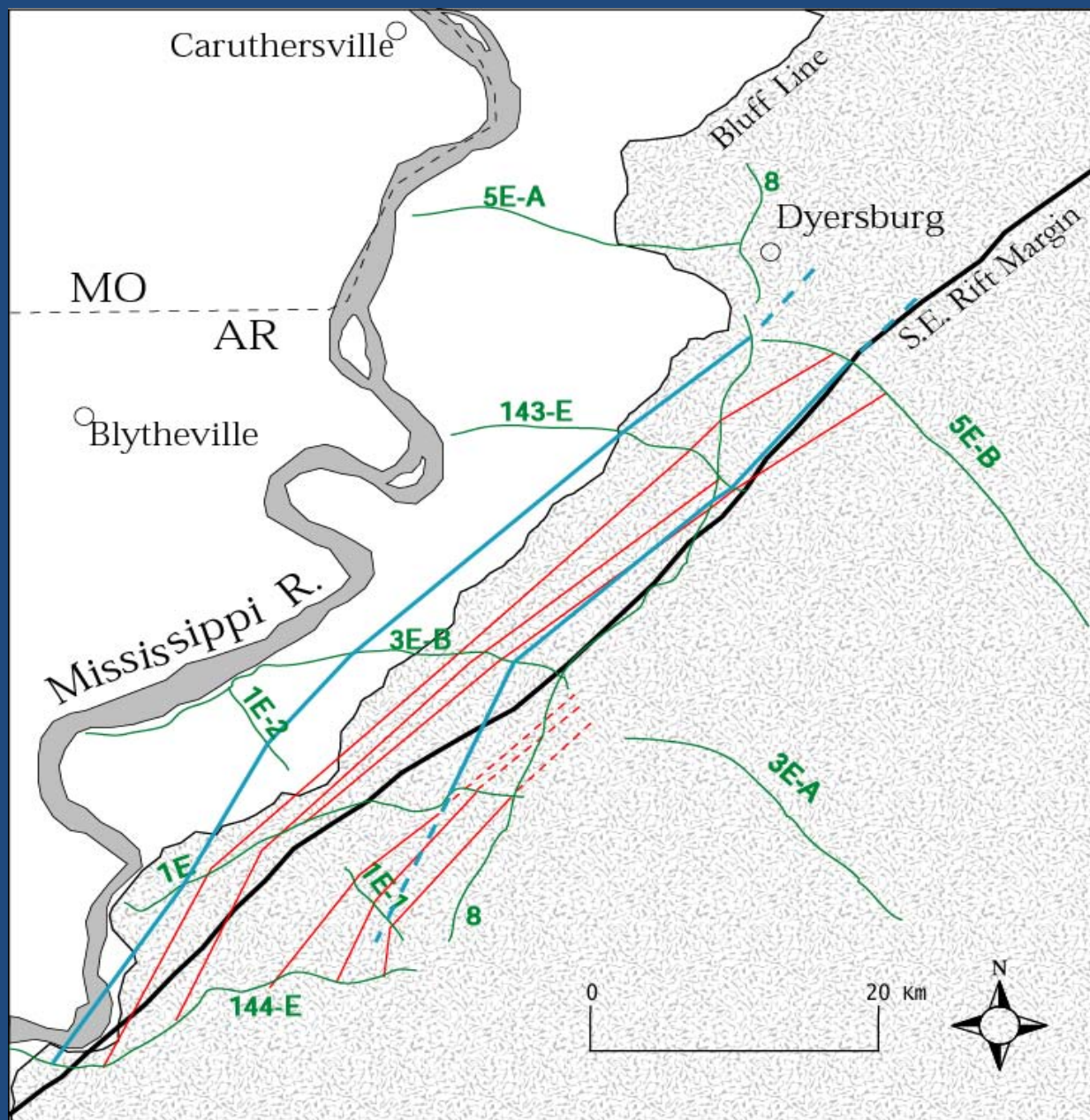
Earthquake chronology for NMSZ from dating and correlation of liquefaction features at sites (listed at top) along NE-SW transect across region (from Tuttle et al., 2002).

Table 1
Displacement history and slip rate on the Reelfoot fault of the New Madrid seismic zone

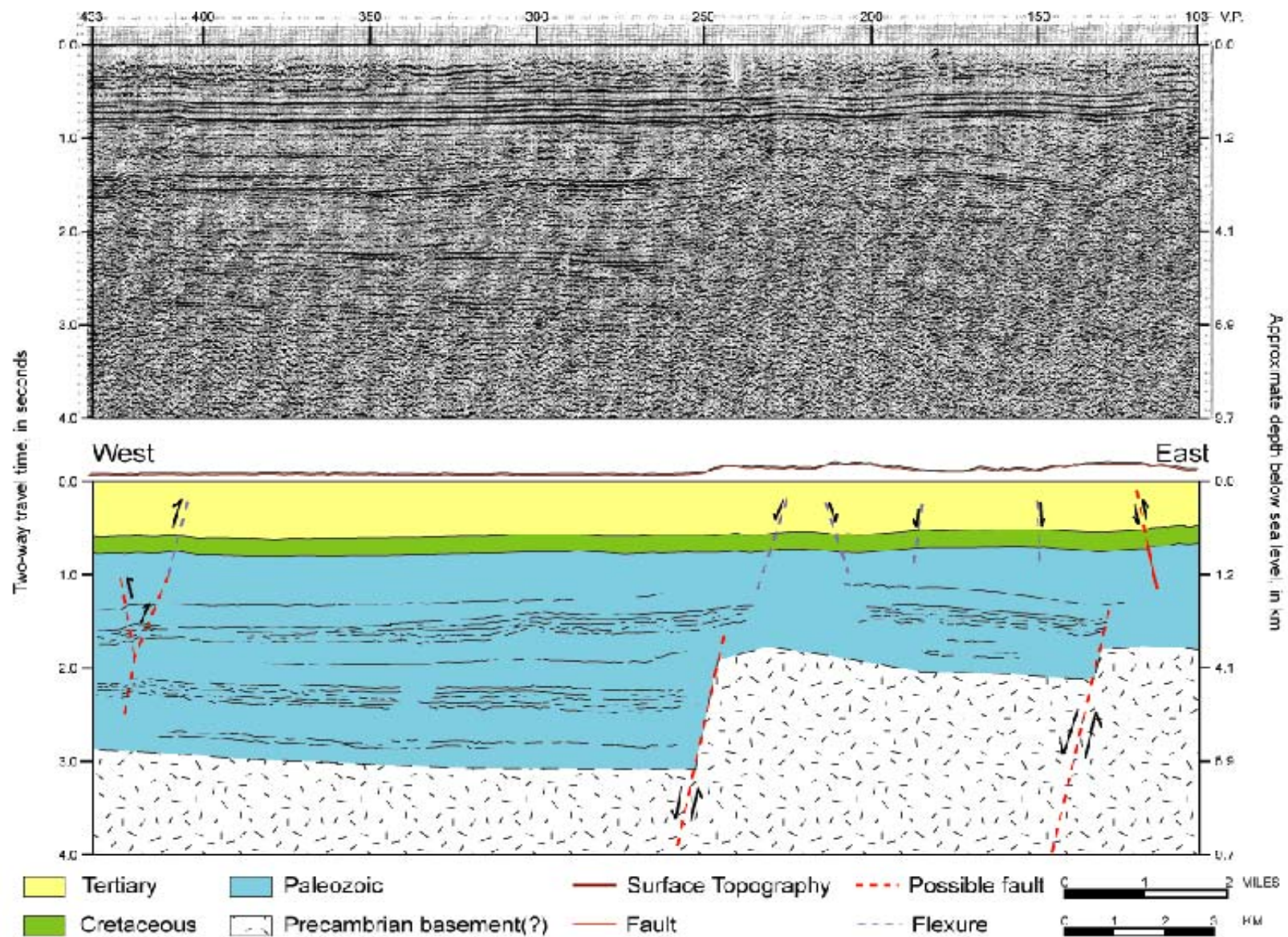
Geologic time	Radiometric time	Slip magnitude (m)	Slip rate (mm year ⁻¹)
Late Cretaceous–present	80 my	73	0.0009
Late Cretaceous	80–65 my	10	0.0007
Paleocene	65–54 my	21	0.002
Late Paleocene–Eocene	54–45 my	11	0.001
Late Eocene–Holocene	45 my–9 ka	15	0.0003
Holocene	9000–present	16	1.8
Late Holocene	AD 900–1812	5.4	6.2



Top of Precambrian crystalline basement rock in Reelfoot rift. Black lines are faults (from Csontos et al., 2008).



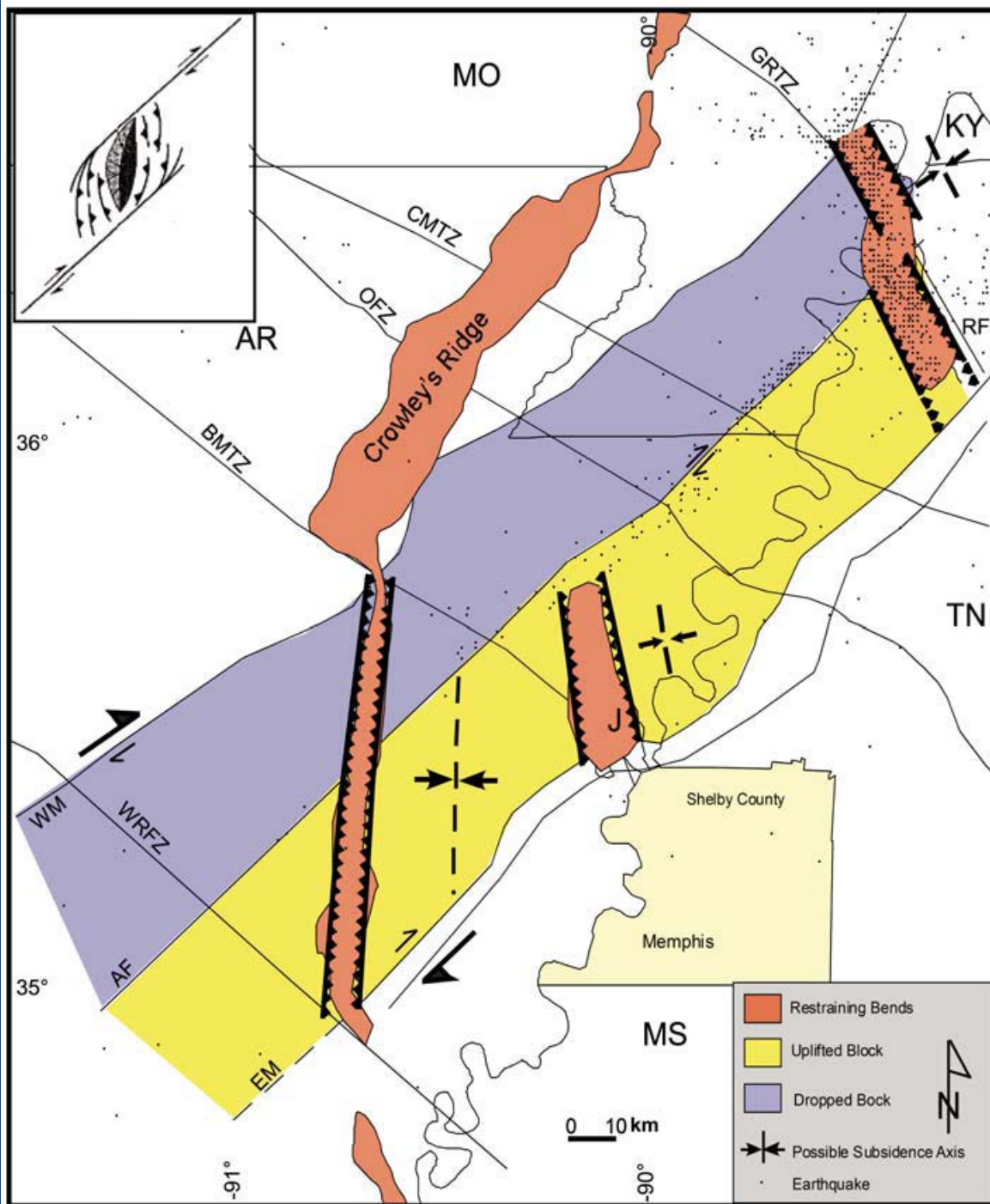
Faulting along eastern margin of the Reelfoot rift. Blue = basement faults, red = shallow faults, green = seismic reflection lines (from Parrish and Van Arsdale, 2004).



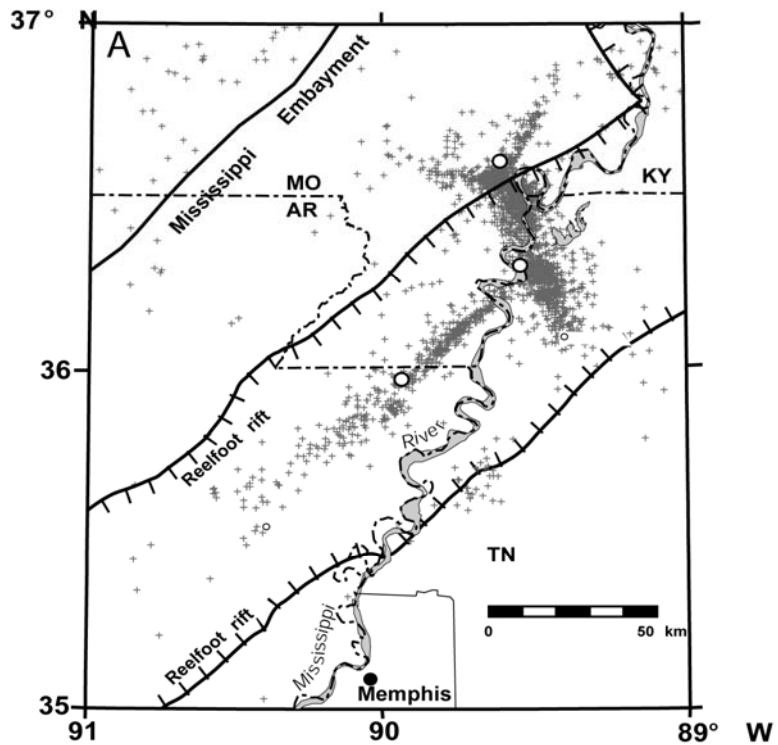
Dow seismic reflection line 143E (from Parrish and Van Arsdale, 2004).



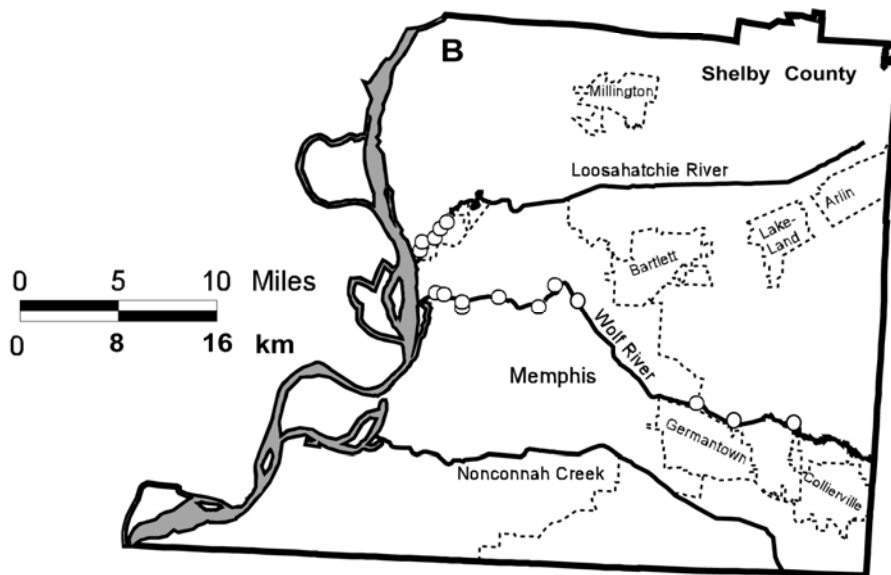
10 m of post 20,000 yr right lateral strike slip faulting at Porter's Gap (from Cox et al., 2006).



Right-lateral shear across the Reelfoot rift is responsible for the New Madrid seismic zone earthquakes (dots) at the northern end of the rift. Quaternary right lateral shear across the rift is also causing the southeast half of the rift to rise, the northwest side to drop, and uplift of the Lake County uplift and its southern continuation (adjacent to RF), Joiner Ridge (J), and the southern half of Crowley's Ridge, NM = New Madrid, RF = Reelfoot fault, WRFZ = White River fault zone, BMTZ = Bolivar Mansfield tectonic zone, OFZ = Osceola fault zone, CMTZ = Central Missouri tectonic zone, EM = Eastern Rift margin faults, WM = Western Rift margin fault, AF = Axial fault (from Csontos et al., 2008).



New Madrid seismic zone, Shelby County, and earthquake liquefaction deposits along the Loosahatchie and Wolf Rivers (from Broughton et al., 2001).



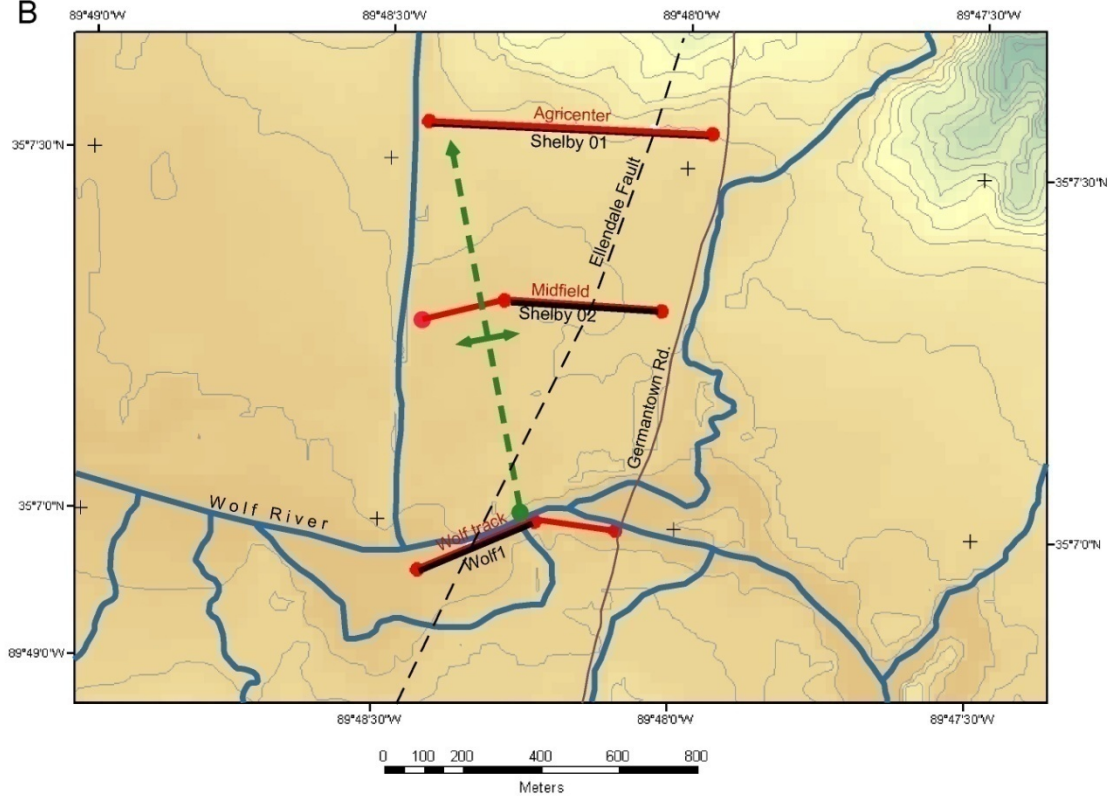


Sand dike in bank of Wolf River in Memphis formed during earthquake liquefaction (from Broughton et al., 2001).

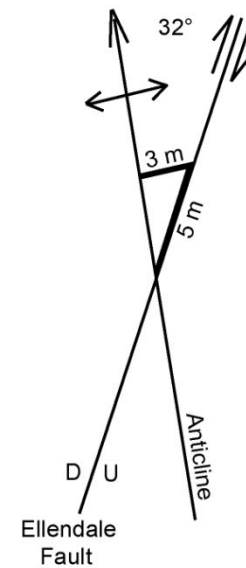
A



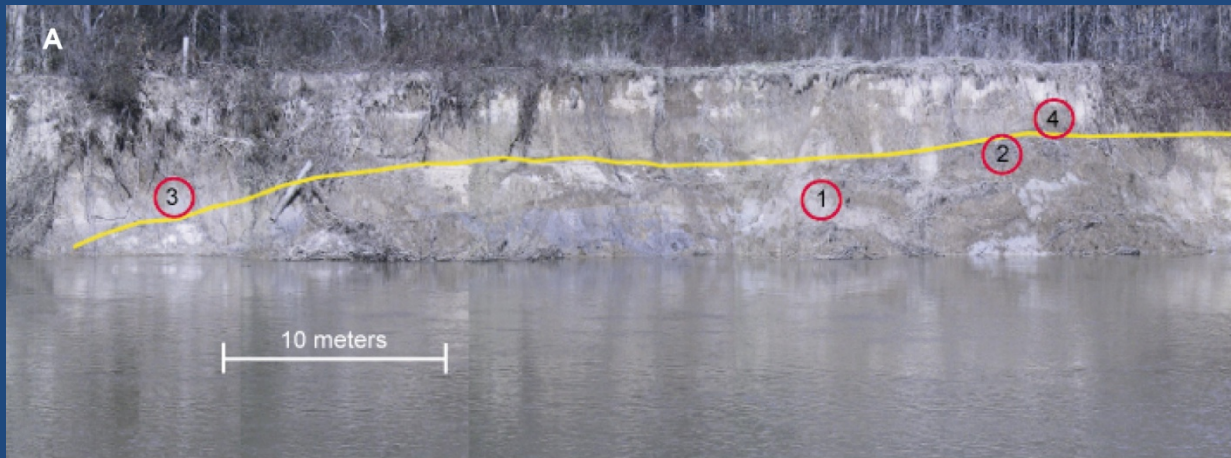
B



C



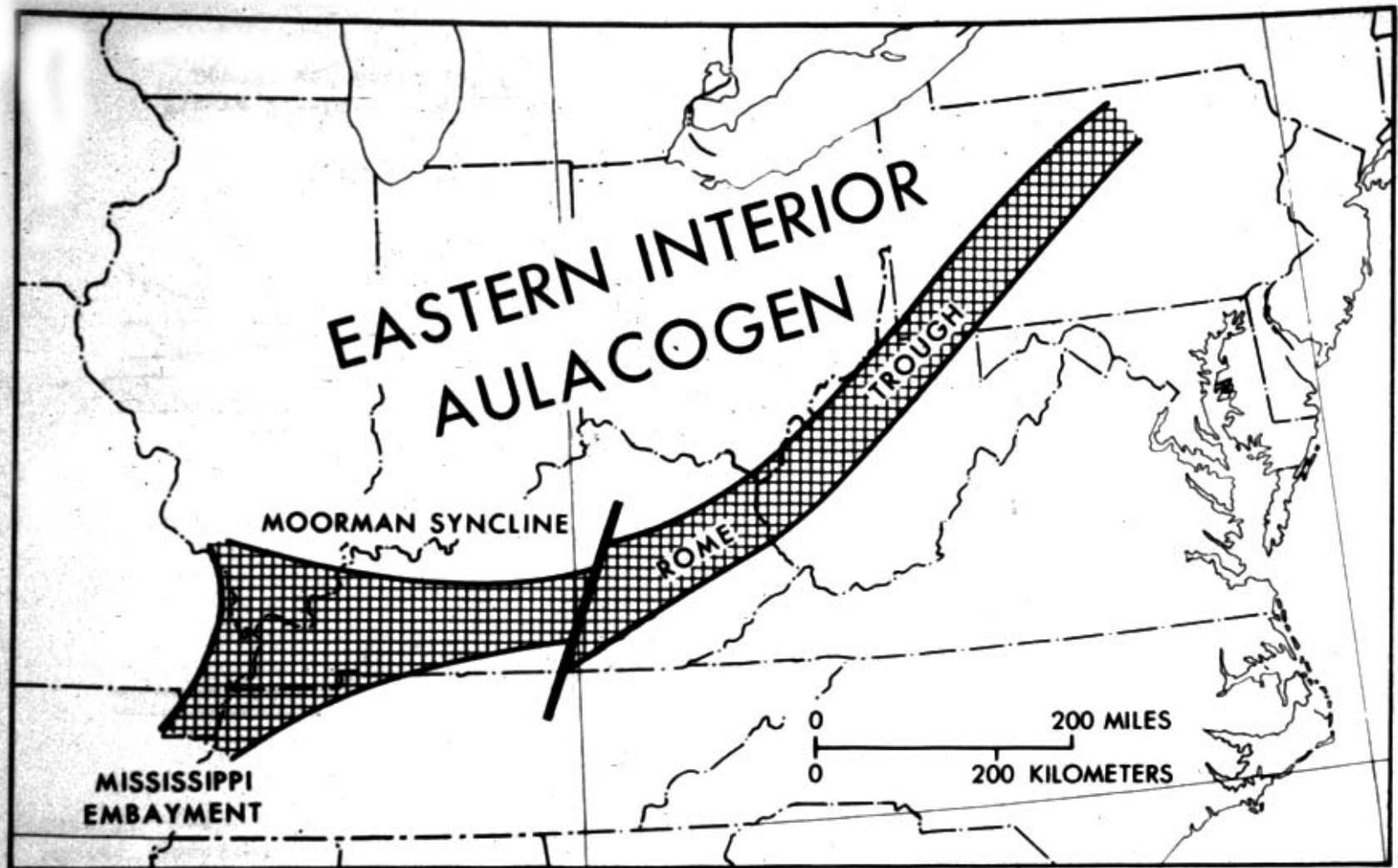
Anticline in northern bank of Wolf River in Shelby County. Anticline attributed to right lateral strike slip faulting (from Velasco et al., 2005).



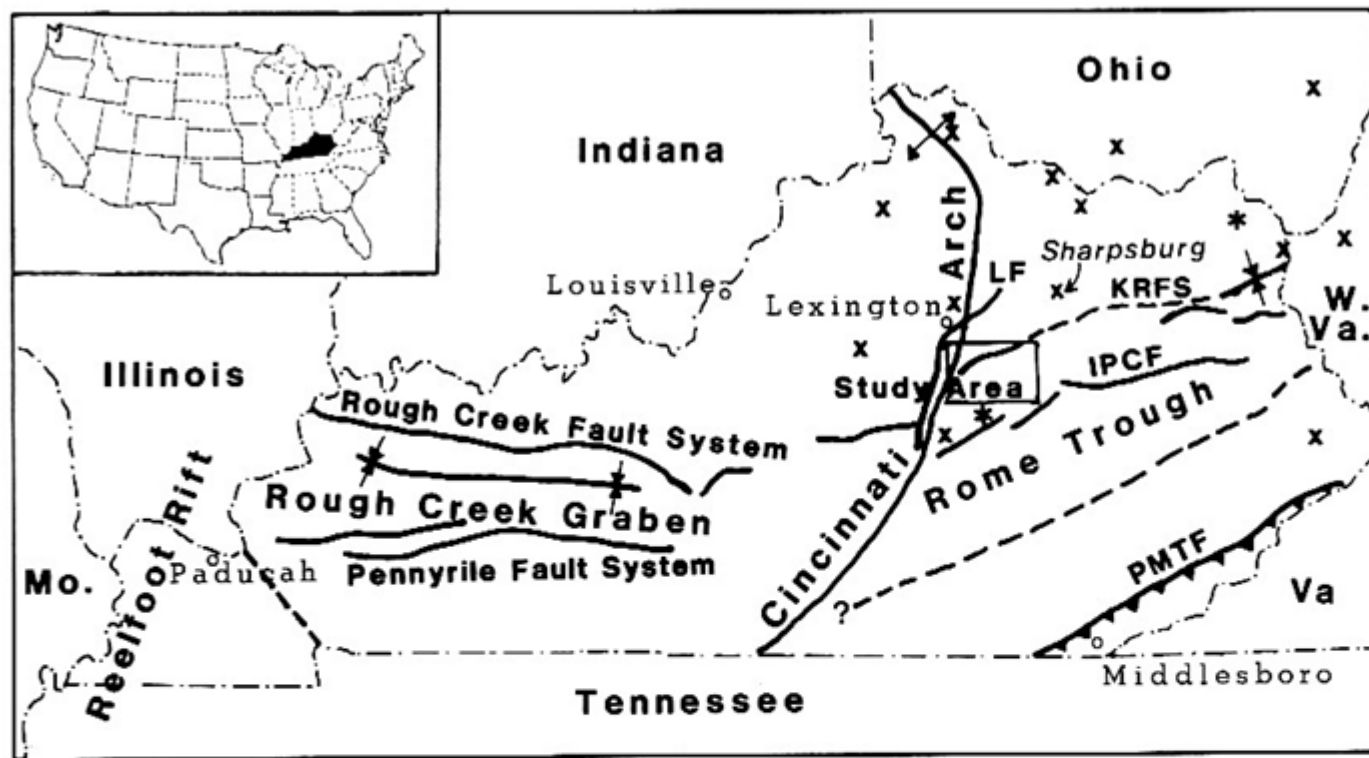
B



Unit 3 truncated by unit 4 indicates folding/faulting occurred ~ 400 AD (from Velasco et al., 2005).



Rome Trough in eastern Kentucky and West Virginia.



KRFS Kentucky River Fault System

LF Lexington Fault

PMTF Pine Mountain Thrust Fault

IPCF Irving-Point Creek Fault

x Earthquake Epicenter

* Two Earthquake Epicenters

? - - - Trough Boundary

— Fault

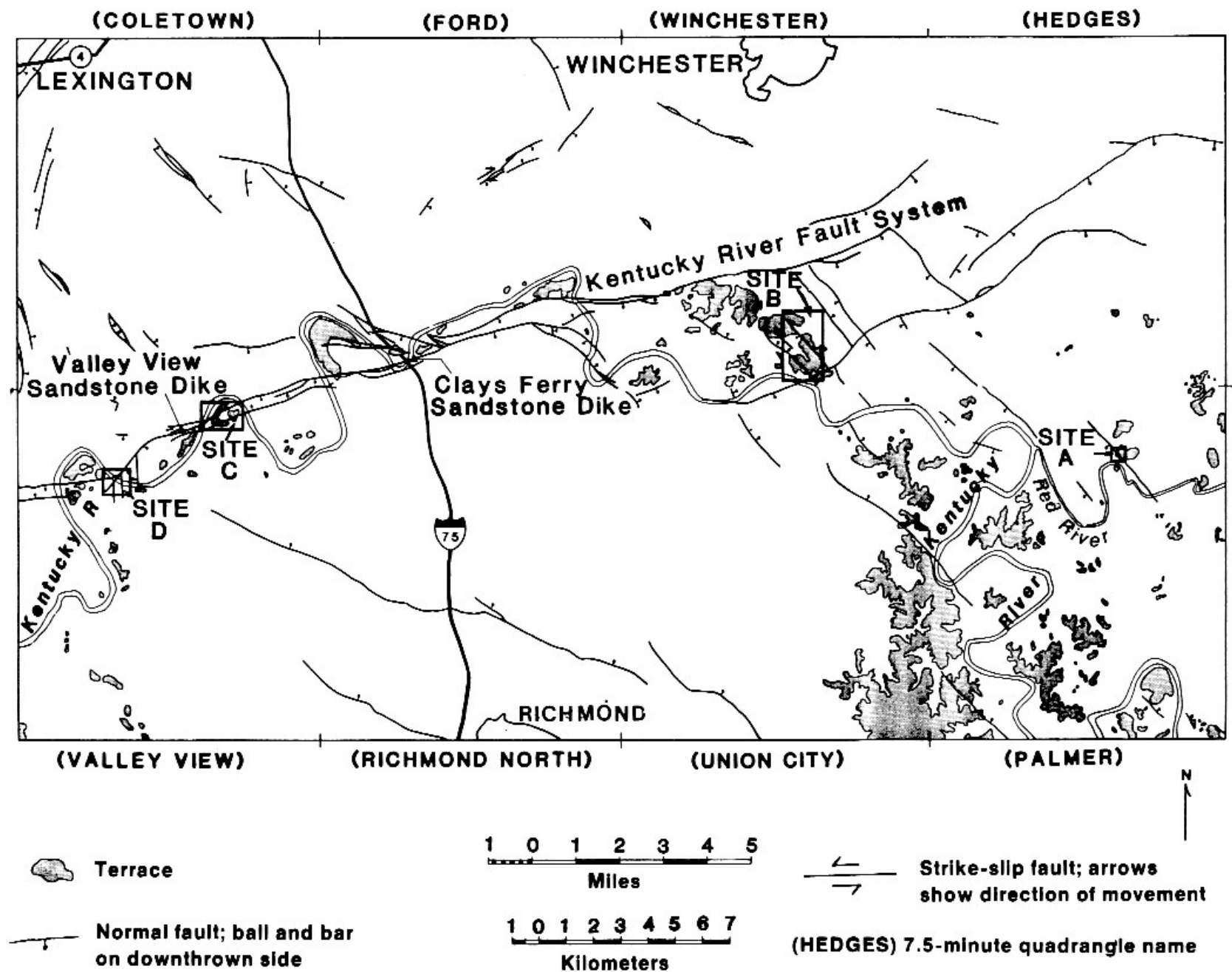
Thrust Fault
Sawteeth on
Upper Plate

Syncline

Anticline

Geological Society of America Bulletin, v. 97, p. 1382-1392, 11 figs., 1 table, November 1986.

Kentucky River fault study area along northern margin of the Rome trough. Stars are earthquakes from 1854-1985 (from Van Arsdale, 1986).



Kentucky River terraces and Kentucky River fault system. Trench study sites A-D (from Van Arsdale, 1986).



Kentucky River terraces are ~400 feet above the Kentucky River.

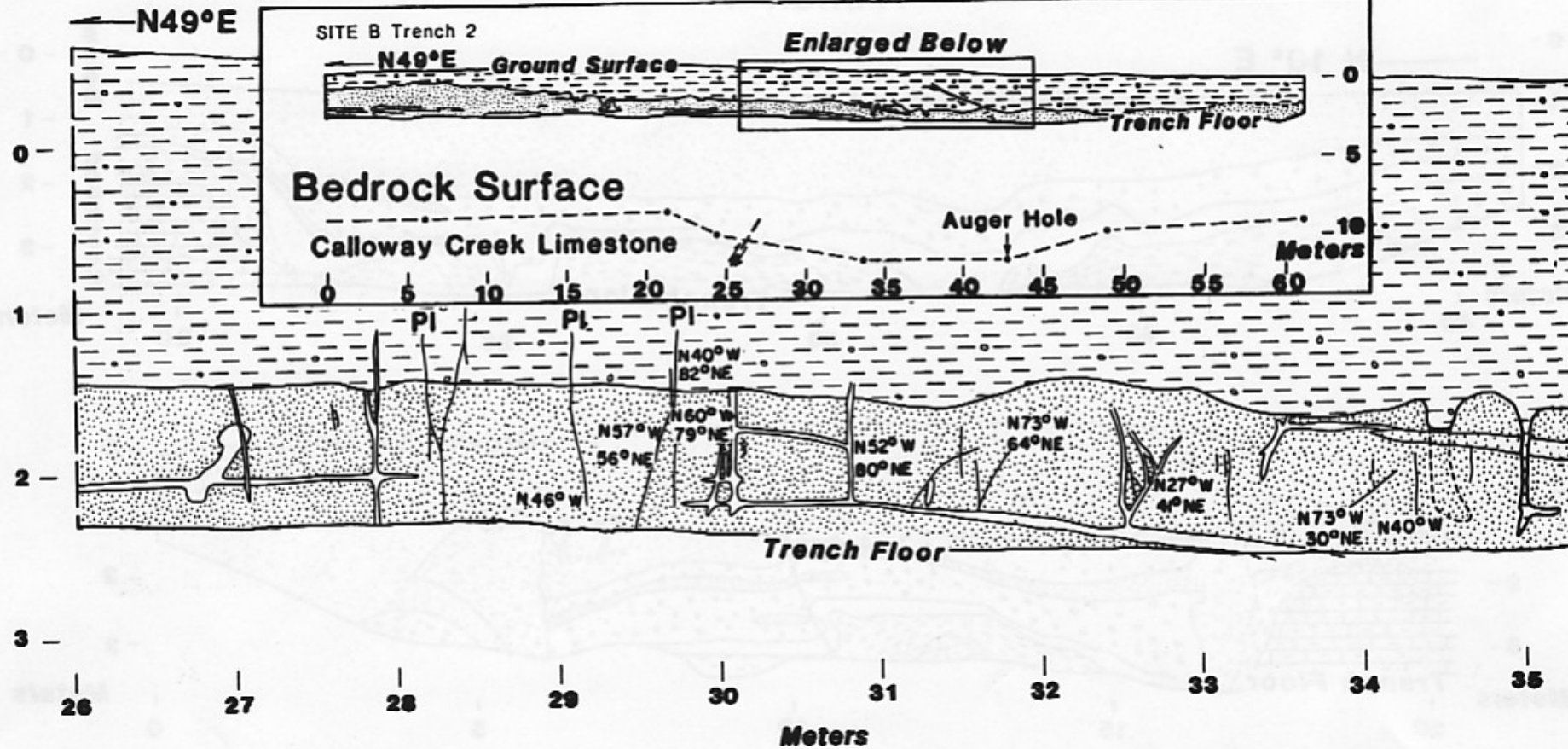


Trench across a bedrock fault and overlying Kentucky River terrace alluvium.

Middle Section of SITE B Trench 2

Meters

+1 —



Trench log in Kentucky River terrace alluvium and overlying colluvium (from Van Arsdale, 1986).



NE verging fold in Kentucky River terrace alluvium.



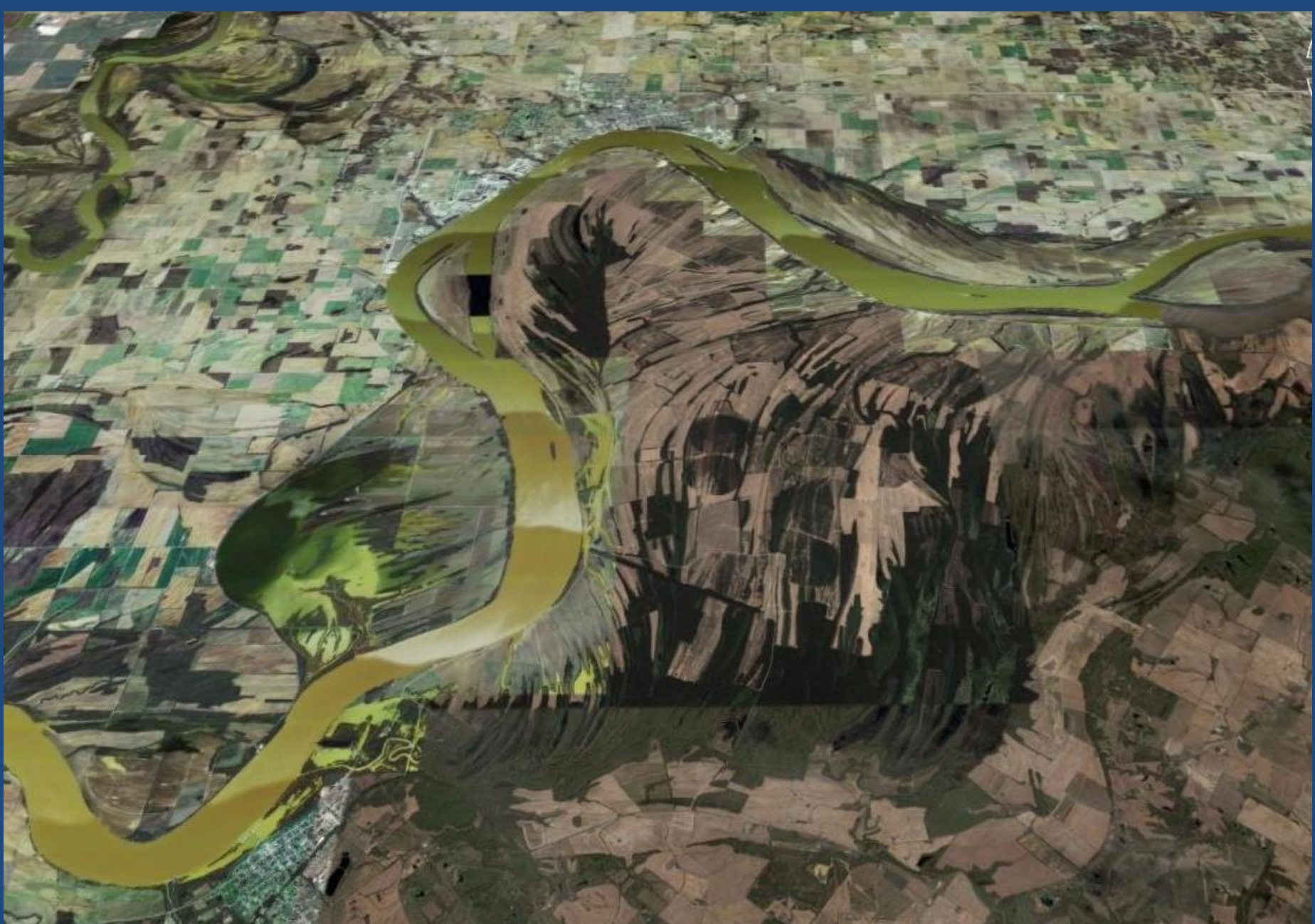
NE verging thrust fault in Kentucky River terrace colluvium.

Site	Trench	Most recent fault movement	Fault separation	Magnitude (Mb) of possible associated earthquake
C	2	<5 m.y.	1.1 m?	6.5
B	1	<5 m.y. (<900,000 yr?)	0.7 m	6.3
B	2	<900,000 yr	0.05 m	5.1
C	1	<350 yr	folding	?

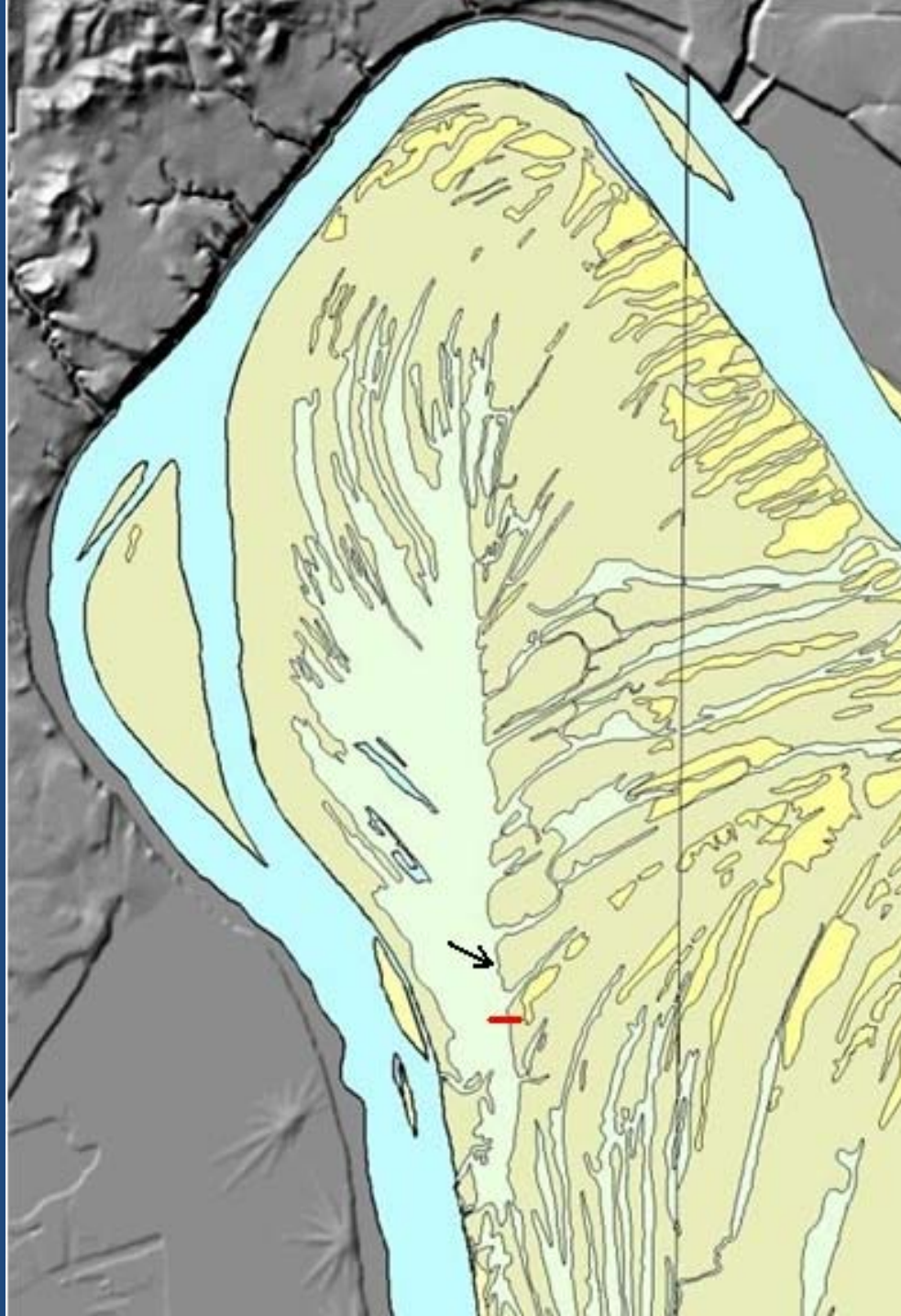
Estimated timing of fault movement at Kentucky River fault sites B and C (from Van Arsdale, 1986).



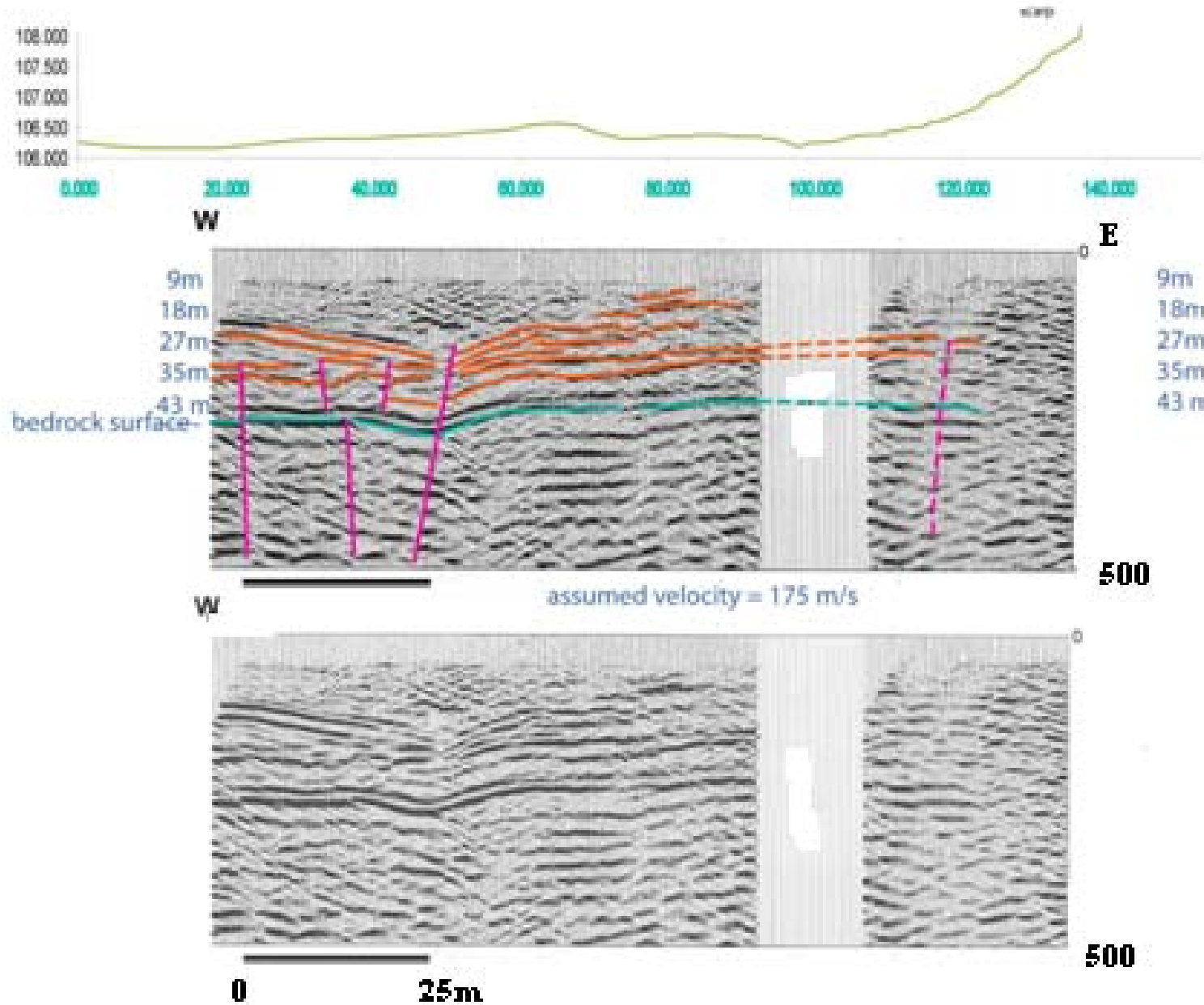
Hovey Lake fault in Wabash Valley fault system (from Woolery, 2005).



Google Earth perspective illustrating west-facing scarp in Ohio River flood plain of western Kentucky (from Counts et al., 2008).

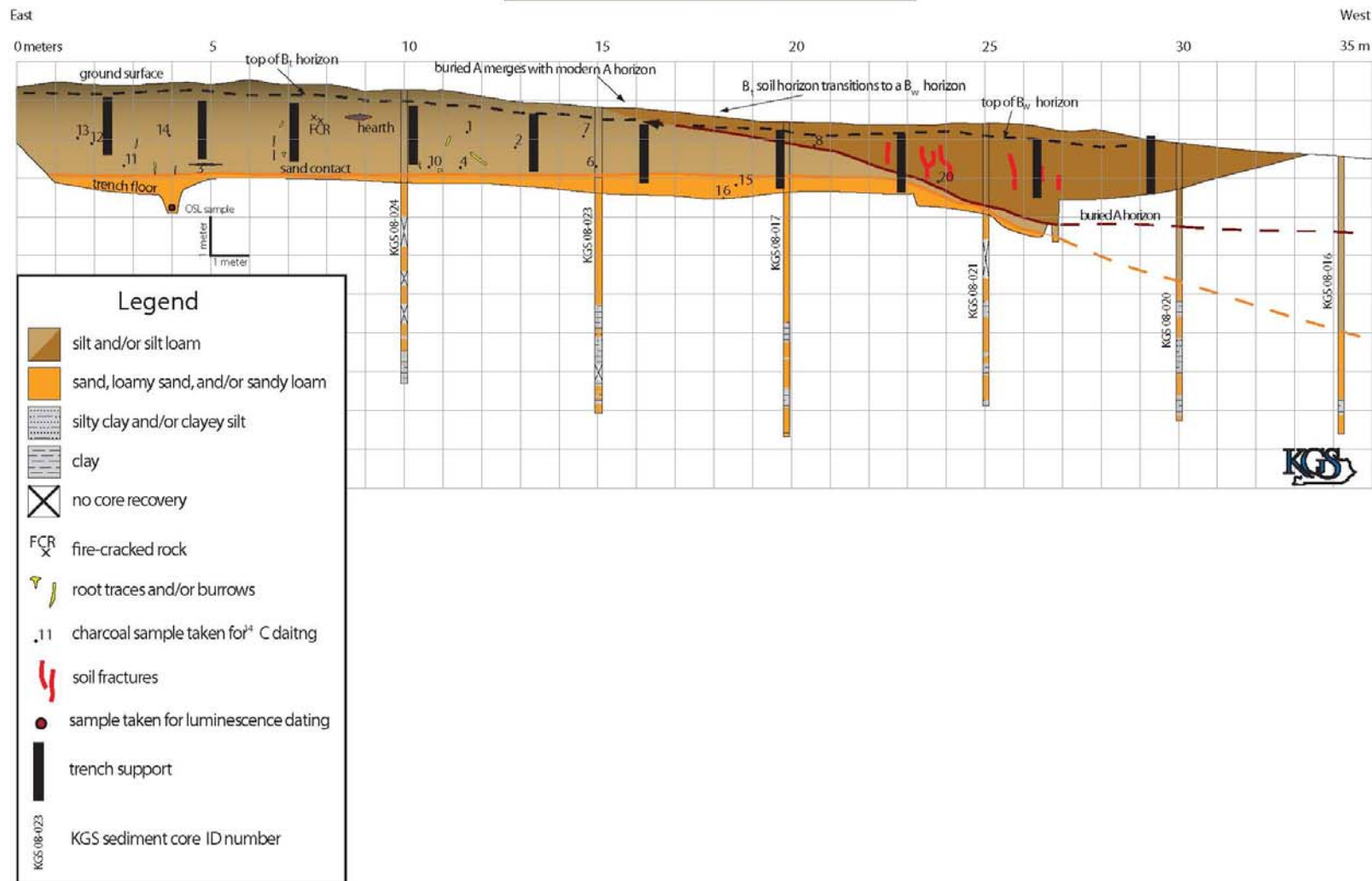


North-trending Uniontown fault scarp with seismic reflection line in red and trench location at head of arrow (modified from Counts et al., 2008).



Shallow S-wave seismic reflection line across Uniontown fault (from Counts et al., 2008).

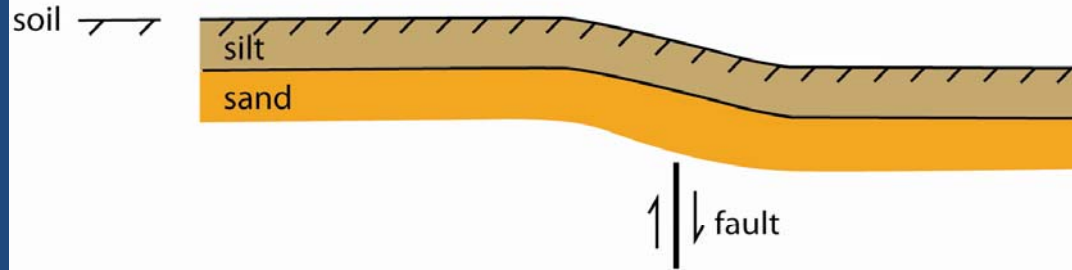
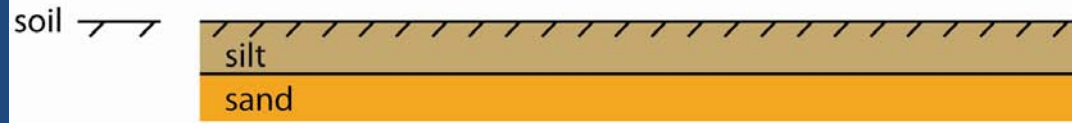
Stull Trench Site, Union County, KY
 Ronald C. Counts
 University of Cincinnati / Kentucky Geological Survey
 Roy Van Arsdale
 University of Memphis



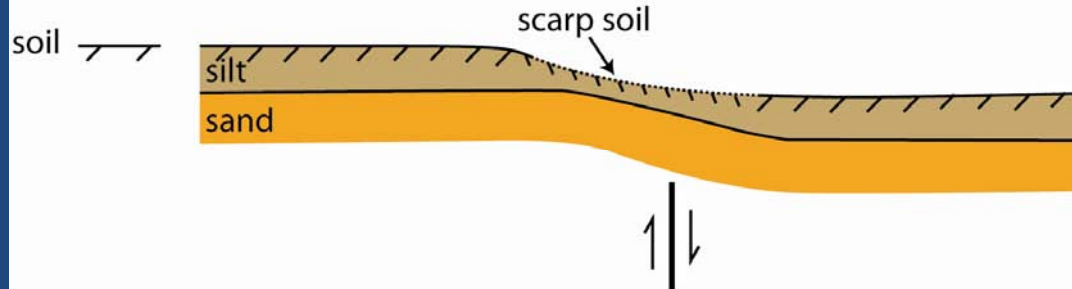
Trench log across Uniontown fault in western Kentucky (from Counts et al., 2009).

East

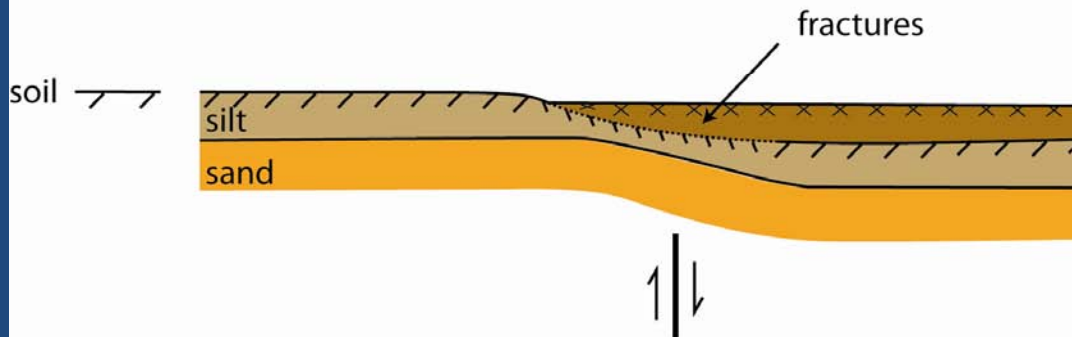
West



monoclinal flexure



erosion of scarp;
formation of scarp soil



depositional burial
of downthrown side
and most of the
eroded scarp

Quaternary Uniontown
fault scarp evolution
(from Counts et al.,
2009).

References Cited in Slides

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Commerce Geophysical Lineament and Northwestern Margin of the New Madrid Seismic Zone

**Summary of Recent Research in southeastern Missouri
and southern Illinois**

**Robert Givler and John Baldwin
William Lettis & Associates, Inc.**

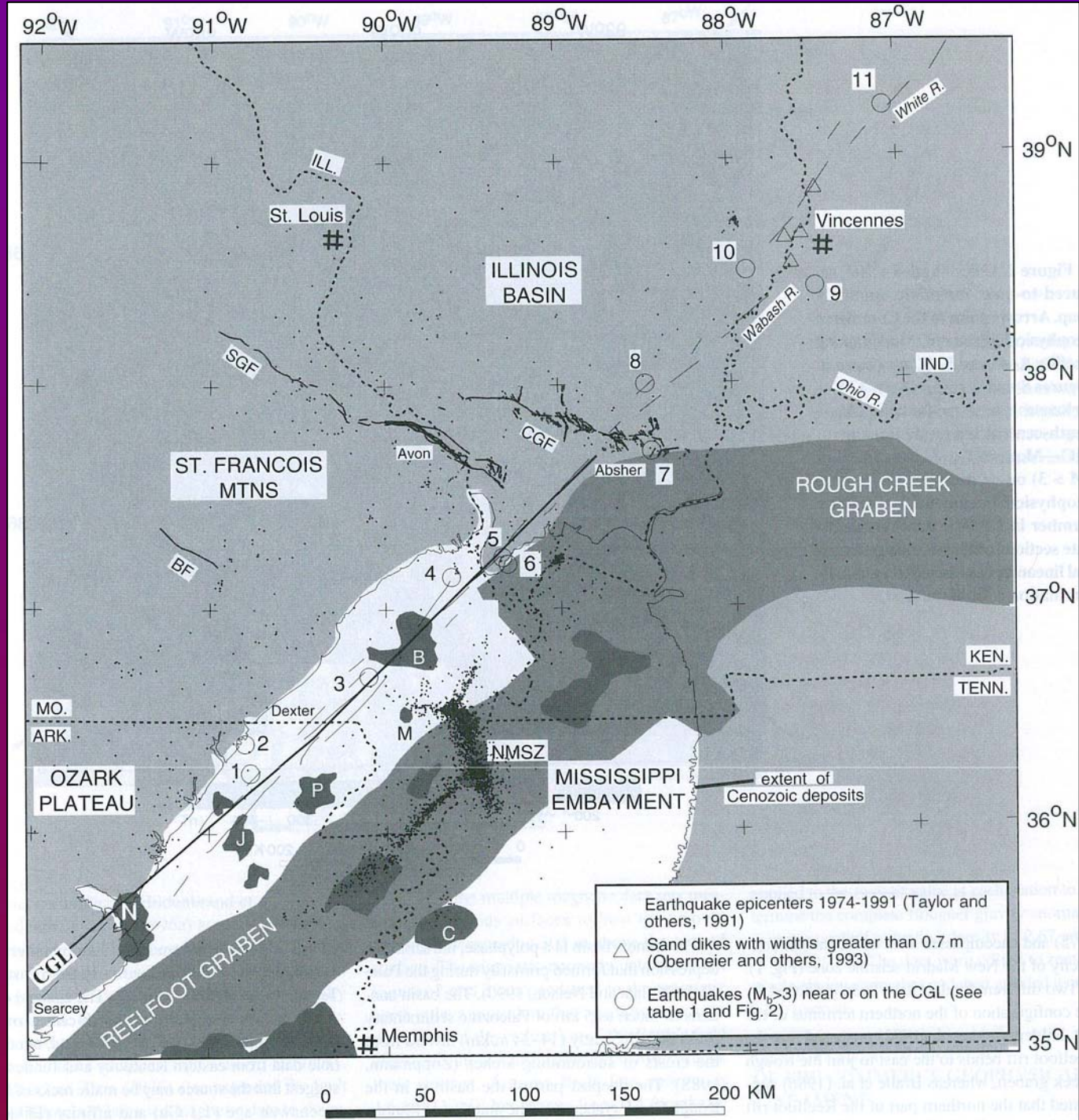
**CEUS SSC Workshop No. 2
February 18-20, 2009**



William Lettis & Associates, Inc.

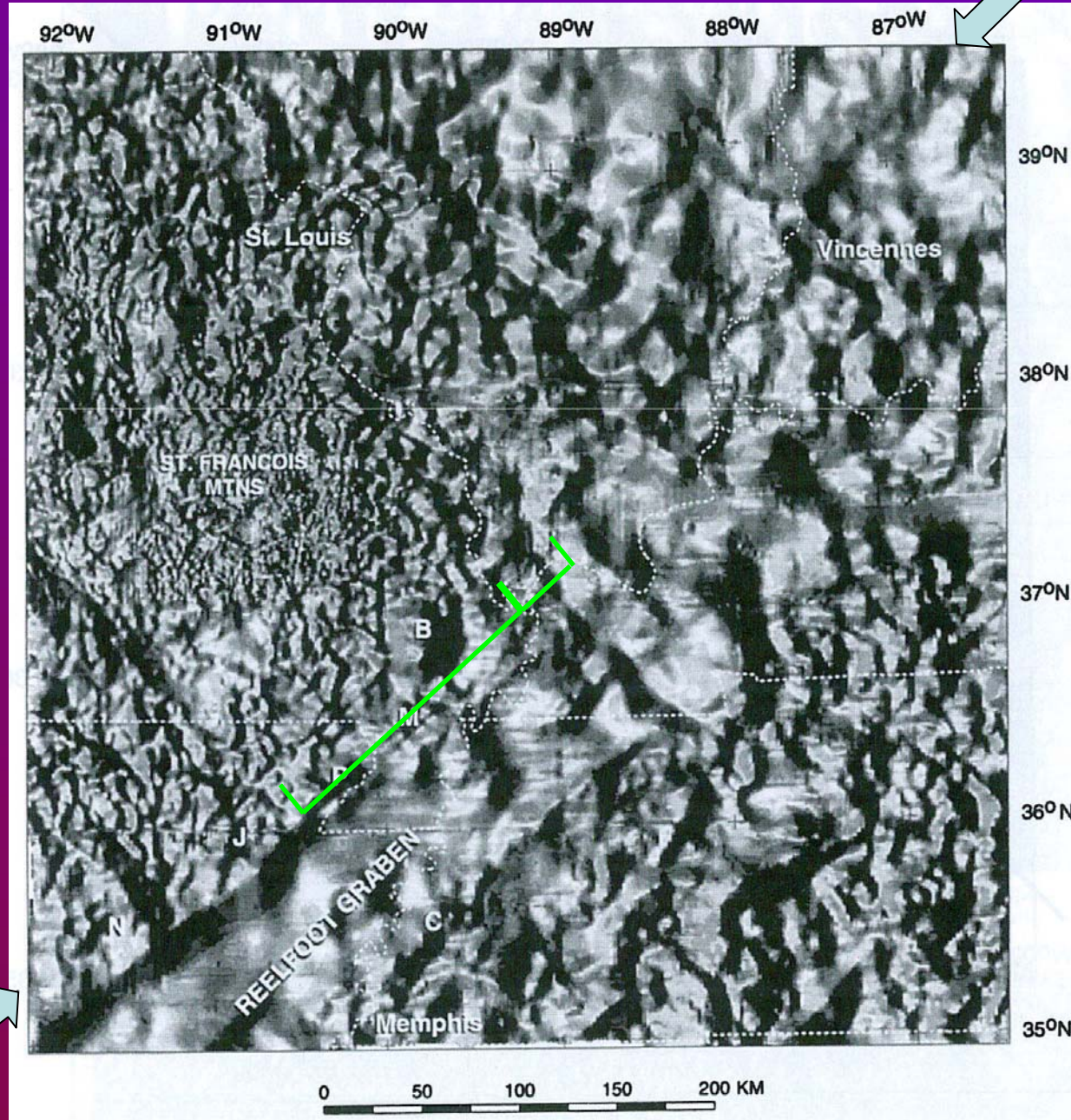
CGL

- Northeast-trending
- 400-600 km long
- 5- to 10-km wide
- Mafic dike swarm
- Quaternary strike-slip and normal faulting

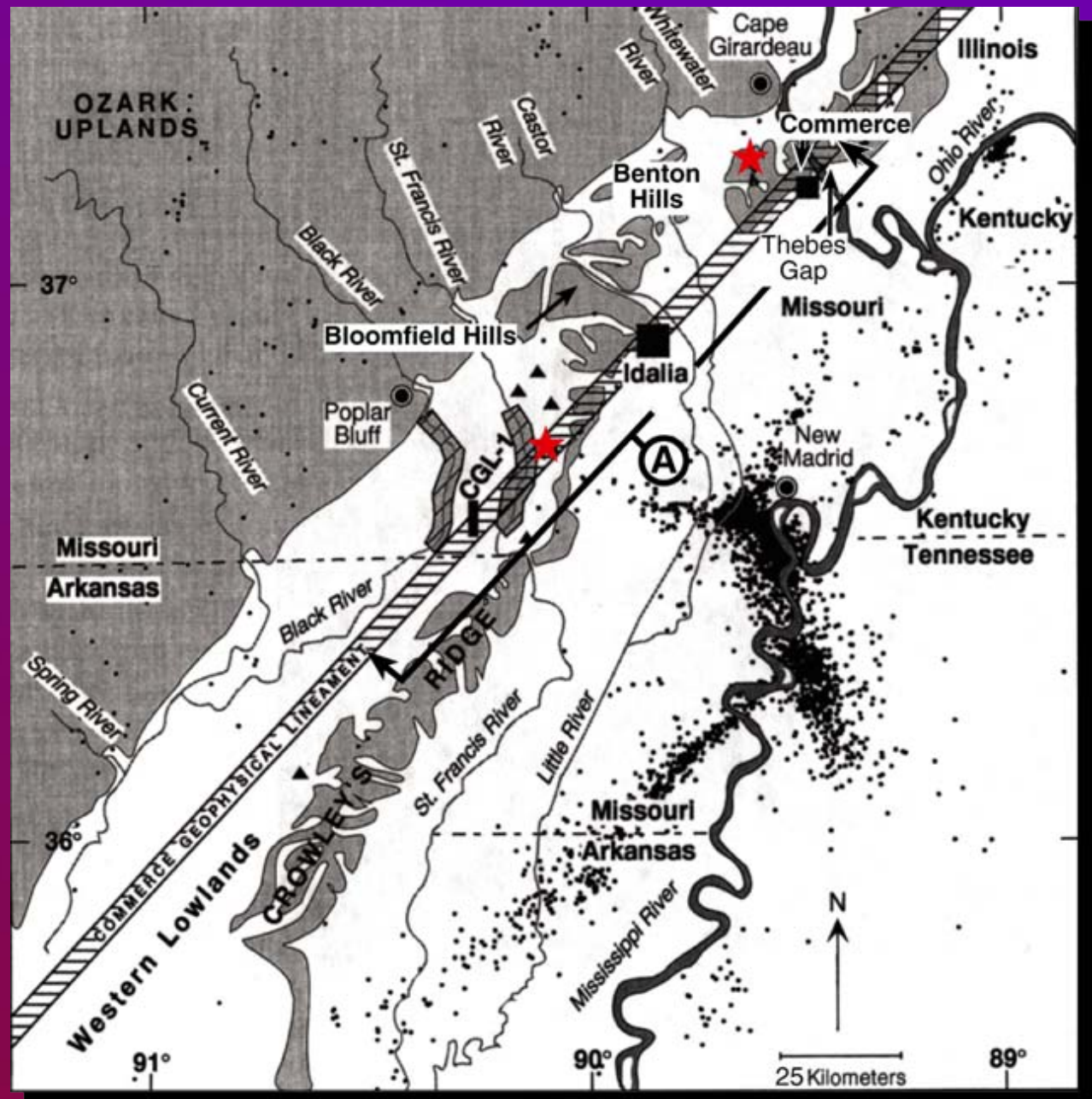


Aeromagnetic Data

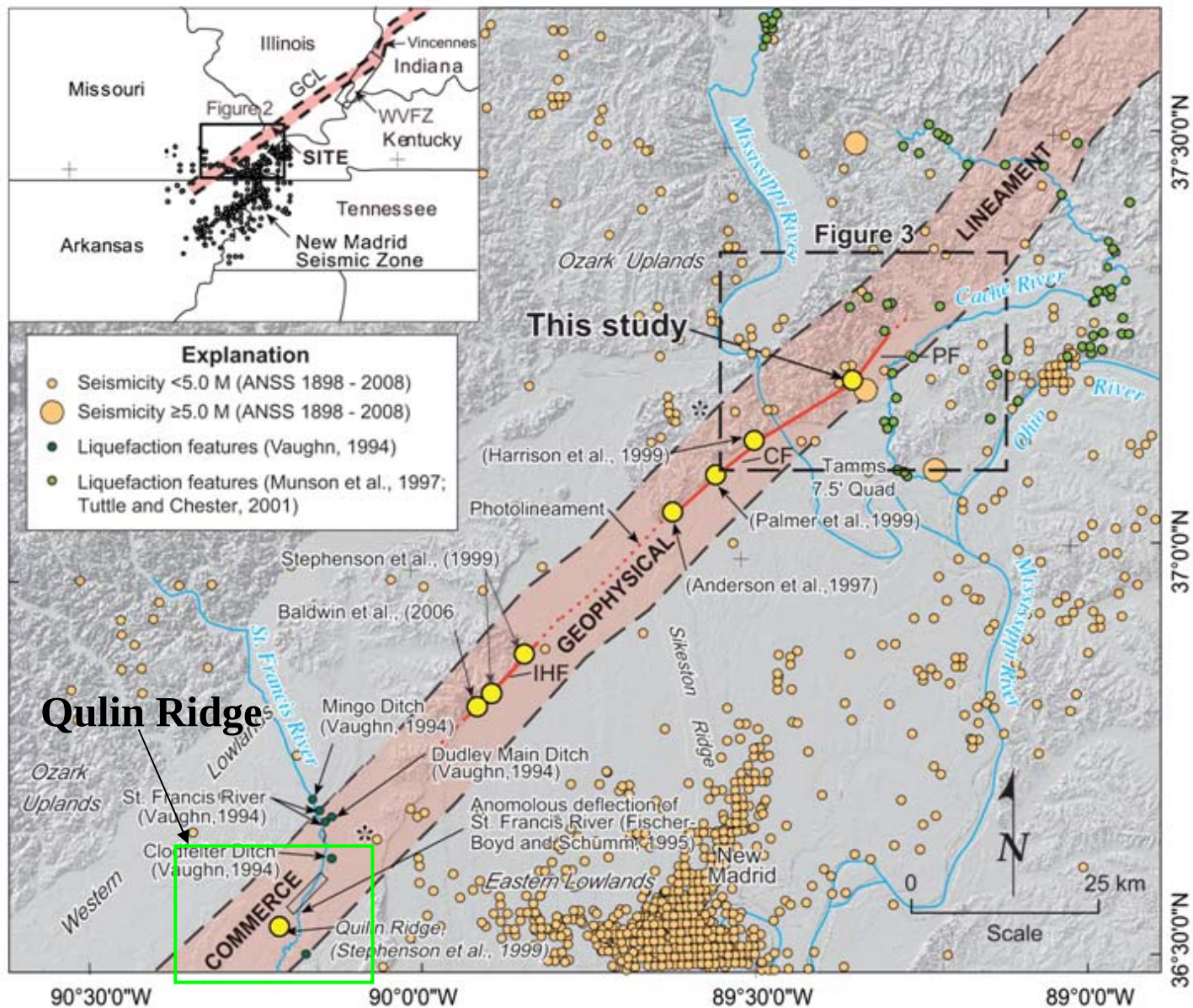
- Reelfoot rift
- Lineaments
- Sections
 - Newport
 - Commerce
 - Tripoli
 - Junction



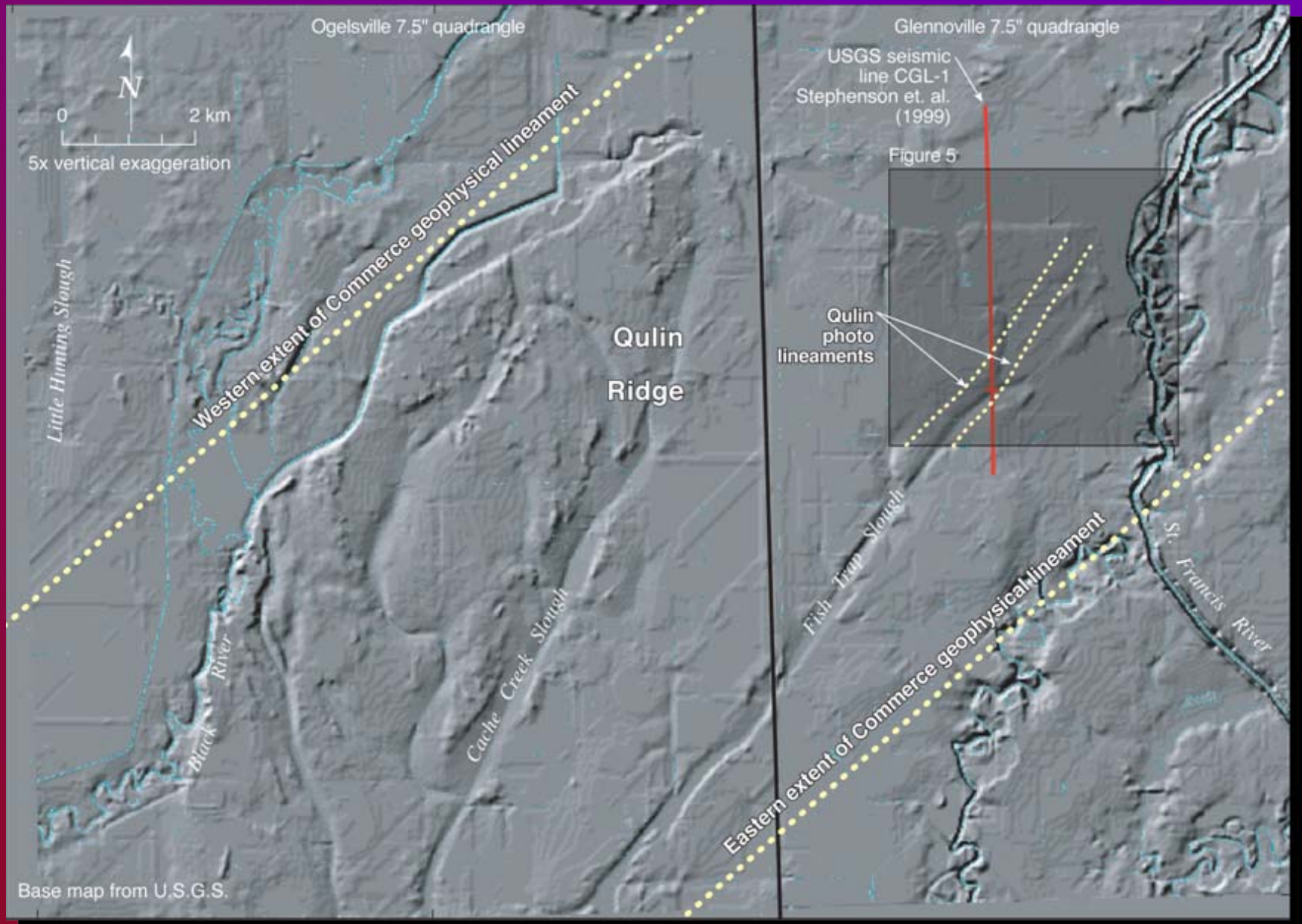
Regional Geologic Setting



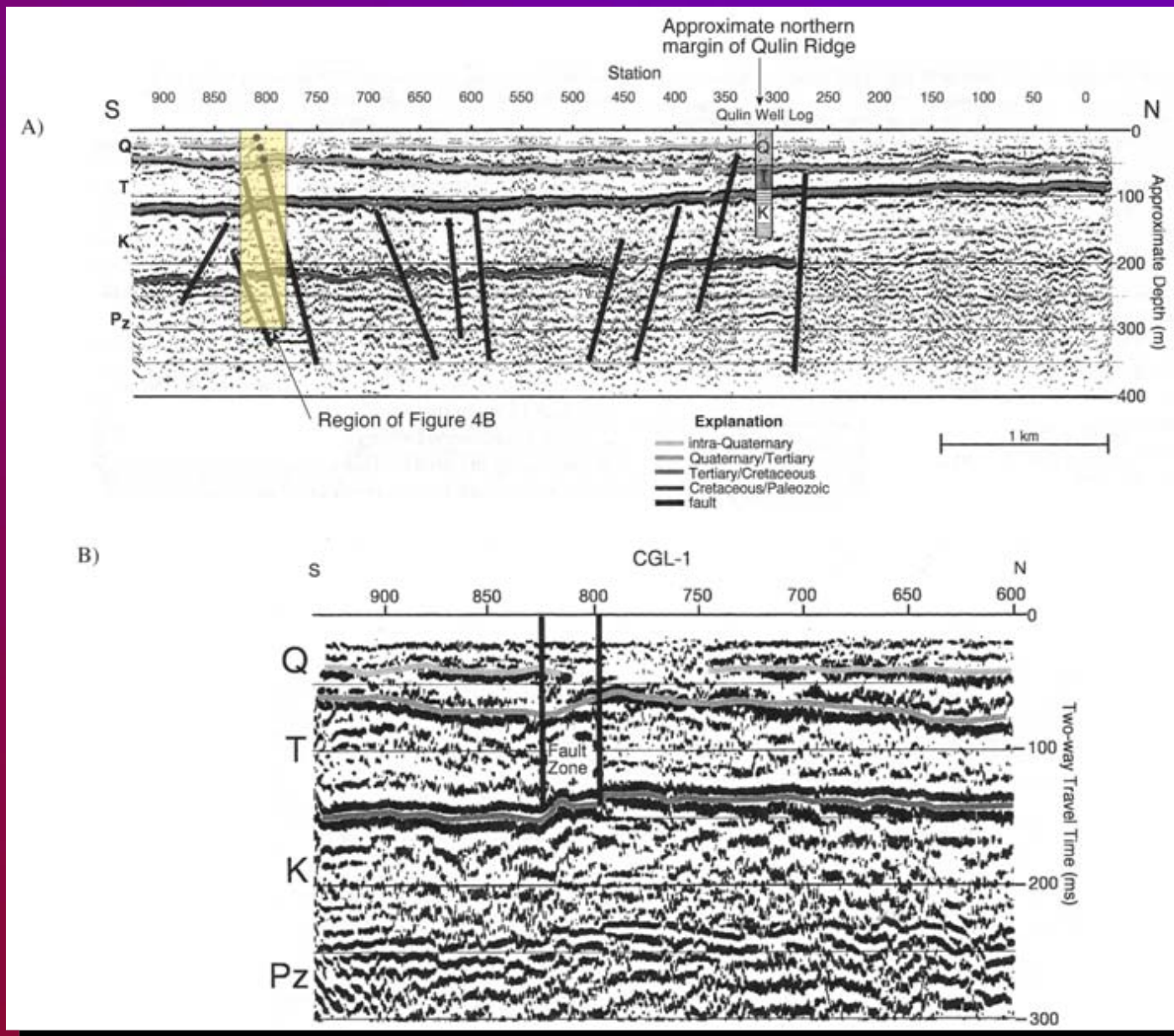
Studies along the CGL



Shaded Relief Map of Qulin Ridge



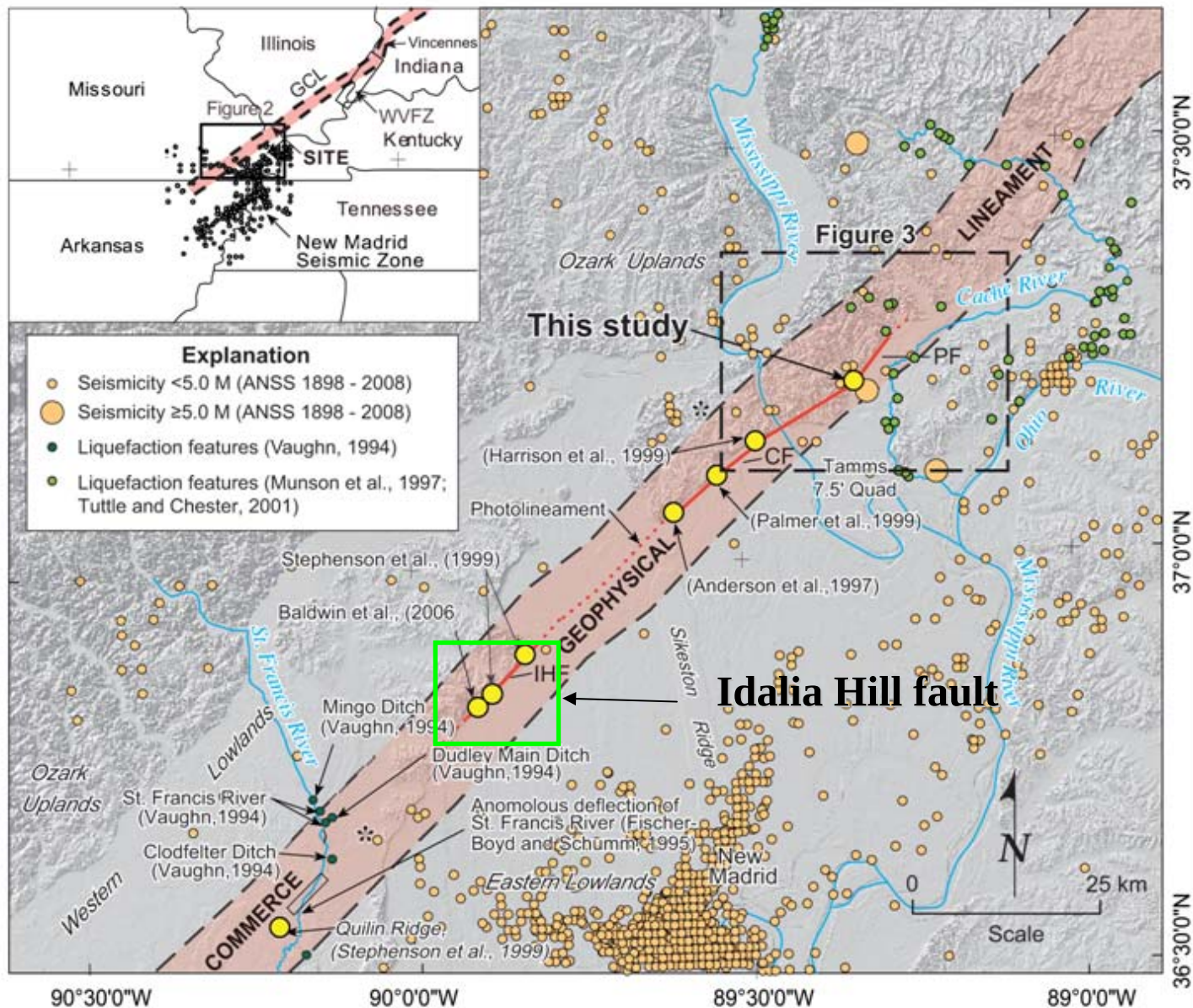
Seismic Profile CGL-1 of Stephenson et al.



Qulin Ridge Summary

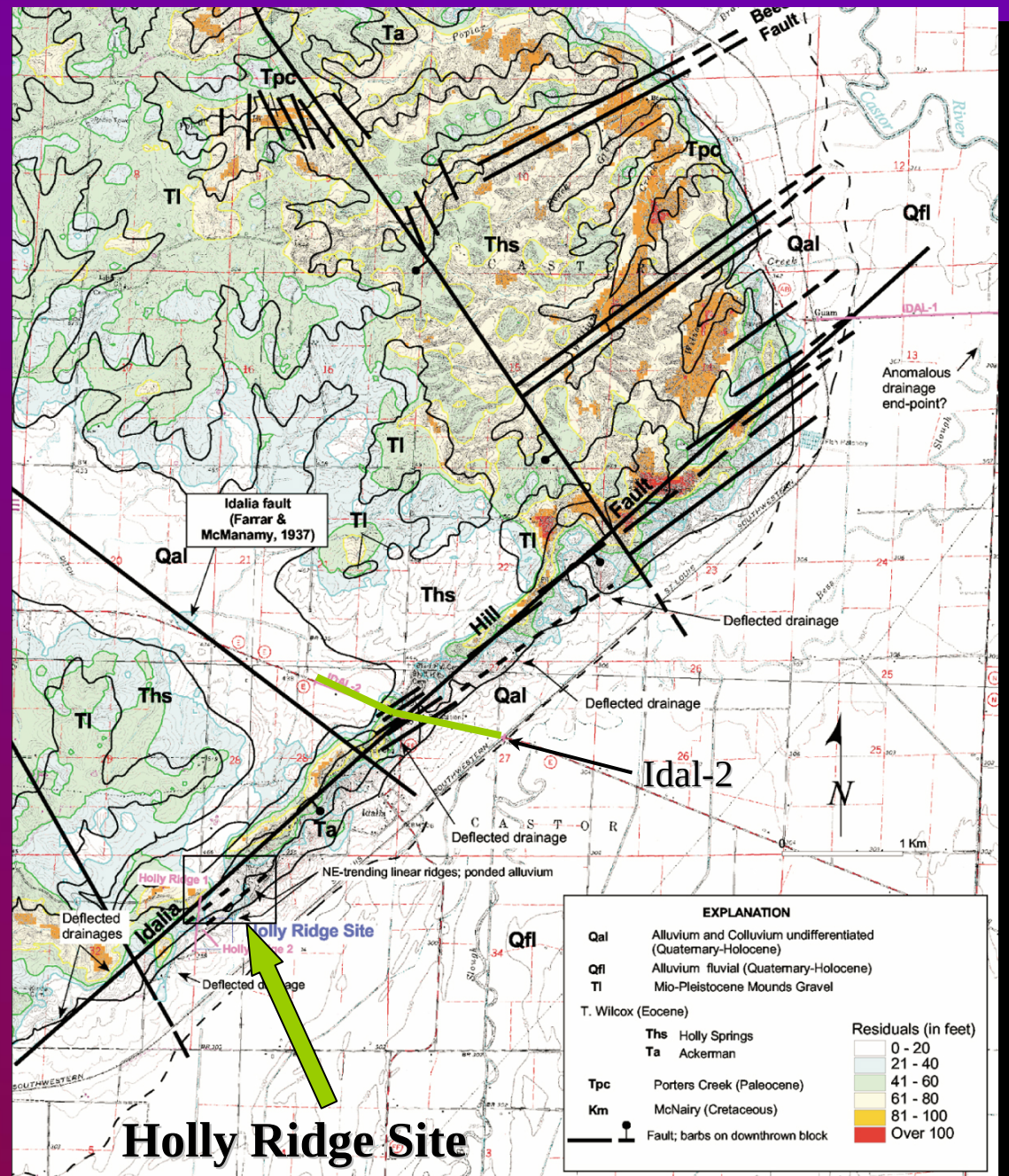
- (1) Fluvial geomorphic anomalies associated with the Black and St. Francis Rivers (Fischer-Boyd and Schumm, 1995)
- (2) Four prehistoric events occurred between about 23,000 to 17,000 yr BP, 13,400 to 9000 yr BP, A.D. 240 to 1020 and A.D. 1440 to 1540 (two latest attributed to NMSZ) (Vaughn, 1994)
- (3) Seismic reflection surveys image a 0.5-km wide zone of thin of Quaternary deposits and Quaternary faulting and warping

Studies along the CGL

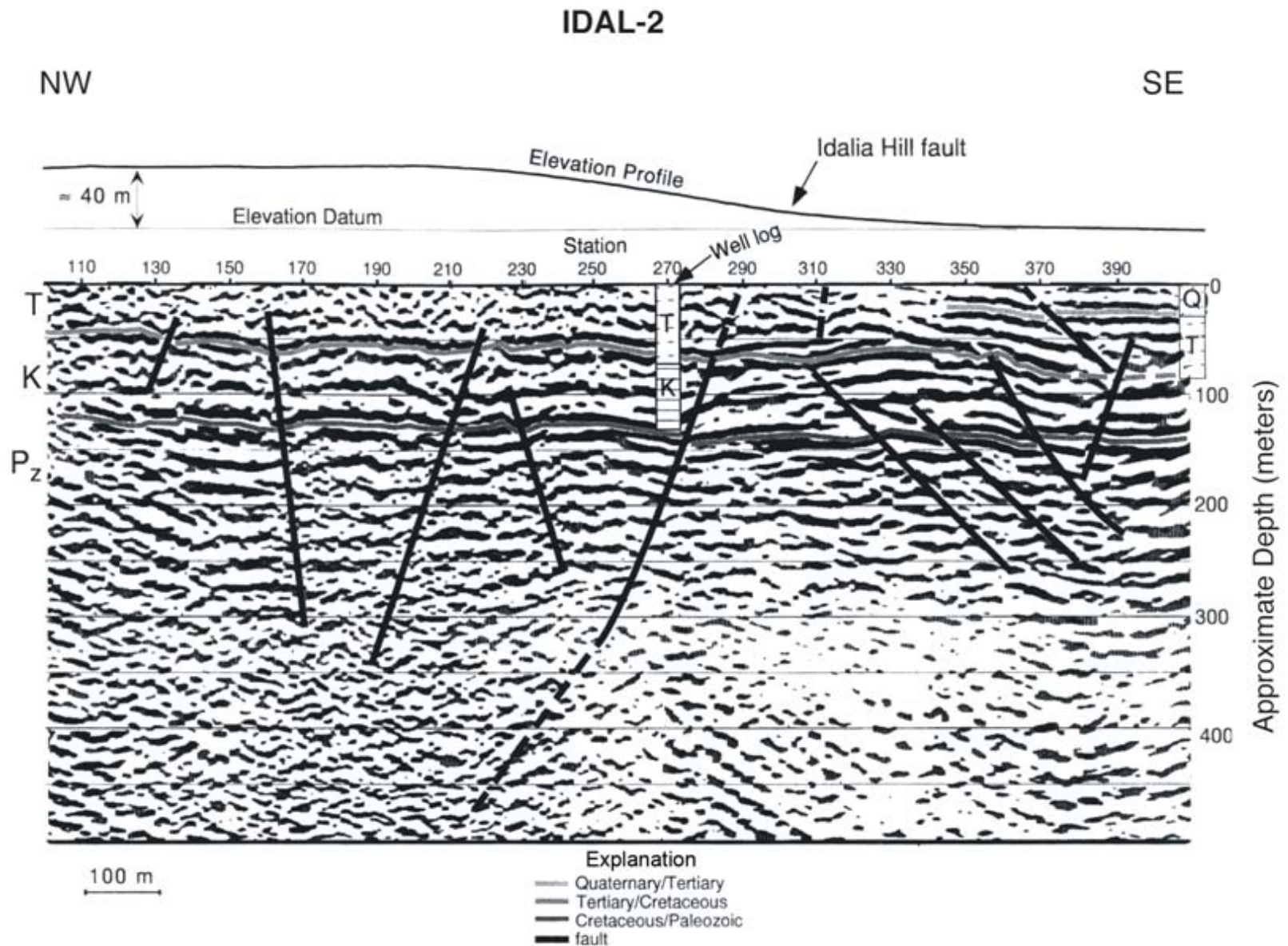


Holly Ridge Geology

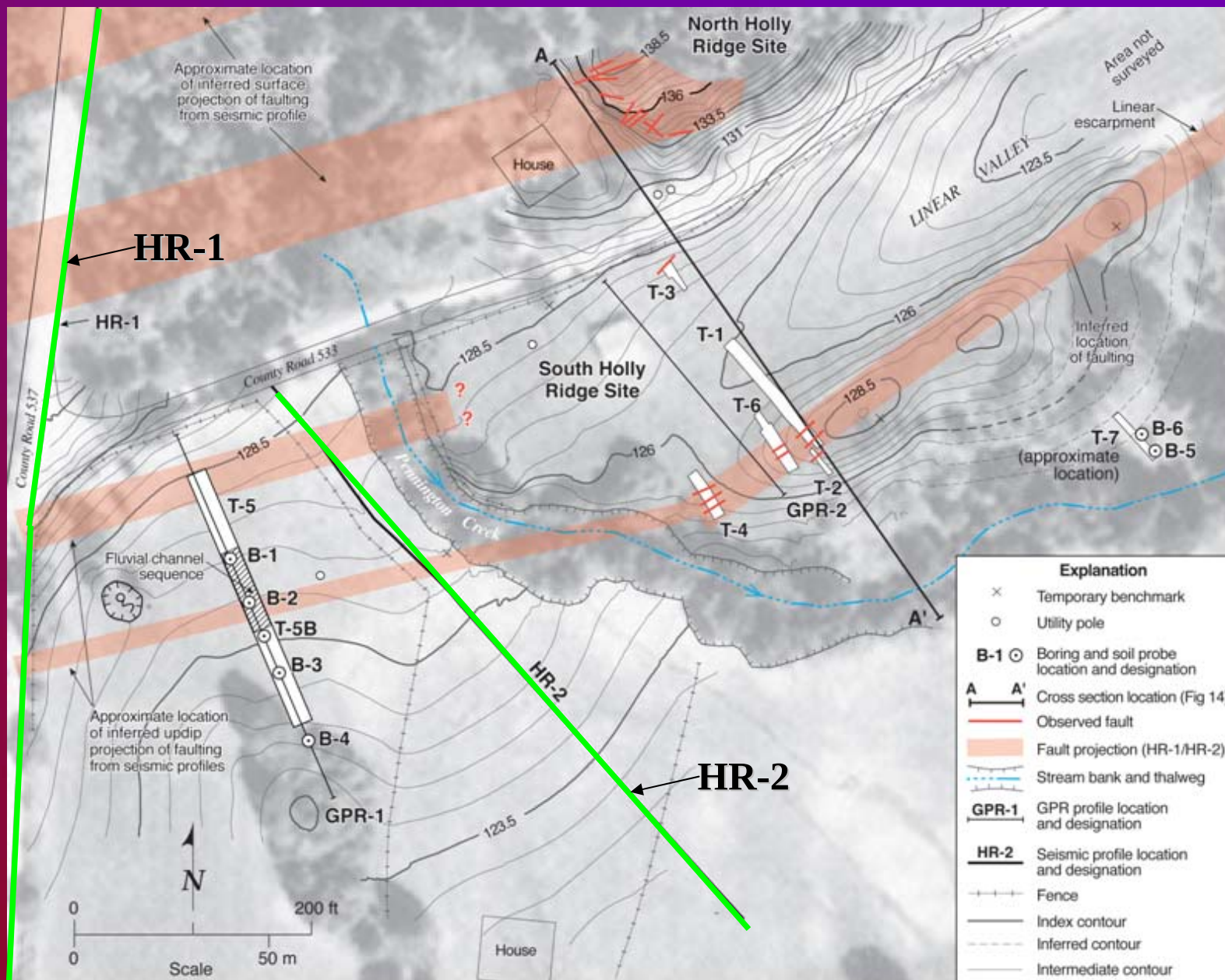
- Idalia Hill Fault
- Northeast-trending bluff line
- Geomorphology



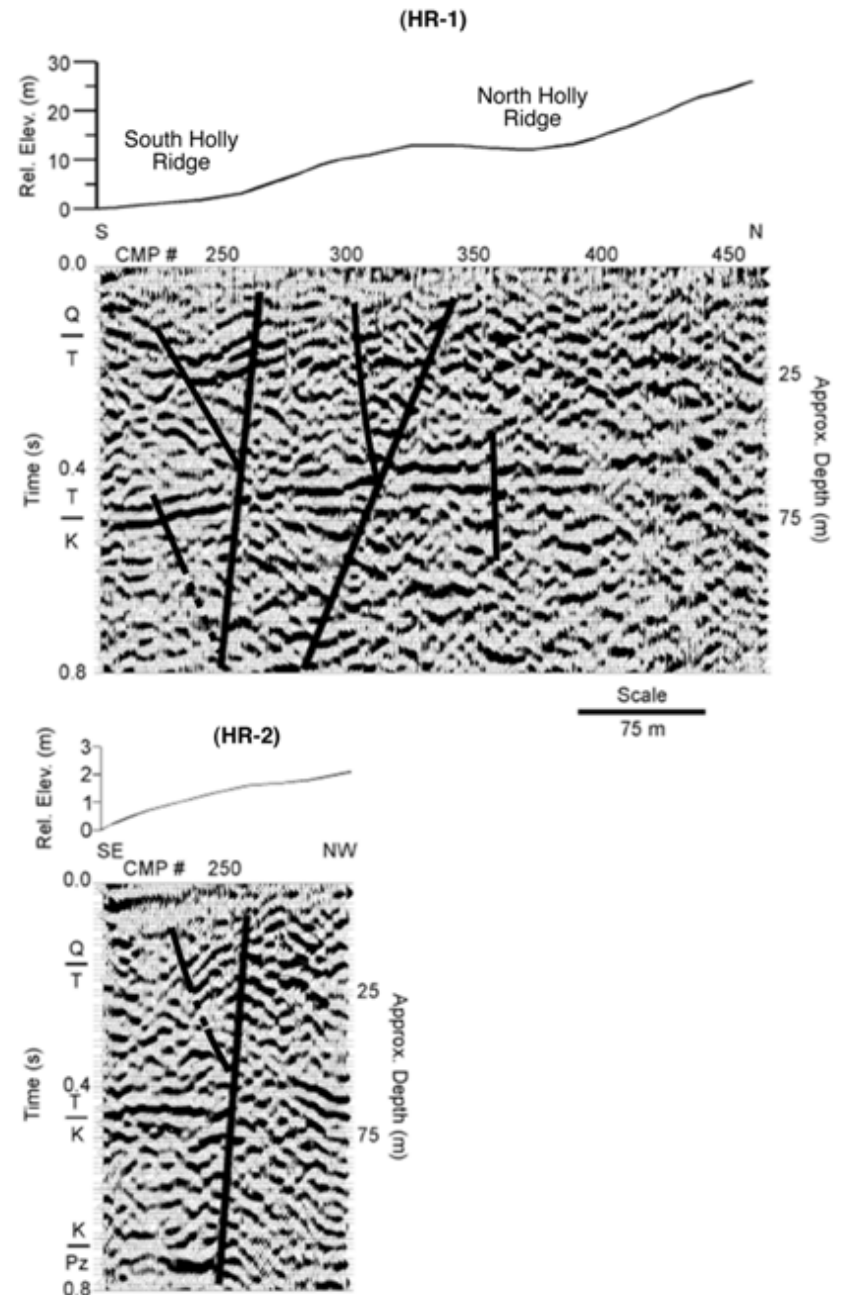
Seismic Reflection Profile IDAL-2



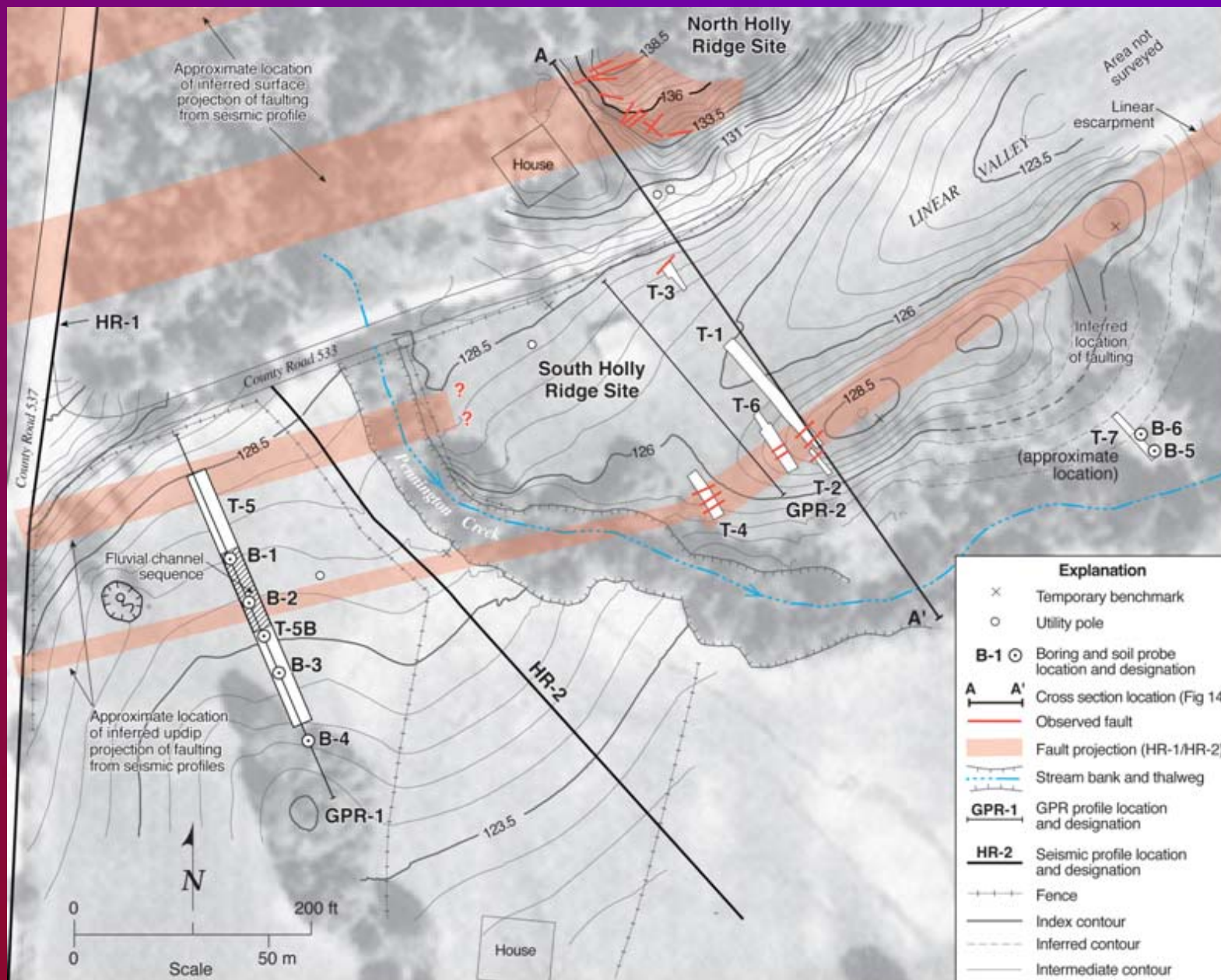
Site Map



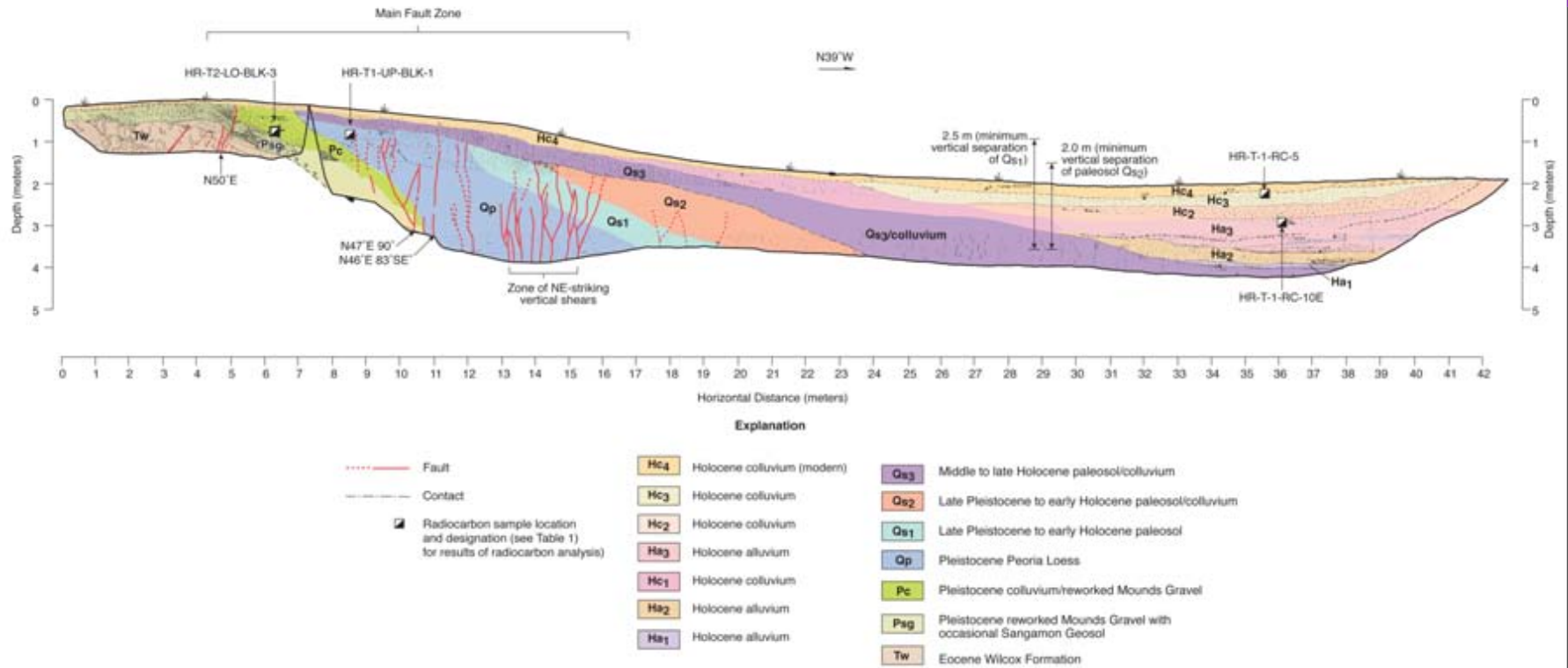
Interpreted Shear-wave Seismic Reflection Profiles



Site Map

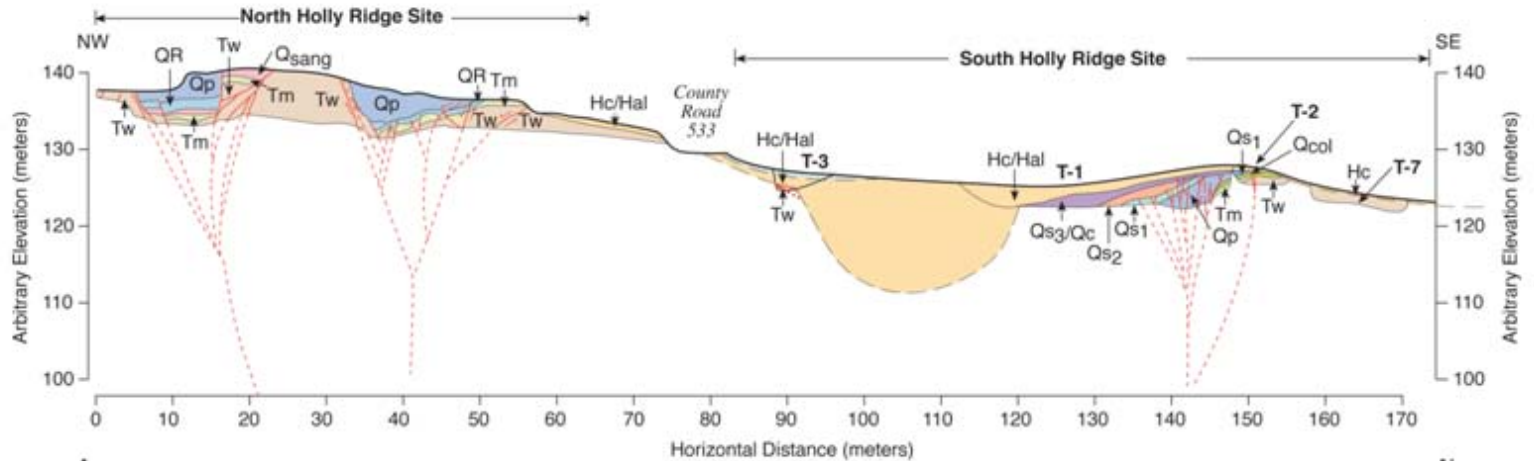


Trench T-1

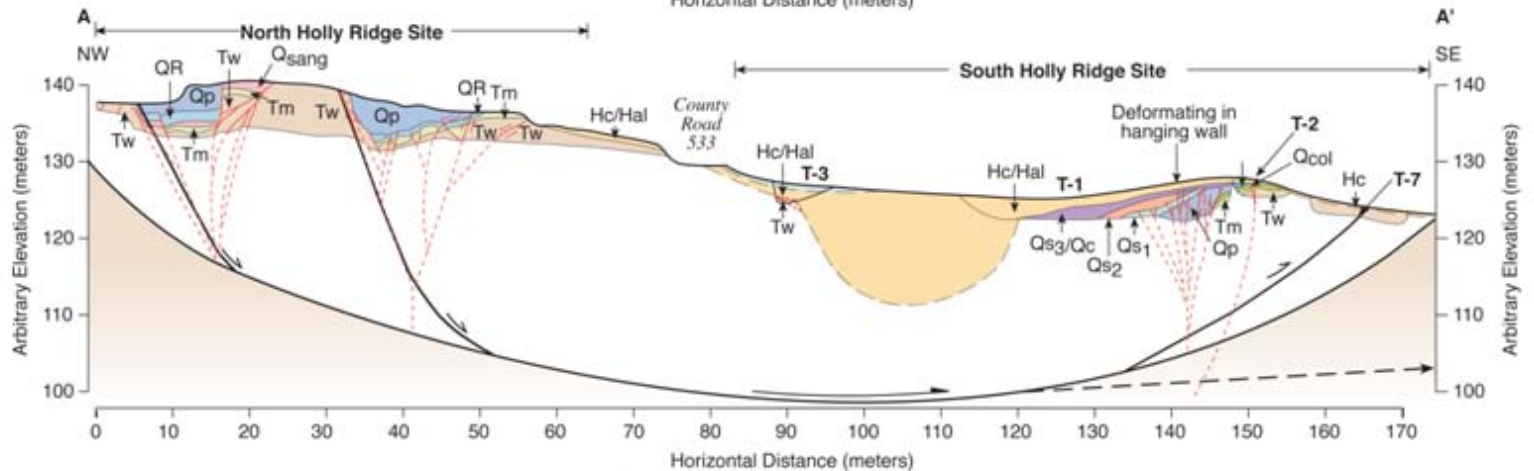


Schematic Cross Section A - A'

Tectonic Model



Landslide Model



Explanation

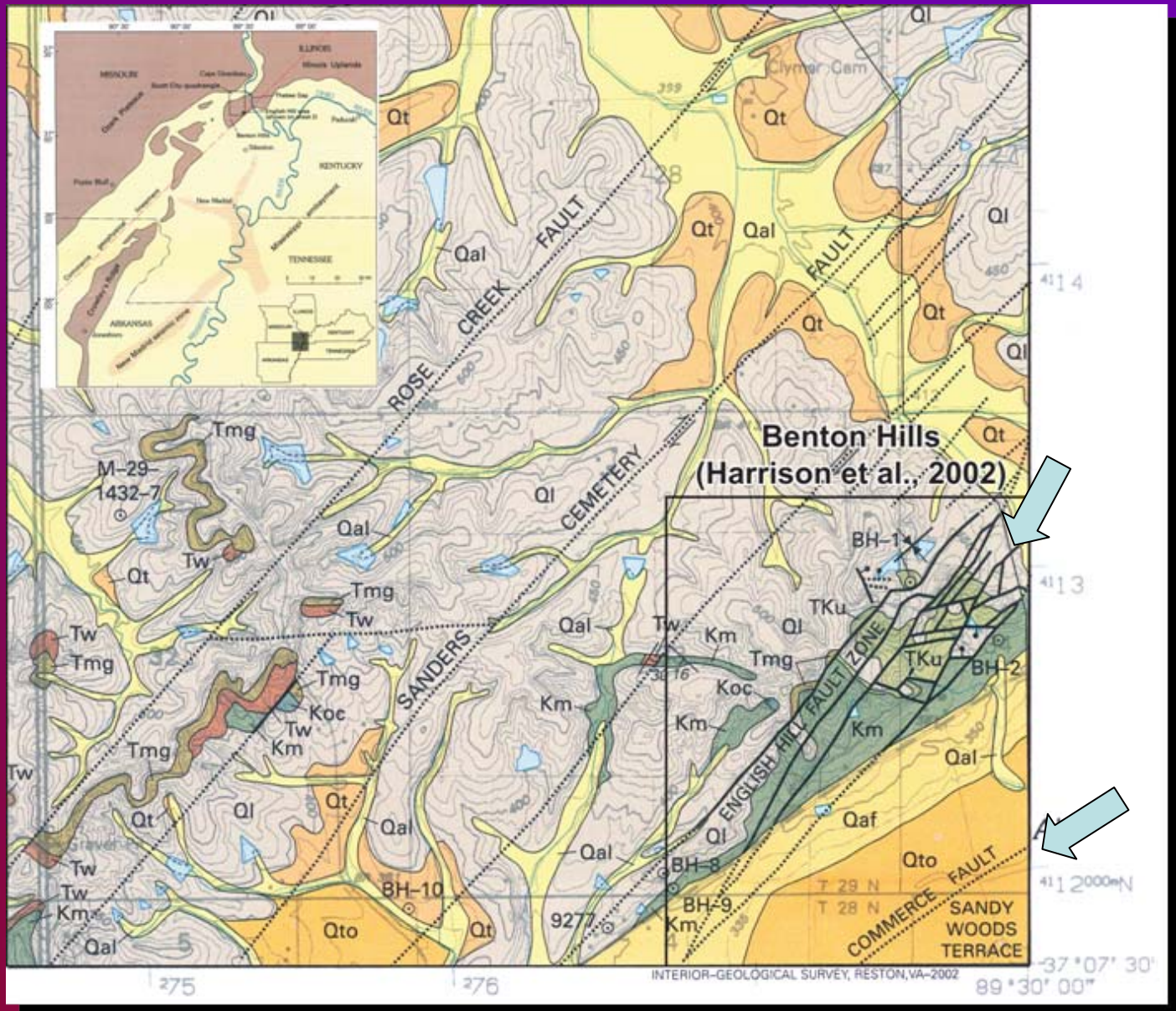
Hc/Hal	Undifferentiated Holocene colluvium and alluvium	QR	Pleistocene Roxana Loess
Qs3/Qc	Middle to late Holocene paleosol/colluvium	Qcol	Pleistocene colluvium
Qs2	Late Pleistocene to early Holocene paleosol/colluvium	Qsang	Sangamon Geosol
Qs1	Late Pleistocene to early Holocene paleosol	Tm	Pleistocene reworked Mounds Gravel
Qp	Pleistocene Peoria Loess	Tw	Wilcox Formation

Bloomfield Hills - Idalia Summary

- (1) Near-surface deformation coincides with geomorphology and faults imaged in seismic reflection profiles
- (2) Deformation interpreted as predominantly tectonic-related
- (3) Quaternary faulting interpreted from several seismic profiles and trenches
- (4) Two poorly constrained events: (1) predates 23.6 to 18.9 ka; (2) between 18.5 and 7.6 ka

[illegible]

Benton Hills: Commerce Fault



Harrison et al. (2002)

Benton Hills Summary

- (1) Faults are predominantly tectonic in origin
- (2) Strike-slip sense of displacement
- (3) Faulting is episodic throughout Cenozoic with four events in late Quaternary
 - (a) pre- to early Roxana time (60 to 50 ka)
 - (b) pre-Peoria time (35 to 25 ka)
 - (c) Near or just after 4980 to 4740 yrs BP (C14)
 - (d) 1310 to 1210 yrs BP (C14)

Figure 3

Explanation

- Seismicity <5.0 M (ANSS 1898 - 2008)
- Seismicity ≥5.0 M (ANSS 1898 - 2008)
- Liquefaction features (Vaughn, 1994)
- Liquefaction features (Munson et al., 1997; Tuttle and Chester, 2001)

Penitentiary fault

Figure 3

This study

Geophysical

COMMERCE

St. Francis River

Cache River

Mississippi River

Lowlands

Ozark Uplands

Eastern Lowlands

New Madrid

St. Francis River (Vaughn, 1994)

Clodfelter Ditch (Vaughn, 1994)

Quillin Ridge (Stephenson et al., 1999)

Mingo Ditch (Vaughn, 1994)

Dudley Main Ditch (Vaughn, 1994)

IHF

Sikeston Ridge

7.5' Chad

CF

PF

Photolineament

Lineament

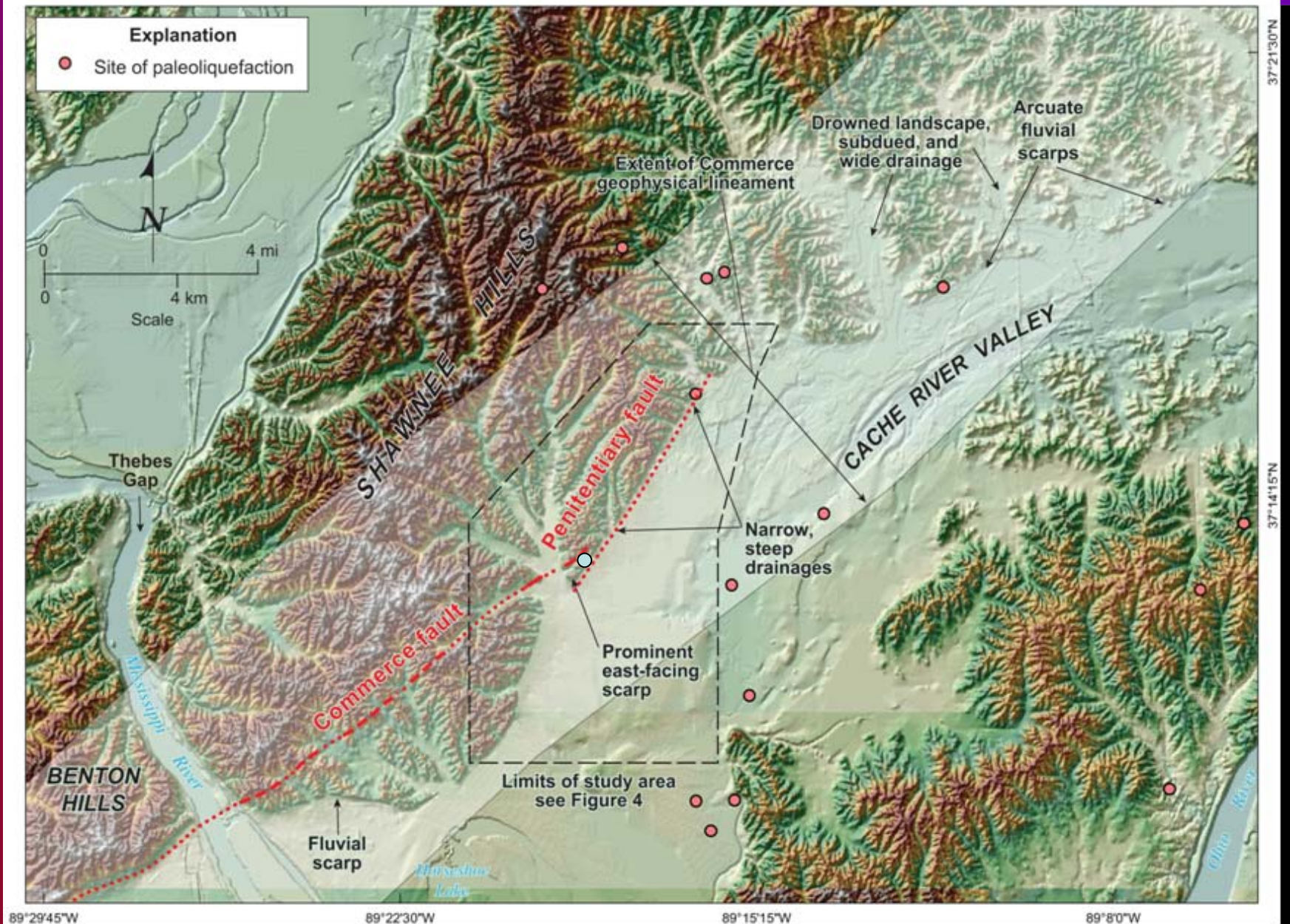
Scale

0 25 km

90°30'0"W 90°0'0"W 89°30'0"W 89°0'0"W

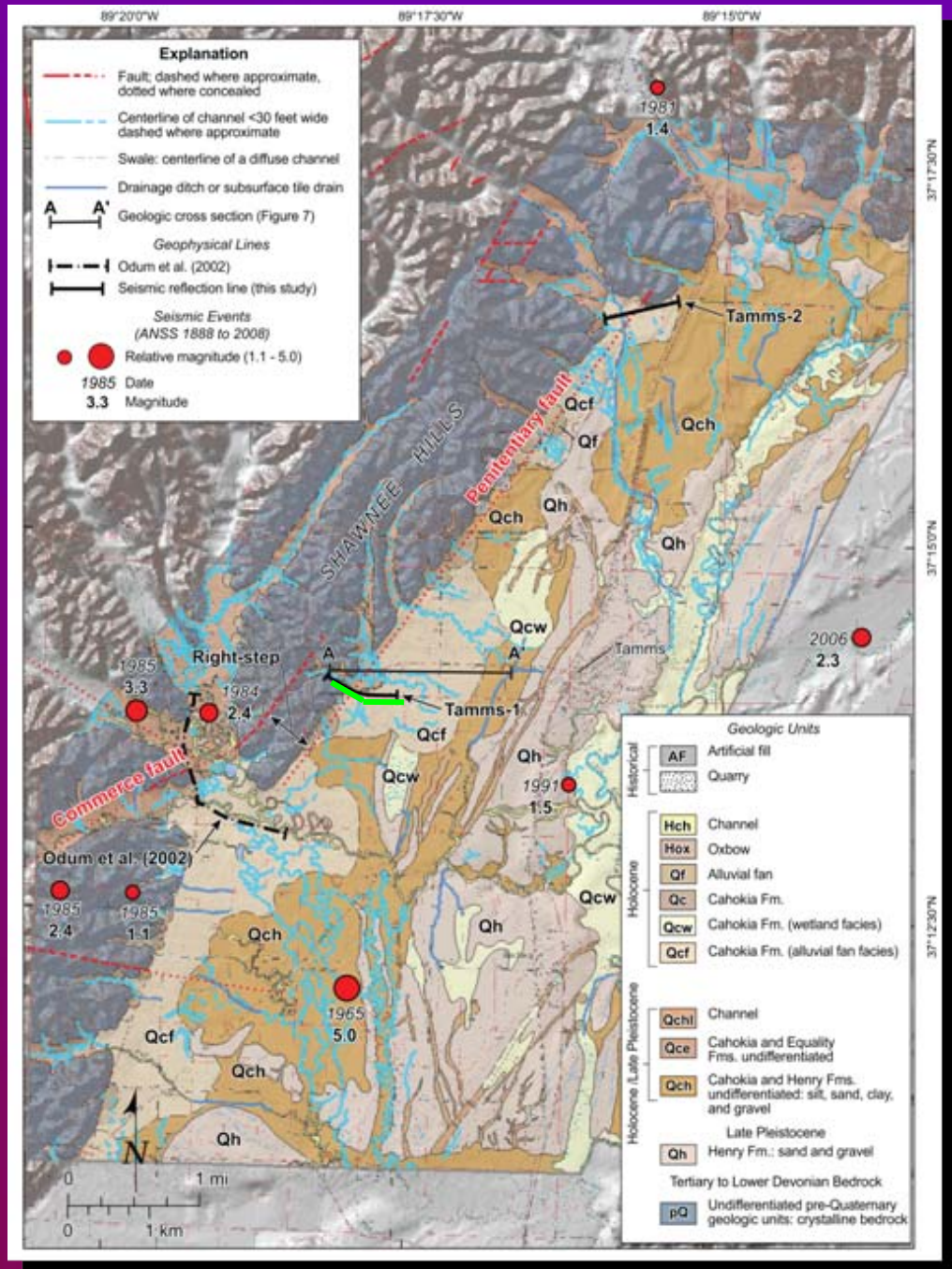
36°30'0"N 37°0'0"N 37°30'0"N

Cache River Valley, Southern Illinois



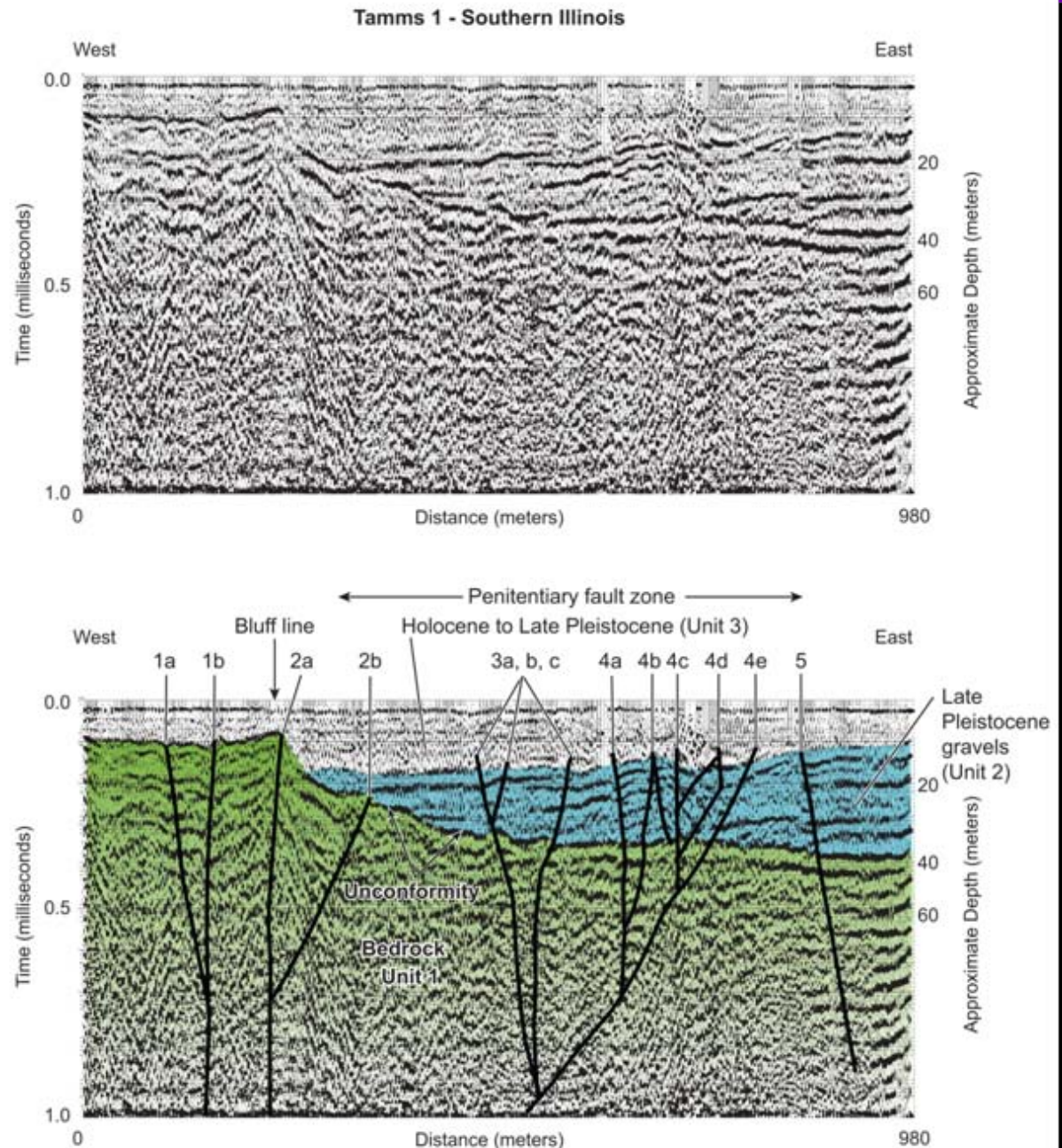
Penitentiary Fault

- Geomorphology
- Earthquakes
- Geophysical Profile
 - Odum et al. 2001
 - WLA (2008)
- Cross Section



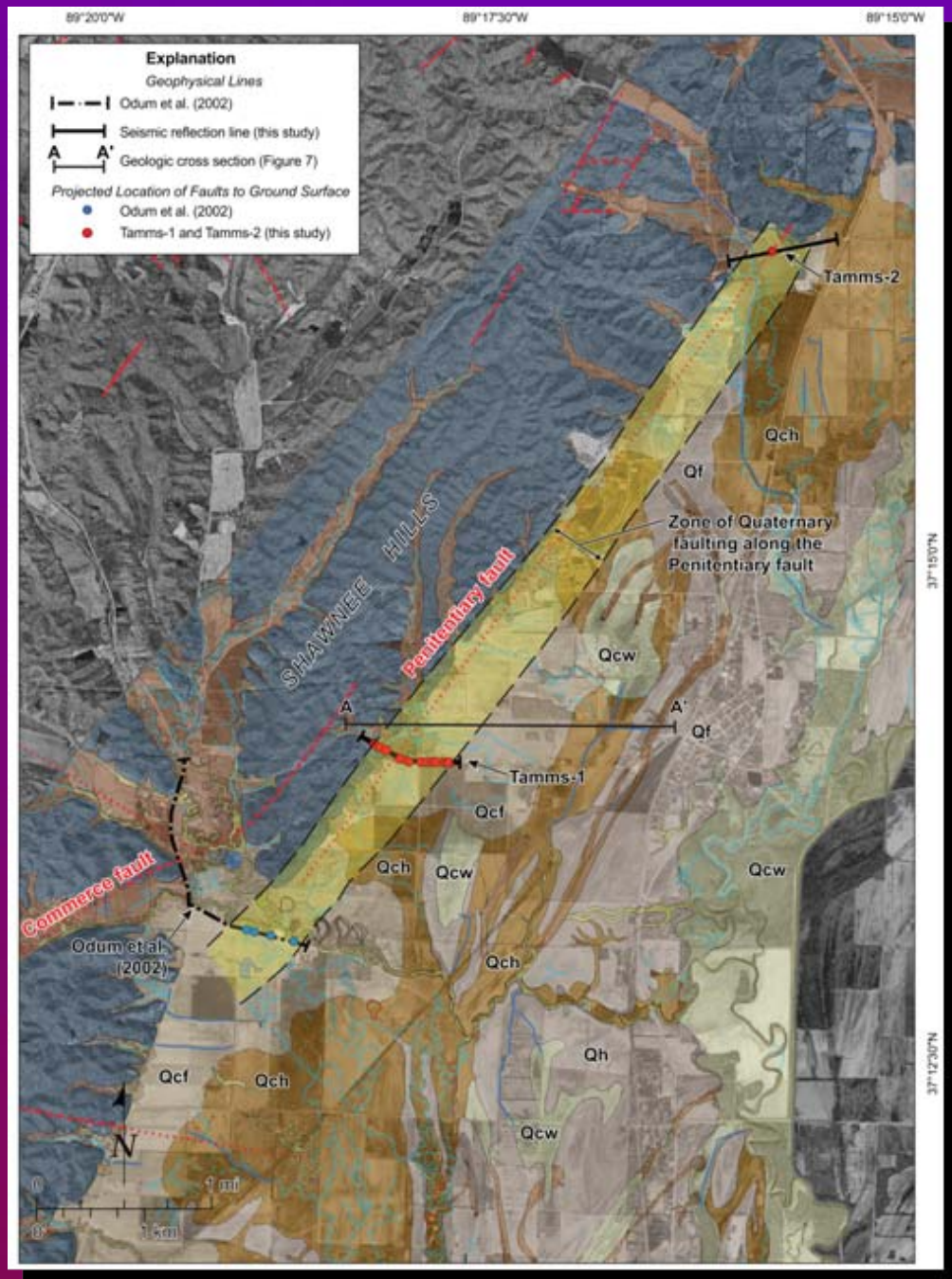
Shear -wave Seismic Reflection Survey

- Bedrock -Paleozoic Chert
- Buried east-facing escarpment (100 ft)
- Bedrock unconformity
- Multiple faults disrupting latest Pleistocene gravels
- Possible early Holocene deformation



Penitentiary Fault

- Coincident with CGL
- 3 seismic lines document possible Q-faulting
- Reactivated fault-line scarp
- Late Pleistocene and possible early Holocene faulting
- Continuation of Penitentiary fault to the north is poorly constrained



[illegible]

CGL Summary

- (1) Where overlain by NE-striking faults episodic activity is evident
- (2) Weak alignment of historical microseismicity (strike-slip)
- (3) Weak alignment of historical microseismicity (strike-slip)
- (4) Multiple trenching and geophysical profiles support Late Quaternary activity
- (5) From paleoliquefaction (western lowlands) and earthquake timing data (Bloomfield and Benton Hills), appears to have been active into at least the early Holocene.
- (6) Evidence for Late Quaternary deformation along a 75- to 120-km long section between southeastern Missouri and southern Illinois
- (7) Modeling suggests a structure extending to ~10 km in depth
- (8) Earthquake timing data is sparse but suggests long recurrence intervals and possibly episodic behavior

Some Mississippi Valley Holocene faulting and liquefaction beyond the New Madrid seismic zone

Randy Cox
Dept of Earth Sciences
Univ of Memphis



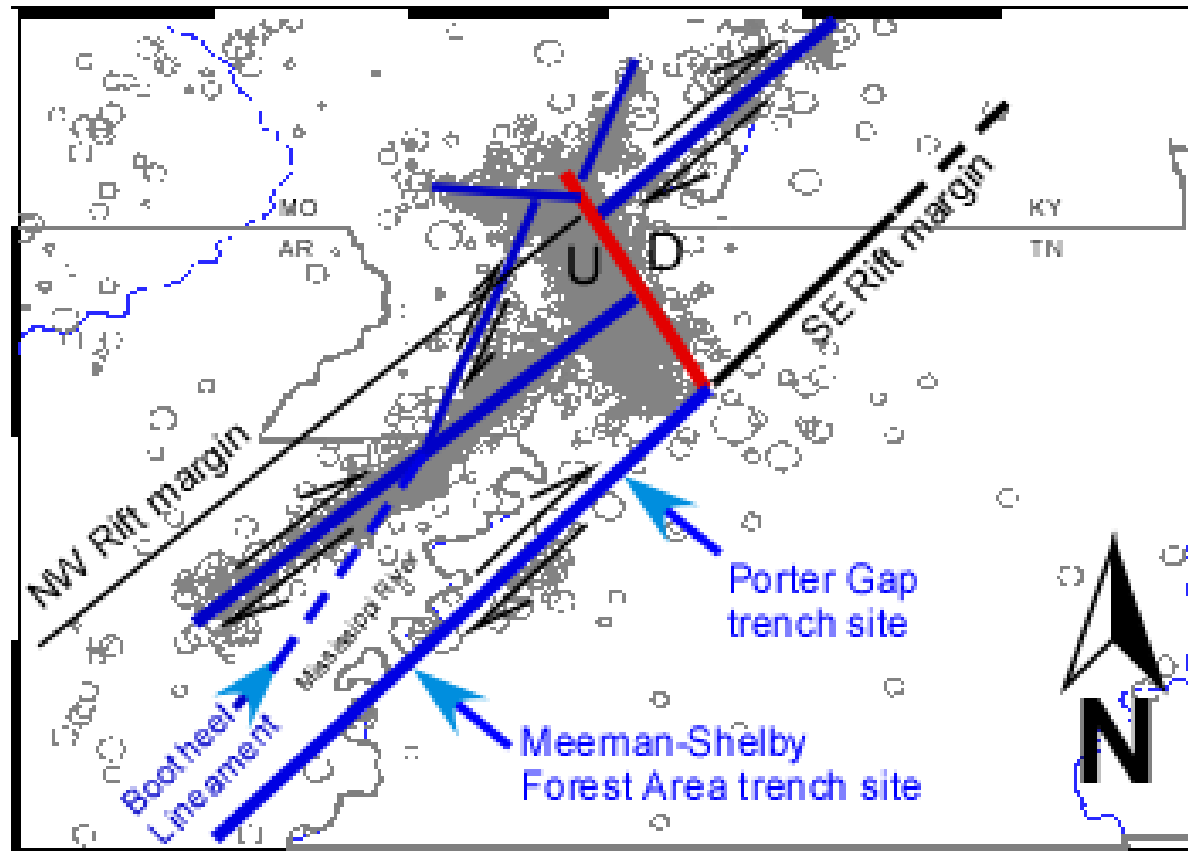
The background image is a photograph of a geological outcrop. It shows a complex pattern of sedimentary layers and faults. A prominent fault line runs diagonally from the upper left towards the center. The rock colors are primarily shades of yellow, tan, and brown, with some darker, possibly carbonaceous, layers. The texture is rough and weathered.

Part 1

Southeast
Reelfoot
Rift Margin
Surface Faulting

91W
37N

88W



$n \geq 5$ ○

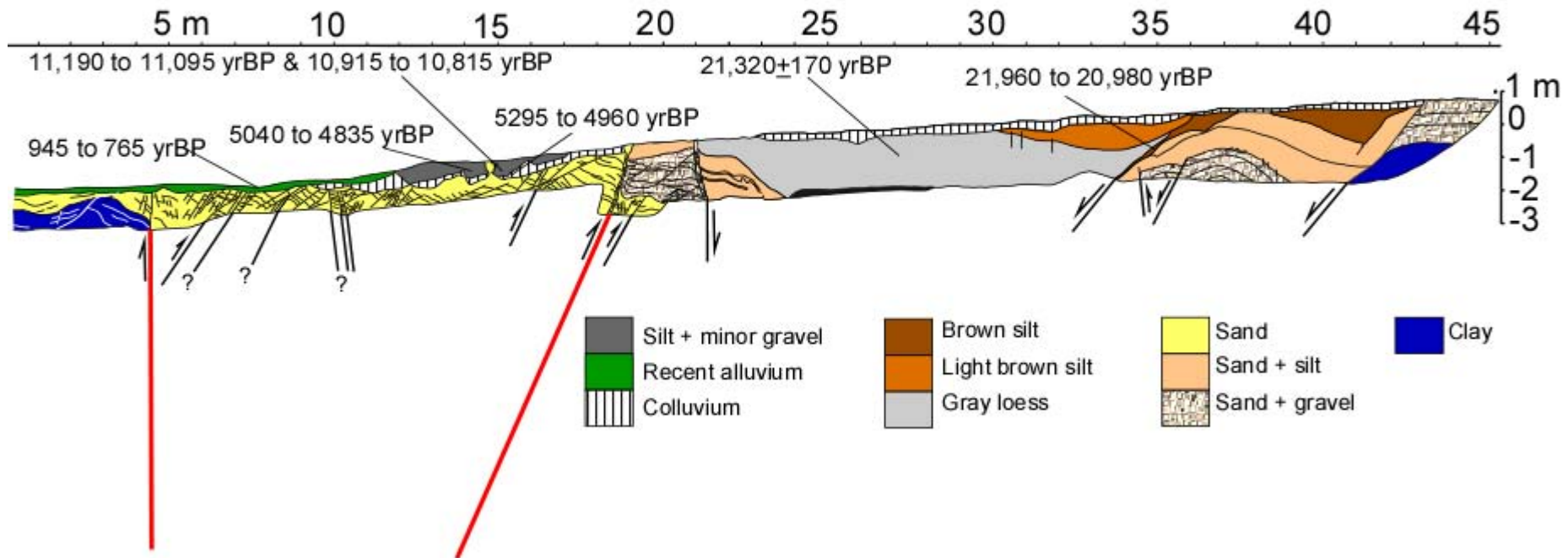
$n \geq 4$ ○

$n \geq 3$ ○

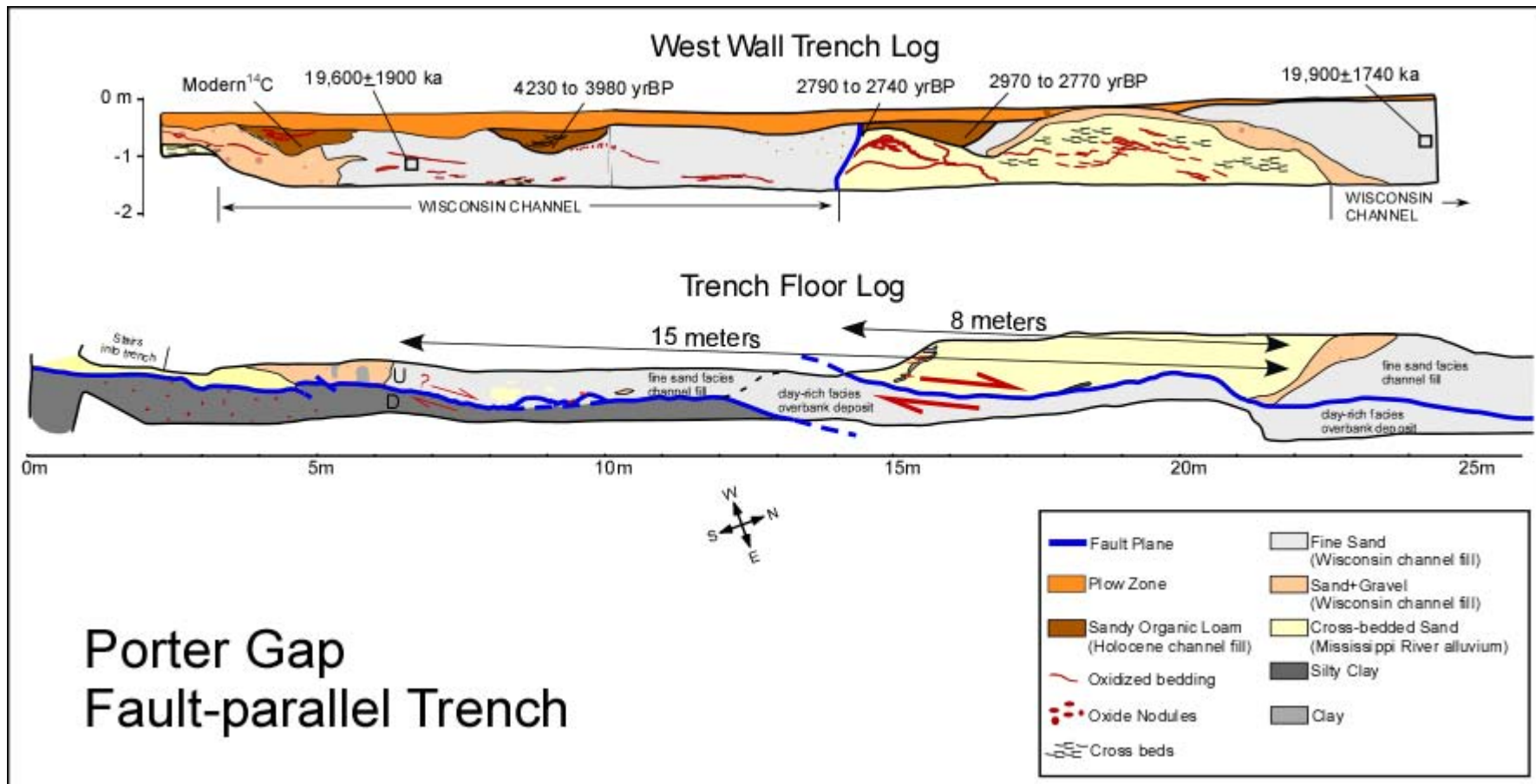
$n \geq 2$ ○

$n \geq 1$ ●

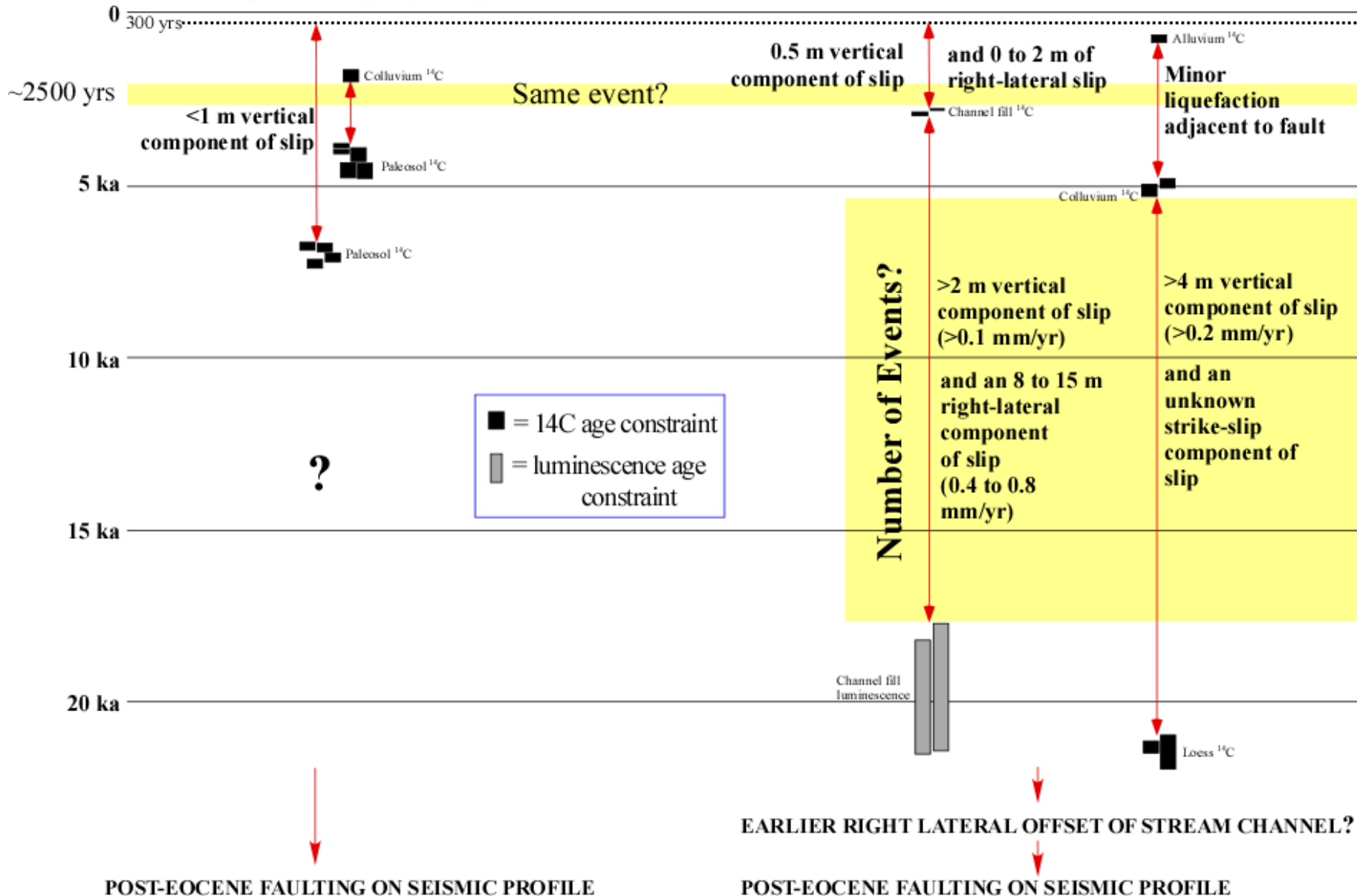
Porter Gap Trench 1



Offset Eocene horizons in
shallow S-wave reflection profiles



MEAMAN-SHELBY FOREST FAULT ← ~80 km → PORTER GAP FAULT 1 PORTER GAP FAULT 2



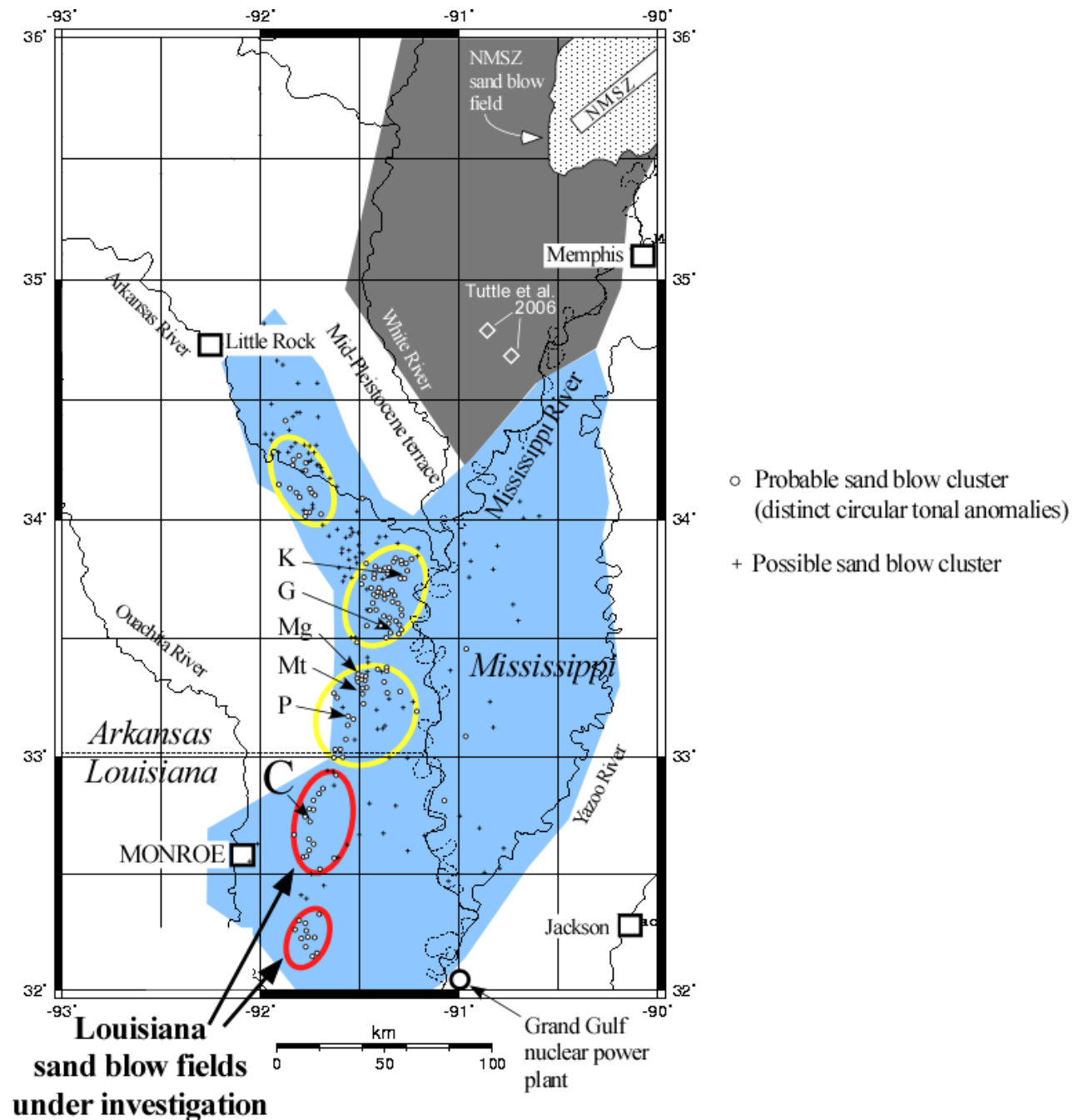
- **Known**
 - 0.5 to 0.8 mm/yr right-slip component since late Wisconsinan on one of at least two principal fault strands
 - >0.3 mm/yr total dip-slip component for both of the two principal fault strands
 - Small (0.5 m vertical, <2 m right-slip) late Holocene activity (~2500 yr BP)
- **Unknown**
 - Total rate of slip across fault zone
 - Number of faulting events
 - Length of ruptures
- **Uncertainties**
 - Great

A wide-angle photograph of a vast, flat landscape, likely a coastal plain or marsh. The ground is covered in dense, low-lying vegetation, possibly salt-tolerant plants, in shades of brown and green. Two people are walking away from the camera in the middle ground, providing a sense of scale. The horizon is flat and distant, with a few small trees visible on the left. The sky is a pale, uniform color, suggesting an overcast day.

Part 2

Southern Mississippi Embayment Sand Blows

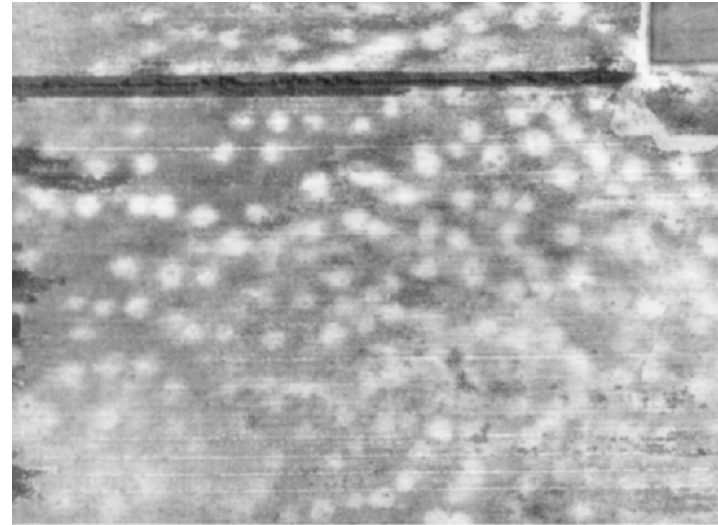
SAND BLOW AERIAL PHOTO SURVEY



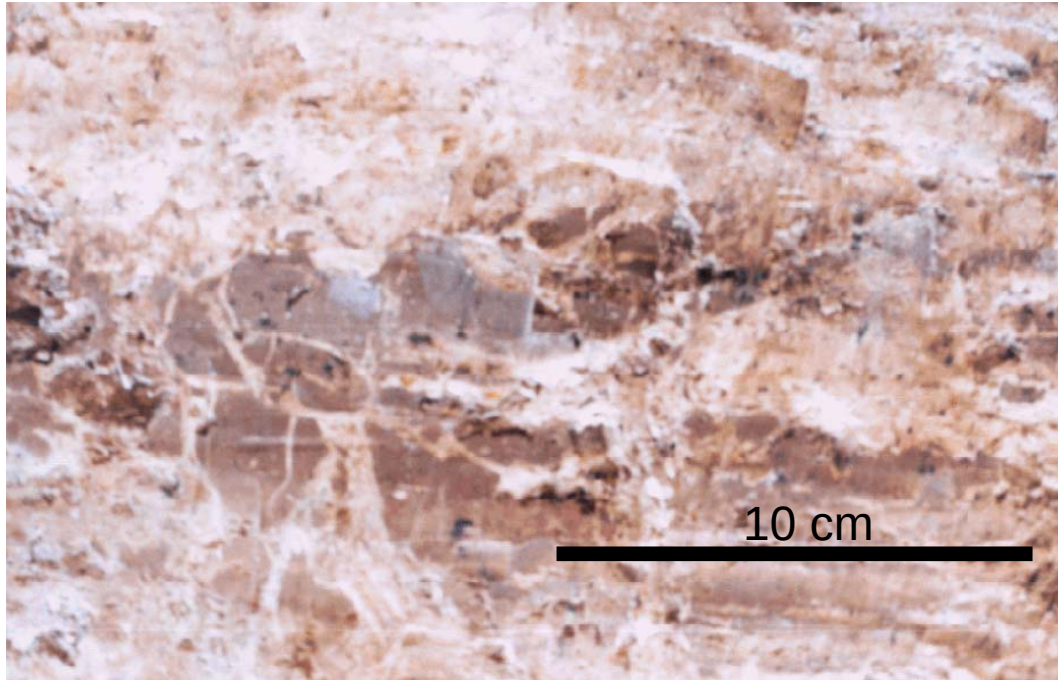
“Popcorn” sand blows



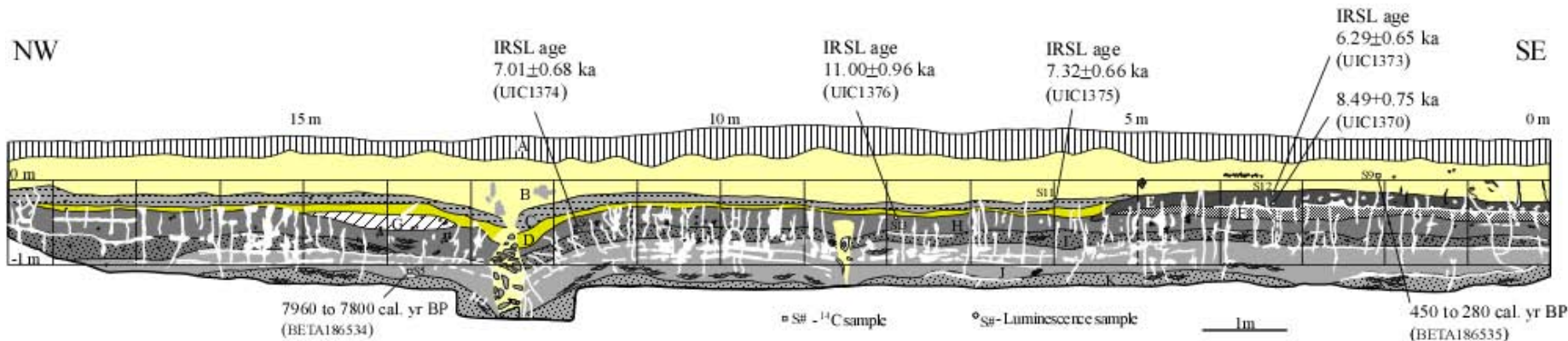
Blows in New Madrid seismic zone



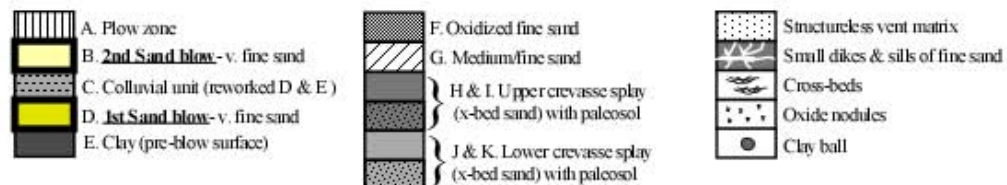
Blows in southern Arkansas



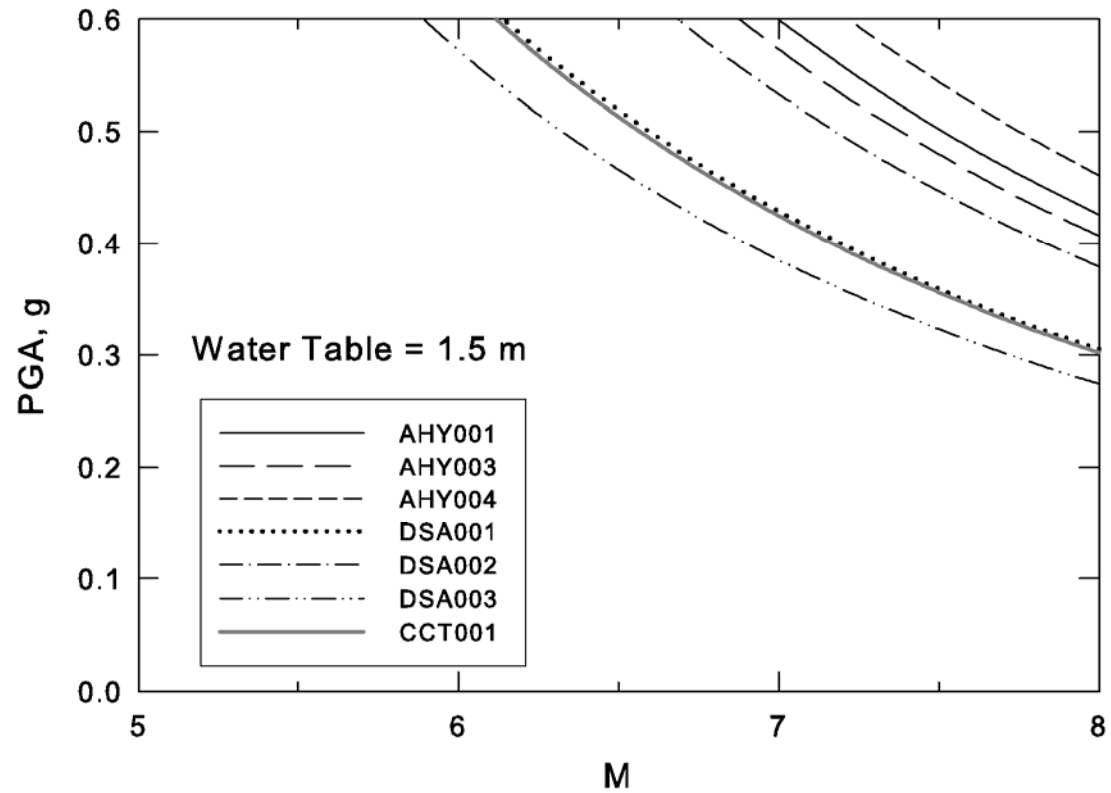
Hydraulic fracturing of sub-blow clay

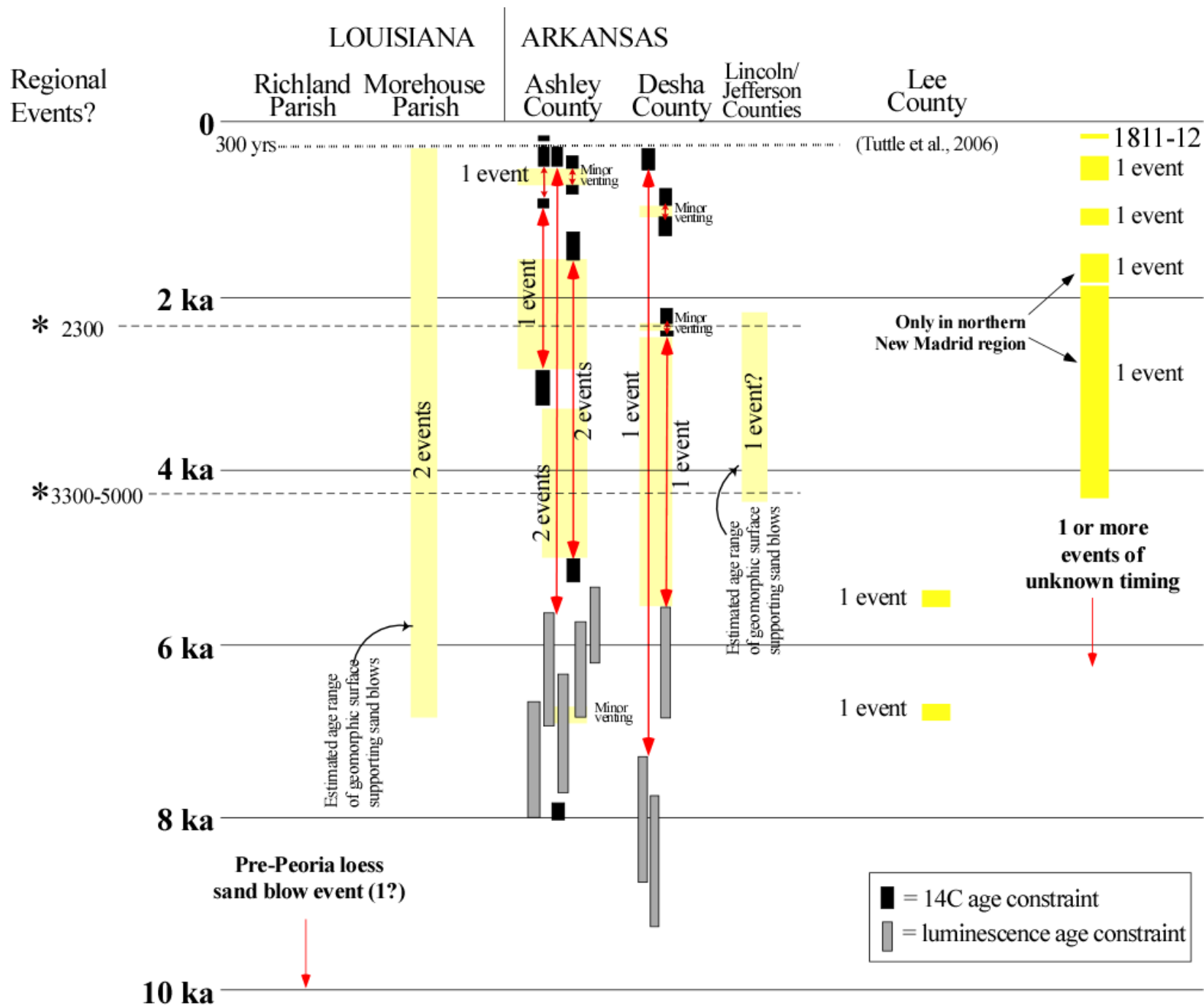


MORGAN TRENCH LOG ASHLEY CO., ARKANSAS



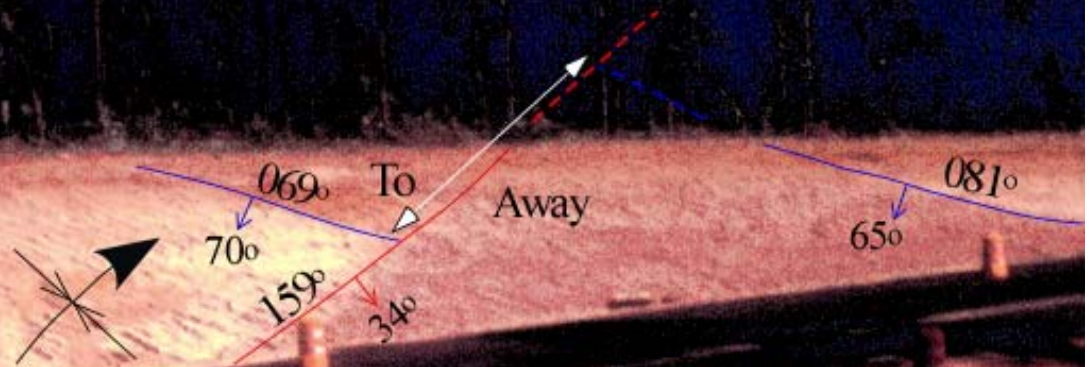
Cone Penetration Tests





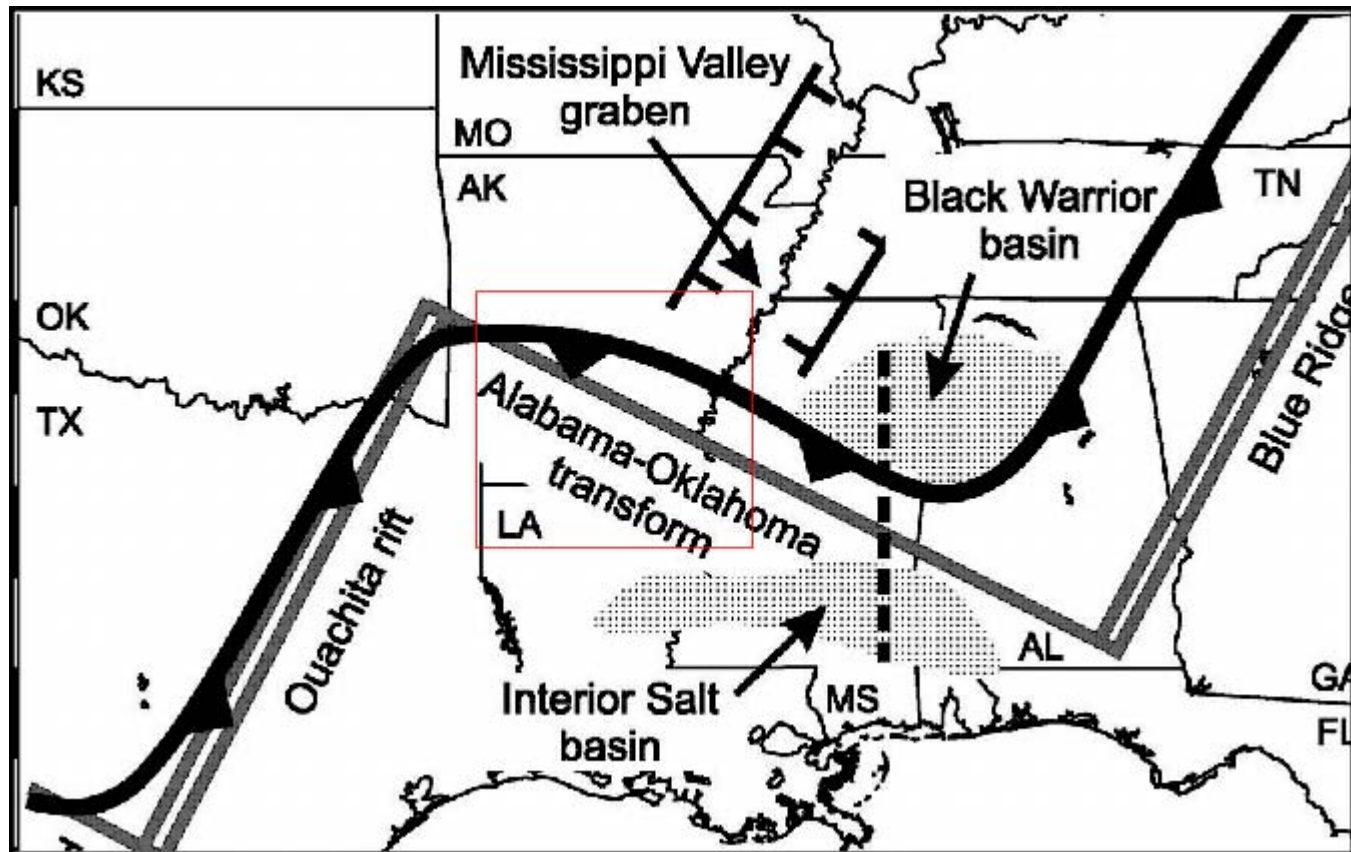
- **Known**
 - Multiple events
 - Hydraulic fracturing
 - Minimum radii of fields suggests $M \geq 6$
 - Cone penetration tests indicate $M \geq 6$
- **Unknown**
 - True radii of fields
 - Epicenters
 - Recurrence (1000 to 2000 years?)
- **Uncertainties**
 - Great

Part 3



Saline River Fault System

Craton Margin

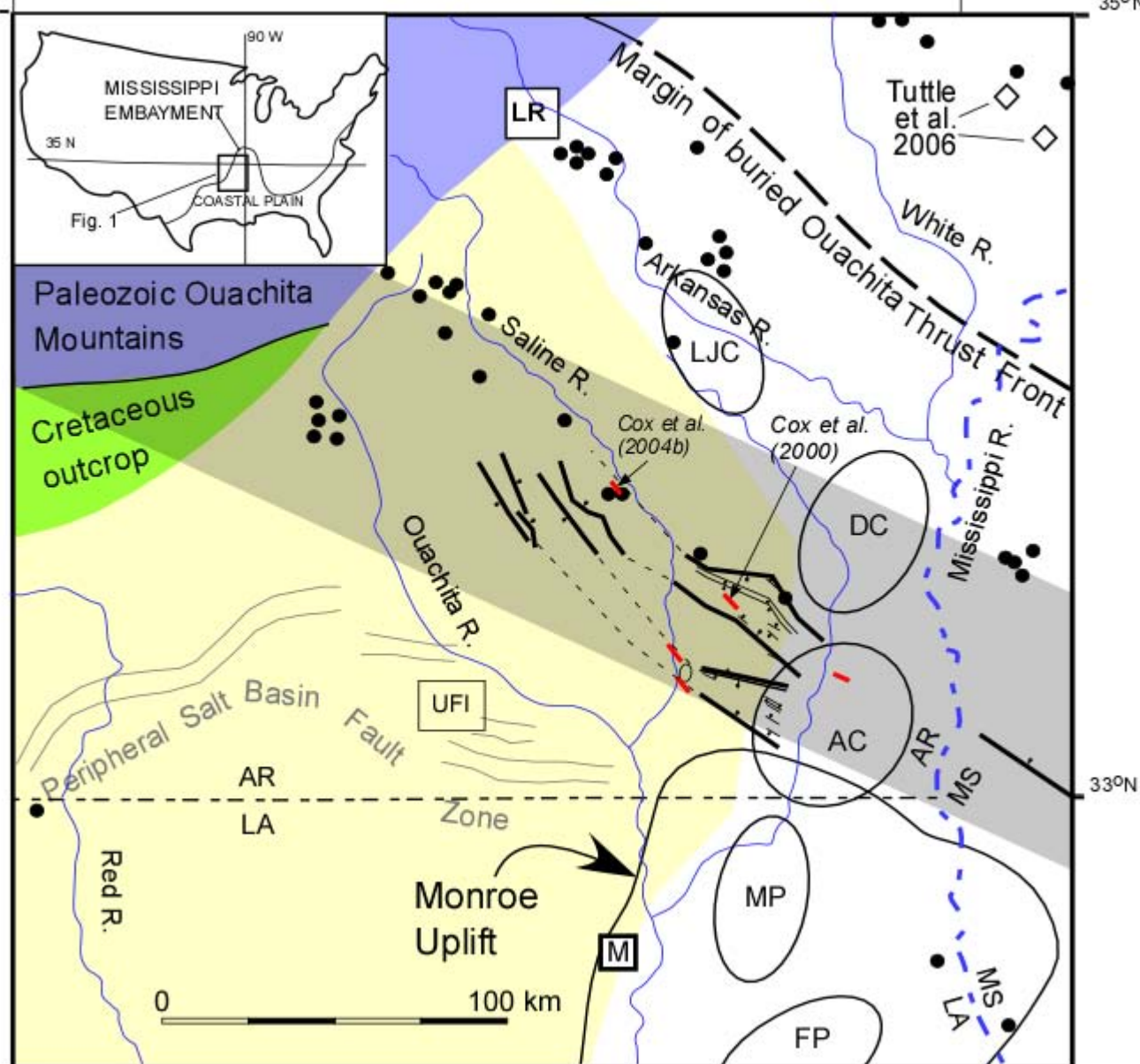


94°W

CRATON MARGIN PALEOSEISMICITY

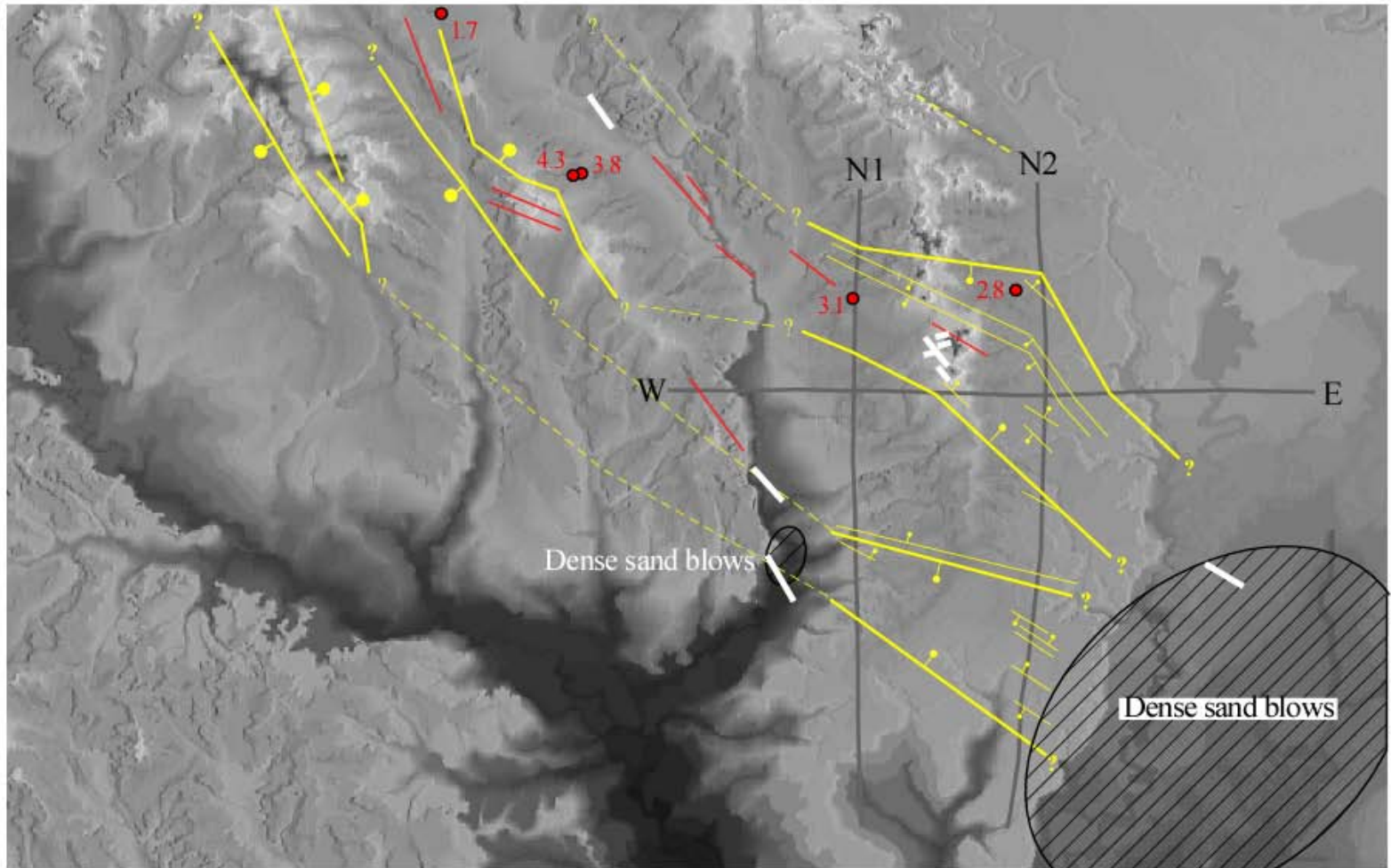
91°W

35°N



MAPPED SALINE RIVER FAULT SYSTEM

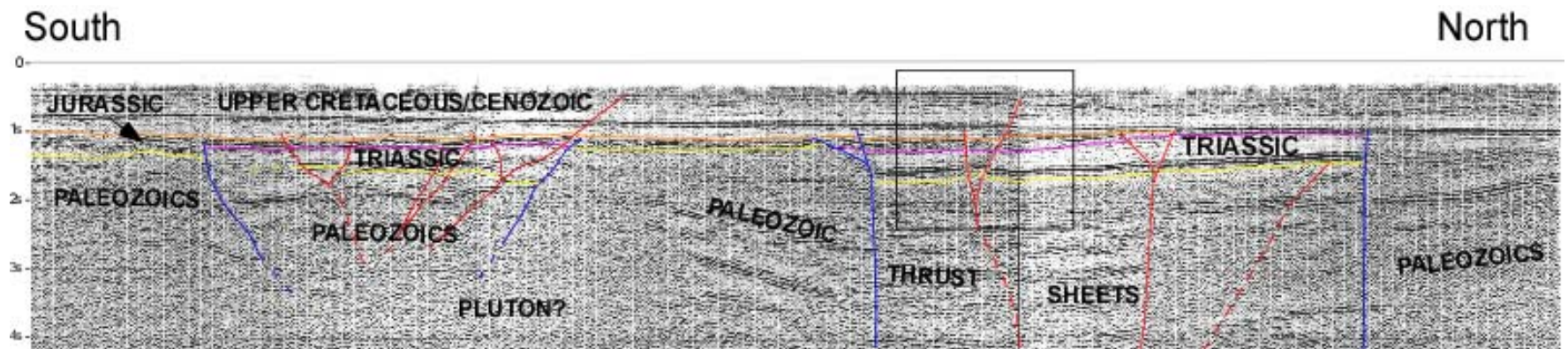
92.85°
33.99°



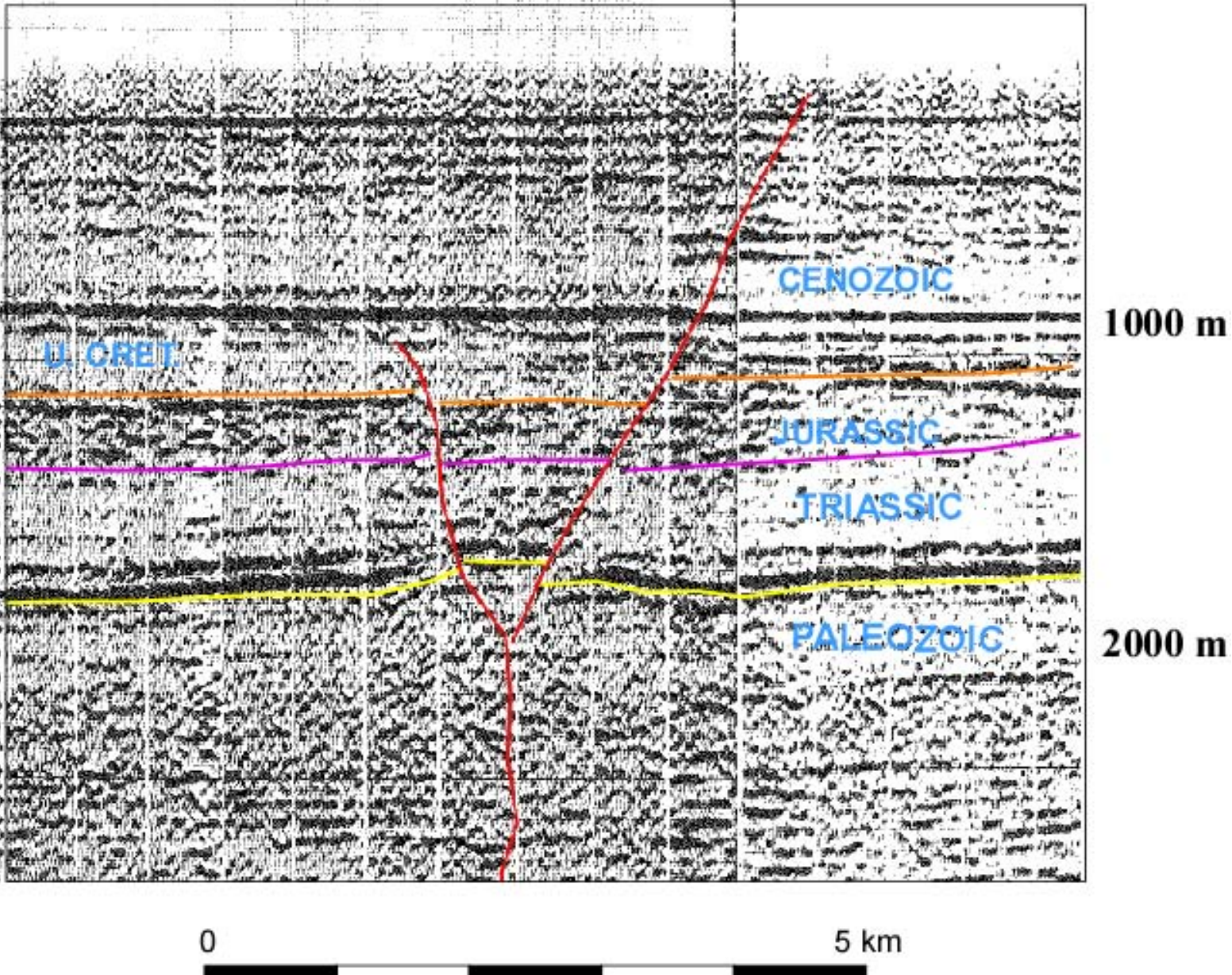
50 km

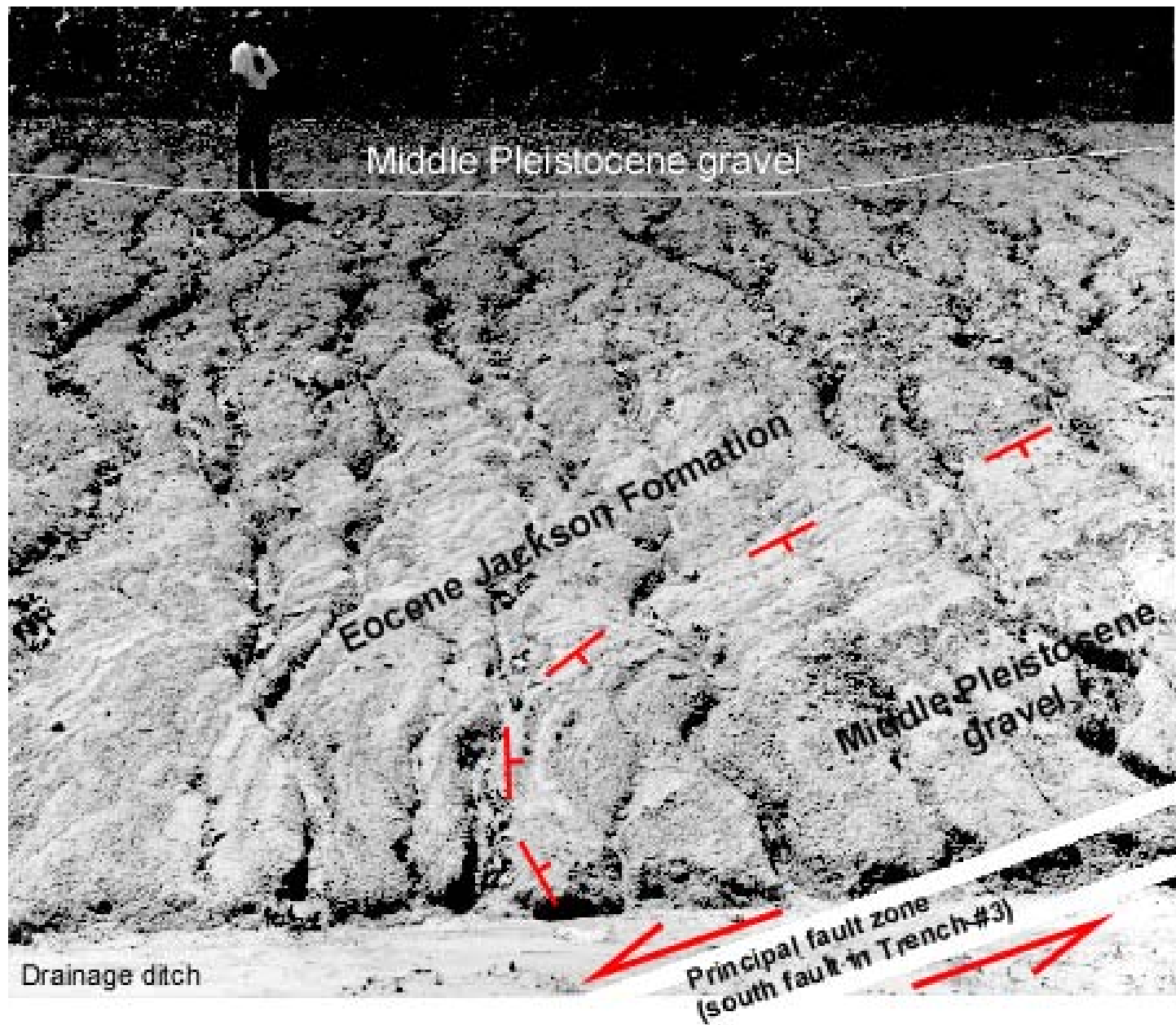
33.01°
91.29°

Part of east seismic line showing triassic grabens



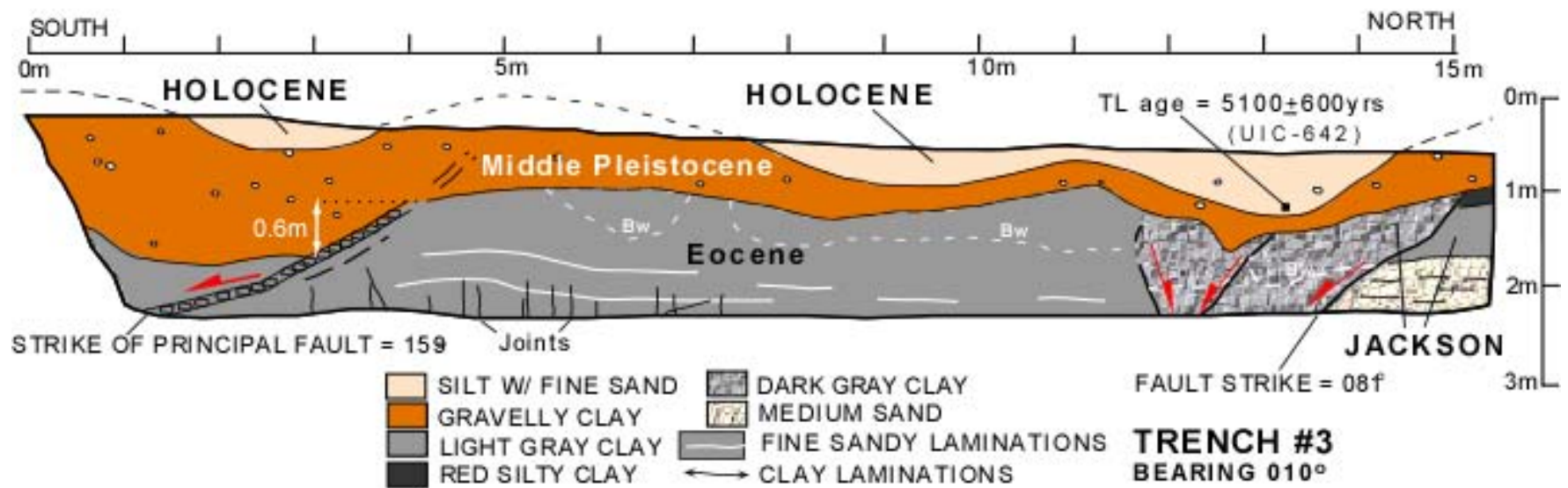
Flower structure



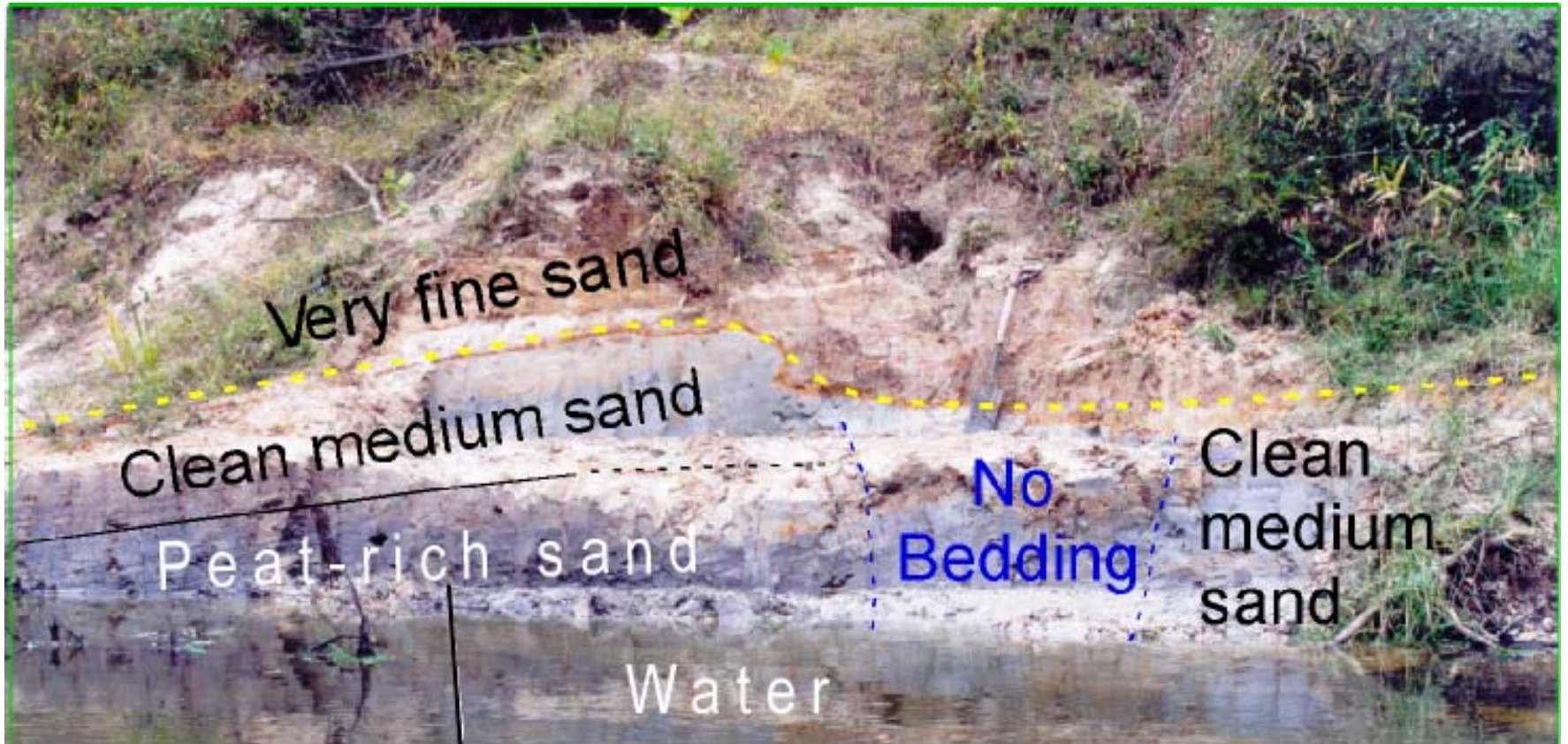


Monticello, Arkansas roadcut

Monticello trench log

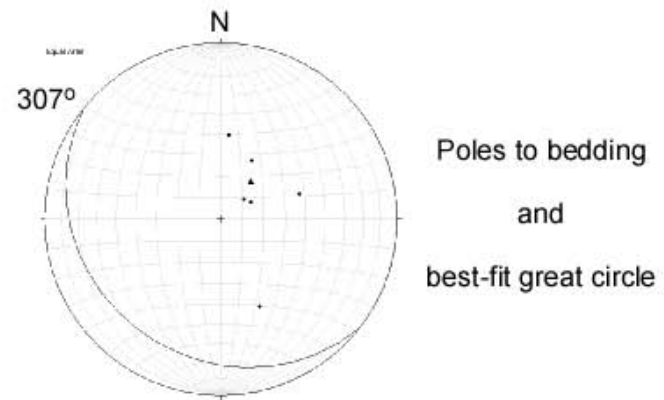
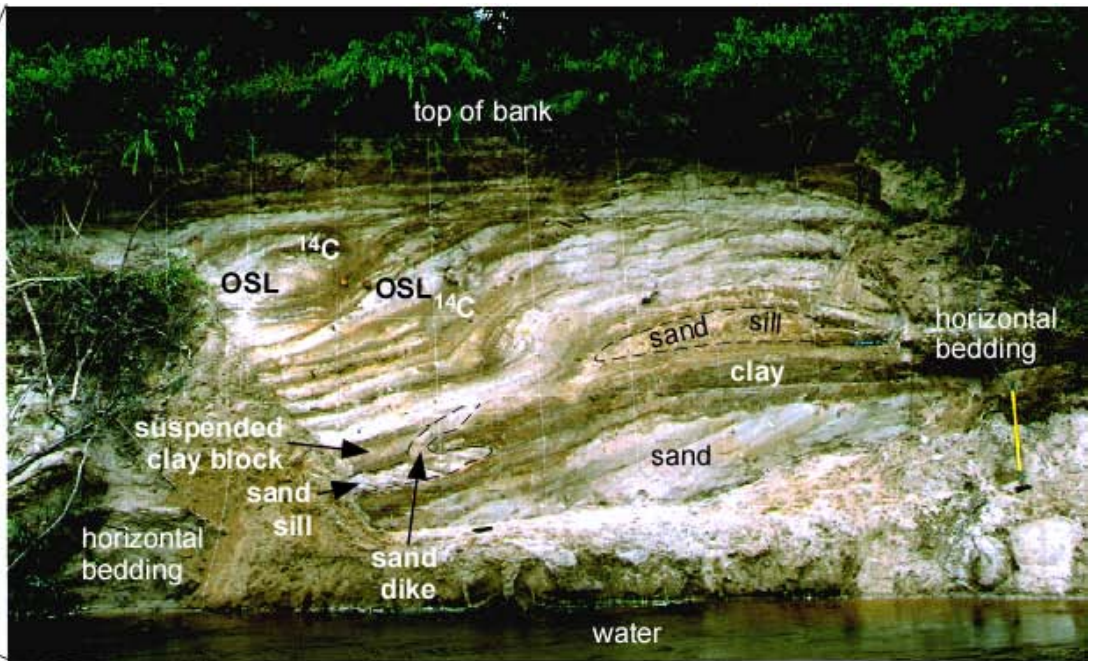
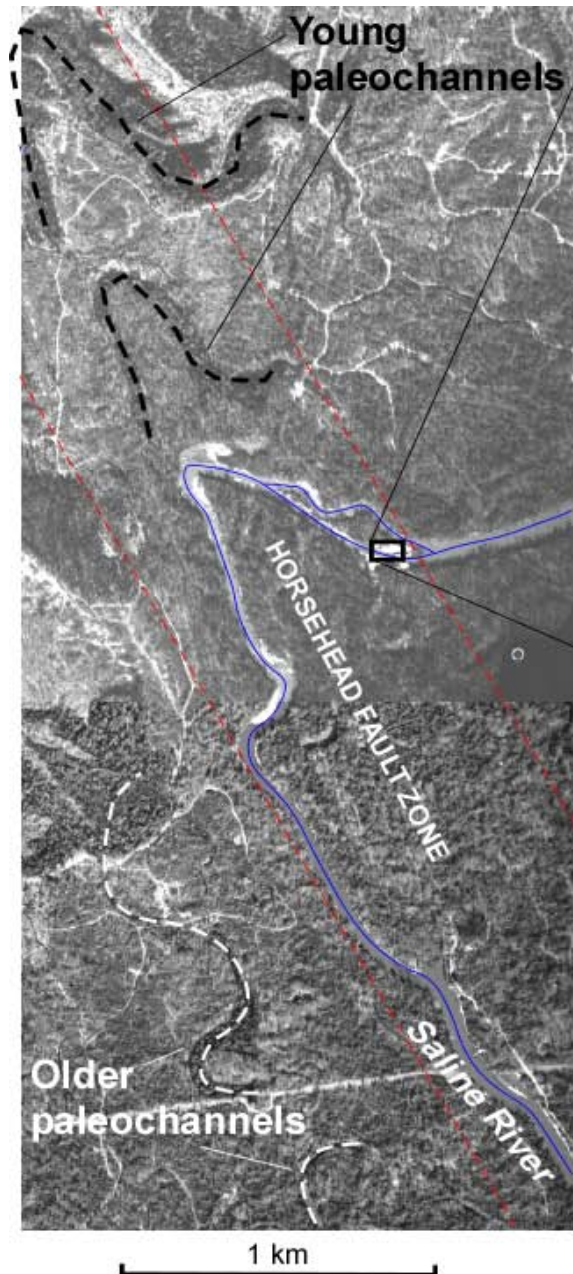


Rison, Arkansas cutbank

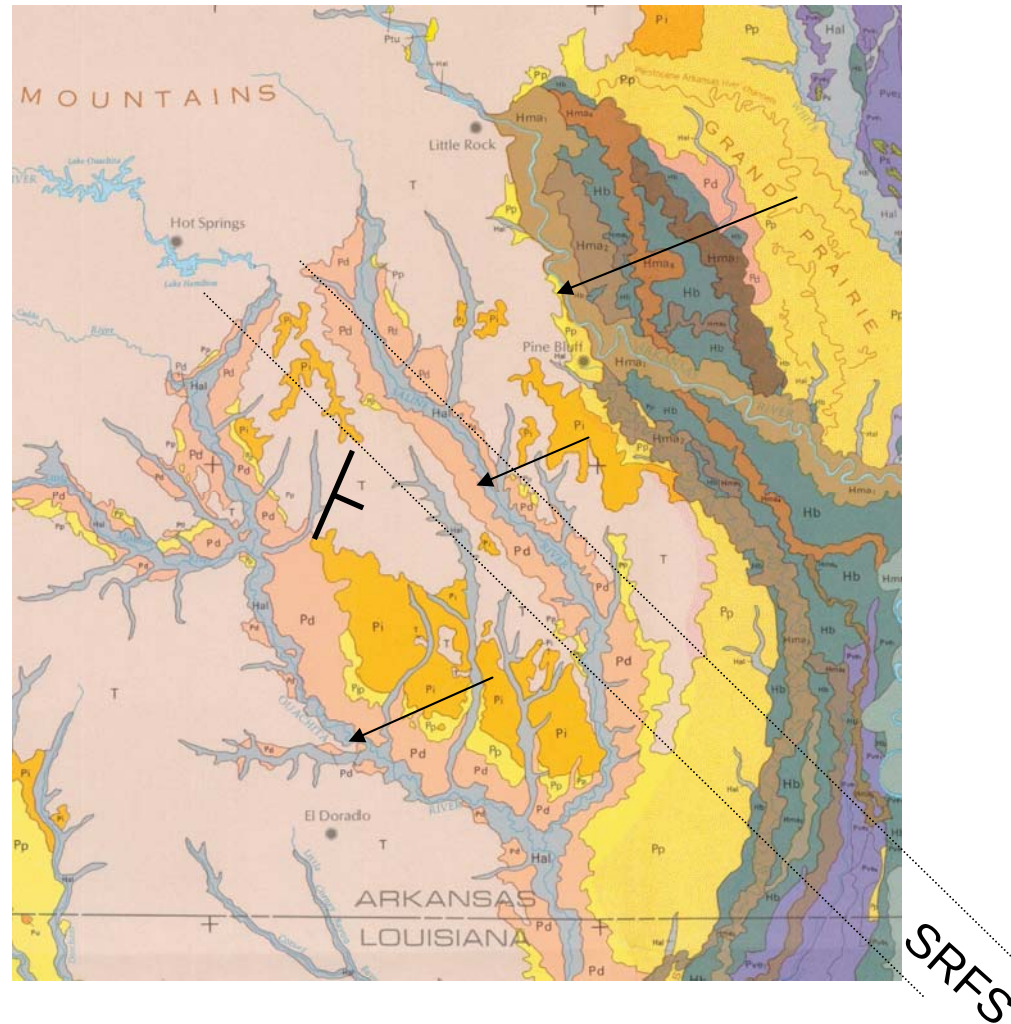


Cal BP 720 to 550

Horsehead Bend, Saline River, Bradley Co., Arkansas

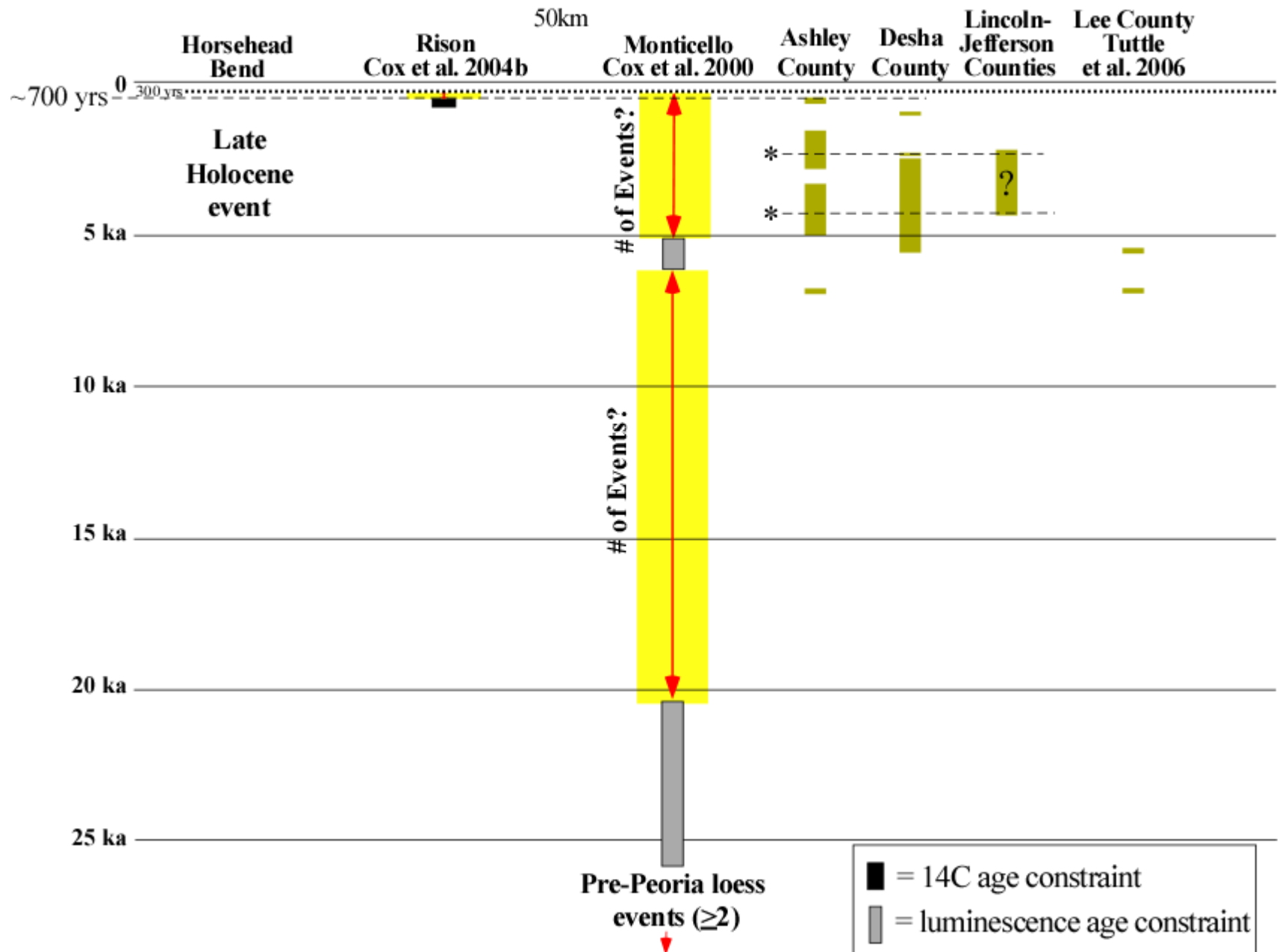


Asymmetric terraces = long-term Quaternary tilting



Saline River faulting events

Sand blow fields



- **Known**
 - **Saline River fault system = reactivated Triassic graben system following the craton margin (Alabama-Oklahoma transform fault)**
 - **One or more late Holocene faulting events on 2 different faults (Monticello fault & Horsehead fault) within Saline River fault system**
 - **Left-lateral slip component (1.3 mm/yr on principal? strand)**
 - **The timing and location of faulting is consistent with regional liquefaction timing**
- **Unknown**
 - **Rate of slip across fault zone**
 - **Number of faulting events**
 - **Length of ruptures**
- **Uncertainties**
 - **Great**

Reprints available at:

https://umdrive.memphis.edu/xythoswfs/webui/_xy-10366681_docstore1

or

<https://umdrive.memphis.edu/randycox/public/CEUS%20neotectonics%20papers>

Paleoliquefaction Interpretation of the Vincennes Earthquake, Wabash Valley Seismic Zone

Russell A. Green

*Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Tech*



Palo Alto, CA



February 19, 2009

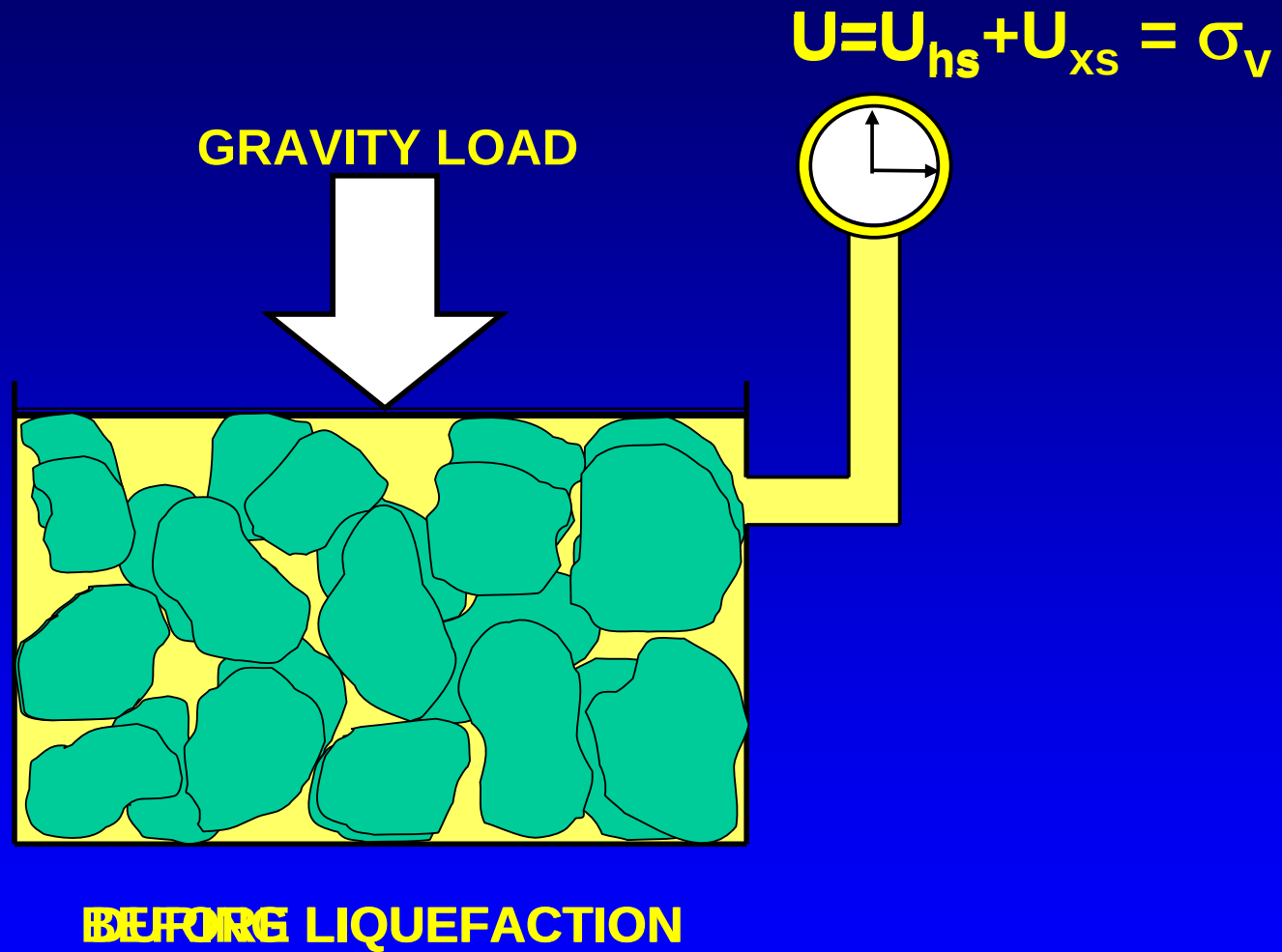
Collaborators:

- Dr. Scott M. Olson, University of Illinois
- Dr. Stephen Obermeier, USGS, Emeritus
- Dr. Patrick Munson, Indiana University, Emeritus

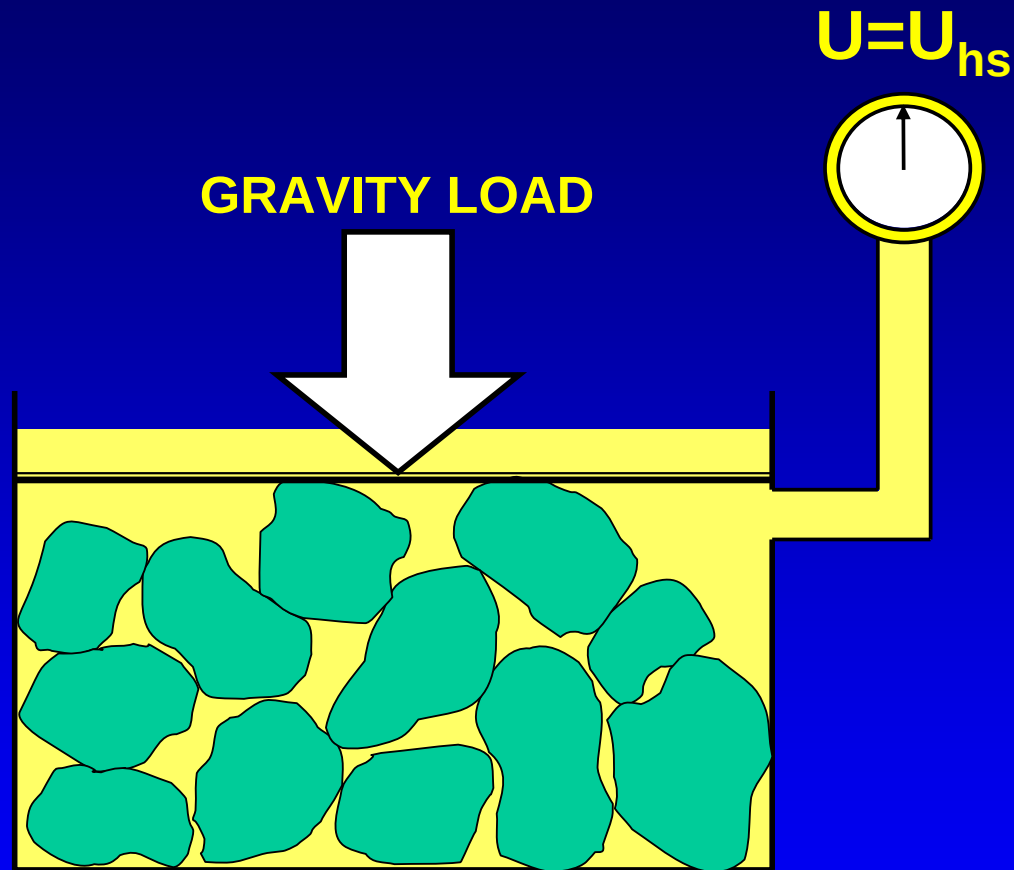
Outline:

- Review of Liquefaction Phenomenon
- Back-calculating Earthquake Magnitude
- Wabash Valley – Vincennes Earthquake
- Questions Asked to Address
 - Paleoliquefaction data – seismic source constraints
 - Large M, distant eqk vs. Small M, regional eqks
 - Uncertainties
 - Ground motion predictive relationships
 - Field interpretations
 - Back-analysis
- Some Hazards of Paleoliquefaction Field Interpretations

Review of Liquefaction Phenomenon

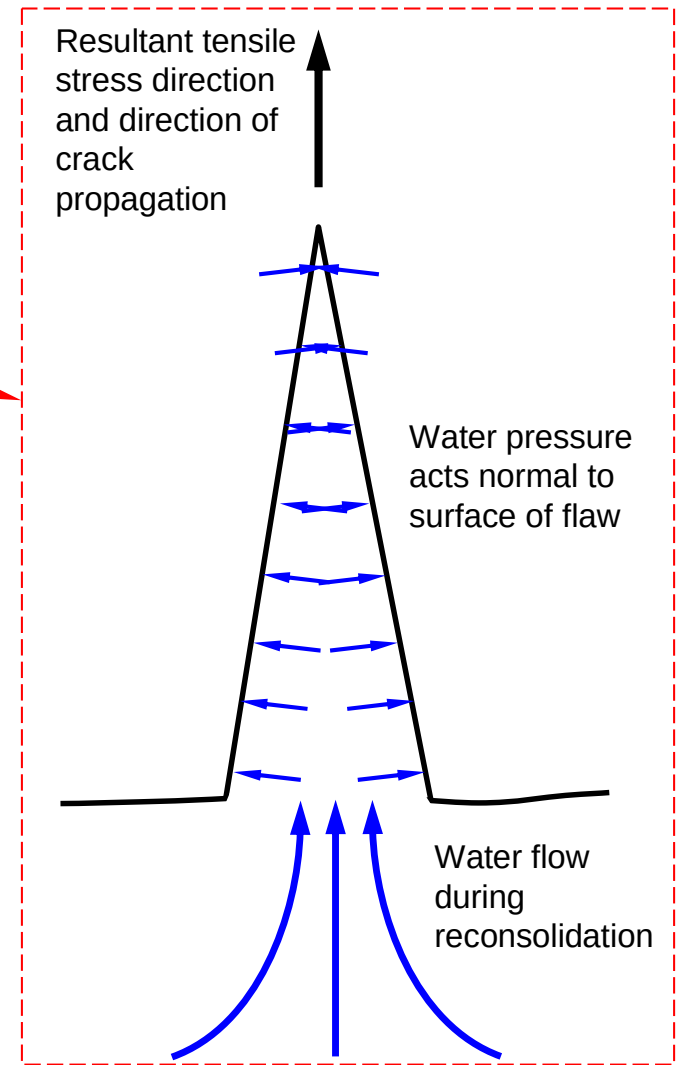
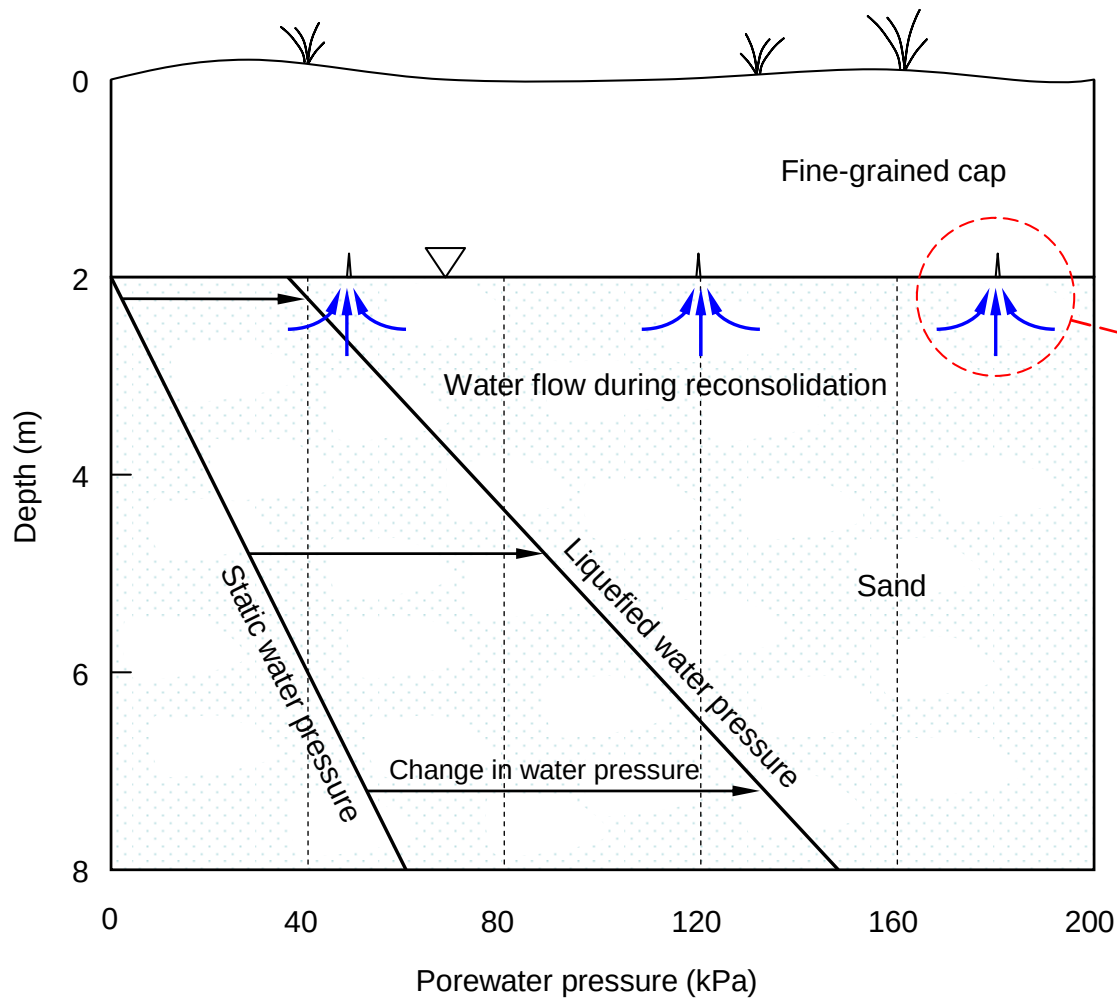


Review of Liquefaction Phenomenon



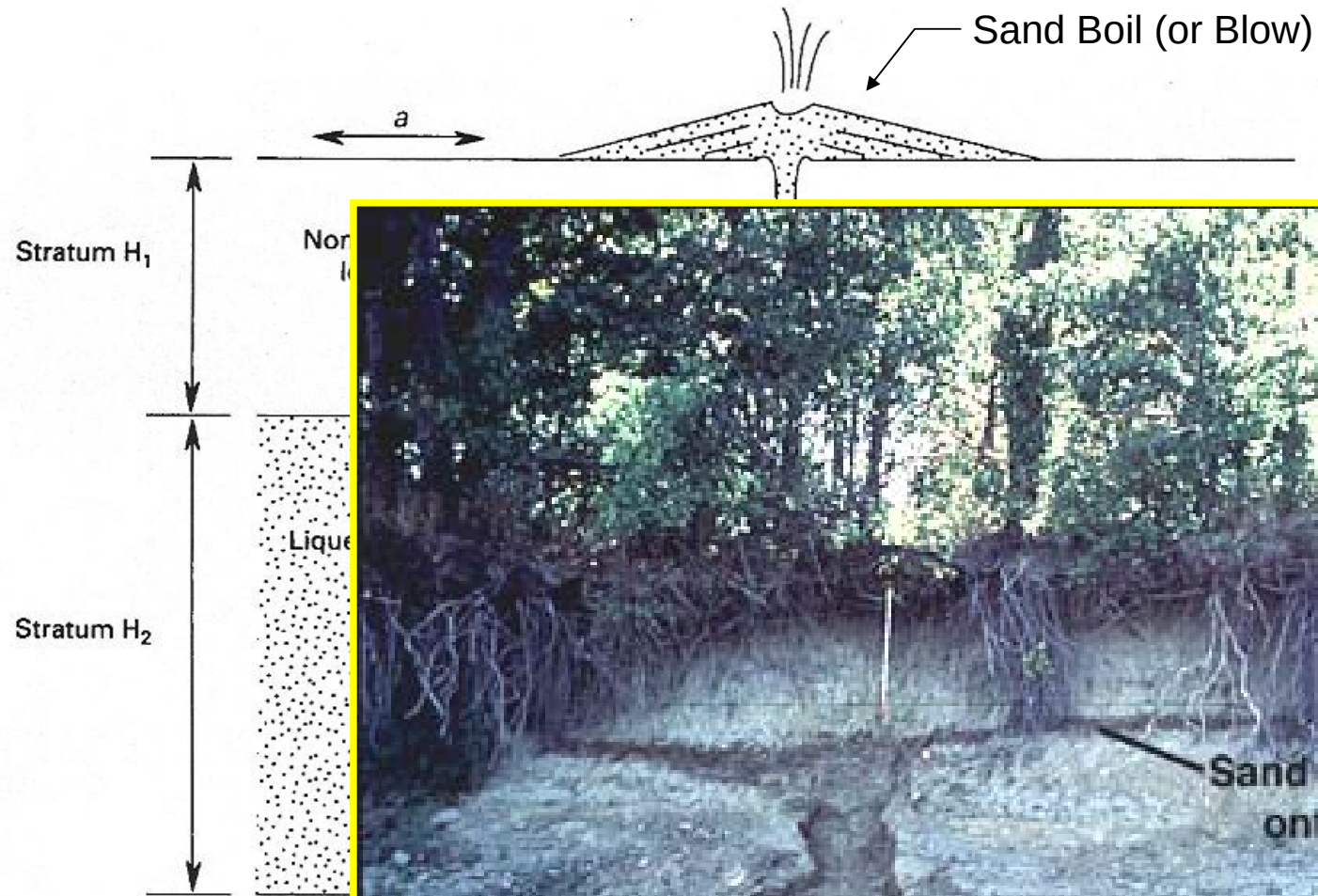
POST DENSIFICATION

Review of Liquefaction Phenomenon



(Olson et al. 2009)

Review of Liquefaction Phenomenon



Surfacial Evidence of Liquefaction



**1964 Niigata, Japan
(Steinbrugge Collection)**



**Crater formation & Spreading of Sand at Ten-Mile Hill
1886 Charleston Earthquake (from Dutton 1889)**

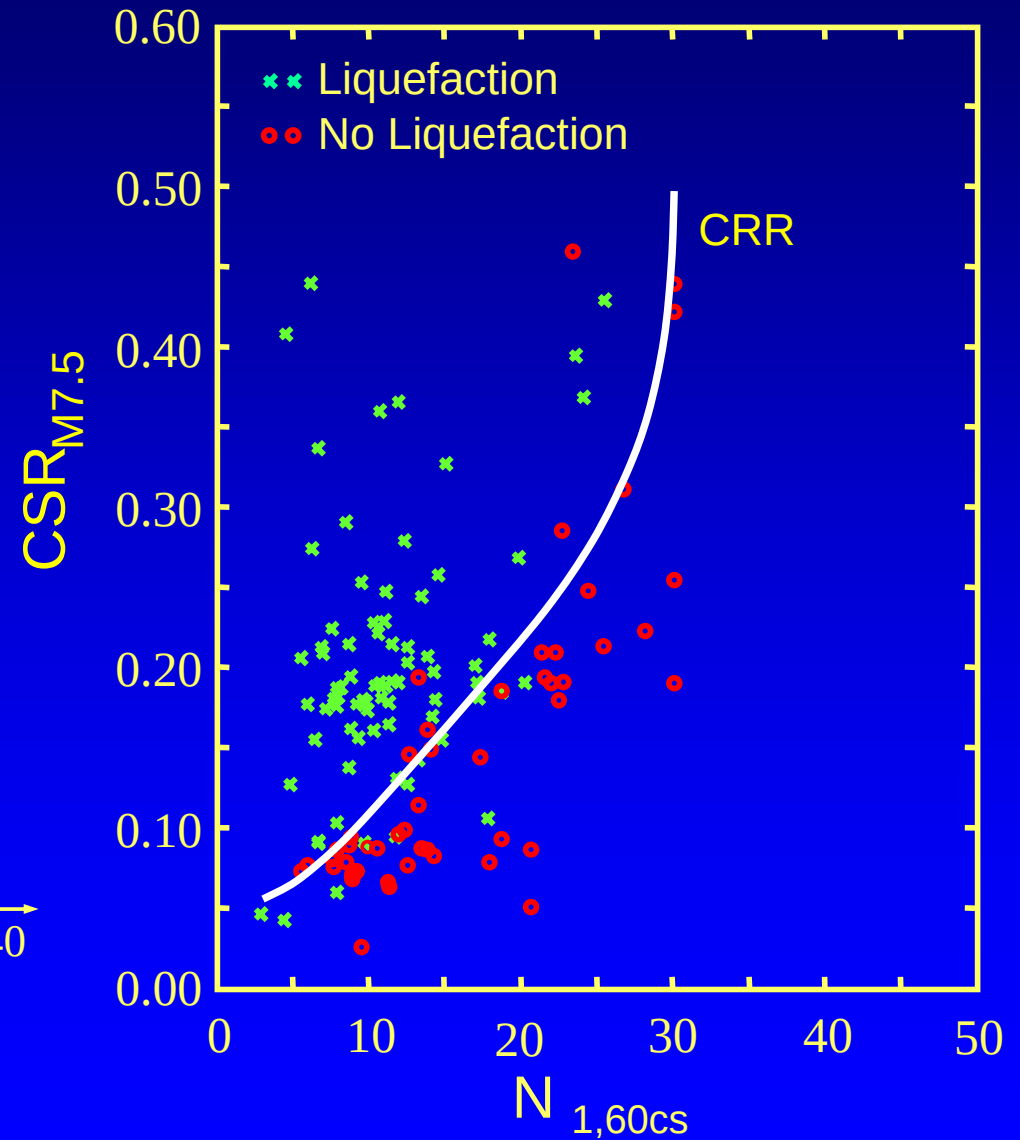
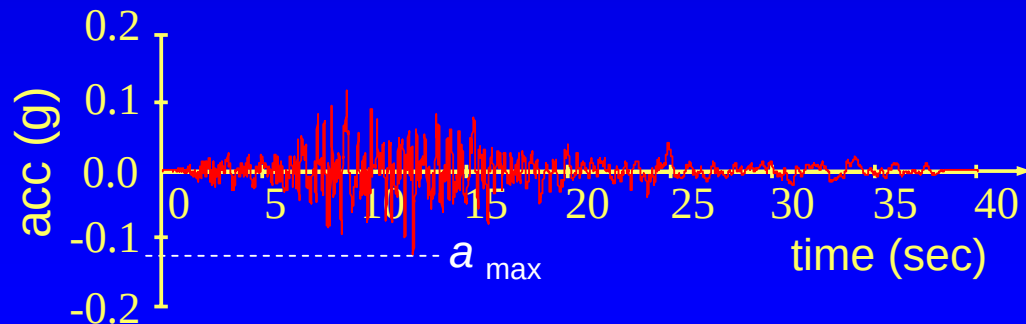
1964 Niigata, Japan Earthquake



“Simplified” Liquefaction Evaluation Procedure

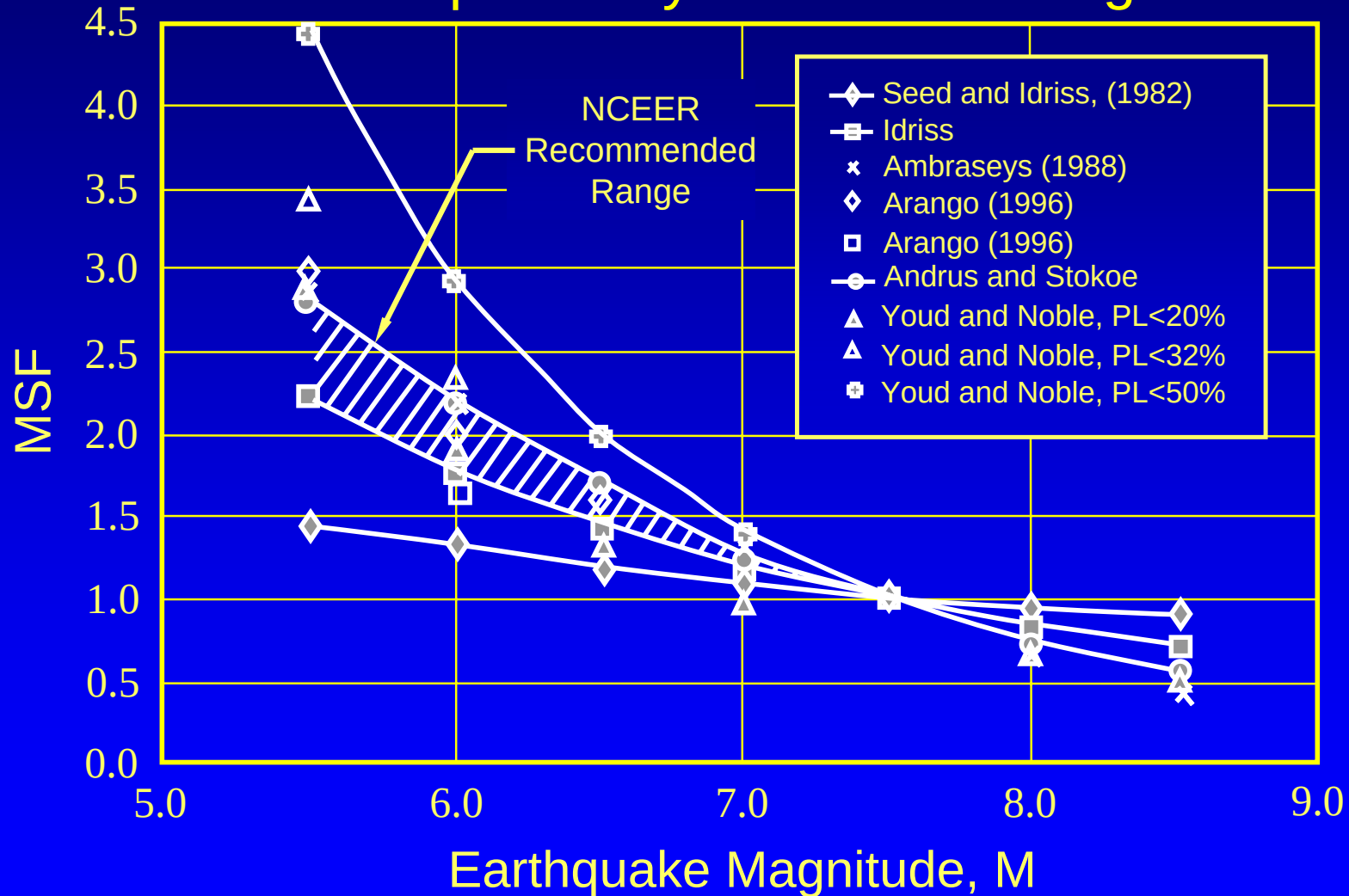
$$CSR_{M7.5} = 0.65 \underbrace{\frac{\tau_{\max}}{\sigma'_v}}_{\text{amplitude}} \underbrace{\frac{1}{MSF}}_{\text{duration}}$$

$$CSR_{M7.5} = 0.65 \underbrace{\frac{a_{\max}}{g} \frac{\sigma_v}{\sigma'_{v0}} r_d}_{\text{amplitude}} \underbrace{\frac{1}{MSF}}_{\text{duration}}$$



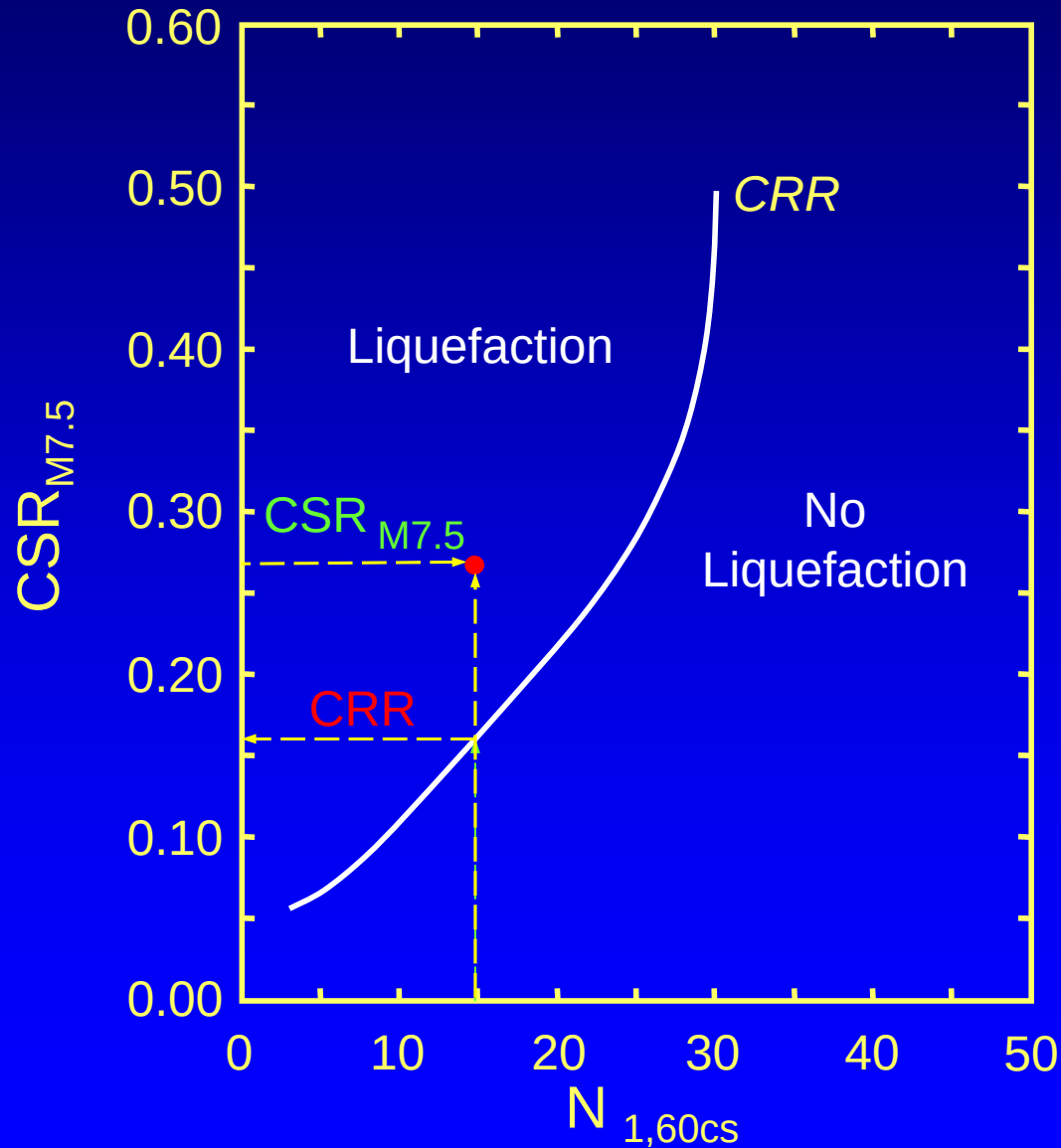
Simplified Liquefaction Evaluation Procedure

MSF Proposed by Various Investigators



(NCEER 1997)

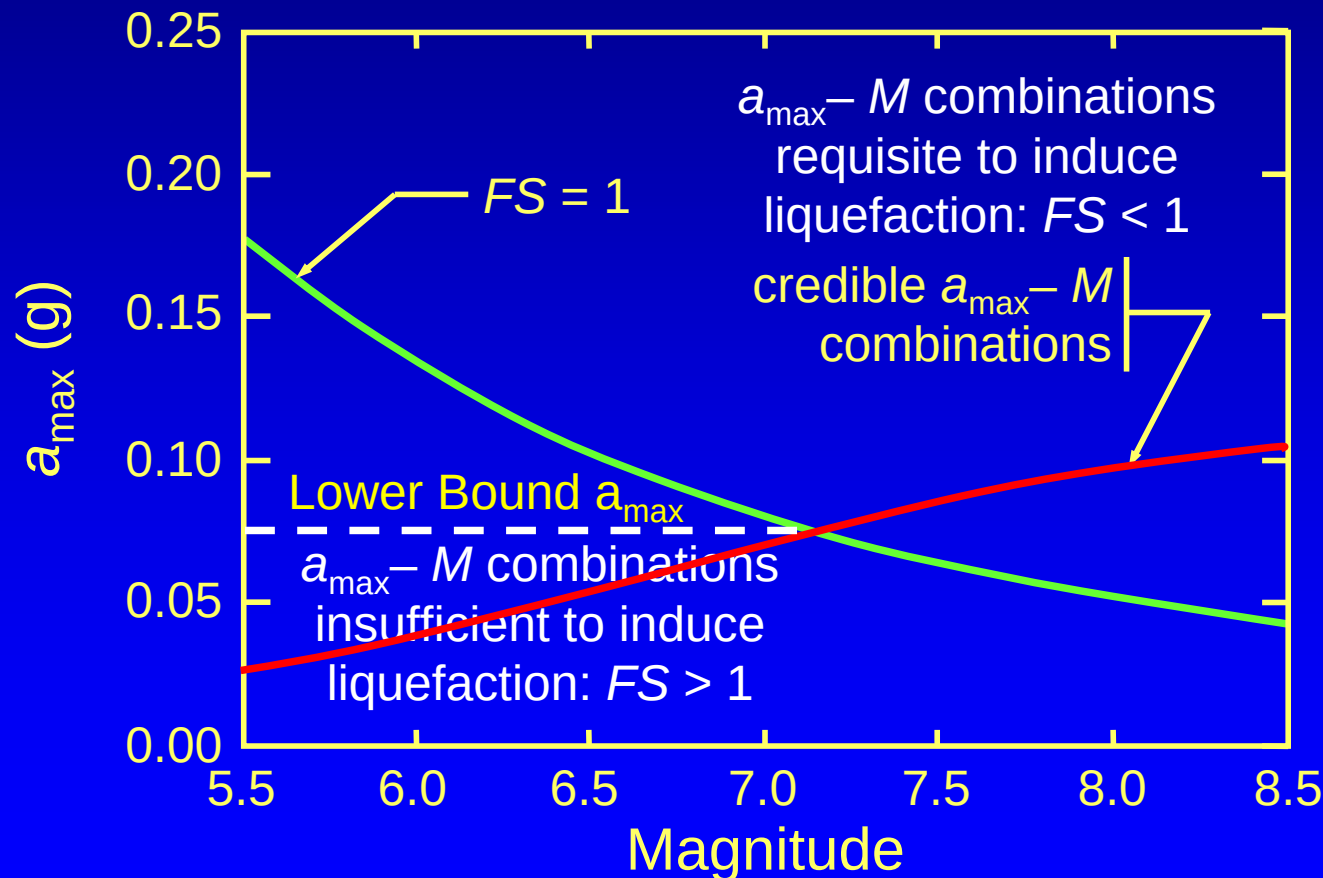
Simplified Liquefaction Evaluation Procedure



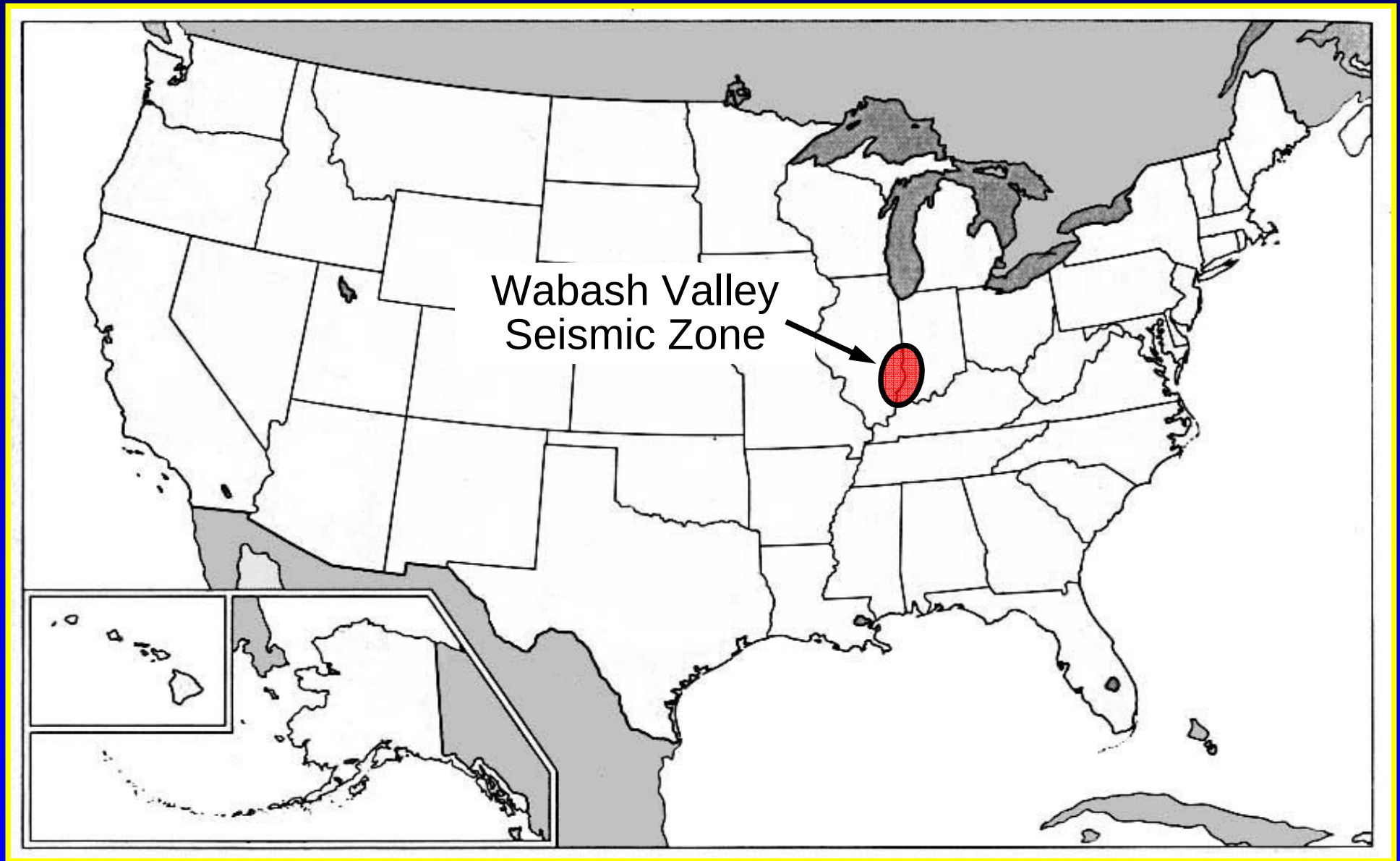
$$FS = \frac{CRR}{CSR_{M7.5}}$$

Back Analyses (simplified procedure)

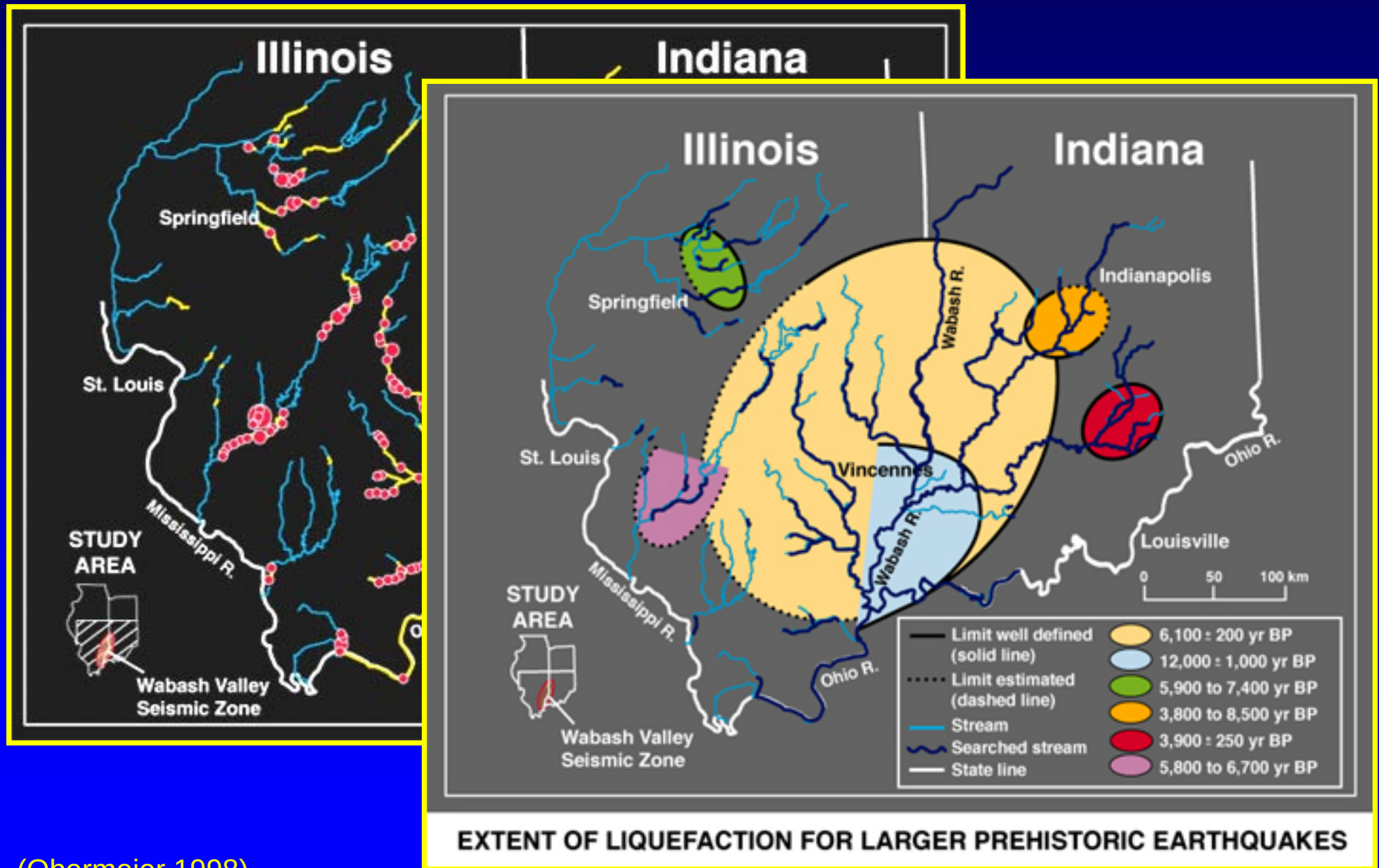
$$FS = \frac{CRR}{CSR_{M7.5}} = 1 \quad \Rightarrow \quad a_{\max} = CRR \text{ MSF} \frac{g \sigma'_{v0}}{0.65 \sigma_v r_d}$$



Wabash Valley Seismic Zone

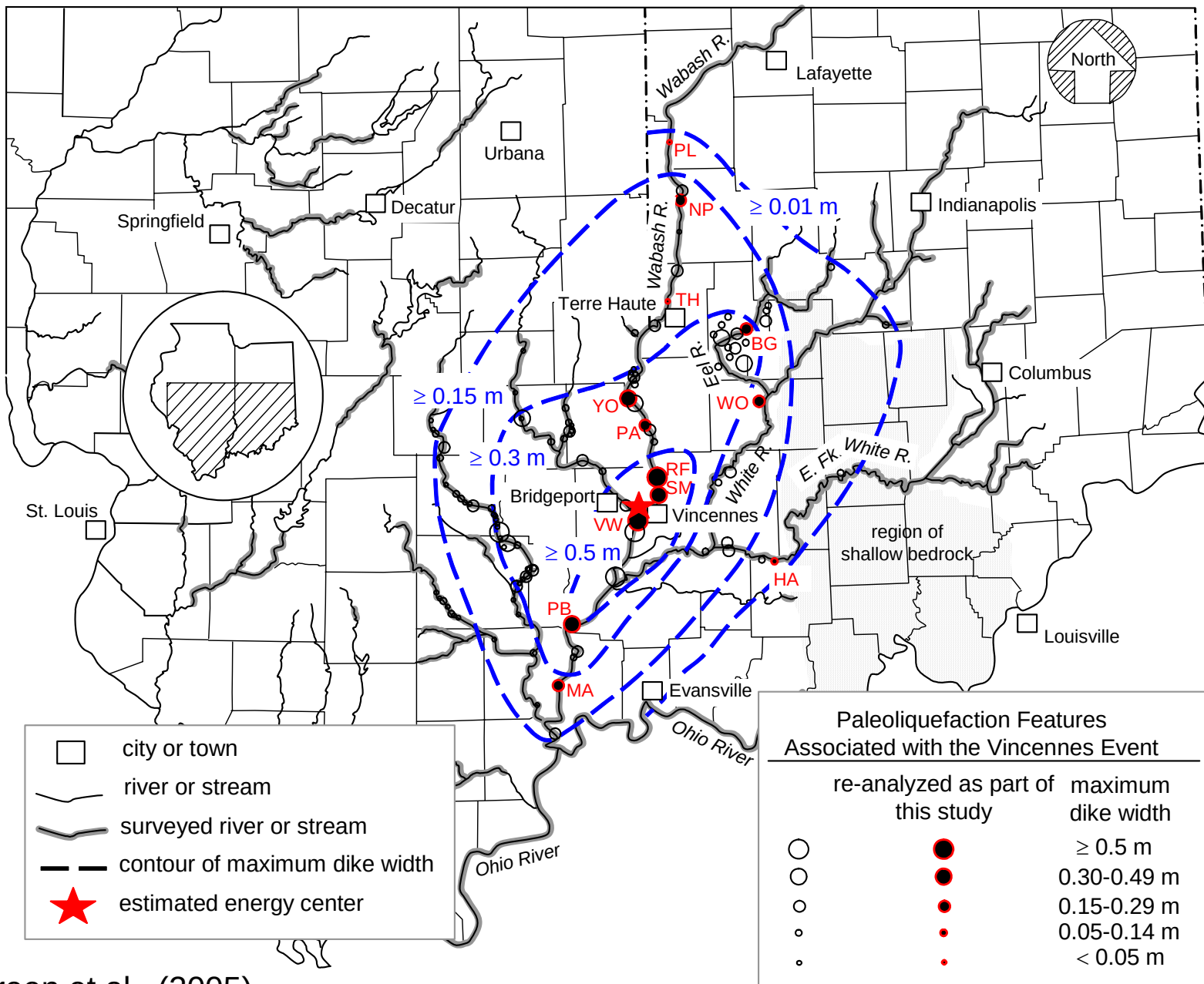


Wabash Valley Seismic Zone

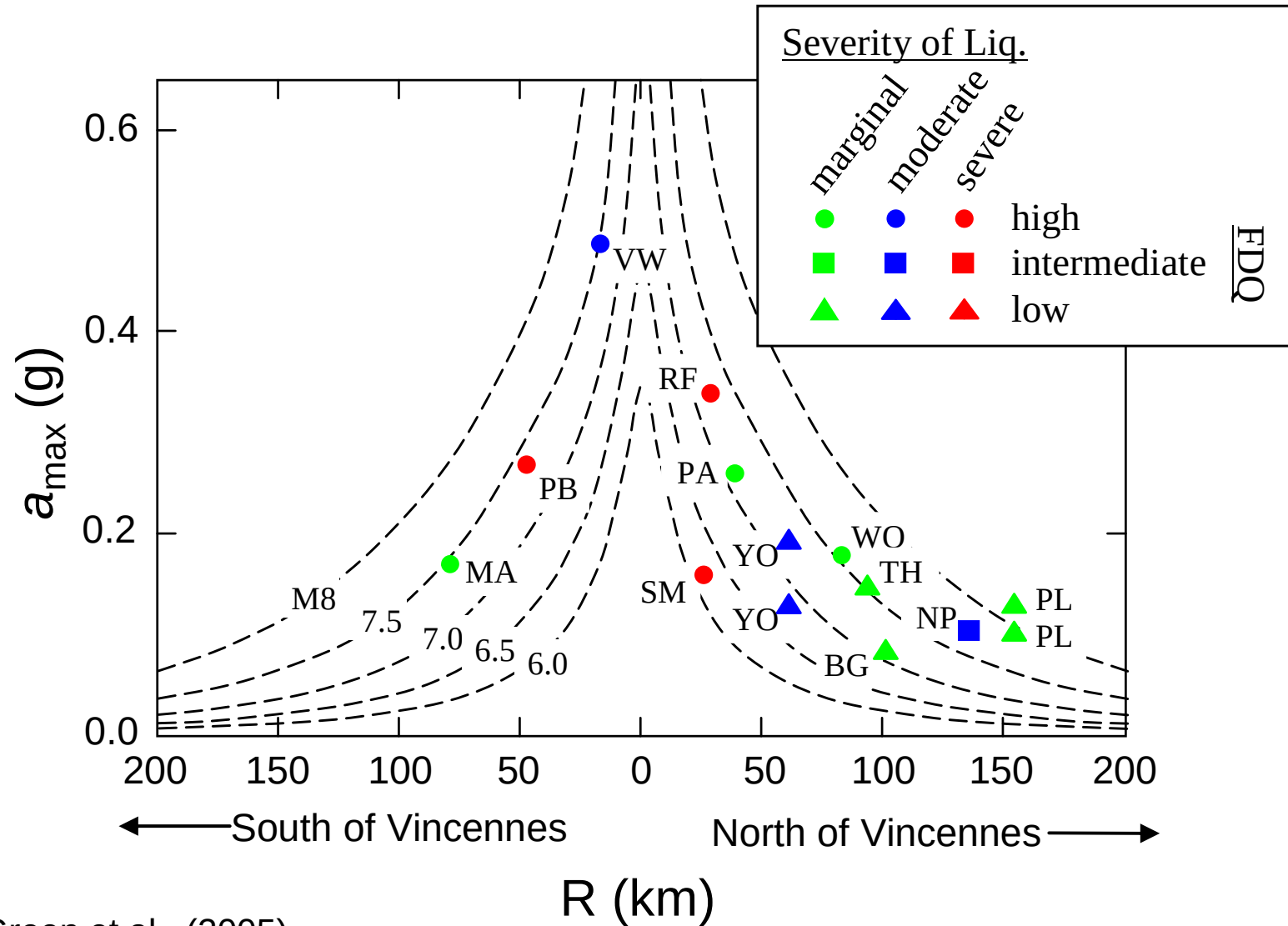


(Obermeier 1998)

Vincennes Earthquake (~6100 yrs BP)



Magnitude of the Vincennes Earthquake

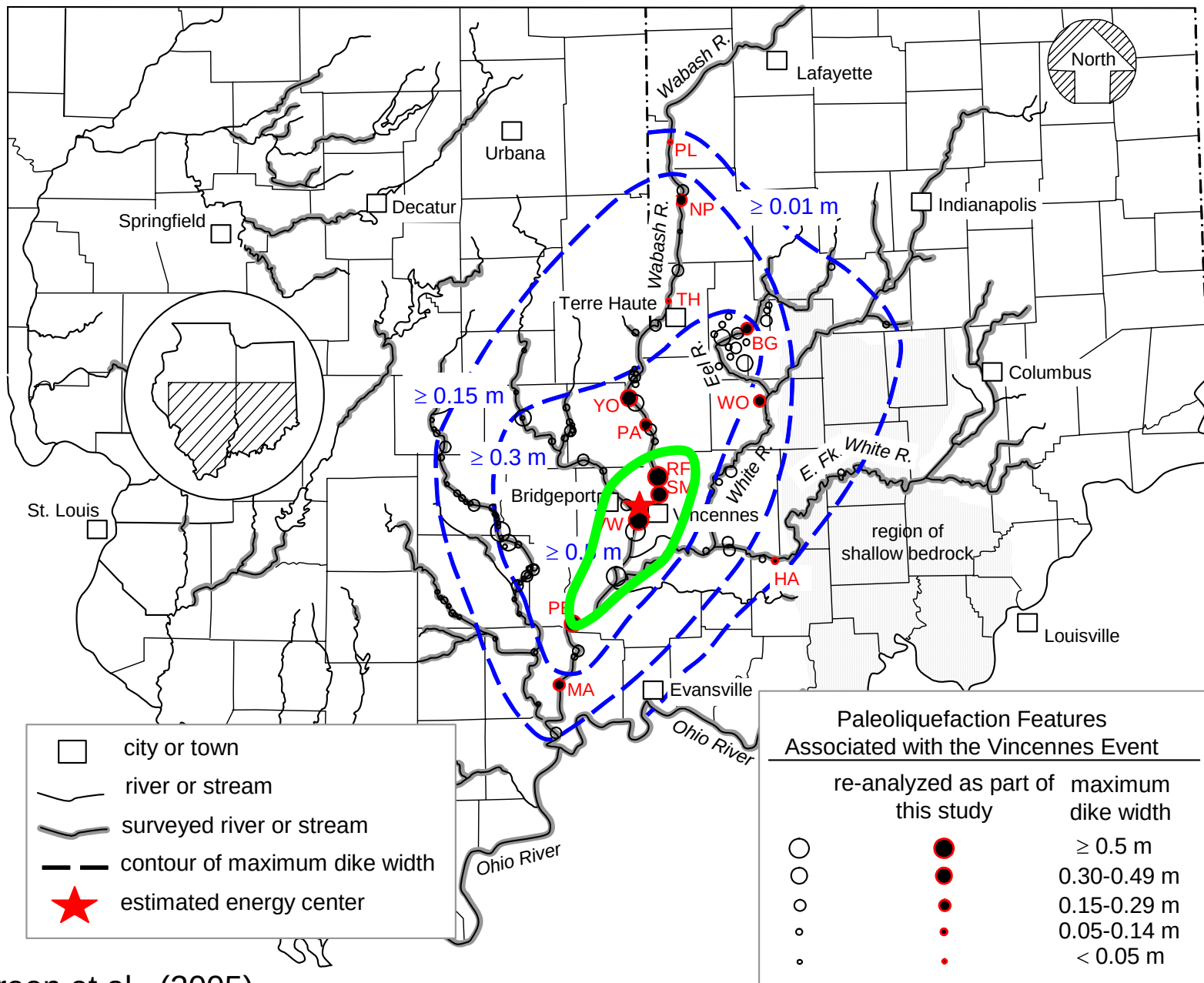


Green et al. (2005)

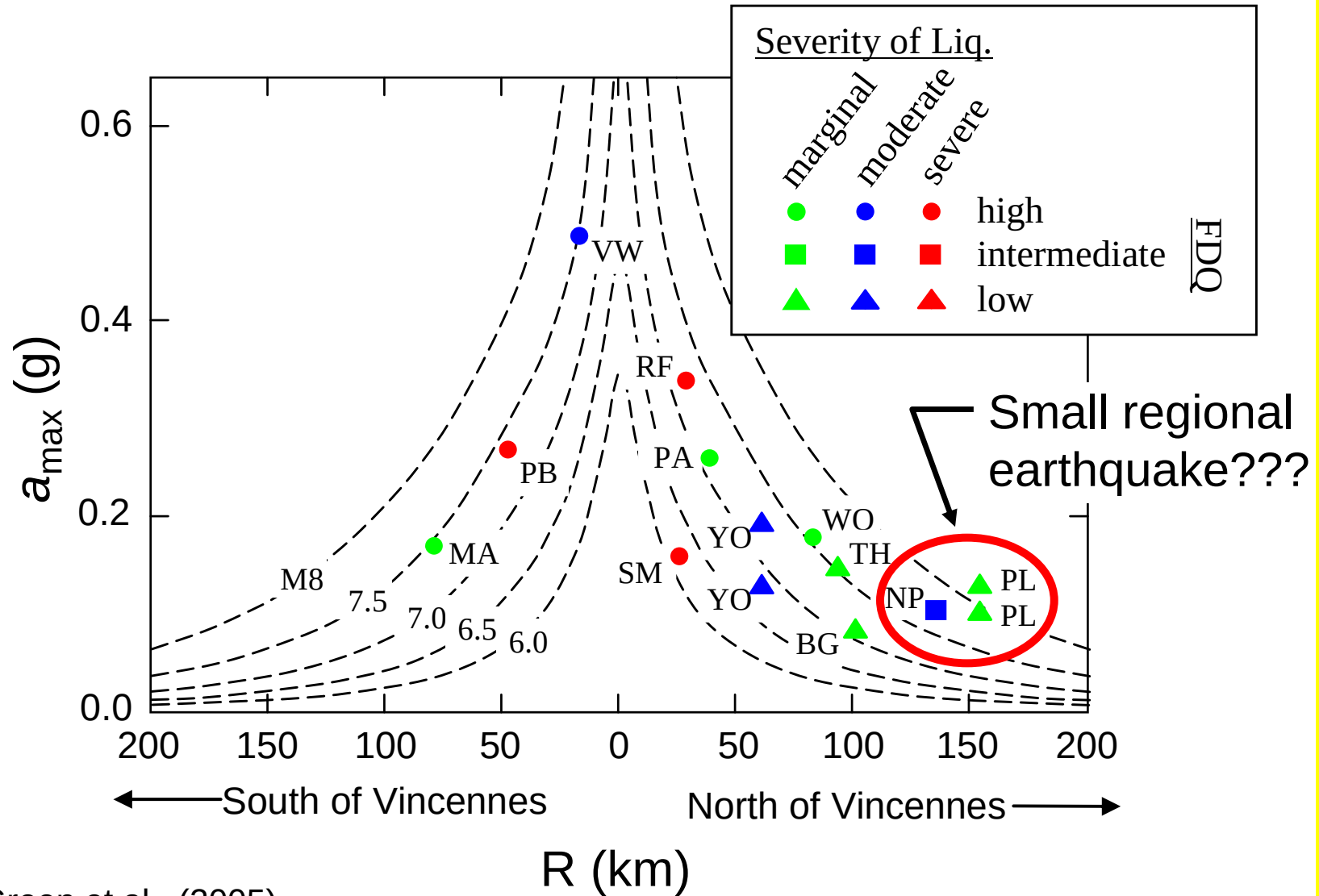
Questions Asked to Address

- 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 earthquake)?
- What is your uncertainty in using liquefaction to assess $M_{\max}$?

Constraints on Seismic Source?



Local Small M vs. Distant Large M



Green et al. (2005)

Uncertainty in Back-Calculated $M_{\max}$?

Sources of Uncertainty:

- Ground motion predictive relationships
 - Epistemic (uncertainty) and aleatory (randomness) uncertainties of predicted motions (seismologist)
 - Site amplification (geotech/seismologist)
 - Determination of site-to-source distance used in back-calculation (geologist/geotech/seismologist)
- Field interpretations
 - Was the feature earthquake induced? (geologist/geotech)
 - Does the absence of paleoliquefaction features in a deposit mean that it never liquefied? (geologist/geotech/seismologist)
 - Linking of features to causative paleoearthquake (geologist/geotech)
 - Estimation of location of ground water table at the time of the earthquake (geologist/geotech)
 - Estimation of the location of the ground surface at the time of the earthquake (geologist)

Uncertainty in Back-Calculated $M_{\max}$?

Sources of Uncertainty (continued):

- Back analysis
 - Proper determination of geotechnical parameters, e.g., selection of appropriate penetration resistance, influence of aging (geotech/geologist)
 - Appropriateness of simplified liquefaction evaluation procedure for use in the CEUS, e.g., MSF, r_d (geotech)

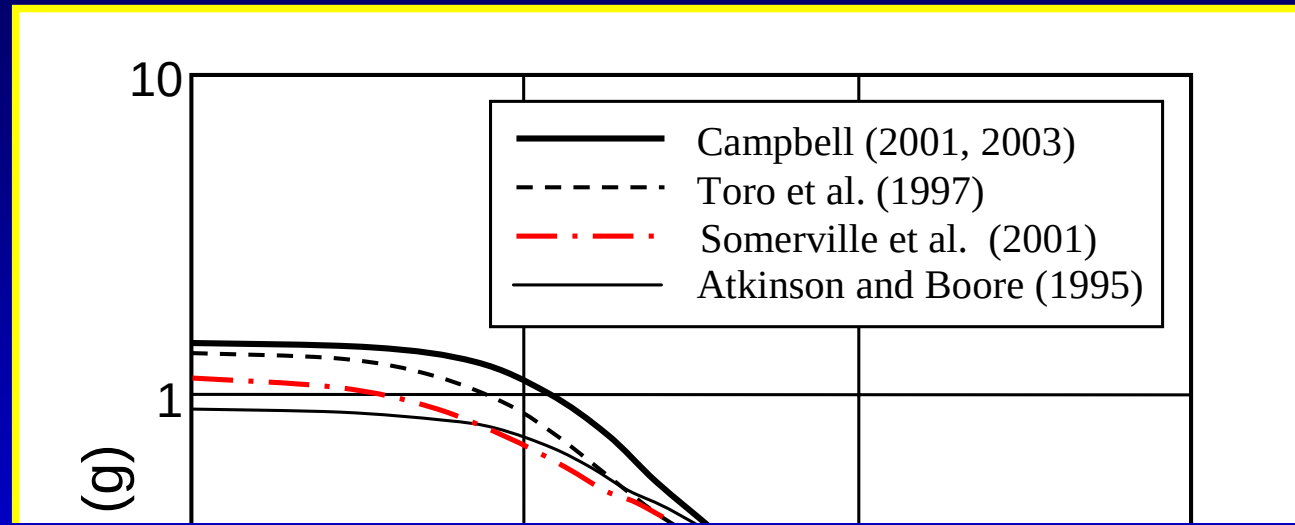
Over all Uncertainty:

Assessment of combined epistemic (uncertainty) and aleatory (randomness) uncertainties using modern earthquake analog

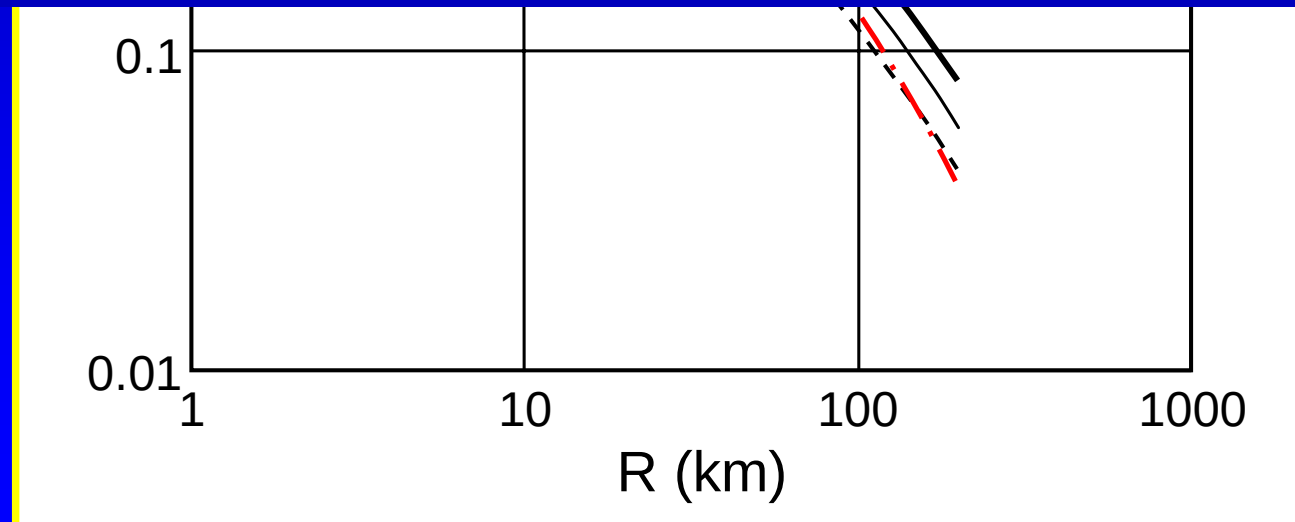
CEUS Ground Motion Predictive Relationships

Region	Tectonic Environment	Attenuation Relation
Central - Eastern US	Non-Rifted zones:	Somerville et al. (2001)
	Rifted zones:	
	Unknown faulting	Campbell (2003)
	Mid-continent:	Toro et al. (1997)
	Gulf Coast:	
	Thrust faulting	Atkinson and Boore (1997)
New York City	Unknown faulting	Jacob et al. (1990)

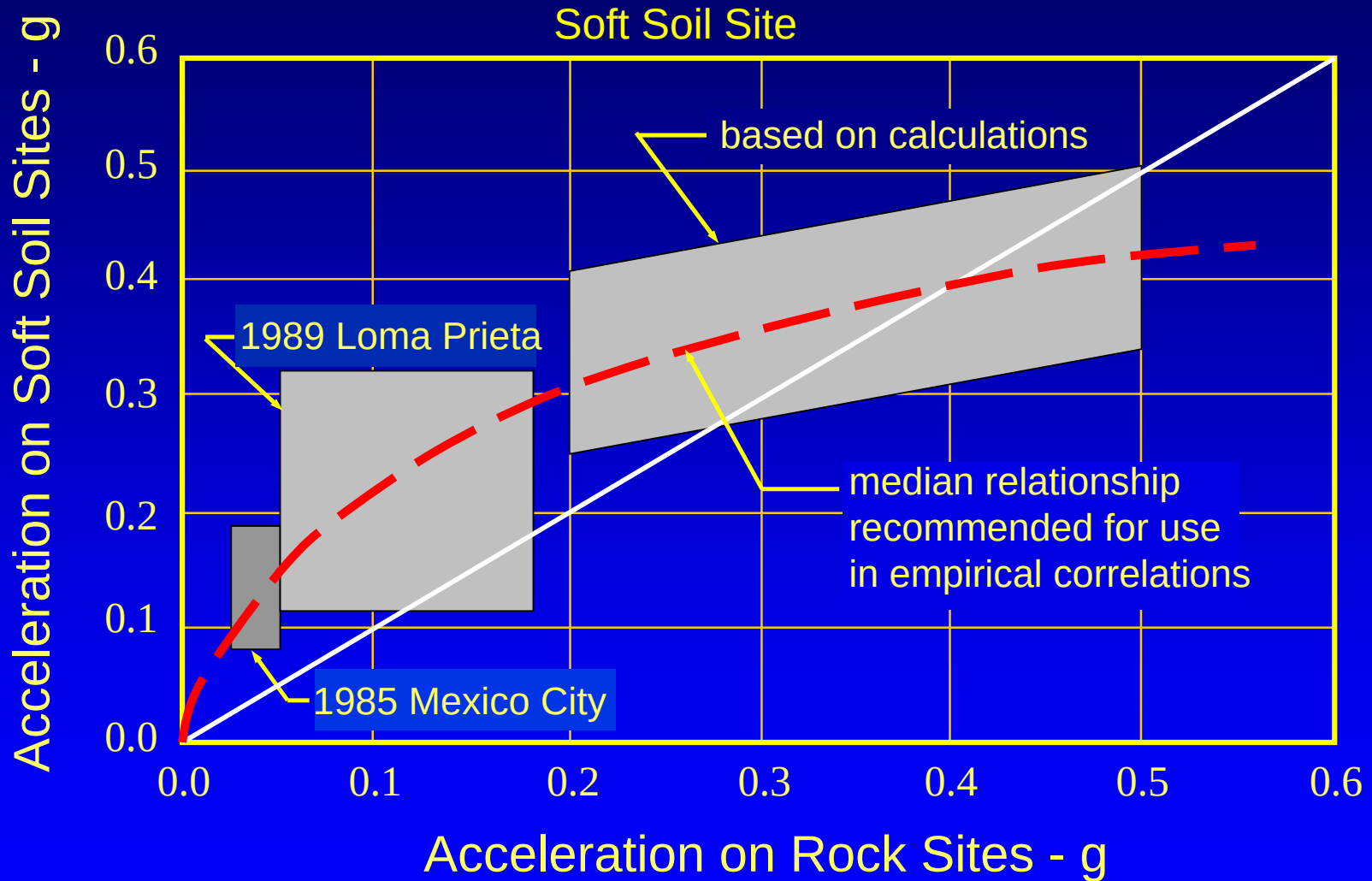
Attenuation Relations for Rock Sites in CEUS



NGA East

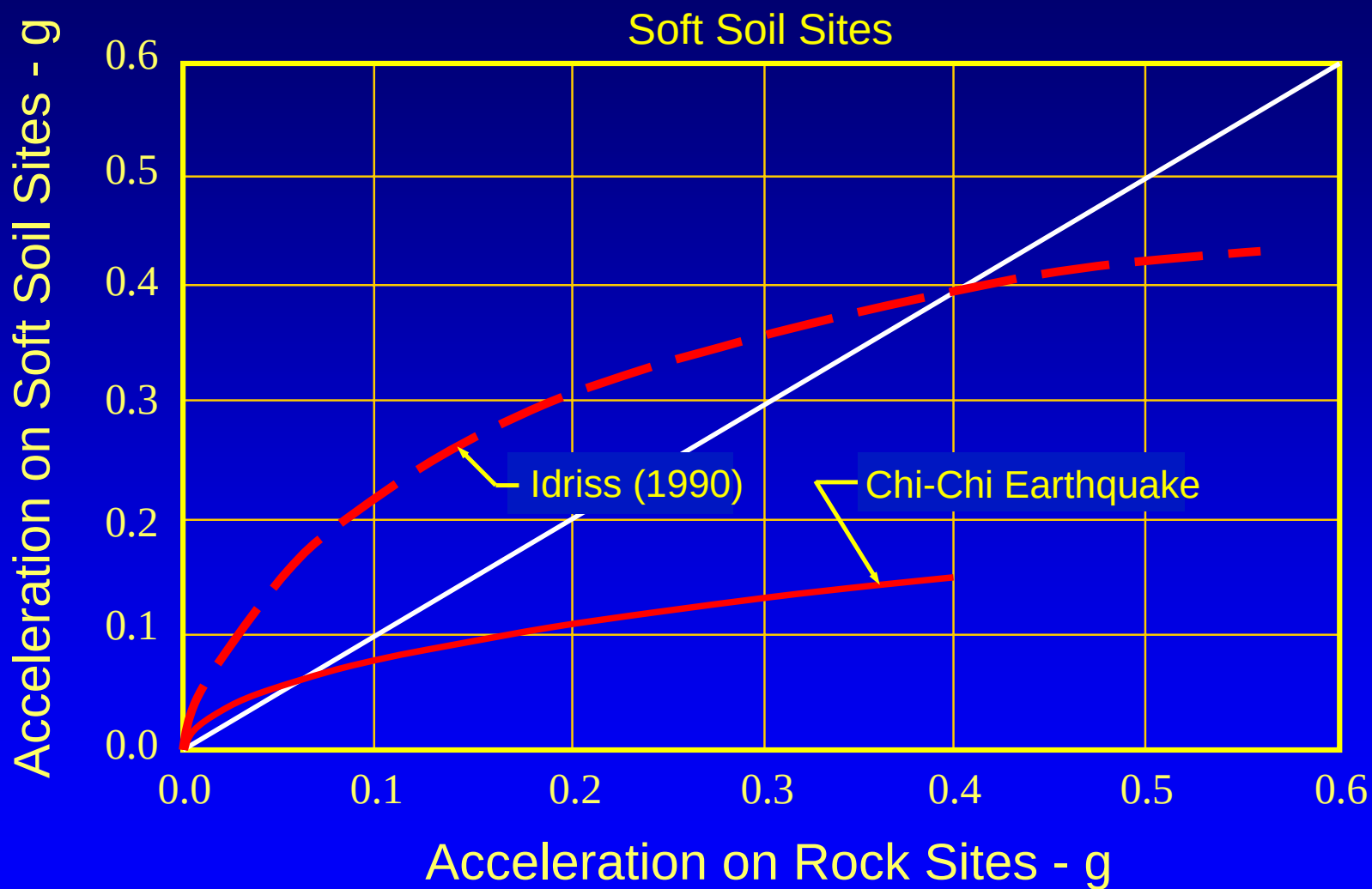


Site Amplification

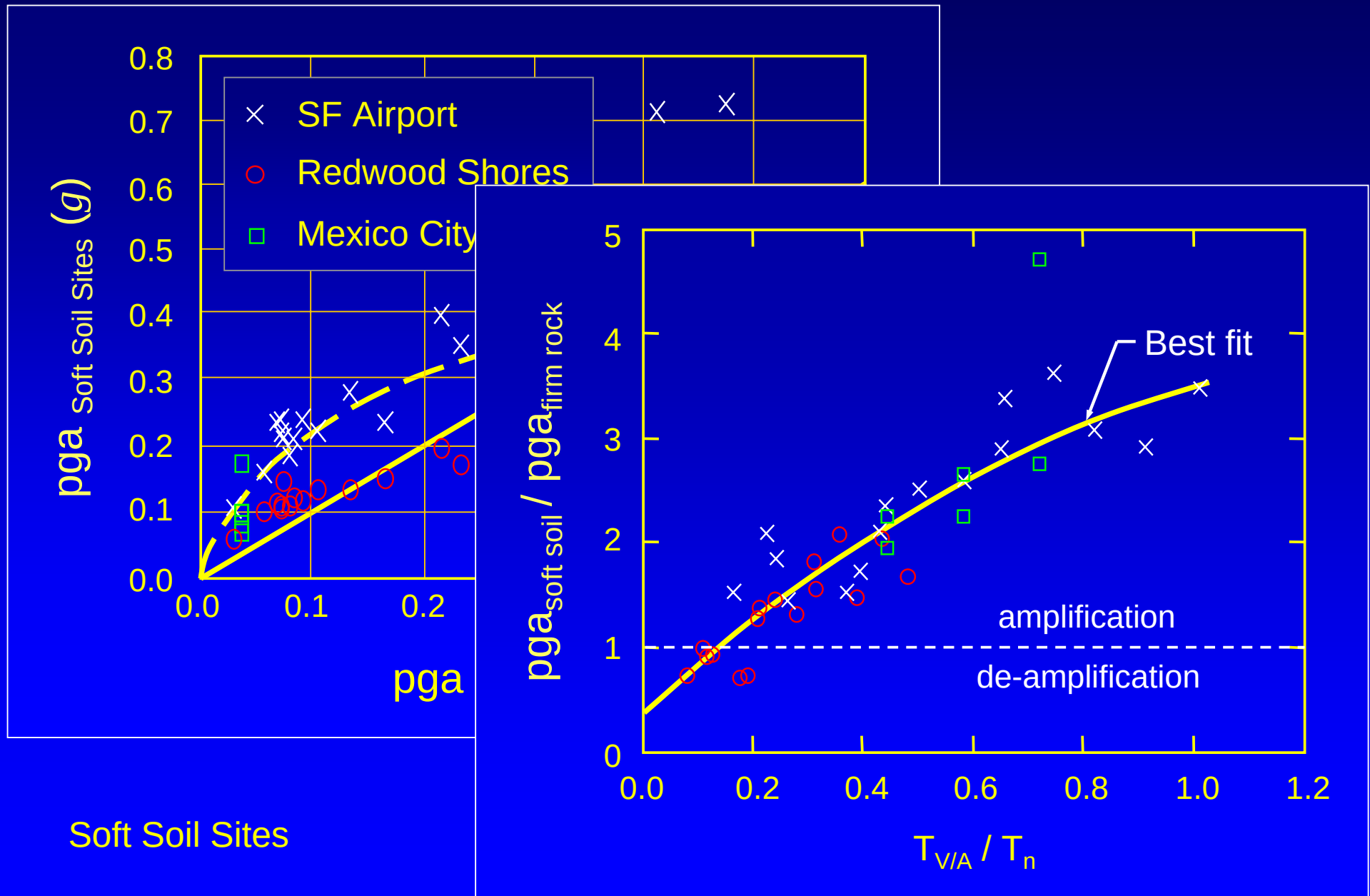


(Idriss 1990)

Site Amplification



Alternative Presentation of Site Amplification Data



Site Amplification

59 ft
72 ft
509 ft

Young Bay Mud

$\gamma = 100$ pcf
 $V_s = 295$ fps

Old Bay Sediments

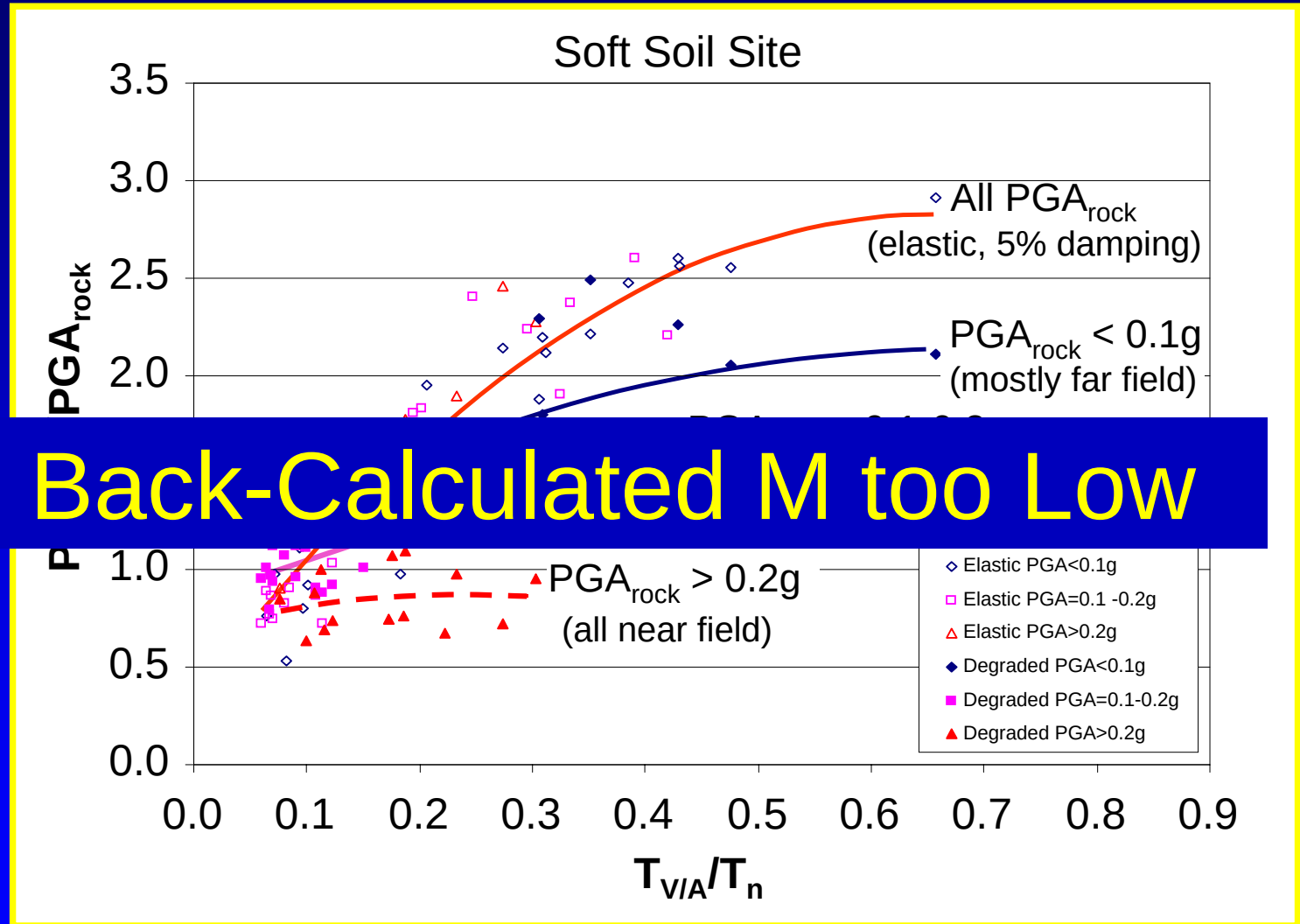
$\gamma = 105$ pcf
 $V_s = 853$ fps

Old Bay Sediments

$\gamma = 110$ pcf
 $V_s = 1247$ fps

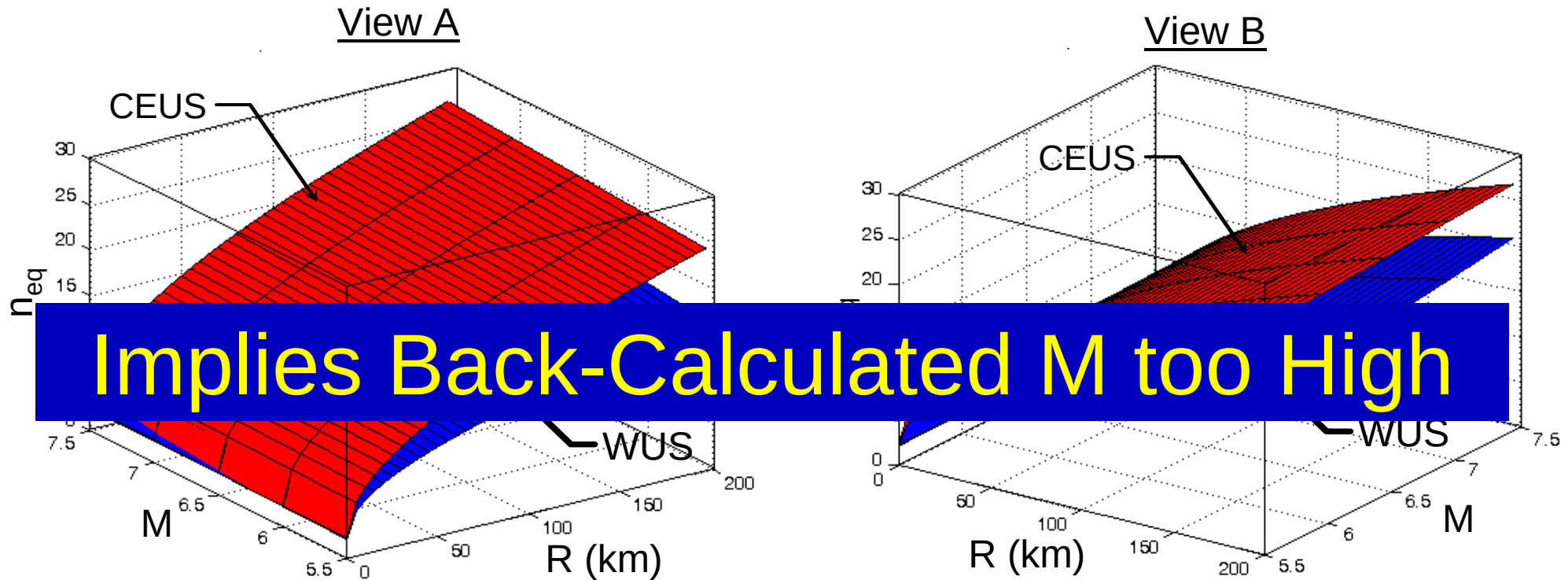
Bedrock

$\gamma = 140$ pcf
 $V_s = 4000$ fps



CEUS Magnitude Scaling Factors

Preliminary Correlations for n_{eq} (WUS vs. CEUS)

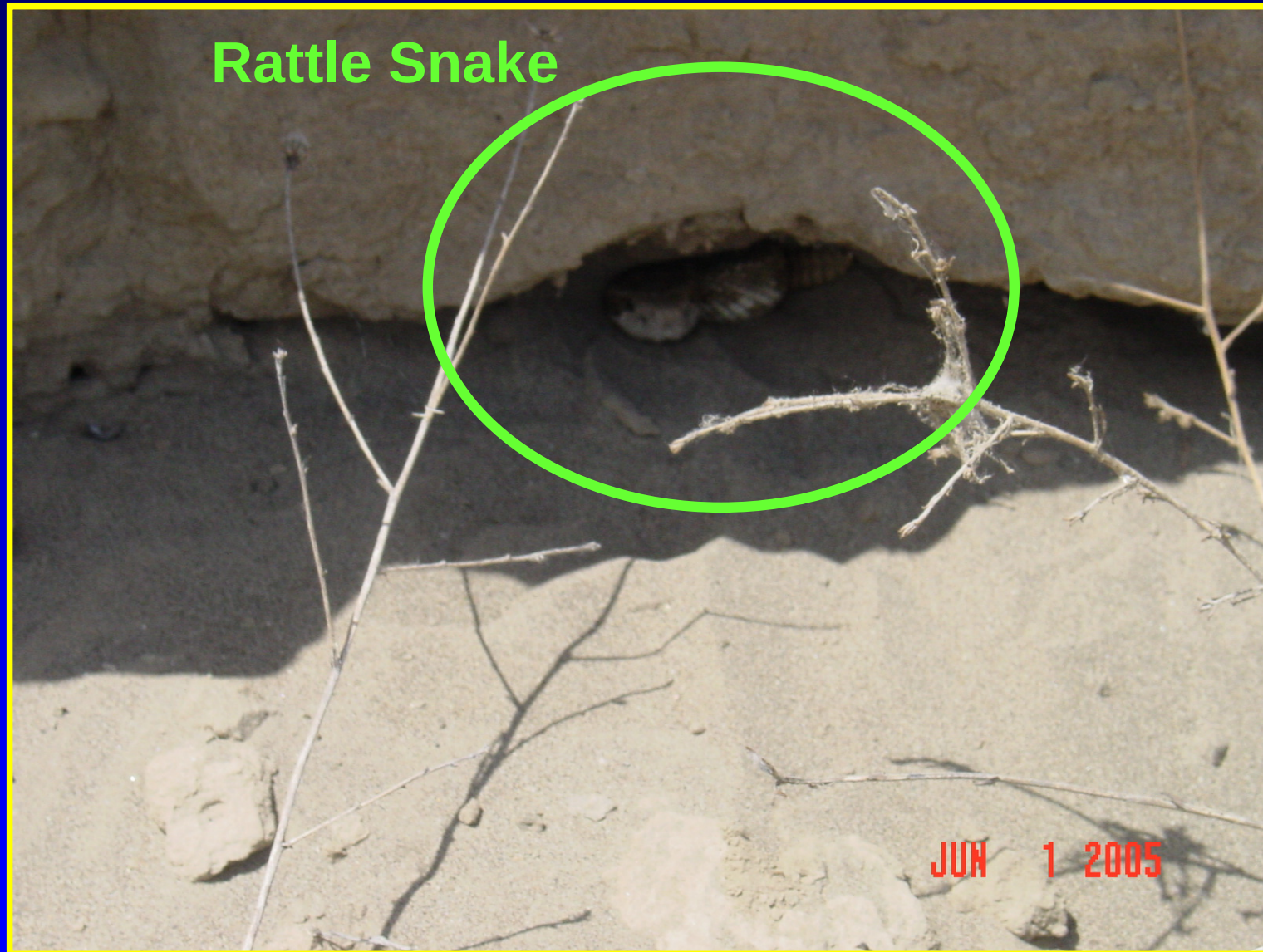


$$MSF_{CEUS} = \left[\frac{n_{eq \text{ M7.5 WUS far field}}}{n_{eq \text{ M CEUS}}} \right]^m$$

Assessment of Overall Uncertainty Using Modern Earthquake Analog

- Use back-analysis procedure to estimate the M of modern earthquakes.
- Vary the amount and quality of liquefaction data used.
- Compare back-calculated and instrumental magnitudes
- Develop relationship relating error of back-calculated M as a function of amount and quality of liquefaction data used.

Some Hazards of Paleoliquefaction Field Studies



Pasco, Washington

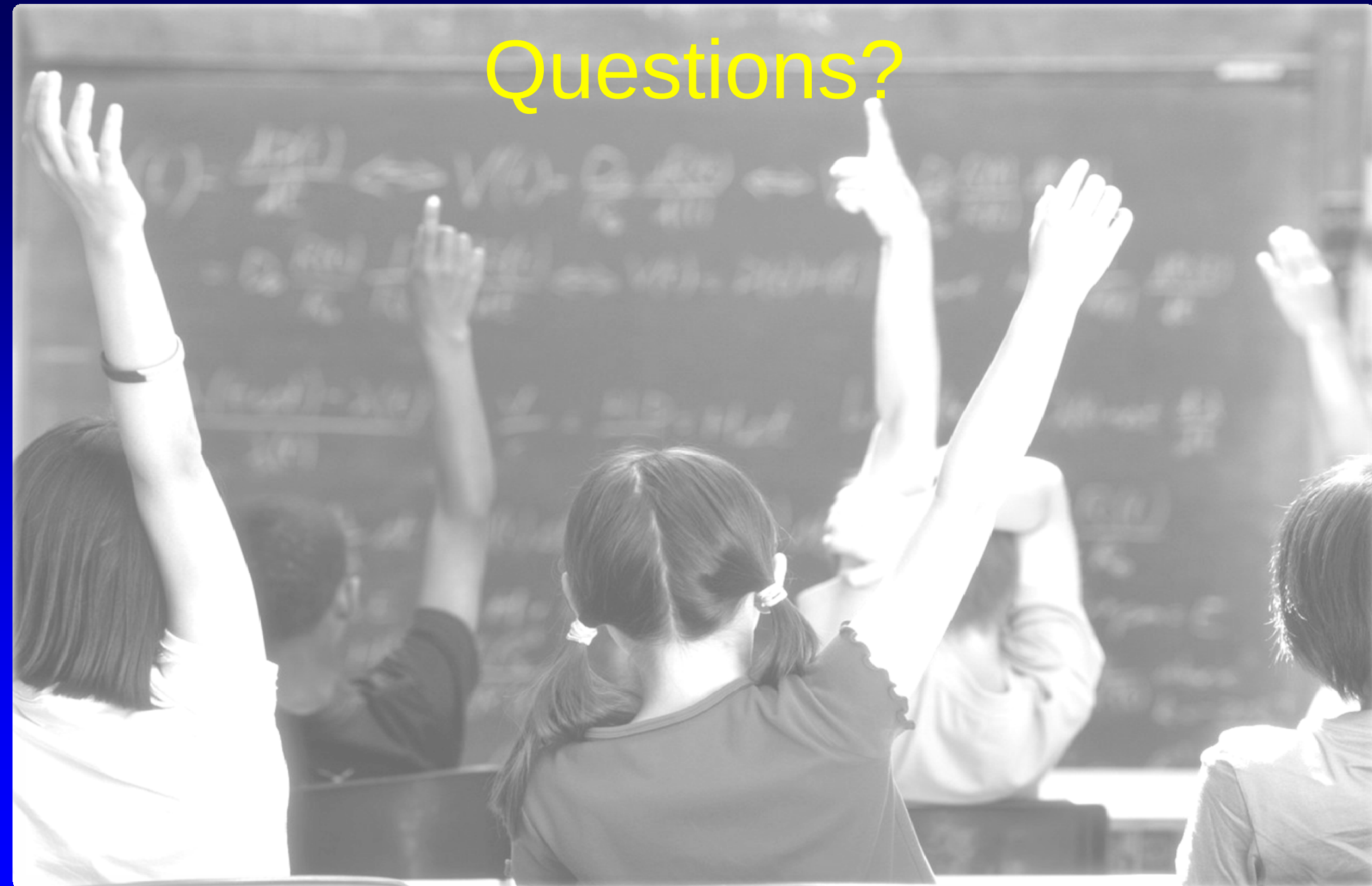
Some Hazards of Paleoliquefaction Field Studies

Mound of
Bees



Griffin, Indiana

Questions?



Fun with Deep Dynamic Compaction



Quantifying Uncertainties in Paleoliquefaction Studies

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University of Illinois at Urbana-Champaign
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CEUS SSC Project
Workshop #2
February 18 - 20, 2009

Collaborators / Acknowledgments

- ◆ Dr. Min Woo Seo
- ◆ Prof. Junho Song
- ◆ Prof. Y.K. Wen
- ◆ Ms. Cora Johnson
- ◆ Mr. Jason Buenker

- ◆ Prof. Russell Green (Virginia Tech)
- ◆ Dr. Stephen Obermeier (EqLiq Consulting)

- ◆ USGS award number 06HQGR0013

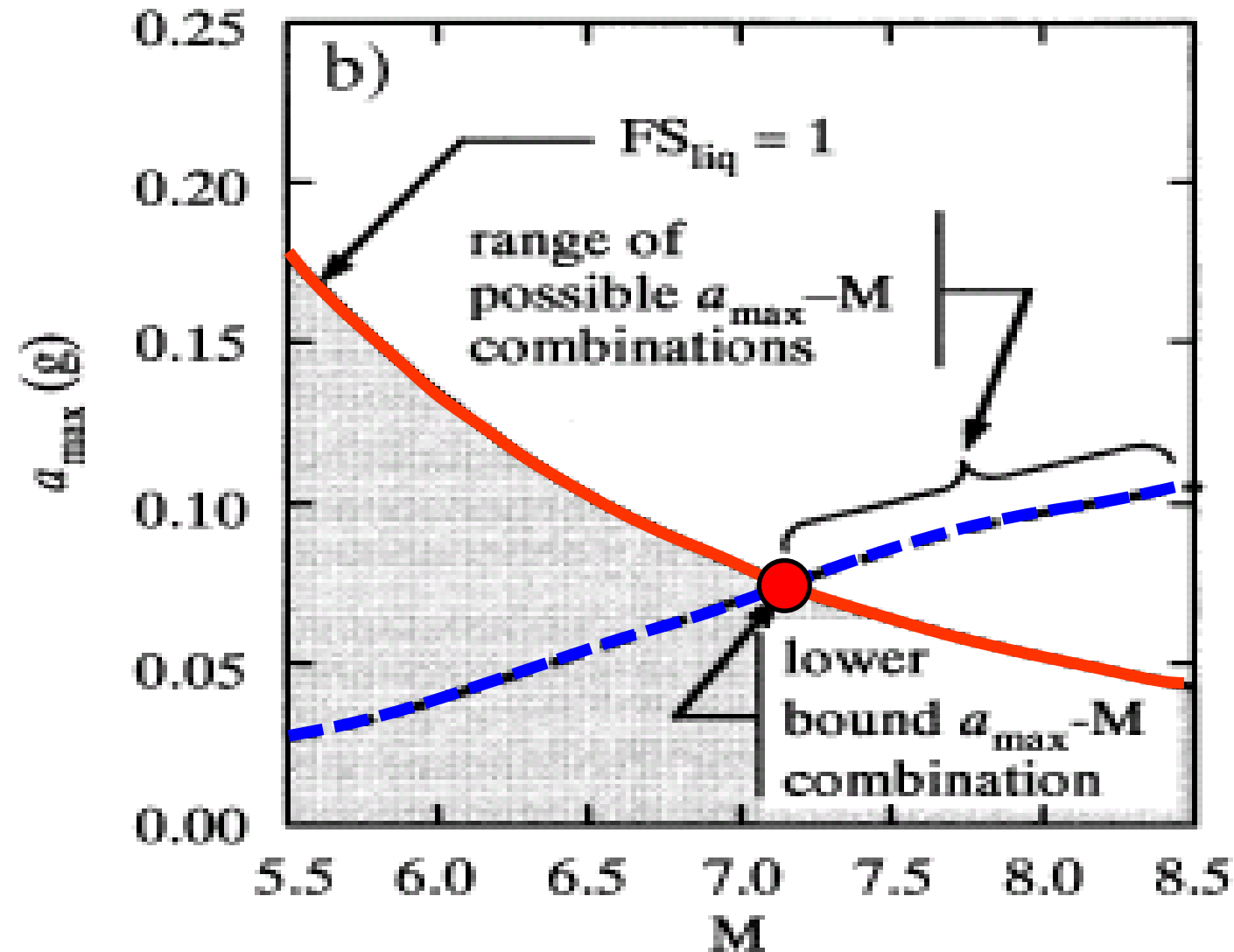
Outline

- ◆ Existing paleoliquefaction back-analysis methods
- ◆ Developing a regional magnitude bound
- ◆ Quantifying some uncertainties in back-analysis
- ◆ Benchmark case of Vincennes earthquake
- ◆ Specific questions
 - Limitations of magnitude bound approach
 - Uncertainties in paleoliquefaction studies for $M_{\max}$
 - Range of $M_{\max}$ for New Madrid, Charleston, and Wabash
 - $M_{\min}$ required to generate liquefaction

Existing Methods for Paleoliquefaction Back-analysis

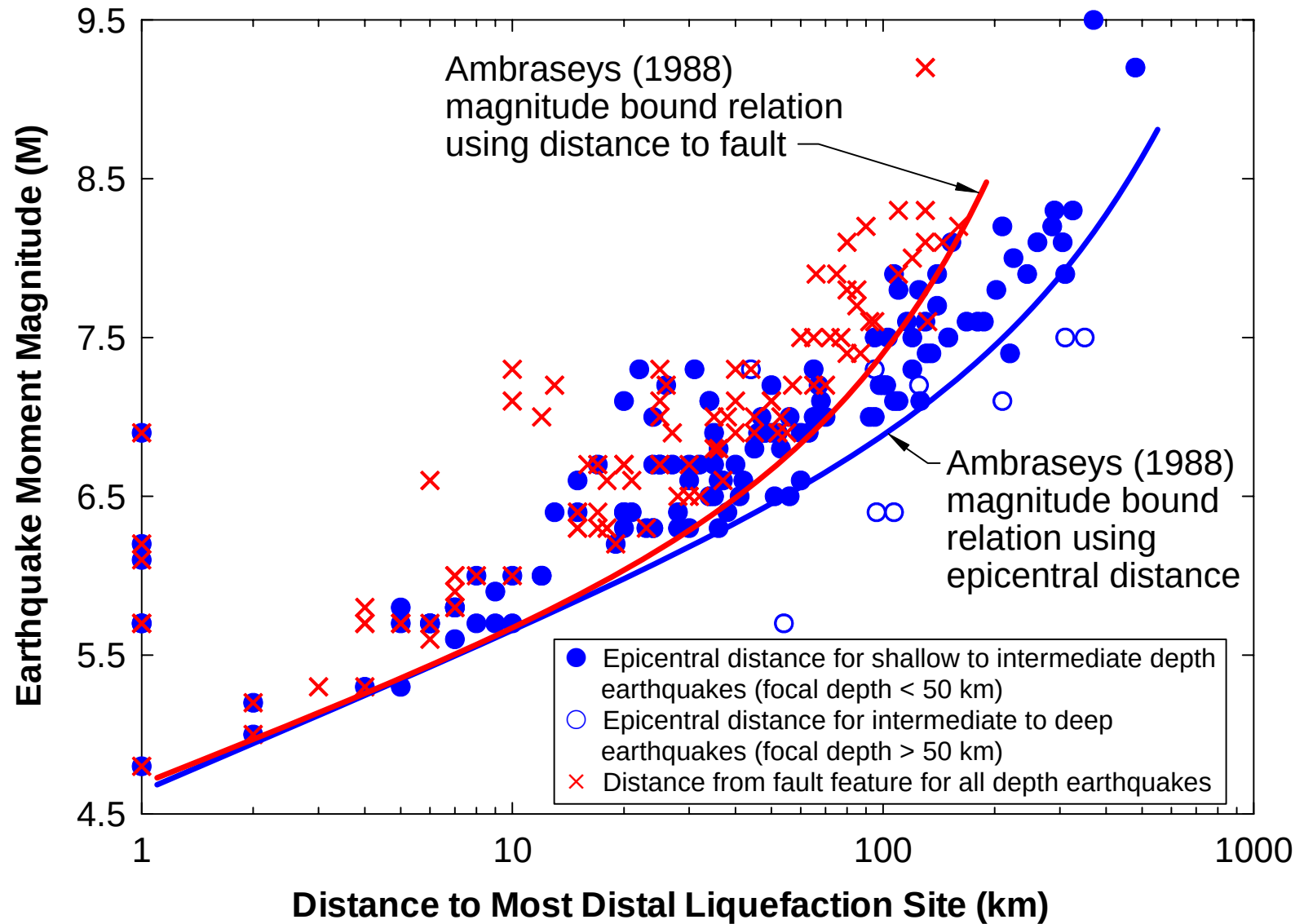
- ❖ Cyclic stress method
- ❖ Magnitude bound method
- ❖ Cyclic strain method
- ❖ Energy method
- ❖ Ishihara method
- ❖ Regional method proposed by Olson et al. (2005a)

Cyclic Stress Method



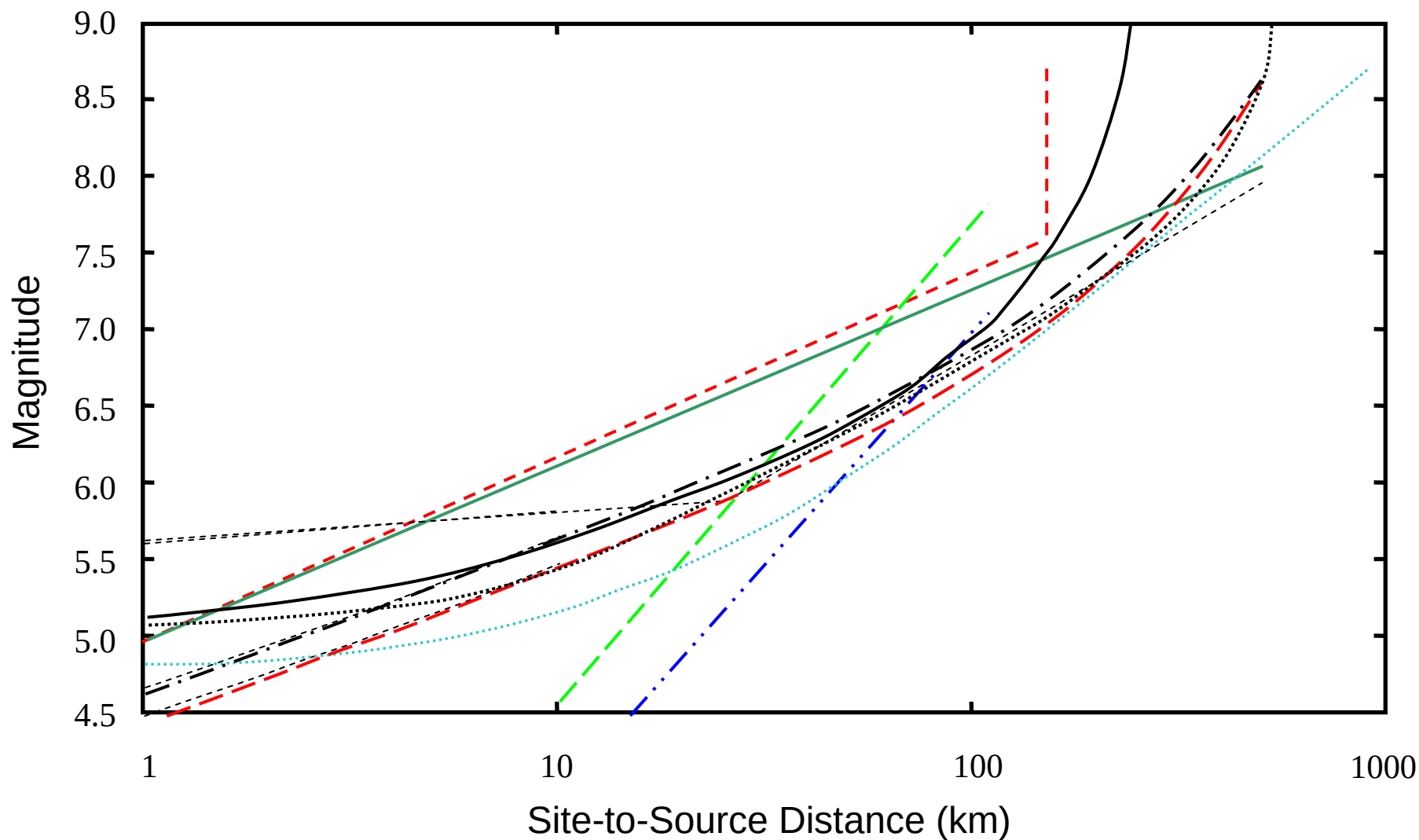
$$FS_{liq} = \frac{CRR}{CSR}$$

Magnitude Bound Method



after Ambraseys (1988)

Various Magnitude Bounds – Regional and Worldwide

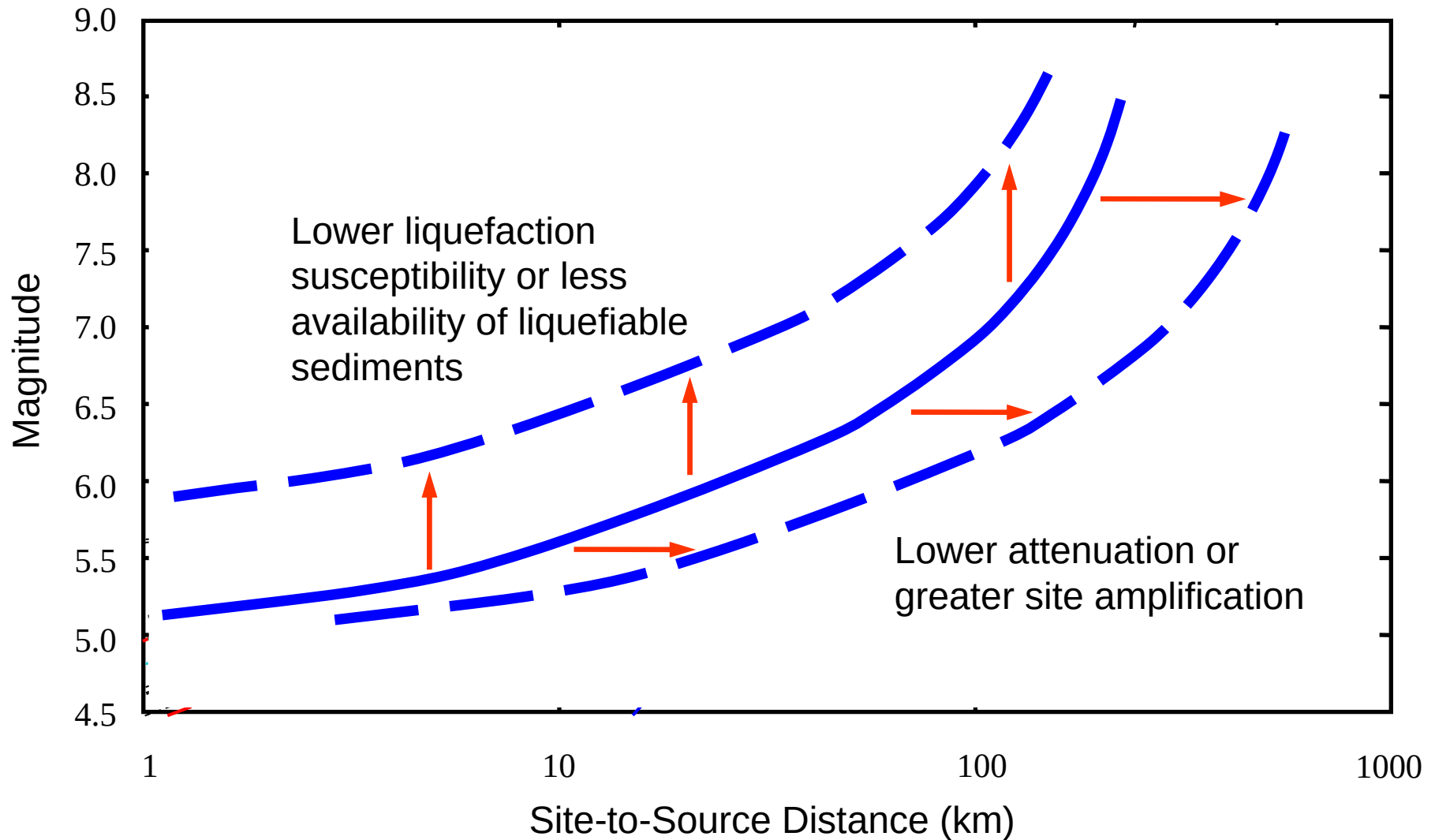


Green et al. (2006)

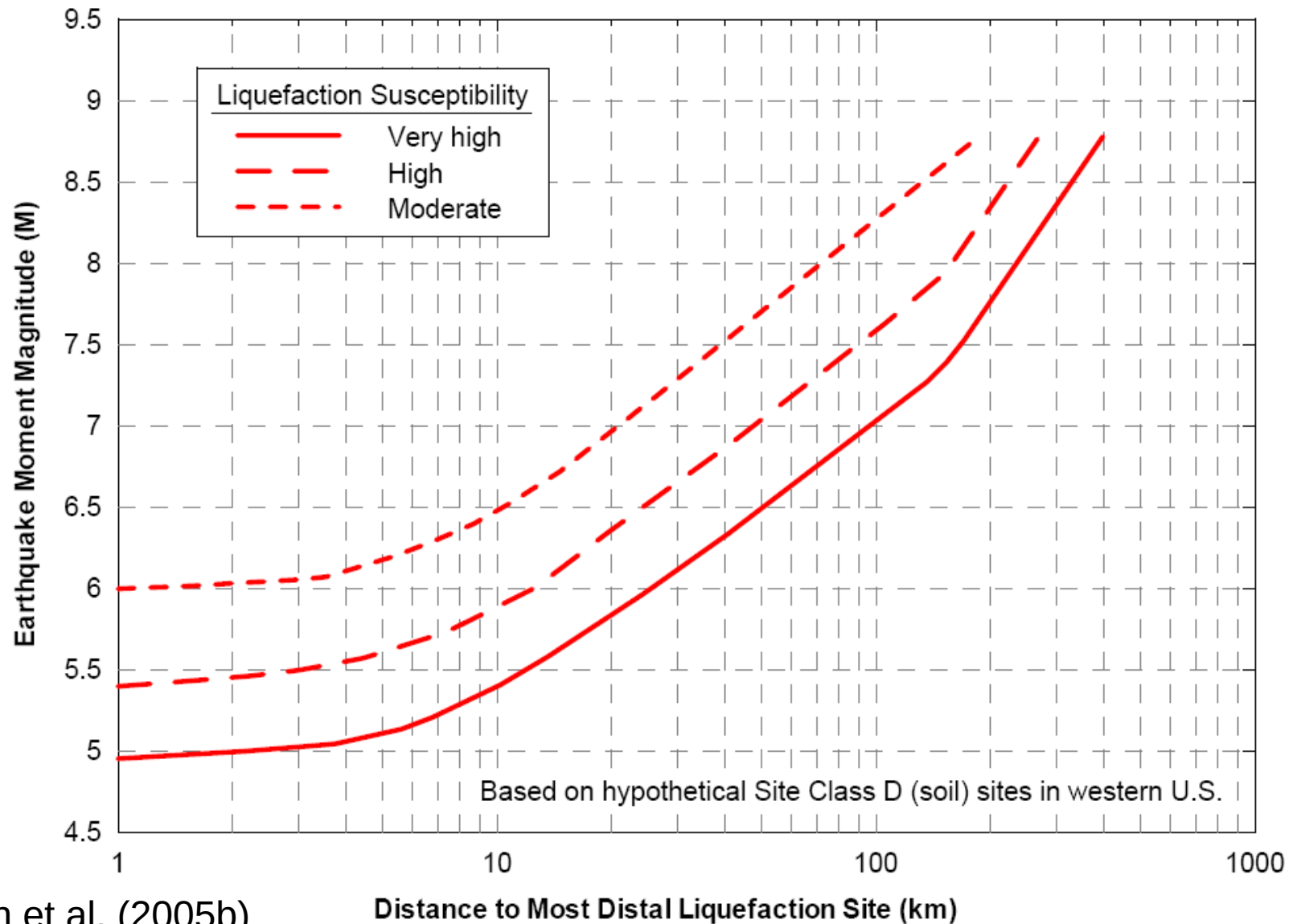
Factors affecting Magnitude Bound

- ◆ Source characteristics
- ◆ Transmission characteristics (attenuation & site effects)
- ◆ Regional soil liquefaction susceptibility

Developing a Regional Magnitude Bound

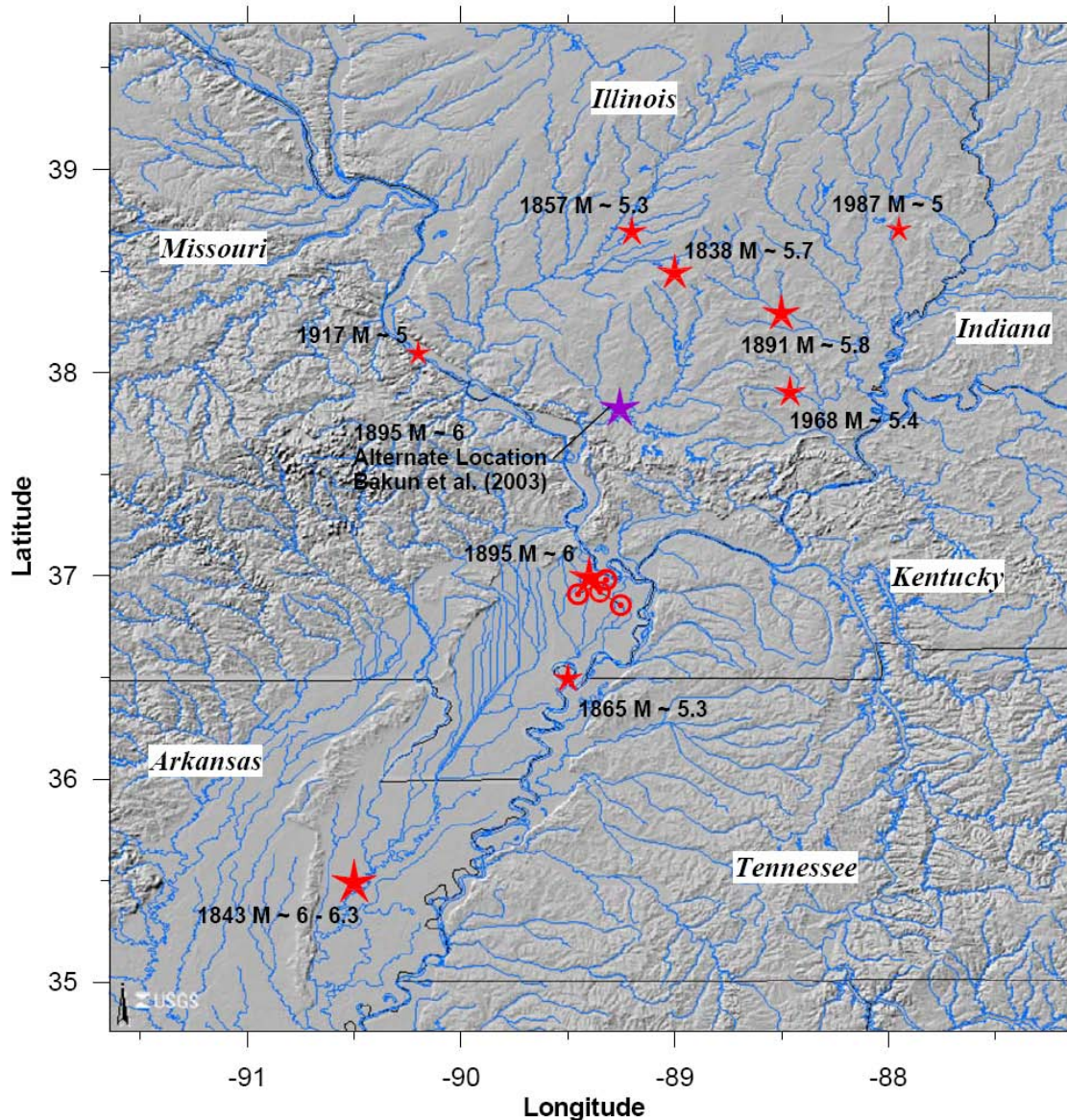


Developing a Regional Magnitude Bound



Olson et al. (2005b)

CEUS Magnitude Bound



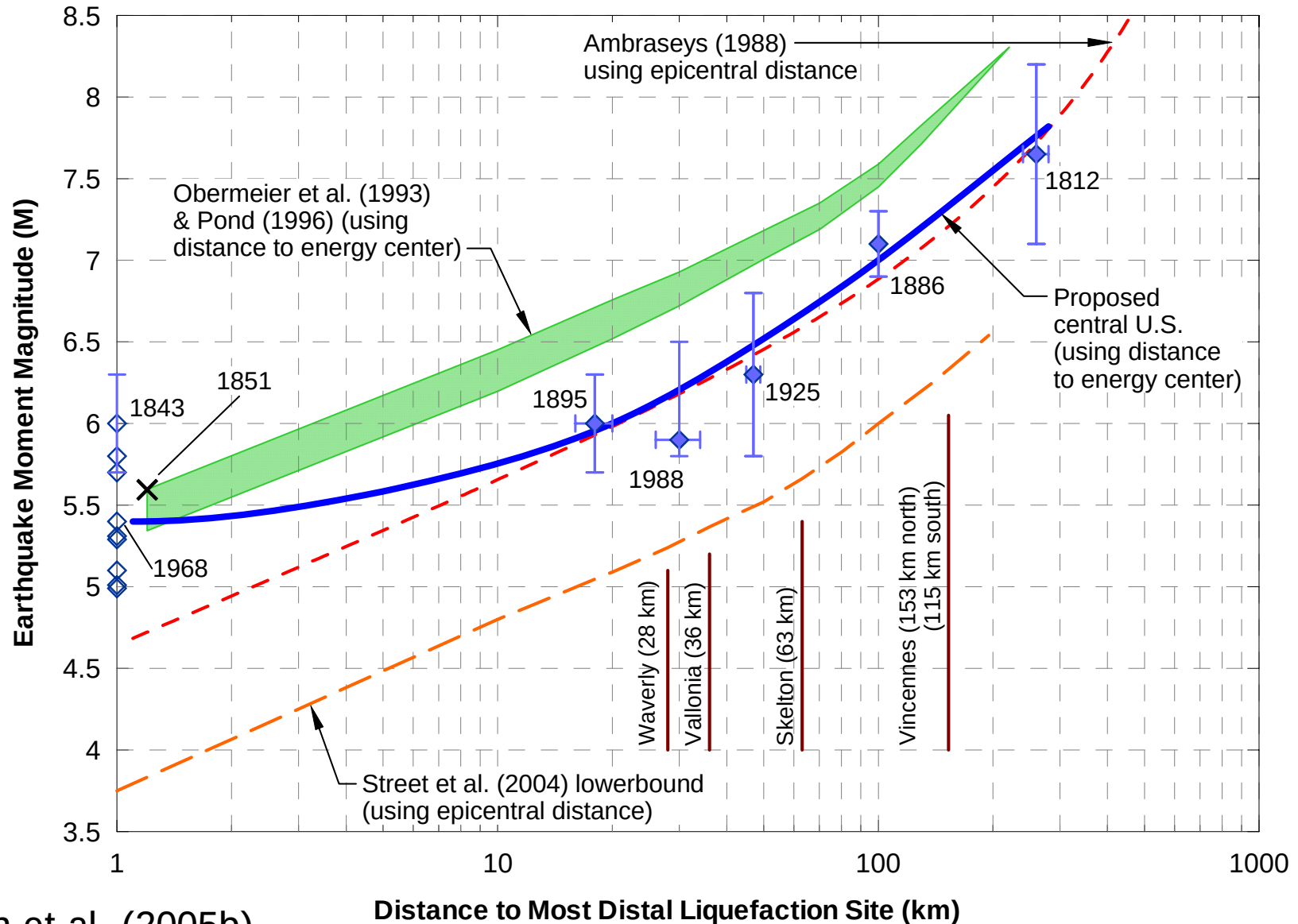
Historical earthquakes with $M > \sim 5$ and associated liquefaction features in central U.S. from 1812 - 2002. Database of felt effects maintained by M. Hopper contained reports of liquefaction features associated only with 1895 Charleston, MO earthquake as shown by open circles.

Olson et al. (2005b)

CEUS Magnitude Bound

Date	Earthquake	Estimated Location of Epicenter		Reference	Estimated M ^(a)	Reference	Plotted M	Estimated R ^(b) (km)	Reference	Plotted R (km)
		Latitude	Longitude							
2/7/1812 ^(c)	New Madrid, Missouri alternate location	36.5°N	89.6°W	Wheeler (2003)	7.6 - 7.7 ± 0.5	Atkinson et al. (2000)	7.65 ± 0.55	275	Obermeier (1988)	260 ± 10
		36.3°N	89.4°W	Bakun & Hopper (2004b)	7.6 - 7.7 ± 0.5	Wheeler & Perkins (2000)		250	Street & Nuttli (1984)	
					7.8	Bakun & Hopper (2004a)				
					7.4 - 7.5	Hough et al. (2000)				
					8.0 ± 0.33	Johnston (1996)				
6/9/1838	east of Centralia, Illinois	38.5°N	89°W	Wheeler (2003)	5.7	Wheeler (2003)	5.7	0	Hopper (2004)	0
		38.59°N	90.22°W	Bakun & Hopper (2004b)	3.9	Bakun & Hopper (2004b)				
1/5/1843	near Marked Tree, Arkansas	35.5°N	90.5°W	Wheeler (2003)	6.3	Wheeler (2003)	6.3	0	Hopper (2004)	0
		35.9°N	89.9°W	Bakun & Hopper (2004b)	6.2	Bakun & Hopper (2004b)				
					6.0	Bakun et al. (2003)				
					6.3	Johnston (1996)				
10/8/1857	north of Centralia, Illinois	38.7°N	89.2°W	Wheeler (2003)	5.3	Wheeler (2003)	5.3	0	Hopper (2004)	0
					4.5	Bakun & Hopper (2004b)				
8/17/1865	New Madrid, Missouri	36.5°N	89.5°W	Wheeler (2003)	5.3	Wheeler (2003)	5.3	0	Hopper (2004)	0
		35.54°N	90.40°W	Bakun & Hopper (2004b)	4.7	Bakun & Hopper (2004b)				
8/31/1886	Charleston, South Carolina	32.9°N	80.0°W	SCSN (2004) ^(d)	6.9	Bakun & Hopper (2004a)	7.1 ± 0.2	90	Youd et al. (1989); Johnston (1996); Obermeier et al. (1989)	100
					7.3 ± 0.26	Johnston (1996)		100	Obermeier et al. (1989); Amick et al. (1990).	
					7.0	Nuttli et al. (1992)				
					7.2	Campbell (1986)				
					6.9	Nuttli (1983)				
9/27/1891	near Fairfield, Illinois	38.3°N	88.5°W	Wheeler (2003)	5.8	Wheeler (2003)	5.8	0	Hopper (2004)	0
		38.34°N	89.27°W	Bakun & Hopper (2004b)	4.9	Bakun & Hopper (2004b)				
10/31/1895	Charleston, Missouri alternate location	37°N	89.4°W	Wheeler (2003)	5.7 - 6.3 (6.0)	Bakun et al. (2003)	6.0 ± 0.3	16 - 20	Obermeier et al. (1993)	18 ± 2
		37.82°N	89.32°W	Bakun & Hopper (2004b)	6.2	Bakun & Hopper (2004b)		19	Hopper (2004)	
					6.6	Wheeler (2003)		~100	Bakun et al. (2003); Street et al. (2004)	
					6.6 ± 0.29	Johnston (1996)				
					5.9	Stover & Coffman (1993)				
					6.2	Street et al. (1986)				
4/9/1917	Monroe County, Illinois	38.1°N	90.2°W	Wheeler (2003)	5.0	Wheeler (2003)	5.0	0	Hopper (2004)	0
		38.84°N	89.38°W	Bakun & Hopper (2004b)	5.2	Bakun & Hopper (2004b)				
2/28/1925	Charlevoix-Kamouraska, Quebec, Canada	47.76°N	69.84°W	NRC (2004) ^(e) ; Bakun et al. (2003)	6.2	NRC (2004) ^(e)	6.3 ± 0.5	45 - 50	This study Street et al. (2004)	47 ± 2
					6.3 ± 0.5	Bakun et al. (2003)		148		
11/9/1968	near Boughton, southern Illinois	37.91°N	88.46°W	Wheeler (2003)	5.4	Wheeler (2003)	5.4	0	Hopper (2004); Heigold (1968)	0
		37.96°N	88.46°W	Heigold (1968)	5.5	Heigold (1968)				
					5.3	Bakun & Hopper (2004b)				
6/10/1987	east of Olney, Illinois	38.71°N	87.95°W	Wheeler (2003); Taylor et al. (1989)	5.0	Wheeler (2003); Taylor et al. (1989)		0	Hopper (2004)	0
11/25/1988	Saguenay, Quebec, Canada	48.12°N	71.18°W	NRC (2004) ^(e) ; Bakun et al. (2003)	5.9	NRC (2004) ^(e)	5.9 (5.8 - 6.5)	30 ± 4	Law (1990); Tuttle et al. (1990)	30 ± 4
					5.8 ± 0.1	Somerville (1991)				
					6.5 ^(f)	Somerville et al. (1990)				
					6.5 ^(g)	Boore & Atkinson (1992)				

CEUS Magnitude Bound



Olson et al. (2005b)

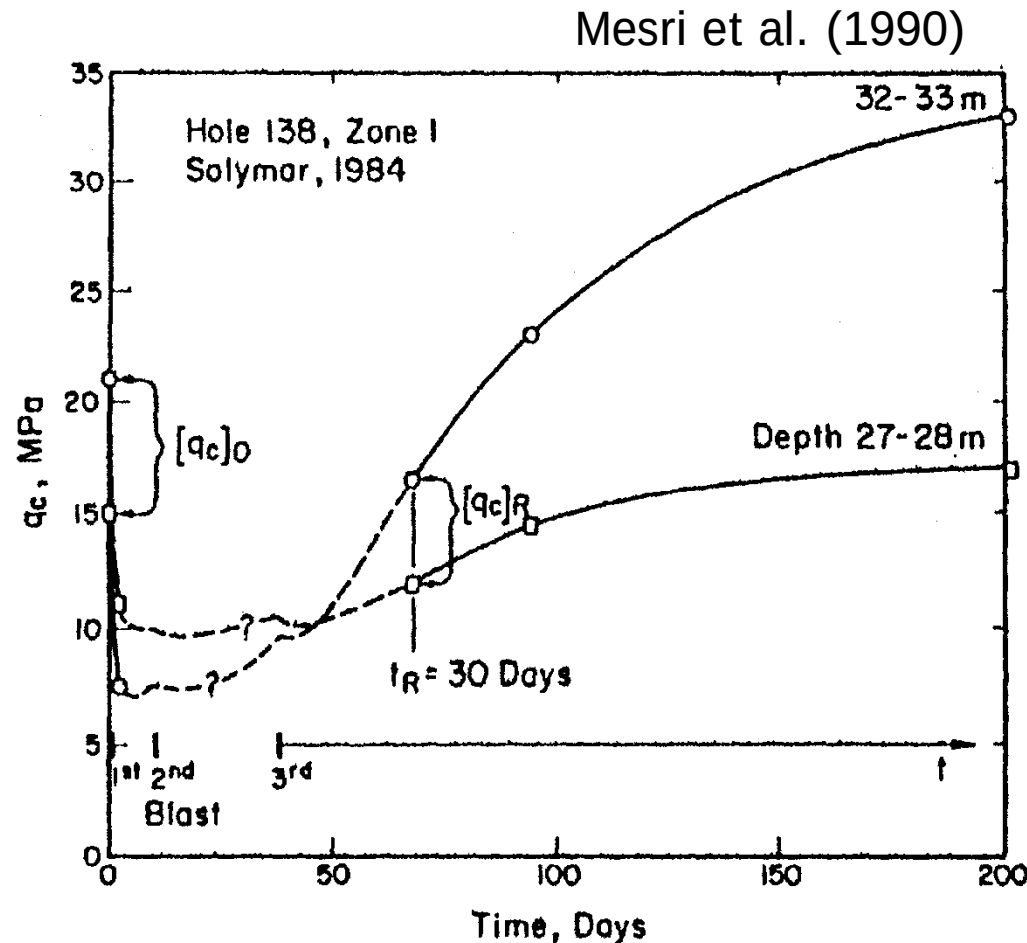
Sources of Uncertainty

- ❖ Liquefaction susceptibility
- ❖ Field observations, ground failure mechanism, and field setting
- ❖ Seismicity and seismic demand
- ❖ In situ testing techniques
- ❖ Magnitude bound method

Liquefaction Susceptibility –Aging

❖ Aging is the process by which soils develop a structure over time that results in improved soil properties (e.g., shear strength, stiffness, and penetration resistance)

- mechanical sources (secondary compression and preshearing)
- chemical sources (cementation and bonding)



Liquefaction Susceptibility –Aging

- ❖ Penetration tests for modern liquefaction database collected some time after causative earthquake
- ❖ These data already include several log cycles of time for secondary compression after reconsolidation

Time after earthquake required for reconsolidation, t_{95} (days)	$t_{\text{elapsed,avg}}$ (days)	$\log_{10}$ ($t_{\text{elapsed,avg}}/t_{95}$)	$t_{\text{elapsed,max}}$ (days)	$\log_{10}$ ($t_{\text{elapsed,max}}/t_{95}$)	$t_{\text{elapsed,min}}$ (days)	$\log_{10}$ ($t_{\text{elapsed,min}}/t_{95}$)
1	1030	3.0	7050	3.8	45	1.7
7		2.2		3.0		0.8
14		1.9		2.7		0.5

Liquefaction Susceptibility – FC & Overburden Stress

- ❖ Increasing FC decreases penetration resistance
- ❖ Increasing σ'_{v0} increases penetration resistance

Factor	Model	Weight
FC adjustment	Kayen and Mitchell (1997)	0.25
	Youd et al. (2001)	0.25
	Cetin et al. (2004)	0.25
	Idriss and Boulanger (2006)	0.25
Overburden stress correction, K_σ	Seed and Harder (1990)	0.1
	Harder and Boulanger (1997)	0.1
	Youd et al. (2001)	0.5
	Idriss and Boulanger (2006)	0.3

Liquefaction Severity



Severe



Moderate

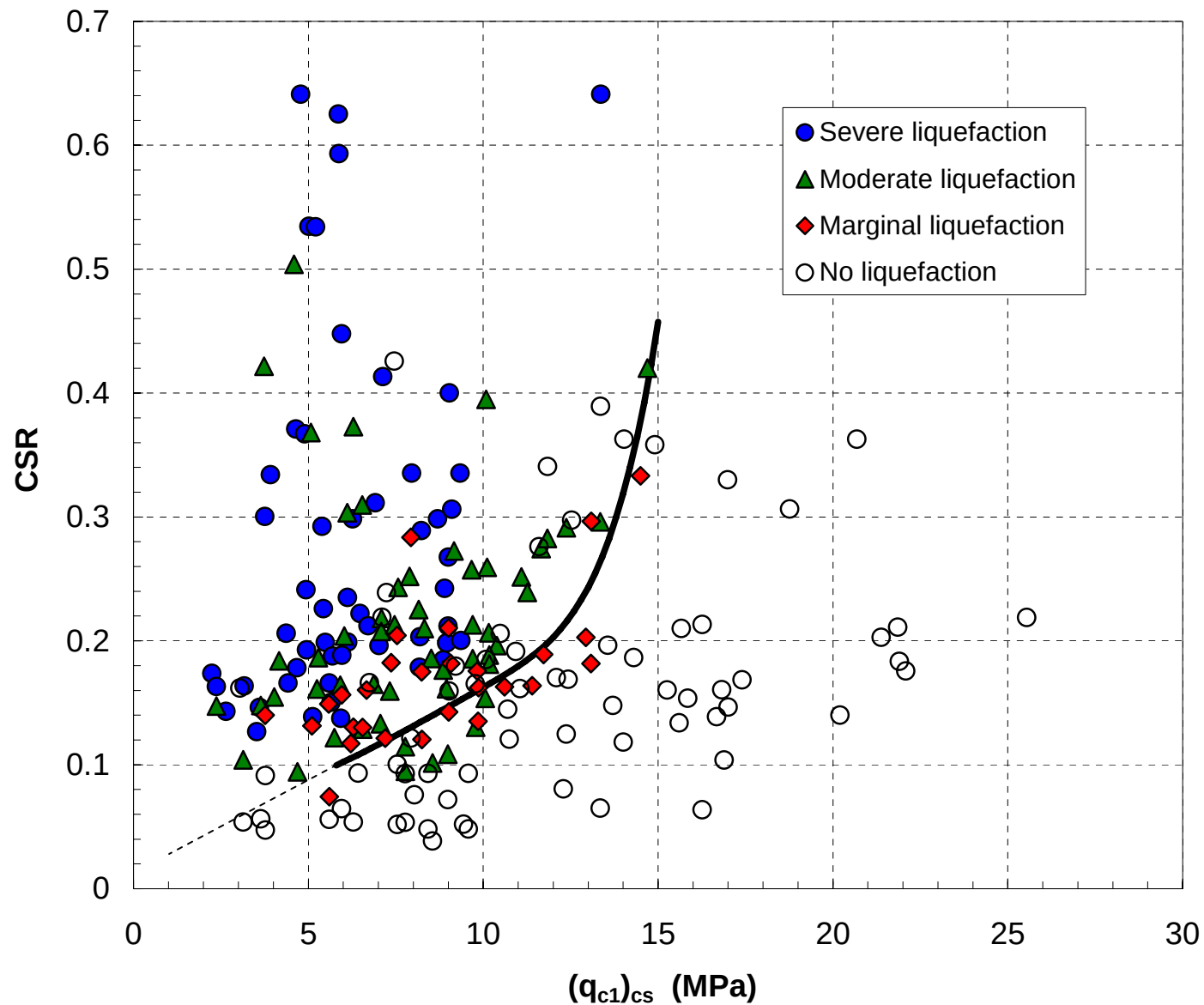


Marginal

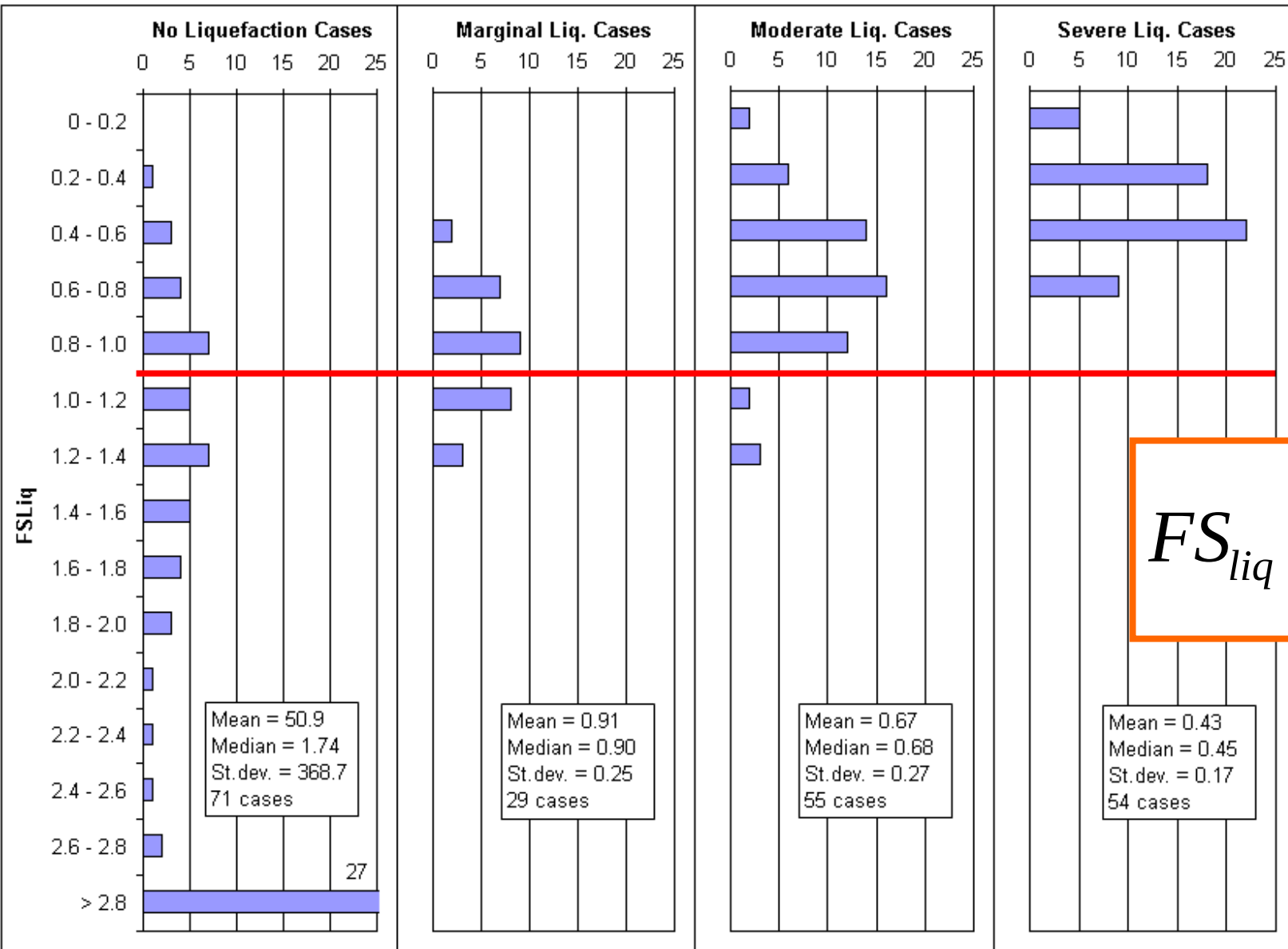
Liquefaction Severity

Olson et al. (2005)/Green et al. (2005)		Bray et al. (2000)/Juang et al. (2005)	
Category	Description	Category	Description
No liquefaction	- No sand blows - No lateral spreading features - No subvertical sand dikes - Possible subhorizontal sand sills	No observed ground damage	- No settlement - No building tilt - No lateral movement - No sand boils
Marginal liquefaction	Effects that are barely discernable (e.g., cracking of cap at ground surface) or weakly developed (e.g., scattered small sand blows)	Minor to moderate damage	- Settlement < 25 cm - Building tilt < 3° - Lateral movement < 10 cm
Moderate liquefaction	- Lateral spreads with dikes ~ 15 cm in width - Scattered large sand blows	Major ground damage	- Settlement ≥ 25 cm - Building tilt ≥ 3° - Lateral movement ≥ 10 cm - Building collapse
Severe liquefaction	- Dikes ~ 0.5 m wide or larger - Numerous large sand blows - Severe warping or distortion of ground surface or of thick fine-grained strata at depth		

Effect of Severity on FS_{liq}



Effect of Severity on FS_{liq}



$$FS_{liq} = \frac{CRR}{CSR}$$

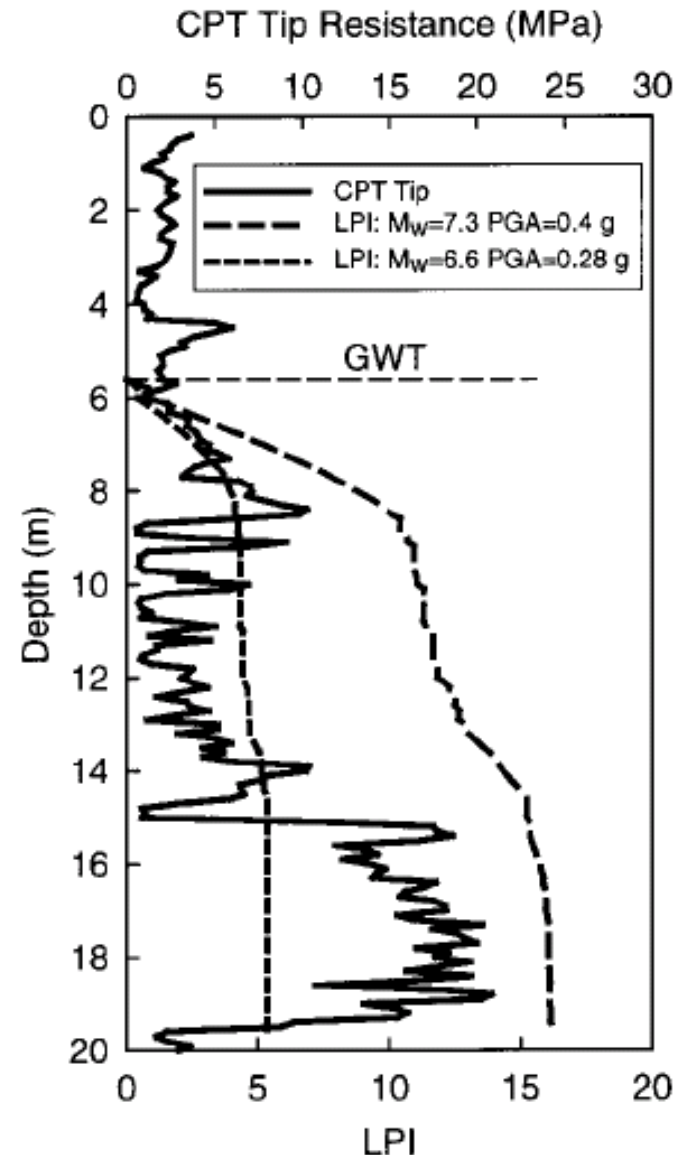
Liquefaction Potential Index (LPI)

- ❖ FS_{liq} is effective, but doesn't consider stratigraphy (i.e., thick cap, very thin liquefiable sand)
- ❖ LPI considers the depth of liquefiable layers, layer thickness, and FS_{liq}

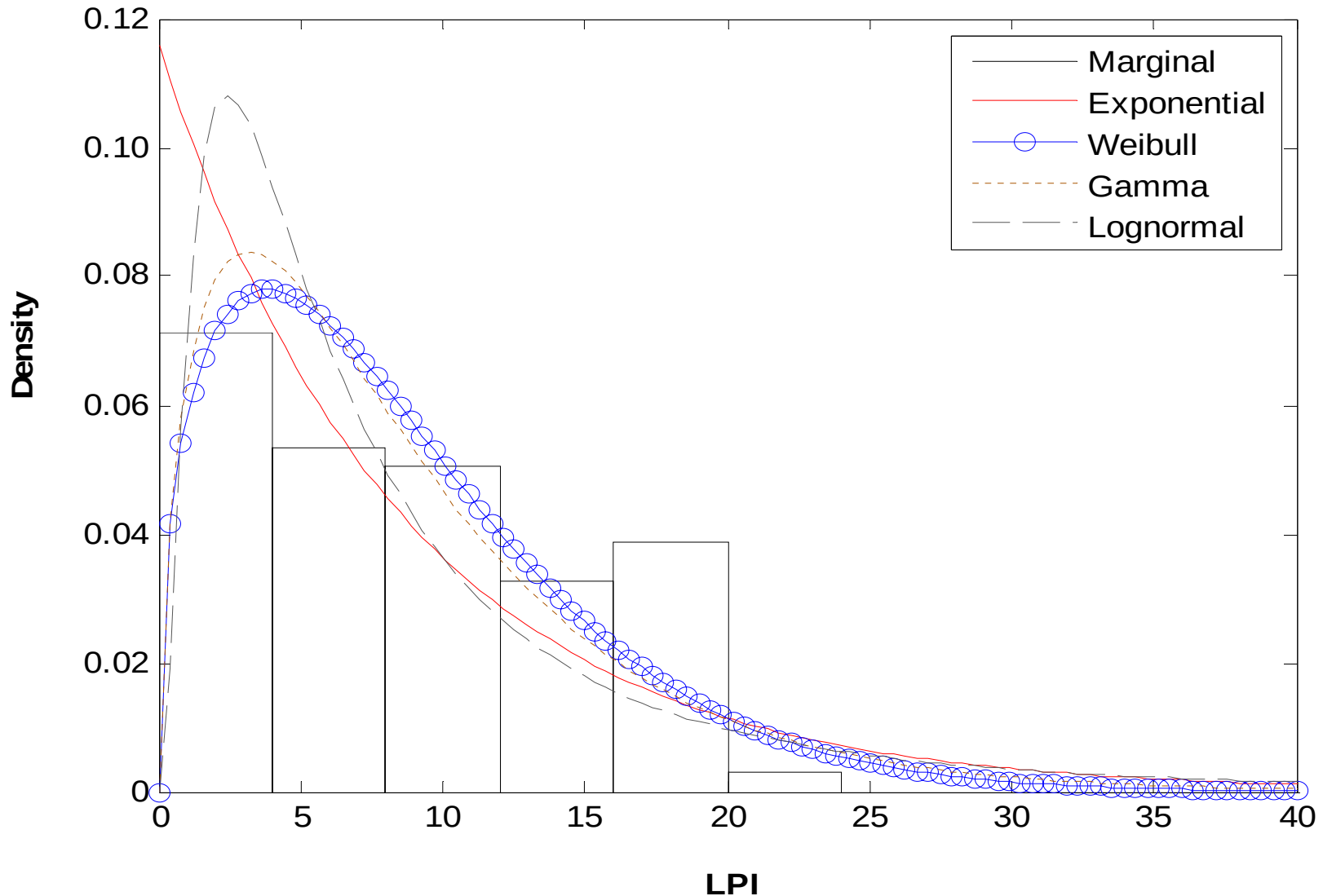
$$LPI = \int_0^{20} F(FS, z) W(z) dz$$

where $F(FS, z) = 1 - FS \geq 0$

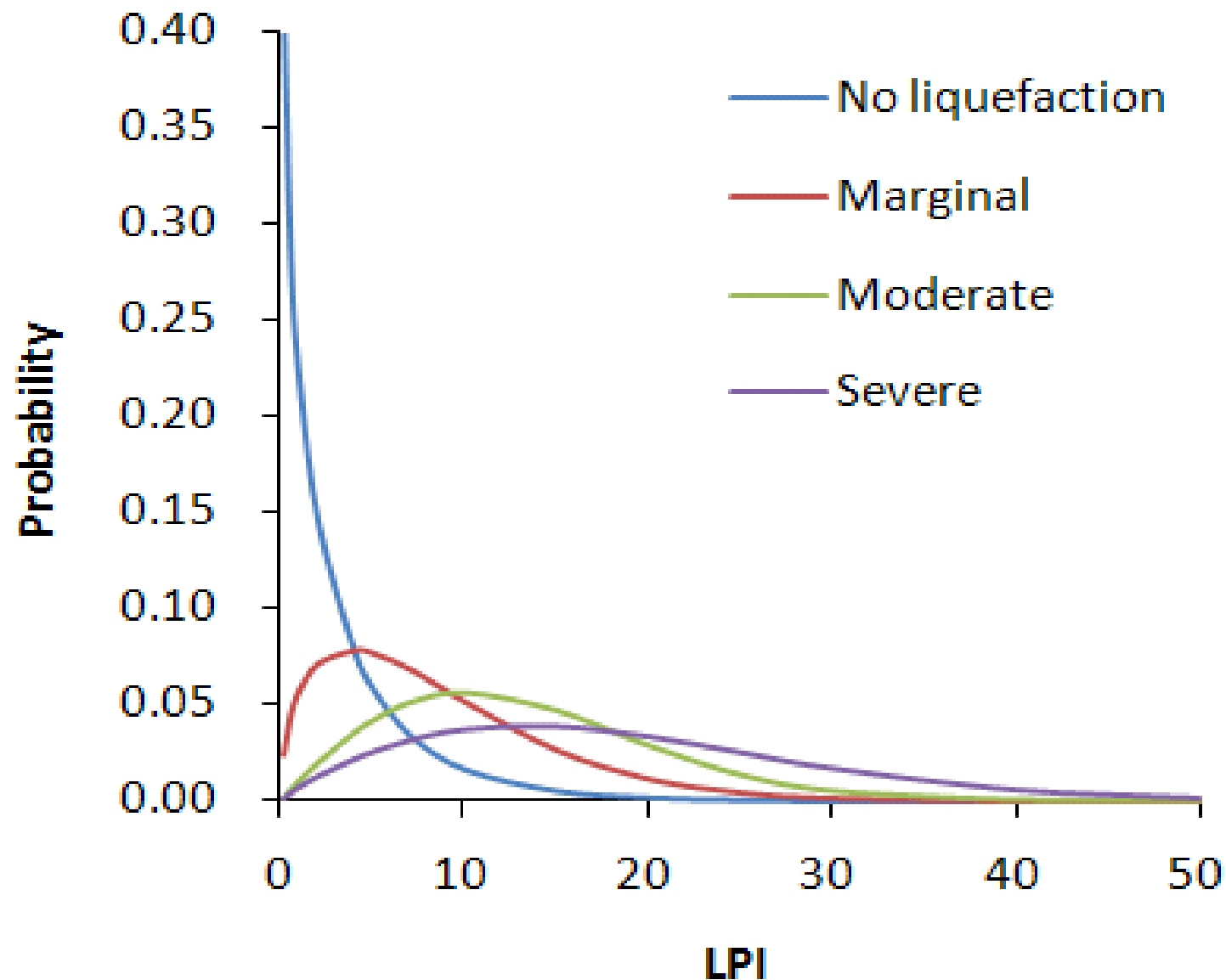
and $W(z) = 10 - 0.5z$ (m)



Using LPI to Assess Marginal Liquefaction Severity

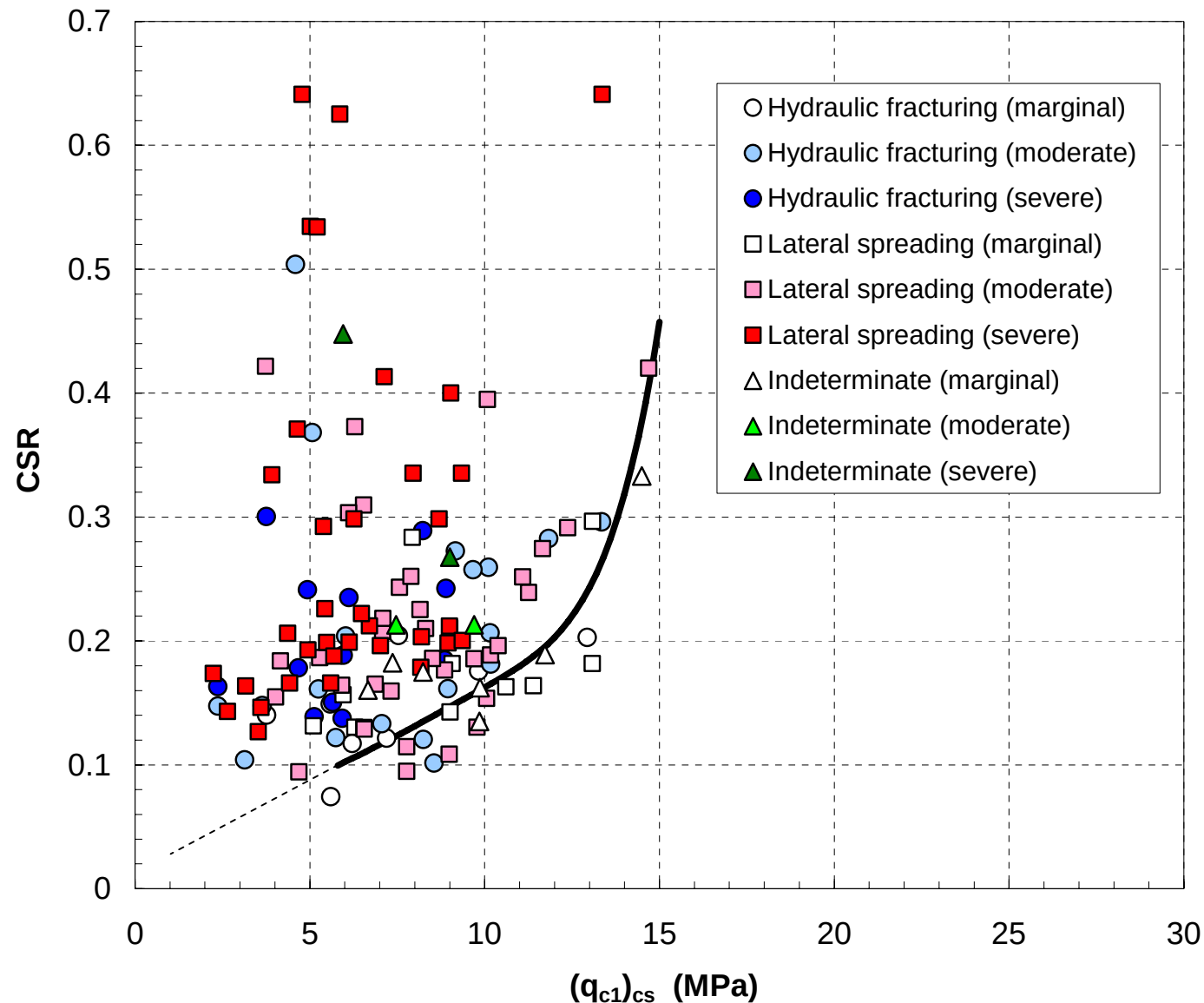


Distributions for LPI and Severity



Field Observations, Failure Mechanism, Field Setting

Does failure mechanism (hydraulic fracturing, lateral spreading, or surface oscillations) influence liquefaction resistance?



Field Observations, Failure Mechanism, Field Setting

❖ Field data quality (FDQ) index

- Variability of geologic setting (e.g., braid bar, point bar, etc.)
- Depth of potential source beds at time of earthquake
- Depth of GWT at time of earthquake
- Mechanism of ground failure
- Liquefaction severity (as it relates to making field interpretations)
- Number, spacing, and locations of borings/in situ tests
- Vertical and lateral variability of sediments
- Method of observation (plan view v. sectional view)
- Length and quality of bank exposure

❖ Classifications: Low, Intermediate, High

Field Observations, Failure Mechanism, Field Setting

◆ Using FDQ to estimate some uncertainties

Variable	Reported COV range (mean)	References	COV assigned to FDQ ranking		
			High	Intermediate	Low
Unit weight (kN/m ³)	3 – 20 (9) 3 – 7 (–) 0 – 10 (–) ⁽¹⁾	Phoon and Kulhawy (1999) Kulhawy (1992); Duncan (2000) Lacasse and Nadim (1996)	5	10	15
Fines content (%)	1 – 43 (20) ⁽²⁾ 9 – 70 (25) ⁽³⁾	Baecher and Christian (2003) Baecher and Christian (2003)	15	25	35
Measured N-value	26 (–) 14 – 100 (15 – 45) 19 – 62 (54) ⁽³⁾ 25 – 50 (–)	Harr (1987) Kulhawy and Trautmann (1996) Phoon and Kulhawy (1999) Baecher and Christian (2003)	25	35	45
Measured q _c -value	37 (–) 8 – 22 (5 – 15) 10 – 81 (38) ⁽⁴⁾ 20 – 60 (–)	Harr (1987) Kulhawy and Trautmann (1996) Phoon and Kulhawy (1999) Baecher and Christian (2003)	15	25	35

Notes: (1) Reported values for buoyant unit weight
 (2) Reported values for sand content.
 (3) Reported values for clay content.
 (4) Reported values for tests performed in sand.

Field Observations, Failure Mechanism, Field Setting

- ❖ 3σ approximation for other uncertainties for random variables that cannot be quantified readily

$\mu =$ **Best estimate**

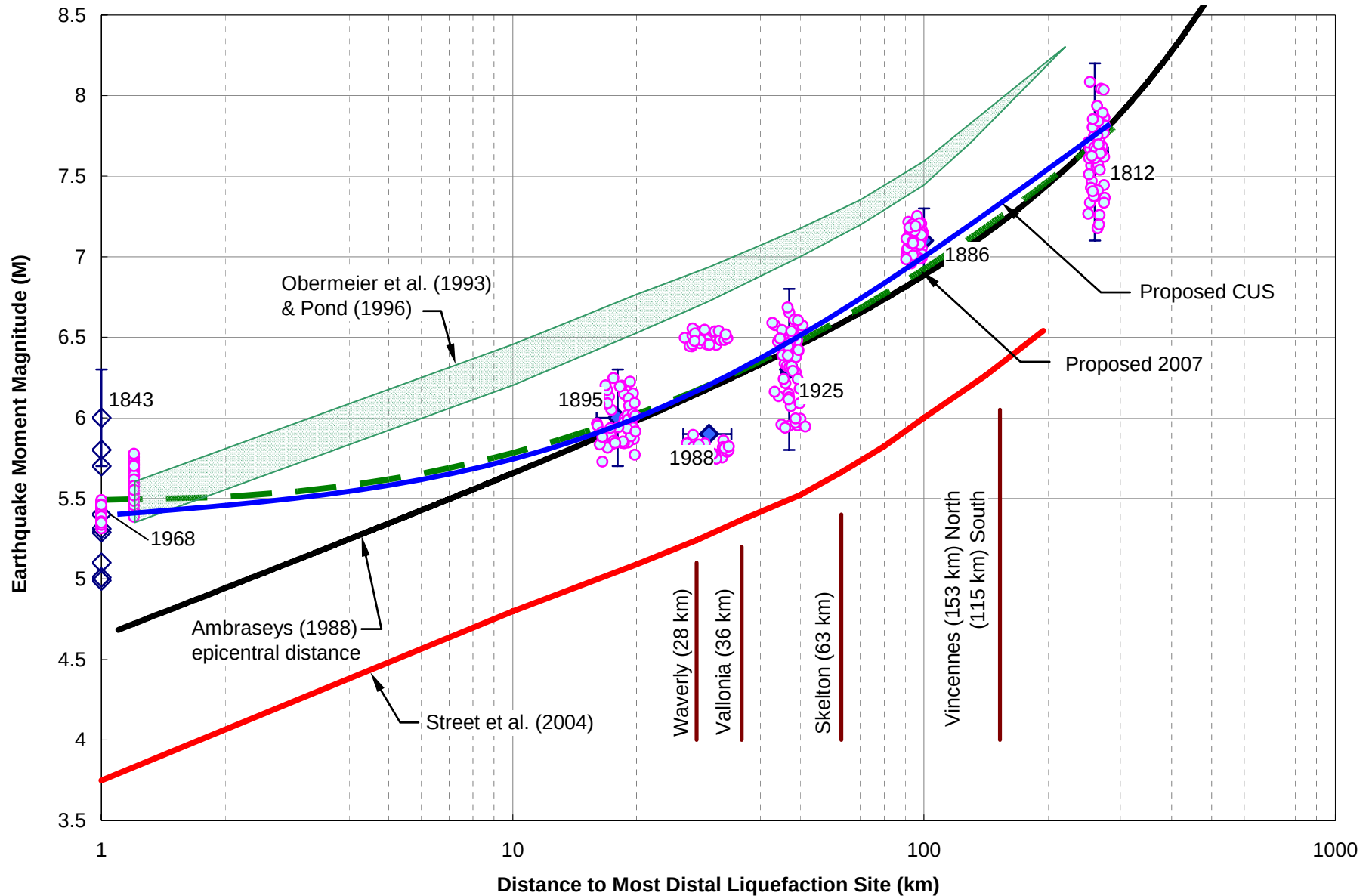
$$\sigma = \frac{\text{Upper bound value} - \text{Lower bound value}}{6}$$

Seismicity and Seismic Demand

◆ Seismic demand factors

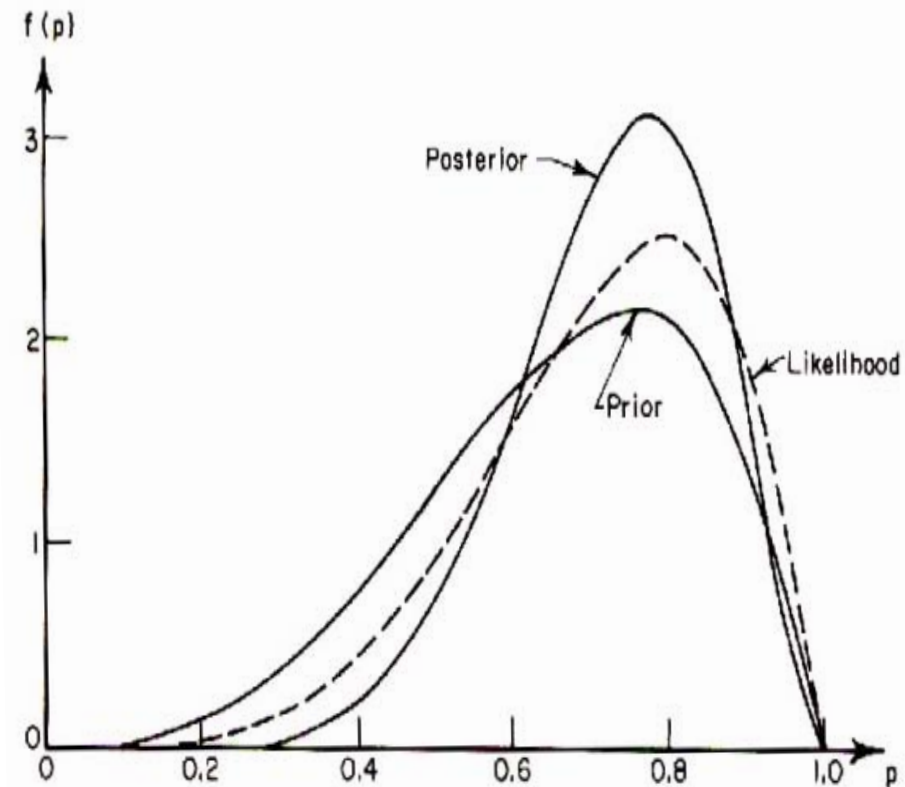
Factor	Model	Weight	Comment
MSF	Seed and Idriss (1982)	0.20	Initial estimates of weight based on particular model's use in practice.
	Youd and Noble (1997) ($P_L = 50\%$)	0.10	
	Andrus and Stokoe (1997)	0.35	
	Idriss (1999)	0.35	
r_d	Youd et al. (2001)	0.75	Initial estimates of weight based on particular model's use in practice.
	Iwasaki et al. (1978)	0.25	
Bedrock attenuation	Atkinson and Boore (1995)	0.25	Attenuation relationships and weighting factors taken as identical to those used by the USGS in the 2001 U.S. seismic hazard maps. Aleatoric uncertainties estimated by individual investigators.
	Frankel et al. (1996)	0.25	
	Toro et al. (1997)	0.25	
	Somerville et al. (2001)	0.125	
	Campbell (2003, 2004)	0.125	

Probabilities for CEUS Magnitude Bound

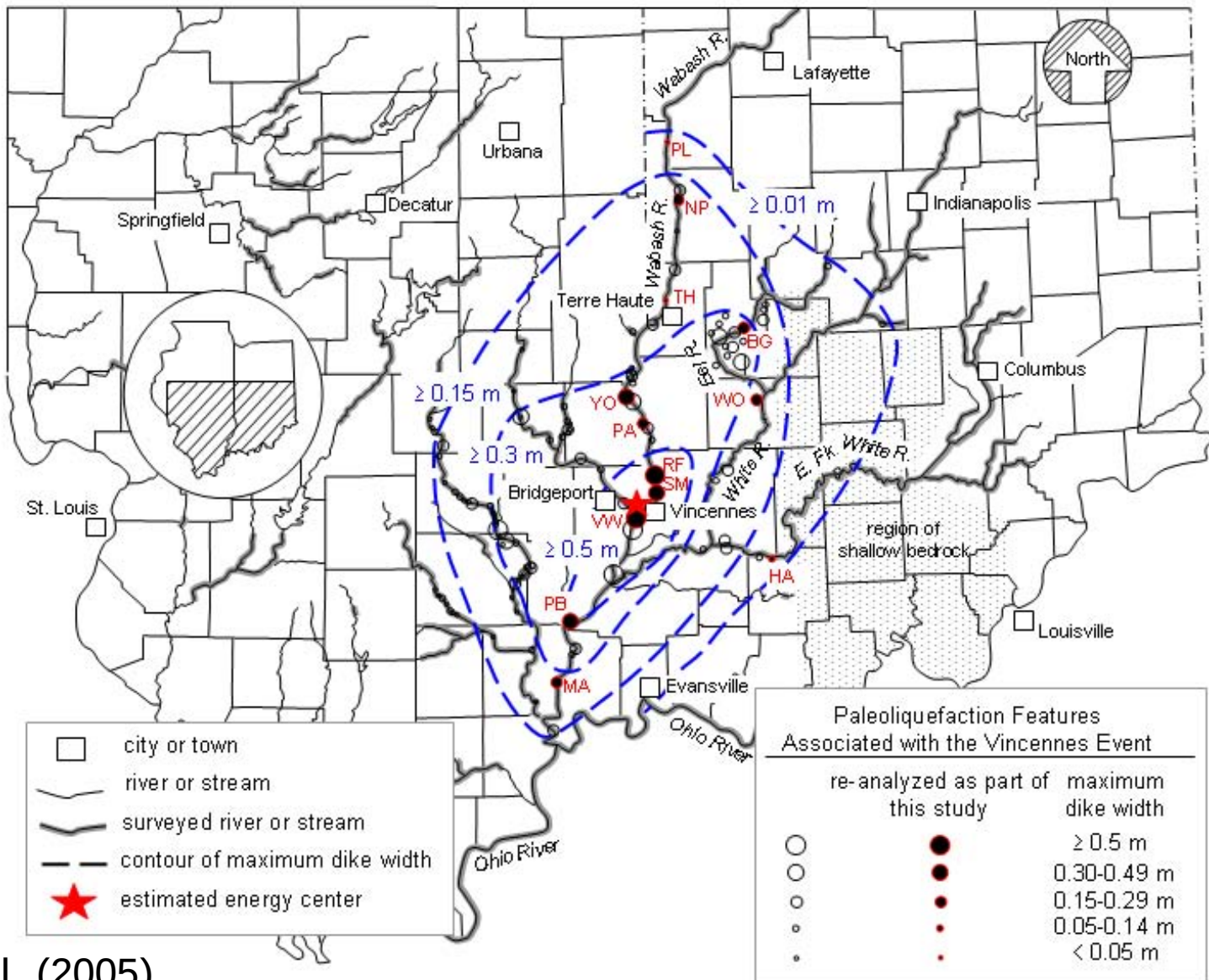


Bayesian Updating Method

- ❖ **Subjective judgments**
based on intuition, experience, or indirect information are incorporated systematically with **observed data** to obtain a balanced estimation (conditional probability)
- ❖ Prior distribution from magnitude bound method combined with likelihood function from sites of observed liquefaction (or no liquefaction) to yield posterior distribution



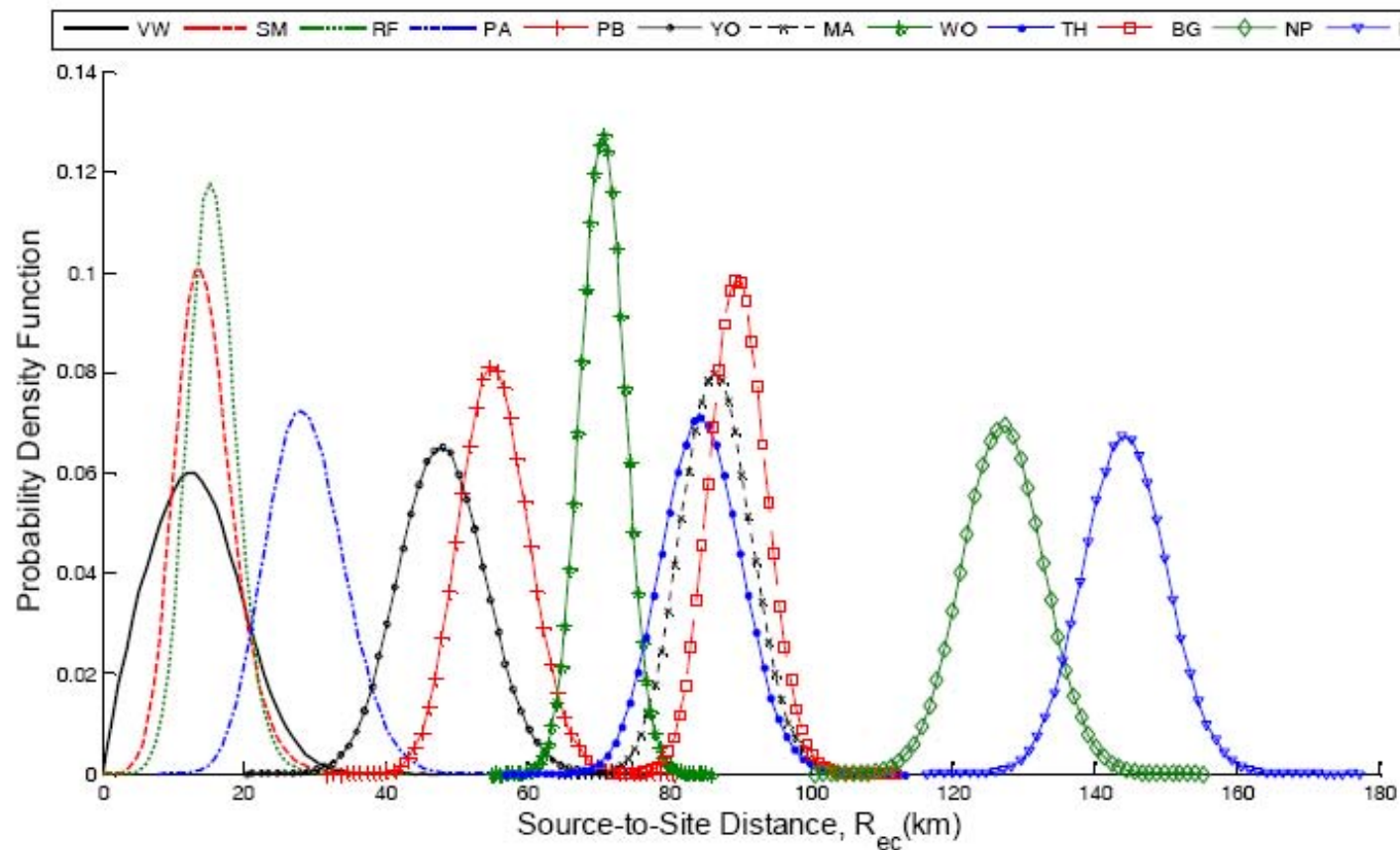
Example for Vincennes Earthquake, Wabash Valley



Green et al. (2005)

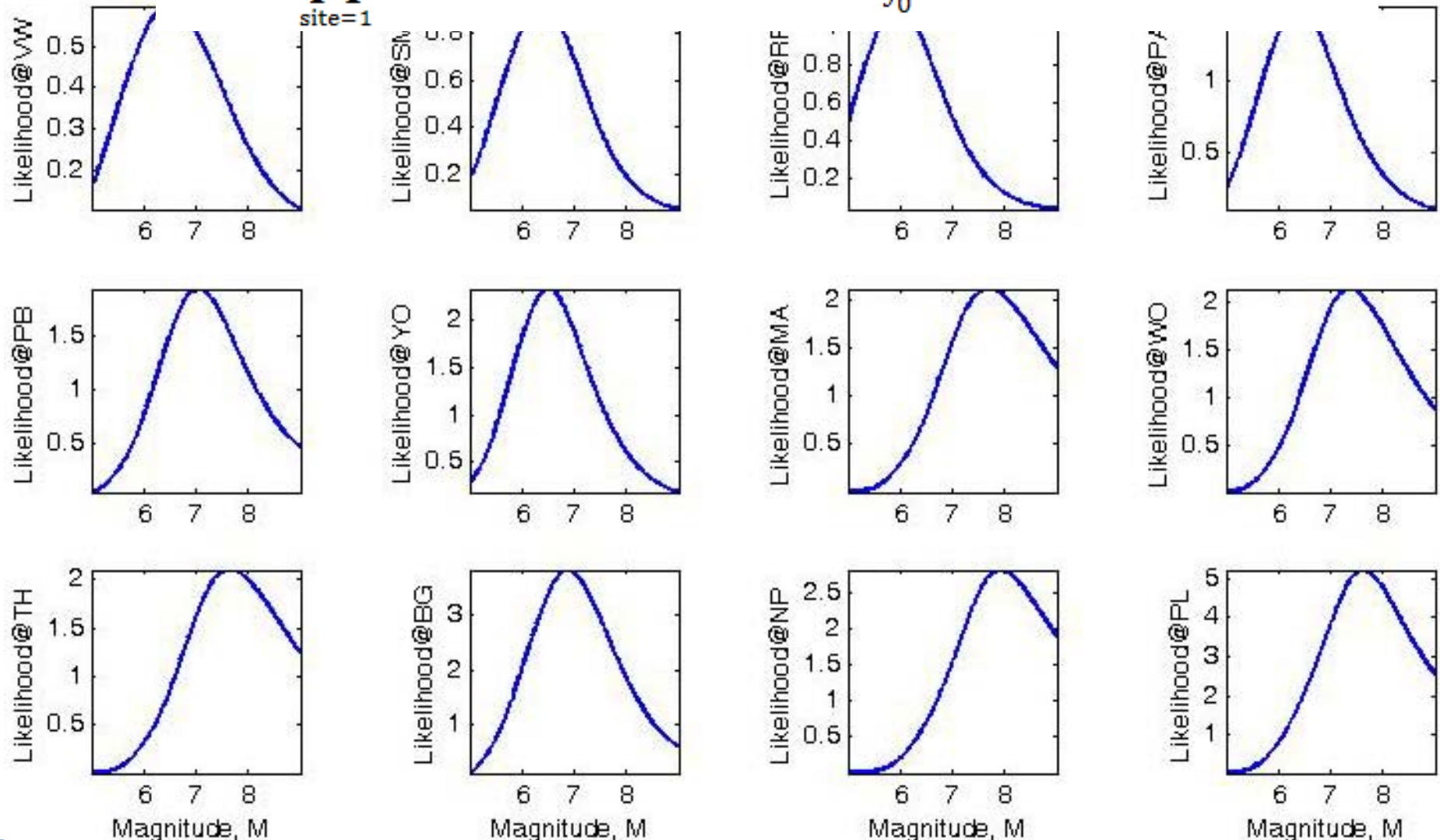
Energy Center and Source-to-Site Distance

Approach	Reference	Weight
Centroid of maximum dike widths (best estimate)	This study	0.3
Centroid of maximum dike widths (upper bound)	This study	0.1
Centroid of maximum dike widths (lower bound)	This study	0.1
Deterministic energy center	Obermeier (1998a)	0.5

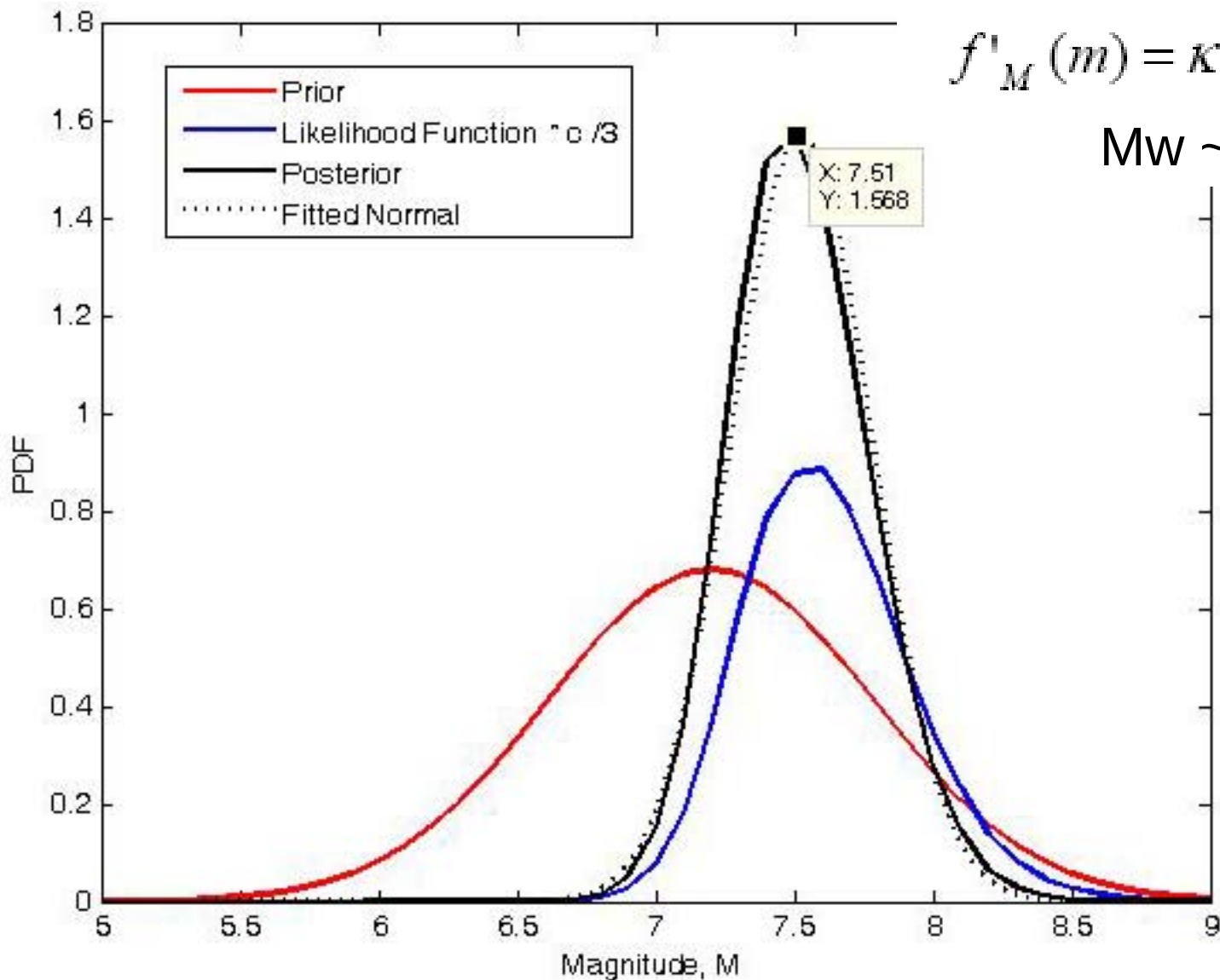


Vincennes Earthquake, Wabash Valley

$$L(m) = \prod_{site=1}^{site=n} [P(LPI_{site}|m) = P(LPI_{severity})] = \int_0^{\infty} p(LQ^i|lpi) \cdot f(lpi|m) \cdot d(lpi)$$



Vincennes Earthquake, Wabash Valley



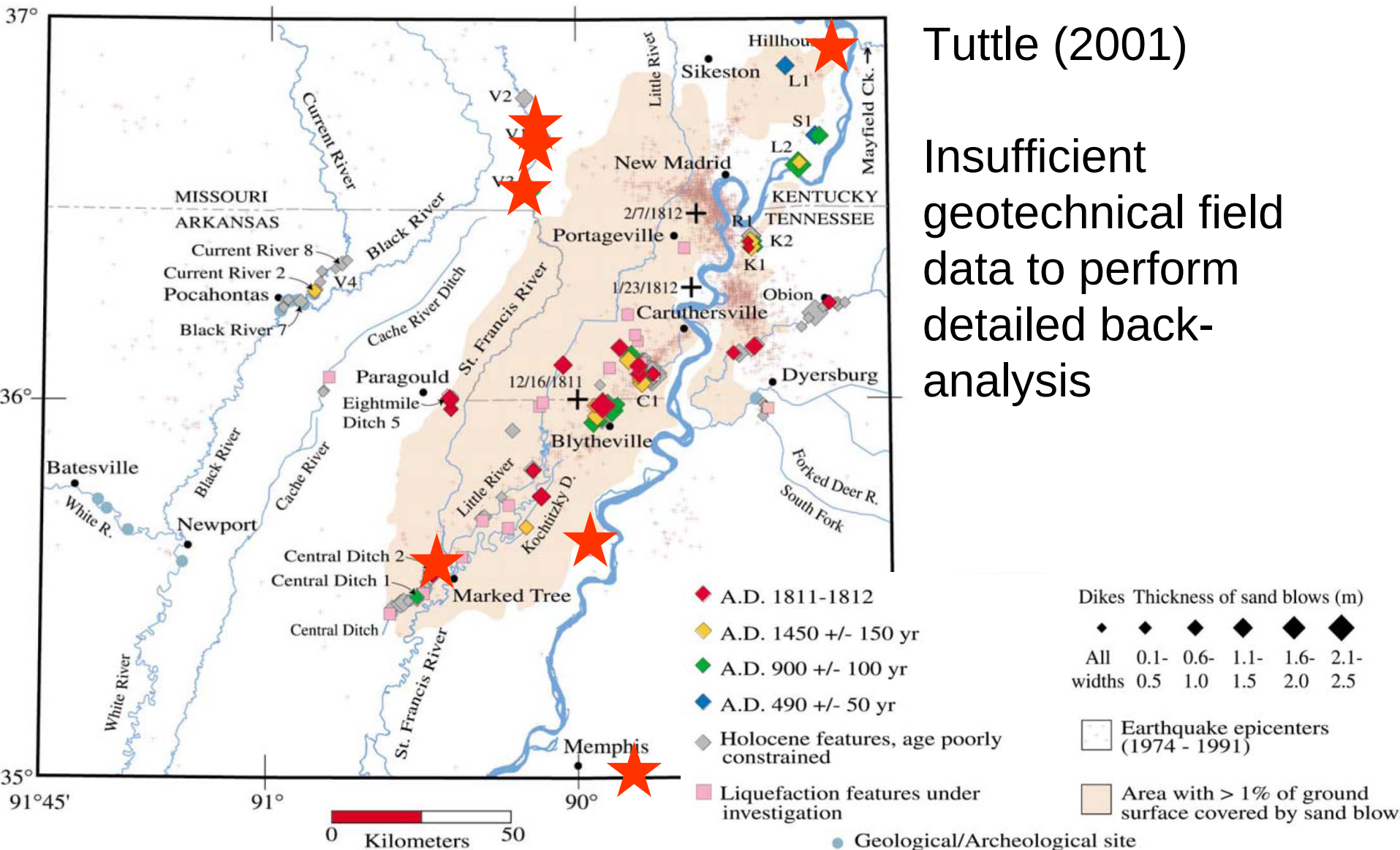
$$f'_M(m) = \kappa \cdot L(m) \cdot f_M(m)$$

$$M_w \sim 7.5 \pm \sim 0.3$$

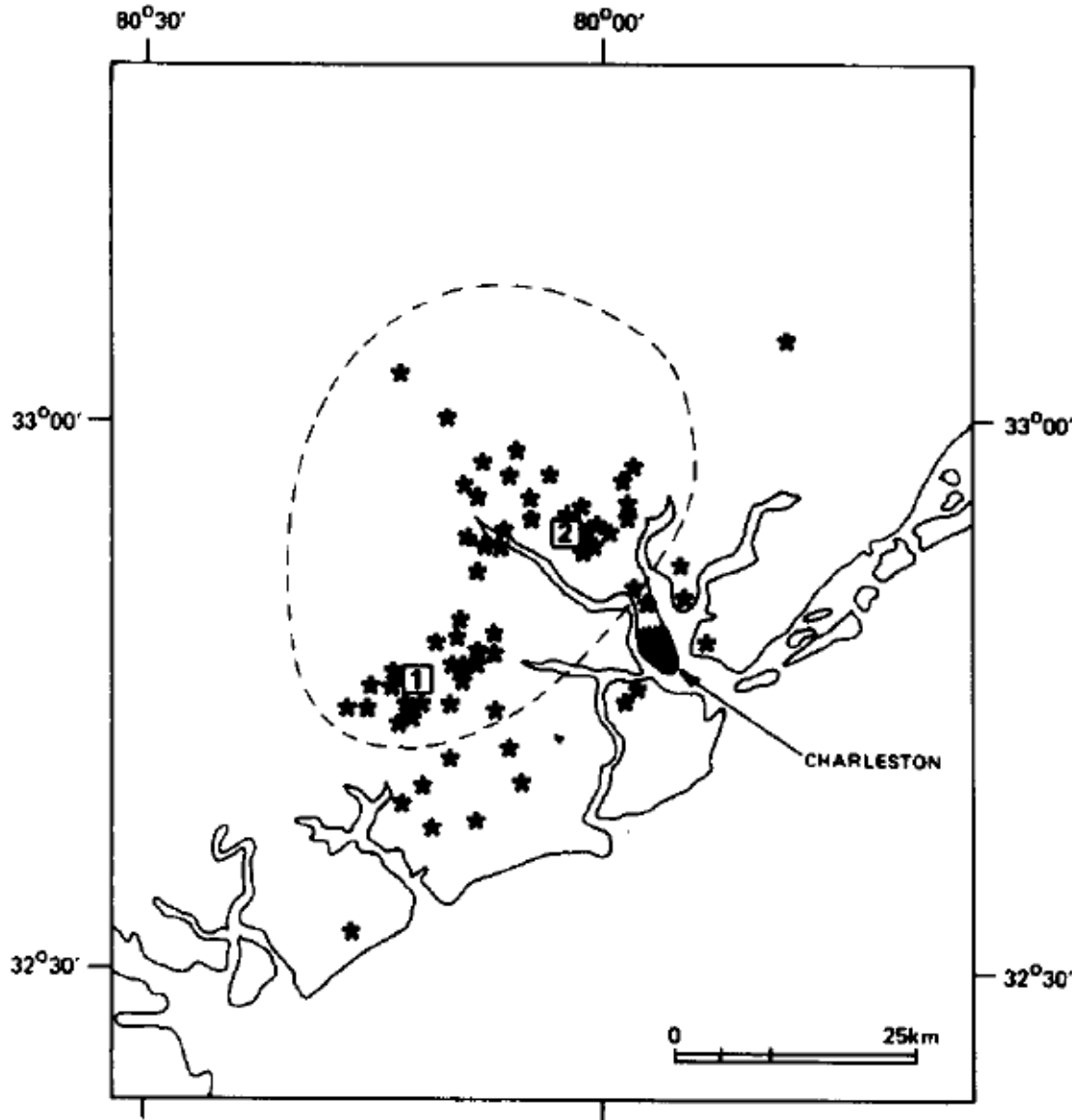
New Madrid Seismic Zone

Tuttle (2001)

Insufficient
geotechnical field
data to perform
detailed back-
analysis



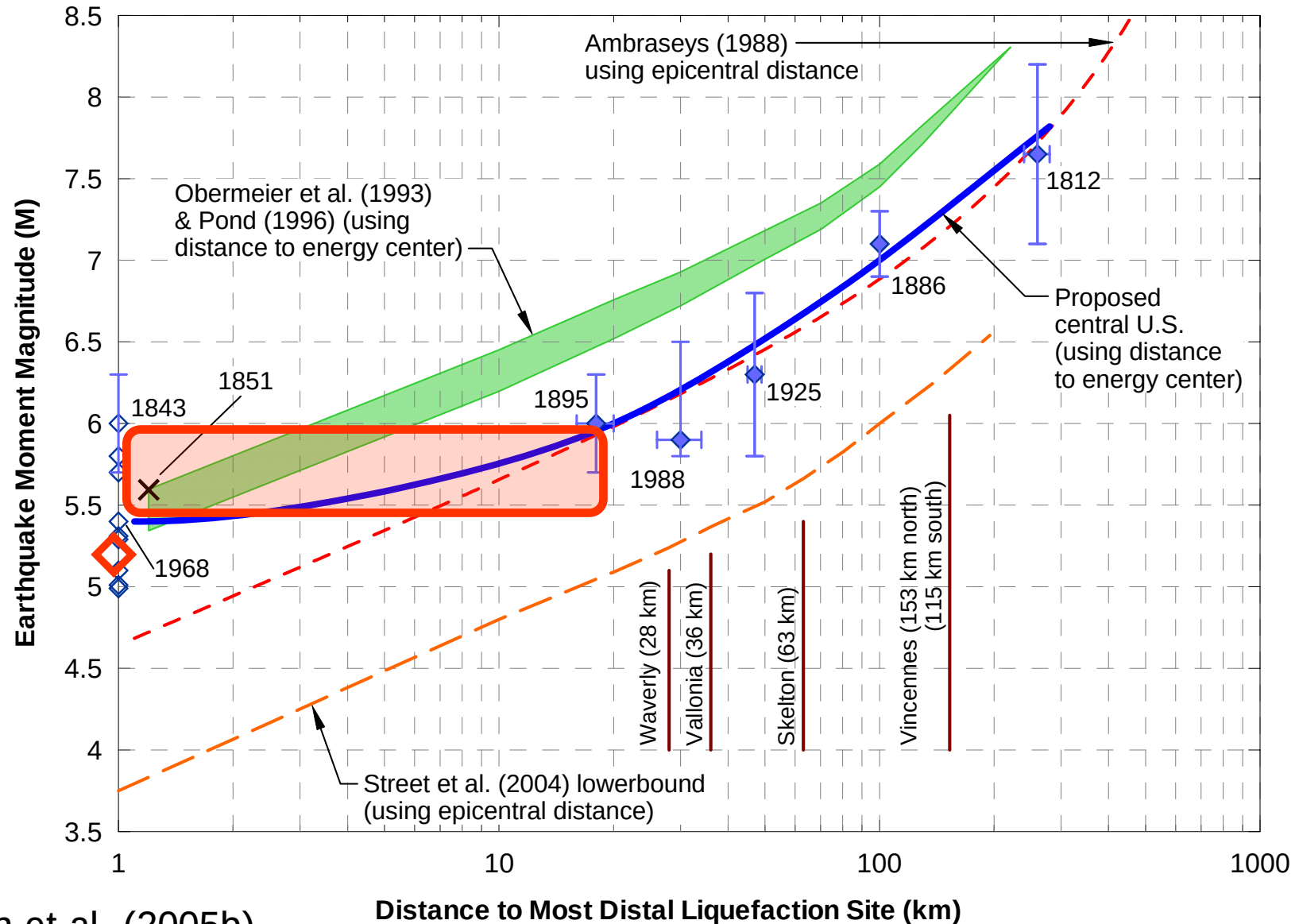
Charleston, SC



Amick et al. (1992)

Only a handful of these sites have reliable CPT, SPT, and Vs data (Hu et al. 2002)

CEUS Minimum Magnitude

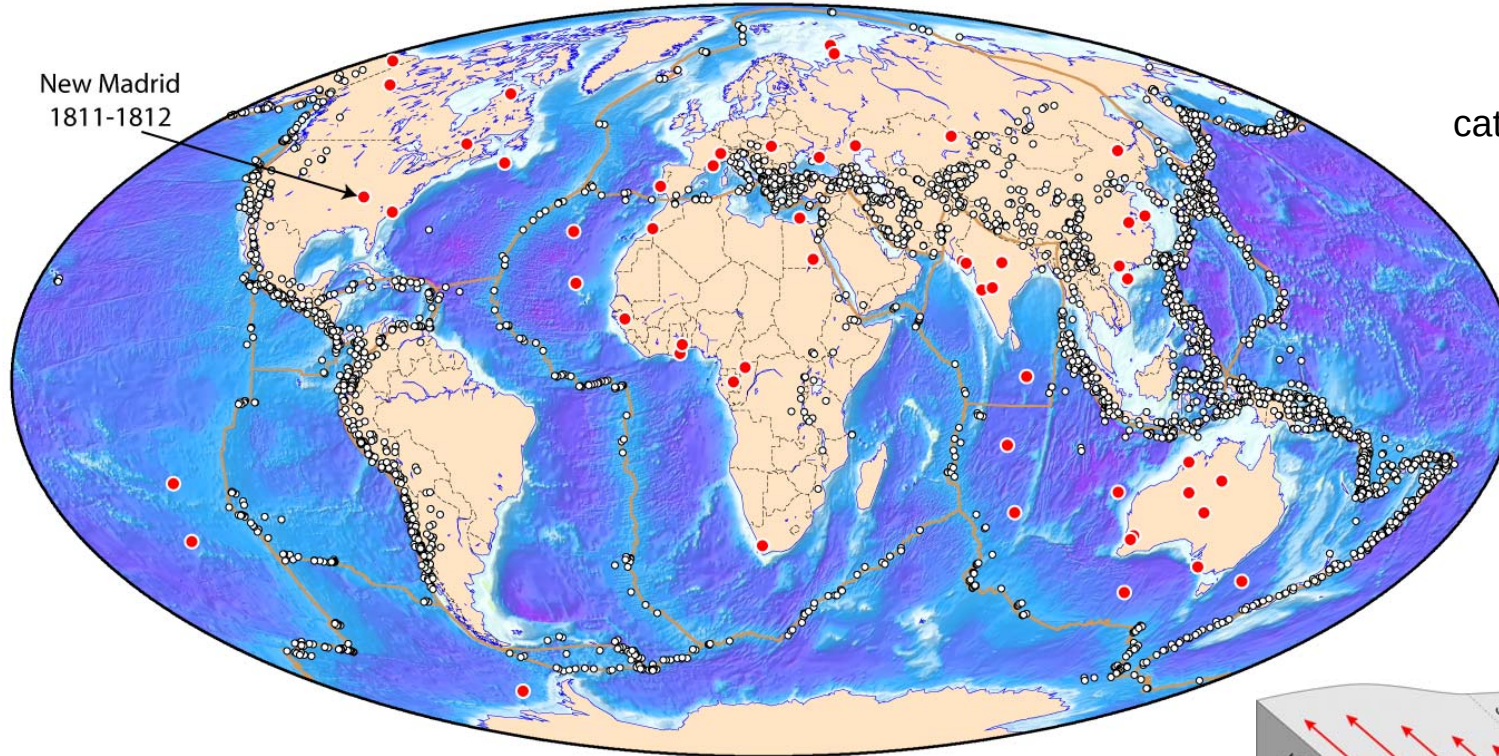


Olson et al. (2005b)

Thanks for your attention!

Questions?

olsons@illinois.edu

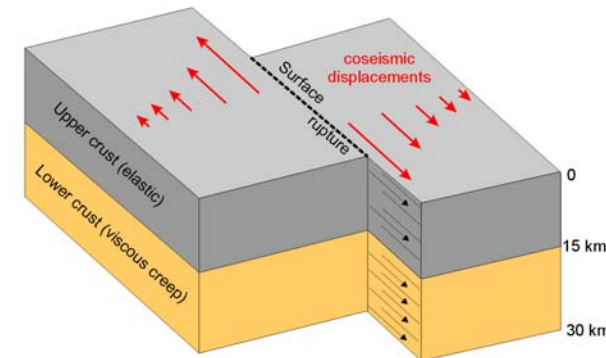
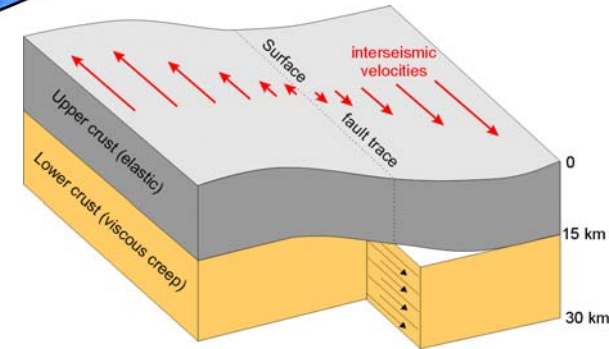


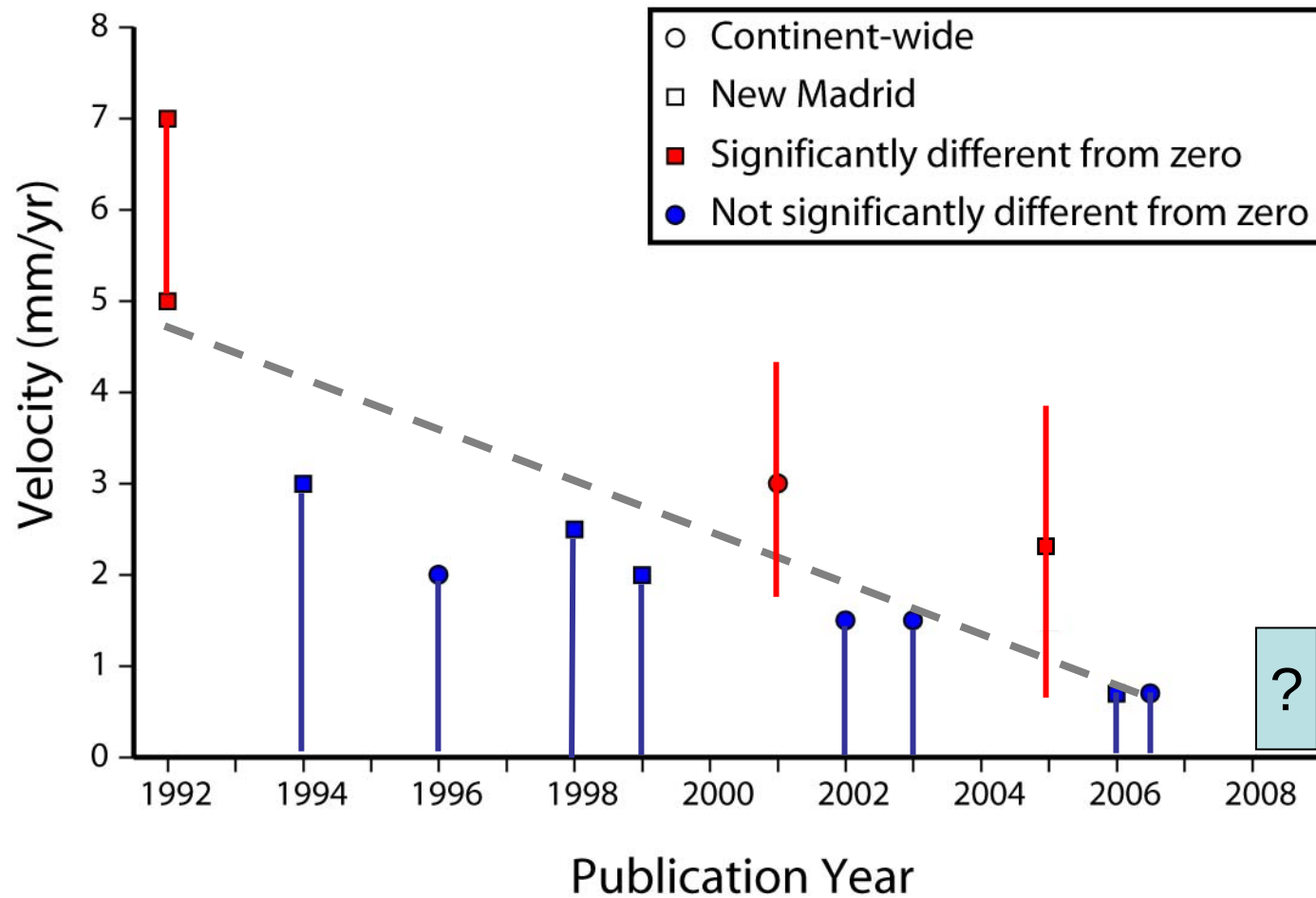
M>6 - NEIC
catalog, historical
+ recorded

Steady-state “elastic rebound” model: strain accumulation rate = rate of seismic strain release (over a few 1,000 years)

- Geodesy and paleoseismology should agree
- Works well at plate boundary faults
- Present-day strain accumulation has predictive power
- Hope: this also applies to SCRs

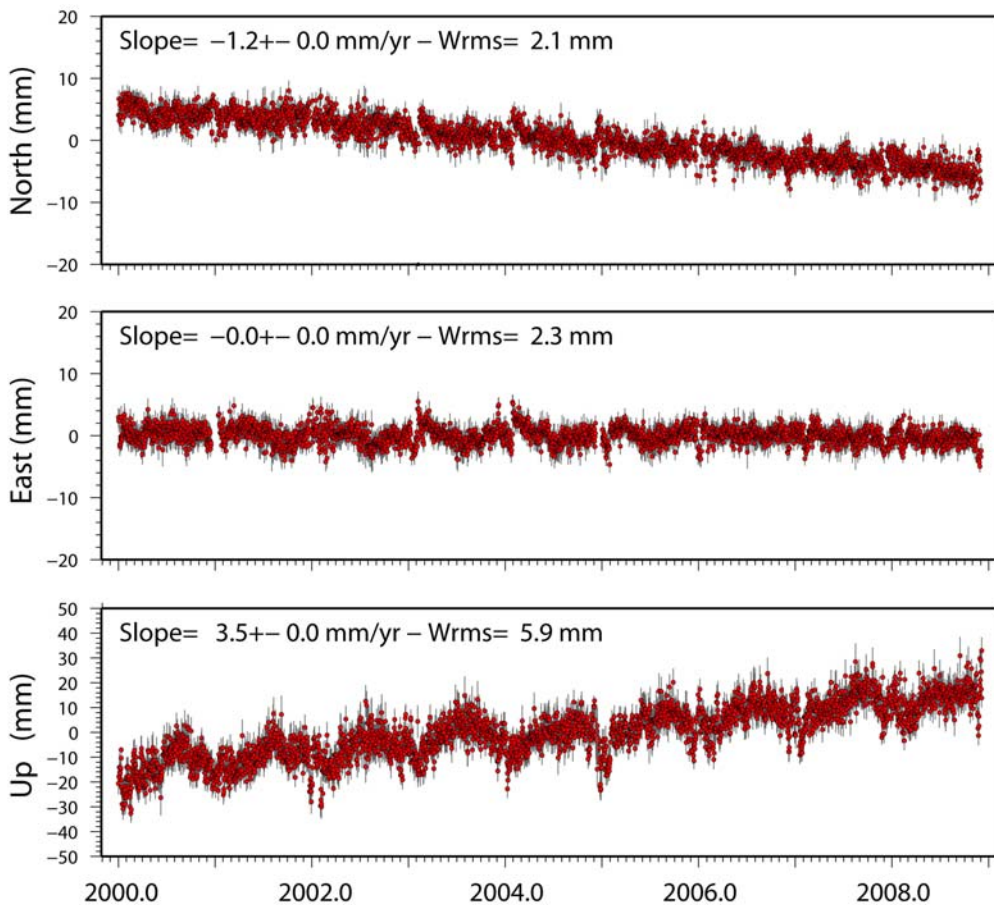
Let us test this at NMSZ and plate-wide.





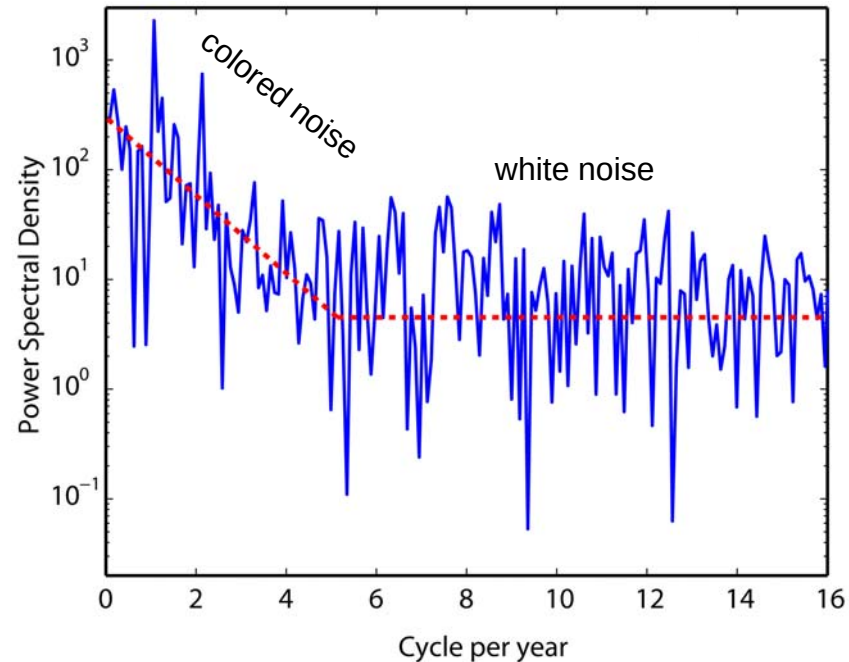
- Prediction at linear rate is 0.3 mm/yr at $t = 2009$
- ... measurement at 2009 = not significantly different from zero, upper bound = 0.2 mm/yr

- (1) Liu et al., 1992
- (2) Snay et al., 1994
- (3) Argus and Gordon, 1996; Dixon et al., 1996
- (4) Weber et al., 1998
- (5) Newman et al., 1999
- (6) Gan and Prescott, 2001
- (7) Sella et al., 2002
- (8) Marquez-Azua and DeMets, 2003
- (9) Smalley et al., 2005
- (10) Calais et al., 2005
- (11) Calais et al., 2006



Time series of daily GPS positions, Algonquin (ALGO). Note:

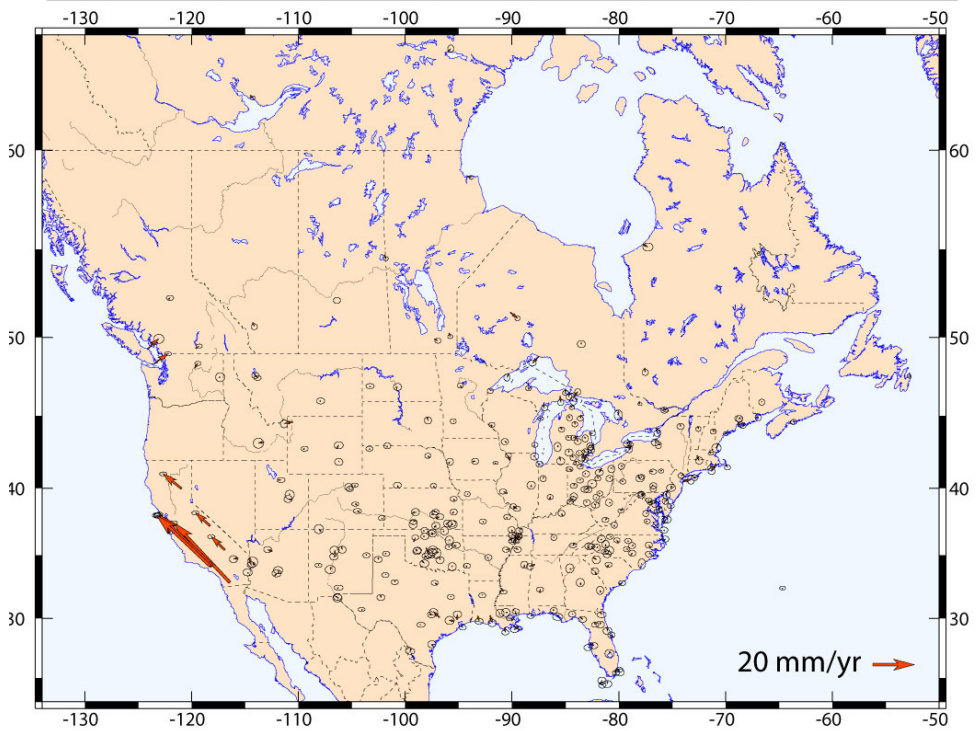
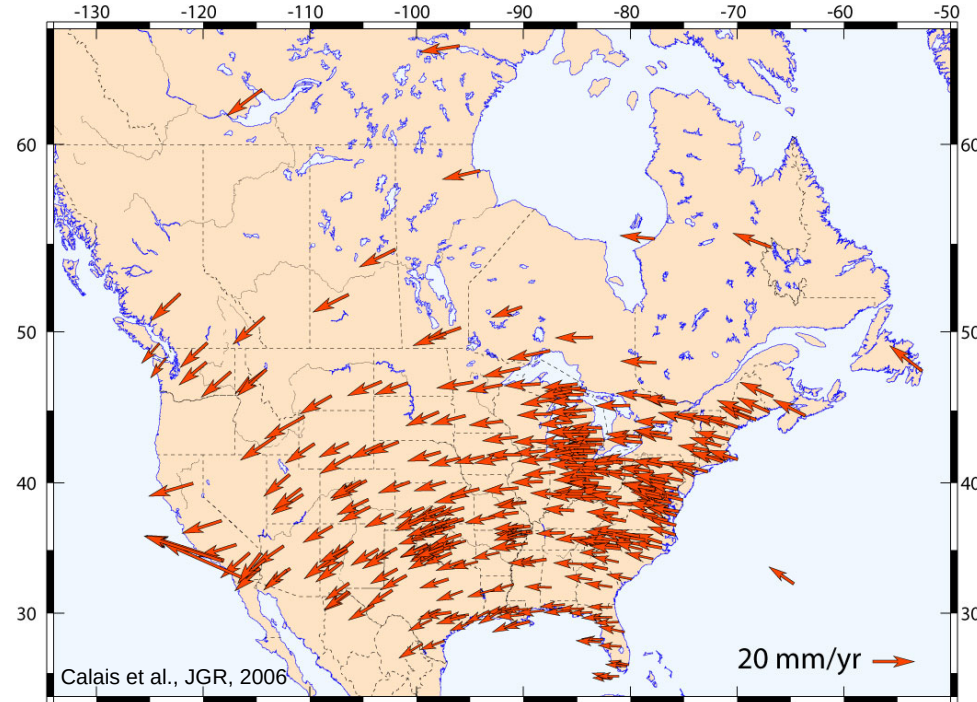
- Wrms scatter: 2 mm horizontal
- S-ward + up motion = GIA
- Seasonal on vertical snow loading
- Formal velocity uncertainties = 0.0 mm/yr?

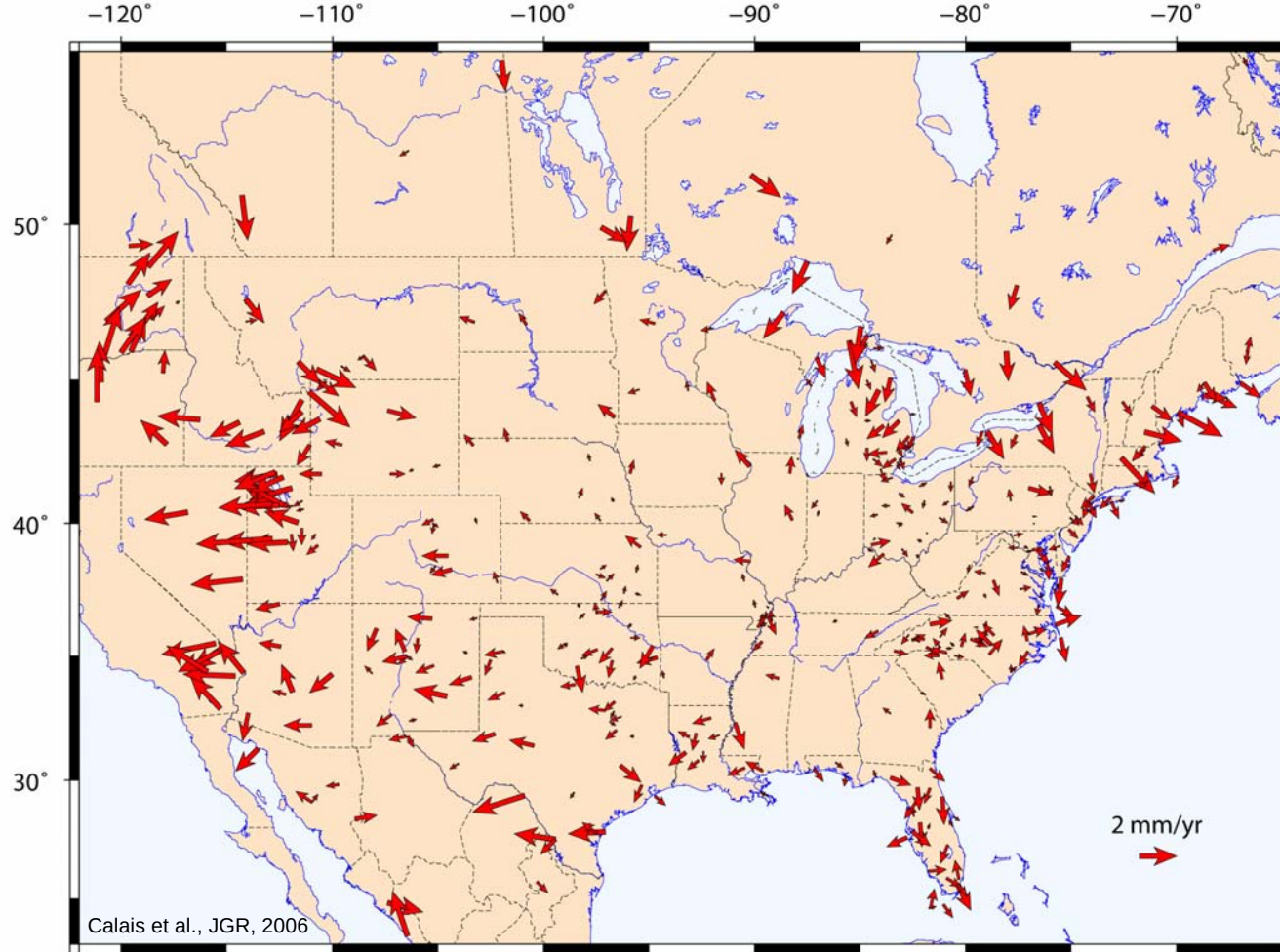


Spectral analysis of GPS time series:

- While + colored noise: origin unclear but process can be accounted for in precision estimates
- Amplitude is site dependent
- Realistic uncertainty estimates must account for colored noise
- Uncertainties x 4 to 10 compared to WN only

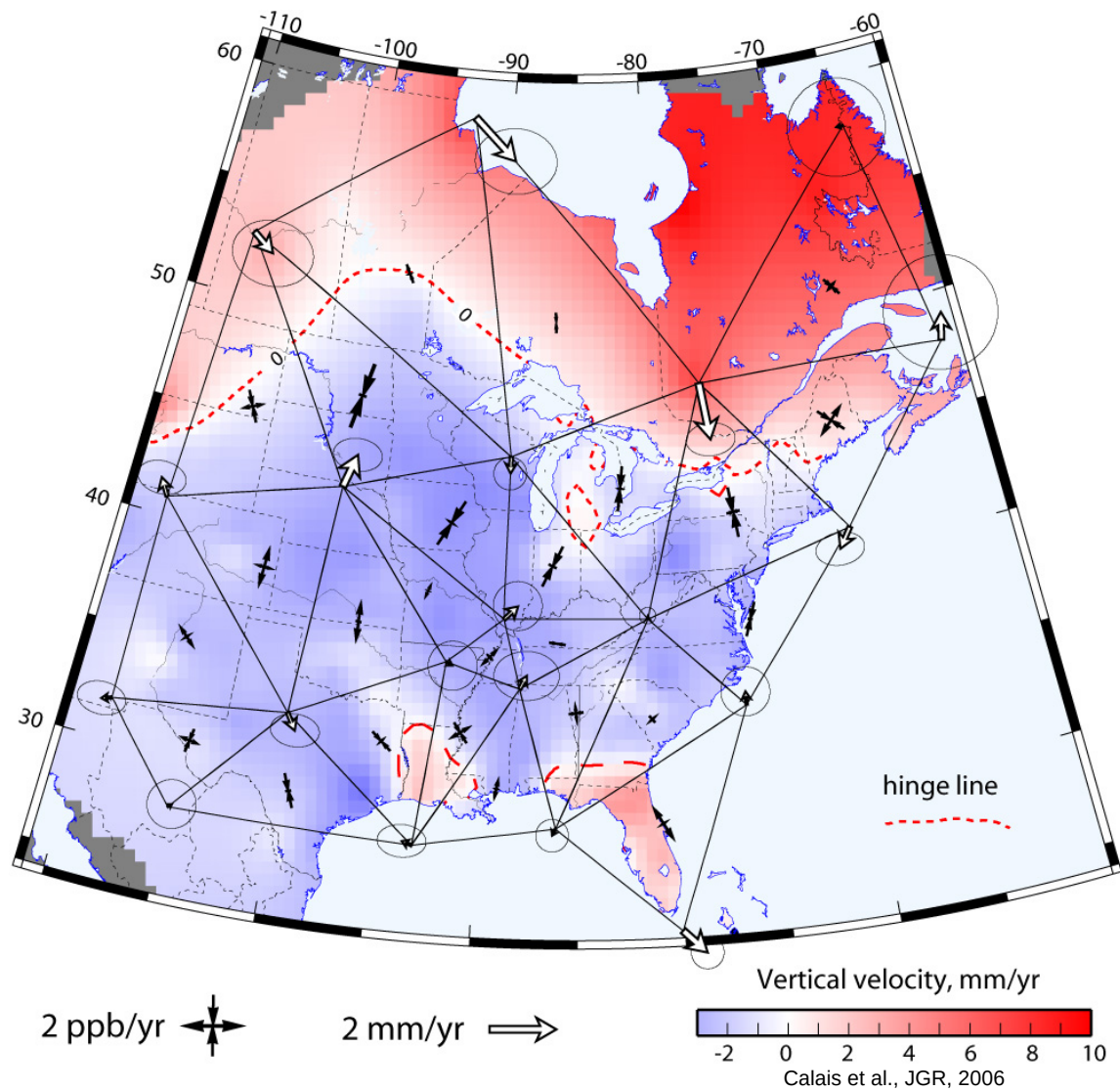
- Phase processing => one position per day per site = vector of estimates + full covariance matrix
- Reference frame:
 - Daily solutions stacked for n days => combined solution (estimates + full covariance)
 - Helmert transformation (translation, rotation, scale) estimated between combined solution and a given frame
 - Parameters of interest (position and velocity) estimated simultaneously, with their uncertainties, in that frame.
- Velocity analysis:
 - Transformation to another frame (e.g. stable North America)
 - Involves rotation + vector subtraction
 - Residual velocities w.r.t. stable North America





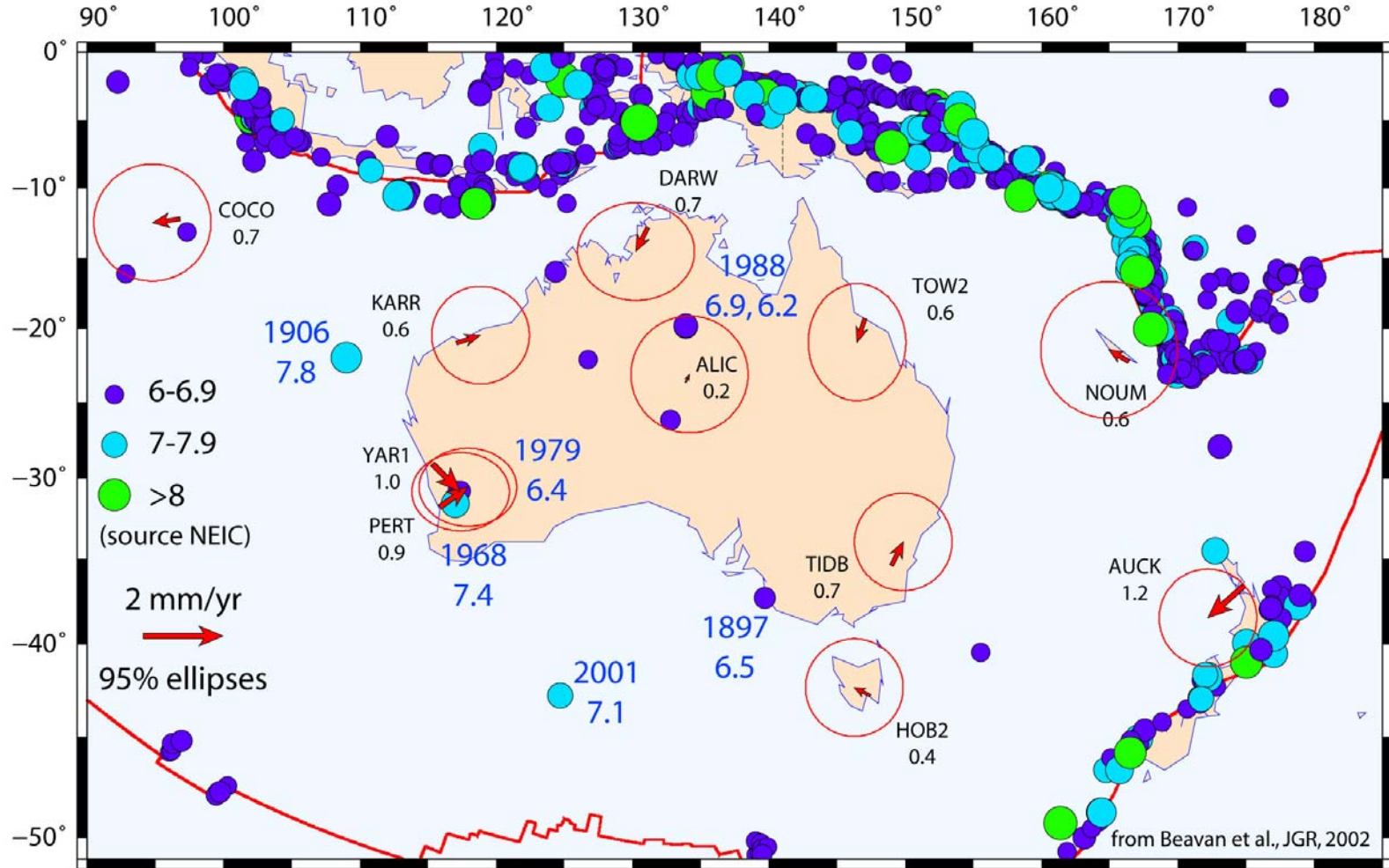
Zooming in:

- Deformation west of Rocky Mountains
- East of RM: most velocities are NOT significant at 95% confidence
- WRMS of residual velocities = 0.6 mm/yr
- PGR signal stands out
- Other interesting patterns - but below data resolution



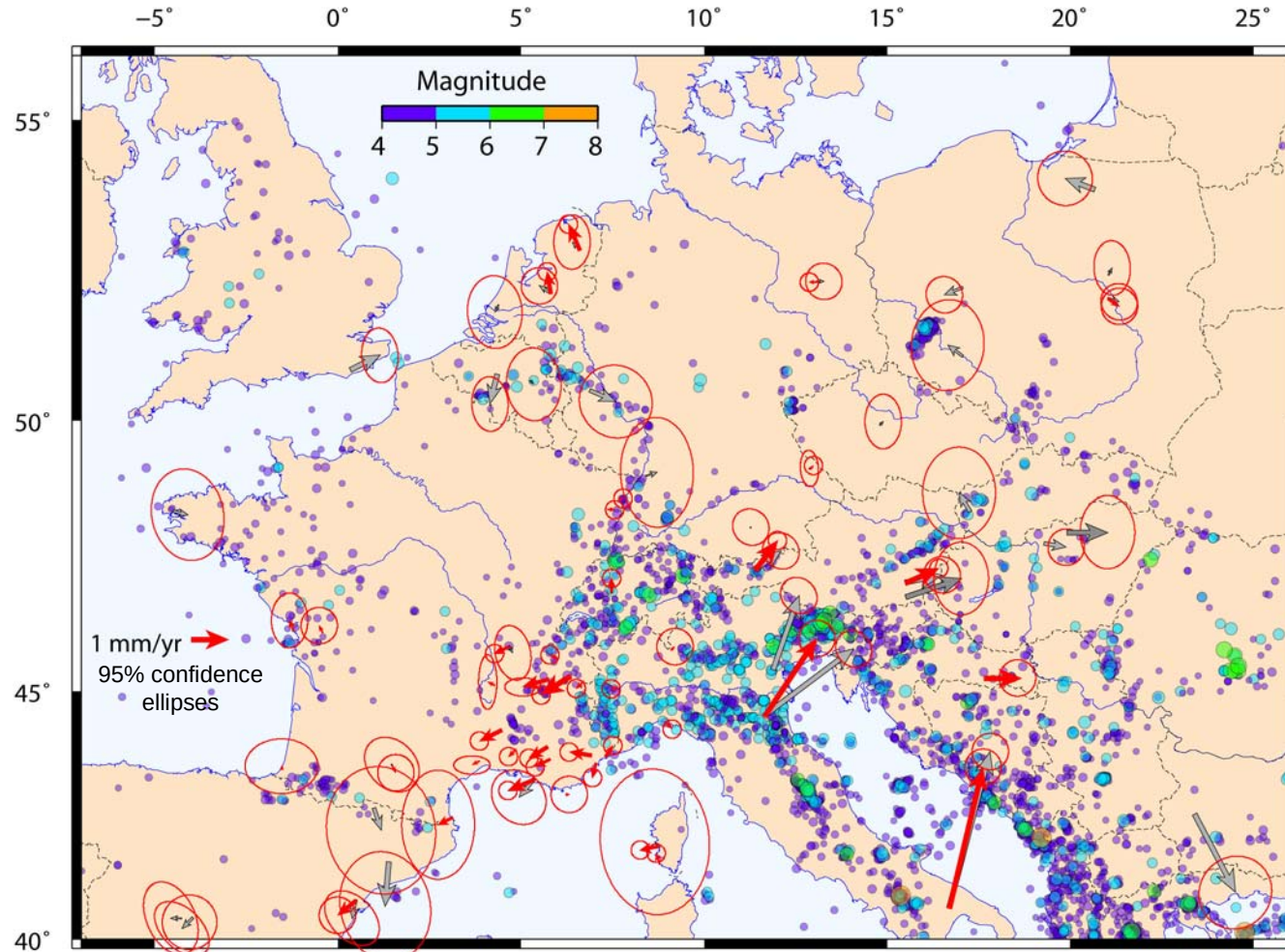
Compressional strain localizes around GIA uplift area
(forebulge)

Strain signal geometrically consistent with GIA effect



Australian plate, WRMS of
residual velocities = 0.4 mm/yr

(from Beavan et al., 2002)



Velocities from Fages, 2008; Nocquet and Calais, 2003; Grenerczy et al., 2003

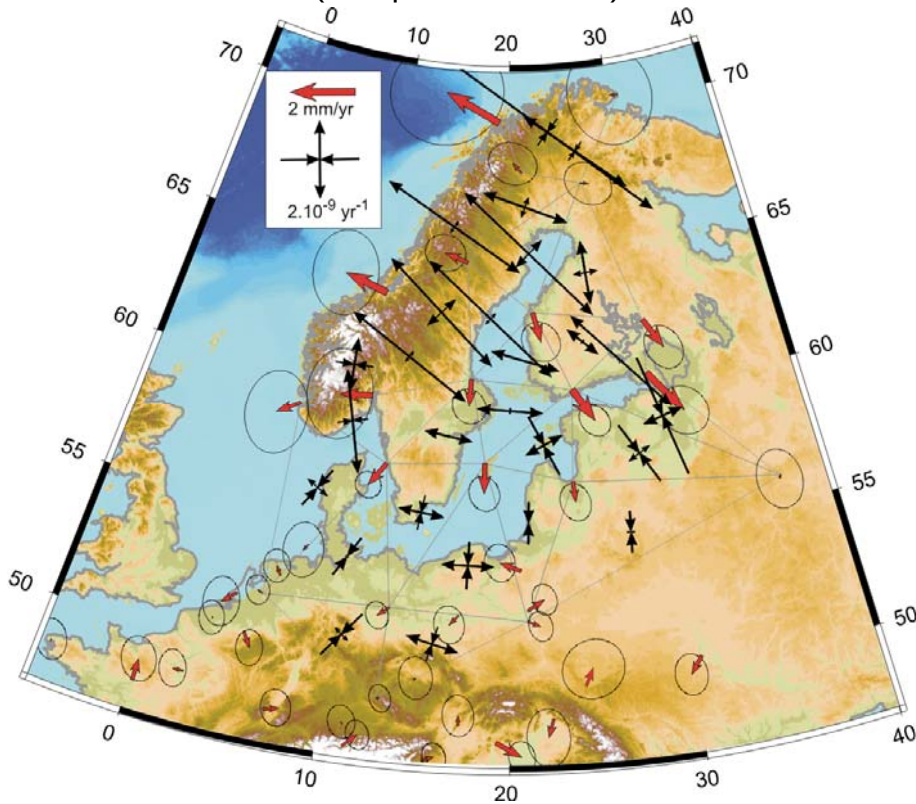
Seismicity 1000 to Present (Grunthal et al, 2009)

Central Europe = 0 ± 0.2 mm/yr
 Rhine graben = 0 ± 0.4 mm/yr
 Pyrenees WRMS = 0 ± 0.4 mm/yr

Western Alps = 0.5 mm/yr extension
 Pannonian basin = 1 mm/yr east motion

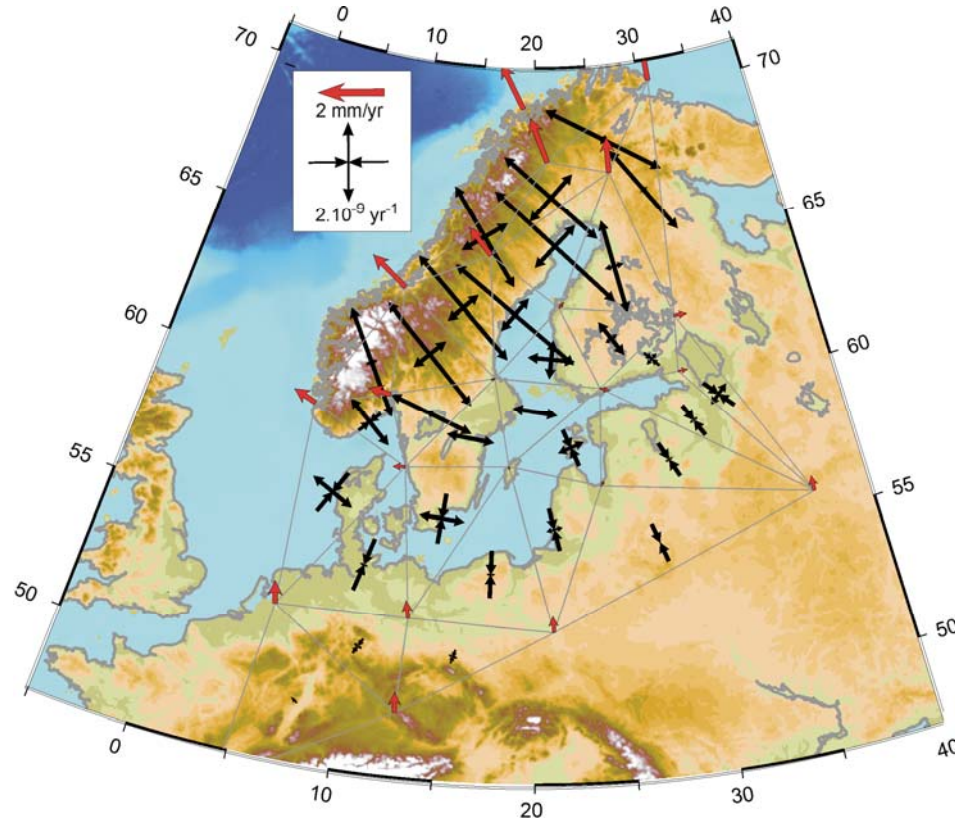
CGPS measurements

(Nocquet et al., 2005)



GIA model

(Milne et al., 2001)

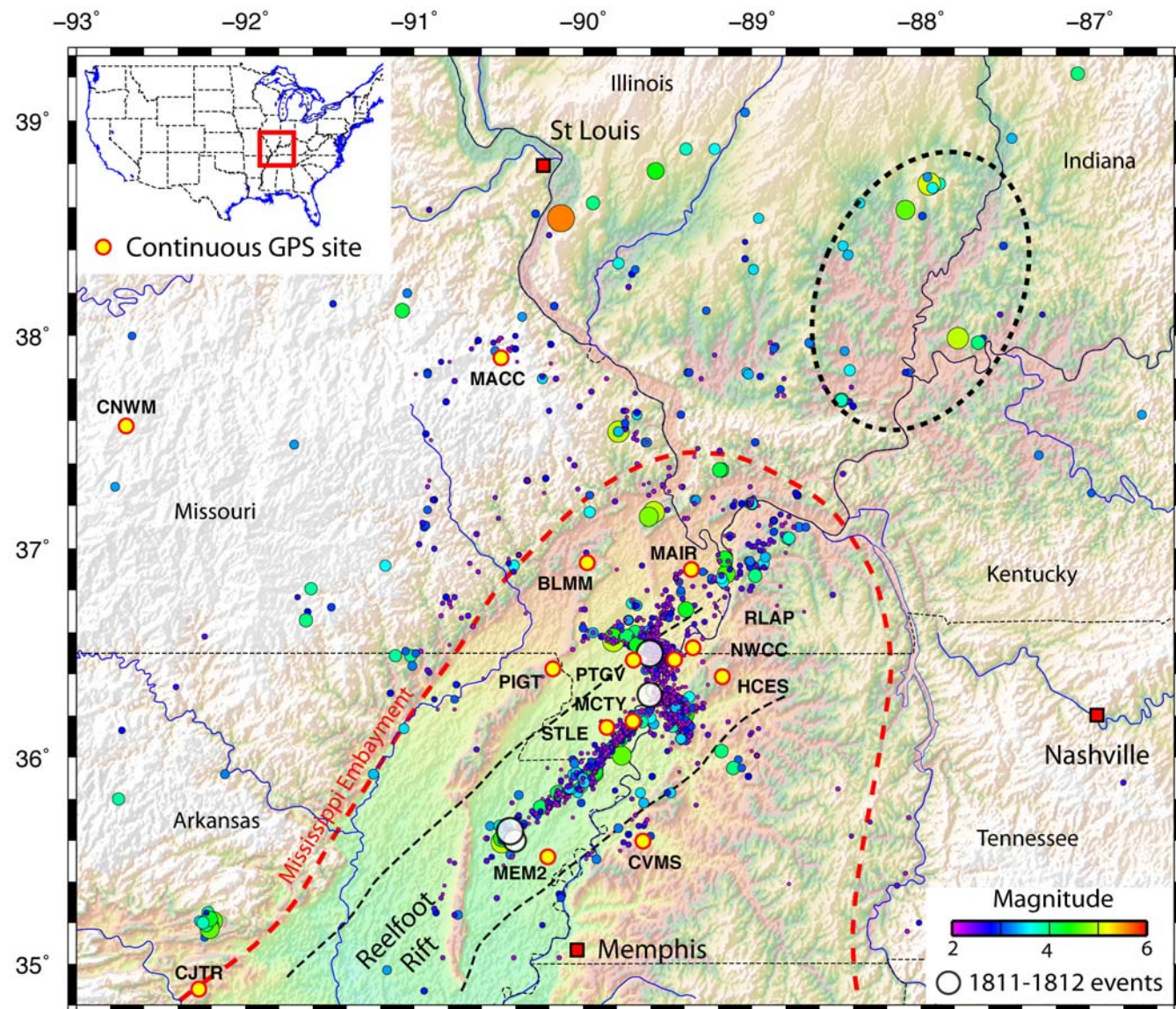


GPS detects with confidence:

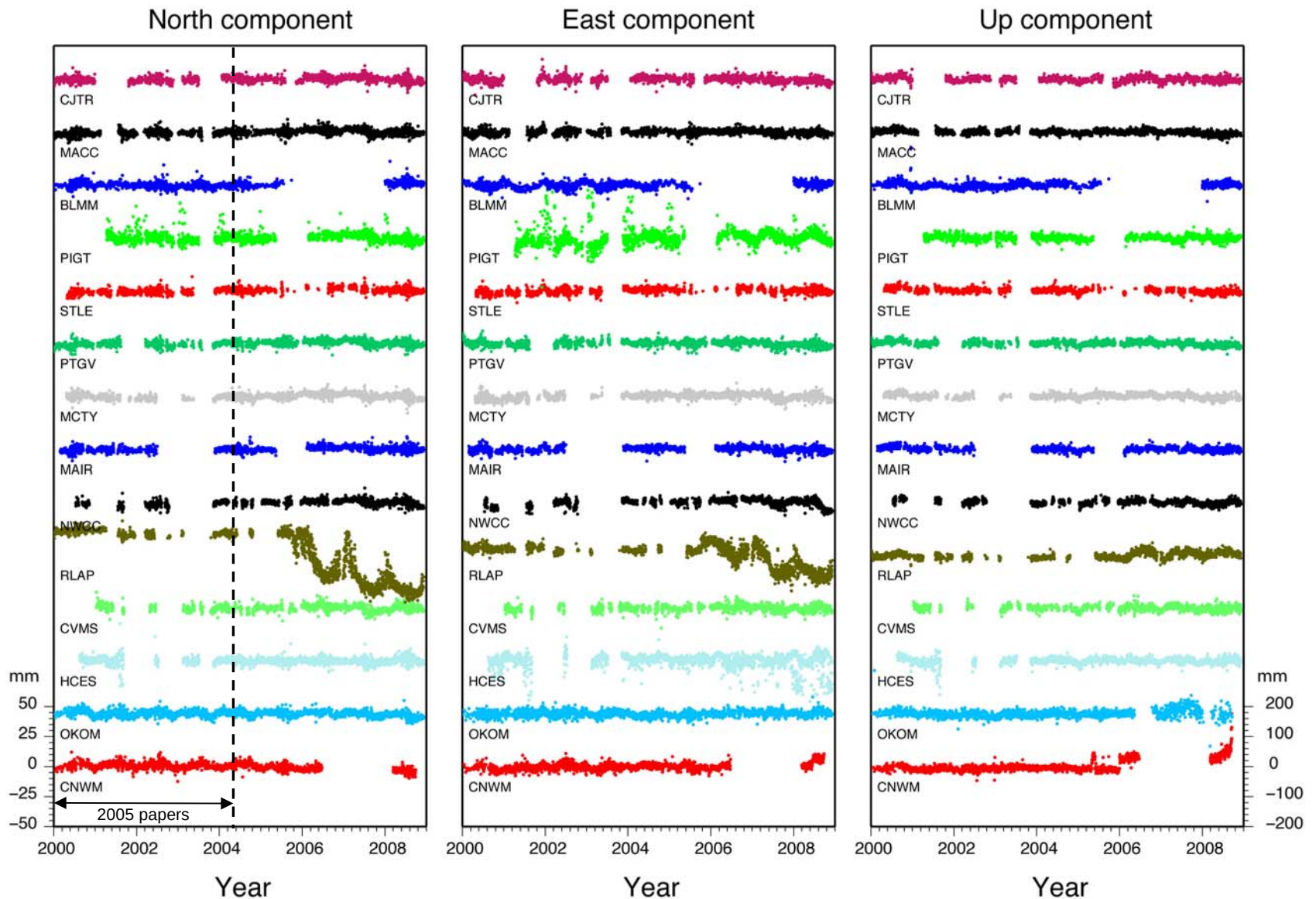
Velocities $> 0.5 \text{ mm/yr}$

Strain rates $\sim 10^{-9} \text{ /yr}$

(Note that GPS velocities today are consistent
with 10,000 year time scale process)



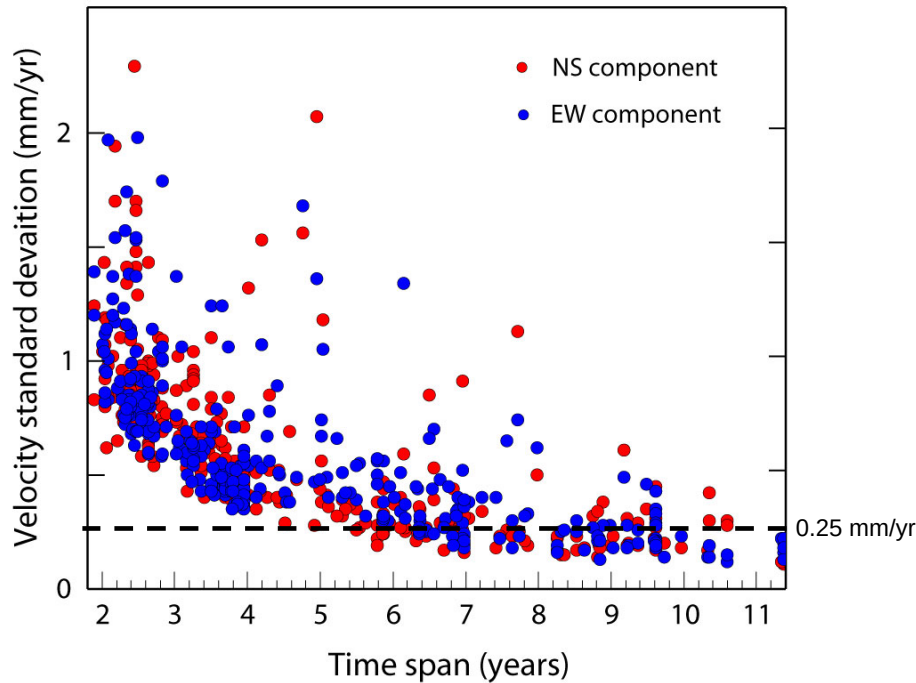
New Madrid: only “active” intraplate system where a local continuous GPS network is available (GAMA + CORS)



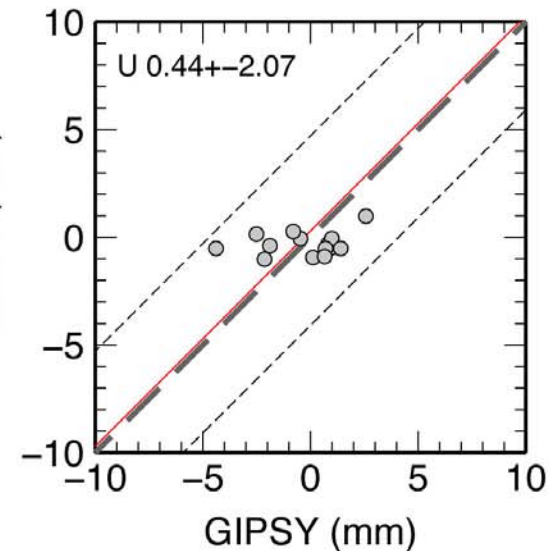
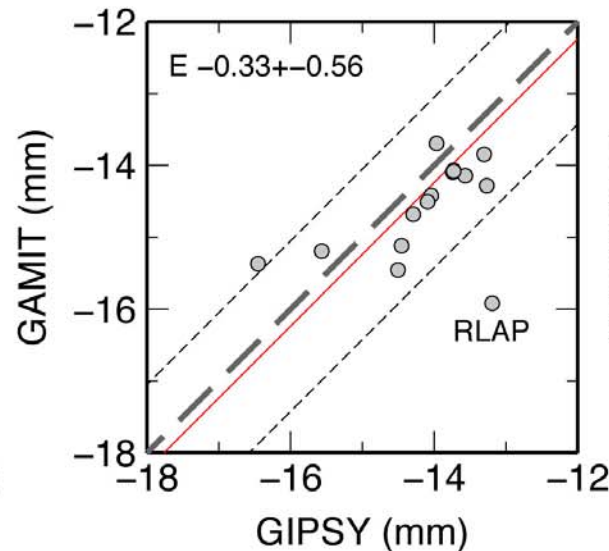
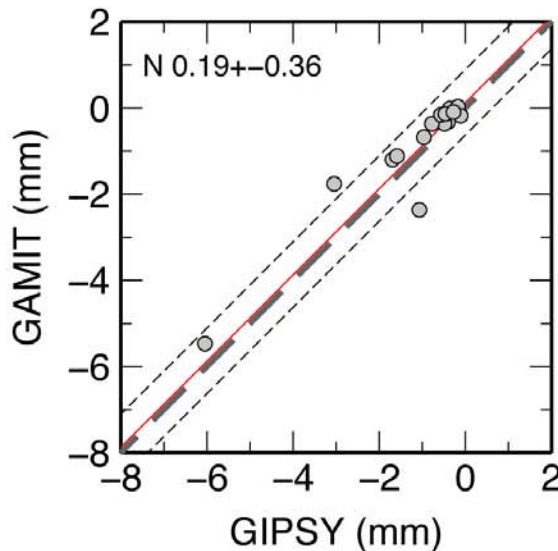
The “data”: daily position time series expressed with respect to Stable North America.

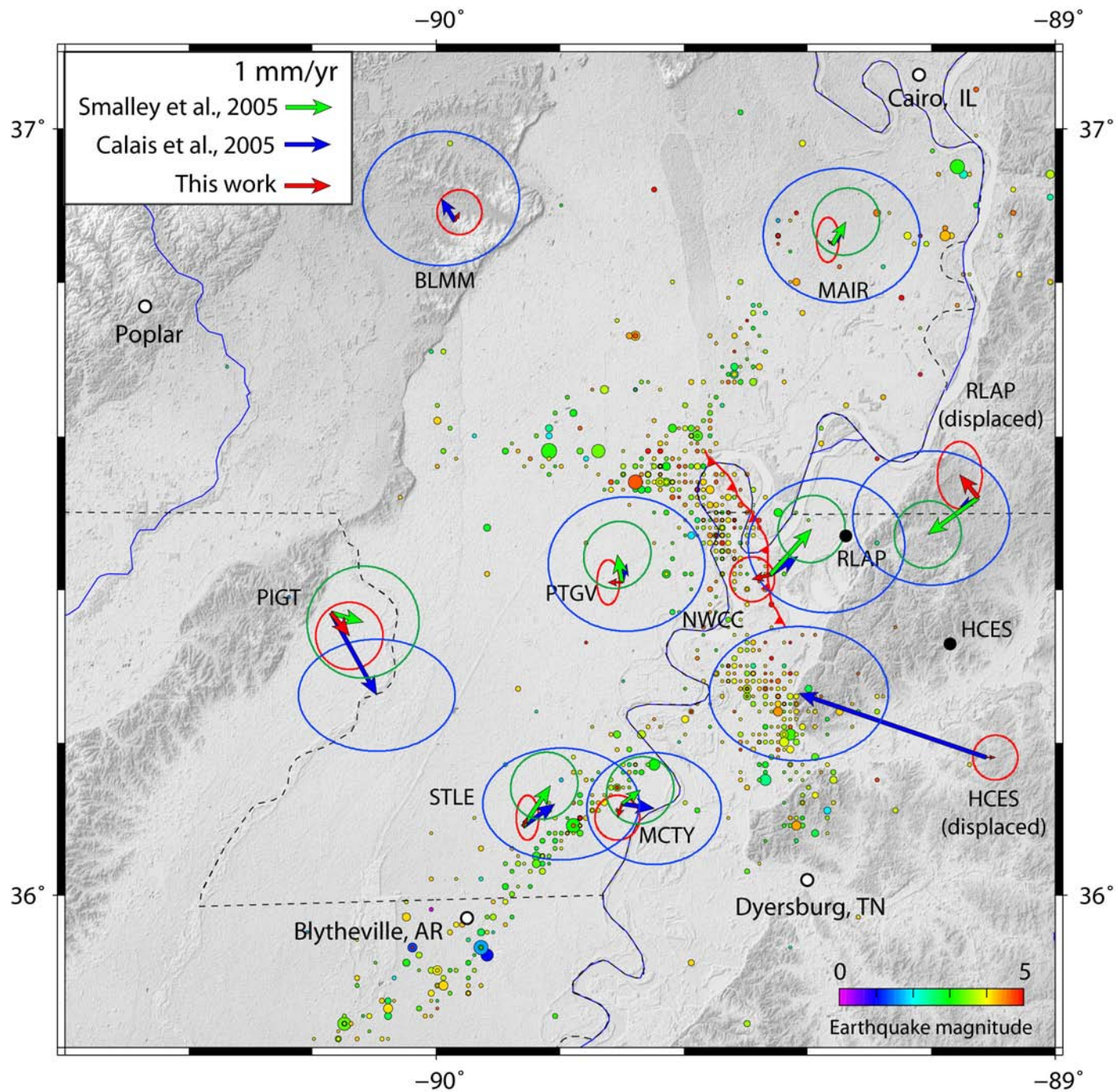
The good (most), the bad (PIGT, NWCC) and the ugly (RLAP)

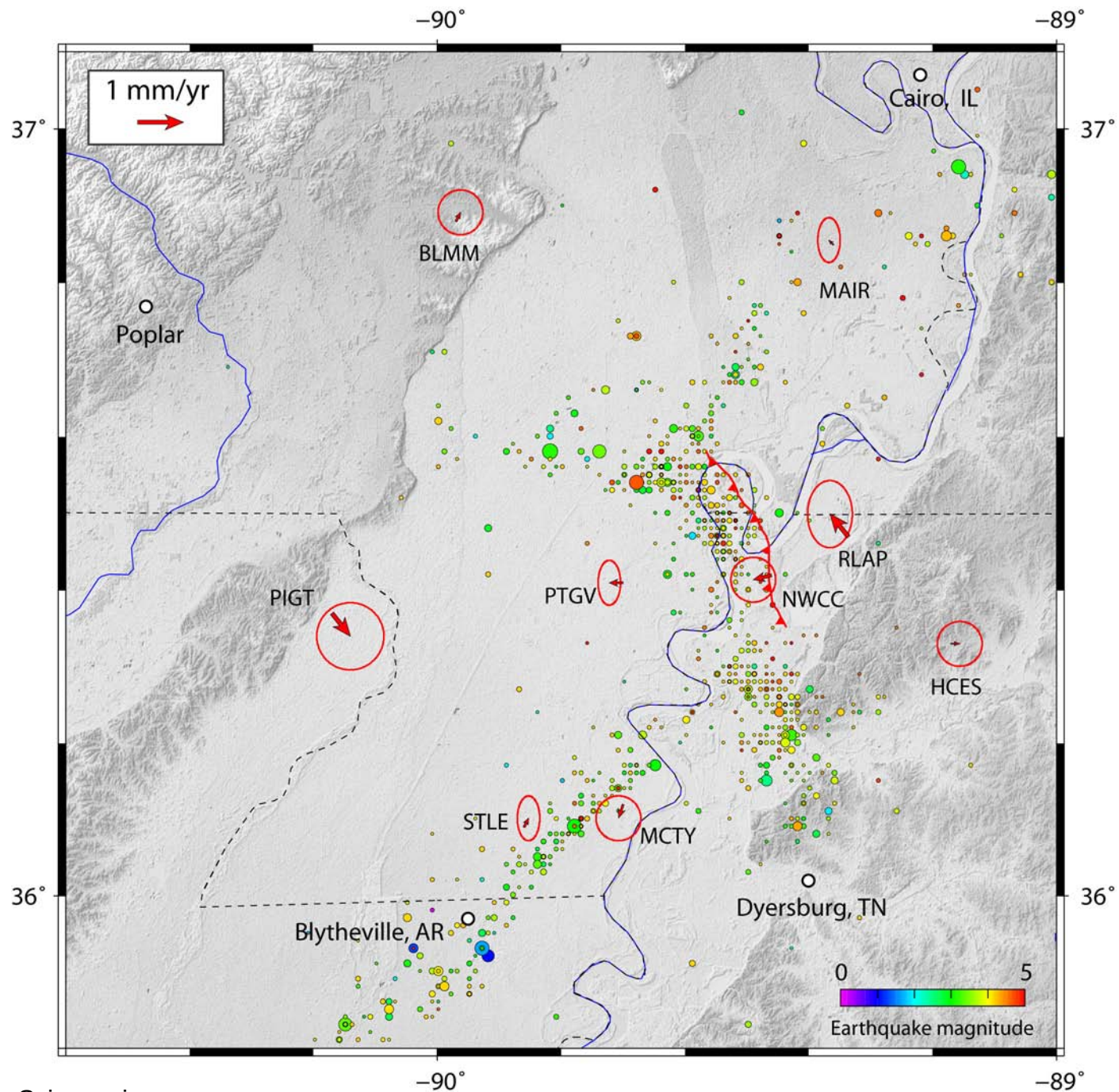
Note additional data since last publications (Smalley et al., Calais et al., 2005)



- Precision < 0.5 mm/yr at 10 years
- Accuracy:
 - ~0.8 mm/yr on horizontal components
 - ~ 3 mm/yr on vertical components



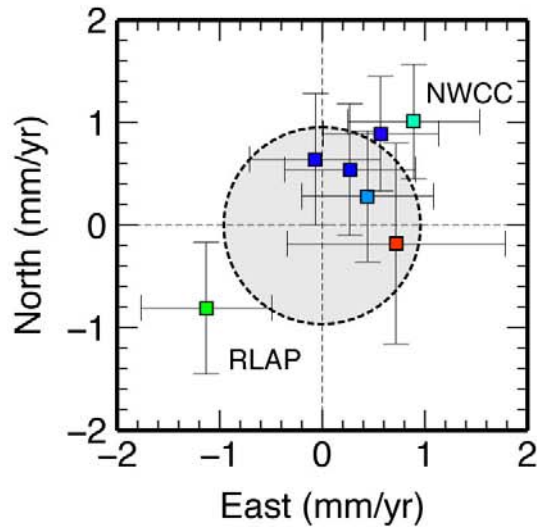




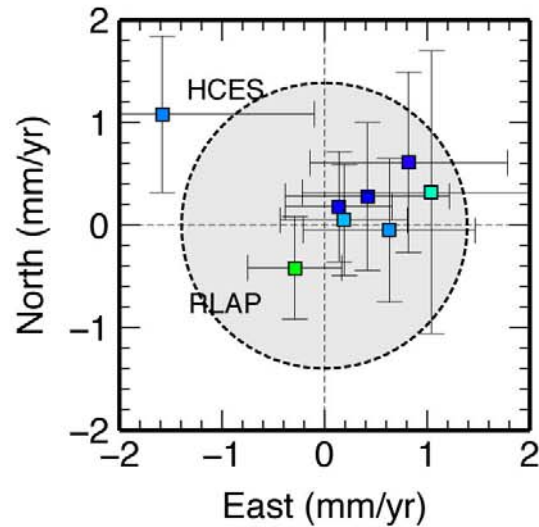
Smalley et al., 2005

Calais et al., 2005

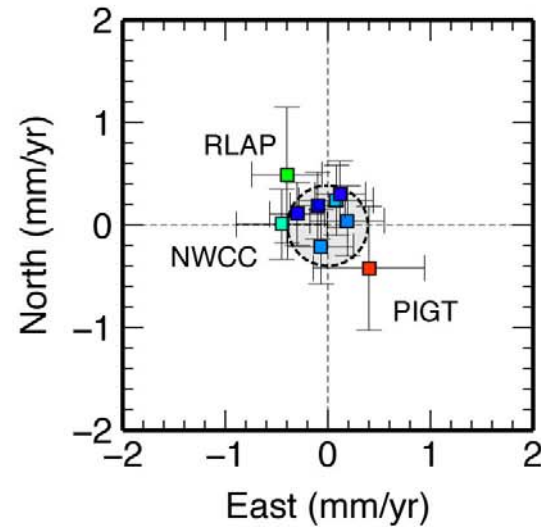
This work



WRMS = 0.2 mm/yr
Bias = 0.8 mm/yr



WRMS = 1.4 mm/yr
Bias = 0.5 mm/yr



WRMS = 0.2 mm/yr
Bias = 0.0 mm/yr

(95% confidence -- 2 sigmas)

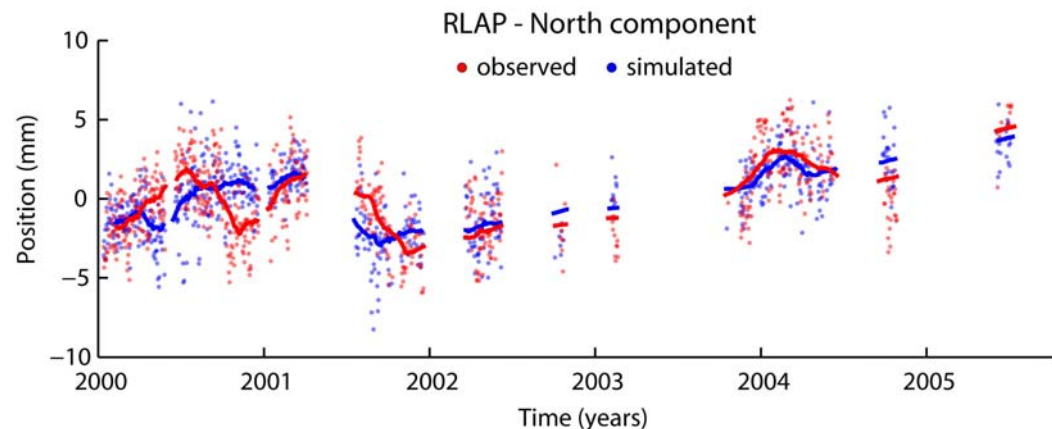
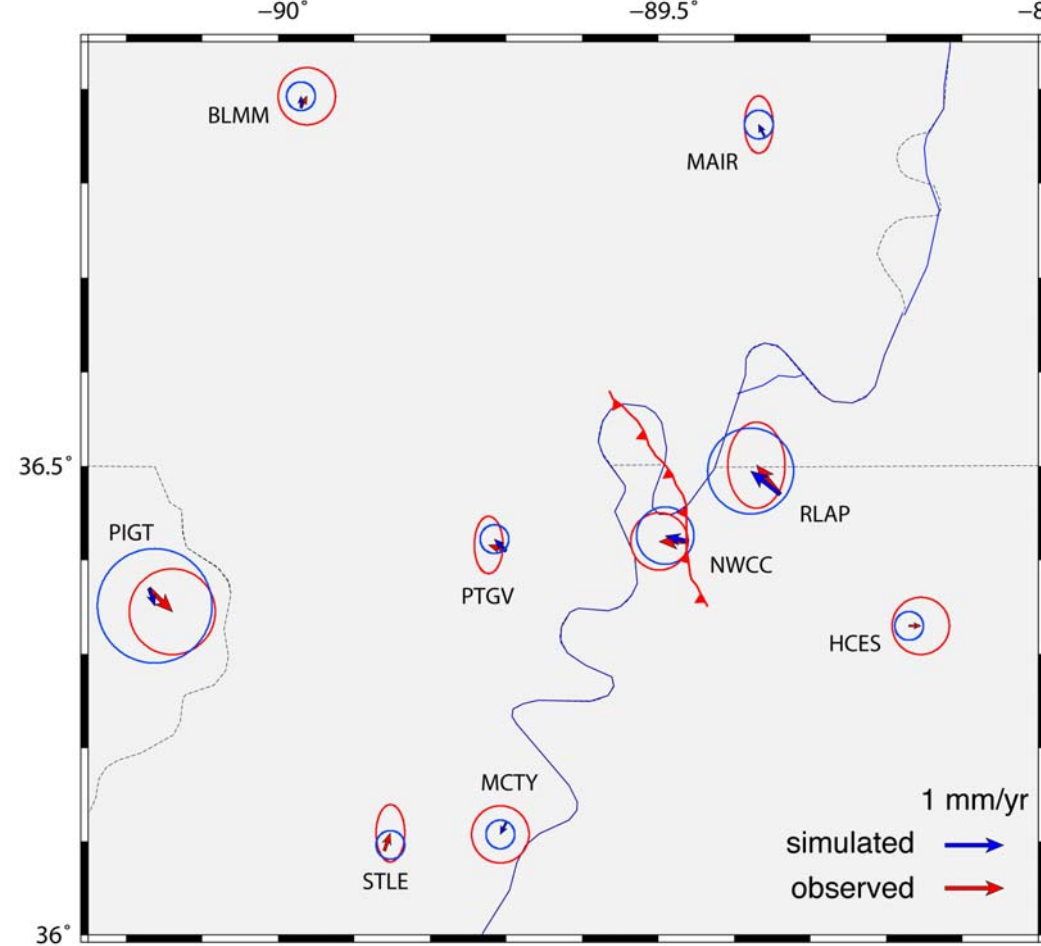
- Velocity uncertainties have decreased by at least a factor of 2 at all sites
- Residual velocities have decreased as well, WRMS = 0.2 mm/yr
- Sites with the worse quality position time series such as RLAP also have the largest velocity residuals

- Synthetic position time series:

$$p(t) = \underbrace{0}_{\substack{\text{secular} \\ = \text{zero}}} \times t + \underbrace{\text{loading}}_{\substack{\text{atmos}+ \\ \text{hydro}}} + \underbrace{WN + RWN}_{\substack{\text{from actual} \\ \text{time series}}}$$

- Sample at time of actual data
- 1000 time series per site
- Colored noise + loading $\Rightarrow$ non-zero long term velocities
- Simulated velocity field statistically equivalent to observed
- Simulated time series: fluctuations comparable to observed (RLAP)

$\Rightarrow$ Observations do not require site motions different from zero



Strain rates

Whole network:

Strain rate tensor:

$\epsilon_{psxx} = -4.55 \pm 5.39$ ppb/yr

$\epsilon_{psxy} = 0.88 \pm 3.64$ ppb/yr

$\epsilon_{psyy} = 4.12 \pm 4.40$ ppb/yr

Principal strains:

$\epsilon_{ps1} = 4.20 \pm 5.34$ ppb/yr (most extensional)

$\epsilon_{ps2} = -4.64 \pm 5.34$ ppb/yr (most compressional)

Second invariant:

$snd = 0.30 \pm 1.30$ ppb/yr

Delaunay triangulation:

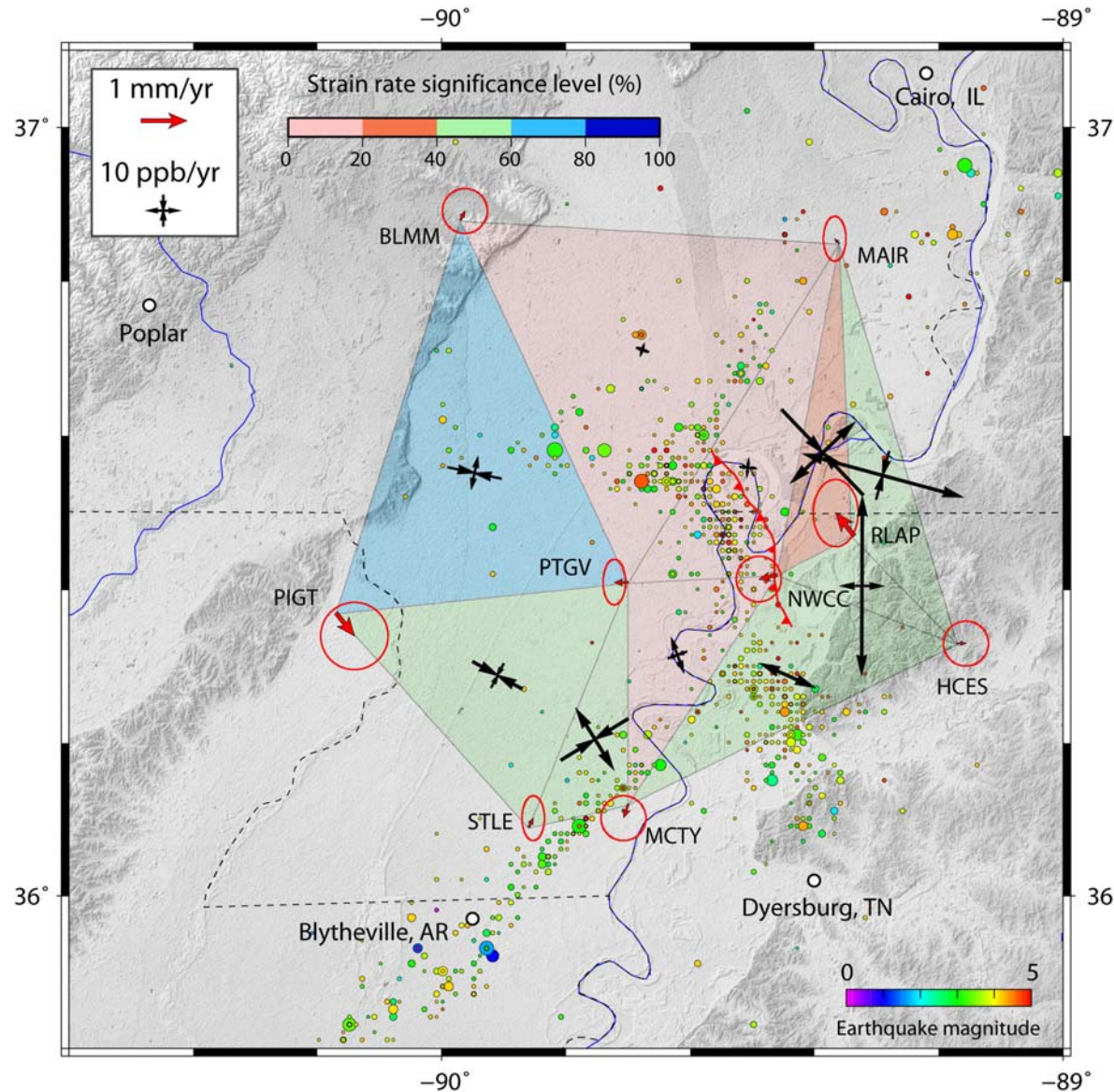
For 6 data - 4 unknowns = 2 dof:

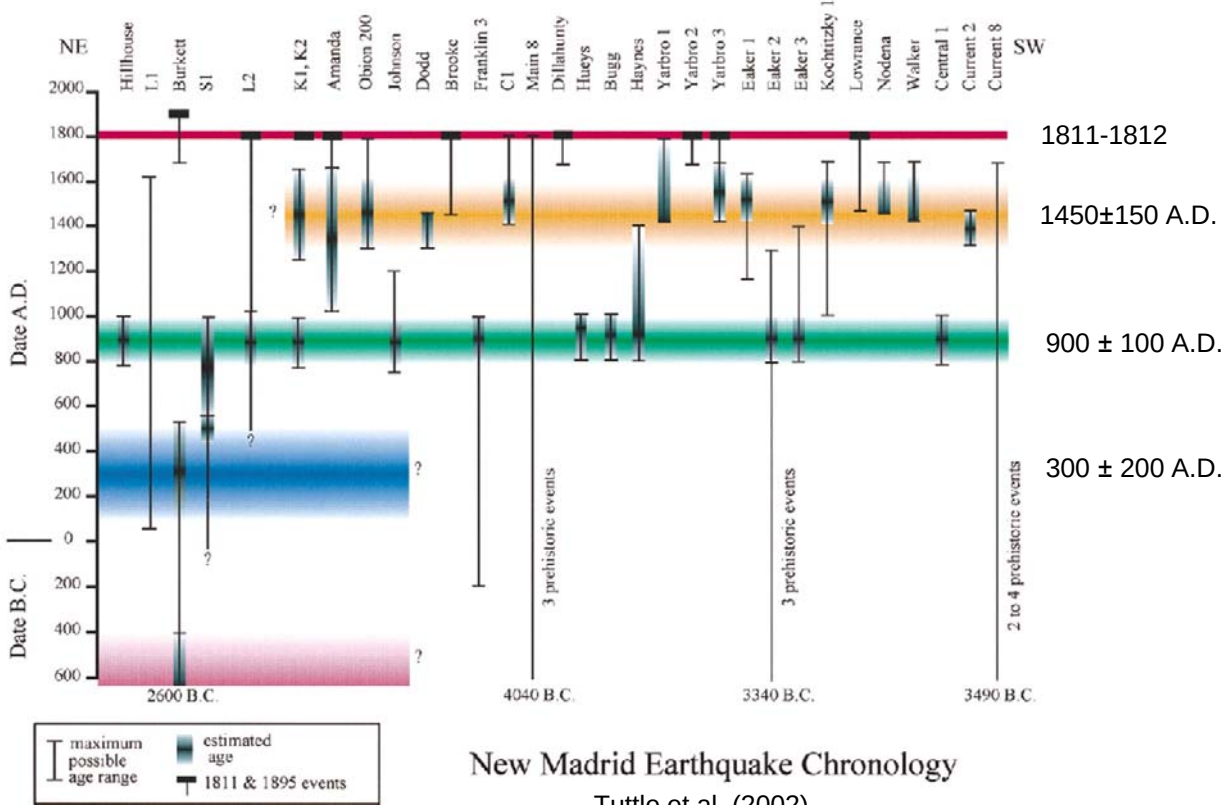
95% confidence $\Rightarrow \chi^2 = 5.99$

99% confidence $\Rightarrow \chi^2 = 9.21$

Triangle	Chi2	Signif. (%)
BLMM PIGT PTGV	2.56	72.2
HCES MAIR RLAP	1.60	55.1
HCES MCTY NWCC	1.05	40.8
MAIR NWCC PTGV	0.28	13.1
BLMM MAIR PTGV	0.35	16.1
MCTY NWCC PTGV	0.35	16.1
HCES NWCC RLAP	1.74	58.1
MAIR NWCC RLAP	0.87	35.3
MCTY PTGV STLE	1.41	50.6
PIGT PTGV STLE	1.59	54.8

$\Rightarrow$ No significant strain rate
at 95% confidence.

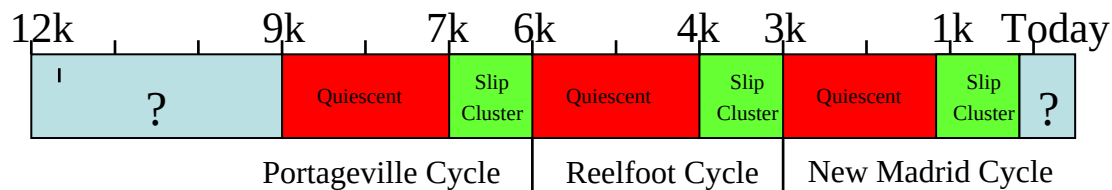




Mapping and dating of liquefaction features

⇒ 500 year average recurrence over past 2,000 years

Holocene Punctuated Slip

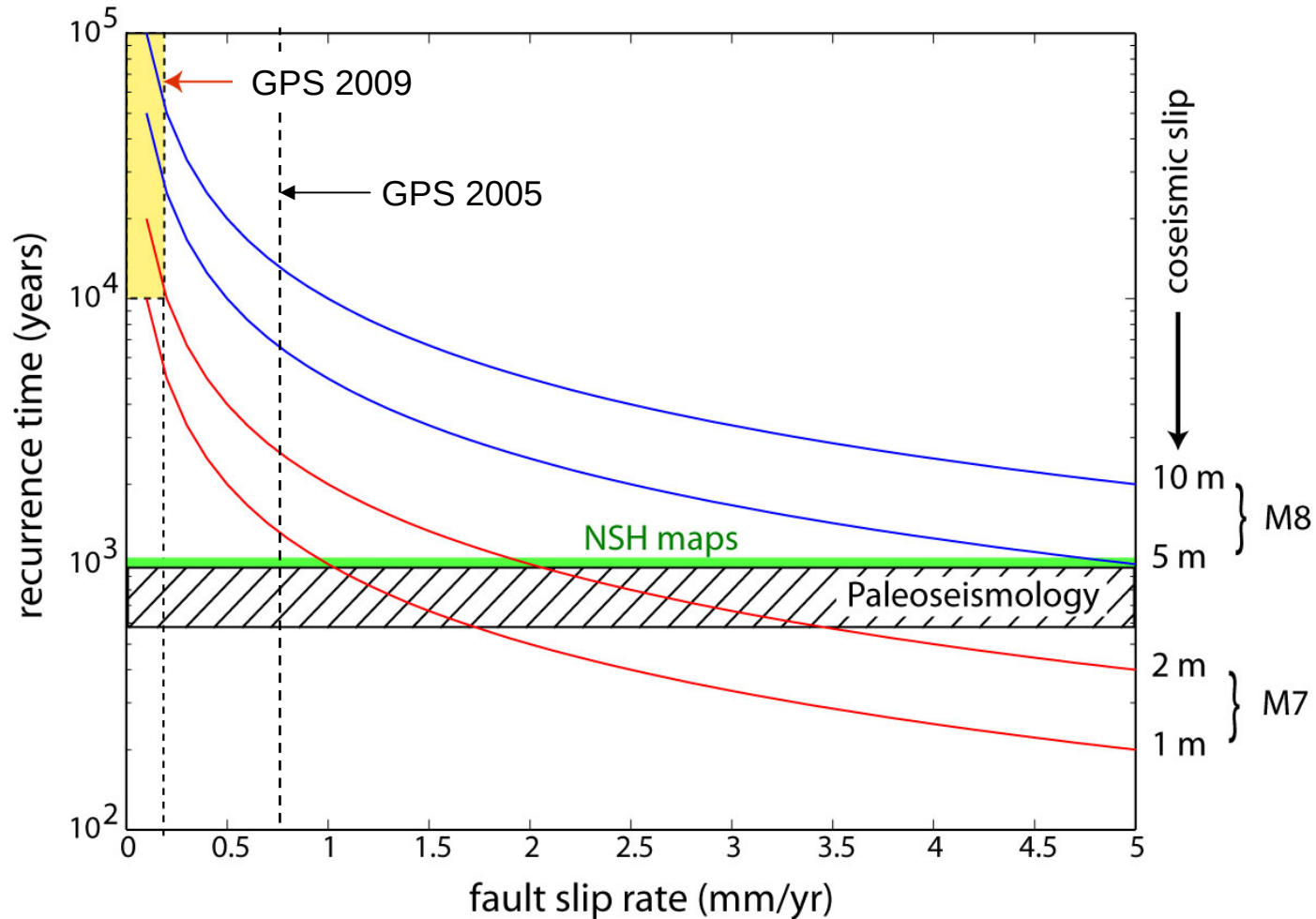


Holbrook et al., 2006

Mississippi course straightening events:

⇒ 900 year average recurrence since mid-Holocene

⇒ Seismicity appears temporally clustered



Assuming steady-state strain accumulation and release:

- 500 yr average repeat time over ~2,000 yr $\Rightarrow$ 2 mm/yr for low M7
- 900 yr average repeat time over ~5,000 yr $\Rightarrow$ 1 mm/yr for low M7
- 0.2 mm/yr $\Rightarrow$ minimum repeat time = 10,000 years for low M7

$\Rightarrow$ Current strain accumulation rate in the NMSZ cannot sustain the ~5,000 yr seismicity rate

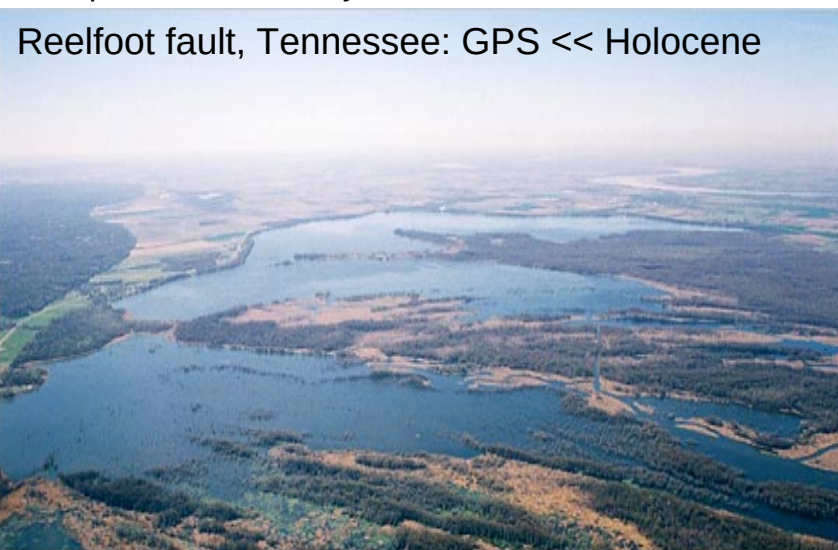
$\Rightarrow$ NMSZ not in steady state at that time scale

Wasatch fault, Utah: GPS = Holocene



- Average repeat time for $M > 6.5$ (on any single segment) = 1,200 to 2,600 years
 - Topography: up to 3600 m
 - Slip rate $1.6 \text{ mm/yr} \pm 0.4 \text{ mm/yr}$
-
- Average repeat time for $M > 6.5$ = 500 years
 - Topography: up to 70 m
 - Slip rate $0 \pm 0.2 \text{ mm/yr}$

Reelfoot fault, Tennessee: GPS << Holocene



Wasatch fault, Chang et al. JGR 2006:
 GPS $1.6 \pm 0.4 \text{ mm/yr}$, geol $1.7 \pm 0.5 \text{ mm/yr}$ over 10 Ka
 (Friedrich et al. 2003)
 [note that 1992-1995 GPS = $2.7 \pm 1.3 \text{ mm/yr}$...]

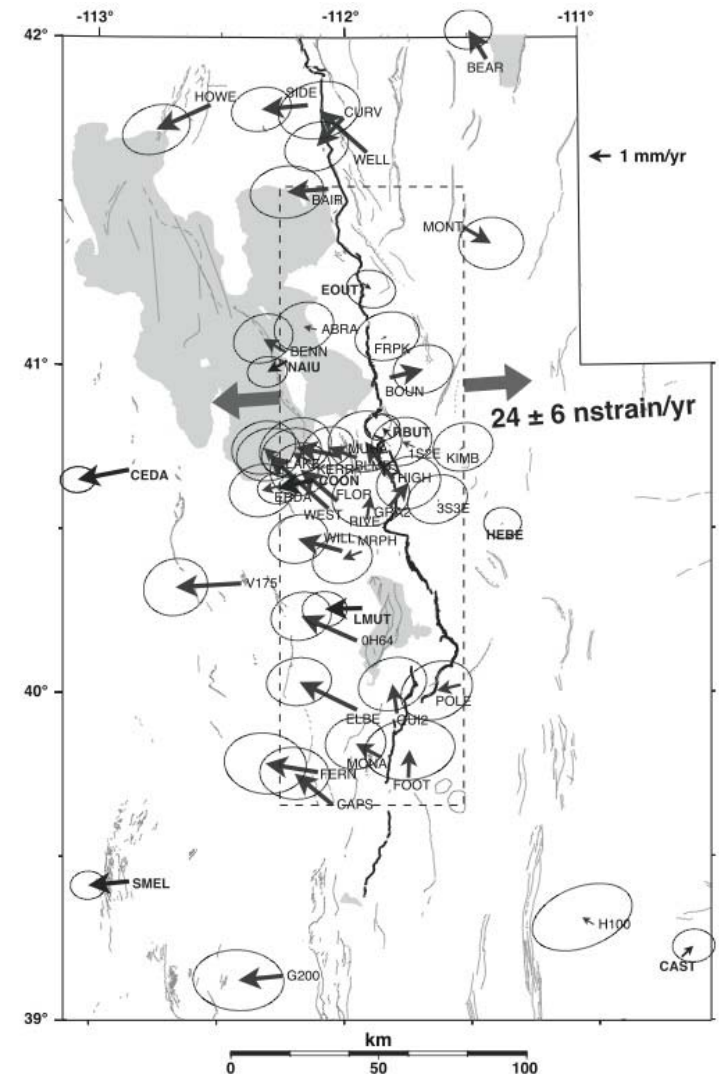


Figure 5. Horizontal velocity vectors, in a stable North America reference frame, derived from the 1997–2004 continuous and the University of Utah 1992–2003 campaign GPS observations. Weighted error ellipses (see text) represent the 95% confident intervals. Gray lines are Quaternary faults, and black lines highlight the Wasatch fault. Thick gray arrows represent the direction of the principal extension assuming a homogeneous strain field in the dashed box.

- Some slow faults are in steady-state at the 10,000 yr time scale -- some are not
- NMSZ is not in steady state:
 - Loading (= stressing) rate varies with time
 - and/or
 - Fault strength varies with time
- It is time to think outside the “rebound model box”

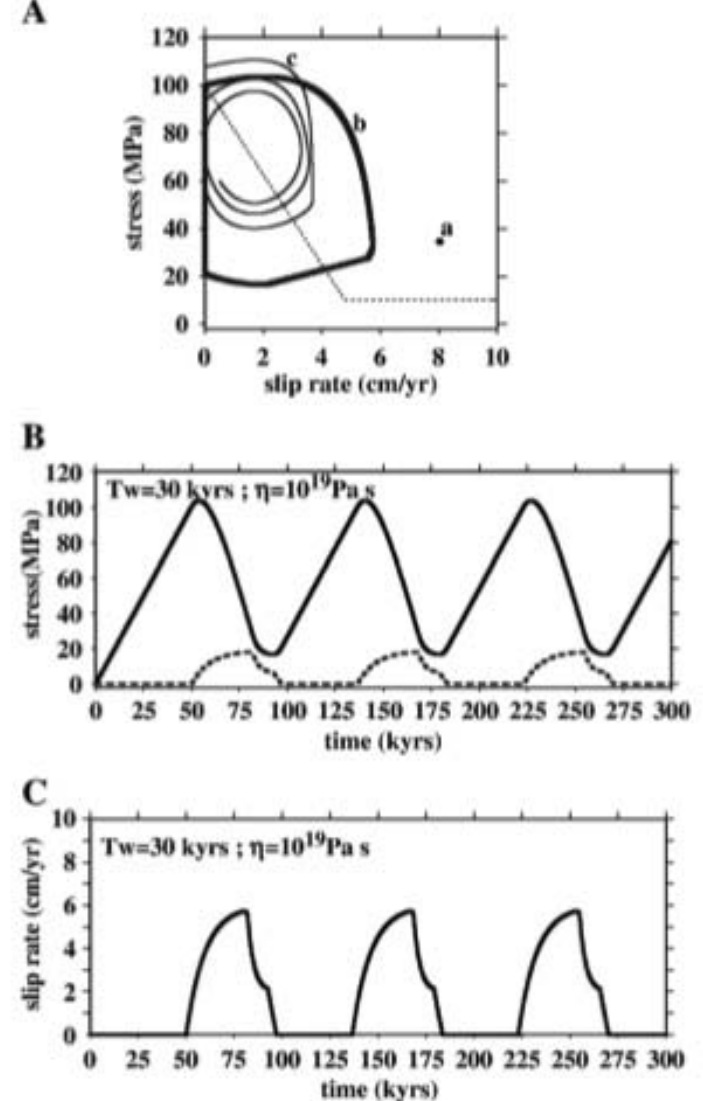
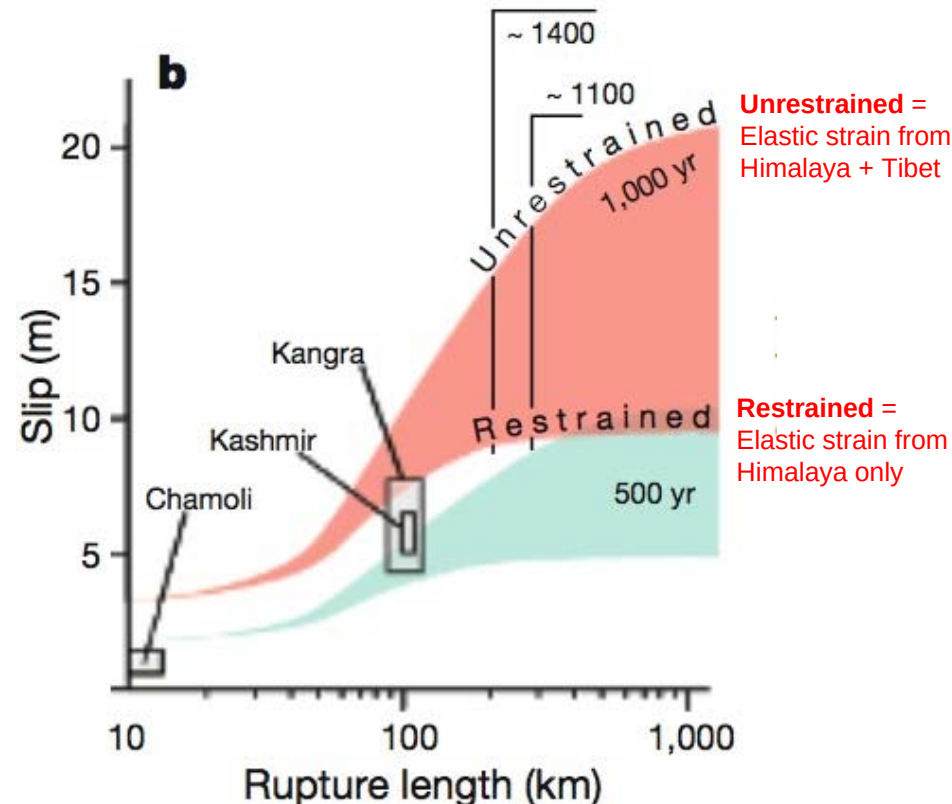
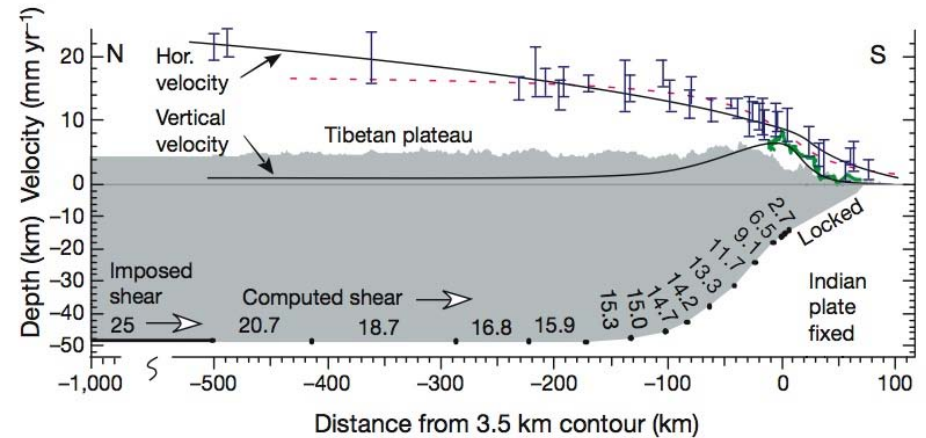
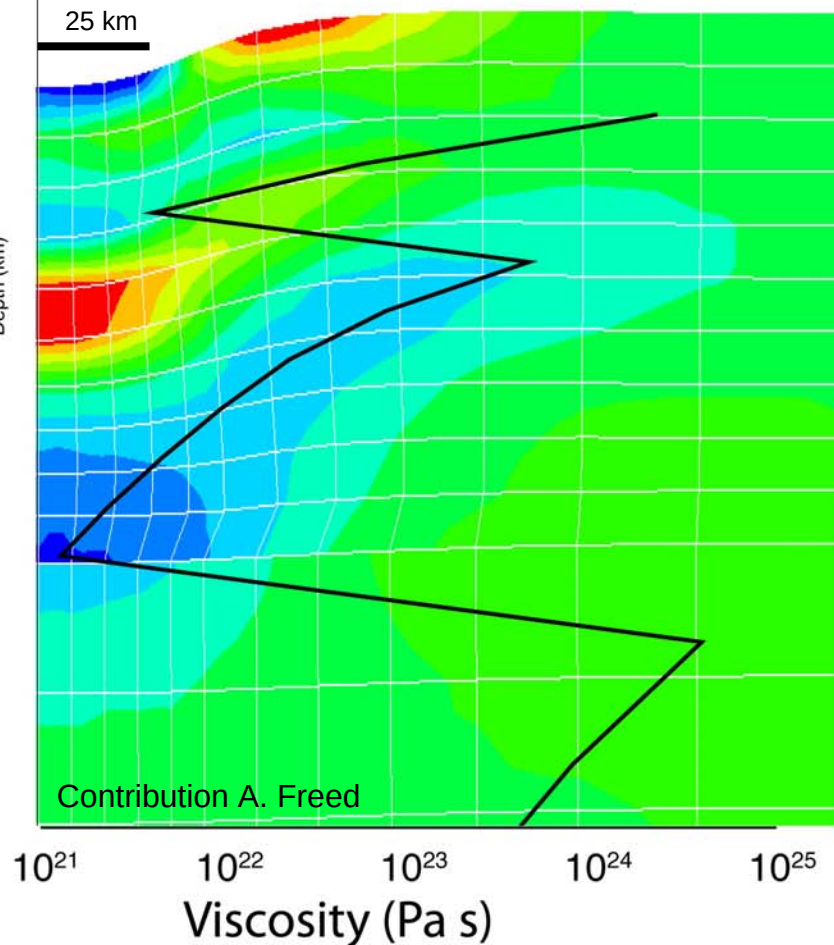
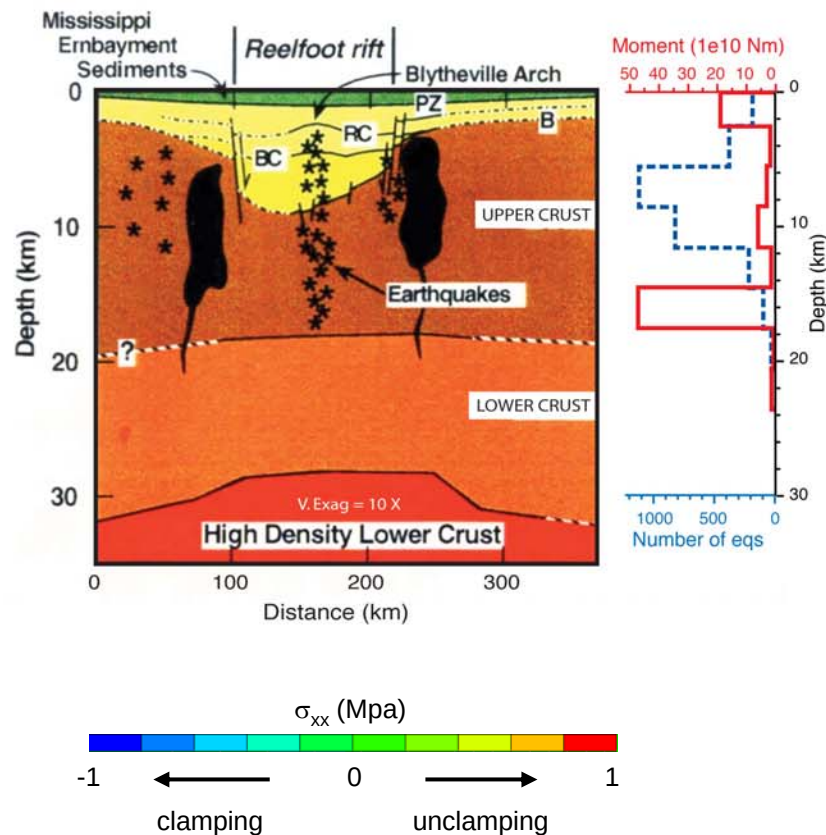


Fig. 4. A) Stress slip rate evolution of the slip rate weakening system for two loading velocities (2 and 8 cm/yr) and for 2 weakening times (30 and 40 kyr). Velocity of 8 cm/yr always leads to constant slip rate (a). A moderate loading velocity leads to a periodic attractor ($T_w = 30$ kyr, curve b) or progressively damp ($T_w = 40$ kyr, curve c). B) Stress evolution for case (b) (total fault stress in solid line and viscous stress in dashed line). C) Slip rate evolution of case (b) displaying episodic fault behaviour.

- The more we measure, the closer to zero we get...
- The more we look, the more potential active faults we seem to find...





- Earthquakes are the result of stress changes rather than strain accumulation
- Let us assume that:
 - Continental faults are near failure (cf. Zoback et al.)
 - Small stress perturbations perturbations (~ 1 MPa) are sufficient to trigger earthquakes (if fast enough w.r.t. Maxwell time of relaxing layers)
 - Source of stress changes = sediment line load (50 m thick x 50 km wide, Gouw and Autin 2008) deposited 10,000 years ago
 - Load acting on plate with layered rheology (CEUS geothermal parameters from McKenna et al 2007 + assumed rock types)

=> bending stresses between 15-20 km sufficient to trigger earthquakes

Conclusions

- Q3. Do current data allow one to discern tectonic rates from **measurement uncertainties**?
 - Not in the NMSZ = 0 ± 0.2 mm/yr
 - Together with seismic record over past ~5,000 years => time-dependent deformation
 - Bad news: past may not reflect the future
 - Good news: beyond the elastic rebound model
- Q1. What is your confidence that observed **geodetic rates reflect long-term tectonic deformation** rates or short term seismicity pattern and rates?
 - Define long-term?
 - Geodetic rates for NMSZ are different from Holocene - it is not a steady-state system
- Q2. Have you compared the geodetic signature of **other zones of seismicity in stable continental regions**?
 - Yes - the longer one measures, the lower the strain rates.
 - Is local strain accumulation a prerequisite for earthquakes?

Compare geodetic and geologic rates elsewhere

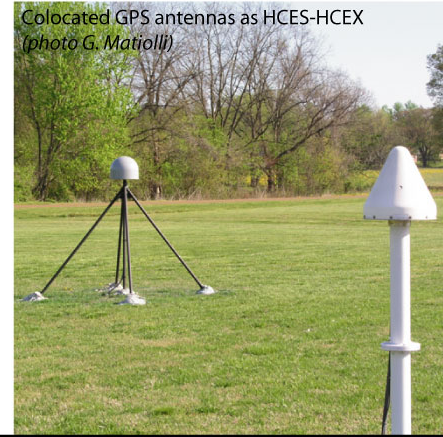
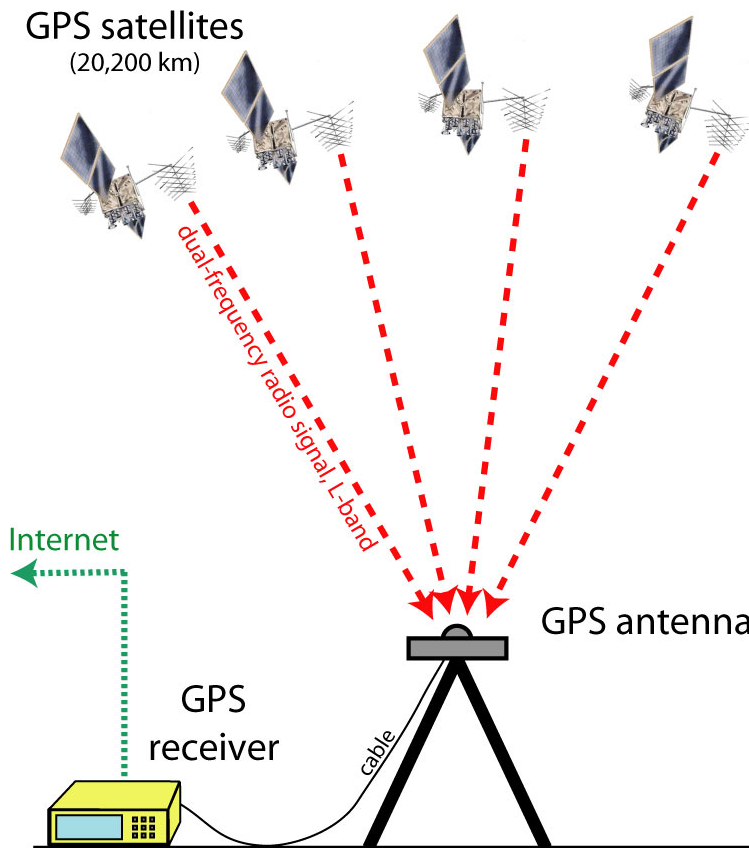
Agreement:

- Nuvel1 and Geodesy, 3.2 Ma
- California
- Dead Sea: Klinger, etc
- New Zealand (Nicol and Wallace, EPSL 2007): deformation rates are consistent with the notion of near-constant rates since 1.5 Ma
- Wasatch - Chang et al JGR 2006: GPS 1.6 ± 0.4 , geol 1.7 ± 0.5 over 10 Ka (Friedrich et al. 2003), Bennet GJI 2007
- Basin and Range: Pancha et al BSSA 2006
- Red Sea, Reilinger and McClusky AGU 2008 - data agree within uncertainties over 11 Ma
- Hispaniola (Prentice, Calais)
- North Anatolias fault: Kozaci, Dolan. Finkel - AGU 2007 - geologic slip rates indistinguishable from GPS at 25 ± 1 mm/yr since 3500 Ma.
- Eastern California Shear Zone: Frankel et al. JGR 2007, 8.5-10 mm/yr, identical to 9 mm/yr GPS for past 70 Ka

But also lack of:

- Dolan et al Geology 2007
- Weldon et al GSA Today 2004, long-term slip rate on the San Andreas fault at Wrightwood is considerably faster than the geodetic rate there, although the geodetic rate is in agreement with the geologically determined rate for the past 1100 yr.
- This study

GPS satellites
(20,200 km)



4 satellites => solve for latitude, longitude, elevation, time

$$\Phi_i^k(t) = \rho_i^k(t) \times \frac{f}{c} + (h^k(t) - h_i(t)) \times f + ion_i^k(t) + trop_i^k(t) - N_i^k + \varepsilon$$

Phase measurement	=	Sat-rec. distance	+	Clock errors	+	Ionospheric delay	+	Tropospheric delay	+	Phase ambiguity	+	Other noise sources
Precision < 1% wavelength => mm or better		Satellite orbit precision ~1 cm		Cancel out with double differences		First order terms vanishes with two frequencies		Estimated (to better than X mm)		Estimated, 95-98%		Cannot be corrected: monument stability, multipath

Plate Motions Are Steady

Richard G. Gordon

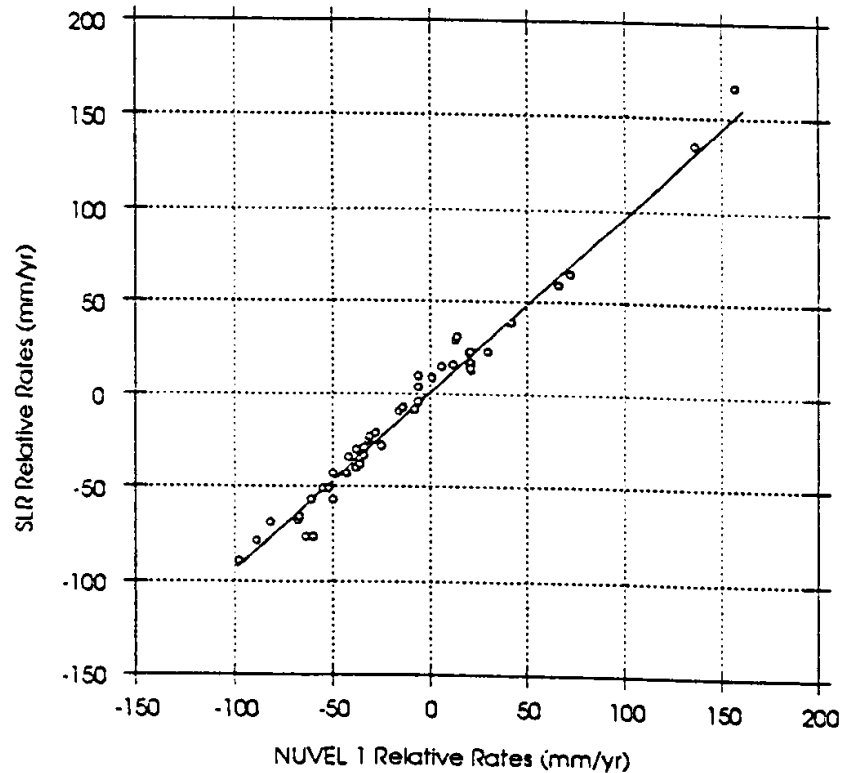


Fig. 11. Comparison of SLR determined geodesic rates with those implied by the NUVEL 1 geologic plate motion model for 54 lines connecting stations on five plates that are well within plate interiors and crossing at least one plate boundary. The slope of the line is 0.949 ± 0.019 .

Wasatch fault, Chang et al. JGR 2006:
GPS 1.6 ± 0.4 , geol 1.7 ± 0.5 over 10 Ka
(Friedrich et al. 2003)

Note that 1992-1995 GPS = 2.7 ± 1.3 mm/yr...

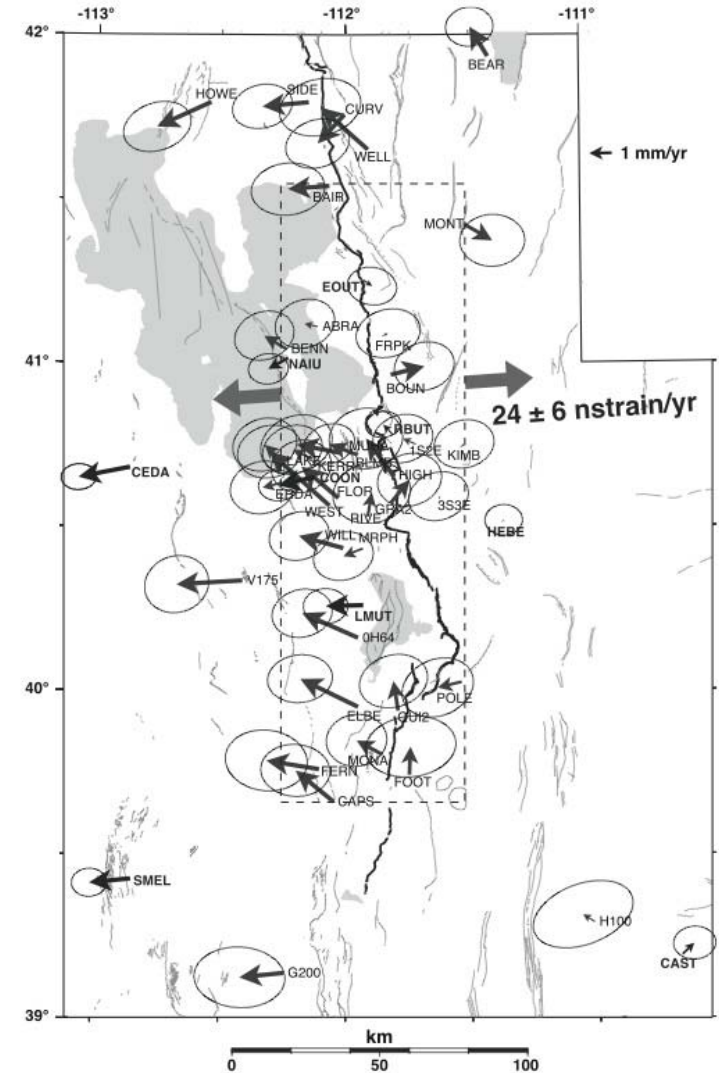
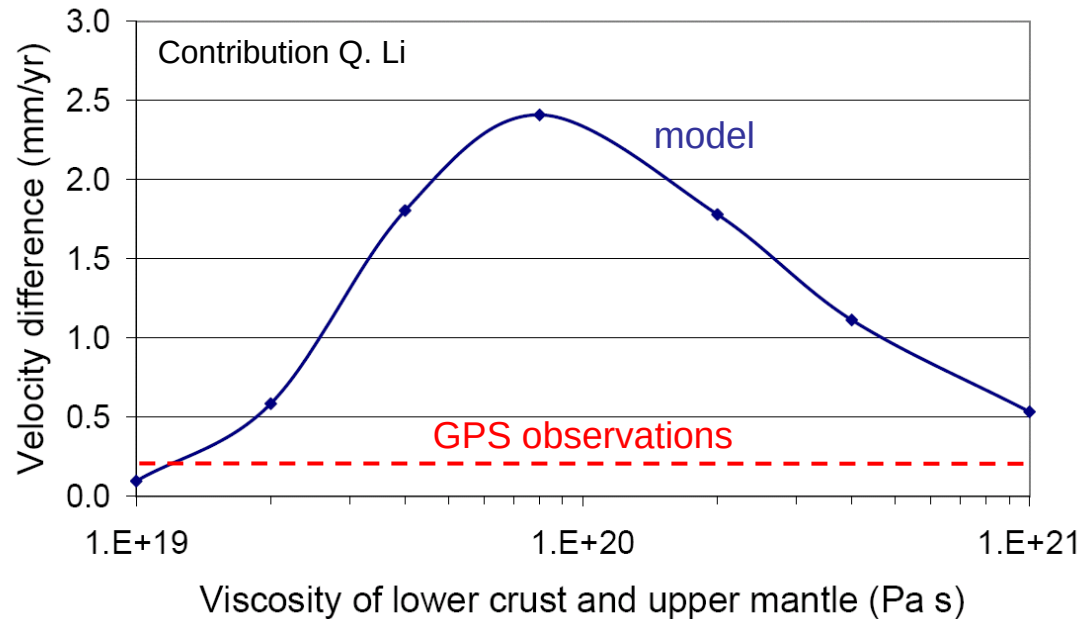


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Velocity difference across fault 200 years after a M8 earthquake



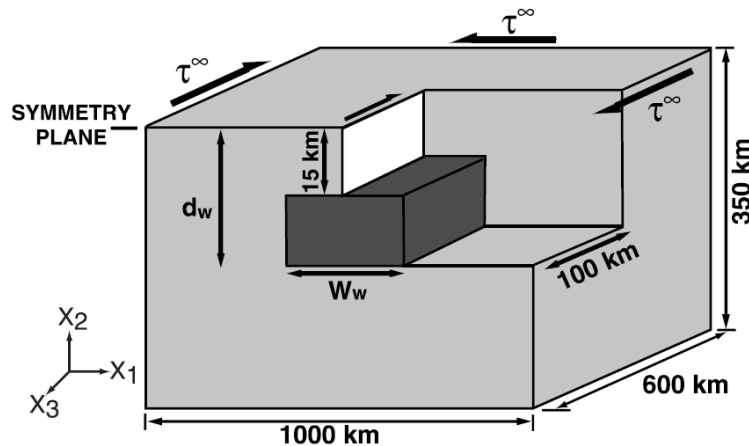
Local loading models:

- Kenner and Segall (2000, relaxing lower crust) => minimum predicted strain rate = 5.5×10^{-9} /yr (for lower crust viscosity = 10^{21} Pa s)
- Pollitz et al. (2001, sinking mafic body) => 2.4 mm/yr (lower crust viscosity 10^{20} Pa s).

Inconsistent with current GPS ($\epsilon < 0.2 \times 10^{-9}$ /yr, $v < 0.2$ mm/yr), unless very low or very large viscosity.

Other issues:

- Weakening mechanism: what initiates the process?
- Rheology?



(Kenner and Segall, 2000)