Seismic Hazard Maps

A presentation by
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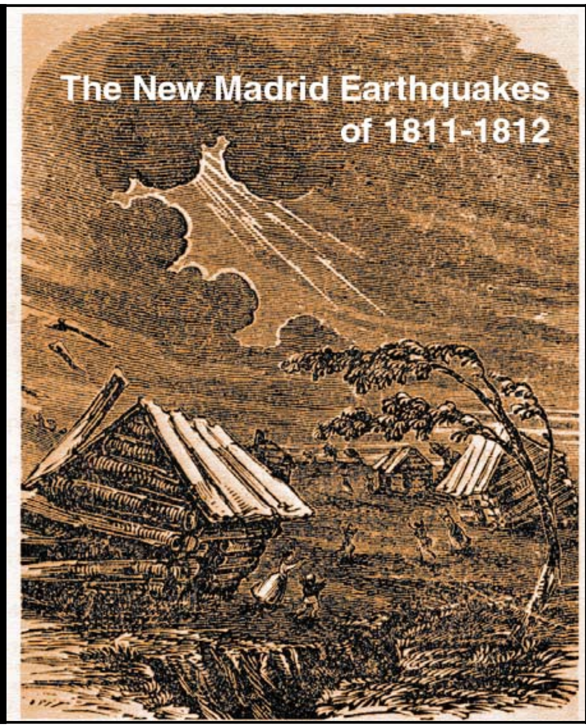
November 22, 2004

1811-12 New Madrid Earthquakes



1886 Charleston Earthquake

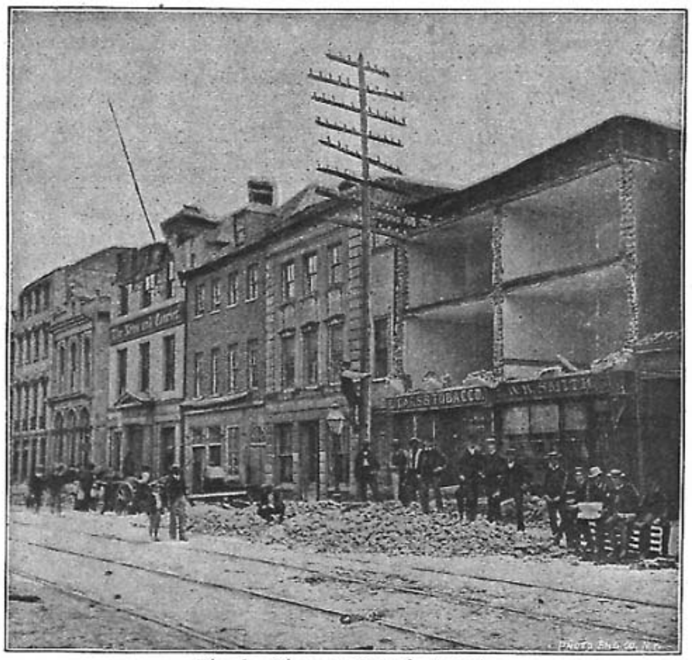
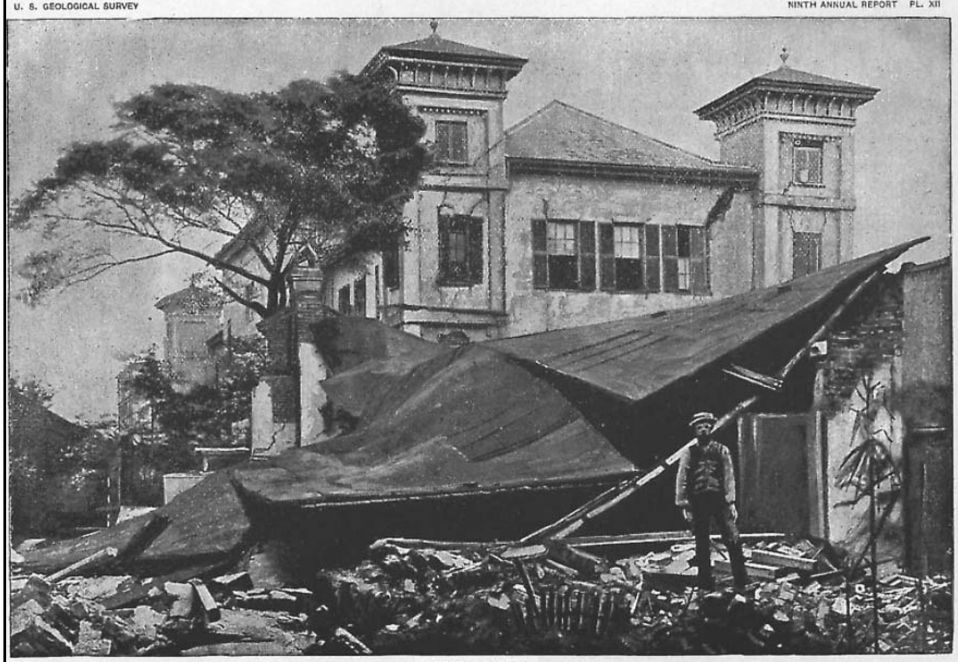


Fig.1 View on Broad street

U. S. GEOLOGICAL SURVEY NINTH ANNUAL REPORT PL. XII



ROPER HOSPITAL.

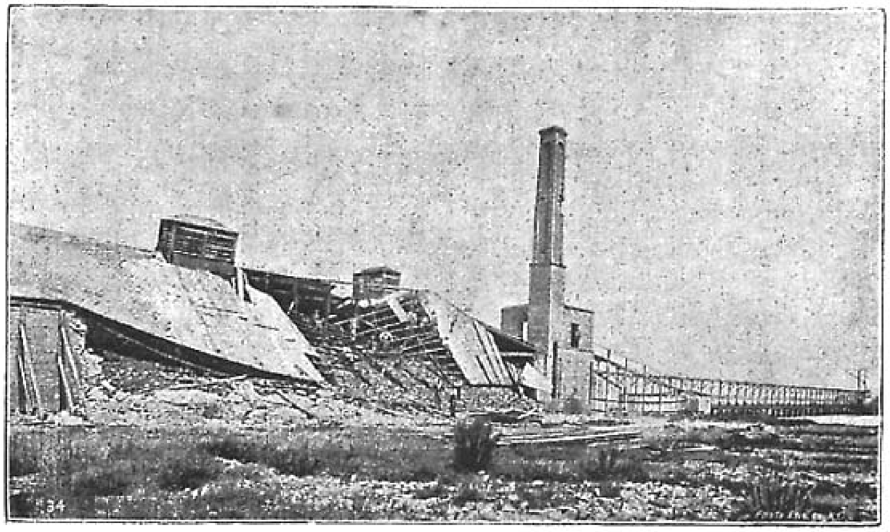


FIG. 6. The city gas-works.

U. S. GEOLOGICAL SURVEY NINTH ANNUAL REPORT PL. XX

A LARGE CRATERLET.

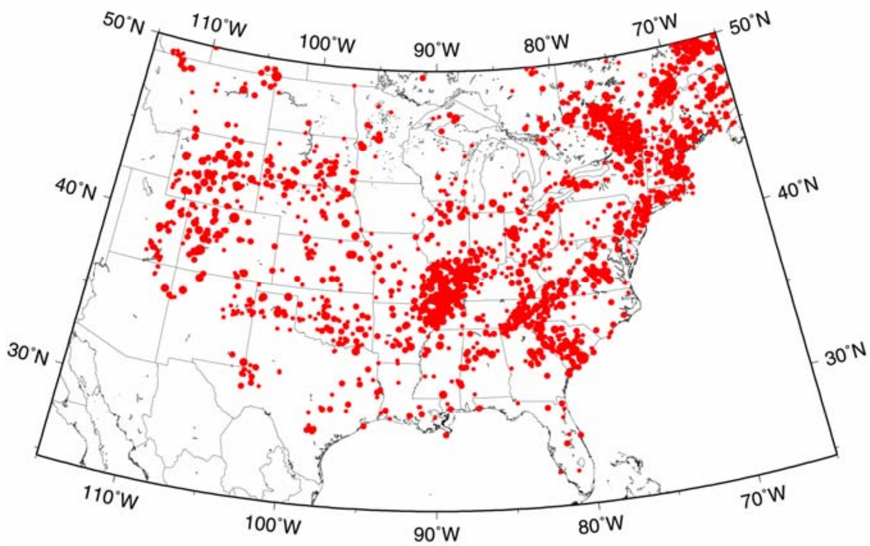
Overview

- Seismic Hazard Maps
  - What are seismic hazard maps?
  - What goes into making seismic hazard maps?
  - How are uncertainties handled?
  - What about site amplification from soils?

Seismic Hazard Maps Summary

There have been devastating earthquakes in the past in the central U.S. And there will be devastating earthquakes in the future. Because of large population centers with vulnerable infrastructure, there is a strong need to prepare for these rare, devastating events.

CEUS Earthquakes 1700-1995



What are Seismic Hazard Maps?

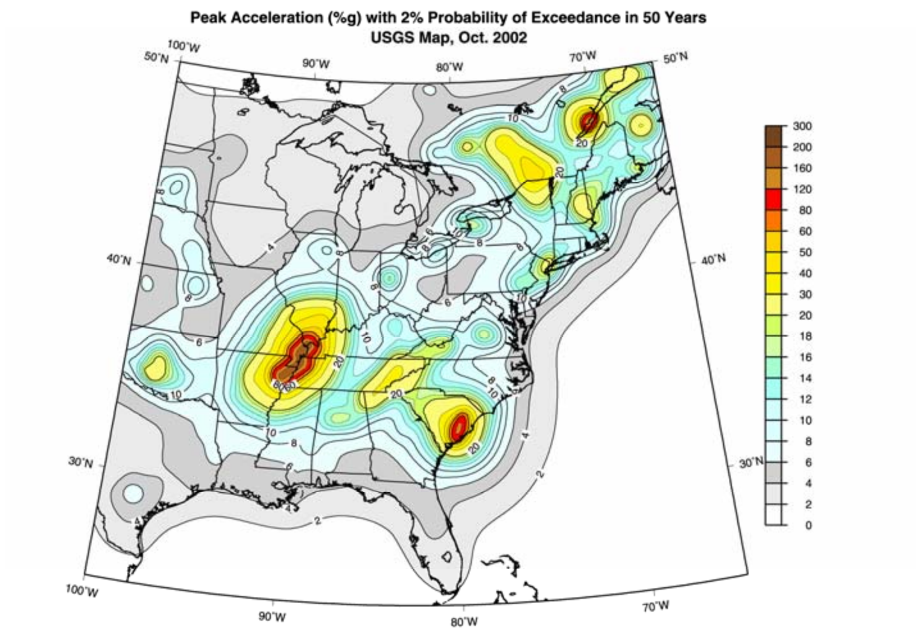
- Mainly they are earthquake shaking maps that indicate ground motions expected from earthquakes.
- Basically there are two classes:
  - Scenario (Deterministic)
  - Probabilistic

What Question Does Each Type Address?

- Scenario (Deterministic):
  - What ground motions can I expect from a specific earthquake scenario?
- Probabilistic:
  - What is the likelihood (probability) of ground motions from future earthquakes in a region?
- Note that both are based on ground-motion probability distributions.

National Seismic Hazard Maps

- Developed from the Best Earth Science Information
- Represent Current Understanding of Seismic Ground Motion Hazard
- Incorporates Uncertainty in our Knowledge
- Show Average (Expected) Ground Motion for given Level of Risk, NOT the Worst Case
- They are NOT Engineering Design Maps!

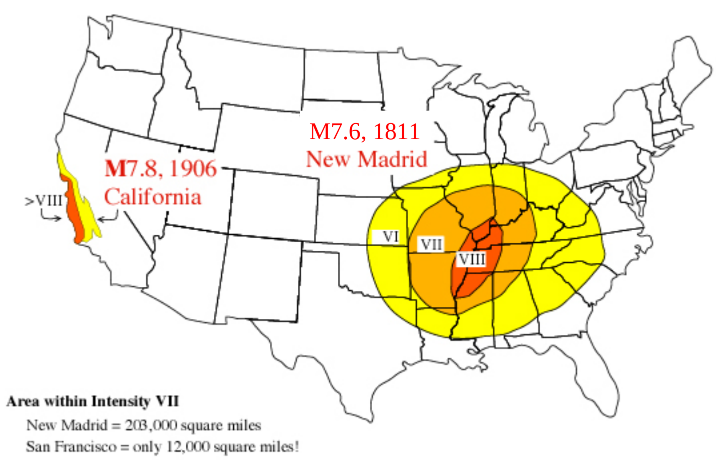


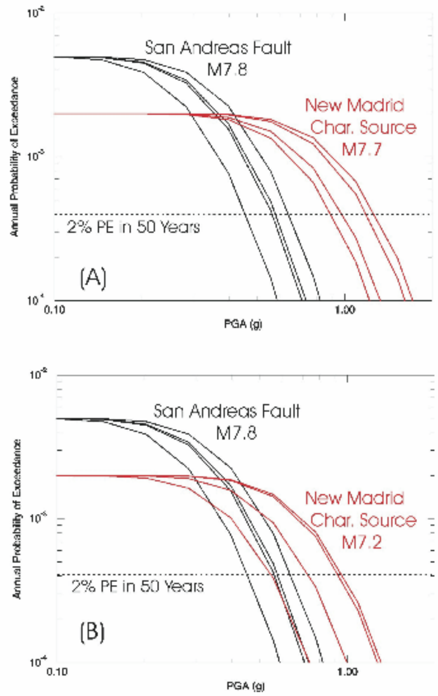
Basic Earthquake Hazard
Lets keep it simple!

- Larger earthquakes cause more damage!
- Earthquake hazard increases with earthquake magnitude and occurrence rate.
- Earthquake shaking decreases more slowly with distance in the central and eastern U.S. than in the western U.S.
- For the same magnitude, eastern U.S. earthquakes have larger high-frequency ground motions than western U.S. earthquakes.

The Largest Earthquakes Dominate

- The largest earthquakes are more damaging over a larger area.
- Generally in the eastern U.S., the rate of smaller earthquakes can underestimate the rate of larger earthquakes.





Frankel, 2004

1988 Armenia Earthquake:

Devastation from a rare M6.9 earthquake in an area known to have such events.

Figure 6.12 Remains of five-story precast-frame communications building in Spitak. It is presumed that the weak floor diaphragms contributed to this failure.

Figure 6.13 Partially collapsed, nine-story residential precast-frame building in Leninakan

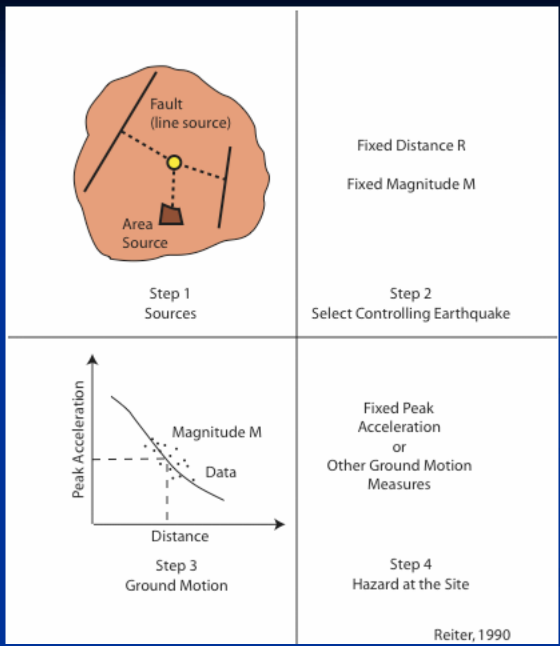
CEUS Seismic Hazard Conclusions

- There is a significant earthquake hazard in the central U.S. and it should not be ignored!
- There is a strong need for cost-effective engineering mitigation to reduce future losses from major earthquakes.

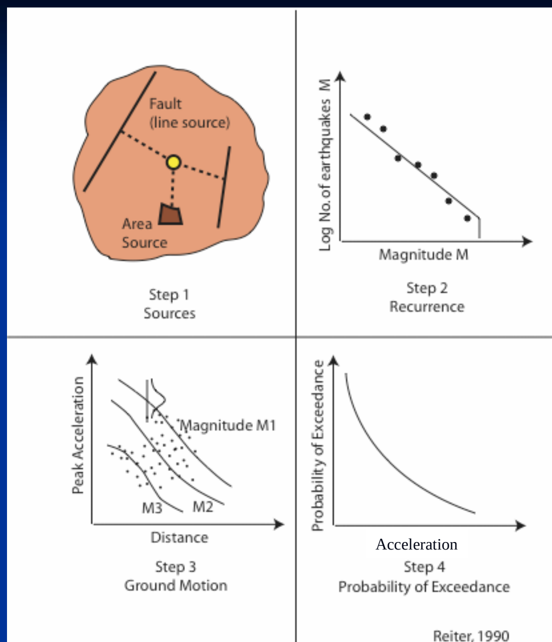
The Details!

What Information Is Needed?

- Earthquake Sources
- Earthquake Recurrence Rates
- Earthquake Ground Motions as a Function of Distance and Magnitude (Attenuation Relations)



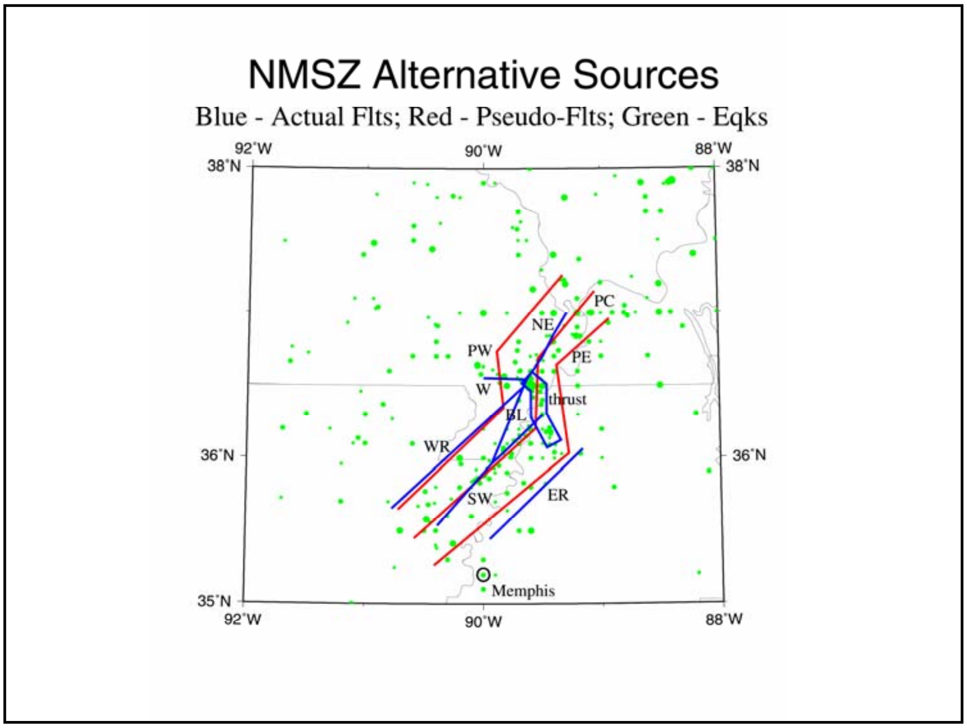
Steps in Deterministic Seismic Hazard Analysis

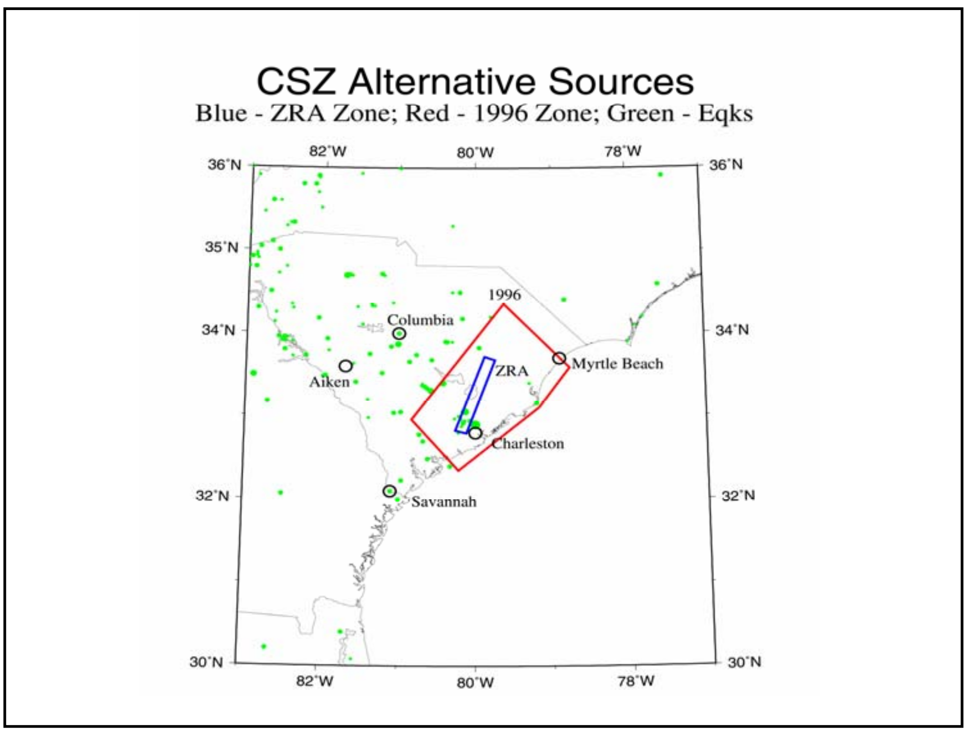


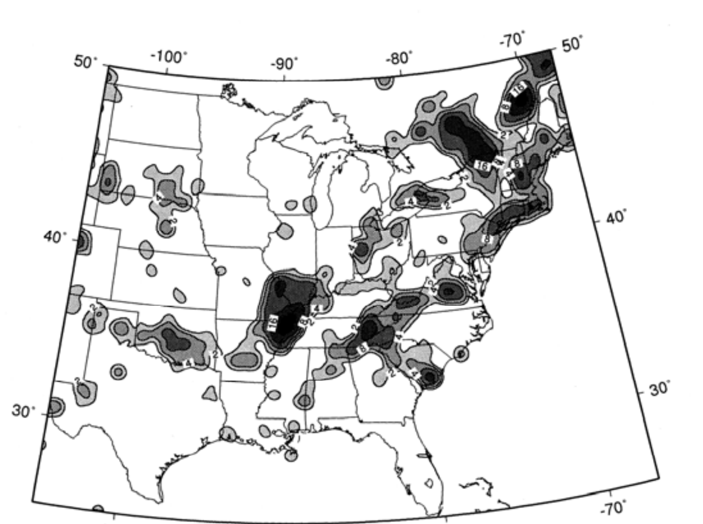
Steps in Probabilistic Seismic Hazard Analysis

Types of Source Models

- Fault Models (Line Sources)
- Area Models
  - Distributed Line Sources
  - Distributed Point Sources (Eqk. Hypocenters)
    - Zoneless Model (Smoothed Seismicity Model)
    - Zone Models

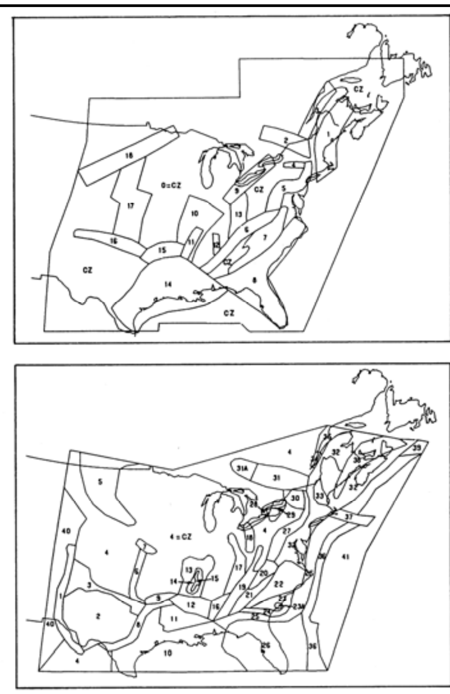

NMSZ Alternative Sources
Blue - Actual Flts; Red - Pseudo-Flts; Green - Eqks
92°W
90°W
88°W
38°N
36°N
35°N
PC
NE
PW
PE
W
thrust
BL
WR
SW
ER
Memphis


CSZ Alternative Sources
Blue - ZRA Zone; Red - 1996 Zone; Green - Eqks
82°W
80°W
78°W
36°N
35°N
34°N
32°N
30°N
1996
Columbia
Aiken
ZRA
Myrtle Beach
Charleston
Savannah



▲ **Figure 4** Contour map of smoothed 10^a values derived from m_b 3 and larger earthquakes since 1924 (correlation distance of 50 km). The values represent number of events in 11 km square grid cell, for 60 years, with magnitude between 0 and 0.1.

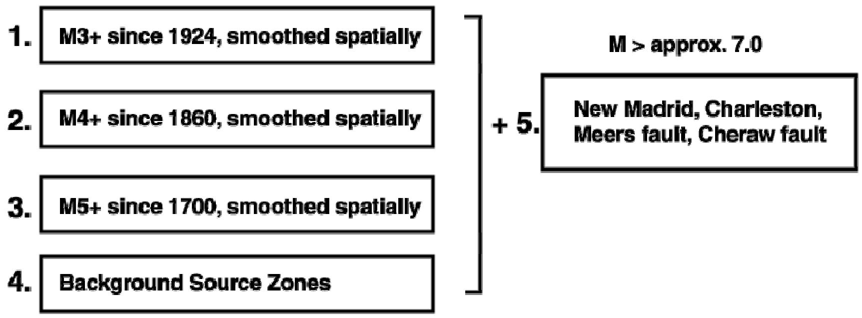
Frankel, 1995



Reiter, 1990

Models used for the Central and Eastern U.S. in the 1996 National Probabilistic Seismic Hazard Maps

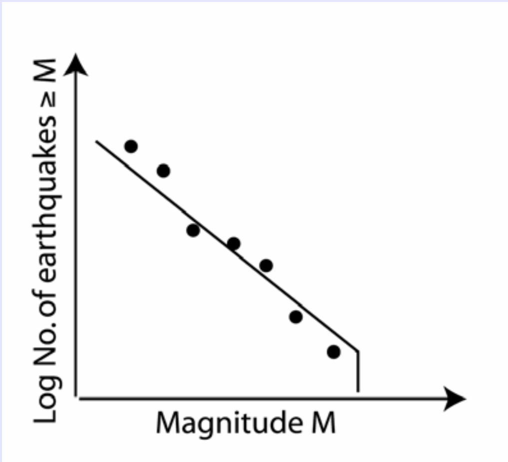
Mmax = 5.6 in craton
Mmax = 7.5 outboard of craton
Mmax = 7.5 for Wabash Valley
mblg min = 5.0 for hazard calculation



Frankel et al., 1996

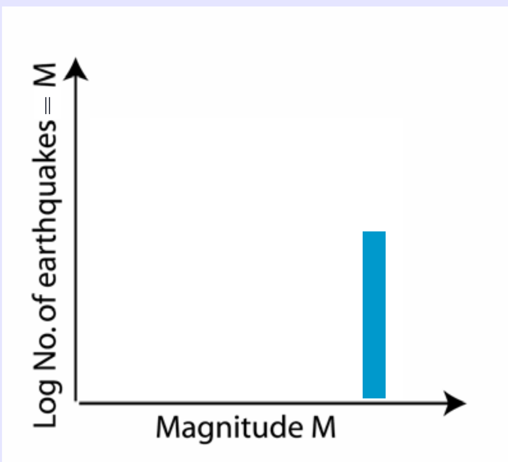
Earthquake Recurrence Distributions

- Gutenberg-Richter (Power Law)
- Characteristic (Individual Fault)



And how often earthquakes of each size occur

Guttenberg-Richter Distribution



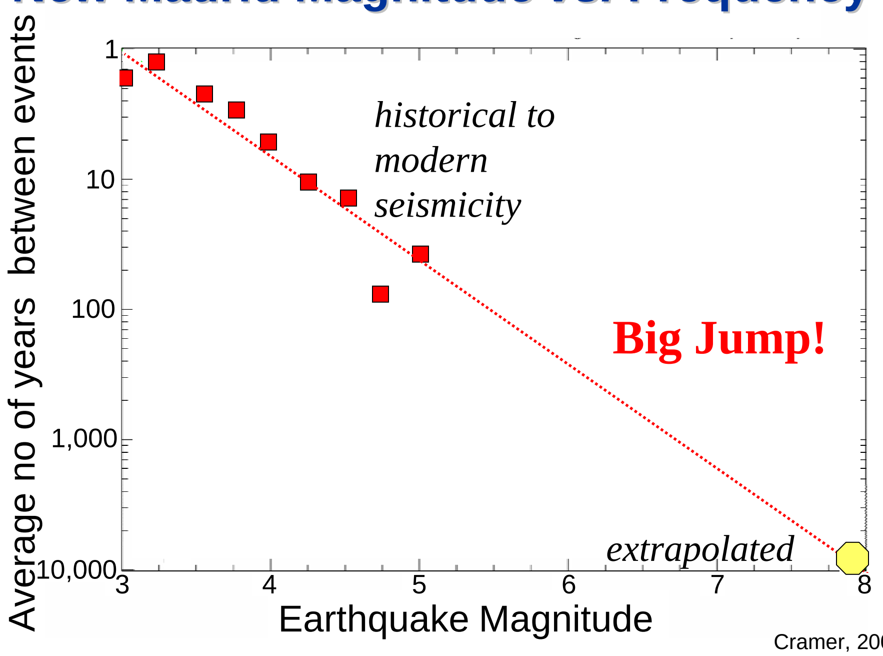
And how often earthquakes of each size occur

Characteristic Distribution

Determining Recurrence Rates

- Geodesy
  - Observed Strain Across Faults (Plate Boundaries)
  - Record of several years to decades
- Historical Earthquake Activity
  - Record of several hundred years or less in most of U.S., with decreasing completeness of record back in time.
- Paleoseismicity (Geology)
  - Record of perhaps 20,000 years

New Madrid Magnitude *vs.* Frequency

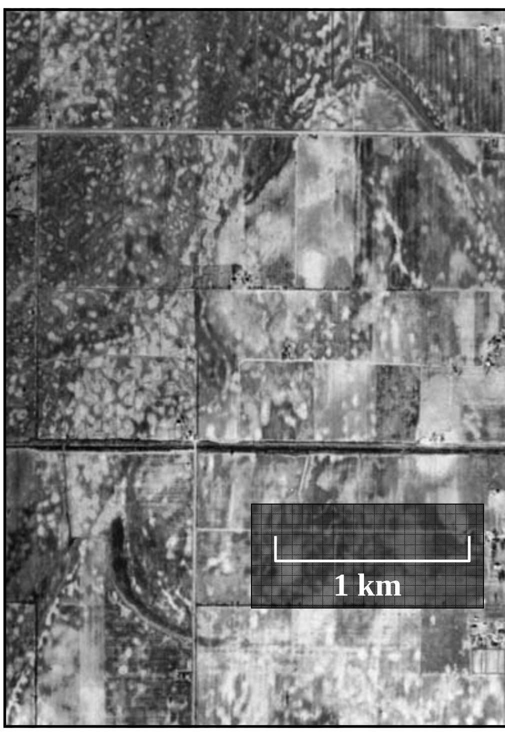


Cramer, 2001

Interpreting the location, timing, and magnitude of prehistoric earthquakes

PALEOSEISMOLOGY

Unlike in California, we don't have surface faults to study. In the New Madrid seismic zone, our most powerful tool has been ancient liquefaction deposits, which we can date with carbon-14 and Native American artifacts



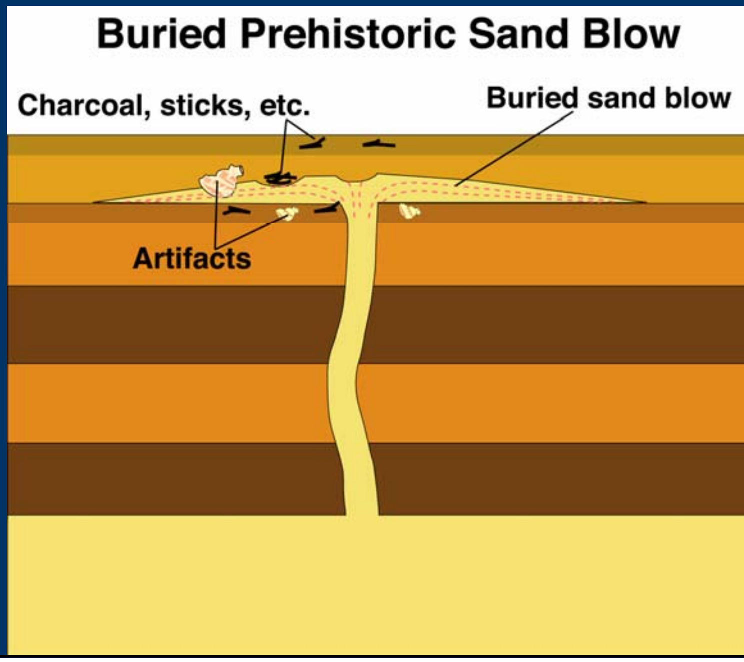
Sand Blows in Southeastern Missouri

- Each white spot is a sand blow from 1811-1812 or earlier earthquakes

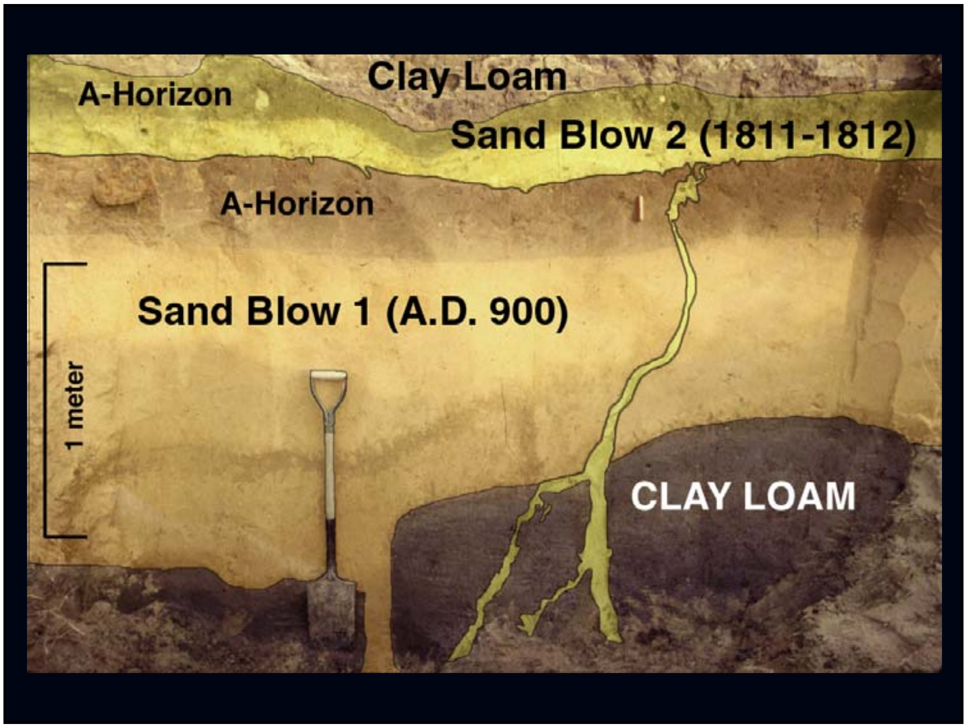
We can use sand blows to date old earthquakes if:

- they bury old plant remains of archeological artifacts we can date
- the sand blows are themselves buried by materials we can date

- We then know the earthquakes occurred between the two time periods



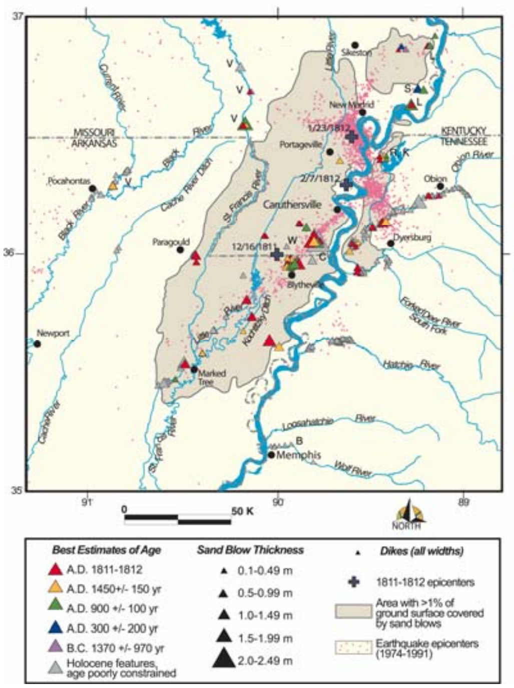
An example of a sand blow in a drainage ditch, southeast Missouri



After digging dozens of trenches through sand blows

And examining hundreds of miles of river banks...

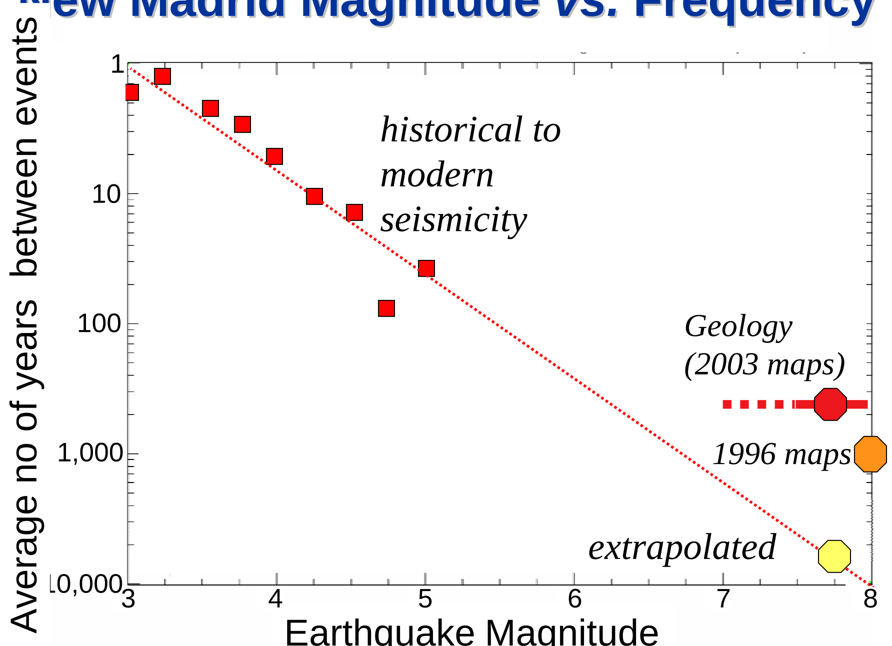
And plotting them on maps



We now know:

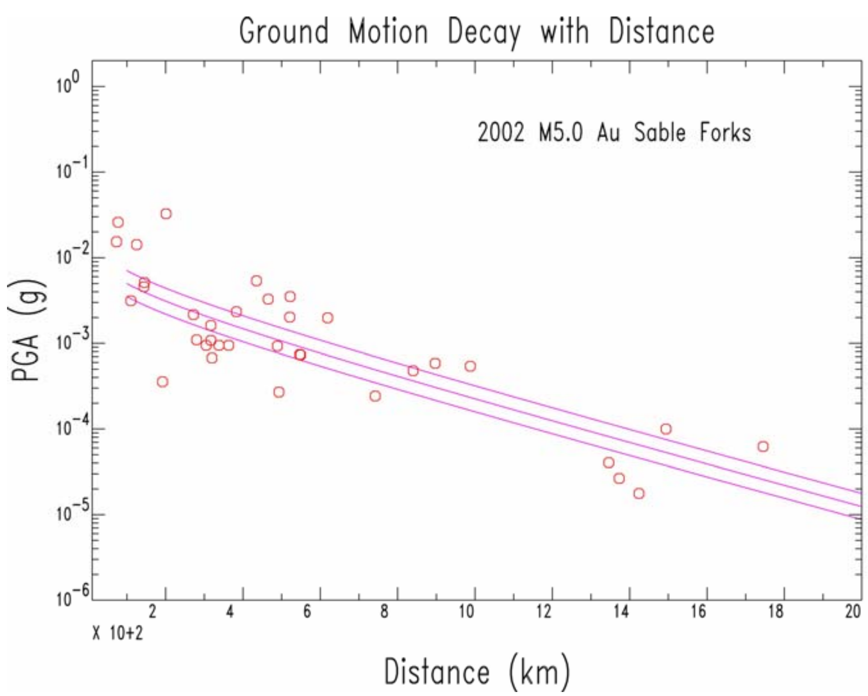
- Large earthquakes in 1450 and 900 A.D.
- The average time between the large earthquakes is about 500 years
- The prehistoric earthquakes were approximately the same size as the 1811-1812 earthquakes
- Each may actually represent sequences of large earthquakes, as in 1811-1812

New Madrid Magnitude *vs.* Frequency

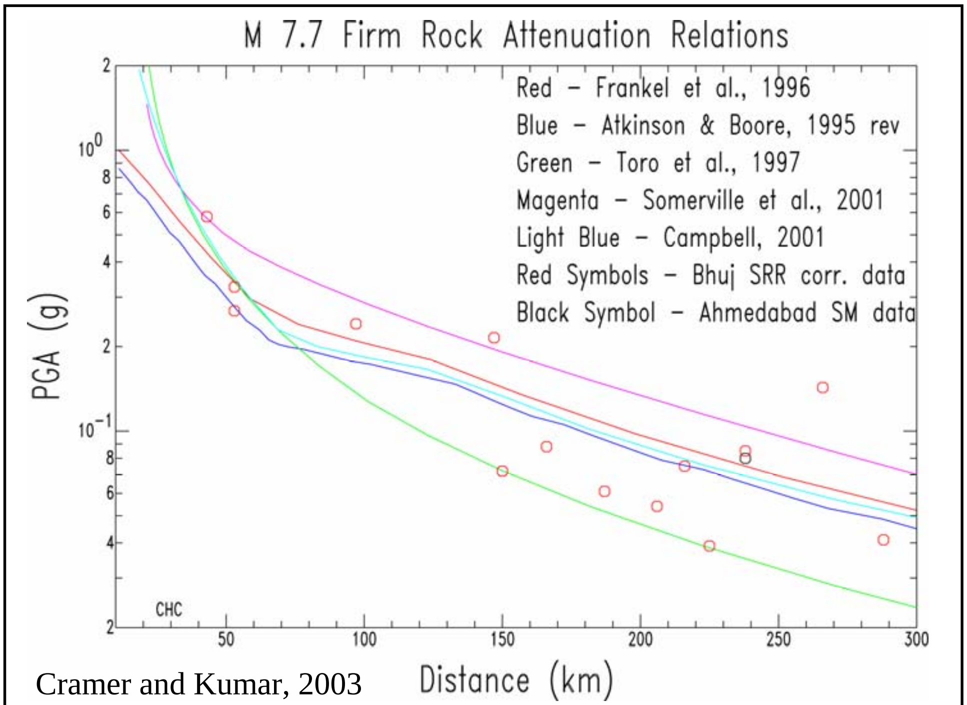


Cramer, 2001

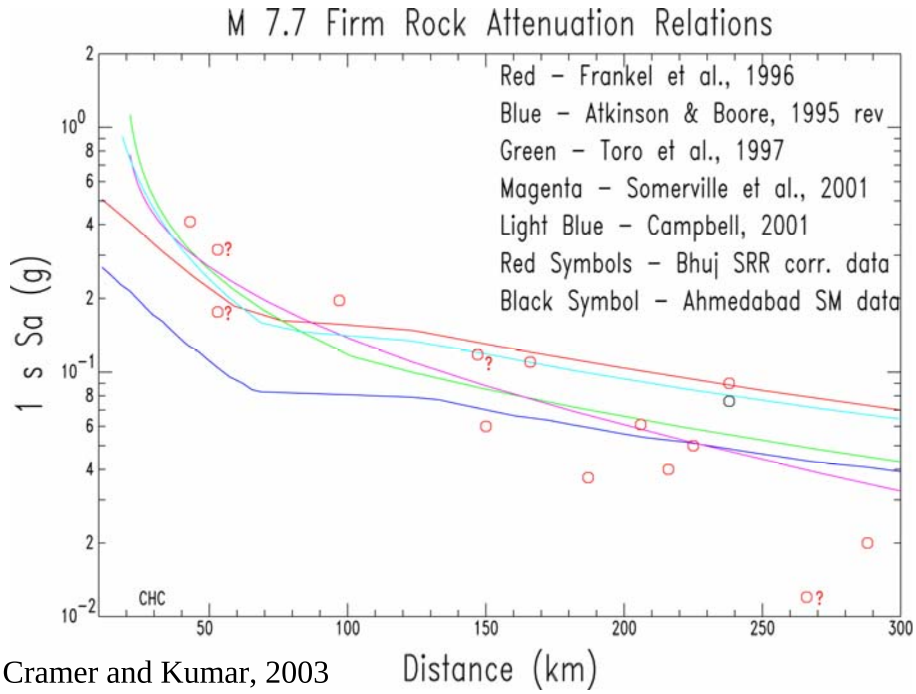
Estimating Ground Motions



ENA Ground Motion Attenuation Relations

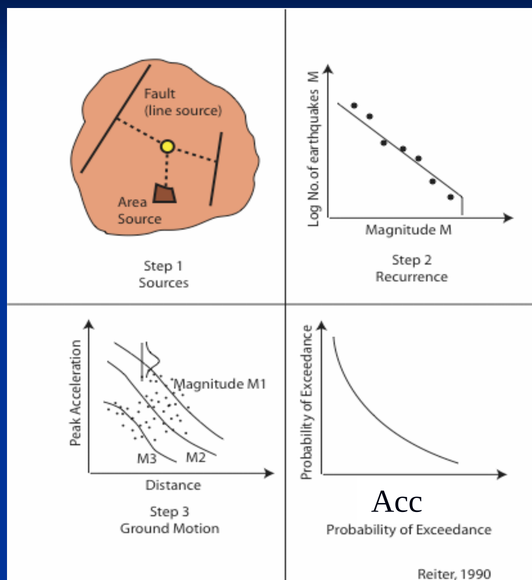


Cramer and Kumar, 2003



Cramer and Kumar, 2003

Putting It All Together: Hazard Curves



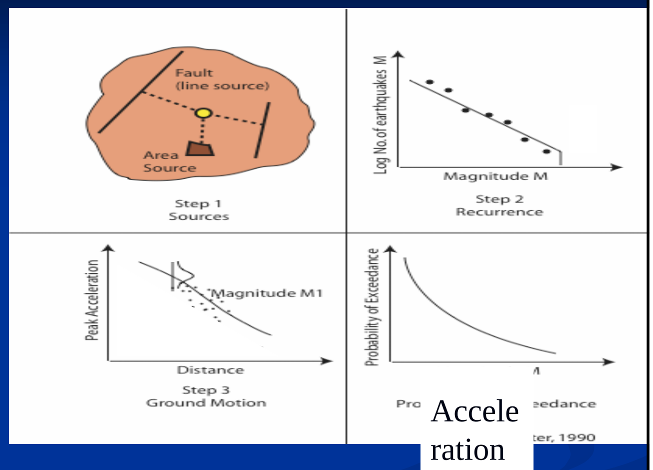
What is a Hazard Curve?

Single Earthquake

Ground Motion Hazard = Rate times Pe(M,d)

where Pe(M,d) is the probability of exceeding a given ground motion level as a function of magnitude and distance.

How is a Hazard Curve Formed?



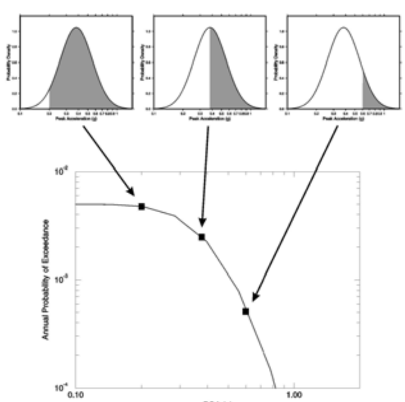


Figure 2. Construction of a hazard curve for a single source, in this case **M**7.8 earthquakes on the San Andreas fault, with return time of 200 years. Hazard curve is for a site 15 km from fault. At top are plots showing the area under the log-normal distribution for PGA values greater than 0.2g, 0.38g, and 0.6g. The median PGA is 0.38g. The hazard curve values are calculated using equation (1). The probability densities are plotted in equal increments of log ground motion.

Frankel, 2004

All Modeled Earthquakes

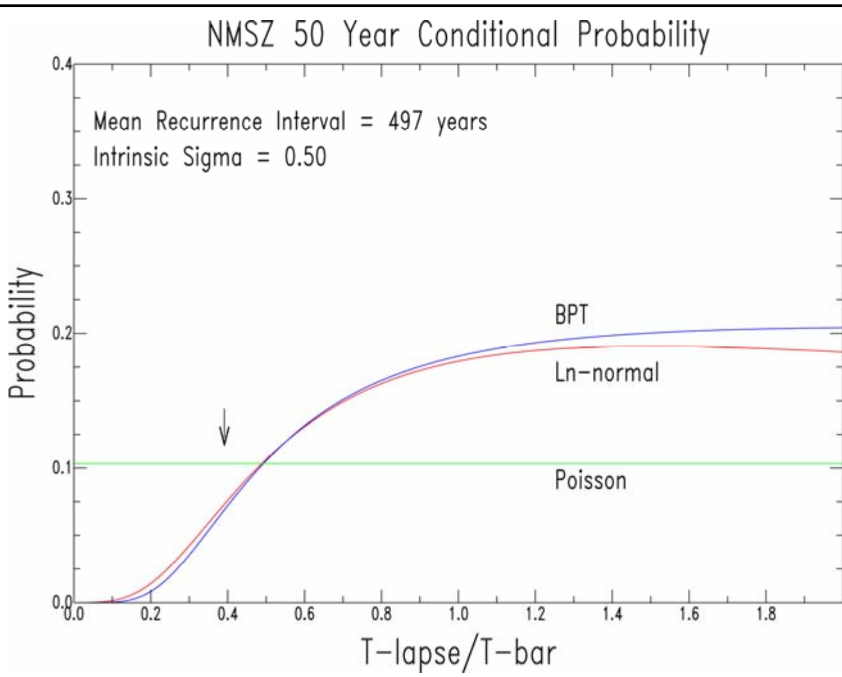
Total Hazard Curve = Sum($Rate_i$*$Pe(M,d)_i$)

- Note that you always sum probabilities and never ground motions!

Poisson vs. Time Dependent

Types of Seismic Hazard Maps

- Poisson or Time Independent
  - Earthquakes occur randomly in time
- Time Dependent (characteristic model)
  - The occurrence of earthquakes is dependent on the time since the last one.



1812 2012 2212 2412 2612 2812

New Madrid Probabilities

- M > 7:
  - Time Independent
    - » 10% in 50 years
  - Time Dependent
    - » 7% for the next 50 years
- See USGS Fact Sheet FS-131-02 "Earthquake Hazard in the Heart of the Homeland"

Charleston Probabilities

- M ~ 7:
  - Time Independent
    - » 10% in 50 years
  - Time Dependent
    - » 2% for the next 50 years

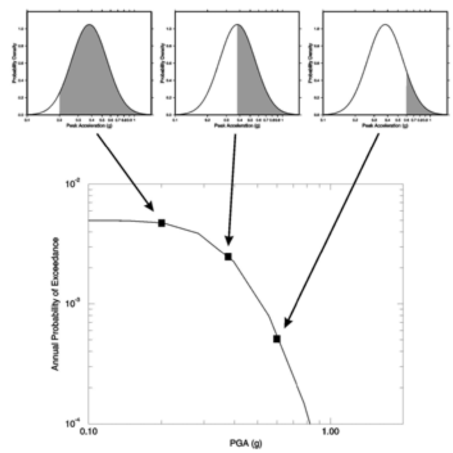
Including Uncertainties

Types of Uncertainty

- Random (Aleatory) Uncertainty
  - Generally not reducible with more knowledge
- Model or Knowledge (Epistemic) Uncertainty
  - Can be reduced with improved understanding

Generally handled differently in calculations!

15



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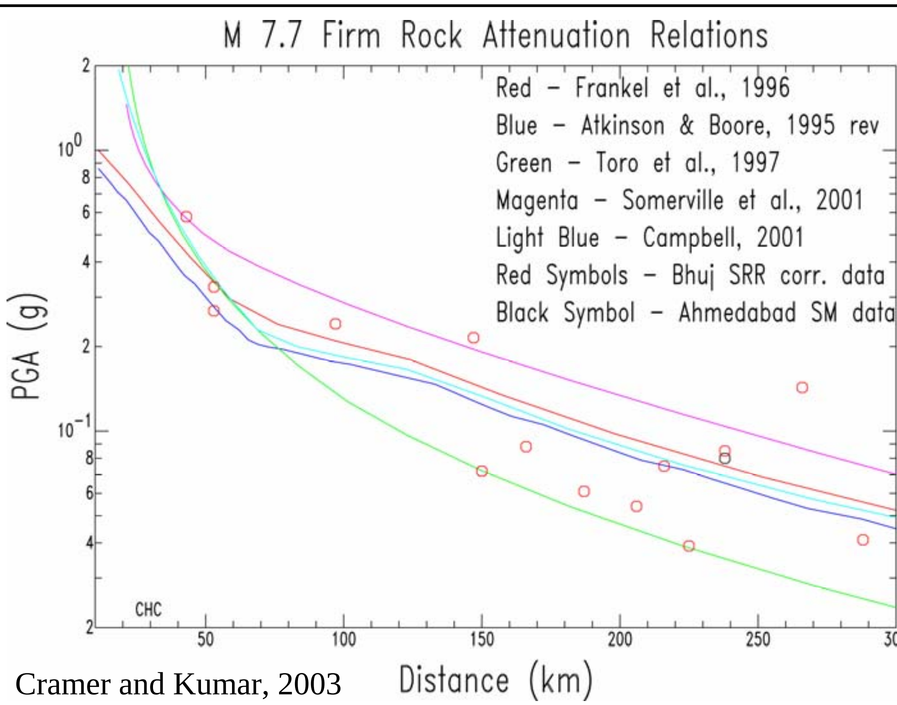
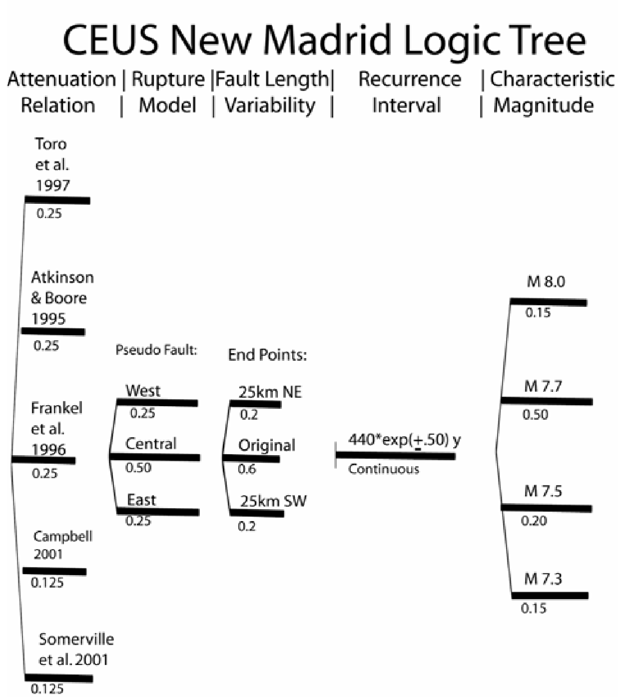
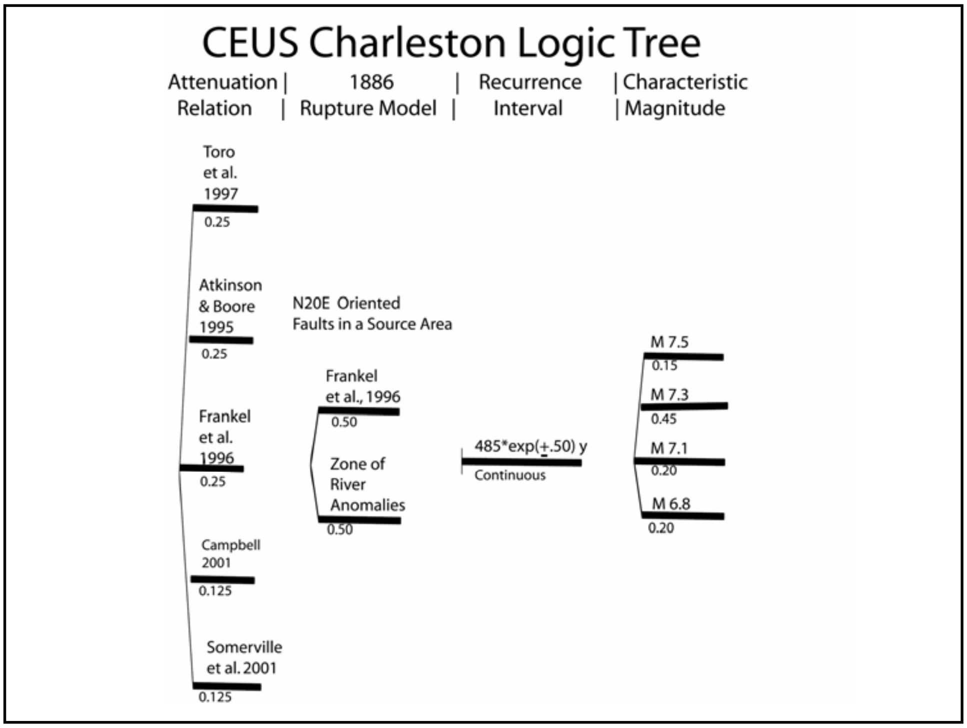


Cramer and Kumar, 2003

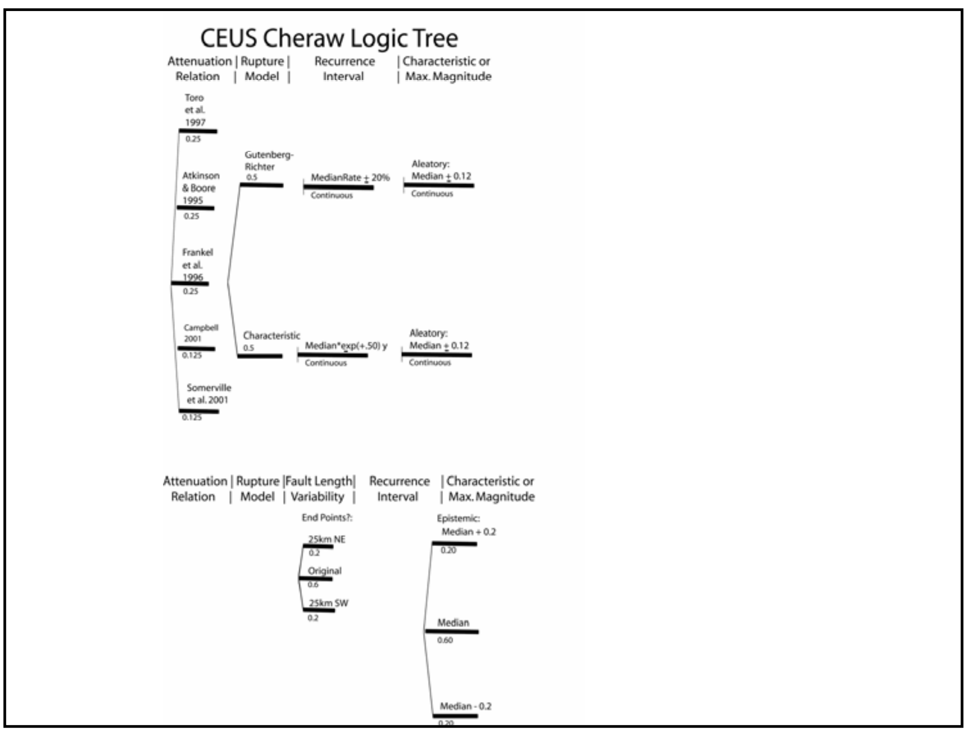
Handling Epistemic Uncertainty

- Logic or Decision Trees





CEUS Charleston Logic Tree
Attenuation | Relation
1886 | Rupture Model
Recurrence | Interval
Characteristic | Magnitude
Toro et al. 1997
0.25
Atkinson & Boore 1995
0.25
Frankel et al. 1996
0.25
Campbell 2001
0.125
Somerville et al. 2001
0.125
N20E Oriented Faults in a Source Area
Frankel et al., 1996
0.50
Zone of River Anomalies
0.50
485*exp(±.50) y
Continuous
M 7.5
0.15
M 7.3
0.45
M 7.1
0.20
M 6.8
0.20



CEUS Cheraw Logic Tree
Attenuation | Relation
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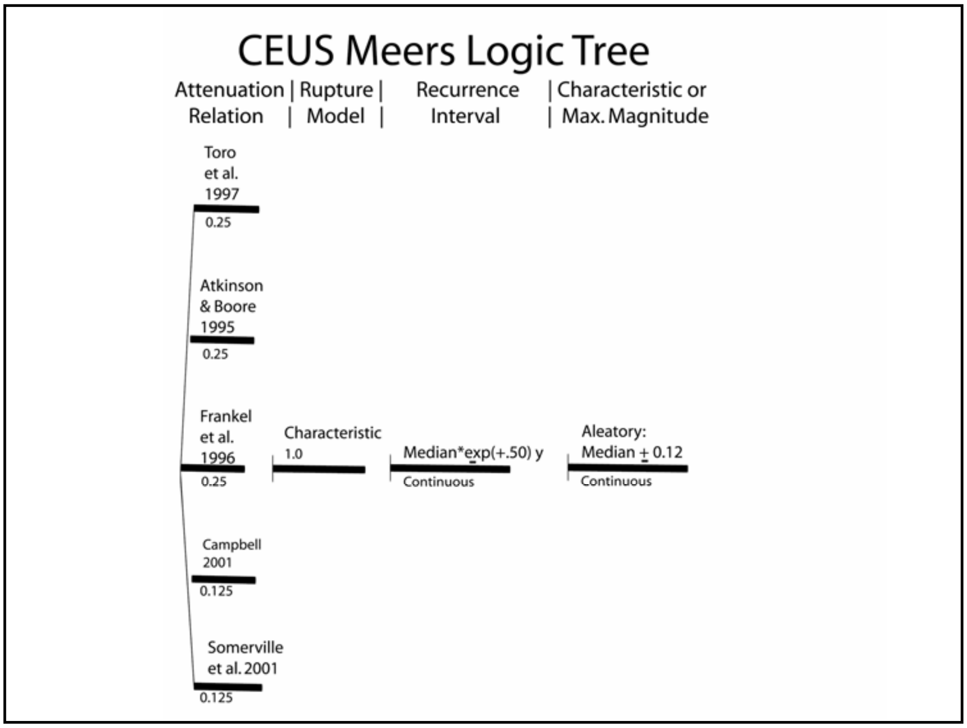
Recurrence | Interval
Characteristic or | Max. Magnitude
Toro et al. 1997
0.25
Atkinson & Boore 1995
0.25
Frankel et al. 1996
0.25
Campbell 2001
0.125
Somerville et al. 2001
0.125
Gutenberg-Richter
0.5
MedianRate ± 20%
Continuous
Aleatory: Median ± 0.12
Continuous
Characteristic
0.5
Median*exp(+.50) y
Continuous
Aleatory: Median ± 0.12
Continuous
Attenuation | Relation
Rupture | Model
Fault Length | Variability
Recurrence | Interval
Characteristic or | Max. Magnitude
End Points?:
25km NE
0.2
Original
0.6
25km SW
0.2
Epistemic:
Median + 0.2
0.20
Median
0.60
Median - 0.2
0.20


CEUS Meers Logic Tree
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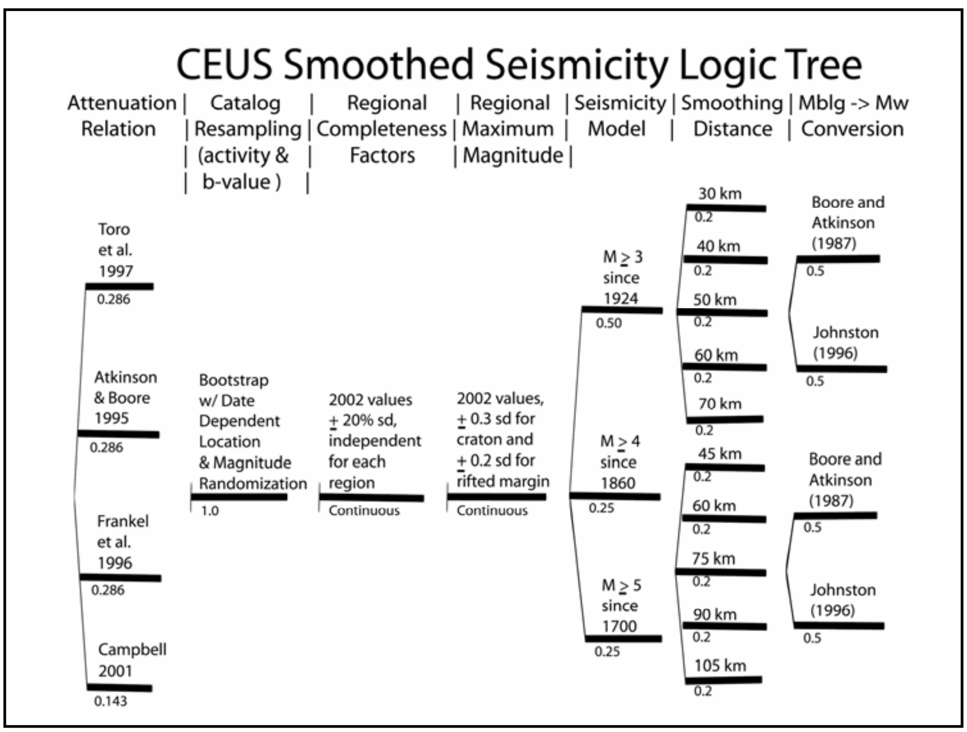
Toro et al. 1997
0.25
Atkinson & Boore 1995
0.25
Frankel et al. 1996
0.25
Campbell 2001
0.125
Somerville et al. 2001
0.125
Characteristic
1.0
Median*exp(+.50) y
Continuous
Aleatory: Median ± 0.12
Continuous


CEUS Smoothed Seismicity Logic Tree
Attenuation Relation | Catalog Resampling (activity & b-value) | Regional Completeness Factors | Regional Maximum Magnitude | Seismicity Model | Smoothing Distance | Mblg -> Mw Conversion
Toro et al. 1997
0.286
Atkinson & Boore 1995
0.286
Frankel et al. 1996
0.286
Campbell 2001
0.143
Bootstrap w/ Date Dependent Location & Magnitude Randomization
1.0
2002 values ± 20% sd, independent for each region
Continuous
2002 values, ± 0.3 sd for craton and ± 0.2 sd for rifted margin
Continuous
M ≥ 3 since 1924
0.50
M ≥ 4 since 1860
0.25
M ≥ 5 since 1700
0.25
30 km
0.2
40 km
0.2
50 km
0.2
60 km
0.2
70 km
0.2
45 km
0.2
60 km
0.2
75 km
0.2
90 km
0.2
105 km
0.2
Boore and Atkinson (1987)
0.5
Johnston (1996)
0.5
Boore and Atkinson (1987)
0.5
Johnston (1996)
0.5

Urban earthquake hazard mapping in the Central U.S.

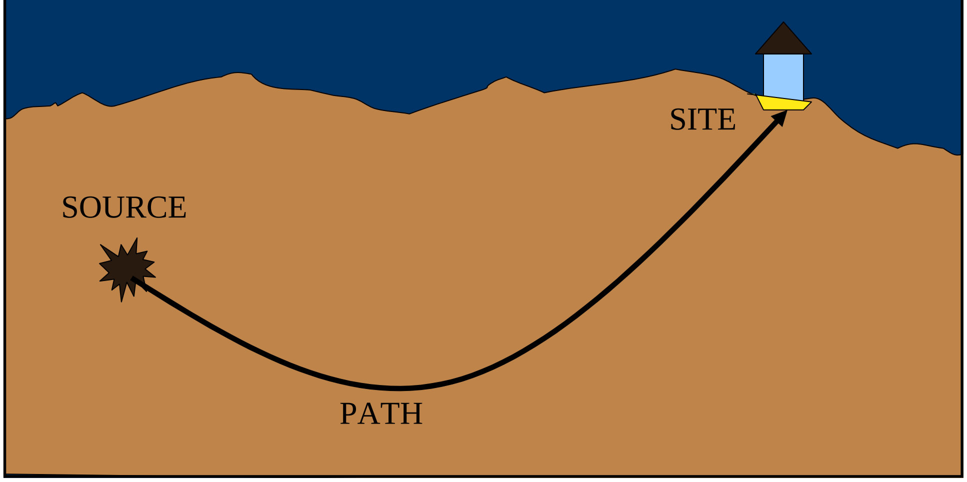
What is an urban earthquake hazard map?

- Show expected levels of shaking/ amplification or likelihood of ground failure (liquefaction, landslides)
- The scale is useful locally, but not site specific
- Includes the effects of the local geology

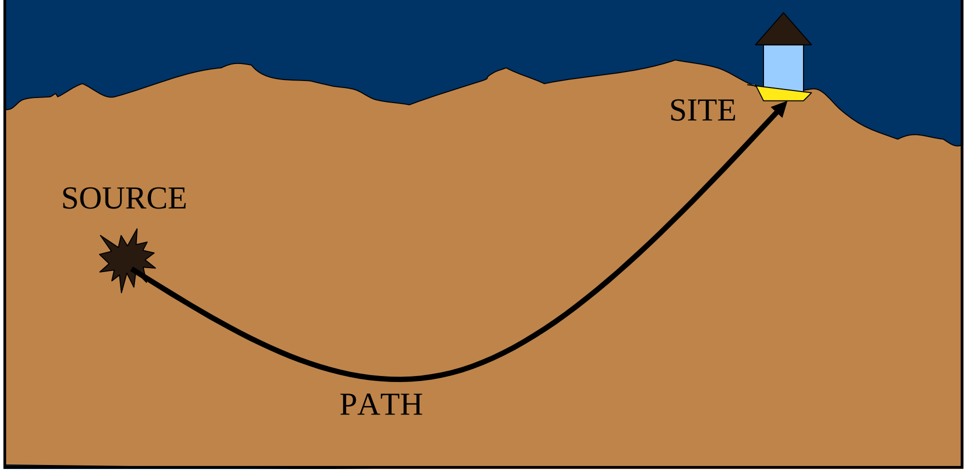
Memphis vs National Maps

- NEHRP D and 1 km thick vs B/C boundary
- Ground Motions relative to national maps
  - PGA is similar
  - 0.2 s Sa for Memphis maps are 0-30% lower
  - 1.0 s Sa for Memphis maps are 100% higher

What determines the shaking that affects a structure?



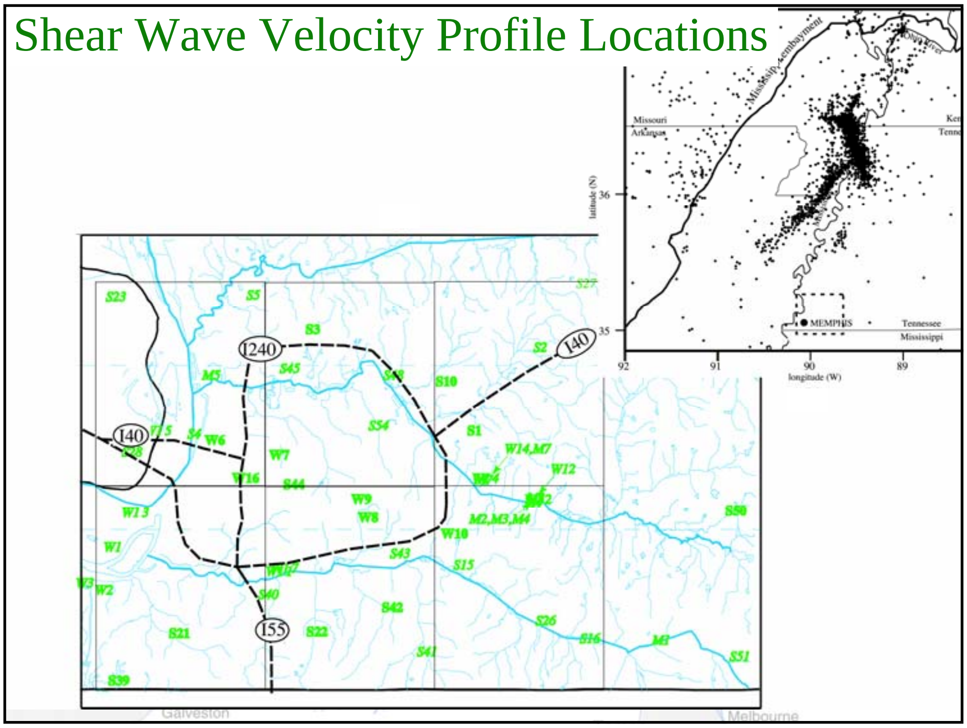
The urban hazard maps include the site effects



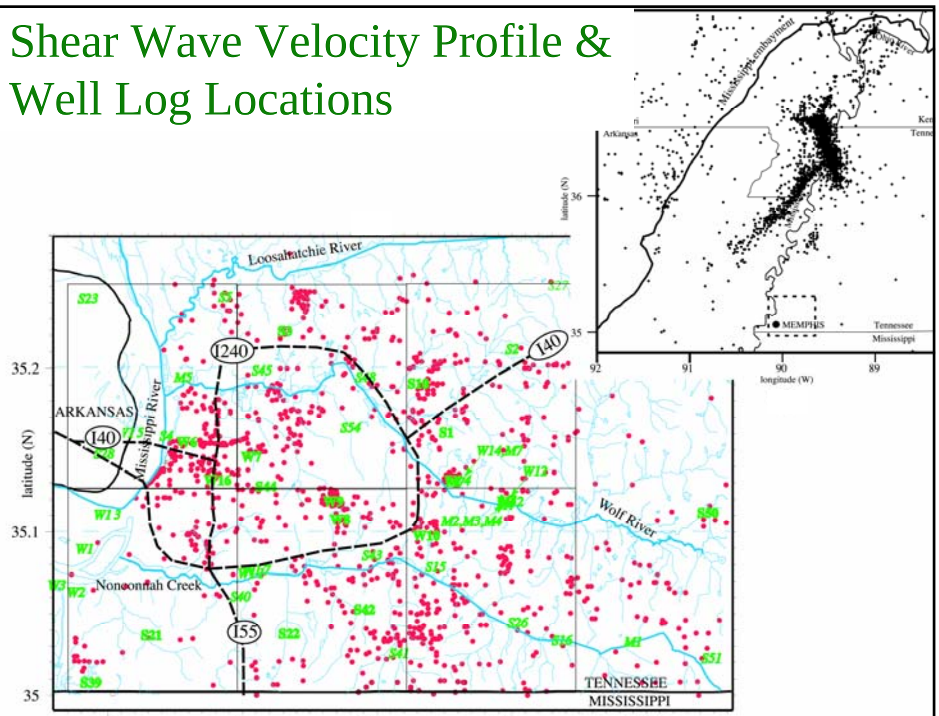
Basic Methodology

- Use three dimensional geology (well data)
- Generate site amplification distributions (median and ln sd) at each grid point
- Modify hard-rock ground motion attenuation relations with site amplification distribution prior to hazard calculation at each grid point.
- Calculate hazard using national map PSHA model for CEUS.

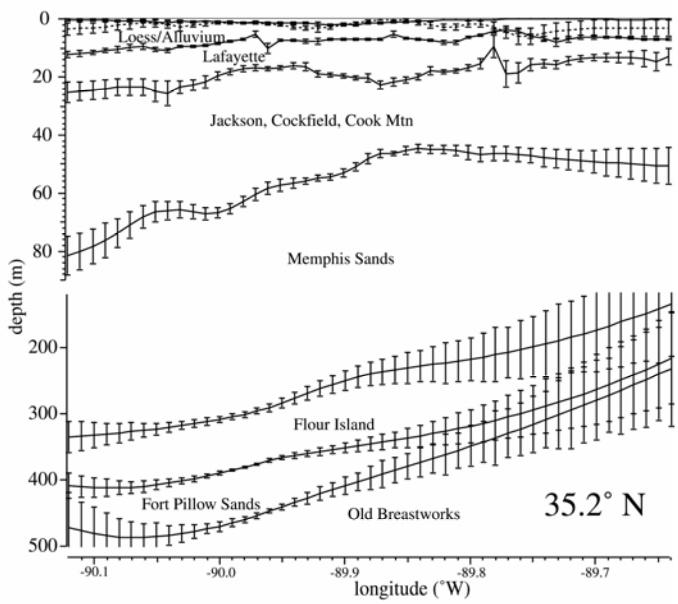
Shear Wave Velocity Profile Locations



Shear Wave Velocity Profile & Well Log Locations

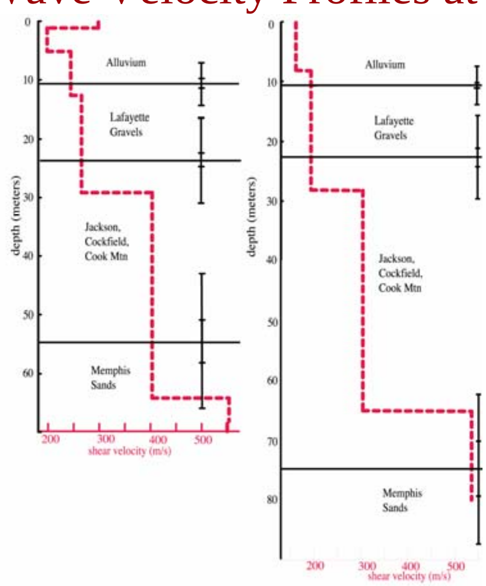


Stratigraphy with Modeling Uncertainties



Gomberg et al. 2003

Sedimentary Layers & Shear Wave Velocity Profiles at 2 Sites

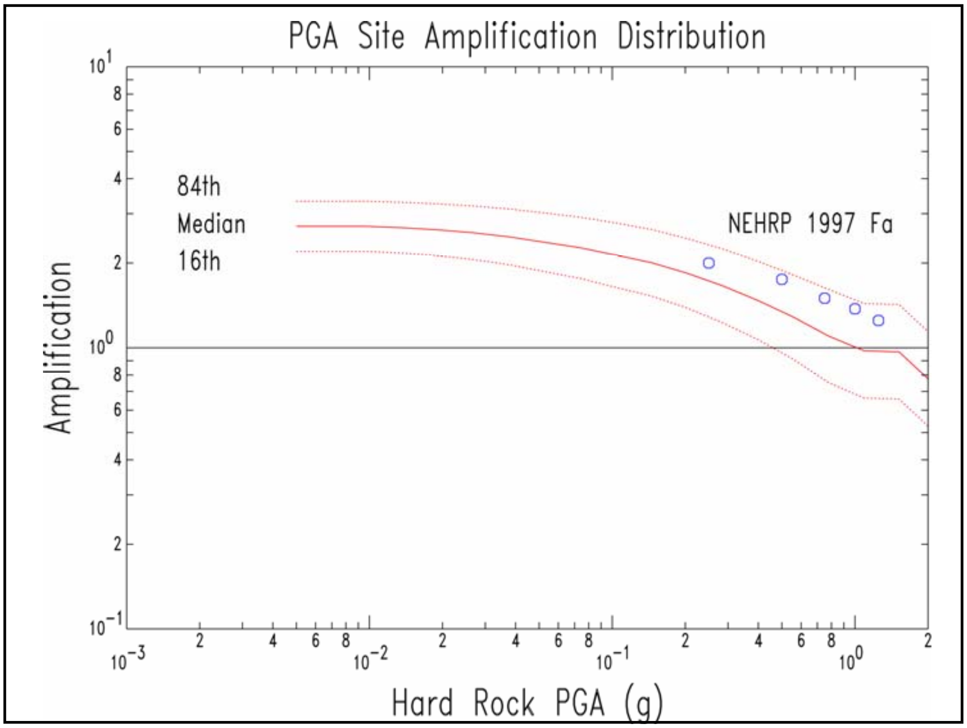


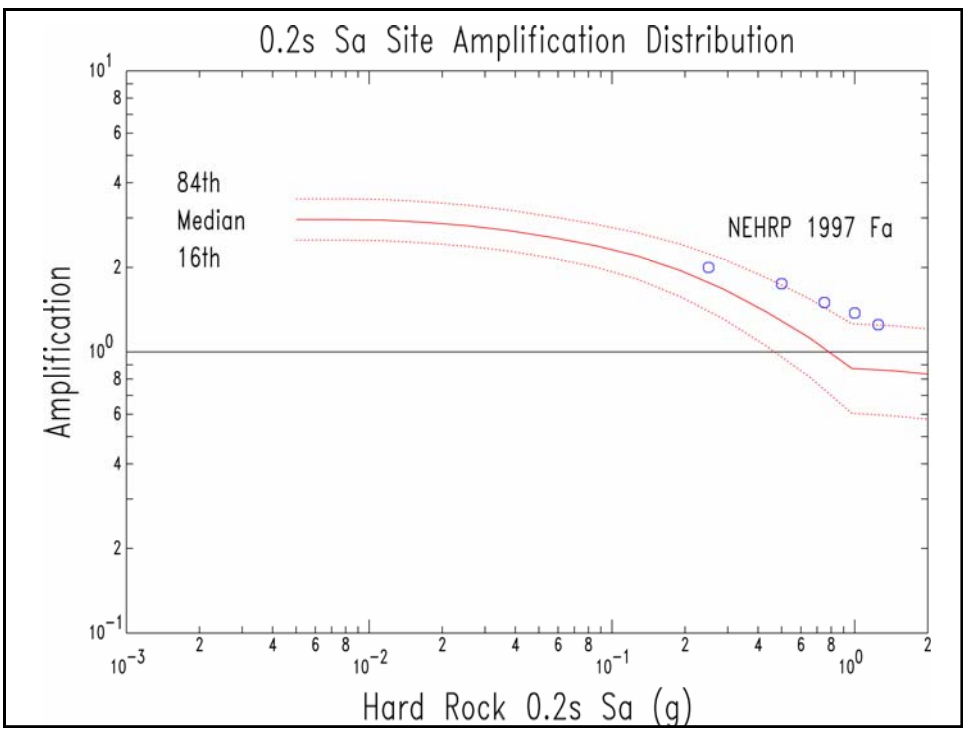
Site Amplification Approach

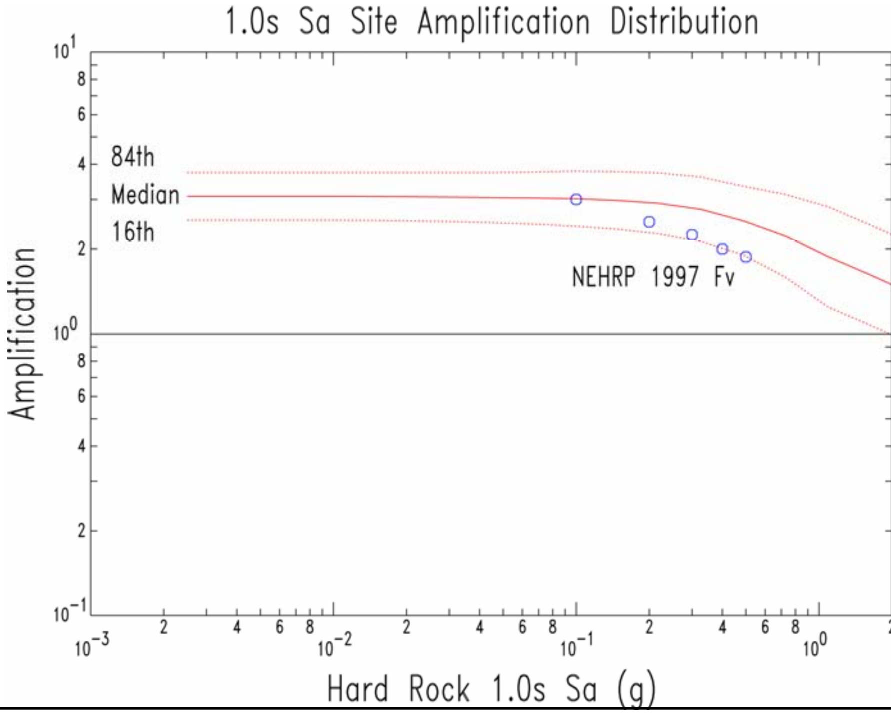
- Monte Carlo Randomization
  - Input time series (record)
  - Soil profile (Vs and depth-to-top)
  - Dynamic Soil Properties (EPRI, 1993)
- Method
  - Randomly select soil profile and time series.
  - For 3 periods (PGA, 0.2 s, 1.0 s), scale to 10 ground motion levels (0.01 - 1.0 g).
  - Calculate soil column response (1D) for each period and ground motion level.
  - Develop amplification distribution from 100 iterations.

Typical Examples

- Compare to NEHRP 1997 site factors
- Three ground motions
  - PGA
  - 0.2 s Sa
  - 1.0 s Sa


PGA Site Amplification Distribution
Amplification
Hard Rock PGA (g)
84th
Median
16th
NEHRP 1997 Fa

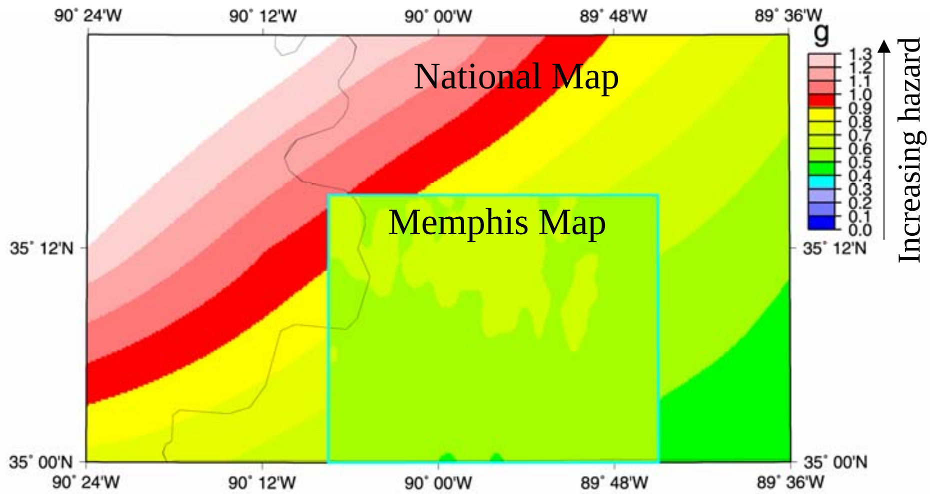

0.2s Sa Site Amplification Distribution
Amplification
Hard Rock 0.2s Sa (g)
84th
Median
16th
NEHRP 1997 Fa



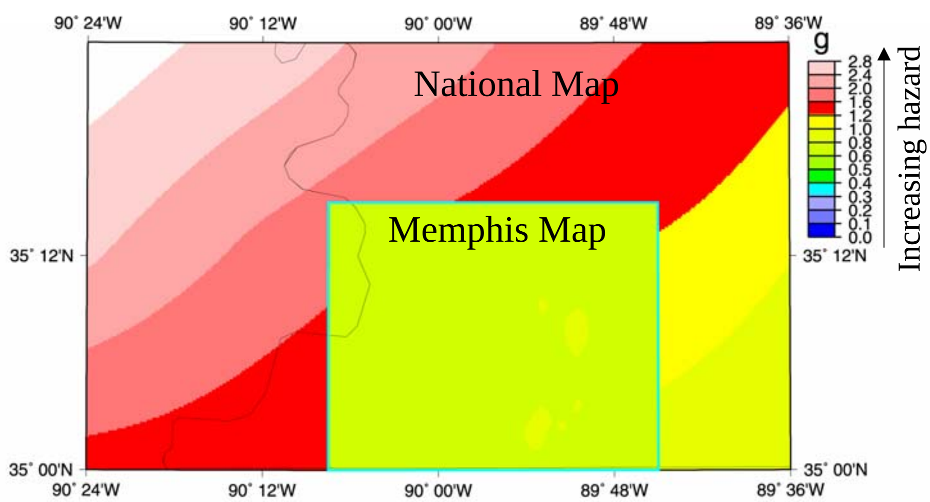
Comparison of National and Memphis Seismic Hazard Maps

- Periods:
  - PGA
  - 0.2 s Sa
  - 1.0 s Sa

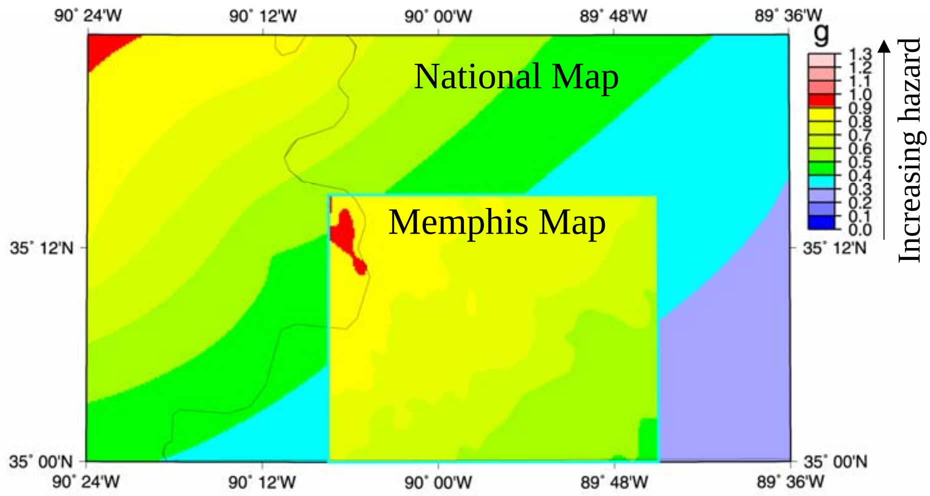
At PGA (peak ground acceleration), two maps are very similar



Effects of the thick sediment pile beneath Memphis: High frequencies-likely to affect shorter structures (0.2 sec SA)



Effects of the thick sediment pile beneath Memphis: Low frequencies-likely to affect tall and long structures (1.0 sec SA)

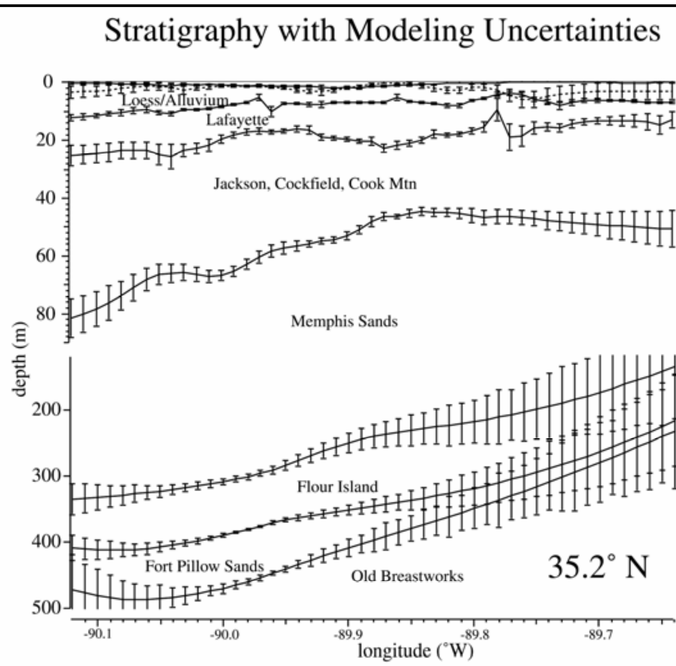


Sources of Uncertainty

- Input Time Series
- Soil Profile
- Dynamic Soil Properties
- Choice of Soil Response Code
- Dynamic Pore Pressure Changes (future)

Input Rock Seismograms

- Used M~7 to M8 records from seven earthquakes and one NMSZ synthetics database:
  - 1989 M6.9 Loma Prieta - G01
  - 1992 M7.1 Cape Mendocino - CPM
  - 1992 M7.3 Landers - JOS
  - 1995 M6.9 Kobe - KJM
  - 1999 M7.4 Kocaeli - GBZ, IZT
  - 1999 M7.6 Chi Chi - TCU
  - 1999 M7.1 Duzce - 1060
  - Atkinson and Beresnev, 2002 - M7.5, M8.0



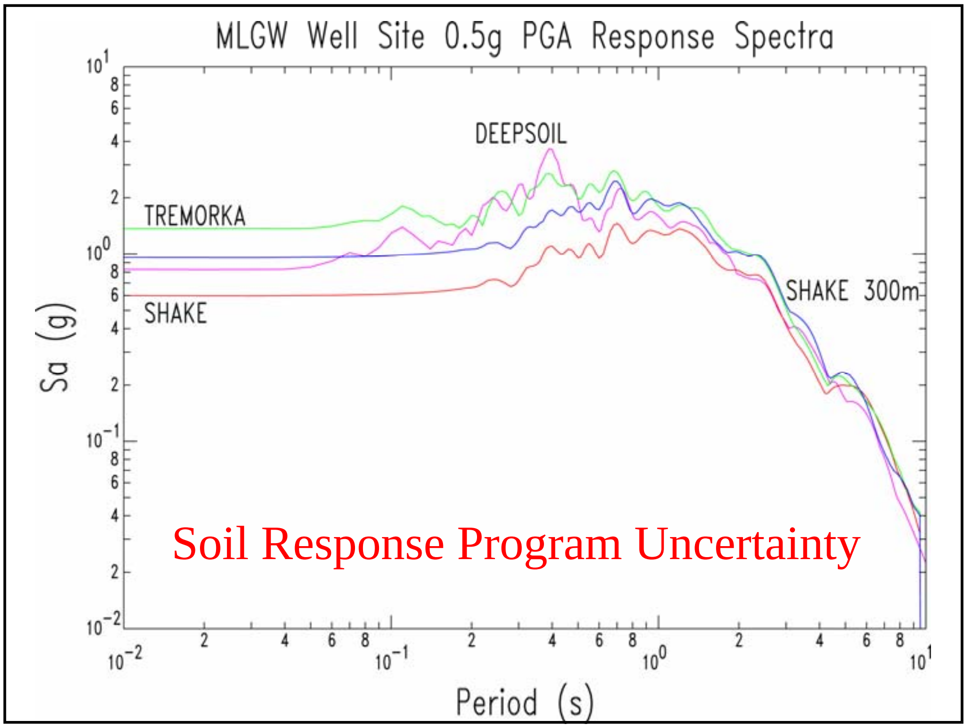
Gomberg et al. 2003

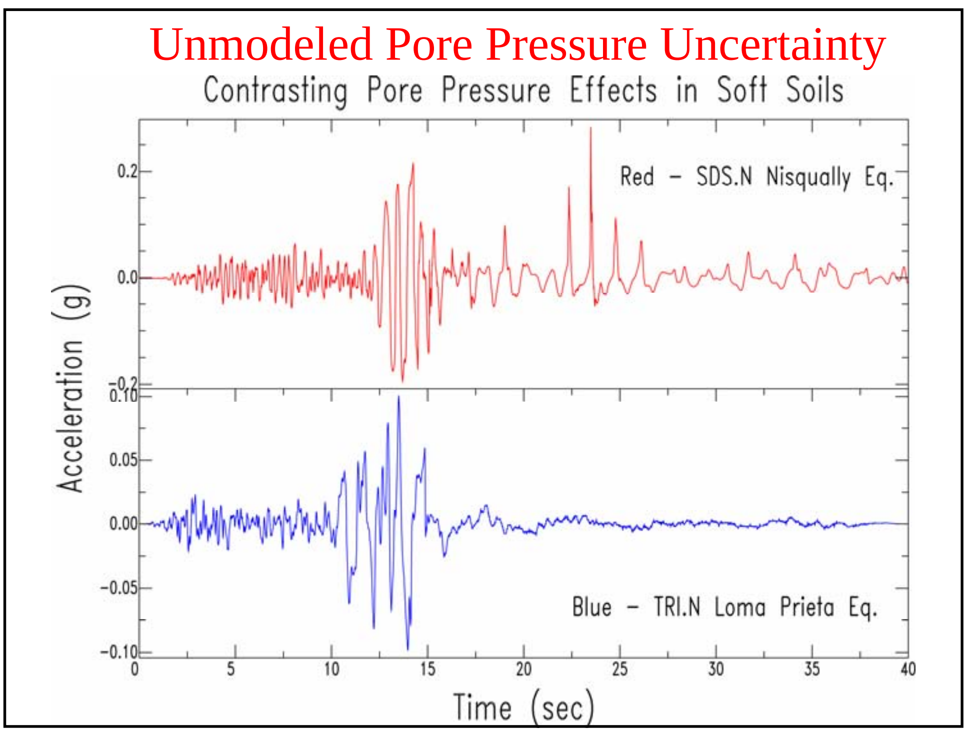
Vs Uncertainty (m/s)

Alluvium	169. ± 24.
Loess	191. ± 35.
Lafayette Sand & Gravel	268. ± 72.
Upper Clairborne Clay	360. ± 50.
Memphis Sand	550. ± 200.
Flower Island Clay	675. ± 100.
Fort Pillow Sand	775. ± 50.
Old Breastworks Clay	850. ± 50.
Cretaceous Sediments	1175. ± 125.
Paleozoic Limestones	3400. ± 150.

Dynamic Soil Properties

- No measurements for Mississippi embayment
- EPRI (1993) modulus and damping curves with their ln sd of 0.35

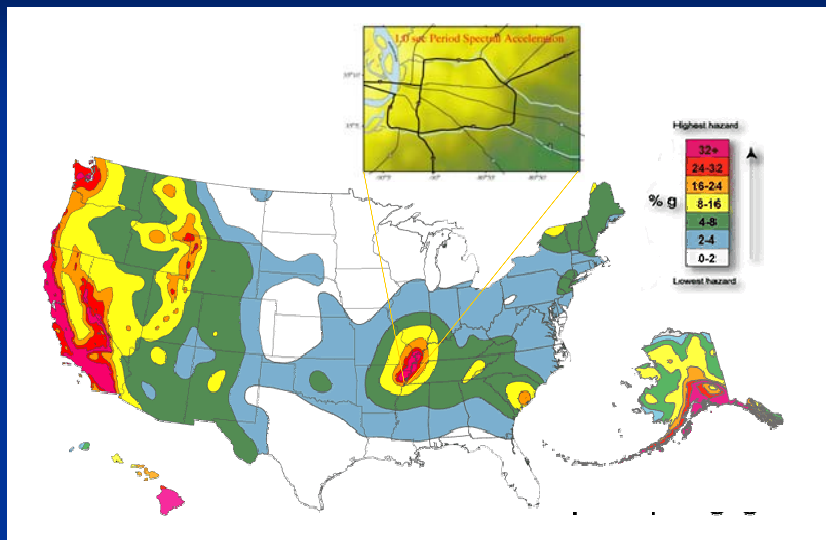

MLGW Well Site 0.5g PGA Response Spectra
DEEPSOIL
TREMORKA
SHAKE
SHAKE 300m
Soil Response Program Uncertainty
Sa (g)
Period (s)


Unmodeled Pore Pressure Uncertainty
Contrasting Pore Pressure Effects in Soft Soils
Red – SDS.N Nisqually Eq.
Blue – TRI.N Loma Prieta Eq.
Acceleration (g)
Time (sec)

Summary of Uncertainties (ln sd)

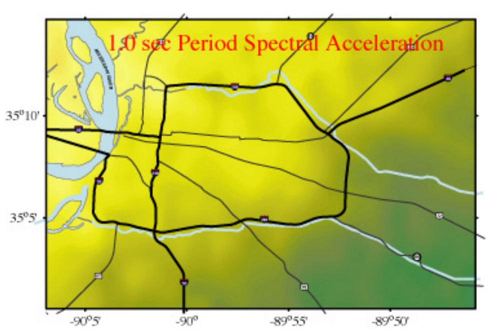
Type\ Sensitivity	PGA	0.2 s	1.0 s
Overall	0.2-0.5	0.1-0.4	0.1-0.4
Input Time Series	0.2-0.3	0.1-0.3	0.1-0.3
Soil Profile (Vs)	0.1-0.2	0.1-0.2	0.1-0.2
Dyn. Properties	0.03-0.3	0.03-0.2	0.03-0.3
Top Layer Lithology	< 0.02	≤ 0.08	≤ 0.03
Soil Response Code	median ranges ± 50 %		
Pore Pressure	significant but not modeled yet		

National vs. Local Maps



National vs. Local Maps

Urban hazard maps may be probabilistic or deterministic (i.e., use a scenario).



Who might use them?

1998: Three Urban Earthquake Hazard Maps Planned

Why Memphis?

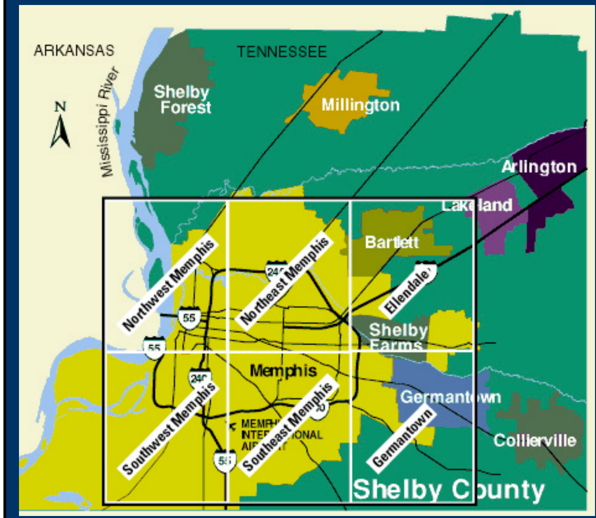
- Typical of the central and eastern U.S.
  - few seismically engineered buildings and infrastructure
  - dense urban population near major seismogenic faults
  - Sits on a very thick pile of Mississippi River sediments
- Closest major urban area to the New Madrid seismic zone
- A sound scientific foundation had already been established in the region

USGS
science for a changing world
Memphis/Shelby Hazard Mapping Project

Advisory Board

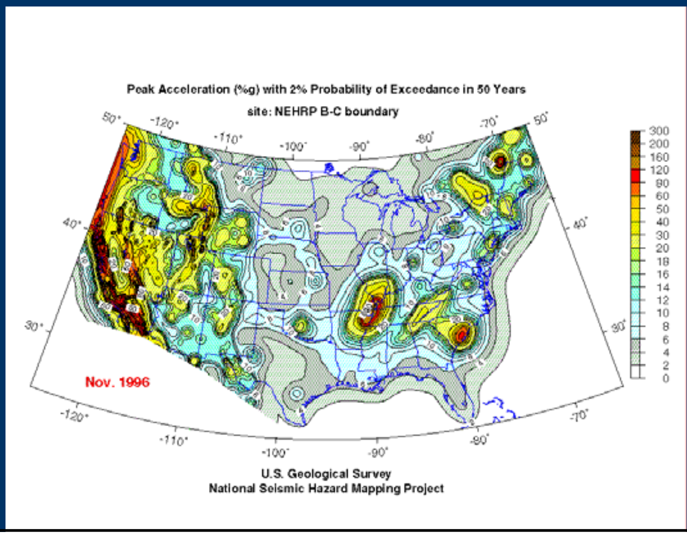
- Chosen from users, others with experience outside the region, universities, consultants, government, including: Utilities, Insurance, Emergency Management, City and County Government, Red Cross, Utilities

USGS
science for a changing world
Memphis/Shelby Hazard Mapping Project

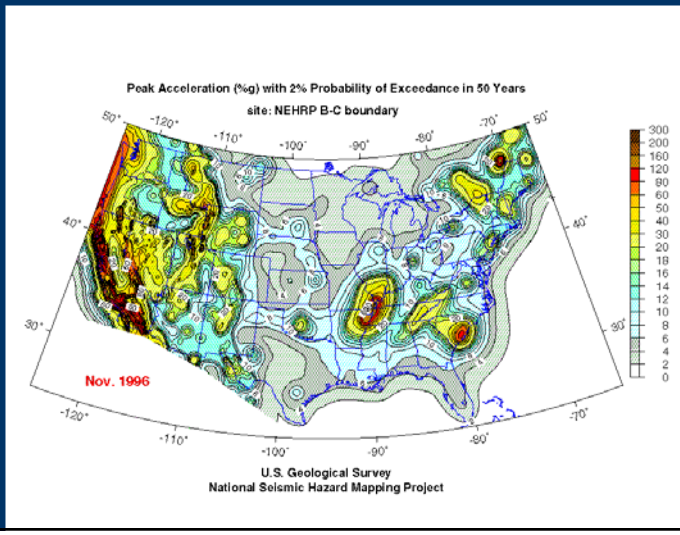


Map Area

Memphis maps are consistent with USGS National Probabilistic Seismic Hazard Maps



Differs from the National map in the addition of local soil conditions

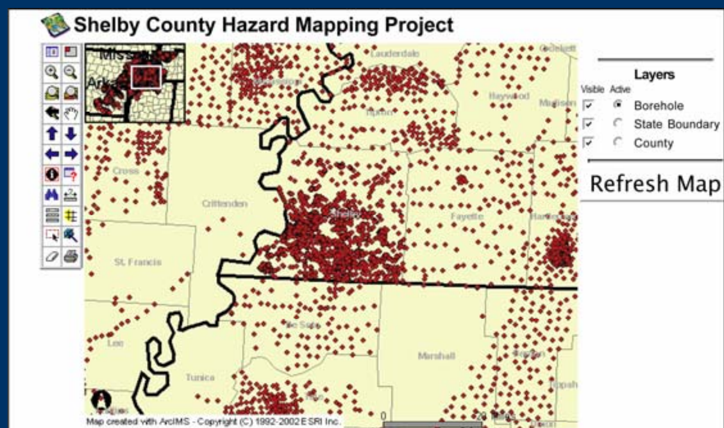


Products include

- Online database of all available subsurface information
- Surficial geological maps of all quads
- Probabilistic ground motion maps (2% chance of exceedance in 50 y; PGA, 0.2 sec, 1.0 sec)
- Scenario ground motion maps (repeat of 1811-1812 New Madrid; **M** 6.0 near Memphis)
- Liquefaction hazard maps

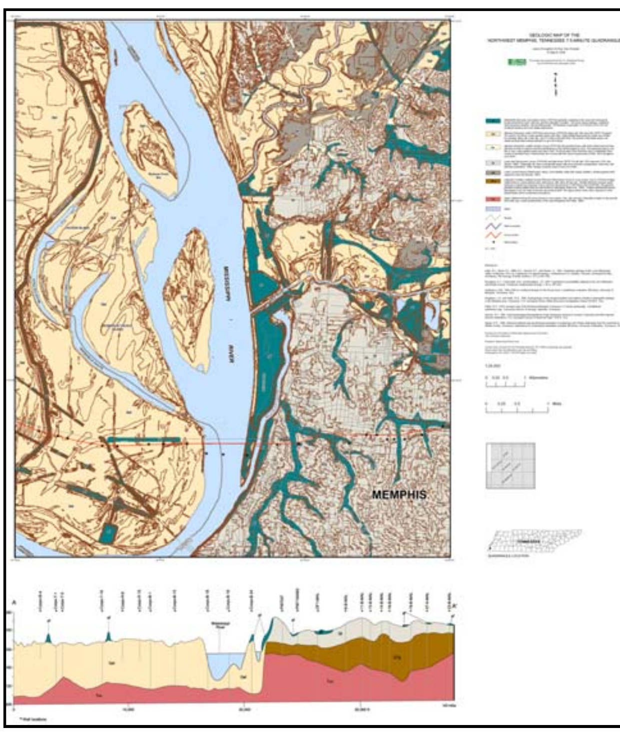
All products will be available digitally

Online database of all available subsurface information: COMPLETE



Borehole

Rec	FID	#SHAPE#	ID	INDEX_ID	LONGITUDE	LATITUDE	ELECTRIC	GEOLOGIST	DRILLER	REPORT	BOREHOLE	MAP	N_A
1	5011	[point]	5013	TN157_000371	-89.736472	35.194533	y						
2	5601	[point]	5603	TN157_000963	-89.732183	35.197689					y		
3	5602	[point]	5604	TN157_000964	-89.732183	35.197789					y		
4	5603	[point]	5605	TN157_000965	-89.732083	35.197789					y		

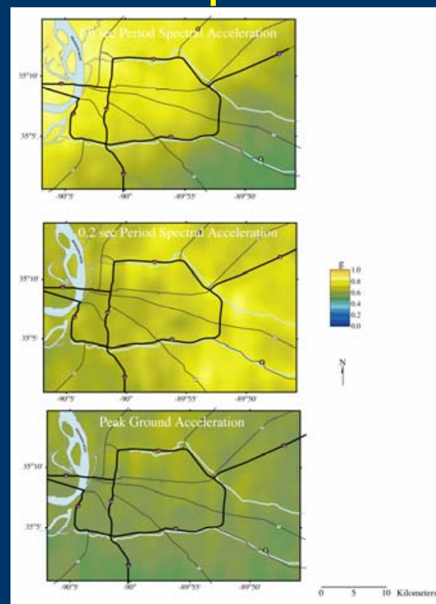


Surficial geological maps: Completed and online

Memphis Northwest Broughton and Van Arsdale, 2004

Ground motion maps

- All ground motion calculations complete (probabilistic and scenario)
- Map layout being finalized
- User guides in preparation

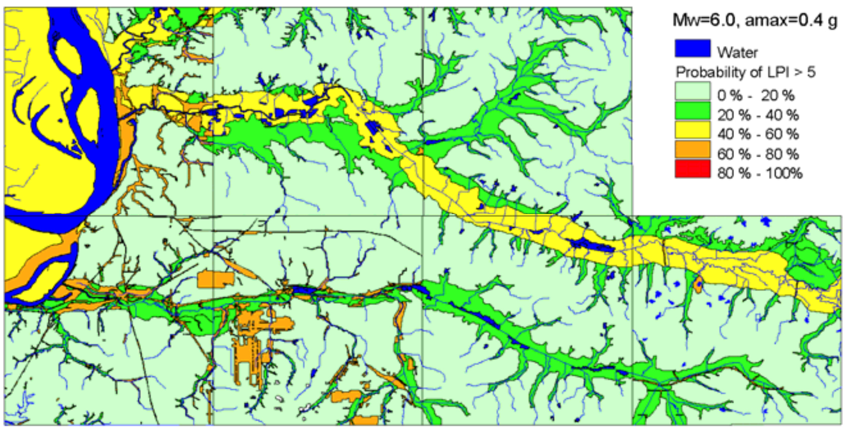


Liquefaction Hazard Maps: Winter/04

- Use engineering data (CPT and SPT) to characterize geologic units
- Factor of safety calculated as a function of depth
- Liquefaction potential index used measure of liquefaction susceptibility for given level of shaking and earthquake magnitude

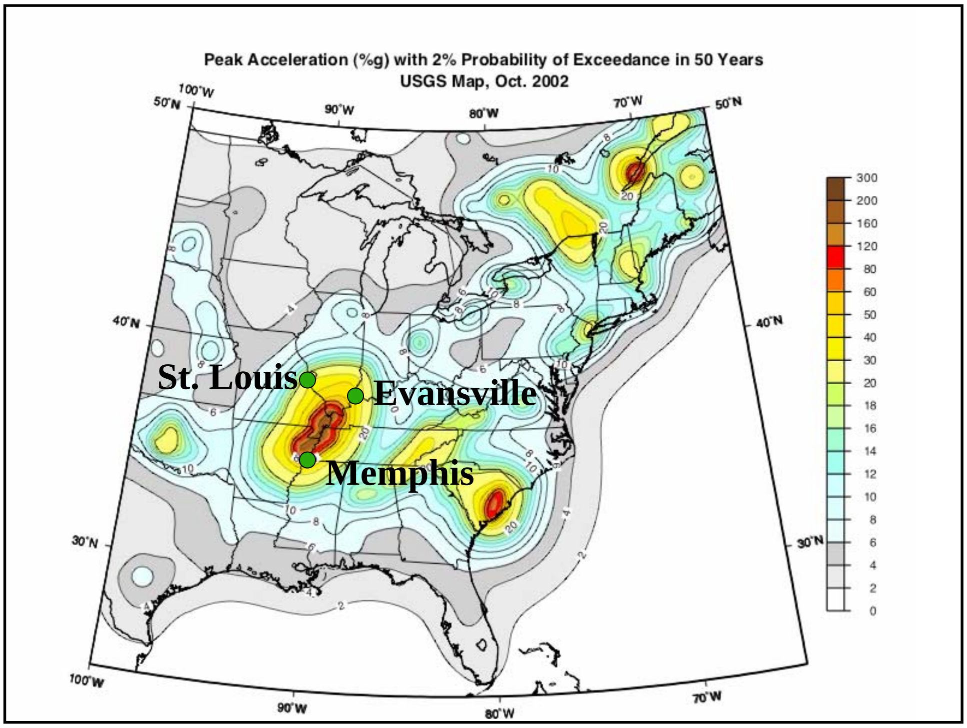
Work by Glenn J. Rix and Salome Romero-Hudock, Georgia Institute of Technology.

Liquefaction Hazard Maps: Winter/04



Byproducts of the Process

- Brought many groups together (engineers, emergency planners, earth scientists, utilities)
- Research and dozens of publications on
  - Central U.S. earthquake recurrence, magnitudes, and hazard
  - Central U.S. tectonics
  - New logic tree for hazard analysis
  - Improved understanding of uncertainties
  - Non-linear soil response
- Spawned a desire for maps by other communities



St. Louis and Evansville

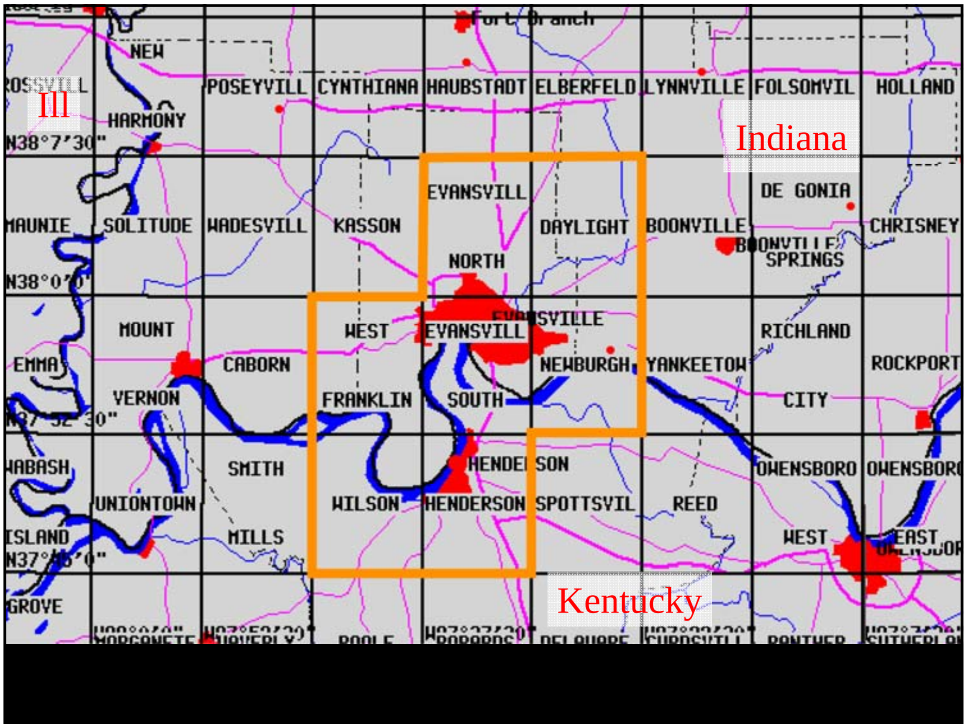
- Apply lessons learned to other central U.S. urban areas and increase local ownership in the mapping process
- St. Louis and Evansville each ready to move forward on hazard maps
- At Little Rock 5-Year Planning Meeting, decided to go forward on both in spite of limited funding

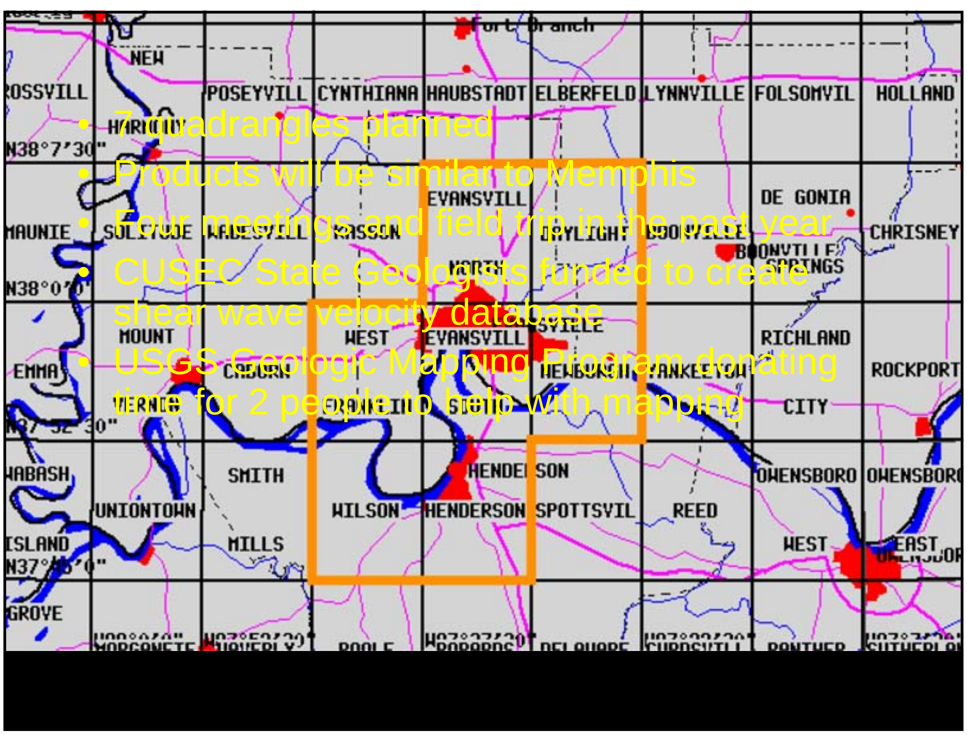
St. Louis Area Map

- Largest metropolitan area in the region
- Hazard from New Madrid seismic zone and local sources
- Geology more complex than Memphis
- More local leadership and participation by Missouri and Illinois Surveys
- Surficial Geology completed on Illinois side
- Working group formed
- Contacts: Phyllis Steckel and Buddy Schweig

Evansville, Indiana

- Small urban area with an extremely proactive business and government community
- Hazard from Wabash Valley seismic zone, News Madrid seismic zone, and other local sources (recent M4.5 earthquake with light damage)
- Much geological and geotechnical data already collected (mapping in progress by KGS, IGS, USGS)
- Local leadership and participation by Indiana, Kentucy, and Illinois Surveys
- Working group formed
- Contacts: Dave Williams (KGS) , Joan Gomberg (USGS), Christine Martin (Southwest Indiana Disaster Resistant Community Corp)


Ill
Indiana
Kentucky
NEW
POSEYVILL
CYNTHIANA
HAUBSTADT
ELBERFELD
LYNNVILLE
FOLSOMVIL
HOLLAND
HARMONY
EVANSVILL
DE GONIA
MAUNIE
SOLITUDE
WADESVILL
KASSON
DAYLIGHT
BOONVILLE
CHRISNEY
NORTH
SPRINGS
MOUNT
WEST
EVANSVILL
RICHLAND
EMMA
CABORN
NEWBURGH
YANKEETOW
ROCKPORT
VERNON
FRANKLIN
SOUTH
CITY
WABASH
SMITH
HENDERSON
OWENSBORO
OWENSBORO
UNIONTOWN
WILSON
HENDERSON
SPOTTSVIL
REED
ISLAND
MILLS
WEST
EAST
GROVE


• 7 quadrangles planned
• Products will be similar to Memphis
• Four meetings and field trip in the past year
• CUSEC State Geologists funded to create shear wave velocity database
• USGS Geologic Mapping Program donating time for 2 people to help with mapping

Some things we have learned

- Involvement of local users and researchers at earliest stages is critical if the results of the map are going to be accepted
- Be flexible
  - Each city has different circumstances
  - The pace of work is subject to the availability of funding and people
- We have successfully used these hazard map products to drive central U.S. earthquake research in a more directed way than ever before

Special Zones