Meeting for the Central and Eastern United States (CEUS) Earthquake Hazards Program—October 28–29, 2009

Fogelman Conference Center, University of Memphis, Memphis, Tennessee

By Martitia Tuttle, Oliver Boyd, and Natasha McCallister

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List of Abbreviations

AD	Anno Domini
AMS	Accelerator Mass Spectrometry
ANSS	Advanced National Seismic System
ANT	Advanced Nuclear Technology
APC	Action Plan Committee
BP	Before Present
CERI	Center for Earthquake Research and Information
CEUS	Central and Eastern United States
CEUSAC	Central and Eastern United States And Canada
CEUS-SSC	Central and Eastern United States Seismic Source Characterization project
CGPS	Continuous Global Positioning System
CMS	Conditional Mean Spectra
CORS	Continuously Operating Reference Stations
COSMOS	Consortium of Organizations for Strong Motion Observation Systems
CPT	Cone Penetration Test
CS	Cellular Seismology
CUS	Central United States
CUSEC	Central United States Earthquake Consortium
CUSSO	Central United States Seismic Observatory
CUSVM	Central United States Velocity Model
DOE	Department of Energy
EAEHMP	Evansville Area Earthquake Hazards Mapping Project
EHP	Earthquake Hazards Program
ENA	Eastern North America
EPRI	Electric Power Research Institute
ESMA	EarthScope in Mid America
ETAS	Epidemic-Type Aftershock Sequence
ETSZ	Eastern Tennessee Seismic Zone
FA	Flexible Array
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GAMA	Global Position System Array for Mid America
GSC	Geological Survey of Canada
GIS	Geographic Information Systems
GMPE	Ground Motion Prediction Equation
GPS	Global Positioning System
H/V	Horizontal divided by Vertical ground motion
InSAR	Interferometric Synthetic Aperture Radar
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Centre
LiDAR	Light Detection and Ranging
LLNL	Lawrence Livermore National Laboratory
LNG	Liquefied Natural Gas
LPI	Liquefaction Potential Index
MAEC	Mid America Earthquake Center

Mmax	Maximum Magnitude
MoDOT	Missouri Department of Transportation
MSFS	Motagua-Swan Fault System
MS&T	Missouri University of Science and Technology
MT	Magnetotelluric
NAM	North America
NCEER	National Center for Earthquake Engineering Research
NEDB	National Earthquake Database
NEES	Network for Earthquake Engineering Simulation
NEHRP	National Earthquake Hazard Reduction Program
NGA	Next Generation of Ground Motion Attenuation Models
NMSZ	New Madrid Seismic Zone
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
NVT	Non-Volcanic Tremor
OSL	Optically Stimulated Luminescence
PAGER	Prompt Assessment of Global Earthquakes for Response
PASSCAL	Program for Array Seismic Studies of the Continental Lithosphere
PBO	Plate Boundary Observatory
PGA	Peak Ground Acceleration
PPRP	Participatory Peer Review Panel
ReMi	Refraction Microtremor
Sa	Spectral Acceleration
SASW	Spectral Analysis of Surface Waves
SCPT	Seismic Cone Penetration Test
SCR	Stable Continental Region
SEMA	Missouri State Emergency Management Agency
SLAEHMP	St. Louis Area Earthquake Hazards Mapping Project
SLU	St. Louis University
S&ME	Soil and Material Engineers, Inc.
SOG	Seismicity Owners Group
SPT	Standard Penetration Test
SRFZ	Saline River Fault Zone
SSHAC	Senior Seismic Hazard Assessment Committee
SUSN	Southeastern United States Network
TA	Transportable Array
TI	Technical Integration team
UBC	Uniform Building Code
USArray	United States Array
USGS	United States Geological Survey
VGDB	Virtual Geotechnical Database
VOAD	Voluntary Organizations Active in Disasters
Vp	P-wave velocity
Vs	Shear wave velocity
Vs30	Average shear wave velocity in the upper 30 meters

WPC	Wright Padgett Christopher, Inc.
WPP	Wave Propagation Program
WVSZ	Wabash Valley Seismic Zone

Meeting for the Central and Eastern United States (CEUS) Earthquake Hazards Program—October 28–29, 2009

Fogelman Conference Center, University of Memphis Memphis, Tennessee

By Martitia Tuttle,[1] Oliver Boyd,[2] and Natasha McCallister[3]

Introduction

On October 28th and 29th, 2009, the U.S. Geological Survey (USGS) Earthquake Hazards Program held a meeting of Central and Eastern United States (CEUS) investigators and interested parties in Memphis, Tennessee (Tenn.). The purpose of the meeting was to bring together the CEUS earthquake-hazards community to present and discuss recent research results, to promote communication and collaboration, to garner input regarding future research priorities, to inform the community about research opportunities afforded by the 2010–2012 arrival of

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EarthScope/USArray in the central United States, and to discuss plans for the upcoming bicentennial of the 1811–1812 New Madrid earthquakes. The two-day meeting included several keynote speakers, oral and poster presentations by attendees, and breakout sessions. The meeting is summarized in this report and can be subdivided into four primary sections: (1) summaries of breakout discussion groups; (2) list of meeting participants; (3) submitted abstracts; and (4) slide presentations. The abstracts and slides are included "as submitted" by the meeting participants and have not been subject to any formal peer review process; information contained in these sections reflects the opinions of the presenter at the time of the meeting and does not constitute endorsement by the U.S. Geological Survey.

Acknowledgments

We wish to thank Tom Pratt for a thorough review and Jill McCarthy and Amber Irish for time spent addressing Tom's comments and improving the manuscript.

Images on the front cover: (left) Seismic-hazard map from the USGS hazard mapping website, (upper right) detail of seismic hazard in New Madrid from USGS hazard mapping website, and (lower right) seismicity in New Madrid region from U.S. Geological Survey Fact Sheet 2009–3071.

Report on Earthquake Hazards Program Meeting

Meeting Summary

In late October 2009, an Earthquake Hazards Program meeting of CEUS investigators and interested parties was held in Memphis, Tenn. The goal of the meeting was to bring together the CEUS earthquake-hazards research community to present and discuss recent research results, to promote communication and collaboration, to garner input regarding future research priorities, to inform the community about research opportunities afforded by the 2010–2012 arrival of EarthScope/USArray in the central United States, and to discuss plans for the upcoming bicentennial of the 1811–1812 New Madrid earthquakes. The two-day meeting was attended by about 100 people from universities and consulting firms from across North America. Major institutions represented included the U.S. Nuclear Regulatory Commission, State Geological Surveys of states in the central United States, the Central U.S. Earthquake Consortium (CUSEC) and the West Tennessee Seismic Safety Commission. In addition, scientists from a number of USGS offices also attended.

The meeting was structured around short oral presentations (10-minute limit) and several poster sessions; there were also several longer invited presentations. Invited speakers included David Applegate, USGS Senior Science Advisor for Earthquake and Geologic Hazards; Chuck Langston, Director of the Center for Earthquake Research and Information (CERI); and Anne Trehu, Director of the EarthScope National Office. David Applegate spoke about "Earthquake Hazards Program Priorities and Future Directions"; Chuck Langston explored "Research Challenges in the CEUS"; and Anne Trehu described various aspects of EarthScope and related research opportunities. In addition, Chris Cramer of CERI, Jim Wilkinson of CUSEC, and Tish Tuttle of the USGS (now at M. Tuttle and Associates) briefed the meeting on preparations, activities, and products planned for the Bicentennial of the 1811–1812 New Madrid earthquakes.

Investigators gave short oral and poster presentations organized in sessions on the following topics: earthquake sources; earthquake ground motion; paleoseismology; long-term deformation and deformation modeling; the New Madrid seismic zone; the Charleston, South Carolina seismic zone; historical seismicity; seismic velocity modeling and site response; seismic-hazard mapping and engineering applications; and educational outreach. In addition, there were breakout sessions on similar topics during which participants were asked to identify the most pressing earthquake-hazard issues and the most promising ways to address those issues. The session facilitators reported back to the larger group, and research priorities were further discussed. Reports from the breakout sessions are presented below.

The meeting was organized by the USGS staff in Memphis: Tish Tuttle (now at M. Tuttle and Associates), Oliver Boyd, and Natasha McCallister. Steve Horton of CERI and Walter Mooney of the USGS also helped plan, organize and facilitate parts of the meeting. The Central U.S. Multi-Hazards Initiative provided financial support for the meeting.

Breakout Sessions: Input on Research Priorities for the USGS Earthquake Hazard Program

Earthquake Sources and Magnitudes

Facilitator: John Ebel
Co-Facilitator: Sue Hough

Participants: Haydar Al-Shukri, Scott Ausbrooks, Mike Blanpied, Mike Bograd, John Ebel, Sue Hough, Joe Gilman, Peggy Guccione, Dave Hoffman, Shannon Mahan, Steve McDuffie, Walter Mooney, Kent Moran, Jerry Prewett, Alan Ruffman, John Tinsley, Tish Tuttle, Rus Wheeler

The purpose of this breakout session was to identify the important research questions concerning earthquake sources and earthquake magnitudes in the CEUS, and to consider possible ways to address these research questions. The discussion quickly focused on the importance of historical earthquake data (and by extension, paleoseismological earthquake data) to learn about seismic source zones in the CEUS. This focus emerged because most knowledge regarding seismic source zones in the CEUS comes from historic earthquake information, due to the relatively low level of instrumentally recorded earthquakes throughout the region. The participants in the discussion agreed that historic earthquake research is not adequately emphasized or funded. In particular, several participants felt that there is much to learn about historic earthquakes through additional research. Many newly identified historical earthquakes have been identified through digital archive searches of old newspapers. Furthermore, historical CEUS earthquake research over the past decade has upgraded the sizes of some earthquakes while decreasing the sizes of others. Mistaken earthquakes, triggered earthquakes, and non-tectonic seismic events have also been identified. Several participants felt strongly about the need for a centralized public database of original historic earthquake reports, perhaps maintained by the USGS.

The discussion also highlighted the need for more paleoseismic work in the region, especially for source zones where there currently are few or no known paleoseismological indicators of past earthquakes. One example is the eastern Tennessee seismic zone. The group did some brainstorming about new research techniques, such as age-data indicators in the geology or high-resolution LiDAR (Light Detection And Ranging) surveys that might yield new information about the active seismotectonic sources in the CEUS. It was generally acknowledged that it might be challenging to receive positive results from these new research techniques in the short term. One caveat is that these methods might reveal structures that are unrelated to seismogenesis. There was also a suggestion that additional bedrock-geology mapping may be needed in some areas.

The discussion briefly touched on how to estimate magnitudes for earthquakes in the CEUS. Changing instrumentation requires careful calibration to ensure consistent magnitude estimates. Also, moment magnitude is the desired magnitude scale for earthquakes of all sizes, but reliable moment magnitudes can only be computed for earthquakes about M 4.5 in the region; methods must be developed to extend the moment magnitude calculations down to lower magnitudes. Finally, research must continue into the question of how to estimate the magnitudes of historic earthquakes.

Below is a summary of the major discussion points during the breakout session. For each discussion point a group vote was taken to assign a high (H), medium (M), or low (L) priority.

Priority List (H, high; M, medium; L, low):

- (H) Macroseismic information should be investigated and Spanish/foreign archives should be considered. Special attention should be paid to site effects. Calibration events may help investigators to evaluate historic information.
- (H) Paleoliquefaction evidence should be studied for other source zones. Investigators should document evidence and or the lack of evidence of strong ground shaking. Caves can be explored as a possible new area to find constraints on past ground-shaking information.
- (H) A database of age results from liquefaction events, cave formations, landslides, etc., will be helpful to future investigators.
- (H) Targeted LiDAR may lead to identification of earthquake related surface features. Possible targets are New England and central New Hampshire. However, the structure seen in LIDAR may be unrelated to seismogenesis.
- (M) Offshore sources should be more closely considered including the Atlantic and Gulf Coast. For example, can tsunami deposits and turbidite deposits be found and can they be used to constrain earthquake hazard? In New England, are there earthquakes that extend onto the continental slope and are they associated with submarine channels in sediments? What is the cause of 1800s/1890s increased seismicity around southwest Nova Scotia? Would an ocean-bottom seismometer deployment be helpful?
- (L–M) For site response, surface geological mapping including depth to bedrock is essential. This work would provide an important partnership with the states.
- (L) The use of geological indicators may give some insight into past seismic activity. Some examples include age-dating of landscapes to learn about the long-term landscape evolution (for example, cosmogenic dating for degrading of landscapes may not be ideal for trenches/CEUS) and river migration.
- (L) Oil company reflection images and other active source studies of the subsurface can be obtained to help elucidate possible active structures. However, oil company data are usually proprietary and cannot be published.

Ground Motion, Near-Surface Velocity Structure, and Site Amplification

Facilitator: Gail Atkinson
Co-Facilitator: Rob Williams

Participants (partial list): John Ake, Martin Chapman, Jer-Ming Chiu, Chris Cramer, Art Frankel, Dave Gaunt, Youseff Hashash, Tim Larson, Shahram Pezeshk, Larry Salomone, Arash Zhandieh, Zhenming Wang

This group held a wide-ranging discussion of earthquake ground motions, seismic velocity structures, and site amplification in the CEUS. The discussion focused on several issues, including: weaknesses in the understanding of CEUS attenuation, a lack of knowledge about the site conditions for seismograph sites that would be used to refine attenuation estimates, strong support for efforts to collect more data on near-surface seismic velocities and establishment of a publicly available database of existing seismic velocity data, and a common interest in the installation of more seismographs to fill holes in the coverage of existing networks. Another concern that arose was the need to review the applicability of western-United-States-derived relations on attenuation, non-linearity, and stress drop to the CEUS.

Attenuation Issues (High priority)

The discussion began with group recognition of the need for improved attenuation models (and verification) at all distance scales, especially less than 70 kilometers (km), but also through the transition zone and out to regional distances. The regional variability of attenuation is not well constrained in areas like New Madrid, southeastern Canada, and the northeastern United States. More ground-motion data from the CEUS is needed to address this problem; ground-motion information from smaller magnitude earthquakes is available and needs to be collected and analyzed. A project entitled Next Generation Attenuation for the central and eastern United States (NGA East) is aimed at collecting currently available data, including those across stable continental regions (SCRs). A top priority of NGA East is to make the best use of such data. Although more instruments are now in place thanks to the Advanced National Seismic System (ANSS), even denser networks are still needed in order to collect more data at a broader range of distances. There was brief discussion concerning the establishment of a better connection between "attenuation" in seismological terms—that is, wave propagation and seismic phases—versus engineering focus on decay of amplitudes. Ultimately, we need a deeper physical understanding of the bridge between seismology and engineering.

Instrumentation (High priority)

As noted above, the consensus of the group was that more seismic-monitoring stations are needed to collect ground-motion data and constrain attenuation relations in the CEUS. The arrival of EarthScope instrumentation, which is rolling through the region over an 18-month time period as the array moves from the West Coast to the East Coast, provides a short-term opportunity to collect relatively dense seismic data. Moreover, if a funding source can be found to purchase the equipment and operate the stations long term, these instruments could be kept permanently. The Incorporated Research Institutions for Seismology (IRIS) has a formal policy to allow groups to purchase EarthScope instruments. The instruments are left in the ground, and IRIS is reimbursed for the cost of a new replacement instrument. Many stations have already been left in place under this program.

One difficulty in trying to find a benefactor for new permanent seismic stations is the lack of detailed operations and maintenance costs for the EarthScope sites. The concern was also expressed that the time to act is limited, and that the instruments may already be removed prior to any decision making. There was some discussion of the possibility of purchasing the EarthScope instrumentation after the Transportable Array experiment is over; another suggestion was to take over operation of the vaults for later installation and equipment purchase. It was also noted that the current sampling rate for USArray may not be high enough for earthquake-engineering purposes. It would be better to have accelerographs co-located with broadband instruments to receive fuller data sets because broadband instruments clip at close distances and thereby preclude the possibility of improved attenuation relations at less than 70 km.

Site Effects (Low priority for borehole arrays. High priority for basic data on velocity structure at existing stations)

There was broad agreement that the data from the current Central U.S. Seismic Observatory (CUSSO) downhole seismograph installation in southwestern Kentucky is crucial for understanding CEUS ground motions, especially for the New Madrid and Wabash Valley seismic zones. The CUSSO data should be made publicly available in near real time and used to look at site effects.

In an ideal science-funding world, the group would support the need for borehole arrays of seismometers to gain information on site effects. The information could be used for source studies if dense arrays can be deployed. Borehole array depths stretching as far as 1 km would be ideal but very expensive. The borehole arrays would be extremely useful in understanding soil nonlinearity. We are unaware if soil nonlinearity models from the western United States are applicable to eastern settings such as the Mississippi embayment, and more testing of the applicability of nonlinear models for eastern stratigraphy is required.

There was a strong consensus that basic site information (for example, seismic velocity and surficial geology) is needed for characterizing existing seismograph stations. In the CEUS, only about 20 percent of seismic stations have site-characterization measurements. If site conditions at existing stations are poorly known, then new models of attenuation and non-linearity will be adversely affected. The group discussed how NEHRP and similar programs can be leveraged to obtain this type of information; one potential program that could support such an effort might be the Nuclear Regulatory Commission's NGA East project. The group agreed that site-characterization studies of seismograph stations should be given a high priority; fortunately, efforts are being made in the west through American Recovery and Reinvestment Act stimulus funding to collect this information. Because of limitations in site-characterization methodologies, it was recommended that two techniques (or more) be used (for example, Refraction Microtremor (ReMi) and Spectral Analysis of Surface Waves (SASW) or reflection/refraction).

Liquefaction is another big issue that falls under the category of site effects. Because site-specific data and sophisticated laboratory studies are needed to assess liquefaction probabilities, the liquefaction problem is difficult to address regionally. Liquefaction studies are typically only done for high-value facilities.

Velocity Model (Moderate priority for 3D velocity models.)

The discussion group supported the acquisition of Vs30 seismic velocity data that can be used to address such problems as nonlinear soil behavior. They further recommended that a greater emphasis be put on acquiring deeper P- and S-wave velocity profiles that could extend to the base of sedimentary basins. Currently in the Mississippi embayment there are about 1,000 shallow surveys from about 30- to 50-meter (m) depth, but far fewer measurements that reach 100 m or more. The deeper seismic-velocity information is needed, particularly near the center of the basin, to improve ground-motion simulations and better constrain time histories.

In addition to the need for more individual (1-D) seismic velocity profiles, there was recognition that a 3-D seismic velocity model is also needed. Currently, USGS scientists are developing such a model (referred to as a “community velocity model”) for the Mississippi embayment. This model extends from just north of St. Louis, Missouri, and Evansville, Illinois, to just south of Memphis, Tennessee, and Little Rock, Arkansas.

Time History Models and Scaling (Moderate priority)

Scaling of time histories from earthquakes in the CEUS to match a target spectrum for the design of engineered structures is an engineering issue of importance where seismological input such as spectral acceleration and duration is necessary. This area has had little focus in the central and eastern United States, and while it was not a focus of the meeting, it is an issue that needs to be addressed.

Source Issues (High priority)

The group brainstormed a number of questions on source issues:

1. How do we take knowledge of small earthquakes and scale up to larger events?
2. Can we use a constant-stress model to scale from small to large earthquakes?
3. Is the variability of stress drop bigger in eastern North America than in the west?
4. What is the regional variability of stress drop, if any?
5. How can we better understand the source processes and how they translate to models of the amplitude spectrum (or other characterizations)?

See discussion for “Earthquake Sources and Magnitudes” breakout session.

Numerical and Analytical Models (Moderate priority)

There was a short discussion regarding whether or not we are happy with the tools we have to interpret seismic data. This discussion spanned a range of issues: source scaling, wave propagation, site response, and nonlinearity. It was agreed that it is beneficial to improve modeling methods in anticipation of testing them as data are gathered. For example, when modeling 3D propagation of Lg waves, significant (computing) resources are required. In general, there is a gap in many areas between standard practice (for example, the use of the program “Shake” for site response) and other procedures that may be more appropriate.

Our priority list of activities for the USGS includes:

- Improved attenuation models (and verification) at all distance scales, especially less than 70 km, but also through the transition zone and out to regional distances. We need to address the question of whether attenuation varies regionally or is the same in the central United States compared to the eastern United States and Canada.

- Increased numbers of permanent seismograph installations to fill in monitoring holes and increase the density of the network.
- More ground-motion data to resolve attenuation issues; even data at smaller magnitudes are valuable and need to be collected and analyzed. We need to address the question of how strong and widespread non-linear effects will be in soft sediment areas.
- Analysis of site effects at the current CUSSO borehole seismometer station installation in Kentucky. For this to happen, the community needs access to the CUSSO data, which is currently not available to the public.
- More site-specific seismic velocity and geology information at existing seismograph stations. In addition, deeper penetrating P- and S-wave velocity profiles are needed—not just Vs30.
- More complete information on the basin velocity structure extending to as great a depth as possible, but to at least 200 m.
- A USGS-sponsored seismic velocity and/or site characterization database.

Geodesy and Modeling Ground Deformation

Facilitator: Michael Hamburger
Co-Facilitator: Eric Calais

Participants: Oliver Boyd, Eric Calais, James Davis, Michael Hamburger, Kathryn Hanson, Beatrice Magnani, Mary Parke, Thomas Pratt, Leonardo Ramirez-Guzman, Bob Smalley, Ron Zurawski

The geodesy and modeling ground deformation breakout session addressed the use of measurements of surface deformation to address basic scientific questions and issues related to seismic-hazard mitigation. We considered the quality and quantity of surface-deformation measurements and what could be done to improve their utility. We also considered issues related to modeling surface deformation observations and opportunities for EarthScope.

Two major issues exist with respect to geodesy and estimation of seismic hazards in the CEUS. Most importantly, surface deformation rates in the CEUS are low, and continuous geodetic monitoring has only been available for two decades. Therefore, the signal of strain accumulation that one would expect on active faults (by analogy with plate boundaries) remains elusive. Furthermore, monumentation and data are of variable quality, and high-quality observations are sparse. As a result, substantial uncertainty remains in our understanding of active deformation of the CEUS both in terms of its rate and spatial distribution.

The second major issue concerns a lack of understanding of earthquake processes in an intraplate setting: How do these processes relate to surface deformation? How does deformation vary with space and time? What is driving deformation? How do models of intraplate fault dynamics differ from those operating in interplate settings? A practical implication of this lack of understanding is that it is difficult to properly design geodetic networks to measure a deformation signal that has not yet been observed.

The group recommended several priorities for improving assessment of seismic hazards in the CEUS using geodesy. Specifically, the group suggested that improved density and quality of long-term geodetic observations are needed and that these observations must be coupled with modeling to help guide station deployment and data interpretation. The group recommended development of a comprehensive set of precise geodetic measurements that would provide baseline measurements prior to any future earthquake in the region, re-measurements of existing networks (including New Madrid, Wabash Valley, Charleston), improvement of monumentation for existing permanent networks (including Continuously Operating Reference Stations (CORS), National Oceanic Atmospheric Administration, Federal Aviation Administration), and continuous monitoring of data quality at existing permanent GPS networks. More specific questions and issues raised during the breakout session are provided below.

Large-scale scientific questions identified are:

- What are the spatial variability and rate of deformation in the CEUS? How do spatial variability and rate of deformation relate to seismic sources?
- How do earthquake processes in the CEUS relate to our fundamental understanding of earthquake physics?

- What are the local deformation patterns associated with intraplate seismic zones?
- How does background deformation compare inside and outside of intraplate seismic zones?
- What are some fundamental models of an intraplate seismic cycle?
- Is there detectable strain accumulation before large earthquakes in continental interiors?
- How applicable are interplate seismic models to plate interiors?
- Are there distinct processes in intraplate seismic zones?
- How do stresses in the crust relate to deformation processes?
- What are the active seismogenic/inactive structures in intraplate seismic zones?
- How strong are faults in intraplate zones? What can we infer from earthquake stress drop?
- What can we learn from large structures that are inactive (such as the Midcontinent Rift and Grenville Front)? Why are some large structures inactive? Have they been active recently? Will they reactivate?
- What is the relation between stress and strain in continental interiors?
- Does geodesy help to constrain seismic moment release?

Improvements to geodetic networks and data-gathering efforts include:

- Conducting more in-depth analysis of existing geodetic data;
- Expanding geodetic monitoring to include known geologic structures/seismicity areas (for example, Meers Fault, S. Illinois/Fluorspar District, E. Tennessee seismic zone);
- Conducting tests of the stability of North America reference frame;
- Increasing the density of existing permanent geodetic networks with campaign and semi-continuous deployments;
- Building hybrid models of continuous GPS + semi-continuous or campaign GPS;
- Improving CORS network by upgrading, for example, the monumentation (15–20 stations are slated for improvement);
- Improving/expanding the Plate Boundary Observatory (PBO) network ($20–30,000/station);
- Re-measuring campaign stations (for example, Northwestern/Jet Propulsion Laboratory (JPL) network);
- Utilizing LiDAR, Interferometric synthetic aperture radar (InSAR), and other geodetic techniques to identify areas of crustal deformation;
- Deploying high-rate GPS gradiometer for intraplate strain measurements.

Modeling issues include assessing:

- Long-term, large-scale tectonic loading;
- Models of local deformation sources (role of density variation, impacts on local strain variability);
- Role of mantle processes as a constraint on intraplate deformation;
- Sedimentary loading, erosion, climate change, hydrologic loading, glacio-isostatic adjustment, lateral mass transfer, and sediment loading at the Gulf of Mexico;
- Time-variable processes;
- Thermal processes;
- Boundary conditions such as driving forces and rheology;
- Additional data such as Vp/Vs ratio and heat flow to constrain rheology in the modeling;

- The possibility of a “Virtual CEUS,” akin to “Virtual California,” where a heterogeneous and complex numerical model of the CEUS is developed to investigate the time evolution of strain and seismic potential;
- Transfer processes to address how deformation at depth is coupled with surface deformation.

Opportunities for EarthScope deployments include:

- Analysis of existing campaign data and the addition of new campaign measurements;
- Linkage with USArray deployments;
- Addition of backbone sites (co-located USArray/PBO sites);
- Modeling of lithosphere dynamics;
- Identification of heterogeneities and their role in intraplate deformation;
- Monument installation for semi-continuous stations;
- Increasing the spatial density of geodetic observations;

Highest Priority Issues for USGS are:

- Development of a comprehensive set of precise geodetic measurements that would provide baseline measurements prior to any future earthquake in the region;
- Re-measurement of existing networks (New Madrid, Wabash Valley, Charleston, etc.);
- Improvement of monumentation at existing networks (CORS, NOAA, FAA, etc.);
- Continuous monitoring of data quality at existing GPS networks.

Intraplate Earthquake Processes

Facilitator: Chris Powell
Co-Facilitator: Heather Deshon

Participants (partial list): Mahari Ayele, Martin Chapman, Randy Cox, Heather DeShon, Margret Guccione, Michael Hamburger, Robert Hatcher, Charles Langston, Michael Towle, Samuel Panno, Miguel Pando, Christine Powell, John Tinsley, Walter Mooney, Russell Wheeler

We posed the following question: why do intraplate earthquakes happen? This led to a lively discussion with a number of consensus opinions. These opinions include the following thoughts: (1) Although the role of plate tectonics in driving intraplate earthquake activity is undeniable, thinking outside of the plate-tectonics box may be necessary to understand why intraplate earthquakes occur where they do. (2) CEUS seismicity appears to concentrate in distinct places; there are enough seismic stations operating such that a uniform distribution of seismic stations with spacing comparable to the New Madrid seismic zone (NMSZ) seismic network would not reveal undetected seismic zones such as the East Tennessee seismic zone (ETSZ), NMSZ, and Charlevoix. (3) Inherited structure in the crust and in the lithosphere from past tectonic events is important and can help us understand why earthquakes concentrate in certain places. (4) Not all inherited structure is equal; this can help us understand why features such as the mid-continent geophysical anomaly are not seismically active. (5) Favorable orientation in the present-day stress field seems to be important, although some historically weak faults that have favorable orientation are not seismogenic. (6) There must be other factors beyond inherited structure that play important roles in earthquake occurrence such as local perturbations in stress, strain and material properties, variations in temperature and the presence of fluids. (7) The recurrence rate of large intraplate earthquakes may be telling us something fundamental about the physics of intraplate earthquakes that we do not understand. (8) Earthquake activity in the CEUS may migrate from place to place or may migrate within a seismic zone. (9) Stalagmite history suggests that the CEUS has experienced significant earthquake activity for at least the last 7,000 years (yr).

We suggest the following priorities for research projects:

- Use Earthscope instrumentation and/or smaller experiments to investigate the presence of inherited structure in the crust and lithosphere. Are there fundamental differences between crustal and lithospheric structure associated with active CEUS seismic zones and places that are aseismic?
- Conduct targeted experiments involving the flexarray, the portable magnetotelluric array, and campaign GPS surrounding active seismic zones to determine if there are distinct differences in crustal rheological properties and composition that make the active portions of the crust "unique." Integrate various data sets to better constrain interpretations.

- Investigate areas of preexisting weaknesses that are currently aseismic (for example, mid-continent geophysical anomaly, Nemaha Ridge, Meers Fault) to assess the differences between these locations and locations of active seismicity.
- Conduct physical and numerical modeling to determine the influence of known structure, intrusions, rates of deformation, and erosion on earthquake occurrence, clustering, and recurrence rates.

We conclude with a very important point: A large role that the USGS can play is providing active sources for the targeted experiments. This includes reflection seismology experiments and participation in flexarray experiments associated with the passage of EarthScope.

Community Velocity Model and Earthquake Simulations

Facilitator: Leo Ramirez-Guzman (Rob Graves was not able to attend)

Participants (partial list): Jer-Ming Chiu, Carlos Huerta, Heather DeShon, Charles Langston, and Leonardo Ramirez-Guzman

The discussion was centered on: (1) the availability of information to adequately model the velocity and density structure of the central United States (CUS), (2) the appropriateness of extrapolating from geologic models, and (3) the ease of modifying and performing simulations using the CUS Velocity Model (CUSVM) currently under development. There was common agreement on the necessity for more velocity measurement campaigns, especially regarding the shallow structure of the region, which influences the inversions that help to constrain the deep structure. Attendees suggested that the CUSVM could be used as the initial condition for detailed local inversions. Participants discussed the usefulness of geologic models as guides in regions where information is scarce; extrapolations made only on geologic information need to be thoroughly tested. The facilitator gave a brief description of the model under development and conveyed information about how easy it would be for the research community to modify and incorporate new information, as well as to test hypotheses of wave propagation in the central United States. The participants proposed desirable tests to the model before it could be used by the earthquake-engineering community in the assessment of seismic hazard.

Our priority list for USGS activities include:

- Support of seismic velocity measurement campaigns;
- Making the CUSVM model available to the community—allowing accessibility and modifications to the model;
- Maintenance and support of wave propagation solvers;
- Incorporation of available fine-scale sediment structures and velocity models generated in different hazard mapping projects;
- Validation of the CUSVM using a well-defined dataset that tests the model’s ability to simulate surface wave dispersion and amplitudes of shear waves—the set could be the 2008 Mt. Carmel and the 1991 USGS explosions experiment;
- Researching attenuation on multiple scales;
- Evaluating the model’s ability to reproduce other datasets, for example, waveform gradiometry, slow deformations, or gravity.

Seismic-Hazard Mapping

Facilitator: Chris Cramer
Co-Facilitator: David Gaunt

Participants: Not provided

The seismic hazards breakout session was a guided discussion on urban hazards maps, seismic-hazard mapping efforts related to the New Madrid Earthquakes Bicentennial, and a listing of possible directions and priorities.

The first issue discussed was the value of the urban seismic-hazard mapping efforts and whether or not they should continue. The suggested subtopics for discussion were: (1) usefulness, (2) data availability, (3) role in building codes, and (4) whether urban hazard mapping efforts should include an assessment of risk in project efforts. The consensus on the usefulness of urban seismic-hazard maps is that they are useful to emergency managers, insurance companies, and engineers; the group therefore concluded that urban seismic-hazard mapping efforts in the CEUS should continue. Concern was expressed that the context and limitations of the maps (not site-specific, among other points) should continue to be emphasized to users. Not all engineers use the urban seismic hazard products, but several do for background material.

Regarding data availability, the consensus was that geological, geophysical, and geotechnical databases should be made available. More detail on site response should be accessible to the engineering community. It would be beneficial to identify ways to extend database availability past the life of a specific project (Memphis in particular). Session participants also suggested maintaining the availability via state geologic surveys and using the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) model of a virtual database center with links to various repositories.

The role of urban hazard maps in building codes (and other regulatory applications) raised several points, including that 1:24,000 quadrangle maps should not be used for site-specific analysis (although they could serve as a guide). The earth science community's responsibility is to produce the "best" hazard maps and allow the engineering community to determine and set the building codes. Another area where urban hazard products could be applied would be the California model of "zone maps" (zones where site-specific determination and mitigation should be considered by developers) for earthquake-related landslide, liquefaction and, shaking hazards. A consideration should be made towards providing more detailed urban seismic-hazard maps that move toward being more site-specific. Limitations of the urban maps must be more efficiently communicated. Also, a better quality assurance study of the methodology (including soil response codes) should be conducted to assess the appropriateness and accuracy of the maps.

Two suggestions were discussed regarding whether or not the urban hazard mapping project should provide risk (loss) assessment products: (1) whether this role is more appropriate for the Federal Emergency Management Agency (FEMA), and (2) whether urban hazard maps could be tied into products like the USGS product, Prompt Assessment of Global Earthquakes for Response (PAGER). Additionally, it was suggested that urban hazard mapping products could be made available for use in FEMA's Hazus software to be more useful to emergency managers and those who evaluate risk in general.

At this point, the discussion shifted to suggestions for improving the quality and resolution of input information. The effect of soil geology is becoming more widely recognized and points to the need for more and better shear-wave velocity (Vs) measurements and the use of geophysics (refraction and reflection) to improve geologic layer estimates between existing well logs and geotechnical measurements. A clear definition of bedrock is needed, as definitions differ in California and CEUS. General practice should move towards applying soil-response models to hard-rock (bedrock) ground motions and away from the current practice of applying soil class factors. (This has already occurred in urban seismic-hazard mapping but needs to be emphasized.) Additionally, some panel participants requested that urban hazard mapping better identify areas of relandscaping (removal and redistribution of material), fill, filled quarries, and liquefaction hazard.

The group then asked who should be involved in the urban seismic-hazard mapping process? The initial list of suggestions included researchers, government agencies, the business sector, and the public. Additional responses added building-code officials and engineers. The group agreed that all of these types of individuals and more should be involved in the process at some level, and it was suggested that the urban hazard mapping process should involve an educational element as well as product generation and dissemination. Members of the discussion group discussed the trend/habit to "one-stop-shop" in the government permitting process, and urban seismic-hazard mapping products should be made available through those venues.

One last suggestion was to conduct one or more comprehensive reflection line(s) across an urban area to identify areas of potentially active faulting beneath cities. The context of this suggestion was Memphis, but is applicable in general. Recent results of a Mississippi River survey by Beatrice Magnani at CERI, which identified faulting near Memphis, was given as an example (unpublished data). Overall, the group agreed that although the scientific value of such efforts is clear, it may not be cost effective in all urban settings.

The group eventually asked what products and activities related to seismic-hazard maps would be desirable to complete for the New Madrid Earthquakes Bicentennial in 2011–2012. Six suggestions were made (not in order of priority): (1) update and expand the Memphis urban hazard maps to all of Shelby County; (2) generate maps for Little Rock, Arkansas (Ark.), and the New Madrid area communities; (3) conduct a cross-Memphis (approximately E–W) seismic reflection survey to identify potentially active faults beneath Memphis; (4) produce hazard maps at several scales such as regional, quadrangle, and more detailed (smaller scale); (5) produce new scenario maps beyond current New Madrid M7.7 and Marked Tree M6.2 scenarios, particularly for new geologic features (that is, the new Mississippi River fault feature mentioned above) and for M greater than or equal to six earthquakes near specific CUS communities; and (6) drill and instrument a deep borehole in the Mississippi embayment targeting fault intersections (possibly use directional drilling and try to partner with exploration industry).

When asked which of these desirable products and activities can reasonably expect to be completed for the bicentennial, the consensus was the various hazard maps and the cross Memphis reflection line (first five tasks listed in the previous paragraph).

Urban hazard mapping priorities were also discussed. Criteria for setting priorities should be based on the hazard/risk of an urban area, community involvement, and researcher interest.

Federal Emergency Management Agency document, FEMA 366, provides guidance concerning hazard/risk and would assist in setting priorities. Several target urban areas were suggested by advocates present (not in priority order): Memphis, Tenn., update; Little Rock, Ark.; Charleston, South Carolina (S.C.); New York, New York (N.Y.); Boston, Massachusetts (Mass.); and Providence, Rhode Island (R.I.). The consensus of the participants was that consideration should be given to conducting urban hazard mapping projects in more than one urban area at the same time to meet the high demand for such products in these communities. Additionally, there is a need to educate the public and the next generation of earth-science and engineering professionals and to provide them with the appropriate knowledge and understanding of seismic hazard and hazard maps.

The following is a list of considerations for future urban seismic-hazard mapping.

Criteria for project selection should include:

- Hazard vs. Risk (FEMA 366)—infrastructure at risk should be as important a consideration as ground shaking hazard;
- Community Involvement—evidence for user community involvement/interest in a working group or advisory committee;
- Researcher Interest—availability of a research community sufficient to develop urban hazard maps for a project.

Possible future projects can be done for multiple cities simultaneously to meet the high demand for this type of product and include Charleston, S.C.; Little Rock, Ark.; New York, N.Y.; and Boston, Mass. Projects need a component of education for the public and the next generation of hazard mapping professionals to provide hazard mapping professionals with the appropriate knowledge and understanding of hazard maps.

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The New Madrid earthquakes of 1811–1812 are the largest earthquakes to have struck the central and eastern United States (CEUS) in historic times. Magnitude estimates for these events vary from Mw 7 to 8, with median estimates of Mw 7.5–7.7 (Petersen and others, 2008). Clearly, if these types of events were to occur again, the impact to the built environment could be devastating. Over the last few years, important new information has been obtained regarding source characterization, wave propagation effects and site response in the New Madrid area. Additionally, recent advances in earthquake simulation algorithms and computational resources now allow us to compute realistic estimates of ground shaking from large earthquakes over a very large spatial extent. With the rapidly approaching bicentennial anniversary of the New Madrid earthquakes, we have a unique opportunity to provide valuable public outreach on the potential hazard presented by earthquakes in this region.

The objective of this project is to provide quantitative estimates of the ground motions that were experienced in the greater New Madrid region during the three major earthquakes of 1811 and 1812. Using broadband ground motion simulation procedures, we will estimate the ground motions that were generated by these earthquakes using the most up-to-date information available for these ruptures. Since little is known about the details of the rupture process during these earthquakes, we will also examine the sensitivity of the ground motion response to key elements of the source characterization, such as slip distribution, rupture velocity and hypocenter location. From the computed broadband ground motions, we will calculate instrumental intensities and generate synthetic ShakeMaps that can be compared with inferred modified Mercalli intensities (for example, Hough et al, 2000). Our simulation efforts will be guided by ongoing modeling studies of past CEUS earthquakes (for example, Ni and others, 2009) and will incorporate the latest available information on subsurface velocity structure (for example, Ramirez-Guzman, and others, 2009) and Vs30 (for example, Brackman, T., and M. Withers, 2006).

Our project will complement ongoing USGS efforts to characterize the ground motions that might occur for a repeat of the 1811 and 1812 earthquakes. We have been actively involved in three previous ground motion simulation projects coordinated by the USGS. Two of these projects involve simulations of Hayward and San Andreas earthquake scenarios in the San Francisco Bay region, including recreations of the 1868 Hayward and 1906 San Francisco earthquakes (for example, Aagaard and others, 2008a, b). The third project is the ShakeOut Scenario exercise, which considers a hypothetical Mw 7.8 rupture of the San Andreas fault in Southern California (Jones and others, 2008). The target of the proposed work is to use rigorous seismological modeling of broadband strong ground motions in order to provide a more comprehensive framework for assessing earthquake hazards in the New Madrid region. Direct products for earthquake loss reduction in CEUS from this work include the development of ground motion maps from large earthquakes for use in emergency planning and loss estimation, and the development of broadband ground motion time histories and response spectra for use in the design and retrofit of structures.

Is there a Connection between Seismicity and Deformation in the New Madrid and Wabash Valley Seismic Zones?

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We compare geodetic and geophysical data for two spatially connected intraplate seismic zones in the central U.S.: the Wabash Valley seismic zone (WVSZ) of southern Indiana and Illinois and the New Madrid seismic zone (NMSZ) of the Mississippi valley. In both cases, regional seismic and potential field data provide evidence for high-angle, basement-penetrating, faults that define narrow, elongate Precambrian grabens that lie beneath relatively undeformed Paleozoic or Mesozoic rocks. Although only the NMSZ has experienced large-magnitude earthquakes in the historical record, both areas have a Quaternary history including numerous moderate to large magnitude events. They are separated by an enigmatic tectonic zone characterized by basement uplift, major Precambrian strike-slip and normal fault zones, and Mesozoic and Cenozoic magmatism. We examine data from a 56-site campaign GPS geodetic network in the southern Illinois Basin to infer present-day deformation in the WVSZ. We combine newly acquired data in 2007 with that from five previous GPS campaigns from the period 1997–2002. Results from the regional network show highly improved position and velocity estimates of these campaign sites relative to previous campaign measurements, with station velocities indicating systematic northwestward motion of about 0.5–0.7 mm/yr with respect to the Stable North American Reference Frame. Average strains for the entire network show marginally significant strains, with an orientation rotated 45° from the overall direction of intraplate stress in the U.S. mid-continent. We also present results from eight years of GPS observations (2000–2008) from the dense Shawnee network, which appear to be consistent with the regional strain models from the regional network.

In addition, we examine models that test the effect of the 1811–1812 New Madrid earthquakes on the near- and far-field strain and seismicity rates in the region through the processes of instantaneous elastic deformation in the lithosphere and associated postseismic viscoelastic flow in the asthenosphere. Our results indicate that significant changes in strain and seismicity rates in the southern Illinois Basin can persist for several hundred years following the New Madrid earthquakes. The seismicity rate can increase by as much as a factor of seven over the background rate in the near-field, but by a much smaller amount in the far-field. However, the effect on the modeled seismicity rates is highly dependent on the choice of lower-crust viscosity. We also investigate the possibility that the New Madrid earthquakes could modify seismicity or strain in the WVSZ by producing triggered slip on a buried fault in the Illinois Basin region. Our initial results demonstrate that elevated seismicity and strain in the WVSZ could result from aseismic slip triggered by viscous relaxation in the lower crust long after the New Madrid earthquakes.

Conditional Mean Spectra as a Bridge between Probabilistic and Deterministic Seismic Hazard Assessment

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The conditional mean spectra (CMS) concept introduced by Baker and Cornell (2006) is a promising technique for developing spectra consistent with the uniform hazard response spectra while accounting for the periods most relevant to a structure. In this presentation I will first provide some background on CMS and then present an application of this concept at a site in St. Louis. The use of this concept resulted in spectra that are consistent with the bimodal hazard at the site from nearby as well as distant (New Madrid) sources. This led to a significant reduction in the estimate of consequences of shaking including liquefaction.

Seismotectonics of the New Madrid Seismic Zone

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I will present results and progress of two NEHRP-funded studies. Results from a recently completed study, "Seismotectonics of the New Madrid Seismic Zone: New Data and Improved Analytical Techniques," include one paper and one MS thesis. In "High Resolution Earthquake Location in the New Madrid Seismic Zone," Dunn and others (2010) find that relocated hypocenters using the double-difference location method align along individual segments of the seismic zone, providing a sharper image of the NMSZ faults. For his thesis, "Earthquake Focal Mechanisms from the New Madrid Seismic Zone," Johnson (2008) determined 290 focal mechanisms. Two main trends of strike-slip nodal planes match seismicity or structures in the northern Mississippi embayment. Nodal planes oriented approximately 50° are parallel to the Reelfoot rift. Nodal planes oriented approximately 30° are parallel to the Northern Arm and the Mississippi embayment axis. Two major trends of reverse faults occur in the Central Segment. One is oriented about 147° and is parallel to the average trend of seismicity in that segment. The other is oriented north-south. This trend is anticipated for reverse faults secondary to through going strike-slip faults oriented about 45° such as the Blytheville fault zone. Normal faults concentrate in the Central Segment and show a variety of nodal plane orientations. An inversion for regional stress field shows a horizontal maximum compressive stress oriented 79º ± 30°. Progress on a currently funded project "Effects of radiation pattern on earthquake ground motion in the NMSZ" will also be presented.

The 1811–1812 New Madrid Sequence—Mainshocks, Aftershocks, and Beyond

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Documented macroseismic effects provide one of the most direct constraints on magnitudes of the 1811–1812 New Madrid mainshocks and large aftershocks, as well as an important reality check on predicted ground motions from future large events. The first critical step in analysis of macroseismic observations is the assignment of intensity values. The uncertainties associated with these interpretations are occasionally the subject of discussion but are rarely, if ever, explored systematically. The reinterpreted intensity values determined by Hough and others (2000) for the 1811–1812 New Madrid mainshocks, for example, are systematically lower than values assigned earlier by Nuttli (1973) and Street (1982), leading to lower magnitude estimates. To explore the uncertainties associated with intensity assignments and develop a set of consensus intensities for the four principal New Madrid events, extant archival accounts were made available to four researchers with experience analyzing historical earthquakes. The independent assignments were then averaged, resulting in 84 intensity estimates for the 12/16/1811 mainshock and 45–49 estimates for the 1/23/1812 and 2/7/1812 mainshocks and the "dawn aftershock" on 12/16/1811. The consensus values are generally lower than those assigned by Hough and others (2000). Using the method of Bakun and Wentworth (1997) with two published attenuation models for the CEUS, intensity magnitude estimates range from MI6.5–7.0 for the December mainshock, "dawn aftershock," and January mainshock, and MI7.3–7.6 for the February mainshock. These results reveal that uncertainties in intensity assignments contribute significantly to uncertainties in magnitude estimates. For the 12/16/1811 and 2/7/1812 mainshocks, magnitude estimates based on assignments by individual experts vary over a range of 0.3–0.4 units. Using preferred magnitudes for the New Madrid mainshocks and other large historical events, including large aftershocks of the 1811–1812 sequence, I consider the magnitude distribution of earthquakes in the central-eastern U.S. The distribution reveals an apparently significant departure from Gutenberg-Richter statistics, an observation that has been used in previous studies to conclude that the characteristic earthquake model is appropriate for the New Madrid seismic zone (as well as the Charleston, SC, source zone). However, using revised magnitudes for historical events, I find the distribution is characterized by a b-value of 1 between roughly M6 and 7.5. The modern, instrumental catalog also reveals a b-value of 1, but an a-value that is roughly 3-10 times smaller. I show that this apparent mismatch is likely the result of catalog limitations. ETAS simulations reveal that, in low strain-rate regions, moment release will be strongly controlled by the tendency of seismicity to cluster. An a-value inferred from a short instrumental record will thus tend to significantly underestimate the long-term rate of small events in the region.

Does Seismicity Delineate Zones where Future Large Earthquakes are likely to Occur in the Central and Eastern United States?

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The spatial distribution of seismicity is often used as one of the indicators of zones where future large earthquakes are likely to occur. This is particularly true for intraplate regions such as the central and eastern United States, where geology is markedly enigmatic for delineating seismically active areas. Although using past seismicity for this purpose may be intuitively appealing, it is only scientifically justified if the tendency for past seismicity to delineate potential locations of future large earthquakes is well-established as a real, measurable, physical phenomenon, as opposed to an untested conceptual model. Based on the method of "Cellular Seismology" (CS) this problem is cast in the form of scientifically testable hypotheses and those hypotheses are tested. CS was inspired by the approach used by the USGS for the seismicity-derived component of the eastern U.S. part of the National Seismic Hazards Maps. The seismicity-derived zonation for those maps is based on the expectation that future large earthquakes will occur near previous earthquakes. The CS method has been applied to a variety of regions around the world to investigate patterns in the extent to which past earthquakes delineate zones where future earthquakes are likely to occur. A common approach for using seismicity to forecast locations of future earthquakes is to use the spatial distribution of rates of activity to delineate zones where future large earthquakes are expected to occur. There are a variety of methods used for rate-based seismicity mapping, and rate-based forecast methods are compared with CS here to evaluate their performance in forecasting locations of earthquakes that have occurred after a forecast was issued. The cases analyzed so far do not reveal any compelling evidence that methods that include information about rates of seismicity perform any better than CS.

The Search for Non-volcanic Tremor in the New Madrid Seismic Zone Using a Phased Seismic Array

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A swarm of microseisms with ground motions equivalent to earthquakes of M_L-1 and smaller was fortuitously detected in 100 of 162, 14-second-duration long-offset vibroseis shotgathers collected for a seismic reflection experiment near Mooring, TN, directly over the Reelfoot fault zone on the afternoon of 16 November 2006. These natural events show up in the shotgathers as near-vertically incident P waves with a dominant frequency of 8–10 Hz and probably occurred at depths of greater than 10 km. The inferred seismicity rate of 250 to 1000 events per hour is two to three orders of magnitude higher than the background seismicity rate for the New Madrid seismic zone. This detection of microseismic swarms in the Reelfoot fault zone indicates active physical processes that may be similar to non-volcanic tremor seen in the Cascadia and San Andreas fault zones and merits long-term monitoring to understand its source. We are planning to deploy a phased seismic array using 19 PASSCAL broadband seismometers over the Reelfoot fault in November 2009. The array will collect continuous data for approximately one year for us to examine the wavefield of approximately 200 expected local earthquakes and the composition of microseismic background noise. We will be searching for repeated episodes of the events that were seen in the 2006 reflection data and will use the array to find locations for possible tremor sources.

New Seismic Design Maps and Associated Web Products for the 2012 International Building and Residential Codes

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In April of 2008, the U.S. Geological Survey (USGS) completed its latest update of the National Seismic-hazard maps (http://earthquake.usgs.gov/hazmaps). This update was timed for use in developing new seismic design maps for U.S. model building codes. Concurrently, the Building Seismic Safety Council (BSSC) Seismic Design Procedures Reassessment Group (SDPRG), with funding from the Federal Emergency Management Agency (FEMA), updated the methodology currently used (for example, for the 2006 and 2009 International Building Code) to derive seismic design maps from underlying hazard maps. Based on both the 2008 National Seismic-hazard maps and the new SDPRG methodology, the USGS has prepared seismic design maps for the 2009 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, the ASCE/SEI 7-10 Standard, Minimum Design Load for Buildings and Other Structures, and the 2012 International Building and Residential Codes.

In addition to the probabilistic uniform-hazard National Seismic-hazard maps, the preparation of new seismic design maps has included computation of (i) deterministic ground motion values and (ii) risk coefficients which transform uniform-hazard values into "uniform-risk" ground motions for design that explicitly targets a specified level of risk, namely 1% probability of collapse in 50 years. This presentation will provide an overview of these computations and will explain the USGS implementation of the new SDPRG methodology for deriving seismic design maps from hazard maps. For example, to approximate the spectral accelerations in the maximum direction of ground motion requested by the SDPRG, the probabilistic and deterministic geometric-mean (of two horizontal components) ground motion values computed by the USGS are amplified by suggested conversion factors.

In much of the central and eastern U.S. (CEUS), the net effect of using the 2008 National Seismic-hazard maps and the new SDPRG methodology is to reduce the short-period (0.2 seconds) seismic design values by about 20% relative to the current seismic design maps (for example, in the 2006 and 2009 International Building and Residential Codes). The net effect on the 1.0 second seismic design values is little to no change. Breakdowns of these effects, for example, CEUS cities including Memphis, will be provided in this presentation.

In addition, associated web products developed by the USGS for user-friendly and accurate use of the new seismic design maps (for example, see http://earthquake.usgs.gov/designmaps) will be described. These products include (i) a webpage for obtaining summary and detailed reports on seismic design values for a user-specified address or set of coordinates that is displayed in Google Maps, (ii) downloadable poster-sized color maps of seismic design values for a specified site class that can be used to visually verify the results of the aforementioned webpage, and (iii) Google Earth/Maps files (that is, KML/KMZ files) for these and some of the other seismic design maps prepared by the USGS.

Long-Term Deformation History in the Mississippi Embayment—The Mississippi River Seismic Survey

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The central U.S. hosts one of the most active intraplate seismic areas in the world, the New Madrid seismic zone (NMSZ). Here the high level of historic and instrumental seismicity clashes with the subdued topography of the Mississippi embayment, minimal geodetic vectors and a puzzling lack of substantial deformation in the post-Late Cretaceous sediments. To explain this apparent paradox it has been proposed that the seismicity in the NMSZ is either (1) very young (at least in its present form), (2) episodic, or (3) migrates throughout a broad region.

In order to test these hypotheses and to understand how the deformation is partitioned within the Mississippi embayment, we collected a 300-km-long, high-resolution seismic reflection profile along the Mississippi River, from Helena, Arkansas, to Caruthersville, Missouri. The profile images a portion of the embayment outside the area of influence of the NMSZ in a region where evidence has been mounting of a seismic source, predating the NMSZ, for which no corresponding structure has yet been identified.

The seismic survey exploited the advantages of marine acquisition (time effective, low cost) using a 245/245 cm^3 (15/15 in^3) mini-GI airgun fired at 13.790 MPa (2,000 psi), a 24-channel 75-m-long active streamer, with 3.125-m group and 12-m nominal shot interval.

The high quality data identified with unprecedented resolution the existence of three zones of deformation and faulting involving

Quaternary sediments. Two of these areas lie outside the NMSZ, confirming the hypothesis that seismicity has migrated spatially within the embayment, at least during the Quaternary, and suggesting that the long-term seismic activity in this area might extend over a broader region than previously suspected.

Can OSL be used to Date Paleoliquefaction Events?

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Paleoliquefaction features (clastic dikes and sills) have been extensively studied in the New Madrid and Wabash Valley seismic zones within an area of the central Mississippi valley (Obermeier, 1989; Obermeier and others, 1991; Munson and Munson, 1996; Counts and others, 2008); the St. Louis region (Tuttle and others, 1999); the Memphis area (Gomberg and others, 2006); and the New Madrid region (Tuttle and Schweig, 1995; Tuttle and others, 2002, 2005, and 2006). Dating the formation of these features is critical for determining the timing of liquefaction features, which are formed during the actual earthquake event. An absence of these features (that is, in east Tennessee) can also be informative (that is, no large earthquakes occurred during this time).

Traditionally, these features have been dated using radiocarbon, Native American artifacts, or stratigraphic analyses. Increasingly, however, optically stimulated luminescence (OSL) dating is being brought to bear upon the question of determining when these liquefaction features formed and the timing of their associated paleoseismic events. OSL has been used in other areas of the world to date paleoliquefaction sites (summaries in McCalpin, 2009), and there are preliminary OSL ages (Counts and others, 2008, Mahan, and others, 2008) within this area that will be included in this poster. OSL dating works best when the sampled sediment comes from either associated river terraces, the actual sand blows, or the underlying alluvial B horizons (which the sand blows would have covered). Post-depositional iron staining or other coatings do not affect OSL. A coherent plan for a more systematic study is also being developed with the hope that future studies can target those areas that have been overlooked or deserve more study.

This poster will attempt to show all the known data for OSL on paleoliquefaction sites for the central Mississippi valley and provide references to the work. Our poster will also detail the rudimentary principles of OSL and show why OSL can be particularly effective for dating paleoseismic events using correct sampling protocol.

Mmax and Lithospheric Structure in Central and Eastern North America

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We introduce a new approach to estimating the seismic potential of continental intraplate regions based on the deep seismic properties of the lithosphere. Our hypothesis is that greater integrative lithospheric strength correlates with lower rates of continental crustal seismicity and with lower maximum earthquake magnitude, also known as Mmax. Integrative lithospheric strength is controlled by lithospheric composition and the geotherm, which is correlated with S-wave velocity. High lithospheric S-wave velocities, typical of cratonic lithosphere, correspond to high integrative lithospheric strength. We have created new global maps of S-wave velocity anomalies (δVs) at a depth of 175 km. We find that δVs ranges from +5% to -5%. We compare the values of these mantle S-wave anomalies with the moment magnitudes of intraplate earthquakes in the overlying crust. We find that only 10% of 460 events with moment magnitudes between 5 to 6; 15% of 110 events with moment magnitudes between 6 to 7; and none of the 14 intraplate events with moment magnitudes greater than 7 occur above mantle lithosphere with δVs greater than 3.5% (cratonic lithopshere). We conclude therefore that integrated lithospheric strength, as indicated by S-wave velocity anomalies, correlates with crustal seismicity. Mmax appears to be M7 for stable cratonic continental regions underlain by δVs greater than 3.5% at 175 km depth. This includes a large portion of the Precambrian continental interior of the central and eastern U.S. with Archean and Neoproterozoic age.

A Phenomenon of a Most Alarming Nature

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This map is a visual compilation of eyewitness accounts of damage to the Mississippi River and the surrounding areas. It is only representative of a few of them. For more information about the New Madrid earthquakes and their effect on the United States go to our website: *http://www.ceri.memphis.edu/compendium*

The New Madrid earthquakes were one of the greatest natural disasters to ever affect the United States. Although the quakes occurred nearly 200 years ago when the expansion of the United States had just crossed the New Madrid area, their effect upon the country was widespread. Although the area was still considered a wilderness, scattered settlements were in the immediate area of the epicenters and the Mississippi River was already a major artery of trade for the young republic. Despite the sparse population there were many eyewitnesses to the event who left detailed written accounts of what they observed when the earthquakes occurred. Many of these accounts were keyed to the contemporary guidebook for travelers on the Mississippi River during 1811–1812, Zadock Cramer's the Navigator. This book provided a step-by-step guide to river navigation accompanied by a map of the river and its navigable channel. Cramer also pioneered the system of numbering the river islands as a handy guide to travelers. The system was so successful that it is used to this day. Cramer's river map serves as the basis of this poster. Although somewhat distorted in its depictions of the bends of the river, it is accurate in its arrangement of islands and other natural features. This poster uses Cramer's map as the basis for showing where damage occurred on the river and the surrounding area. It is not conclusive in its scope and only shows some of the reports of damage that have been uncovered by historic research.

Earthquake Source and Ground Motion Characteristics in the Central and Eastern United States

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Broadband simulation has proved effective in modeling ground motion, with the low frequency motion calculated deterministically and high frequency stochastically. The stochastic modeling approach takes account of earthquake rupture complexities and 3D structure heterogeneity along the propagation path for frequencies above a certain transition frequency, typically taken to be about 1Hz. However, source complexity and structure heterogeneity control ground motion in different ways, as the latter depends on distance and the former may depend on earthquake magnitude. At short distances, waves experience less scattering, and waveform modeling can be achieved at higher frequencies. For smaller earthquakes, the stochastic nature of rupture may only emerge above the corner frequency, which may be quite high. To demonstrate the approach, we simulate ground motions up to 10Hz in the central and eastern United States with a frequency-wave number (FK) algorithm accounting for both rupture complexities and scattering due to heterogeneities. The rupture complexities are implemented as frequency depend radiation pattern, and a scattering matrix is introduced in the spectral domain to transfer energy across different components of ground motion. A frequency dependent free path length is used to characterize the amount of scattering along the propagation path, with higher frequency waves experiencing shorter free path length. We apply this approach to simulating the April 18, 2008, Mt. Carmel event, after the source parameters (moment, source mechanism, focal depth) were inverted from long period waveforms (Pnl waves up to 0.3Hz and S/Surface waves up to 0.1Hz) and a 1D velocity model is obtained with waveform inversion based on linearized differential seismograms. Ground motions up to 10 Hz are simulated and are consistent with the observations. However, at even higher frequencies (up to 100Hz), ray-based approaches need to be used to increase computation efficiency.

Paleoseismic Investigation of the East Tennessee Seismic Zone—Preliminary Results

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The East Tennessee seismic zone (ETSZ) extends some 275 km from just north of Knoxville, TN, southwestward into NW GA and NE Alabama, and reaches a maximum width of 65 km. It is the second most active in the eastern U.S., behind New Madrid, but the principal difference between the ETSZ and New Madrid, Charleston, and other well-studied seismically active areas in the East is that most of them have had at least one historic M>5.5 earthquake, whereas the largest historic earthquake in the ETSZ has been one or more M=4.8 events. The USGS, however, has rated the ETSZ capable of producing M=7.5 earthquakes, based on its size and frequency of activity. Our purpose is to determine if M>5.5 earthquakes have occurred here during the past 10,000–20,000 years, and if so, to begin the process of estimating their maximum magnitude and recurrence intervals. The techniques being used are reconnaissance of aerial photos, and then field examination of banks of streams and reservoirs for evidence of earthquake-related liquefaction and deformation, including faulting. We have found evidence of possible liquefaction features in terrace deposits along several streams (for example, the French Broad River), and had previously observed small faults, folds, and other deformation features of possible seismic origin in Pleistocene to Holocene alluvial materials in the ETSZ. We also have observed a paucity of paleoseismic features in abundant exposures of Holocene deposits during canoe reconnaissance of the Sequatchie River, suggesting the possibility that the western boundary of the ETSZ is roughly that defined by the distribution of present seismicity. Of special note in the Sequatchie River banks, though, are numerous features that mimic clastic dikes, which likely originated from physical and geochemical factors not completely understood. More intense field work will be conducted in streams and along the banks of TVA reservoirs during fall and early winter 2009, following fall-winter drawdown of reservoirs. More intensive investigation (for example, trenching) of specific sites will be made during late fall and winter where liquefaction features or deformation are firmly identified.

Site Amplification in Central and Eastern United States

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Current NEHRP/IBC guidelines for simplified seismic design are mainly based on experience and data from sites in the western U.S. The geologic conditions in the CEUS pose the possibility of unanticipated site amplification that cannot be predicted by the current simplified design guidelines. As part of our work on numerous site investigations over the past decade, we have identified a number of unique geological and geotechnical conditions prevalent in the central and eastern U.S. (CEUS) that may not be captured adequately by current guidelines.

Amplification of ground motions as they pass through a layered structure is directly affected by the velocity structure and impedance contrast between layers within the profile. The rock in the western U.S. is highly fractured due to frequent tectonic activity. However the rock in CEUS is much more competent than it is in active interplate tectonic regions. Abrupt velocity contrasts caused by very hard rock (V_s > 2500 m/s) close to the ground surface are prevalent in the central and eastern U.S. Our analyses indicate that this geologic condition can cause significant amplifications at short structural periods (0.2–0.7 seconds) that produce motions well above those typically predicted by current NEHRP/IBC procedures based on the average shear wave velocity of the top 30 m ($V_{s\text{-}30}$) of the profile. Also, the common CEUS geological condition such as the Atlantic Coastal Plain and Memphis Basin, which typically consists of a stack of unconsolidated sediments up to 1,000 meters thickness, can amplify ground motions at long periods (typically >2 seconds) that greatly exceed the NEHRP/IBC simplified spectra. Conversely, the thick sediment wedge damps high frequency motions and produces a significant reduction of the ground motions at shorter periods. The resulting ground motions at periods less than 1.0 second can be significantly below the simplified guidelines.

In summary, our findings indicate that site classification based on the average shear wave velocity of the top 30 meters ($V_{s\text{-}30}$) appears to work adequately for sites in regions of frequent tectonic activity such as coastal California. In the absence of a sharp velocity contrast, V_{s-30} appears to be a reasonable indicator of site response. Site amplification can be very different in tectonically stable regions such as CEUS, where sharp velocity contrasts between hard rock and overlain soil are common geologic features. Our site response analyses focus on these issues and these findings have direct implications for seismic design practice in CEUS.

Recent and Current Earthquake Hazard Reduction Research at the Puerto Rick Strong Motion Program

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The poster will present a summary of recent and current research projects carried out by the Puerto Rico Strong Motion Program (PRMSP) related to strong motion instrumentation and general earthquake hazard reduction. The poster will present results from recent project such as liquefaction potential of calcareous sands from Western Puerto Rico, efforts on seismic microzonation which include development of geotechnical databases and NEHRP site class maps for major cities of Puerto Rico. The poster will also present the results of a recently completed pilot study that compared estimates of the predominant site periods using different techniques using ambient vibration and also weak motion measurements recorded at a several seismic stations in Mayagüez, Puerto Rico. Specifically the pilot study involved comparison of predominant site periods using the Fourier amplitude spectra, the Fourier spectral ratios between the spectra at the site and at a reference station, and the spectral ratios between the horizontal and the vertical components of ambient vibrations, that is, the Nakamura's technique (Nakamura, 1989). In the near future the PRSMP would like to initiate a comprehensive effort related to development of maps of predominant period of vibration for the main cities of Puerto Rico. The poster will also present a summary of the current state of the PRSMP instrumentation network in terms of number of free-field stations, instrumented buildings, bridges, and dams. The objective of this poster for PRSMP is to show an overview of its recent and current research and to receive feedback, and suggestions from CEUS researchers. The PRSMP welcomes visiting scholars, post-docs, and mainland U.S. researchers to come to Puerto Rico and work on joint projects that will help its mission of reducing earthquake risk in the region.

Major Earthquakes Recorded by the Initiation and/or Regrowth of Speleothems in Midwestern U.S. Caves—Results from a 2008–2009 NEHRP-Funded Investigation

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Studies of the paleoseismic history of the New Madrid seismic zone (NMSZ) have suggested that large earthquakes on the NMSZ have a recurrence interval of about 500 years. Because this estimate is based on about 2000 years of data, and because of gaps in data beyond 2,000 years BP, additional data on paleoseismicity in this area is needed to refine estimates of a recurrence interval. Further, addition data could be used to better characterize the geophysical nature of the NMSZ. More precise estimates of the number and ages of known paleoseismic events and a more complete record would enhance the ability of Federal, State, and local agencies to make preparedness decisions.

Recent work by Panno and others (2009) (which included data from this investigation) suggests that cave deposits in the Midwestern U.S. constitute a unique record of paleoseismic history of the U.S. Midcontinent. Geological features, particularly stalagmites, in caves of southwestern Illinois, Missouri, Indiana, and Arkansas are temporally coincident with known historic and prehistoric seismic activities. The caves in these states contain speleothems that appear to have been initiated by large earthquakes. In our study area, these include hundreds of actively growing, relatively small, white speleothems, the stalagmites of which are growing on older stalagmites, on older flow stone, on breakdown, and on fine-grained sediments. There were two periods of white stalagmite growth initiation in the caves of southwestern Illinois: one group was initiated around 200 years BP, and the other group was initiated about 90 years BP. The ages of the first group coincide with the 1811–12, magnitude VIII (MM scale) NMSZ earthquakes (within 150 km of the epicenter); the ages of the second group coincide with the April 9, 1917, magnitude V (MM scale) Missouri earthquake (Illinois caves examined are within 15 km of the epicenter). The U-Th disequilibria ages of initiation dates for older stalagmites and multi-stage stalagmites fell within the range of all known prehistoric earthquake events. Delta ^{18}O and ^{13}C data for five selected stalagmites from three states followed known changes in climate within the Midwestern U.S. during the Holocene.

We hypothesize that these speleothems were initiated by earthquake-induced opening of fracture-controlled flowpaths in the ceilings of cave passages. On the basis of recently collected data, we suggest that the dates of initiation and regrowth, and perhaps changes in stalagmite growth rates may be used as indicators of historic and prehistoric NMSZ earthquakes in the Midwestern U.S., and probably other seismic zones in the world.

Ground-Motion Prediction Equations for Eastern North America from a Hybrid Empirical Method

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In the field of earthquake engineering, ground-motion prediction models are frequently used to estimate the peak ground motion (PGA) and the pseudo spectral acceleration (PSA). In regions of the world where ground-motion recordings are plentiful (such as WNA), the ground-motion prediction equations are obtained using empirical methods. In other regions such as eastern North America (ENA), with insufficient ground-motion data, other methods must be used to develop ground-motion prediction equations.

The hybrid empirical method is one such method used to develop ground-motion prediction equations in areas with sparse ground motion. This method uses the stochastic method to adjust empirical ground-motion prediction relations developed for a region with abundant strong motion recordings. It estimates strong-motion parameters in a region with a sparse database. The adjustments take into account differences in the earthquake source, wave propagation, and site-response characteristics between the two regions. The purpose of this study is to use a hybrid empirical method and to develop a new hybrid empirical ground-motion prediction equation for ENA, using five new ground-motion prediction models developed by the Pacific Earthquake Engineering Research Center (PEER) for WNA. A new functional form is defined for the ground-motion prediction relation for a magnitude range of 5 to 8 and closest distances to the fault rupture up to 1,000 km. Ground-motion prediction equations are developed for the response spectra (pseudo-acceleration, 5% damped) and the peak ground acceleration (PGA) for hard-rock sites in ENA. The resulting ground-motion prediction model developed in this study is compared with recent ground-motion prediction relations developed for ENA, as well as with available observed data for ENA.

P- and S-Wave Velocity Structure and V_P/V_S Ratios in the New Madrid Seismic Zone

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Three dimensional P- and S-wave velocity models are constructed for the New Madrid seismic zone (NMSZ) using double difference local earthquake tomography (tomoDD). TomoDD incorporates catalog travel times with catalog and waveform cross correlation differential times to solve for P and S wave velocities and for high-resolution earthquake locations. The data set consists of a combination of travel times and differential times recorded by the New Madrid Cooperative Seismic Network (NMCSN) from 2000–2007 and the temporary PANDA deployment from 1989–1992. A total of 4,522 P-wave and 3,953 S-wave arrival times results in 18,662 P-wave and 16,354 S-wave differential times for PANDA stations. We use 15,146 P-wave and 10,387 S-wave arrival times resulting in 63,321 P-wave and 37,187 S-wave differential times from 837 earthquakes recorded by the NMCSN. Additionally, 37,040 P-wave and 18,731 S-wave cross correlation differential times strengthen inversion results.

The NMSZ consists of four intersecting arms of seismicity. There are approximately 200 earthquakes/year recorded in the NMSZ despite the absence of a major plate boundary. Most earthquakes occur along the centrally located Reelfoot fault leading to uneven source distribution. We use a finite difference travel time calculator combined with an irregular inversion grid node spacing of 5 to 20 km horizontally and 1 to 3 km vertically. Model resolution is examined using checkerboard synthetic tests. Resolution is highest close to the source region between depths of 5 to 11 km. P-wave velocity results indicate that velocities close to the source region are low relative to the 1D starting model. S-wave velocity models indicate high velocity anomalies associated with the northern portion of the Reelfoot fault and low velocities to the south. The low P- and S-wave velocities may be indicative of anomalous rock properties, such as increased fluid content and fracturing. A high P- and S-wave velocity anomaly is associated with a known mafic intrusion to the northwest of seismicity.

Insights into the Structure and Long-term Deformation in the New Madrid Region from Seismic Reflection Profiles

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Interpretation of all available seismic reflection profiles in the New Madrid region provides insight into the structure and seismicity of the New Madrid seismic zone (NMSZ). Data used in this study include vibroseis profiles acquired by the USGS, industry vibroseis profiles purchased by the USGS, the COCORP profile across the embayment, and shallow seismic profiles acquired by the USGS. The Blytheville arch is the most prominent feature that can be associated with the NMSZ on the profiles. The arch is an antiform in the Precambrian and early Paleozoic rift strata, as much as 20 km wide and 200 km in length, that coincides with the southeast arm of seismicity within the New Madrid seismic zone. The arch appears to be a structural feature formed by thrust or strike-slip faulting (flower structure) because there is clear faulting on at least one flank of the arch and coherent strata within the arch. Parallel strata within the flanks of the arch indicate that growth was initiated after deposition of the rift strata that are folded in the arch. The prominent erosional surface that truncates the top of the arch indicates that the arch was largely formed before the erosional surface was cut in the Paleozoic. More recent growth of the arch is indicated by slight folding of the erosional surface, particularly slight uplift over the dipping strata on the flanks of the arch. Much of this later growth appears to be Quaternary or Holocene in age because the post-Paleozoic Mississippi embayment strata are parallel within the folds. Prominent faults are evident on the seismic profiles from truncation of rift strata and slight changes in elevation or dip of the erosional unconformity. Prominent faults include one coinciding with the southeast arm of the seismic zone and with the Bootheel lineament, but other faults are evident over a wider area of the embayment. Deeper strata do not appear to extend beneath the Blytheville arch as coherent strata, suggesting that the arch coincides with a major crustal boundary. The data are consistent with a rift model in which middle and lower crustal reflectivity are associated with the rifting, and deformation is distributed across the rift zone.

Tantalizing Suggestions for Late Pleistocene to Middle Holocene Surface Deformation at the Southeastern Margin of Reelfoot Rift, the Marianna Gap in Crowley's Ridge

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The Marianna Gap, a 13-km wide discontinuity in Crowley's Ridge southwest of Memphis, TN, is associated with apparent surface deformation that dates back at least 70 ka but was not fully breached until ca. 4–7 ka. During the late Pleistocene (60–70 ka), Mississippi River braid-stream channels in the western lowlands were deflected from the regional north-to-south flow path to a west-to-east flow path toward the present Marianna Gap. But the gap had not completely formed at this time and the paleochannels were deflected back to the south at margin of Crowley's Ridge. Additional evidence for presence of a continuous ridge during the Pleistocene is an abandoned paleochannel southwest of the gap (Lick Creek) that appears to be the continuation of the L'Anguille River present northwest of the gap. Flow through the abandoned Lick Creek channel is dated at ca. 24 ka and only a thin sequence of silt (either the youngest segment of loess deposition or reworked loess) overlies fluvial sediment in the paleochannel. This stratigraphy suggests that the L'Anguille River flowed west of Crowley's Ridge during deposition of the Peoria Loess and only abandoned this path to flow through the gap ≤10 ka.

Though the ridge was intact during the Pleistocene, the divide was probably relatively low in elevation at the present gap location. In addition to the diversion of paleobraid channels toward this location, the Peoria loess (25–10 ka) west of the gap is relatively thin compared to loess west of the ridge. The decreased loess thickness adjacent to the gap may have been caused by scour as wind was funneled through a low divide or "wind gap" in Crowley's Ridge.

The gap was fully breached by mid Holocene. A large Mississippi River meander bend of meander belt 3 (active between 4–7 ka) crosscuts the ridge. It is unknown if erosion on the outside of the bend was responsible for breaching the divide, or if the gap had been formed earlier and the river merely enlarged and modified its shape.

It is possible that Marianna Gap has a tectonic origin as suggested by a variety of evidence. First, the gap is a few km south of the Reelfoot rift floor edge and is likely at the Reelfoot rift margin. Second, numerous large liquefaction features dated 5–7 ka are present in and around the gap so seismic activity was important in the region during the middle Holocene. Third, the orientation of Crowley's Ridge shifts and is offset by 10 km at the gap, which suggest that it might have undergone lateral movement. Fourth, surface depression suggests vertical movement. Though the final breaching of Crowley's Ridge occurred between ca. 10–5 ka and may be associated with seismic events, surface deformation persisted for tens of thousands of years prior to the destruction of the Crowley's Ridge near Marianna, Arkansas.

Central United States Velocity Model Version 1: Description and Validation

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We describe and test via numerical simulations a velocity model of the Central United States (CUSVM Version 1). Our model covers an area of 650,000 km^2 and includes parts of Arkansas, Mississippi, Alabama, Illinois, Missouri, Kentucky, and Tennessee. The model represents the compilation of research carried out for decades consisting of seismic refraction and reflection lines, geophysical logs, and inversions of the regional seismic properties. The CUSVM has a higher resolution description around Memphis and St. Louis, two of the largest urban areas in the central United States. The density, p- and s-wave velocities are synthesized in a stand-alone spatial data base that can be queried to generate the required input for numerical simulations. We calibrate the CUSVM using three earthquakes located N, SW and SE of the zone encompassed by the model to sample different paths of propagation. The selected stations in the comparisons reflect different geological site conditions and cover distances ranging from 50 to 450 km away from the epicenters. The results indicate that both within and outside the Mississippi embayment, the CUSVM satisfactorily reproduces: (a) the body wave arrival times and (b) the observed regional variations in ground motion amplitude and duration in the frequency range 0–0.75Hz.

Dynamic Testing by Resonant Column and Torsional Shear Methods

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One of the challenges facing modelers is the proper selection of shear modulus G, and damping D for various soil strata. This study examines carefully several aspects of measuring those properties using resonant column and torsional shear methods. One difficulty is trying to decide if the test really generates the properties it is supposed to. Using 3-D finite element models of the testing system I modeled the performance of the tests to determine if it measured the properties the way I understood it to be measured. Other possible anomalies, such as soft (small voids) or hard (gravel or nodules) spots and their impact on the overall behavior of the test were studied. Irregular loading histories were also studied since incorporation of irregular loading at small strains is still unexplored territory for finite element models. As part of a research project I studied the effects of large variations in confining stress and how much torque is required to generate significant non-linear strains in test specimens at high confining stress (approximately 500 psi). This part of the study is being used to complete the fabrication of a high confining-stress testing device.

Numerical models match well with behavior measured in the laboratory. However it is difficult to quantify the variability of behavior in a lab specimen without resorting to more sophisticated measurement methods. Further study using video data acquisition will be performed to more carefully examine the strain fields generated by torsional and resonant column testing.

Overview of Seismic-hazard mapping of Three Pilot Quadrangles in the St. Louis Metro Area

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The greater St. Louis metropolitan area is a densely populated urban zone, bounded by extensive deposits (up to 76 m thick) of unconsolidated sediment (mostly sands) underling well-defined floodplains. The severe curvature of the bedrock channel depressions at their edges may also be sufficient to trap seismic energy and cause incident body waves to propagate through the alluvium as surface waves, producing stronger shaking and longer durations than would be predicted by 1-D analyses. This phenomenon may explain the significant disparities in reported shaking in the channel fills as opposed to bedrock knobs during historic earthquakes. The ground-motions from the New Madrid seismic zone and Wabash Valley seismic zones that consider site-specific impedance contrasts and basin effects were recently evaluated for three pilot quadrangles (Columbia Bottom, Granite City, and Monks Mound) by the PI. The USGS national hazard maps do not include the effects of local geologic structure or soil cover present in the St. Louis metro area. The range in expected site response for a wide spectrum of earthquake magnitudes from three potential source areas was evaluated, and it is hoped that this information can aid in assessing seismic hazards in the St Louis area because St. Louis and St. Charles Counties have recently adopted the 2003 International Building Code, which require assessments of seismic shaking intensity using NEHRP soil classifications. These hazard maps included assessments of the following attributes: (1) probabilistic seismic hazard analysis (2, 5, and 10% probabilities of exceedance in 50 years in predicting the peak ground accelerations [PGA]); (2) selected scenario earthquake analysis for PGA, 0.2 sec and 1.0 sec spectral accelerations (SA); and (3) spectral accelerations at 0.2 second and 1 second periods (at 2, 5, and 10% probabilities of exceedance in 50 years). The sensitivity analyses of seismic site response suggest that the variations of the soil conditions and thickness in the St. Louis area exert: (1) a significant influence on the amplitude, and (2) contrasting shaking characteristics for each of the ground motion parameters, whereas the thickness and shear wave velocity of the weathered bedrock horizon appear to have little impact on site amplification. The peak ground acceleration characteristics reveal that earthquake forces on loessal uplands are expected to be most severe for short period structures, whereas those in the alluvial floodplains will likely be more severe for long-period structures.

Shear Wave Velocity Profiles of Deep Soils in the Mississippi Embayment

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Active and passive surface wave measurements were performed at 11 deep soil sites in the Mississippi embayment overlying the New Madrid seismic zone. Measurements were performed from north of New Madrid, Missouri, to Memphis, Tennessee. Shear wave velocity (V_S) profiles were developed at each site to depths of approximately 200 to 250 m from inversion of Rayleigh wave dispersion curves. The average V_S profile calculated from the 11 sites is in good agreement with a previous reference V_S profile developed for the embayment. Using estimates of lithology at each site, relationships were developed between V_S values and formation type, down to the Memphis Sand Formation. Shear wave velocity values determined for near-surface alluvial deposits and the upper Claiborne unit (Jackson/Cockfield/Cook Mountain Formations) were in good agreement with past studies; however, higher values of V_S for the Memphis Sand Formation were obtained in this study. Single-station, three-component measurements of ambient noise were also performed at each site. These data were analyzed using the Horizontal-to-Vertical Spectral Ratio (HVSR) method to obtain estimates of fundamental frequency and average V_S for the full depth of post-Paleozoic sediments. Although the results are in agreement with previous HVSR measurements in the Mississippi embayment, the average full-depth V_S values appear to be overestimated using this method.

Systematic Historical Seismicity Research—An Essential Adjunct in the Pre-Instrumental Period

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Although instrumental data from modern earthquakes allow the seismologist to give a definitive analysis of a recorded event these are limited to the past 100 years. Historic seismic data can allow the seismologist to reach back 400 years and better address the real seismic hazard from large events that often appear to have a return period in the order of 300–500 years.

Only the provinces of Quebec and New Brunswick have a complete record of their historic seismicity through the work of Pierre Gouin (1917–2005) and soon Ken Burke, respectively. Nova Scotia's record is complete from 1752 to 1867, Newfoundland's and Labrador's record is spotty and a small portion of S. Ontario has a complete record for only one decade (1870–1880). In the U.S. only key larger historic earthquakes have been researched, in particular those that were especially large, located close to a proposed nuclear power plant, or to an LNG terminal, or attracted the interest of a local researcher. No truly systematic and complete historic seismicity compilation is available for central and eastern U.S. Compilations for Caribbean Island nations are patchy at best.

The argument will be made, "We really only need the largest events and we have all these for the past 400 years for at least the thirteen original States of the Union. So why bother with the chatter of the small as-yet unrecognized events?" Well perhaps an example, now enshrined in concrete and steel, may quiet such skeptics?

Canada's first full-fledged environmental assessment occurred in 1977 to evaluate the proposed Lepreau nuclear power station in New Brunswick on the Bay of Fundy just a few short kilometres from the international boundary. The assessment used the available 1962 W.E.T. Smith seismic catalogue; there was no compilation extant for N. Maine. The 1973–74 study of earthquakes found that the maximum event that had ever been experienced at the site was at "...intensity VII (MMI), or Richter magnitude 6.0 ..." The plant was then built to satisfy this 1973–1974 seismic constraint.

The 1982 central New Brunswick earthquake sequence and the Cape Cod proposed Pilgrim nuclear plant prompted a U.S.-funded reassessment of the four largest known N.B. and northern Maine earthquakes in 1904, 1869, 1855 and 1817. Instead of one large event in Passamaquoddy Bay in 1904 just west of the plant with a maximum magnitude of 5.0, we ended up in 1985 with three events ranging in magnitude from 4.8, to 5.7, to 5.9. The 1869 and 1817 events had been moved 55 km SW and 175 km SE, respectively, to join the 1904 earthquake (Leblanc and Burke, 1985). One could reasonably argue with hindsight by 1985 that the Canadian plant, as-built virtually on the U.S. border 5–6 years earlier, was under-designed with respect to seismic risk. Since the 1985 reassessment, the 1869 event has been relocated to the NE based on more historic work by Burke in 2004.

The New Madrid Field Trip Guidebook

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The New Madrid Bicentennial will be recognized in 2011–12, to mark 200 years since the 1811–12 New Madrid earthquakes rocked most of the central and eastern U.S. This is an exceptional opportunity for coordinated outreach from the geoscience and engineering communities to business leaders, elected officials, the media, and the general public. Since 2005, six Earthquake Insight Field Trips have been hosted by the U.S. Geological Survey (USGS) and led by Earthquake Insight LLC. Their purpose was to educate business leaders about earthquake hazards and earthquake risks in the central U.S. During the course of the Earthquake Insight Field Trips, at least 50 to 60 stops have been included on the various routes, and another 50 to 60 have been identified and documented, but not included—often due to the difficulty of access by a bus. The stops are located from the St. Louis metropolitan area in the north to the Memphis metro area in the south, and much of the rural area in between. The stops include field illustrations of the geologic setting; locations of significant earthquake-related human histories; examples of earthquake engineering practice; and the economic, business, and community vulnerabilities to earthquake hazards. The New Madrid Field Trip Guidebook is now in progress to make this information more available to specific audiences as well as the general public. Descriptions, explanations of the earthquake-related significance, photos, GPS coordinates, local driving directions, and other information will be included for each stop listed in this USGS Open-File Report.

Development of the Central and Eastern United States (CEUS) Seismic Source Characterization (SSC) Model

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Input to probabilistic seismic hazard assessment (PSHA) consists of two elements: seismic source characterization (SSC) and ground motion characterization (GMC). The 1986 EPRI-Seismicity Owners Group (SOG) study incorporated expert judgment to model epistemic uncertainty and set the standard for Probabilistic Seismic Hazard Assessments (PSHAs) at that time. Current licensing applications for next generation nuclear power plants have used the EPRI-SOG source component as a starting point, with updates as appropriate on a site-specific basis. The CEUS Seismic Source Characterization (SSC) for Nuclear Facilities Project is focused on replacing the SSC component of the EPRI-SOG study. The new CEUS SSC model being developed can be used with the EPRI (2004, 2006) GMC model to calculate seismic hazard until the results of the Next Generation Attenuation East (NGA-East) Project are available.

The CEUS SSC Project is an industry-government partnership formed to develop a seismic source characterization model for any site in the CEUS. It is jointly sponsored by the Electric Power Research Institute (EPRI) Advanced Nuclear Technology (ANT) Action Plan Committee (APC), the U.S. Department of Energy (USDOE) and the Nuclear Regulatory Commission (NRC). The goals of the project are: (a) replace the 1986 EPRI-SOG and LLNL (1993) seismic source characterizations models for the CEUS, (b) capture the knowledge and uncertainties of the informed scientific community using a Senior Seismic Hazard Assessment Committee (SSHAC) Level 3 process, and (c) provide an up-to-date, consistent, stable input for a PSHA. The CEUS SSC project team consists of program and project management, a technical integration (TI) team and staff, a participatory peer review panel (PPRP), specialty contractors, sponsors, and agency experts. The team assembled represents a first-of-a-kind attempt to form a diverse team from all stakeholders from industry, government and academia to participate in this landmark study. The work consists of 17 tasks and three workshops. In addition to a new CEUS SSC model, other important products from this project include: a CEUS earthquake catalog using moment magnitude, a CEUS geological, geophysical and seismological database important for source characterization efforts, specialized modeling tools for SSC and sensitivity analyses to identify hazard-significant issues. The results from this industry-government three-year study will be published by EPRI at the end of 2010.

Earthquake Rupture Directivity and Local Site Effects from a M.73 Earthquake

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We have documented the ground motion effects of earthquake rupture directivity and local site amplification with data from a recent M7.3 earthquake in Honduras. This event occurred on May 28, 2009, at 2:24 AM local time, and struck off the coast of Honduras on the Motagua-Swan fault system (MSFS), part of the boundary between the North America and Caribbean plates. This plate boundary has an average slip rate of 20 mm/year. This left-lateral earthquake had an average slip of 1.5 m on a 100-km-long near-vertical fault plane (Hayes and Ji, 2009). The hypocenter depth is estimated at 10 km. The main shock caused 130 structures, including homes and office buildings, to collapse or suffer significant damage in northern Honduras. Seven deaths were reported. Due to a lack of recordings in the area, the available documentation of the effects of this earthquake are the USGS "Did you feel it?" responses and the data collected during our field seismic intensity investigation. We conducted the intensity study in Honduras between May 30 and June 6, 2009, and focused on areas with local reports of damage, including the cities of La Ceiba, El Progresso, San Pedro Sula, and Puerto Cortes in northern Honduras, and the island of Roatan in the Caribbean Sea. The damage ascertained at these five sites shows that the severity of damage did not decrease with distance from the epicenter as predicted by standard attenuation relations. Instead, damage was concentrated in El Progresso, approximately 75 km south of the SW end of the rupture and 160 km from the epicenter. The island of Roatan, just 30 km from the epicenter, had significantly less damage than El Progresso, and was graded as VI on the Modified Mercalli Intensity scale whereas El Progresso was graded as VIII. These intensity anomalies can be explained by two factors: (1) SW-directed rupture propagation and proximity to a localized 3.0 m slip pulse (asperity) that occurred near the SW end of the fault (Hayes and Ji, 2009) that focused energy toward the city of El Progresso and; (2) local site effects, particularly the rigid Precambrian schists and gneisses on the island of Roatan, in contrast to the soft river deposits (sand, organics and clay) beneath the city of El Progresso. This study demonstrates the impact of seismic directivity, high slip on a fault asperity, and local site conditions on the observed damage patterns from this M7.3 earthquake.

Geodesy and the Enigma of Stable Continental Earthquakes

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The GPS Array for Mid-America (GAMA) was developed under Mid-America Earthquake Center's (MAEC's) Hazard Definition component to potentially detect, but not fully describe, deformation associated with NMSZ seismicity. The most important, and controversial, result was detection of statistically significant shortening at the 95% confidence level between two CGPS sites straddling the Reelfoot scarp, which is the surface expression of the micro seismically defined Reelfoot fault. Outside the immediate area of the seismically active NMSZ faults, CGPS does not detect statistically significant deformation with respect to stable North America.

Whereas large earthquakes in the New Madrid area are clearly not consistent with plate tectonics, the jury remains out on interpretation of CGPS data acquired to date within the paradigm of elastic rebound. What would GPS have observed in the decades leading up to the 1811–1812 earthquake sequence? To date, for both plate boundary and stable plate earthquakes, GPS has not detected a geodetic signature that forecasts the occurrence of an earthquake. In central and eastern North America (NAM), at scales much larger than the faults in the NMSZ, there is little to no tectonic deformation detectable with space geodetic data, including GPS. What is not known with sufficient precision, however, is the deformation field at the scale of the NMSZ faults. Determining deformation associated with the NMSZ, or geologically meaningful upper bounds for it, requires spatial sampling at fault scale. If deformation is local, the lack of observable far field deformation in stable NAM can very well be true, but not useful in terms of explaining the relevant observations—that there have been large, recent repeating earthquakes in New Madrid over the past several thousand years. In addition because deformation expected on local scales remains small (less than several mm/yr), continuous measurements on stable monuments are essential to improve the statistics of the basic measurement.

Whether or not one can identify deformation in the NMSZ depends not only on the magnitude of the difference from stable North America, but also the number of sites defining the deformation and their noise characteristics. The key to distinguishing the NMSZ deformation is being able to identify a statistically significant systematic pattern in the residual velocity field with respect to stable N. America, which requires dense sampling and low noise in the region being tested.

Damage to Ozark Cave Formations, Ozark Caves, and the New Madrid Seismic Zone—A Nascent Paleoseismological Perspective

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Canvassing of selected Ozark caves in Missouri and Arkansas has identified several promising natural laboratories that apparently preserve stratigraphic evidence of repeated, episodic breakage of delicate as well as more massive cave formations (speleothems), including episodic repeated collapse of thin-bedded Paleozoic limestone cave ceiling strata that bury successions of small dripstone deposits, and toppling of columns or stalagmite formations. Field evidence suggestive of earthquake-wrought damage includes the observations that at least four episodes of breakage are preserved in some caves. (Excavation of selected areas likely would reveal earlier events.) Moreover, observed damage is apparently episodic and "quantized" in that broken fragments of soda straw stalactites or columns that rest on active flowstone substrates are either essentially unburied or minimally cemented into place, or are about 30% buried, or 50% to 66% buried, or nearly totally buried, with little or no "in between" stages of burial/breakage observed. Further, as one examines caves located at progressively greater distances from New Madrid, Missouri, at distances greater than 160–180 km, breakage of delicate formations is apparently absent or at least no longer so readily apparent. In some ways, this study is analogous to the "precarious rocks" problem, but is still in its infancy. Not all delicate formations are created equal; certain cave settings seem to be more delicate than others, and additional studies will be required to address the question of how best to quantify "relative delicacy" versus "absolute delicacy" of various cave deposits with respect to earthquake shaking damage. There are many tough analysis of variance issues yet to be resolved.

The emergence of ultra-sensitive analytical mass spectrometers capable of dating cave travertine <100 years old using Uranium-Thorium techniques makes it possible to sample broken formations and determine "kill" dates, as detaching a "soda straw" stalactite from its drip source terminates its growth. An initial round of samples of broken speleothems is presently being radiometrically dated; I anticipate having initial results of the U-series dating within the next couple of months. Presumably our youngest event will be the 1811–1812 earthquake sequence.

Cave conservationists should take heart. No speleothems were broken from growth positions for this study. Rather, only broken fragments preserving the formerly active growth tip were sampled. Obviously, the record of paleoearthquakes preserved in this manner may not be robust, as once broken, formations must re-grow prior to being able to be broken again. There is also no guarantee that all delicate formations are broken in a given earthquake.

In conducting this reconnaissance work, it is imperative to select against caves in which there is extensive vandalism or travertine "mining" or areas in which delicate formations may have been broken owing to human caver traffic or from errant flying mammals. I am pleased to acknowledge initial funding from the Nuclear Regulatory Commission for these studies and the capable assistance and guidance of personnel of the Cave Research Foundation with field phases of this investigation.

Migration of Large Earthquakes Indicates Distributed Strain in the Central United States

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Although incomplete for certain time periods and geographical areas, the paleoearthquake record suggests that the New Madrid fault zone produced 1811–1812 type events every 500–2,000 years during the past 4.5 ky and that other faults related to the Reelfoot rift produced similar events during the past 60 ky. The 1811–1812 New Madrid earthquakes of magnitude 7 to 8 and several similar prehistoric events about 1450 A.D., 900 A.D., 2,350 B.C., and possibly 1,000 B.C., left their mark on the landscape in the form of earthquake-induced liquefaction features and related ground failures, uplift and subsidence of large tracts of land, folding and faulting of river deposits, and abrupt changes to river channels. In addition, very large earthquakes are attributed to faults outside the New Madrid seismic zone proper but still associated with the Reelfoot rift. Seismicity appears to have migrated from one part of the rift to another over the course of 5–15 ky. For example, the northern portion of the Eastern Reelfoot Rift Margin fault in western Tennessee, was active about 11–10 ka, and possibly as recently as 2 ka; the southern portion of the fault near Marianna, Arkansas, may have been active from 6.8–5.5 ka, and possibly as early as 10 ka; and the New Madrid fault zone was active by 4.5 ka and remains active today. These observations suggest that deformation may be localized by the rift, but distributed across multiple faults and over a much larger area than the New Madrid seismic zone. This would result in spatial and temporal variations in fault loading and help to explain possibly low strain rates estimated from recent geodetic measurements. An important implication of these findings is that faults within the Reelfoot rift that have been aseismic during the historical period may become active in the future. With a more complete paleoearthquake record, as well as a better understanding of the geologic structures and tectonic forces controlling the location and periodicity of seismicity, it may be possible to better forecast where and when very large earthquakes are likely to occur in the future. Similar studies in other intraplate areas could show whether the New Madrid region is unique or typical of complex intraplate settings.

Geologic Model Testing in the New Madrid Seismic Zone Region

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Numerous geologic models have been published for the New Madrid seismic zone and Reelfoot rift. We have proposed (Csontos and others, 2008) that the Reelfoot rift consists of the well documented northeast-trending Cambrian basement faults, but that the rift is cross-cut by northwest-trending Proterozoic faults resulting in a Precambrian basement made of fault-bounded blocks. We believe that surface and near-surface landforms like the Lake County Uplift, Joiner ridge, and southern half of Crowley's Ridge are compressional stepovers caused by right-lateral shear across the Reelfoot rift and that these structurally controlled landforms initiate from basement fault intersections. In our model, Quaternary faulting moves throughout the rift and the most recent displacement history may have progressed from the southern portion of the rift to its Holocene location in the northern portion of the rift in the New Madrid seismic zone. This possible northeastern migration of seismicity during the Quaternary may be related to the Quaternary denudational history of the central Mississippi River valley (Van Arsdale and others, 2007).

Our research (Csontos and others, 2008; Csontos and Van Arsdale, 2008) also indicates that the Reelfoot fault is a southwest-dipping reverse fault in the post-Cambrian section, but that it is a normal fault in the underlying Cambrian and Precambrian section. Thus, the Reelfoot fault is an inverted fault that probably originated as the Proterozoic Grand River tectonic zone. In this model, the Reelfoot fault forms the northern boundary of the Reelfoot rift. If true, then the Reelfoot rift basin does not continue northeast into the Rough Creek graben.

These models could be tested. Deep seismic reflection profiles could establish the existence of the basement faults at key locations to test our Reelfoot rift model. Similarly, a deep reflection profile could be acquired across the Reelfoot fault to determine if it is a rift-bounding normal fault. Dating of fault and earthquake liquefaction activity throughout the Reelfoot rift may show migration patterns during the Quaternary that parallel the Mississippi valley denudation history.

The Central U.S. Seismic Observatory (CUSSO) and its Implication

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A combination of strong-motion accelerometers and medium period seismometers are now under installation at varying depths in the 1,950-foot (594 meter) borehole at the Central U.S. Seismic Observatory (CUSSO) in Fulton County, Ky. The borehole penetrated the entire sediment overburden (586 m) and was terminated 8 meters into limestone bedrock. Prior to casing the hole, electrical, sonic velocity (P- and S-wave) and deviation logs were acquired. Other site characterizations have also been conducted at CUSSO.

Estimating strong ground motions of engineering interest in the thick soil/sediment deposits in the upper Mississippi embayment is problematic. The problems include 1) site effects due to thick (>100 m) layers of low shear-wave velocity sediments and 2) non-linearity. The installation of strong-motion accelerometers at CUSSO will give us the ability to measure strong-motions from the bedrock through the soil column to the surface and measure how the soil column changes the characteristics of strong motions as they propagate to the ground surface. The installation of medium period seismometers, (0.06–50 Hz) at CUSSO will also provide real records for studying the effect by the sediments on seismic wave propagation.

CUSSO, in combination of other instrumentations of the Kentucky Seismic and Strong-motion Network as well as other networks in the region, will provide a better constraint on seismic hazard and risk assessments in the central United States.

Status of Data Collection for the St. Louis Earthquake Hazards Mapping Project in 2009

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Subsurface and geospatial data were collected throughout the St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP) area and distributed to project partners. Collection of subsurface data including borehole logs and geophysical data from private and public sources focused on areas of data gaps, such as those in the vicinity of the confluence of the Missouri and Mississippi Rivers, the lower Meramec River, and urban areas developed prior to large scale collection of subsurface information. For example, the Missouri Department of Natural Resources has collected subsurface borehole and geophysical data in the vicinity of the confluence of the Missouri and Mississippi Rivers, which suggests that buried bedrock river channels occur at depths of up to 60 meters below the ground surface in parts of northeastern St. Charles County.

National Geospatial Agency (NGA) 133 Urban Areas Project images with a resolution of 0.3 meters covering the St. Louis metropolitan area for years 2004, 2006, and 2008 were acquired for use by SLAEHMP partners. These images cover the majority of the SLAEHMP project area. The NGA plans to collect imagery with a 0.15-meter spatial resolution in 2010. The Missouri State Emergency Management Agency (SEMA) provided a 1-meter LiDAR dataset of St. Charles County, Missouri, flown in 2008, covering the northern and western portions of the project area including the confluence of the Missouri and Mississippi Rivers. This dataset extends a few kilometers into Illinois, providing valuable information in the vicinity of Alton and Wood River, Illinois.

USGS Estimation of M(MAX) East of the Rocky Mountains

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Seismic-hazard assessments utilize Mmax, the moment magnitude M of the largest earthquake thought to be possible in a specified region. Mmax impacts hazard assessments for residential building codes, critical structures such as nuclear power plants, and other engineered structures and functions of society. In most of the central and eastern United States and adjacent Canada (CEUSAC), long recurrence intervals preclude historical observation of Mmax.

V. Slide Presentations