1-2019

# An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant: January 2013–December 2017

Zhenming Wang
*University of Kentucky*, zmwang@uky.edu

Edward W. Woolery
*University of Kentucky*, ewoolery@uky.edu

N. Seth Carpenter
*University of Kentucky*, seth.carpenter@uky.edu

## Repository Citation

Wang, Zhenming; Woolery, Edward W.; and Carpenter, N. Seth, "An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant: January 2013–December 2017" (2019). *Kentucky Geological Survey Report of Investigations*. 42.
https://uknowledge.uky.edu/kgs_ri/42

**Kentucky Geological Survey**
University of Kentucky, Lexington

# An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant: January 2013–December 2017

Zhenming Wang, Edward W. Woolery, and
N. Seth Carpenter

Report of Investigations 6 doi.org/10.13023/kgs.ri06.13 Series XIII, 2019

## Our Mission

The Kentucky Geological Survey is a state-supported research center and public resource within the University of Kentucky. Our mission is to support sustainable prosperity of the commonwealth, the vitality of its flagship university, and the welfare of its people. We do this by conducting research and providing unbiased information about geologic resources, environmental issues, and natural hazards affecting Kentucky.

## Earth Resources—Our Common Wealth

**www.uky.edu/kgs**

For further information contact:
Technology Transfer Officer
Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, KY 40506-0107

## Technical Level

## Statement of Benefit to Kentucky

Continuing efforts to monitor earthquakes and conduct research have enhanced our understanding of seismic hazards in western Kentucky, which in turn has contributed to a sound scientific basis for developing design ground motions for buildings and facilities in western Kentucky, in particular at the Paducah Gaseous Diffusion Plant.

**ISSN 0075-5591**

# Contents

# Figures

# Tables

# An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant: January 2013–December 2017

**Zhenming Wang, Edward W. Woolery, and N. Seth Carpenter**

## Abstract

From January 2013 to December 2017, the Kentucky Geological Survey monitored earthquakes and conducted research on seismic hazards in the vicinity of the Paducah Gaseous Diffusion Plant, a former uranium enrichment facility, in western Kentucky. Fifteen earthquakes with magnitude greater than 3.0 occurred in the area during this period, and data were collected from the Central U.S. Seismic Observatory and the vertical seismic array at the gaseous diffusion plant. This monitoring improved our understanding of seismic-wave propagation through thick sediments and ground-motion site effects, as well as fault locations in the New Madrid Seismic Zone, ground-motion attenuation, and seismic-hazard assessment. Results have been communicated through publications and presentations at workshops and conferences. The data will contribute to the development of design ground motions for western Kentucky, and specifically for buildings and facilities at the Paducah Gaseous Diffusion Plant.

## Introduction

Engineering seismic design became a major concern for the Paducah Gaseous Diffusion Plant, a former uranium enrichment facility in western Kentucky, when the 1997 National Earthquake Hazards Reduction Program Provisions (Building Seismic Safety Council, 1998) were adopted in the early 2000s. The design 0.2 s response acceleration (PSA) in Paducah, Ky., was increased by about a factor of four, from 0.25 g in the 1994 edition of the provisions (Building Seismic Safety Council, 1995) to 1.083 g in the 1997 edition (Building Seismic Safety Council, 1998) (Table 1). This caused the U.S. Department of Energy to have difficulty obtaining a permit from federal and state regulators to construct a landfill at the plant in the early 2000s (James E. Beavers Consultants, 2010). The design values were developed from the ground motions with 2 percent probability of exceedance in 50 yr produced by the U.S. Geological Survey (Frankel and others, 1996, 2002; Petersen and others, 2008, 2014). Table 2 shows that the ground motions for Paducah estimated by the USGS are higher than the design values (Table 1). These ground-motion estimates and resulting high design values have been an issue for the plant, as well as for western Kentucky in general.

In order to address the seismic-hazard assessment and engineering-design issues for the Paducah Gaseous Diffusion Plant, as well as for western Kentucky in general, the Kentucky Geological Survey, in conjunction with the University of Kentucky Department of Earth and Environmental Sciences, carried out comprehensive research with partial support from the U.S. Department of Energy through the Kentucky Research Consortium for Energy and Environment. Phase I of the research was from 2003 to 2007 and phase II was from 2009 to 2012. We installed and maintained a temporary

**Table 1.** Design ground motions for Paducah, San Francisco, and Los Angeles. *The value was obtained from the effective peak acceleration ($A_a$) × 2.5. †The value (0.10) was the effective peak velocity-related acceleration ($A_V$).

| *NEHRP Recommended Provisions Edition* | *Paducah* | | *San Francisco* | | *Los Angeles* | |
|---|---|---|---|---|---|---|
| | *0.2 s PSA (g)* | *1.0 s PSA (g)* | *0.2 s PSA (g)* | *1.0 s PSA (g)* | *0.2 s PSA (g)* | *1.0 s PSA (g)* |
| 1994 (Building Seismic Safety Council, 1995) | 0.25* | 0.10† | 1.00* | 0.40† | 1.00* | 0.40† |
| 1997 (Building Seismic Safety Council, 1998) | 1.083 | 0.333 | 1.000 | 0.400 | 1.000 | 0.400 |
| 2003 (Building Seismic Safety Council, 2004) | 1.000 | 0.333 | 1.000 | 0.406 | 1.386 | 0.468 |
| 2009 (Building Seismic Safety Council, 2009) | 0.837 | 0.287 | 1.000 | 0.400 | 1.563 | 0.548 |
| 2015 (Building Seismic Safety Council, 2015) | 0.672 | 0.223 | 0.900 | 0.320 | 1.165 | 0.369 |

**Table 2.** Ground motions for Paducah estimated by the U.S. Geological Survey.

| *Ground Motions With 2 Percent Probability of Exceedance in 50 Yr* | | | |
|---|---|---|---|
| *Year* | *PGA (g)* | *0.2 s PSA (g)* | *1.0 s PSA (g)* |
| 1996 | 0.826 | 1.566 | 0.463 |
| 2002 | 0.918 | 1.698 | 0.466 |
| 2008 | 0.754 | 1.423 | 0.412 |
| 2014 | 0.609 | 1.054 | 0.300 |

seismic network in the vicinity of the gaseous diffusion plant and analyzed the USGS probabilistic seismic-hazard maps and scenario ground-motion hazards. Phase I resulted in publications by Wang (2003, 2005, 2006, 2007, 2008), Wang and others (2003), Wang and Ormsbee (2005), Wang and Woolery (2006, 2008), and Woolery and others (2008). Phase II resulted in publications by Wang (2010, 2011), Wang and Lu (2011), Wang and Cobb (2012), Wang and others (2012), and Wang and Woolery (2013). The most significant outcomes from both phases are:

1. A better understanding of earthquake science and seismic-hazard assessment in western Kentucky and the central United States, resulting in a sound scientific basis for the development of design ground motions for buildings and facilities in the area.
2. Downward revision of the design ground motion to 0.33 g PGA for a landfill at the plant, which allowed the Department of Energy to obtain permits from federal and state regulators to construct the landfill.
3. Revision of the Kentucky Residential Codes for western Kentucky, including Paducah.
4. Establishment of the Central United States Seismic Observatory.

This update summarizes the continuing research carried out by the Kentucky Geological Survey and UK Department of Earth and Environmental Sciences from January 2013 to December 2017.

## Seismic and Strong-Motion Network Operation and Data Analysis

The Kentucky Geological Survey continued operation of the Kentucky Seismic and Strong-Motion Network in the vicinity of the gaseous diffusion plant between January 2013 and December 2017. Figure 1 shows the current station and instrumentation configuration, which focuses on monitoring in the New Madrid Seismic Zone. Seismometers for detecting seismic events are in operation at seven of the stations and at least one strong-motion sensor is in operation at 10 stations. Recordings from five of the stations are telemetered to KGS over the internet; the remaining stations are stand-alone, and are visited approximately bimonthly to download recordings. These stations, particularly the seismic stations, record earthquakes on local and global scales. The real-time recordings are shared

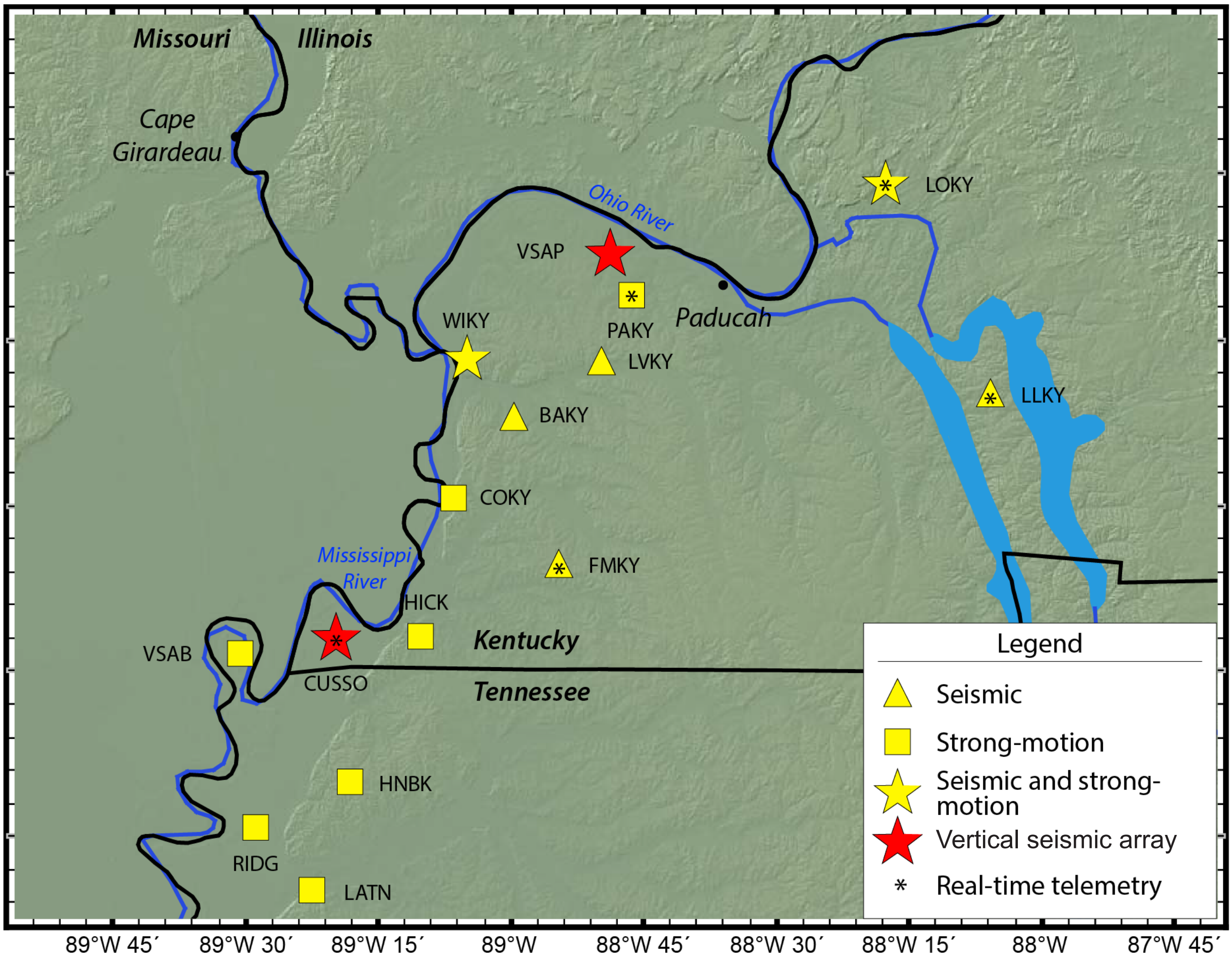


Figure 1. Seismic and strong-motion stations operated in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017. Kentucky Seismic and Strong-Motion station VSAP is located at the plant.

with the neighboring seismic-monitoring network operated by the University of Memphis.

Since 2013, all but one of the telemetered seismic stations have been upgraded with on-site digital data acquisition systems, including PAKY (Paducah Airport), FMKY (Fulgham, Ky.), and LOKY (Salem, Ky.). Strong-motion accelerometers were installed at PAKY and LOKY. All but two of the stations deployed in the Jackson Purchase Region of Kentucky as part of the temporary seismic-monitoring project in the vicinity of the Paducah Gaseous Diffusion Plant (Wang and Woolery, 2013) were removed prior to 2013. Of the remaining two stations, LVKY (Lovelaceville, Ky.) was removed in April 2013 and BAKY (Bardwell, Ky.) continues to operate.

Operation of several stations has been interrupted because of local site issues. The vertical seismic array sites, VSAP and CUSSO in particular, are discussed in the subsequent section. VSAB was flooded in 2013, and plans are to relocate it on higher ground. PAKY was struck by lightning in 2017 and is undergoing repair.

## Seismic-Data Analysis

The recordings from the seismic stations in the vicinity of the gaseous diffusion plant (Fig. 1) were analyzed in tandem with recordings from nearby regional seismic stations operated by other agencies to determine the source parameters of local-area earthquakes. Figure 2 shows the locations of earthquakes with magnitude greater than 1.0 that occurred in the vicinity of the plant from January 2013 to December 2017. Information on the 15 earthquakes of magnitude 3.0 and greater during this period is listed in Table 3. The earthquake clos-

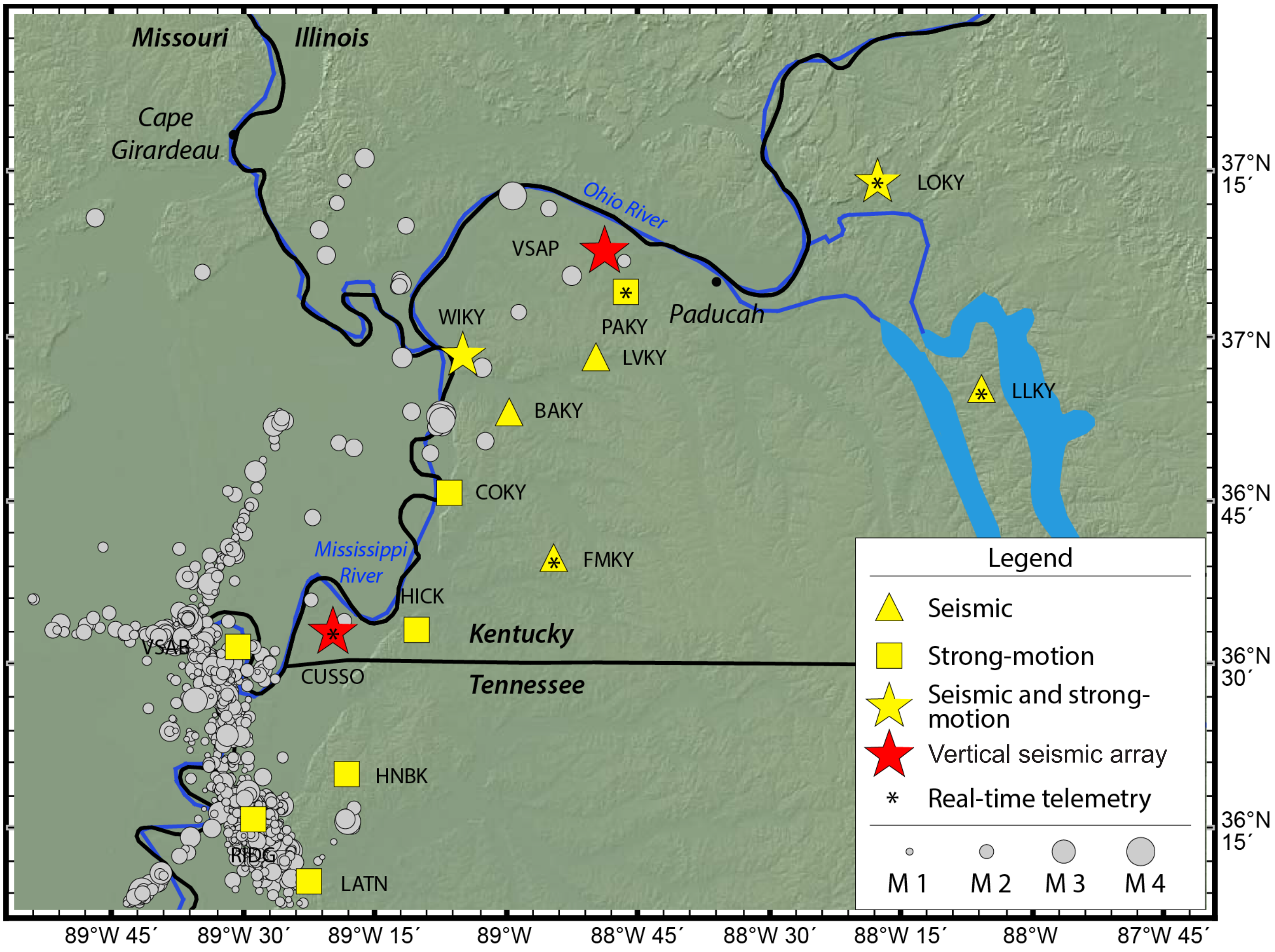


Figure 2. Locations of earthquakes occurring in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017. Kentucky Seismic and Strong-Motion station VSAP is located at the plant.

est to the plant was the magnitude-3.5 event that occurred May 1, 2016, approximately 20 km to the northwest in Ballard County. Figure 3 shows three orthogonal-component recordings from nearby station VSAP (17 km away) and PAKY (24 km away), and the peak ground accelerations recorded at both sites.

## Analysis of CUSSO and VSAP Data

The vertical seismic and strong-motion array at CUSSO was functional intermittently between 2009 and 2012; it recorded many local, regional, and distant events (Woolery and others, 2016a, b). Figure 4 shows the history of instrument operations and recorded earthquakes at CUSSO. All the records from CUSSO were checked and corrected to ensure data quality (Woolery and others, 2016a, b). Some preliminary analysis was conducted on the records (Woolery and others, 2016a, b). VSAP was relocated to outside the perimeter of the Paducah Gaseous Diffusion Plant for security reasons in 2004 and was in operation until 2014, when the borehole accelerometers stopped functioning because of age. Table 4 lists the records from VSAP that were checked and corrected.

The data from CUSSO and VSAP have been used to study seismic-wave propagation and site effects (Rong and others, 2017; Carpenter and others, in review). Figure 5 shows the mean spectral ratio of S-waves between the surface and bedrock ($TF_T$), horizontal-to-vertical ratio (HVSR) of S-waves at the surface ($HV_S$), and theoretical Thomson-Haskell SH-wave transfer functions ($TH_{SH}$) at VSAP (left) and CUSSO (right). As shown in the figure, the theoretical transfer function is very

**Table 3.** Earthquakes of magnitude 3.0 and greater in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017 (from Figure 2).

| *Magnitude* | *Date* | *Time (UTC)* | *Latitude (°N)* | *Longitude (°E)* | *Depth (km)* | *Location* |
|---|---|---|---|---|---|---|
| 3.3 | 08/12/2013 | 21:43:24.30 | 36.261 | –89.301 | 4.4 | Obion, Tenn. |
| 3.1 | 04/07/2014 | 06:24:12.92 | 36.216 | –89.410 | 6.3 | Ridgely, Tenn. |
| 3.1 | 05/15/2014 | 15:44:58.34 | 36.558 | –90.020 | 5.6 | Malden, Mo. |
| 3.1 | 02/28/2015 | 23:08:44.45 | 36.536 | –89.639 | 13.4 | Lilbourn, Mo. |
| 3.0 | 11/25/2015 | 07:08:53.12 | 36.538 | –89.601 | 8.7 | Lilbourn, Mo. |
| 3.5 | 05/01/2016 | 06:12:10.03 | 37.214 | –88.988 | 16.3 | La Center, Ky. |
| 3.0 | 07/05/2016 | 04:51:13.02 | 36.151 | –89.697 | 9.0 | Caruthersville, Mo. |
| 3.4 | 09/09/2016 | 13:45:37.56 | 36.453 | –89.535 | 10.3 | Tiptonville, Tenn. |
| 3.3 | 11/24/2016 | 01:57:37.58 | 36.155 | –89.693 | 8.8 | Caruthersville, Mo. |
| 3.6 | 3/15/2017 | 16:51:10.09 | 36.882 | –89.123 | 8.4 | Wickliffe, Ky. |
| 3.2 | 3/19/2017 | 14:25:12.57 | 36.880 | –89.128 | 12.2 | Bardwell, Ky. |
| 3.0 | 5/14/2017 | 12:56:24.05 | 36.564 | –89.599 | 13.6 | Lilbourn, Mo. |
| 3.3 | 05/16/2017 | 10:21:52.24 | 36.873 | –89.122 | 9.1 | Bardwell, Ky. |
| 3.0 | 07/31/2017 | 02:16:19.62 | 36.306 | –89.490 | 4.8 | Ridgely, Tenn. |
| 3.2 | 08/18/2017 | 15:18:21.07 | 36.447 | –89.592 | 12.6 | Portageville, Mo. |

similar to the observed transfer function ($TF_T$); it also shows that the S-wave HVSR is very similar to the observed transfer function. These results suggest that a 1-D theoretical model (transfer function) provides a good approximation of site effect, and the S-wave HVSR could be used as an empirical transfer function of site effect.

## Seismic-Hazard Assessment and Communication

### *New Madrid Active Faults*

Although the New Madrid Seismic Zone has been and continues to be intensely studied, the locations of active faults within the zone remain uncertain. As shown in Figure 6, the U.S. Geological Survey postulated five alternative locations for the New Madrid faults in its 2008 and 2014 national seismic-hazard maps (Petersen and others, 2008, 2014). Thus, more accurate determination of fault locations in the zone is important for seismic-hazard assessments in western Kentucky. Edward Woolery and his students at the University of Kentucky have been working with researchers at the University of Memphis to better determine these fault locations using both geologic and geophysical field investigations (Pryne and others, 2013; Van Arsdale and others, 2013; Woolery and Almayahi, 2014; Greenwood and others, 2016; Rucker, 2017). As shown in Figure 7, the seismicity and subsurface geologic features clearly indicate the location of the Reelfoot Thrust Fault.

Pryne and others (2013) acquired two exploratory seismic walkaway soundings (MP-35 and MP-80) (Fig. 8) across the northern boundary of a 30 km × 7.2 km stratigraphic uplift in the northeastern vicinity of the New Madrid North Fault to look for evidence of genesis (i.e., neotectonic or fluvial) (Fig. 9). The previously unknown uplift, which Pryne and others (2013) called the Charleston Uplift, was discovered using 520 electric logs from shallow (100 m) lignite exploration wells and geospatial stratigraphic mapping. Although there are no known surface faults bounding this feature, Pryne and others (2013) hypothesized that the more than 30 m of structural amplitude exhibited in the mapping of Quaternary and Tertiary horizons based on well logs had a tectonic origin. The two seismic soundings were performed north of and within the uplift to further test this hypothesis. Results indicate 47 and 60 m of relief across the tops of the deeper Cretaceous and Paleozoic horizons, respectively (Fig. 9). A subsequent University of Kentucky master's thesis by Rucker (2017) used an additional 18 seismic soundings and one ground-penetrating-radar profile to confirm Paleozoic

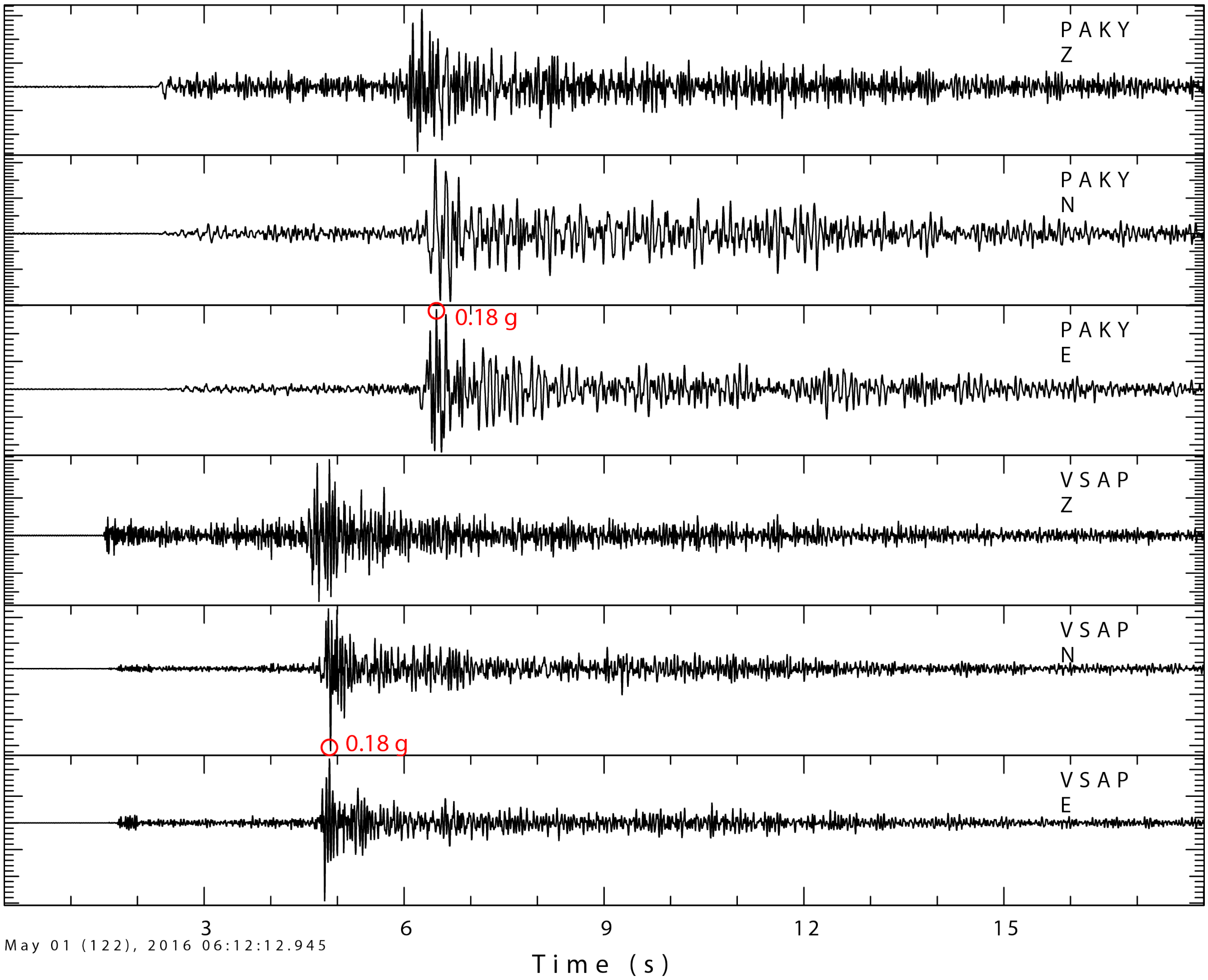


Figure 3. Example recordings by the seismic-monitoring network. Three-component recordings of the May 1, 2016, magnitude-3.5 earthquake near La Center, Ky., from VSAP (17 km away) and PAKY (24 km away). Peak ground accelerations (acceleration due to gravity) are labeled.

and Cretaceous offset across the boundaries of the uplift, and better constrain the surface projection of the uplift (Fig. 10). Results from Rucker's thesis (2017) confirm Paleozoic and Cretaceous offset throughout the uplift, as well as indicate that the preliminary boundaries proposed by Pryne and others (2013) are appropriate. The N46°E trend of the uplift, as well as its coincidence with contemporary microseismicity, suggest that this feature may be related to the New Madrid Seismic Zone, specifically the New Madrid North Fault.

## *Ground-Motion Attenuation*

The ground-motion attenuation relationship, also known as the ground-motion prediction equation, is an important parameter for seismic-hazard assessment. The GMPE for the western United States was developed from ground-motion observations along the West Coast, California in particular (Joyner and Boore, 1981). In contrast, GMPEs for the central and eastern United States are developed either solely from computer simulations or from computer simulations with limited observations of small to moderate earthquakes ($M < 6.0$). For example, Atkinson and Boore (2006) developed a GMPE from synthetic records based on stochastic

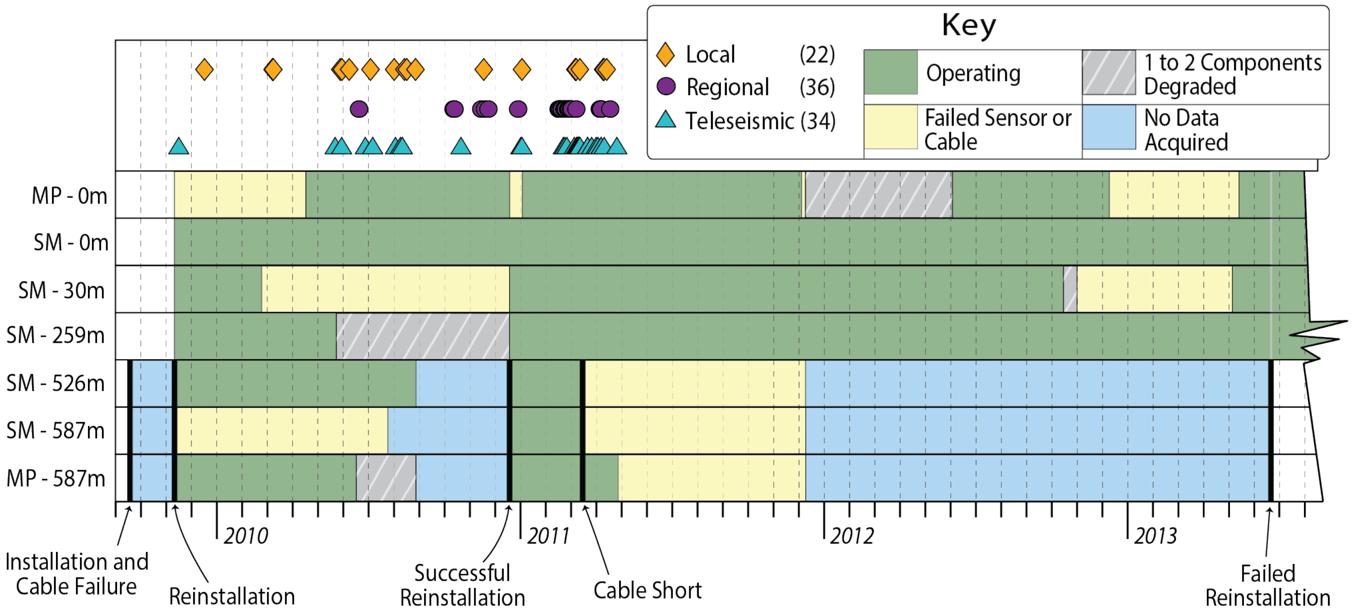


Figure 4. Summary of CUSSO's operational history. MP = median-period seismic sensor. SM = strong-motion sensor. Numbers beside MP and SM are sensor depths below the surface in meters.

**Table 4.** Earthquakes recorded at station VSAP between 2004 and 2014.

| *Date* | *Time (UTC)* | *Latitude (°N)* | *Longitude (°E)* | *Depth (km)* | *Magnitude* | *Distance (km)* |
|---|---|---|---|---|---|---|
| 05/01/2005 | 12:37 | 35.83 | –90.15 | 10.0 | 4.2 | 187 |
| 06/02/2005 | 11:35 | 36.15 | –89.47 | 15.0 | 4.0 | 124 |
| 06/20/2005 | 02:00 | 36.39 | –88.99 | 7.7 | 2.7 | 27 |
| 06/20/2005 | 12:21 | 36.92 | –89.00 | 18.7 | 3.6 | 28 |
| 06/27/2005 | 15:46 | 37.63 | –89.42 | 9.6 | 3.0 | 77 |
| 01/02/2006 | 21:48 | 37.84 | –88.42 | 7.3 | 3.6 | 86 |
| 04/18/2008 | 09:36 | 38.45 | –87.89 | 14.2 | 5.2 | 168 |
| 04/18/2008 | 15:14 | 38.46 | –87.87 | 15.5 | 4.7 | 169 |
| 04/21/2008 | 05:38 | 38.45 | –87.88 | 18.3 | 4.0 | 168 |
| 03/02/2010 | 19:37 | 36.79 | –89.36 | 8.2 | 3.7 | 61 |

finite-fault simulations. Thus, GMPEs for the central and eastern United States need to be refined by ground-motion observations, in particular from large (M > 7.0) earthquakes.

The 2008 Wenchuan, China, earthquake (M 7.9) occurred along the Longmenshan Fault (Burchfiel and others, 2008), which is located on the western border of the South China stable continental region. Although the Wenchuan area is different from the central United States, the eastern part of it, the Sichuan Basin, is located in a stable continental region (Fig. 11) that is similar to the central and eastern United States (Wheeler, 2011). Thus, ground motions from the Wenchuan earthquake could be used to constrain GMPEs for the central United States; a preliminary comparison (Wang and Lu, 2011) suggested using the Wenchuan ground motions was appropriate. A detailed study compared GMPEs developed for the central United States with the one developed from the Wenchuan earthquake (Feng and others, 2015). Figure 12 compares GMPEs for the central United States (Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; Atkinson and Boore, 2006; Pezeshk and others, 2011) with the one developed from the Wenchuan earthquake (Feng and others, 2015). The results show that most of the ground-motion attenuations

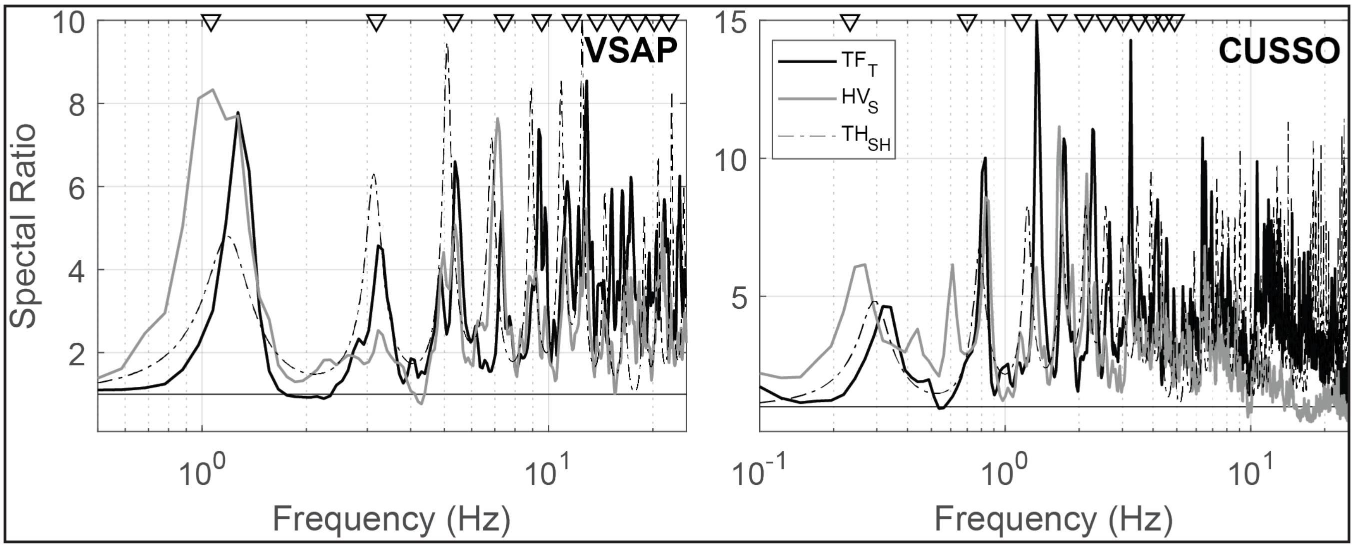


Figure 5. Mean spectral ratios from recordings at VSAP (left) and CUSSO (right), and theoretical Thomson-Haskell SH-wave transfer functions. TF$_T$ and HV$_S$ are surface-to-bedrock and surface horizontal-to-vertical spectral ratios, respectively. TH$_{SH}$ is the theoretical SH-wave transfer function. Inverted triangles show the SH-wave resonance modes predicted for each soil column.

for the central and eastern United States are similar to that for the Wenchuan area, except for the Atkinson and Boore GMPE (2006), which is significantly different at near-source distance. Thus, KGS used ground-motion data obtained from the Wenchuan earthquake to develop a GMPE for the central and eastern United States.

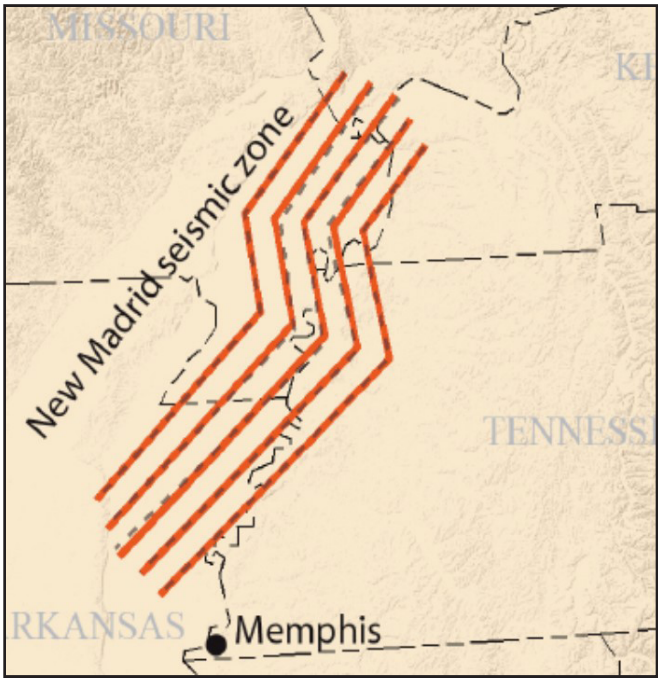


Figure 6. Locations of the active faults in the New Madrid Seismic Zone used in the USGS national seismic-hazard maps (Petersen and others, 2008, 2014). Dashed black lines are from the 2008 update, and the solid orange lines are from the 2014 update.

## *Seismic-Hazard Assessment*

In order to improve understanding and communication about ground-motion hazards in the central United States, KGS participates in workshops and holds discussions with the U.S. Geological Survey and other federal and state agencies about related issues. In July 2013, KGS provided an official comment on the 2014 national seismic-hazard maps. Zhenming Wang, Edward Woolery, and Seth Carpenter attended and gave presentations at a workshop, "CEUS Earthquake Hazards Research Review and Planning," Feb. 25–26, 2014, in Memphis, Tenn. Zhenming Wang participated in the Applied Technology Council/USGS Seismic Hazard User-Needs Workshop, Sept. 21–22, 2015, in Menlo Park, Calif., and gave a presentation, "The USGS National Seismic Hazard Mapping Project: Issues and Improvements." On Jan. 27, 2017, KGS and USGS staff met in Lexington, Ky., with representatives of the Structural Engineers Association of Kentucky and the state's Division of Solid Waste. The participants agreed that the New Madrid Seismic Zone poses a significant hazard to western Kentucky and that scenario-based seismic-hazard analysis can help convey the consequences of a major New Madrid earthquake to nonspecialists; however, the scenarios are limited because

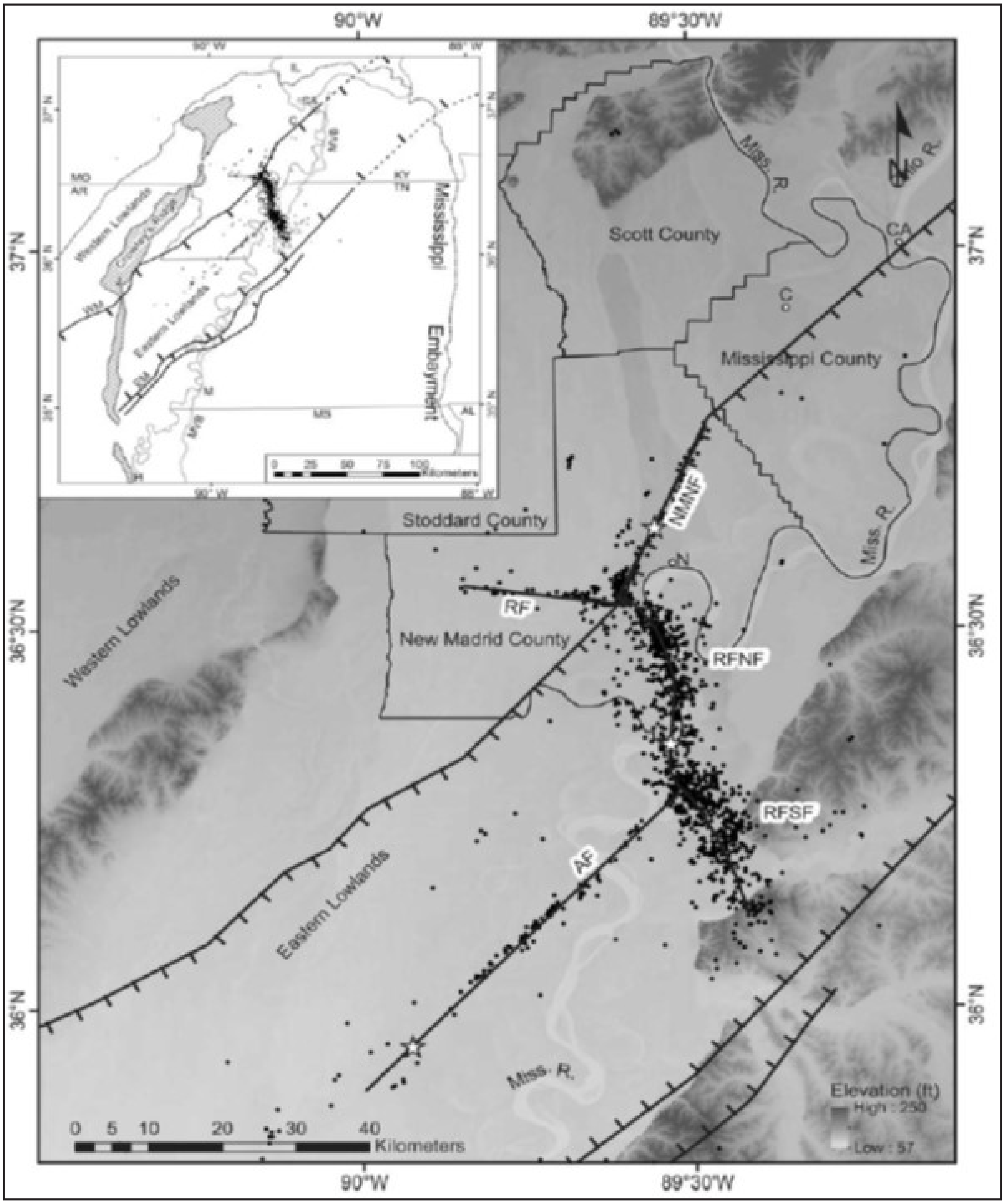


Figure 7. Seismicity (black dots), active faults (black lines), topography (grayscale background), and geologic features in the New Madrid Seismic Zone. AF = Axial Fault (Cottonwood Grove Fault). NMNF = New Madrid North Fault. RF = Reelfoot Fault. RFNF = Reelfoot North Fault. RFSF = Reelfoot South Fault. From Van Arsdale, R., Pryne, D., and Woolery, E., 2013, Northwestern extension of the Reelfoot North Fault near New Madrid, Missouri: Seismological Research Letters, v. 84, p. 1114–1123, doi:10.1785/0120120241. © Seismological Society of America.

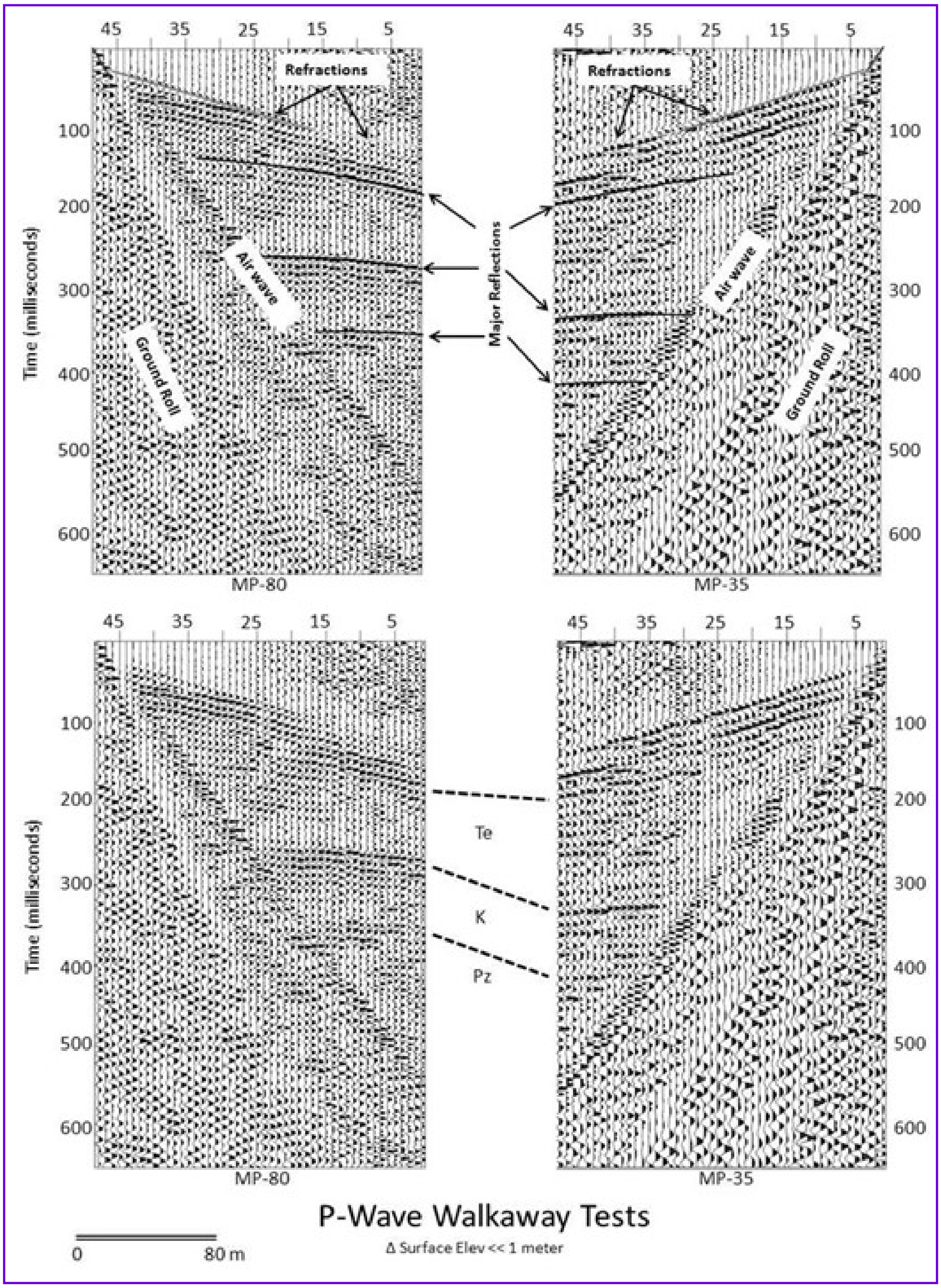


Figure 8. Two seismic-reflection soundings, MP-35 and MP-80, collected north of the Charleston Uplift and within the uplift, respectively. (top) Coherent phases, including ground roll, air wave, direct wave/refractions, and three significant reflections. (bottom) The two most prominent deeper reflections on both profiles are the tops of the Cretaceous (K) and Paleozoic (Pz) horizons. Relief across the K and Pz between the sites is 47 and 60 m, respectively. Approximately 19 m of relief is calculated across the Tertiary horizon. From Pryne, D., Van Arsdale, R., Csontos, R., and Woolery, E., 2013, Northeastern extension of the New Madrid North Fault, New Madrid Seismic Zone, central United States: Bulletin of the Seismological Society of America, v. 107, p. 2277–2294, doi:10.1785/0120120241. ©Seismological Society of America.

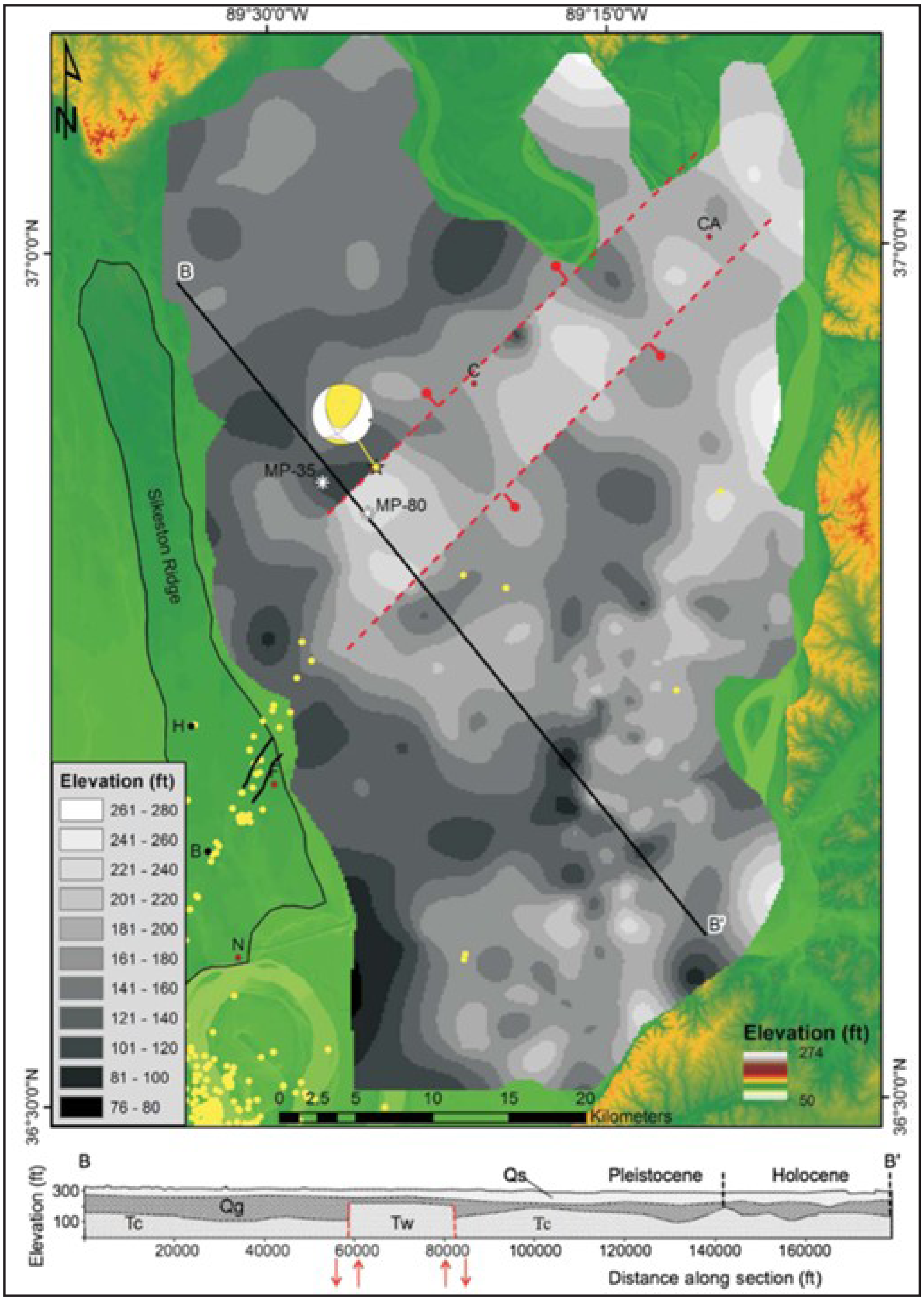


Figure 9. Top of the Paleogene (bottom of Quaternary Mississippi River gravel) structure contoured as separate surfaces, south, within, and north of the Charleston Uplift, and cross section B–B'. Location of the Feb. 21, 2012, earthquake and interpreted faults (represented by red lines with barbs on downthrown side). Red dots = wells. Contour interval = 6 m. C = Charleston. CA = Cairo. F = Farrenburg. N = New Madrid. Qs = Quaternary alluvial sand/silt/clay. Qg = Quaternary gravel. Tc = Tertiary Claiborne Formation. Tw = Tertiary Wilcox Group (Flour Island Formation). Cross section B–B', vertical exaggeration X40. Modified from Pryne, D., Van Arsdale, R., Csontos, R., and Woolery, E., 2013, Northeastern extension of the New Madrid North Fault, New Madrid Seismic Zone, central United States: Bulletin of the Seismological Society of America, v. 107, p. 2277–2294, doi:10.1785/0120120241. ©Seismological Society of America.

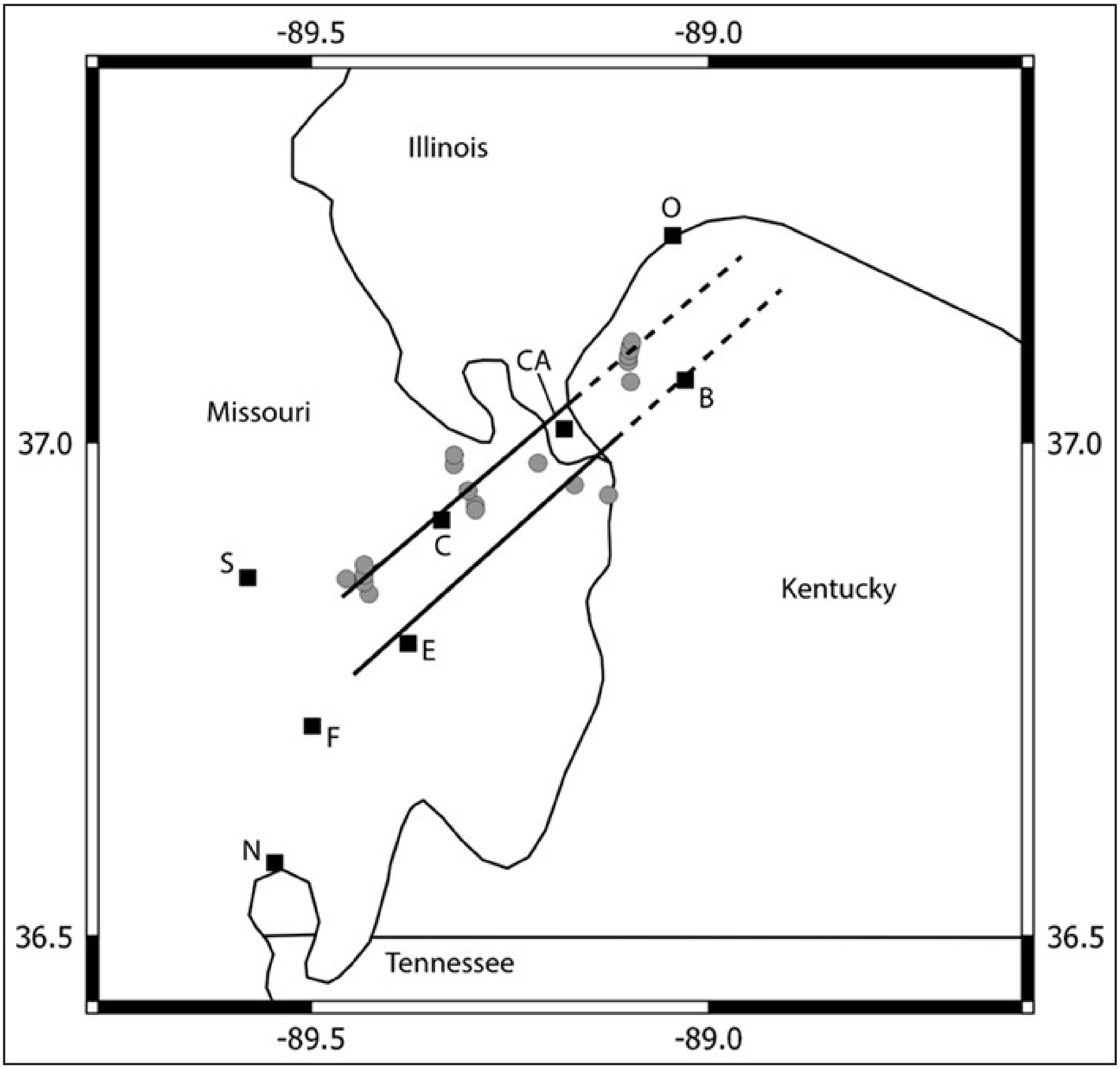


Figure 10. Charleston Uplift and field locations. Solid lines are the boundaries of the uplift from Pryne and others (2013). Dashed lines are the northeastward, straight-line projection of those boundaries into western Kentucky. Gray circles are field sites for seismic sounding. Black squares are population centers in the region: B = Barlow, Ky.; CA = Cairo, Ill.; C = Charleston, Mo.; E = East Prairie, Mo.; F = Farrenburg, Mo.; N = New Madrid, Mo.; S = Sikeston, Mo.; O = Olmsted, Ill. From Rucker (2017).

they cannot seamlessly incorporate uncertainties. KGS's policy is that probabilistic seismic hazard analysis (PSHA) is a valid method, although there may be disagreements among professionals regarding input data and details of the calculations.

KGS also conducts scenario-based seismic-hazard analyses and communicates the results to stakeholders. Figure 13 shows the mean peak ground acceleration for Kentucky from a scenario earthquake of M7.5 in the New Madrid Seismic Zone (Carpenter and others, 2014). Orton (2014) conducted scenario-based hazard analysis on a series of earthquakes in the New Madrid Seismic Zone; her results are summarized in Orton and others (2016) and Wang and others (2016). KGS also used scenario-based seismic-hazard analysis

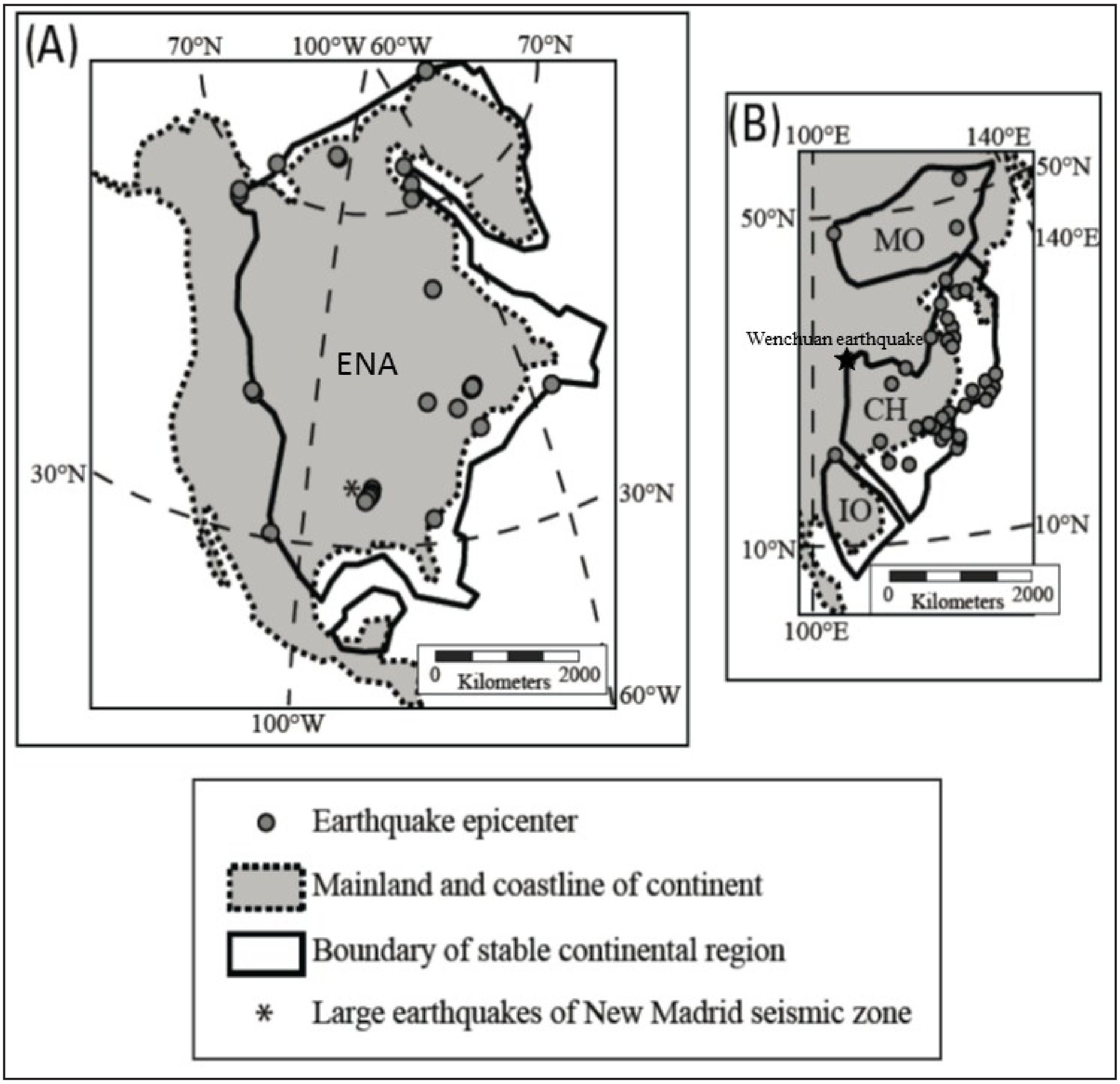


Figure 11. Stable continental regions of North America (A) and South China (B). Star = Wenchuan region. ENA = eastern North America stable continental region. CH = eastern China stable continental region. MO = Mongolia stable continental region. IO = Indochina stable continental region. Modified from Wheeler, R.L., 2011, Reassessment of stable continental regions of Southeast Asia: Seismological Research Letters, v. 82, p. 971–983, doi.org/10.1785/gssrl.82.6.971. ©Seismological Society of America.

to provide potential ground-motion hazards for a small induced earthquake in eastern Kentucky (Wang and others, 2017).

### Potential Loss Estimate and Mitigation Policy

Orton (2014) simulated potential losses for 36 scenario earthquakes with magnitude between 7.1 and 8.2 and focal depths of 10 and 20 km in the New Madrid Seismic Zone using the Federal Emergency Management Agency's Hazus-MH software (www.fema.gov/hazus-software; last accessed 01/15/2019). She also interviewed businesspeople, public officials, and other professionals in western Kentucky whose occupations are associated with

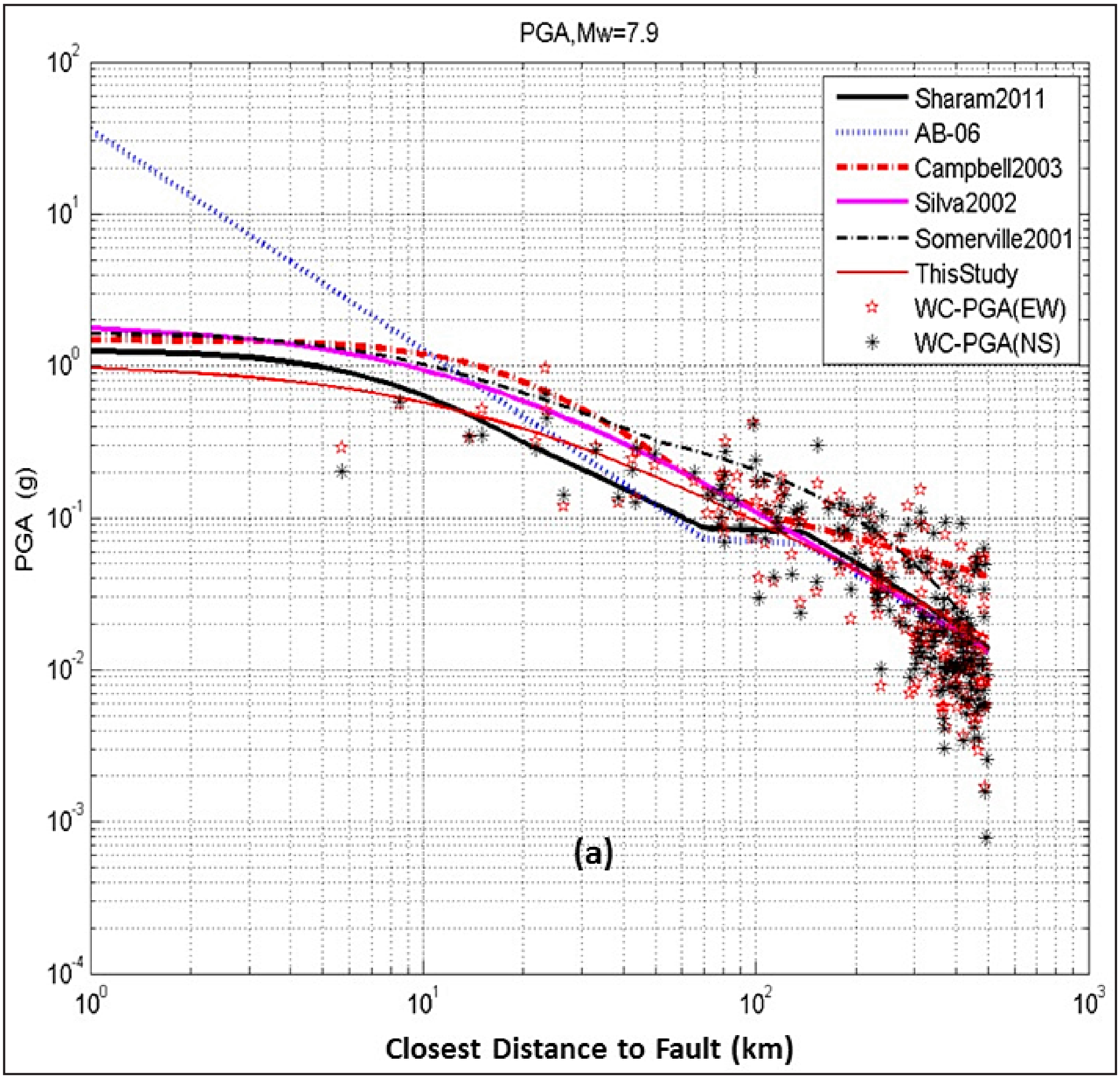
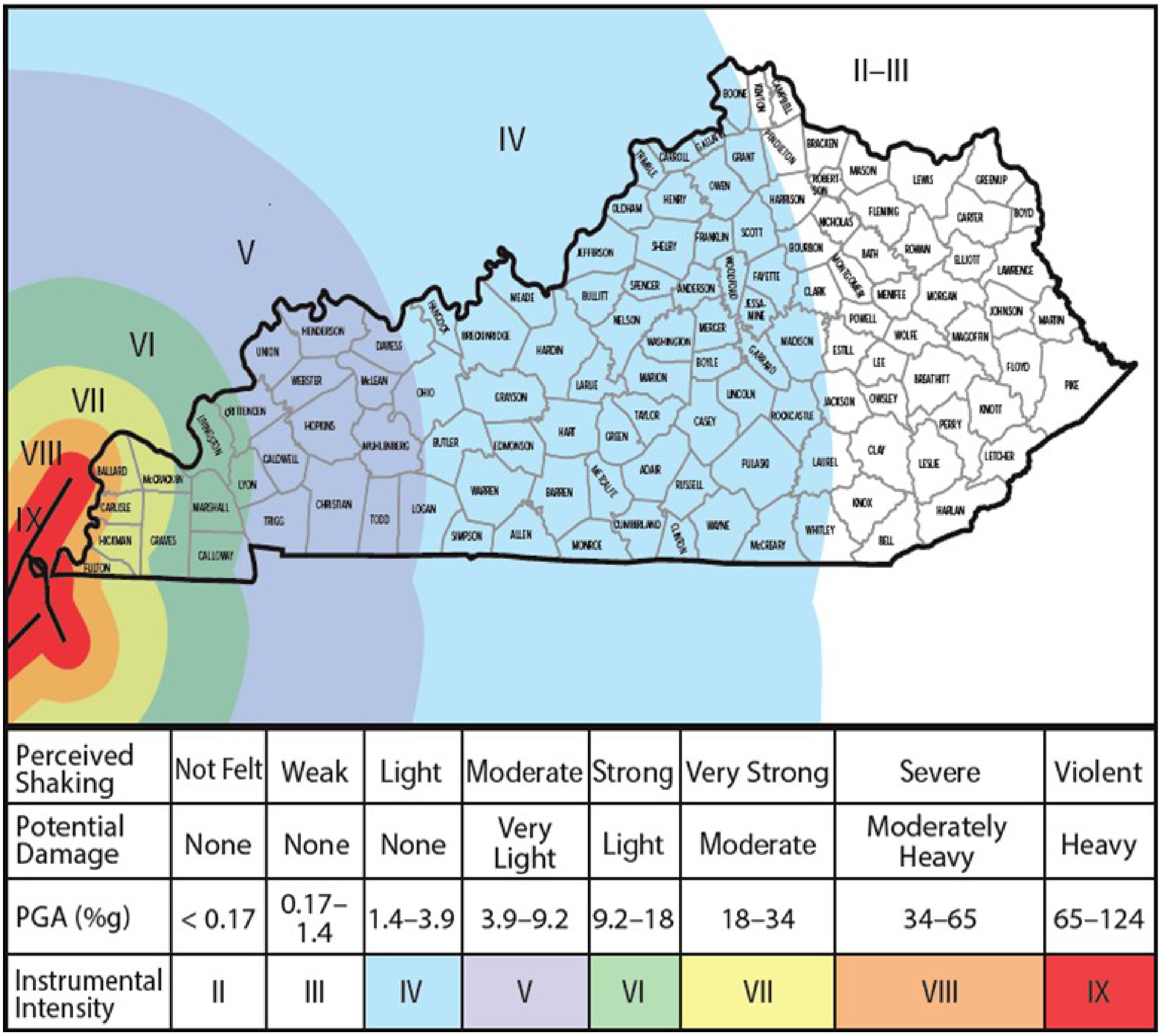


Figure 12. Comparison of ground-motion predictions for the Sichuan Basin and four GMPEs for the central and eastern United States for an M 7.9 earthquake (Feng and others, 2015). Sharam2011 from Pezeshk and others (2011). AB-06 from Atkinson and Boore (2006). Campbell2003 from Campbell (2003). Silva2002 from Silva and others (2002). Somerville2001 from Somerville and others (2001).

seismic mitigation in order to understand the perceived impacts of seismic-hazard assessment and resulting mitigation policies on economic development (Orton, 2014; Orton and others, 2016). The simulation results given in Orton (2014) showed that large uncertainties are inherent in the estimation of earthquake parameters, ground-motion values in particular, for the New Madrid Seismic Zone. Table 5 compares the maximum ground motions between the three scenario events simulated by Orton (2014), the observed values from the Wenchuan, China, earthquake, and probabilistic seismic-hazard analysis estimates by the U.S. Geological Survey for the New Madrid Seismic Zone (Petersen and others, 2014).



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Perceived Shaking | Not Felt | Weak | Light | Moderate | Strong | Very Strong | Severe | Violent |
| Potential Damage | None | None | None | Very Light | Light | Moderate | Moderately Heavy | Heavy |
| PGA (%g) | < 0.17 | 0.17–1.4 | 1.4–3.9 | 3.9–9.2 | 9.2–18 | 18–34 | 34–65 | 65–124 |
| Instrumental Intensity | II | III | IV | V | VI | VII | VIII | IX |

Figure 13. Predicted peak ground acceleration, in percentage of the acceleration of gravity, on hard rock (average shear-wave velocity is greater than 1,500 m/s) from a magnitude-7.5 scenario earthquake in the New Madrid Seismic Zone. From Carpenter and others (2014).

**Table 5.** Comparison of maximum ground motions for New Madrid scenario earthquakes. From Orton and others (2016). PGA = peak ground acceleration. SA0.3 = 0.3 s response acceleration. SA1.0 = 1.0 s response acceleration.

| *Model ID* | *Maximum PGA (g)* | *Maximum SA0.3 (g)* | *Maximum SA1.0 (g)* |
|---|---|---|---|
| A 4026 82 10/20 (M8.2) | 3.308 | 5.263 | 5.839 |
| C 4027 71 10/20 (M7.1) | 1.447 | 1.983 | 1.628 |
| SW Fault 1 (M7.7) | 1.100 | 1.380 | 1.140 |
| Wenchuan (M7.9) | 0.950 | 2.370 | 0.360 |
| national seismic hazard maps (2 percent in 50 yr) | 1.960 | 3.520 | 1.690 |

Orton's (2014) study also showed that the national seismic-hazard maps and resulting mitigation policies, such as building and residential codes, were perceived by her interview subjects to have adverse impacts on economic development in Kentucky, western Kentucky in particular; she did not perform a rigorous benefit-cost analysis to evaluate the possible value of stricter standards in reducing losses should a major New Madrid earthquake occur, however.

## Summary

From January 2013 to December 2017, KGS continued to monitor earthquakes and conduct research on seismic hazards in the vicinity of the Paducah Gaseous Diffusion Plant. Fifteen earthquakes with magnitude greater than 3.0 occurred in the vicinity of the plant during this period. We improved our understanding of seismic-wave propagation through thick sediments and ground-motion site effects using data collected from CUSSO and VSAP. We also improved our understanding of fault locations in the New Madrid Seismic Zone, ground-motion attenuation in the central United States, and seismic-hazard assessment. The data will contribute to the development of design ground motions for western Kentucky, and specifically for buildings and facilities at the Paducah Gaseous Diffusion Plant.

## References Cited

Atkinson, G.M., and Boore, D.M., 2006, Earthquake ground-motion prediction equations for eastern North America: Bulletin of the Seismological Society of America, v. 96, p. 2181–2205.

Building Seismic Safety Council, 1995, NEHRP recommended provisions for seismic regulations for new buildings [1994 ed.]: Federal Emergency Management Agency, FEMA 222, 290 p.

Building Seismic Safety Council, 1998, NEHRP recommended provisions for seismic regulations for new buildings [1997 ed.]: Federal Emergency Management Agency, FEMA 302, 337 p.

Building Seismic Safety Council, 2004, NEHRP recommended provisions for seismic regulations for new buildings [2003 ed.]: Federal Emergency Management Agency, FEMA 450, 356 p.

Building Seismic Safety Council, 2009, NEHRP recommended provisions for seismic regulations for new buildings [2009 ed.]: Federal Emergency Management Agency, FEMA P-750, 372 p.

Building Seismic Safety Council, 2015, NEHRP recommended provisions for seismic regulations for new buildings [2015 ed.]: Federal Emergency Management Agency, FEMA P-1050, 555 p.

Burchfiel, B.C., Royden, L.H., van der Hilst, R.D., Hager, B.H., Chen, Z., King, R.W., Li, C., Lü, J., Yao, H., and Kirby, E., 2008, A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China: GSA Today, v. 18, no. 7, p. 4–11, doi:10.1130/GSATG18A.1.

Campbell, K.W., 2003, Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America: Bulletin of the Seismological Society of America, v. 93, p. 1012–1033.

Carpenter, N.S., Wang, Z., and Lynch, M., 2014, Earthquakes in Kentucky: Hazards, mitigation, and emergency preparedness: Kentucky Geological Survey, ser. 12, Special Publication 17, 11 p.

Carpenter, N.S., Wang, Z., Woolery, E.W., and Rong, M., in review, Estimating site response with recordings from deep boreholes and HVSR: Examples from the Mississippi Embayment of the Central U.S.: Bulletin of the Seismological Society of America.

Feng, J., Wang, Z., Woolery, E., and Li, S., 2015, Comparison of the ground motion attenuation relationship between Wenchuan, China, area and the central and eastern United States: Kentucky Geological Survey, ser. 12, Report of Investigations 28, 45 p., doi.org/10.13023/kgs.ri28.12.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic hazard maps, documentation: U.S. Geological Survey Open-File Report 96-532, 69 p.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Greenwood, M.L., Woolery, E.W., Van Arsdale, R.B., Stephenson, W.J., and Patterson, G.L., 2016, Continuity of the Reelfoot Fault across the Cottonwood Grove and Ridgely Faults of the New Madrid Seismic Zone: Bulletin of the Seismological Society of America, v. 106, p. 2674–2685, doi.org/10.1785/0120150290.

James E. Beavers Consultants, 2010, Seismic hazard reevaluation for the C-746-U contained landfill: A deterministic approach: Knoxville, Tenn., James E. Beavers Consultants, 10 p.

Joyner, W.B., and Boore, D.M., 1981, Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin of the Seismological Society of America, v. 71, p. 2011–2038.

Orton, A.M., 2014, Science and public policy of earthquake hazard mitigation in the New Madrid Seismic Zone: Lexington, University of Kentucky, master's thesis, 189 p., uknowledge.uky.edu/ees_etds/19 [accessed 01/15/2019].

Orton, A., Wang, Z., Wang, L., and Woolery, E., 2016, Earthquake hazard mitigation in the New Madrid Seismic Zone: Science and public policy: Kentucky Geological Survey, ser. 12, Report of Investigations 32, 53 p., doi.org/10.13023/kgs.ri32.12.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 08-1128, 60 p.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014-1091, 243 p.

Pezeshk, S., Zandieh, A., and Tavakoli, B., 2011, Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters: Bulletin of the Seismological Society of America, v. 101, p. 1859–1870, doi:10.1785/0120100144.

Pryne, D., Van Arsdale, R., Csontos, R., and Woolery, E., 2013, Northeastern extension of the New Madrid North Fault, New Madrid Seismic Zone, central United States: Bulletin of the Seismological Society of America, v. 107, p. 2277–2294, doi:10.1785/0120120241.

Rong, M., Fu, L., Wang, Z., Li, X., Carpenter, N.S., Woolery, E.W, and Lyu, Y., 2017, On the amplitude discrepancy of HVSR and site amplification from strong-motion observations: Bulletin of the Seismological Society of America, v. 107, p. 2873–2884, doi:10.1785/0120170118.

Rucker, C., 2017, Constraining boundaries and extent of the Charleston Uplift, northeast New Madrid Seismic Zone, using shallow seismic-reflection methods: Lexington, University of Kentucky, master's thesis, 74 p., uknowledge.uky.edu/ees_etds/50 [accessed 01/15/2019].

Silva, W., Gregor, N., and Darragh, R., 2002, Development of regional hard rock attenuation relationships for central and eastern North America: Pacific Engineering and Analysis, 311 Pomona Ave., El Cerrito, CA 94530, 57 p.

Somerville, P., Collins, N., Abrahamson, N., Graves, R., and Saikia, C., 2001, Ground motion attenuation relations for the central and eastern

United States: Final report, URS Group Inc., to the U.S. Geological Survey, 16 p.

Van Arsdale, R., Pryne, D., and Woolery, E., 2013, Northwestern extension of the Reelfoot North Fault near New Madrid, Missouri: Seismological Research Letters, v. 84, p. 1114–1123, doi:10.1785/0120120241.

Wang, Z., comp., 2003, Proceedings of the Kentucky NEHRP Seismic Hazards and Design Maps Workshop, November 18, 2002, Lexington, Kentucky: Kentucky Geological Survey, ser. 12, Special Publication 5, 38 p.

Wang, Z., comp., 2005, Better understanding and communication of the national seismic hazard maps: Summary of USGS-KGS meeting on seismic hazard assessment in western Kentucky: Kentucky Geological Survey, ser. 12, Special Publication 7, 47 p.

Wang, Z., 2006, Understanding seismic hazard and risk assessments: An example in the New Madrid Seismic Zone of the central United States: Proceedings of the 8th U.S. National Conference on Earthquake Engineering, April 18–22, 2006, San Francisco, Calif., Paper 416, 10 p.

Wang, Z., 2007, Seismic hazard and risk assessment in the intraplate environment: The New Madrid Seismic Zone of the central United States, *in* Stein, S., and Mazzotti, S., eds., Continental intraplate earthquakes: Science, hazard, and policy issues: Geological Society of America Special Paper 425, p. 363–373.

Wang, Z., 2008, A technical note on seismic microzonation in the central United States: Journal of Earth System Science, v. 117, no. S2, p. 749–756.

Wang, Z., 2010, Ground motion for the maximum credible earthquake in Kentucky: Kentucky Geological Survey, ser. 12, Report of Investigations 22, 9 p., doi.org/10.13023/kgs.ri22.12.

Wang, Z., 2011, Seismic hazard assessment: Issues and alternatives: Pure and Applied Geophysics, v. 168, p. 11–25, doi.org/10.1007/s00024-010-0148-3.

Wang, Z., Carpenter, N.S., Zhang, L., and Woolery, E.W., 2017, Assessing potential ground-motion hazards from induced earthquakes: Natural Hazards Review, v. 18, issue 4, doi.org/10.1061/(ASCE)NH.1527-6996.0000264.

Wang, Z., and Cobb, J.C., 2012, A critique of probabilistic versus deterministic seismic hazard analysis with special reference to the New Madrid Seismic Zone, *in* Cox, R.T., Tuttle, M.P., Boyd, O.S., and Locat, J., eds., Recent advances in North American paleoseismology and neotectonics east of the Rockies: Geological Society of America Special Paper 493, p. 259–275, doi:10.1130/2012.2493(13).

Wang, Z., and Lu, M., 2011, A short note on ground-motion recordings from the M7.9 Wenchuan, China, earthquake and ground-motion prediction equations in the central and eastern United States: Seismological Research Letters, v. 82, p. 731–733.

Wang, Z., and Ormsbee, L., 2005, Comparison between probabilistic seismic hazard analysis and flood frequency analysis: Eos, Transactions of the American Geophysical Union, v. 86, p. 45, 51–52.

Wang, Z., Orton, A., Wang, L., and Woolery, E.W., 2016, Seismic hazard mapping and mitigation policy development in the central United States and western China: Natural Hazards, v. 81, p. 387–404, doi:10.1007/s11069-015-2086-y.

Wang, Z., and Woolery, E.W., 2006, Recordings from the deepest borehole in the New Madrid Seismic Zone: Seismological Research Letters, v. 77, p. 131–136.

Wang, Z., and Woolery, E.W., 2008, Seismic hazard assessment of the Paducah Gaseous Diffusion Plant: Kentucky Geological Survey, ser. 12, Special Publication 9, 37 p.

Wang, Z., and Woolery, E., 2013, Operation and maintenance of the seismic network in the vicinity of the Paducah Gaseous Diffusion Plant: April 2009–September 2012: Kentucky Geological Survey, ser. 12, Contract Report 5, 11 p.

Wang, Z., Woolery, E.W., and Hu, C., 2012, The Central United States Seismic Observatory: Site characterization: Proceedings of the 5th International Conference on Environmental and Engineering Geophysics, June 15–18, 2012, Changsha, China, p. 223–227.

Wang, Z., Woolery, E.W., and Shi, B., 2003, Observed seismicity (earthquake activity) in the Jackson Purchase Region of western Kentucky: January through June 2003: Kentucky Geological Survey, ser. 12, Special Publication 6, 16 p.

Wheeler, R.L., 2011, Reassessment of stable continental regions of Southeast Asia: Seismological Research Letters, v. 82, p. 971–983, doi.org/10.1785/gssrl.82.6.971.

Woolery, E.W., and Almayahi, A., 2014, Northeast-oriented transpression structure in the northern New Madrid Seismic Zone: Extension of a shear zone across the Reelfoot Fault stepover arm: Bulletin of the Seismological Society of America, v. 104, p. 2587–2596.

Woolery, E.W., Lin, T., Wang, Z., and Shi, B., 2008, The role of local soil-induced amplification in the 27 July 1980 northeastern Kentucky earthquake: Environmental & Engineering Geoscience, v. 14, p. 267–280.

Woolery, E.W., Wang, Z., and Carpenter, N.S., 2016a, Site characteristics, instrumentation, and recordings of the Central United States Seismic Observatory: Kentucky Geological Survey, ser. 12, Report of Investigations 37, 32 p., doi.org/10.13023/kgs.ri37.12.

Woolery, E.W., Wang, Z., Carpenter, N.S., Street, R., and Brengman, C., 2016b, The Central United States Seismic Observatory: Site characterization, instrumentation, and recordings: Seismological Research Letters, v. 87, p. 215–228, doi:10.1785/0220150169.