An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant

(January 2013–December 2017)

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Introduction

Engineering seismic design has become a major concern for the Paducah Gaseous Diffusion Plant (PGDP) when the 1997 NEHRP Provisions (BSSC, 1998) was adopted in the early 2000s. As shown in Table 1, the design 0.2s response acceleration (PSA) in Paducah, Kentucky, was increased by about a factor of four, from about 0.25g to 1.083g, which is even higher than those in San Francisco and Los Angeles, California. In other words, the seismic design requirement in Paducah was as stringent as that in San Francisco or Los Angeles. Therefore, the U.S. Department of Energy had difficulty to obtain a permit from the federal and state regulators to construct a landfill at PGDP in the early 2000s (Beavers, 2010). The design values were developed from the ground motions with 2 percent probability of exceedance (PE) in 50 years, which were produced by the U.S. Geological Survey (Frankel and others, 1996, 2002; Petersen and others, 2008, 2014). As shown in Table 2, the estimated ground motions for Paducah by the USGS (Frankel and others, 1996, 2002; Petersen and others, 2008, 2014) are higher than the design values (Tab. 1). These high ground motion estimates and resulting high design values have been an issue for PGDP, as well as western Kentucky.

Table 1. Design ground motions for Paducah, San Francisco, and Los Angeles.

Edition	Paducah		San Francisco		Los Angeles	
	0.2s PSA (g)	1.0s PSA (g)	0.2s PSA (g)	1.0s PSA (g)	0.2s PSA (g)	1.0s PSA (g)
1994	0.25[1)]	0.10[2)]	1.00[1)]	0.40[2)]	1.00[1)]	0.40[2)]
1997	1.083	0.333	1.000	0.400	1.000	0.400
2003	1.000	0.333	1.000	0.406	1.386	0.468
2009	0.837	0.287	1.000	0.400	1.563	0.548
2015	0.672	0.223	0.900	0.320	1.165	0.369

[1)] the value was obtained from A_a times 2.5. [2)] the value (0.10) was A_v

Table 2. Estimated ground motions for Paducah by the U.S. Geological Survey.

Ground Motions with 2% PE in 50 years (USGS)			
Year	PGA (g)	0.2s PSA (g)	1.0s 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

In order to address the seismic hazard assessment and engineering design issues for PGDP, as well as western Kentucky, the Kentucky Geological Survey, in conjunction with the Department of Earth and Environmental Sciences, carried out a comprehensive research with partial supports, phase I (between 2003 and 2007) and phase II (between 2009 and 2012), from the U.S. Department of Energy through the Kentucky Consortium for Energy and Environment (KRCEE). The main focus of the research were (1) to install and maintain a temporary seismic network in the vicinity of PGDP, and (2) to conduct a comprehensive analysis on the seismic hazard assessment. The results from the phase I efforts include the publications by Wang (2003, 2005, 2006, 2007, 2008a and b, 2009a and b), Wang and Ormsbee (2005), Wang and others (2003, 2005), Wang and Woolery (2006, 2008), Wang and Zhou (2007), and Woolery and others (2008). The results from the phase II efforts include publications by Wang (2010, 2011a and b, 2012), Wang and Cobb (2012), Wang and Lu (2011), Wang and Woolery (2013), and Wang and others (2012). The most significant accomplishments from the phases I and II are:

1. Gaining better understandings of earthquake sciences and seismic hazard assessment in the central United States. These better understandings had led to more reasonable ground motion estimates and resulting design values for western Kentucky. This can be seen in Tables 1 and 2 that the estimated ground motions and design values have become more reasonable.
2. Resolving the design ground motion, 0.33g PGA, for the landfill seismic design at PGDP. DOE had obtained a permit from the federal and state regulators to construct a landfill with this design value at PGDP.
3. Revising the Kentucky Residential Code with the scenario ground motions for western Kentucky, including Paducah.
4. Establishing the Central U.S. Seismic Observatory.

This update is to provide a summary and some highlights on the continuous efforts carried out by the Kentucky Geological Survey and 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 PGDP between January 2013 and December 2017. Figure 1 shows the current station and instrumentation configuration, which has a focus on monitoring the New Madrid Seismic Zone. Seven of the stations operate seismometers for detecting weak events, and 10 stations operate at least one strong-motion sensor. Recordings from five of the stations are telemetered to KGS over the internet; the remaining stations are stand-alone, which are visited approximately bimonthly to download recordings. These stations, particularly the seismic stations, record earthquakes on local and global scales and the real-time recordings are shared with the neighboring seismic monitoring network operated by the University of Memphis.

Since 2013, all but one of the telemetered seismic stations were upgraded with onsite, digital data acquisition systems, including PAKY (Paducah Airport), FMKY (Fulgham, Ky.), and LOKY (Salem, Ky.). Also, strong-motion accelerometers were installed at PAKY and LOKY. All but two of the stations deployed in the Jackson Purchase of Kentucky as part of the temporary seismic monitoring project in the vicinity of the PGDP (Wang and Woolery, 2013) were uninstalled prior to 2013. Of the remaining two, LVKY (Lovelaceville, Ky.) was uninstalled in April, 2013 and BAKY (Bardwell, Ky.) continues to operate. Operation of several stations has been interrupted due primarily to local, natural site issues. The vertical seismic array sites, VSAP and CUSSO, in particular are discussed in the subsequent section. VSAB experienced flooding in 2013 and is planned for being re-sited on higher ground and PAKY experienced a lightning strike in 2017 and is in repair.

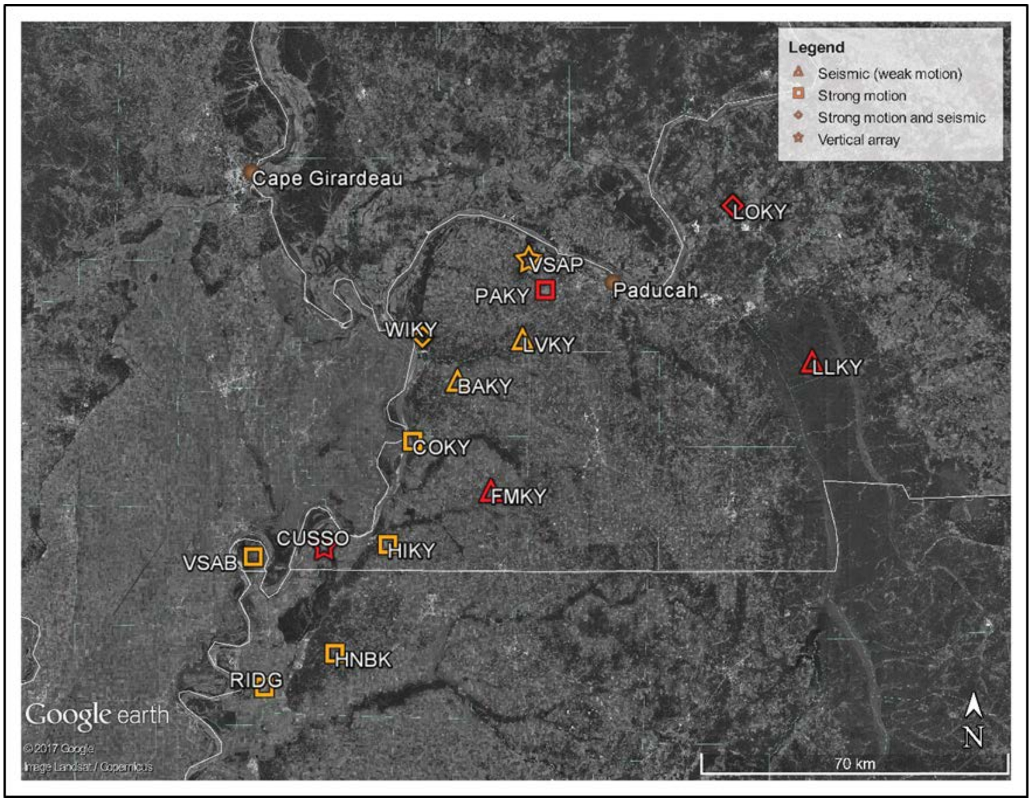


Figure 1. Seismic and strong motion stations operated in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017. Stations with real-time data telemetry are in red; stand-alone (no communications) stations are in orange.

Seismic Data Analysis

The recordings from the seismic stations in the vicinity of PGDP (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 earthquakes with magnitude greater than 1.0 occurred in the vicinity of PGDP from January 2013 to December 2017 and the 15 earthquakes of magnitude 3.0 and greater during this time period are tabulated in Table 3. The earthquake closest to the PGDP in Table 3 was the 2016/05/01 magnitude 3.5 event that occurred approximately 20 km to the northwest in Ballard Co. Figure 3 shows three orthogonal component recordings at nearby VSAP (17 km away) and PAKY (24 km away), and the peak ground accelerations recorded at both sites.

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 Fig. 2).

Magnitude	*Date*	*Time (UTC)*	*Latitude (°N)*	*Longitude (°E)*	*Depth (km)*	*Location*
3.3	2013/08/12	21:43:24.30	36.261	-89.301	4.4	Obion, Tenn.
3.1	2014/04/07	06:24:12.92	36.216	-89.410	6.3	Ridgely, Tenn.
3.1	2014/05/15	15:44:58.34	36.558	-90.020	5.6	Malden, Mo.
3.1	2015/02/28	23:08:44.45	36.536	-89.639	13.4	Lilbourn, Mo.
3.0	2015/11/25	07:08:53.12	36.538	-89.601	8.7	Lilbourn, Mo.
3.5	2016/05/01	06:12:10.03	37.214	-88.988	16.3	La Center, Ky.
3.0	2016/07/05	04:51:13.02	36.151	-89.697	9.0	Caruthersville, Mo.
3.4	2016/09/09	13:45:37.56	36.453	-89.535	10.3	Tiptonville, Tenn.
3.3	2016/11/24	01:57:37.58	36.155	-89.693	8.8	Caruthersville, Mo.
3.6	2017/03/15	16:51:10.09	36.882	-89.123	8.4	Wickliffe, Ky.
3.2	2017/03/19	14:25:12.57	36.880	-89.128	12.2	Bardwell, Ky.
3.0	2017/05/14	12:56:24.05	36.564	-89.599	13.6	Lilbourn, Mo.
3.3	2017/05/16	10:21:52.24	36.873	-89.122	9.1	Bardwell, Ky.
3.0	2017/07/31	02:16:19.62	36.306	-89.490	4.8	Ridgely, Tenn.
3.2	2017/08/18	15:18:21.07	36.447	-89.592	12.6	Portageville, Mo.

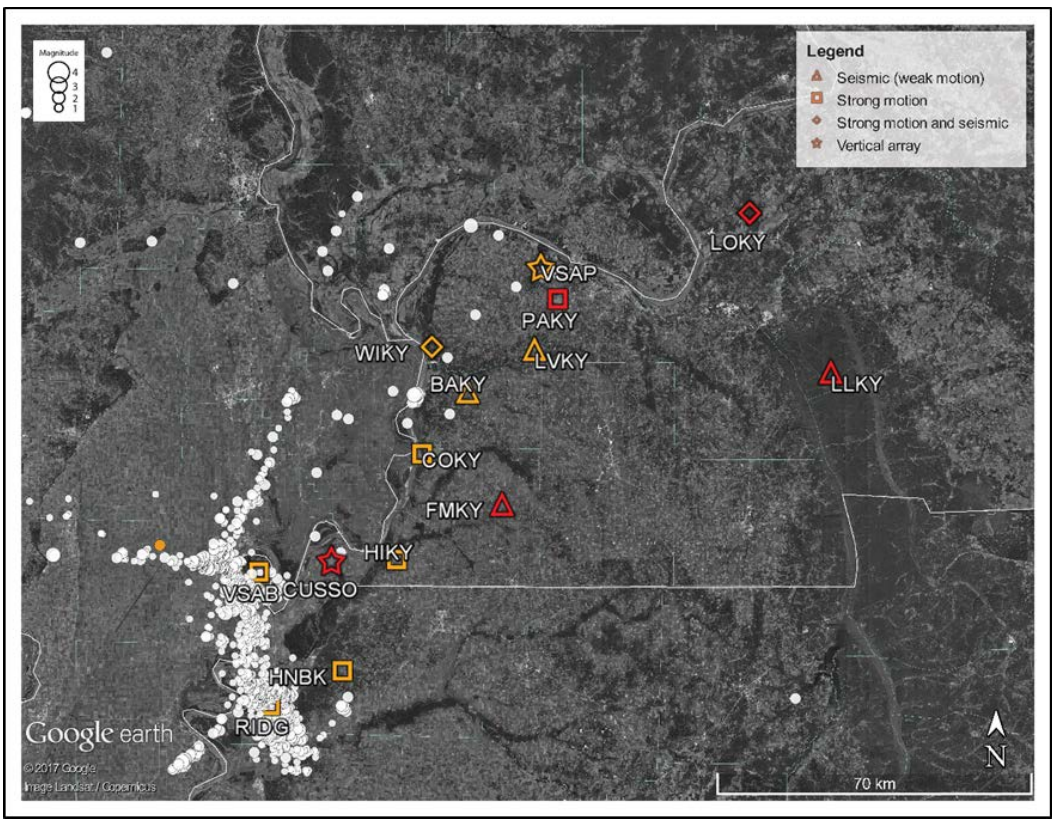


Figure 2. Locations of earthquakes occurring in in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017.

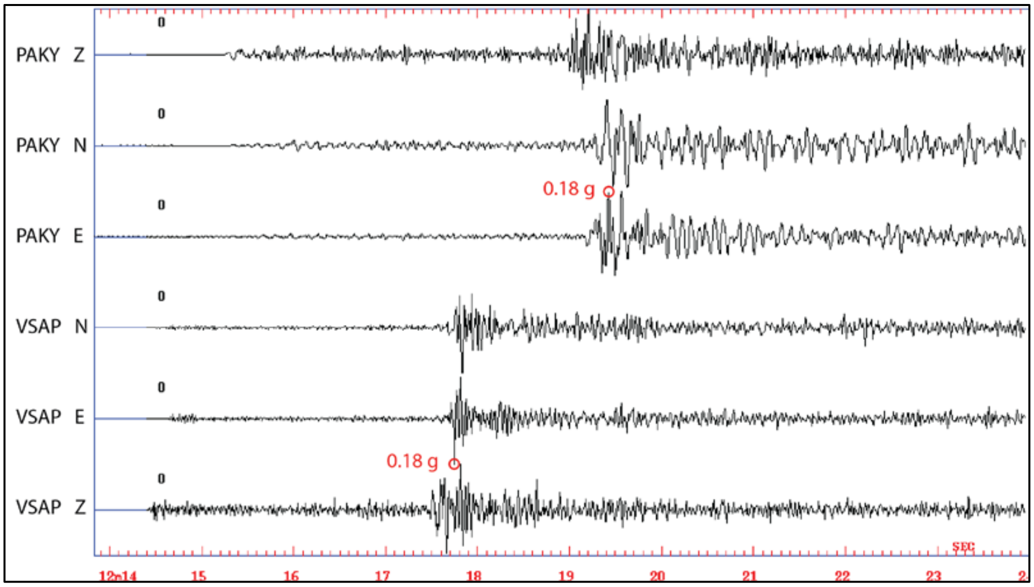


Figure 3. Example recordings by the seismic monitoring network. Three-component recordings of the 2016/05/01 magnitude 3.5 earthquake near La Center, Ky. by VSAP (17 km away) and PAKY (24 km away). Peak ground accelerations in g (acceleration due to gravity) are labeled.

CUSSO and VSAP Data Analysis

Although CUSSO was functional intermittently between 2009 and 2012, it recorded many local, regional, and tele-events (Woolery and others, 2016). Figure 3 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 and b). Some preliminary analyses were also conducted on the records (Woolery and others, 2016a and b). VSAP was relocated to outside the perimeter of PGDP for security reasons in 2004 and in operation until 2014 when the borehole accelerometers were not functional due to aging. . Table 4 lists the records from VSAP that were checked and corrected.

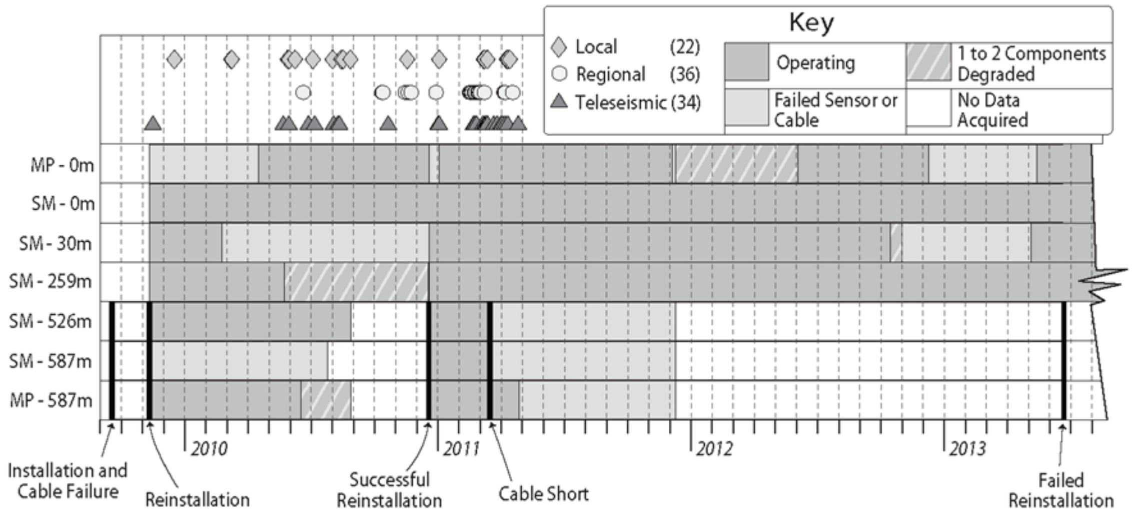


Figure 3. Graphical summary of CUSSO's history.

Table 4. The earthquakes recorded at VSAP between 2004 and 2014.

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

The data from CUSSO and VSAP had been used for studies of seismic wave propagation and site-effect (Rong and others, 2017; Carpenter and others, in review). Figure 4 shows the mean spectral ratio of S-wave between the surface and bedrock (TF_T), horizontal-to-vertical-ratio of S-wave at surface (HV_S), and theoretical Thomson-Haskell SH-wave transfer functions (TH_{SH}) at VSAP (left) and CUSSO (right). As shown in Figure 4, the theoretical transfer function (TH_{SH}) is very similar to the observed transfer function (TF_T). As also shown in Figure 4, the S-wave HVSR is also very similar to the observed transfer function. These results suggest that 1-D theoretical model (transfer function) provides a good approximation for site-effect, and the S-wave HVSR could be used as an empirical transfer function of site-effect.

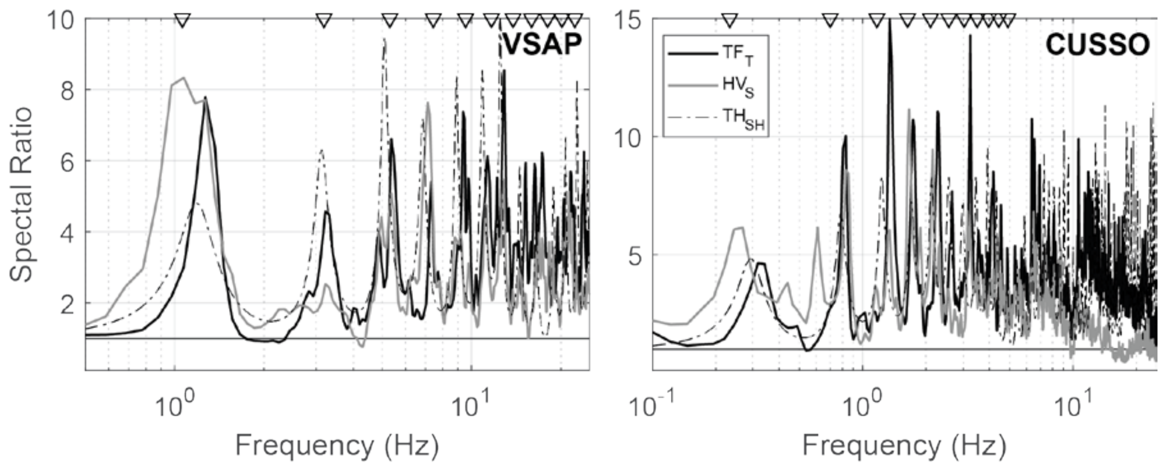


Figure 4. Mean spectral ratios from recordings at VSAP (left) and CUSSO (right), and theoretical Thomson-Haskell SH-wave transfer functions.

Seismic Hazard Assessment and Communication

New Madrid Active Faults

Although the New Madrid Seismic Zone (NMSZ) has been and continues to be intensely studied, the locations of active faults remain largely uncertain. As shown in Figure 5, there are five alternative locations for the New Madrid faults used by the USGS for the 2008 and 2014 national seismic hazard maps (Petersen and others, 2008; 2014). Thus, more accurate fault location determination in the NMSZ is important for the western Kentucky seismic hazard assessment. Edward Woolery and his students have been working with researchers at the University of Memphis to better determine the fault locations using both geologic and geophysical field investigations (e.g., Van Arsdale and others, 2013; Pryne and others, 2013; Woolery and Almayahi, 2014; Greenwood and others, 2016; Rucker, 2017). As shown in Figure 6, the seismicity and subsurface geologic features clearly indicate the location of Reelfoot Fault (i.e., RFNF and RFSF) is well constrained.

Pryne and others (2013) acquired two exploratory seismic walkaway soundings (MP-35 and MP-80) across the northern boundary of a 30 km by 7.2 km stratigraphic uplift in the northeastern vicinity of the New Madrid north fault (NWNF) for evidence of genesis (i.e., neotectonic or fluvial) (Fig. 7). The previously unknown uplift, called the Charleston uplift, was discovered using 520 electric logs from shallow (100 meter) lignite exploration wells and geospatial stratigraphic mapping. Although there are no known surface faults bounding this feature, the 30+ meters of structural amplitude exhibited in the well-log mapping of Quaternary and Tertiary horizons were hypothesized as having a tectonic origin. The two seismic soundings were performed north of and within the uplift to further test this hypothesis. Results indicated 47 m and 60 m of relief across the tops of the deeper Cretaceous and Paleozoic horizons, respectively (Fig. 8). A subsequent masters of science thesis (Rucker, 2017), collected and analyzed an additional 18 seismic soundings and one ground penetrating radar profile to confirm Paleozoic and Cretaceous offset across the boundaries of the uplift, and better constrain the surface projection of the uplift (Fig. 9).

Results confirm Paleozoic and Cretaceous offset throughout the uplift, as well as indicate the preliminary boundaries proposed by Pryne et al. (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.

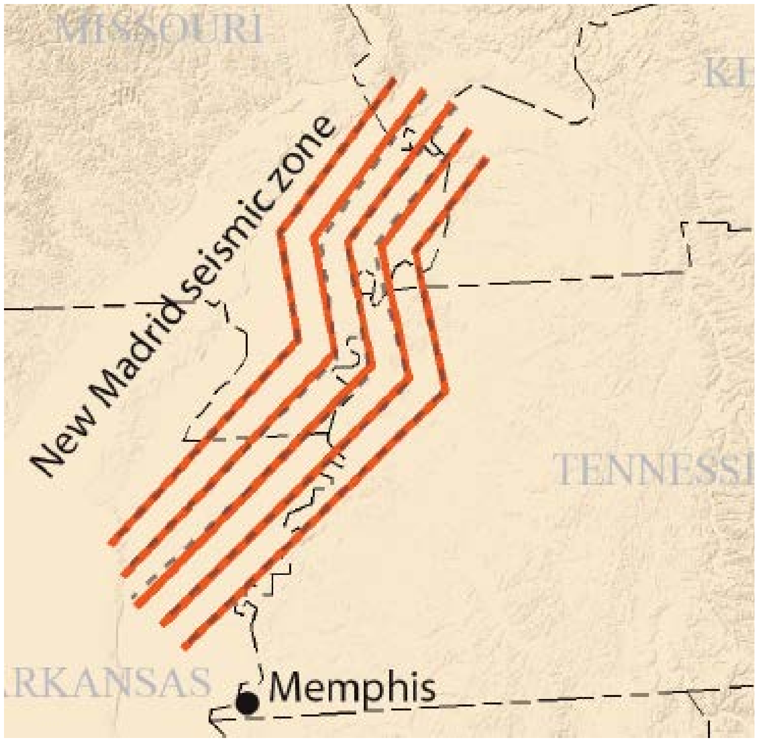


Figure 5. Locations of the active faults in the New Madrid seismic zone used in the national seismic hazard maps by the USGS (Petersen and others, 2008, 2014). Dashed linesthe - 2008 update, and solid lines - 2014 update.

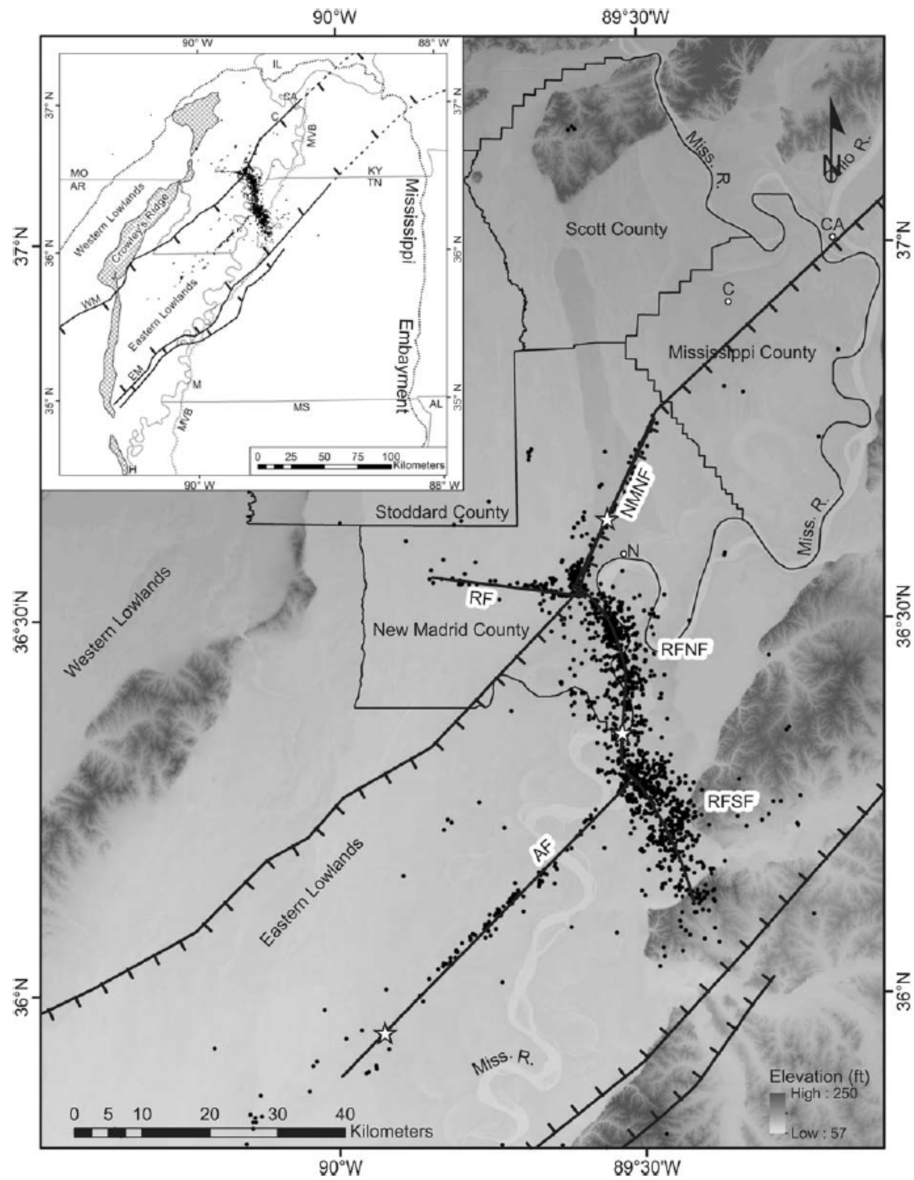


Figure 6. Seismicity, active faults, and geologic feature in the New Madrid Seismic Zone (Van Arsdale and others, 2013).

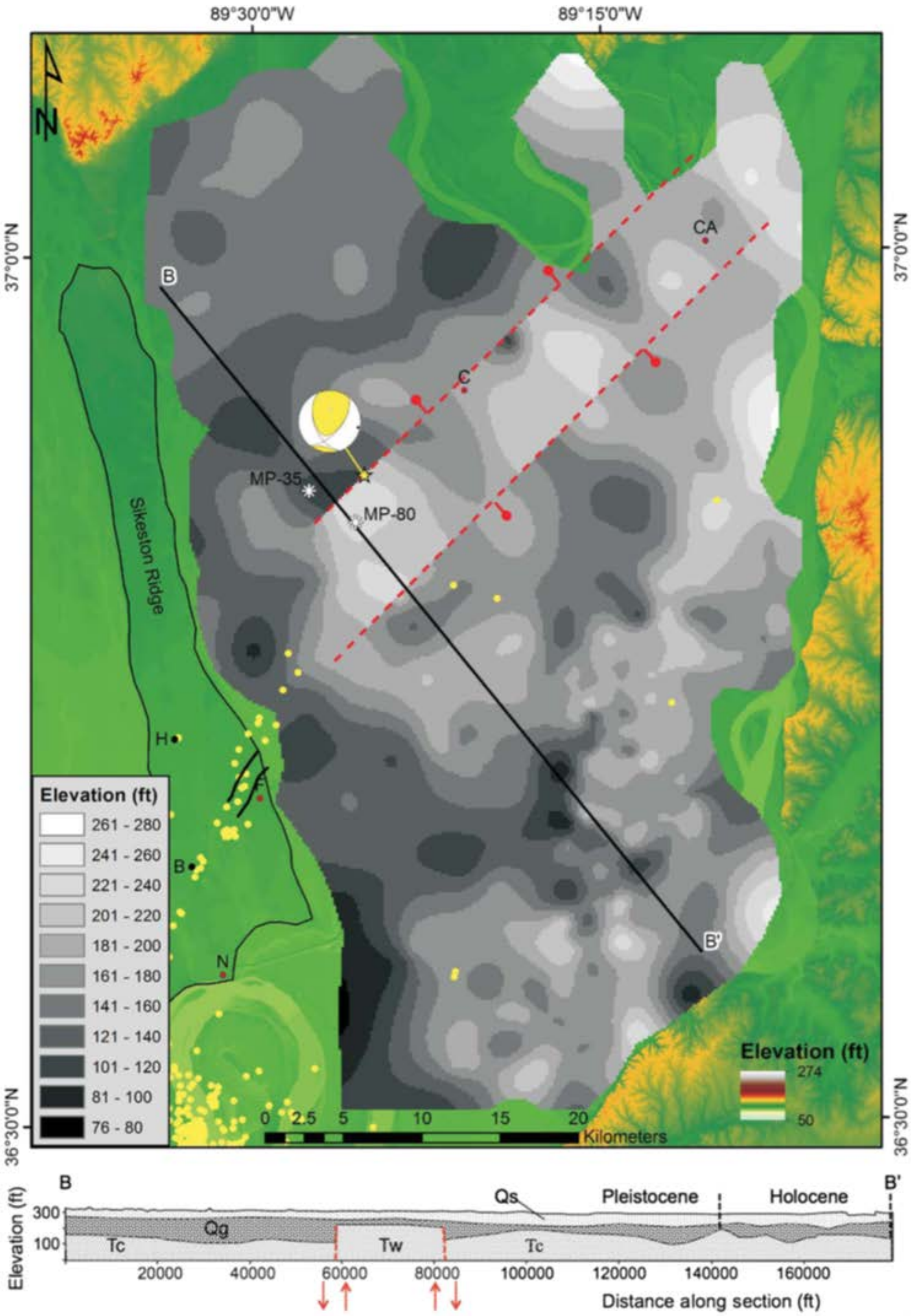


Figure 7. Top of the Paleogene (bottom of Quaternary Mississippi River gravel) structure contour map contoured as separate surfaces, south, within, and north of the Charleston uplift with cross section B-B'. February 21, 2012 earthquake location and interpreted faults (red lines with barbs on downthrown side). Red dots are wells. CI-6 m (20 ft). 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' with VE-40 (modified from Pryne et al., 2013).

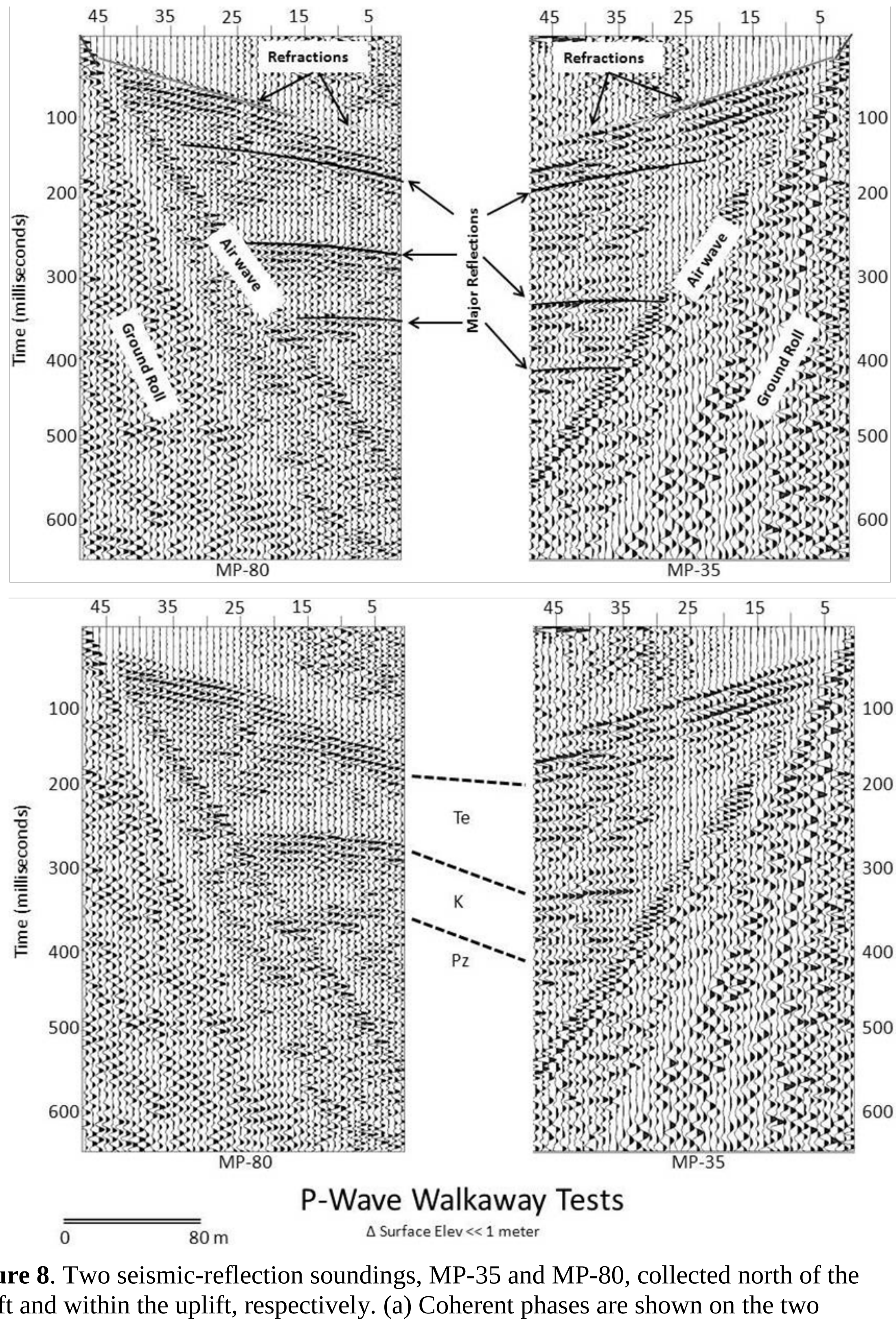


Figure 8. Two seismic-reflection soundings, MP-35 and MP-80, collected north of the uplift and within the uplift, respectively. (a) Coherent phases are shown on the two seismograms, including ground roll, air wave, direct wave/refractions, and three significant reflections. (b) The two most prominent deeper reflections seen 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 m and 60 m, respectively. Approximately 19 meters of relief is calculated across the Tertiary horizon (from Pryne et al., 2013).

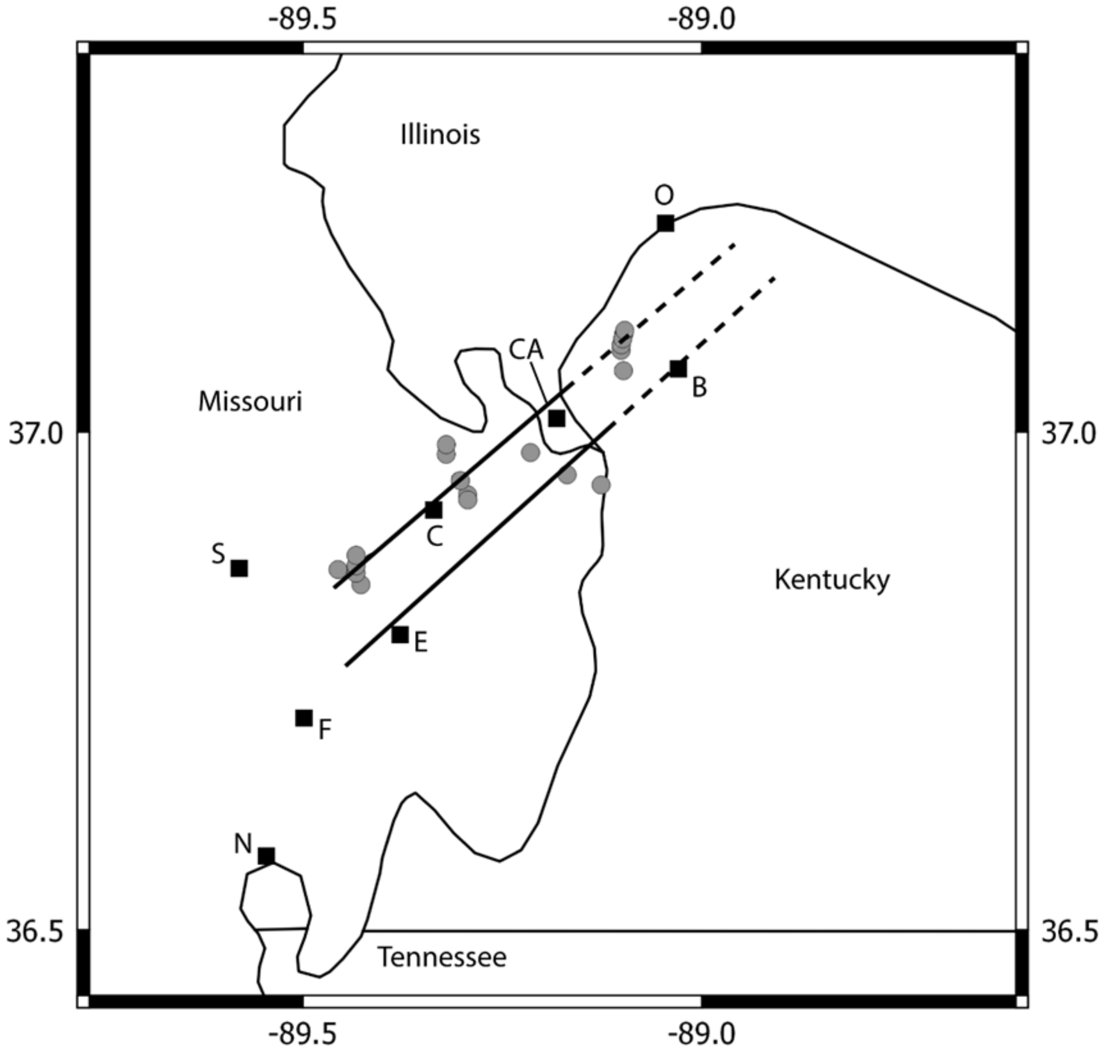


Figure 9. Charleston uplift and field site locations. Solid lines are the boundaries from Pryne *et al.* (2013). Dashed lines are the northeastward, straight-line projection into western Kentucky. Grey circles are seismic sounding field sites. Black squares are population centers in the region. B, Barlow, Kentucky, CA, Cairo, Illinois; C, Charleston, Missouri; E, East Prairie, Missouri; F, Farrenburg, Missouri; N, New Madrid, Missouri; S, Sikeston, Missouri; O, Olmsted, Illinois (from Rucker, 2017).

Ground Motion Attenuation

Ground motion attenuation relationship, or the so-called ground motion prediction equation (GMPE), is one of important parameters for seismic hazard assessment. GMPE is developed from the ground motion observations in the west coast, California in particular (e.g., Joyner and Boore, 1981). However, All the GMPE's for central and eastern United States are developed either solely from computer simulations or from computer simulations with limited observations from small to moderate earthquakes (M < 6.0). For example, Atkinson and Boore (2006) developed a GMPE from synthetic records based on stochastic finite-fault simulation. Thus, GMPEs for central and eastern United States need to be constrained by the observations, for large earthquake (> 7.0) in particular.

The 2008 Wenchuan, China, earthquake (M 7.9) occurred along the Longmenshan Fault, which is located on the western border of the South China stable continental region. As shown in Figure 10 (Weeler, 2011), central and eastern United States and Sichuan Basin are both located in a stable continental region. Thus, the ground motions from the Wenchuan earthquake could be used to constrain GMPEs of central United States. A preliminary comparison (Wang and Lu, 2011) also suggested that it is appropriate to use the ground motions from the Wenchuan earthquake for constraining GMPEs of central United States. A detailed study was conducted to compare the GMPEs of central United States and the one developed from the Wenchuan earthquake (Feng and others, 2015). Figure 11 shows PGA comparisons between GMPEs of central United States (i.e., Somerville and others, 2001; Silva, 2002; Campbell, 2003; Atkinson and Boore, 2006; Pa and others, 2011) and the one developed from the Wenchuna earthquake (Feng and others, 2015). The results show that the ground-motion attenuations of the central and eastern United States are similar to that of the Wenchuan area. In other words, the GMPE's for the central and estern United States and the Wenchuan area have similar characteristics. Thus, the ground-motion data set obtained from the Wenchuan earthquake can be used to develop a GMPE for the central and eastern United States.

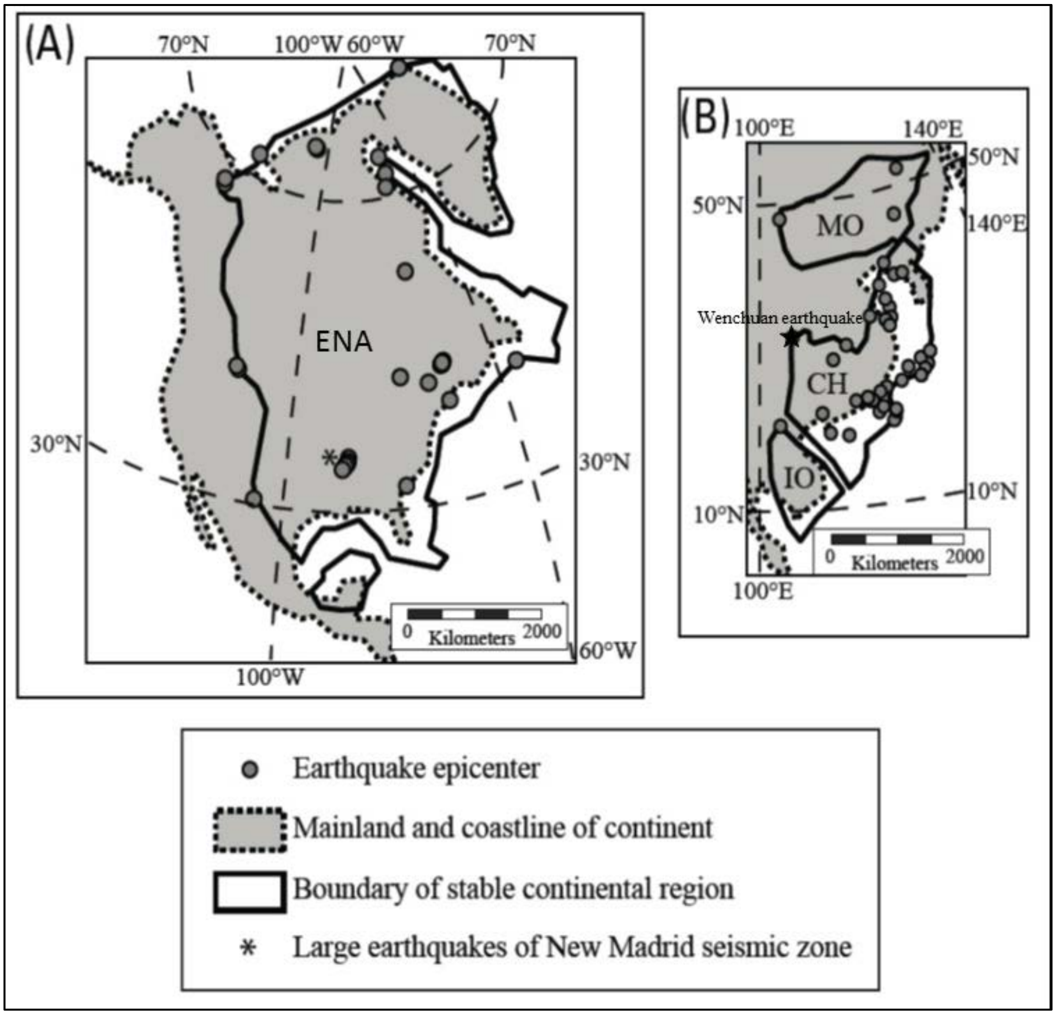


Figure 10. Stable continent regions of North America (A) and South China (B) (modified from Wheeler, 2011). Star: Wenchuan region. ENA: eastern North America stable continent region. CH: eastern China stable continent region. MO: Mongolia stable continent region. IO: Indochina stable continent region.

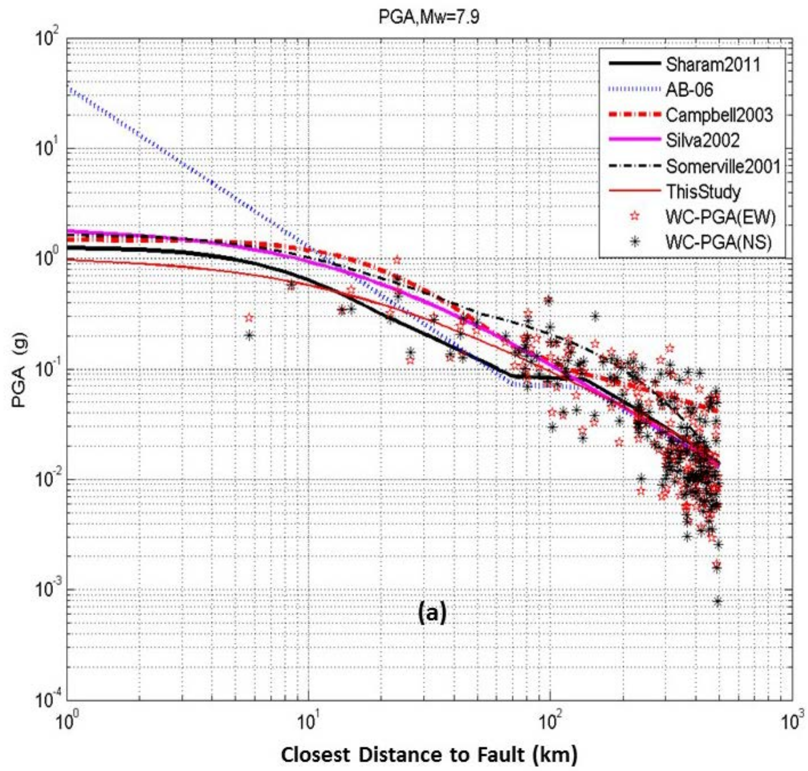


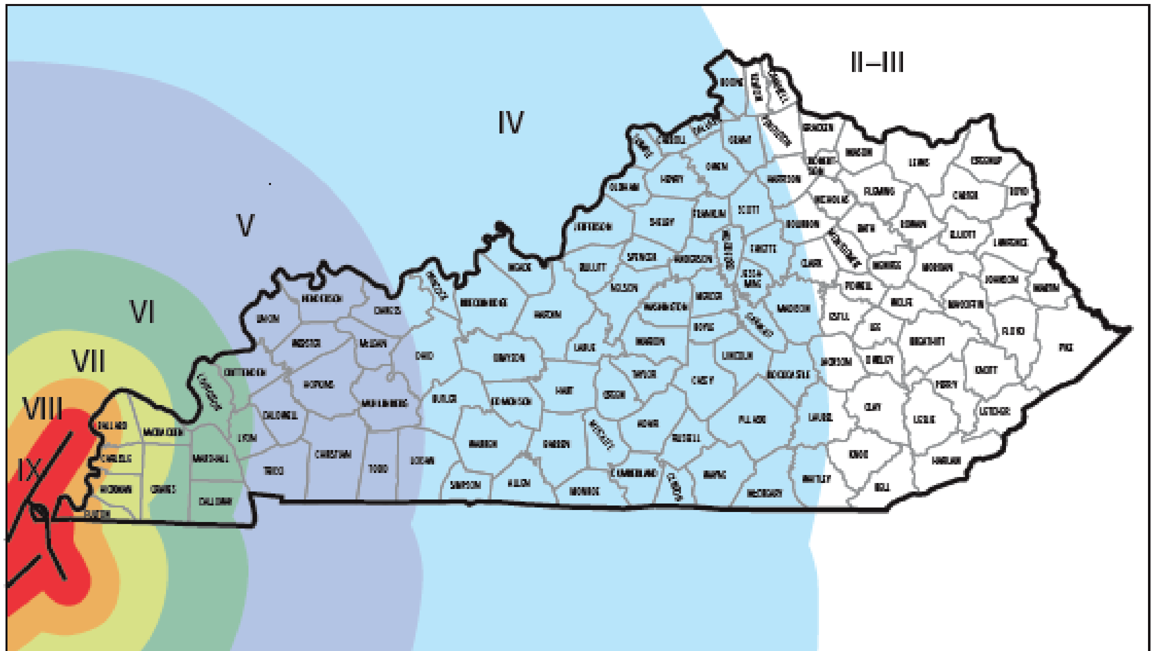
Figure 11. Comparison of ground-motion predictions for the Sichuan Basin and four GMPE's for the central and eastern United States for an M 7.9 earthquake (Jiwei and others, 2015).

Seismic Hazard Assessment

In order to improve understanding and communication about ground-motion hazards in the central United States, KGS continued to participate workshops and discuss the related issues with the U.S. Geological Survey (USGS) and others federal and state agencies. 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 the workshop, "CEUS Earthquake Hazards Research Review and Planning," on February 25-26, 2014 in Memphis, Tenn. Zhenming Wang participated the ATC/USGS Seismic Hazard User-Needs Workshop on September 21-22, 2015 in Menlo Park, Calif., and gave a presentation, "the USGS National Seismic Hazard Mapping Project: Issues and Improvements." On January 27, 2017, KGS and USGS held a meeting, in Lexington, Ky., attended by KGS and USGS staff, and representatives of Kentucky structural engineers and the state's Solid Waste Division. The participants concluded that the New Madrid Seismic Zone poses a significant hazard to western Kentucky, and agreed that scenario-based seismic hazard analysis can help convey this message to the public.

KGS also continued to conduct scenario-based seismic hazard analyses and communicate them to all the stakeholders. Figure 12 shows the mean peak ground acceleration (PGA) for Kentucky from a scenario earthquake of M 7.5 in the New Madrid Seismic Zone

(Carpenter and others, 2014). Alice Orton (2014) conducted scenario-based hazard analyses on a series of earthquakes in the New Madrid Seismic Zone and the results were summarized in Wang and others (2016) and Orton and others (2016). The scenario-based seismic hazard analysis was also applied to provide ground motion hazards for the Xianshuihe Fault Zone in southwest China (Zhang and others, 2017) and potential ground motion hazards from induced earthquake in eastern Kentucky (Wang and others, 2017).



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 12. Predicted peak ground acceleration (PGA), in units of the percentage of the acceleration of gravity, on hard rock from a magnitude-7.5 scenario earthquake in the New Madrid Seismic Zone (Carpenter and others, 2014).

Seismic Risk and Mitigation Policy

Orton (2014) also conducted potential losses from the scenario earthquakes in the New Madrid Seismic Zone using the Federal Emergency Management Agency (FEMA) Hazus-MH software in order to assess seismic risk and mitigation policy. A series of informal interviews in western Kentucky with local businesspersons, public officials, and other professionals in occupations associated with seismic mitigations were conducted to order to assess the impacts of seismic hazard assessment and resulting mitigation policies on economic development (Orton, 2014; Orton and others, 2016). The results showed that the national seismic hazard maps and resulting mitigation policies, such as building and residential codes, have impacts on economic development in Kentucky, western Kentucky in particular. The results also showed that large uncertainties are inherent in the estimation of earthquake parameters, ground-motion values in particular, for the New Madrid Seismic Zone.

Summary

KGS continued 1) to monitor earthquakes and 2) conduct research on seismic hazard and mitigation policies in the vicinity of PGDP from January 2013 to December 2017. There were 15 earthquakes with magnitude greater 3.0 occurred in the area during this period. We had gained a better understanding on seismic wave propagation through thick sediments and ground motion site-effect through research using the data collected from CUSSO and VSAP. We had also gained better understandings on the fault locations in the New Madrid Seismic Zone, the ground motion attenuation in the central United States, seismic hazard assessment, and mitigation policy. Our efforts had led to better seismic design for buildings and facilities at PGDP, as well as in western Kentucky.

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