Operation and Maintenance of the Seismic Network in the Vicinity of the Paducah Gaseous Diffusion Plant (PGDP)

April 2009 – September 2012

Final Report

By Zhenming Wang

Kentucky Geological Survey

228 Mining and Mineral Resources Building

University of Kentucky

Lexington, Kentucky 40506

And

Edward W. Woolery

Department of Earth and Environmental Sciences

101 Slone Research Building

University of Kentucky

Lexington, KY 40506

February 2013

1. **Introduction**

The seismic hazard maps with 2 percent probability of being exceeded in 50 years or once in about 2,500 years, produced by the U.S. Geological Survey (Frankel and others, 1996, 2002; Petersen and others, 2008), show high ground motion in western Kentucky, the Jackson Purchase Region in particular (Fig. 1). These maps have put the Jackson Purchase Region in a high seismic hazard area that is similar to or even higher than San Francisco or Los Angeles, Calif. For example, the predicted peak ground acceleration (PGA) at the Paducah Gaseous Diffusion Plant (PGDP) is about 1.0g. These high ground motion estimates resulted in a high design requirement (0.8g PGA) for a landfill at PDGP, which made it difficult for the U.S. Department of Energy to obtain a permit from the state regulators to construct the landfill (Wang and Woolery, 2008; Beavers, 2010). These high ground motion estimates also resulted in high design requirements for buildings and other structures such as residential buildings in the area. Thus, seismic hazard assessment has become an issue for the economic development in western Kentucky.

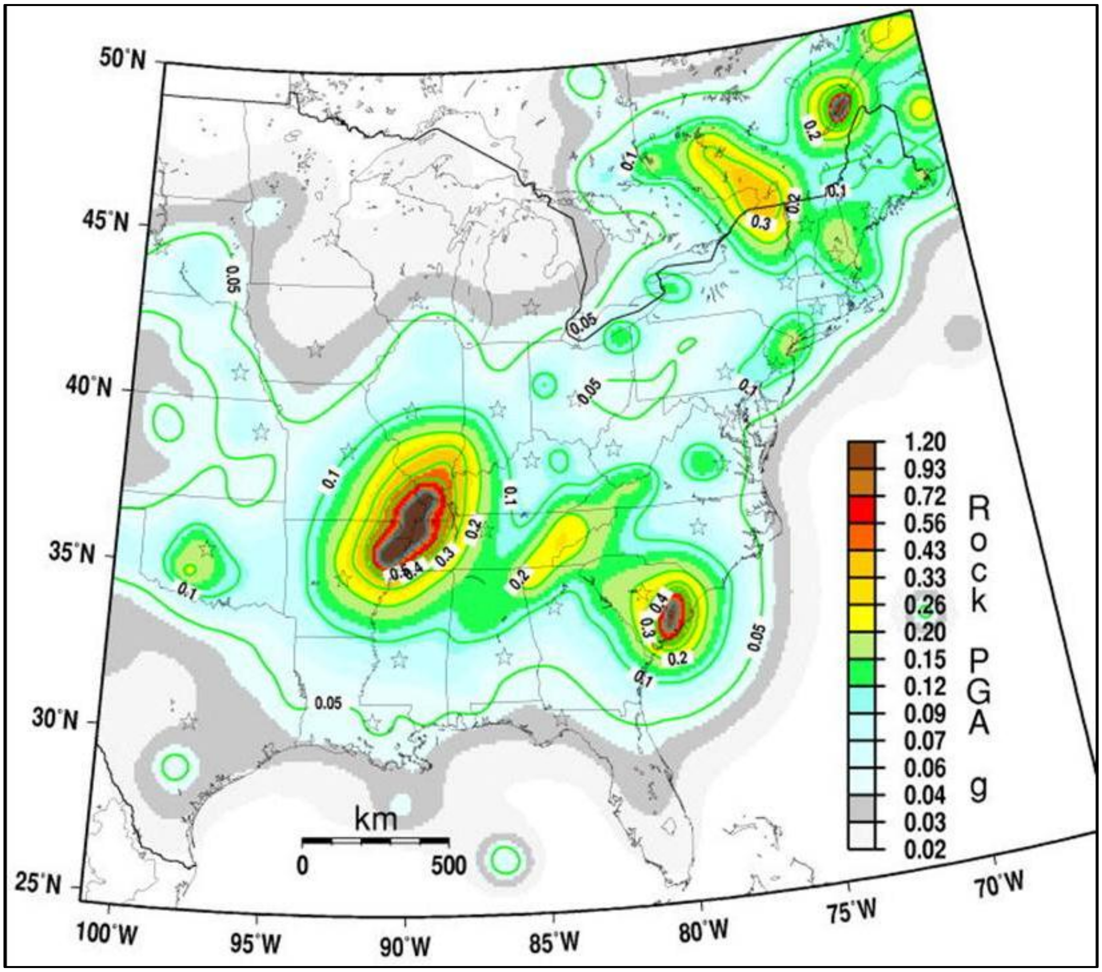

Figure 1. Peak ground acceleration (% g) with 2 percent probability of exceedance in 50 years on rock (Petersen and others, 2008).

An effort to address the seismic hazard issue in western Kentucky was initiated in 2002 with partial support from the Kentucky Office for Economic Development through the Kentucky Consortium for Energy and the Environment (KRCEE) (Wang and others, 2003). The main focus of the initial effort was to temporarily install a dense seismic network with seven short-period stations in the Jackson Purchase Region (Fig. 2) (Wang and others, 2003). These seismic stations, combined with previously installed seismic and strong motion stations, were designed to better monitor and locate earthquakes that occur in the area.

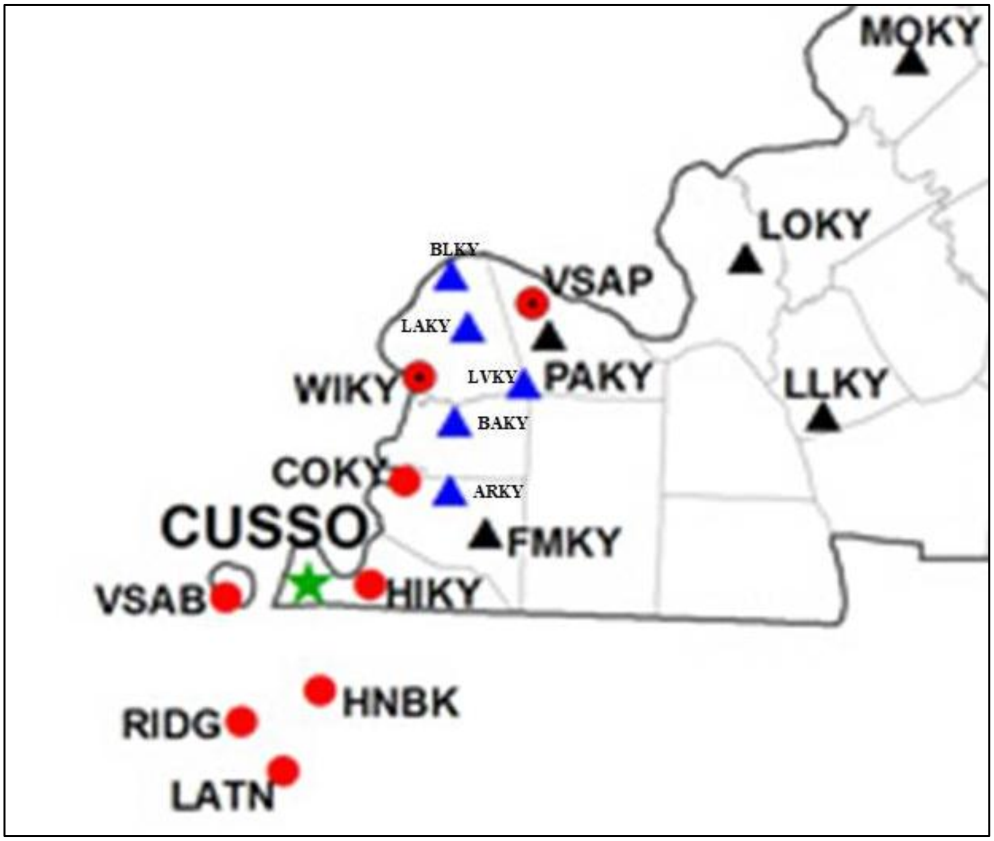

Figure 2. Temporary seismic stations, ARKY, BAKY, BLKY, LAKY, LVKY, VSAP (short-period), and WIKY (short-perid) in the Jackson Purchase Region (Wang and others, 2003).

The effort to address the seismic hazard issue in western Kentucky was enhanced and expanded with support from the U.S Department of Energy (Phase I) through the KRCEE between 2003 and 2007. The main focus of this funding was 1) to conduct a comprehensive study on the seismic hazard assessment for western Kentucky and 2) to procure instruments, install, operate and maintain the seismic network in the Jackson Purchase Region. The study on the seismic hazard assessment was summarized in a report by Wang and Woolery (2008), as well as other publications (Wang, 2005, 2006, 2007, 2008, 2011; Wang and Ormsbee, 2005; Wang and others, 2005; Wang and Zhou, 2007; Wang and Cobb, 2012). The most significant accomplishment on the seismic network during this period (2003-2007) was the drilling and logging of a 1,950 ft. (594 m) deep borehole for the Central United States Seismic Observatory (CUSSO) (Fig. 3) at site VSAS (Fig. 2), funded via UK-KRCEE DOE Grants with supplemental funding from the Kentucky Geological Survey and the U.S. Geological Survey (Woolery and Wang, 2010; Wang and others, 2012).

The deepest CUSSO borehole penetrates 585 m of loose to stiff unlithified sediments (Holocene to Paleocene in age) and 9 m of Ordovician limestone (bedrock). Prior to casing the hole, electrical, sonic velocity (P- and S-wave), and deviation logs were acquired. The overall stratigraphic interpretation is shown in Figure 3 and was based on the cutting samples collected at the wellhead, electronic-logs, and the driller's log. The contact between the surficial alluvium and the underlying Jackson Formation was interpreted to be at 45.7 m below the surface. This boundary marks a distinct lithologic change between the overlying coarse sand and gravel and underlying black clay. The sand and cemented sand correlates with the Claiborne Formation, and the underlying clay correlates with the Wilcox Formation. A distinctive change is also evident in the gamma and spontaneous potential logs (Fig. 3). The contact between the Jackson Formation and the underlying Claiborne Formation was placed approximately 131.1 m below the surface. A lithologic change was interpreted from the driller's log, sonic logs, as well as the electric logs. The boundary separating the Claiborne Formation and the underlying Wilcox Formation is at approximately 274.3 m below the surface. The contact was interpreted from litholigic differences and a distinctive change in the gamma log. The Wilcox Formation is separated from the underlying Porters Creek Clay at approximately 396 m below the surface, and is relatively easy to identify lithologically and geophysically. The Porters Creek is a distinctive, thick sequence of clay and underlies the sandy clay of the Wilcox Formation. This lithologic change is also evident in the gamma and spontaneous potential logs. The contact between the Porters Creek Clay and the underlying Clayton and McNairy Formations is approximately 484.6 m below the surface. Lithologically, there is a distinct contrast between the overlying clays and the underlying sands and clays of the Clayton and McNairy Formations, which is exhibited well on the spontaneous potential log (Fig. 2). The boundary of Clayton and McNairy Formations with the underlying Paleozoic bedrock (limestone) is approximately 585 m below the surface shown on the gamma, spontaneous logs, and sonic logs (Fig. 3).

This report summarizes the effort on the operation and maintenance of the seismic network in the Jackson Purchase Region, particularly in the vicinity of the PGDP, including the installation of CUSSO, with support from the U.S. Department of Energy (Phase II) through KRCEE between 2009 and 2012

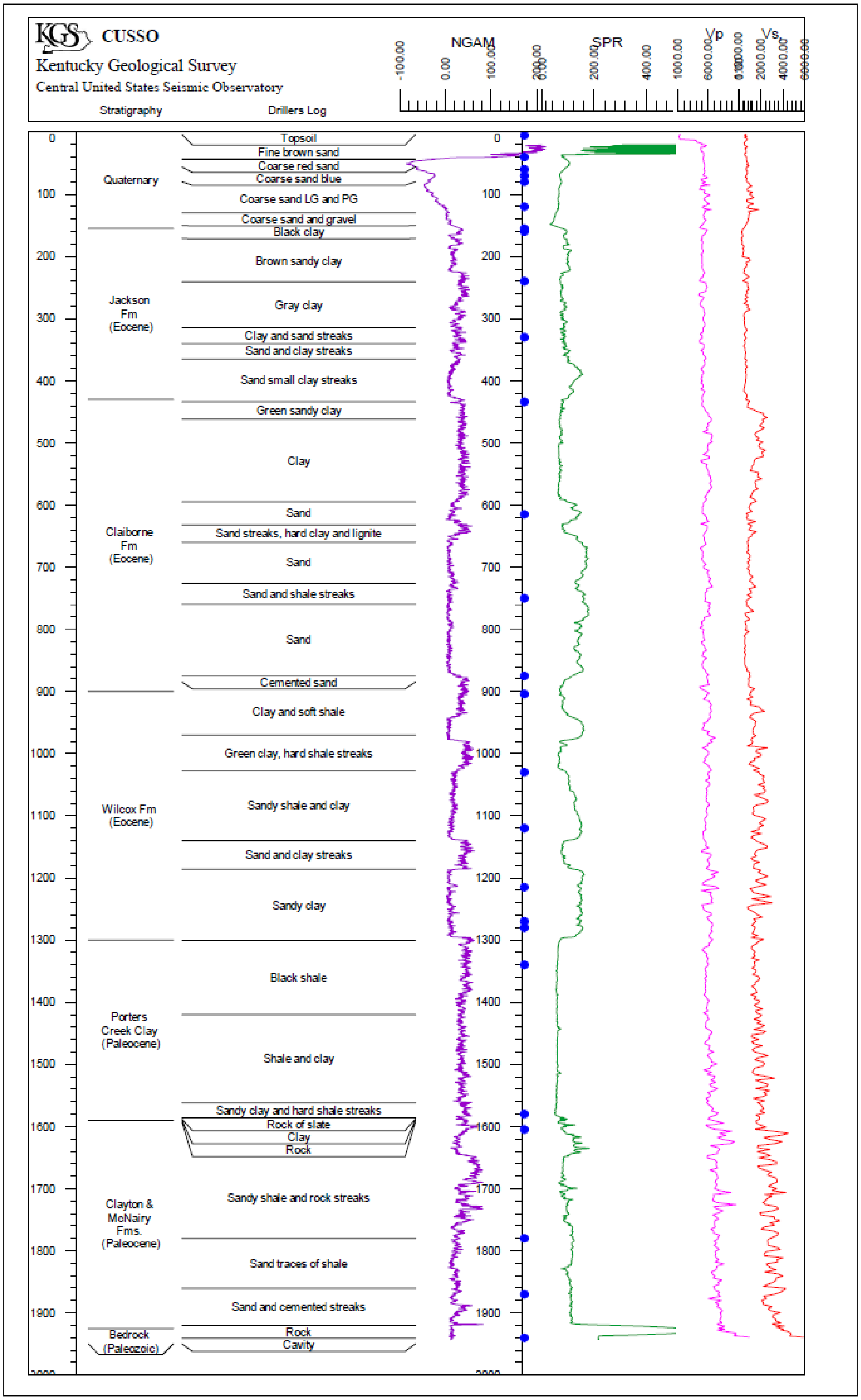

Figure 3. Geologic and geophysical logs at CUSSO.

2. Operation and Maintenance of the Temporary Network

As shown on Figure 2, there were seven short-period stations, including VSAP and WIKY, installed in the Jackson Purchase in late December 2002 and early January 2003 (Wang and others, 2003). These short-period stations were operated and maintained continuously during this funding period. Station BLKY was flooded in May 2011 and all sensors and equipment were destroyed. The recorders (NetDas) at LAKY and ARKY were malfunctioned in June 2011 and June 2012, respectively.

A combination of strong-motion accelerometers and medium-period seismometers was installed at varying depths at CUSSO (Fig. 4):

1) Free surface - EENTEC SP-400 broadband and Kinemetrics FBA-23 strong motion sensors (Fig. 5)
2) 30 m (100 ft) - Kinemetrics strong motion sensors
3) 260 m (850 ft) - Kinemetrics FBA-23 strong motion sensors
4) 512 m (1,680 ft) - EENTEC EA-120 strong motion sensors
5) 595 m (1,950 ft) - EENTEC SP-400 broadband and EA-120strong motion sensors.

The recorder is the Kinemetrics Granite 36-channel system (Fig. 6). Installations of the EENTEC EA-120 at 512 m (1,680 ft) and EENTEC EA-120 and SP-400 at 595 m (1,950 ft) sensors in the 1,950 hole were the most difficult. The sensors were put in place in September 2009 and operated until July 2010 when the sensors at 595 m (ft) were found not working. The sensors were uninstalled in August 2010 and it was found that some of the wires in the cable were short-circuited due to high water pressure. A replacement cable was purchased and the sensors were reinstalled in December 2010. The sensors at 595 m (ft) were found malfunctioned in July 2011 and uninstalled in August 2011. However, all the sensors were not retreated because the lock for the sensors at 512 m (1,680 ft) failed. The sensors at free surface, 30 m (100 ft), and 260 m (850 ft) have been in operation since August 2011.

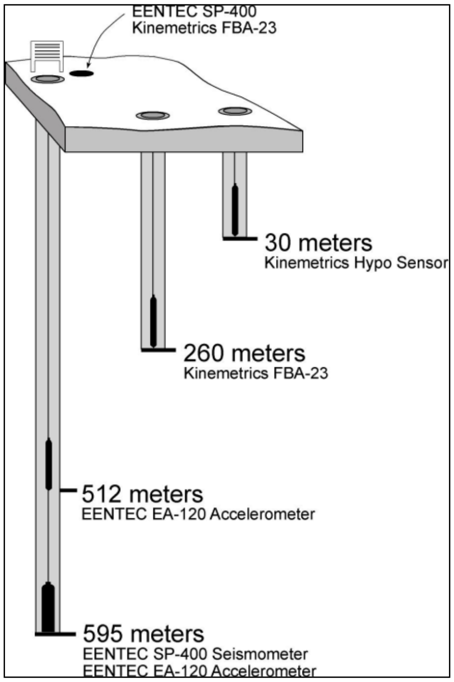

Figure 4. Instrumentation layout at CUSSO.

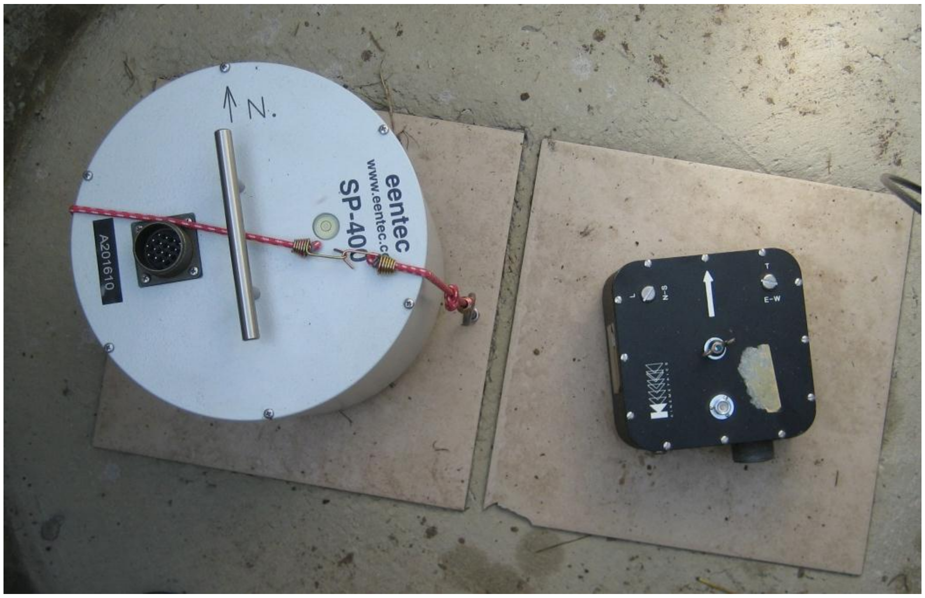

Figure 5. Free-field SP-400 broadband and FBA-23 strong motion sensors at CUSSO.

Figure 6. Granite 36-channel recorder for CUSSO.

3. Data Analyses

As shown in Figure 7, many earthquakes with magnitude between 1.0 and 4.0 occurred in the New Madrid Seismic Zone between January 2009 and September 2012. Only two earthquakes occurred in the Jackson Purchase Region between January 1, 2009 and September 30, 2012 (Table 1). Figure 8 shows the recordings at LVKY from the March 25, 2011 earthquake. Figure 9 shows the acceleration recordings at VSAP from the March 25, 2011 earthquake. The recordings from the temporary stations were used to determine the source parameters of the two earthquakes (Table 1).

Table 1. Earthquakes occurred in the Jackson Purchase Region between January 1, 2009 and September 30, 2012.

Magnitude	Date	Time (UTC)	Latitude	Longitude	Depth (km)	Location
1.9(1)	06/29/09	04:06:15	36.490	89.330	12.8	Tyler, Ky.
2.4(2)	03/25/11	03:12:04	37.046	88.733	6.0	Massac, Ky.

1) and 2) – ID in Figure 7

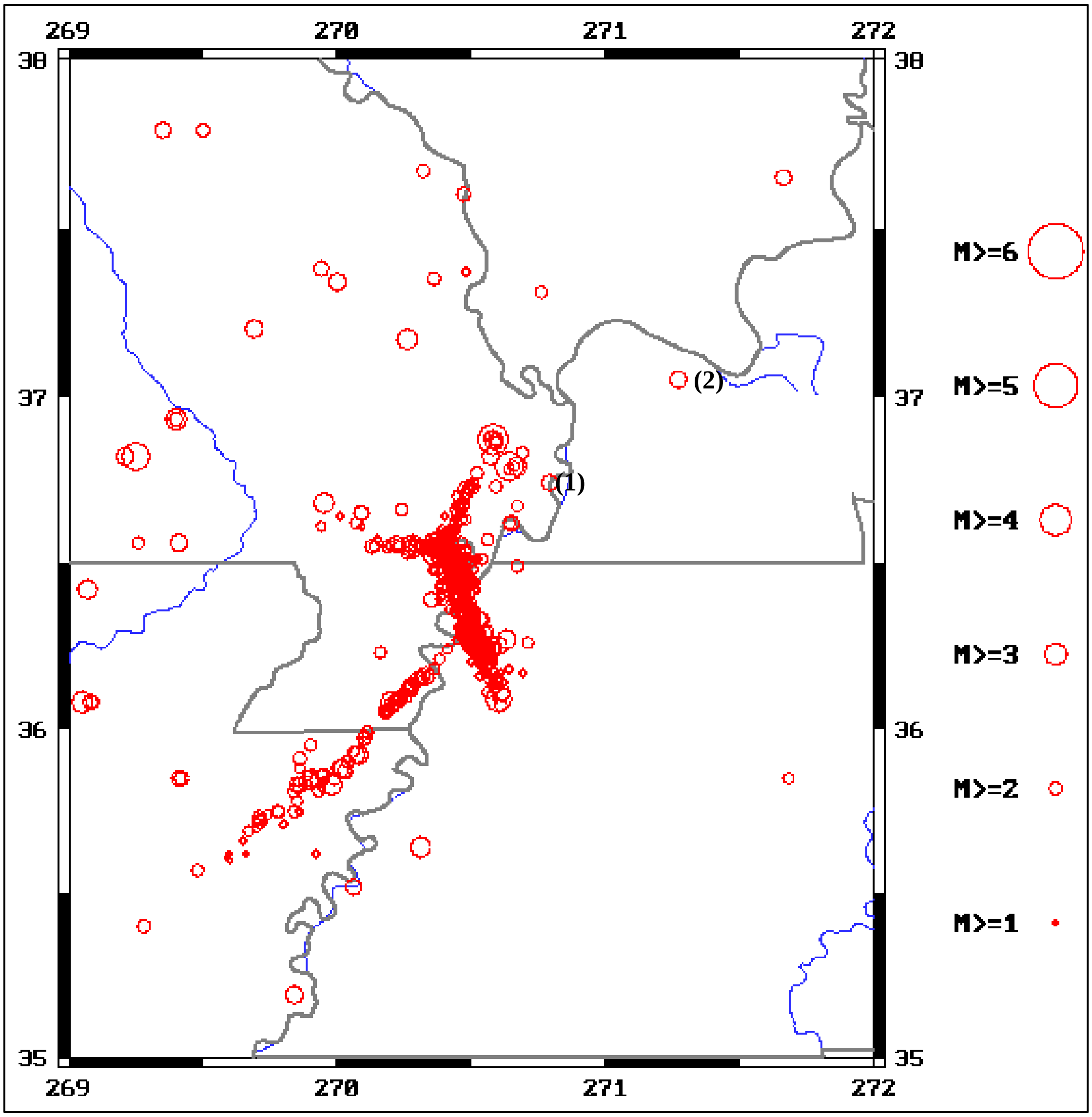

Figure 7. Earthquakes occurred in the New Madrid Seismic Zone between January 2009 and September 2012.

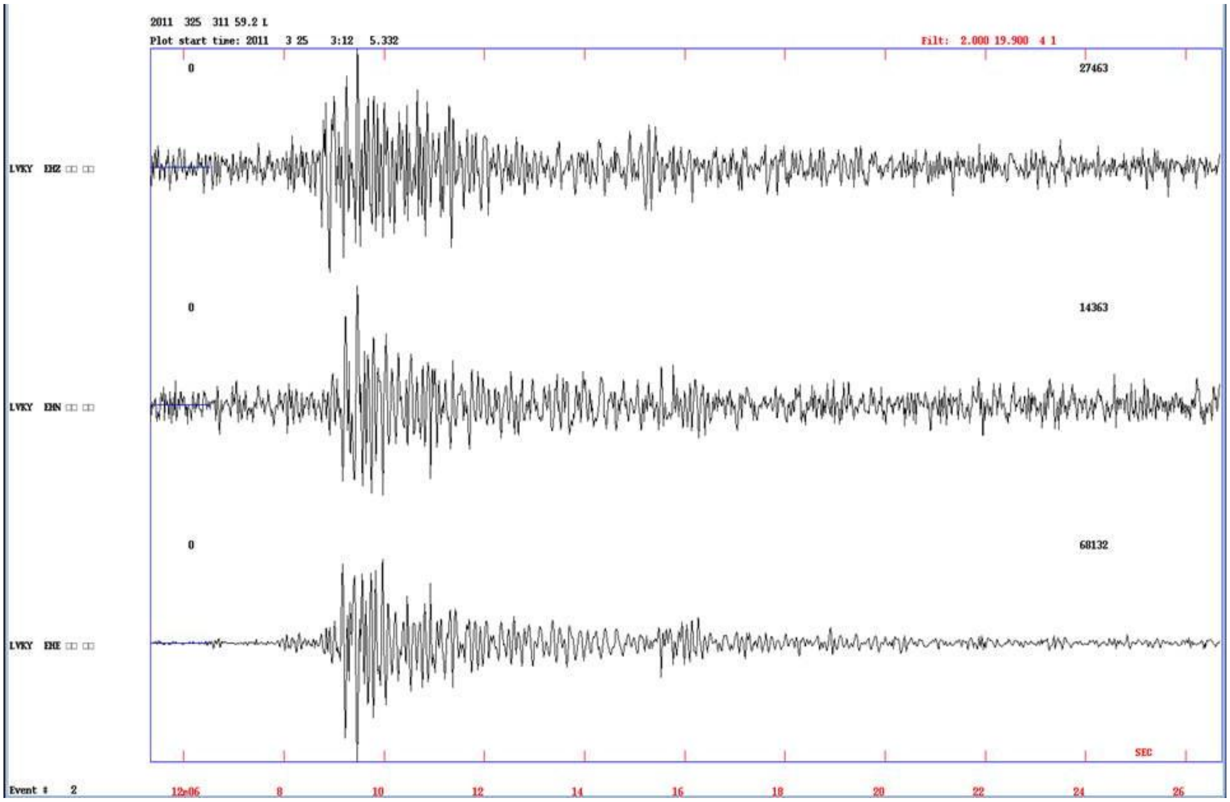

Figure 8. Velocity recordings at station LVKY from the March 25, 2011 earthquake.

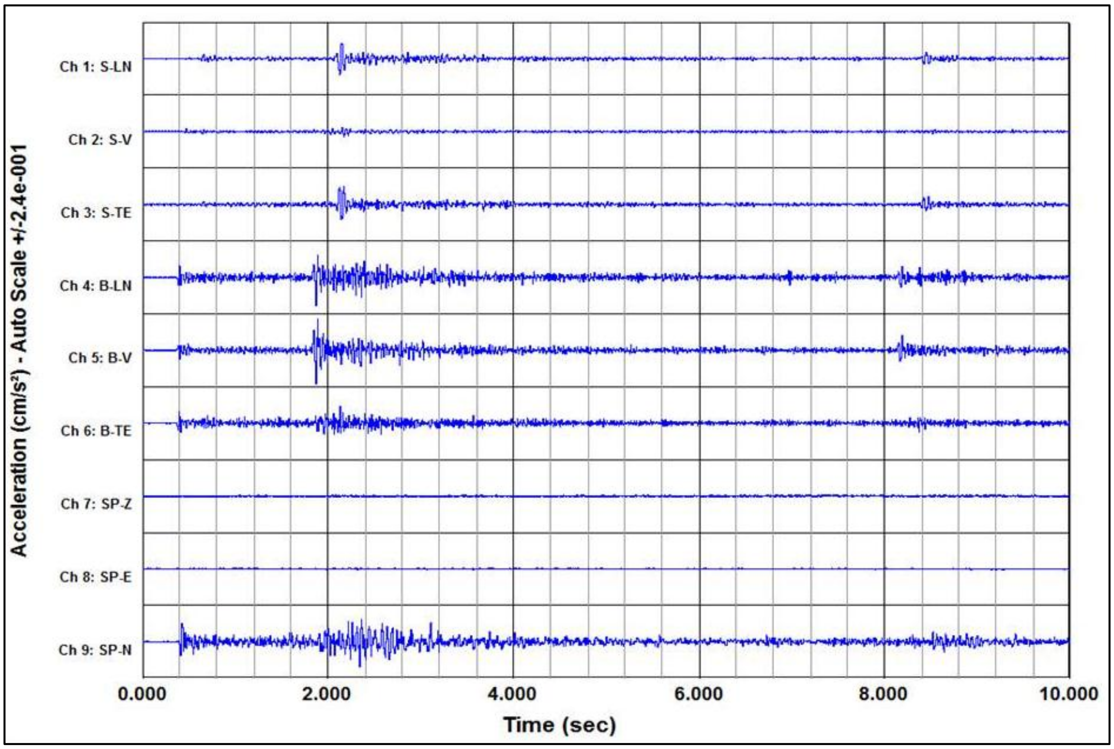

Figure 9. Recordings of the March 25, 2011, earthquake at station VSAP.

Between September 2009 and July 2010, and December 2010 and July 2011 many local, regional, and global earthquakes were recorded, particularly the 2010-2011 central Arkansas earthquake swarm (Horton, 2012) and the March 11, 2011 Japan earthquake (M9.0). Figure 10 shows the velocity recordings at CUSSO from the largest event (M4.7) of the 2010-2011 central Arkansas earthquake swarm (Horton, 2012). The recordings from CUSSO were used to calculate P- and S-wave velocities. The average P- and S-waves velocities for the whole sediment column determined from the first arrivals of P- and S-waves are about 1,750 m/s and 600 m/s, respectively. The average P-wave velocity estimated from first arrivals of earthquake recordings is similar to those from walkaway soundings and the downhole P-wave suspension measurements (Woolery and Wang, 2010; Wang and others, 2012). The S-wave velocity from the suspension log is much lower, however, than velocity from walkaway soundings and the first arrivals of earthquake recordings. The discrepancy is as much as 300 m/s at shallow to intermediate borehole depths. Significant instability and occasional collapse of the borehole wall occurred when the upper part of the borehole was drilled. Consequently, it is speculated that the significant sediment disturbance in the borehole annulus and immediate vicinity adversely affected the accuracy of the S-wave suspension log. The saturated condition of the soft sediment made the downhole P-wave measurements less susceptible to sediment disturbance.

The recordings from CUSSO were also used to analyze P- and S-wave propagation through the sediments (Wang and others, 2012). Figure 11 compares observed velocity (in red) with simulated velocity (in blue) at the surface. The simulation, based on the Haskell-Thomson transfer matrix method (Haskell, 1953), used input parameters derived from in-situ measurements. The input velocity time history was the velocity time history recorded at bedrock. As shown in Figure11, the simulated velocity time history (in blue) is quite similar to the observed velocity time history (in red).

4. Summary

Ten years of installing, maintaining, and operating a dense seismic network is beginning to provide critical preliminary data related to locations and depths of earthquakes in the Jackson Purchase and in the vicinity of the PGDP. Ten years of seismic monitoring is not enough time to make a scientifically defensible conclusion about the extent and nature of the New Madrid faults in the Jackson Purchase Region, the vicinity of the PGDP in particular. Much more time is needed for seismic monitoring in the region. The observed seismicity suggests, however, that the active faults of the New Madrid Seismic Zone may not extend into the Jackson Purchase Region. This could have significant impact on the seismic hazard assessments, particularly the national seismic hazard maps (Frankel and others, 1996, 2002; Petersen and others, 2008) in which the New Madrid faults were extended into the Jackson Purchase Region (Fig. 12). This is why seismic monitoring, a dense seismic network in the Jackson Purchase Region, is important for the health and safety of the citizens of western Kentucky as well as for the economic development of the State.

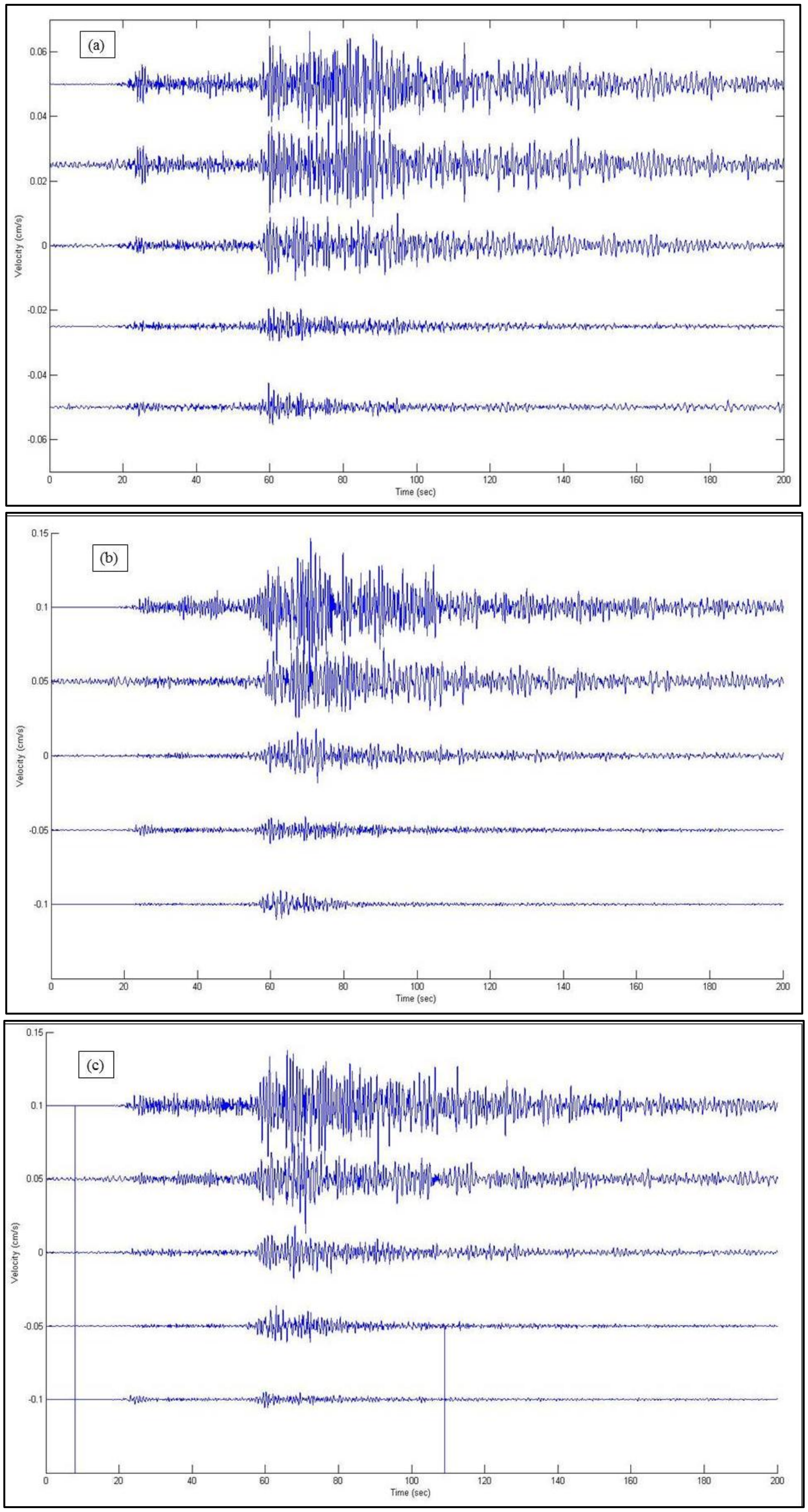

Figure 10. Velocity recordings from strong motion sensors at CUSSO from the largest even (M4.7) of the 2010-2011 central Arkansas earthquake swarm. (a) – vertical components, (b) – horizontal component 1, and (c) horizontal component 2.

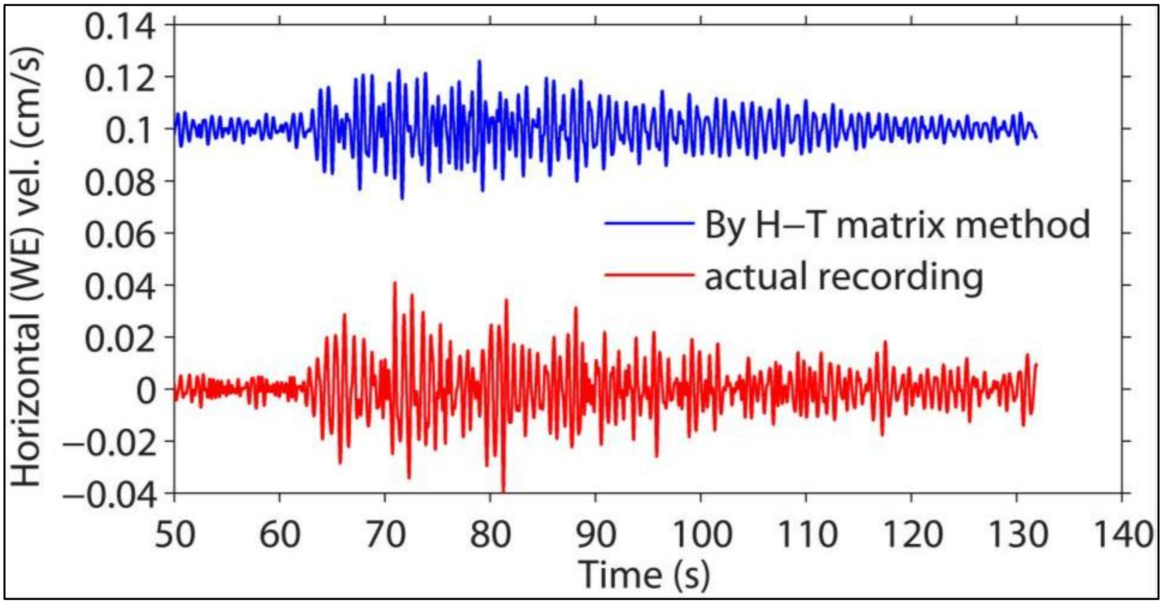

Figure 11. Comparison of actual and 1-D simulation of horizontal (east-west) S-wave velocity.

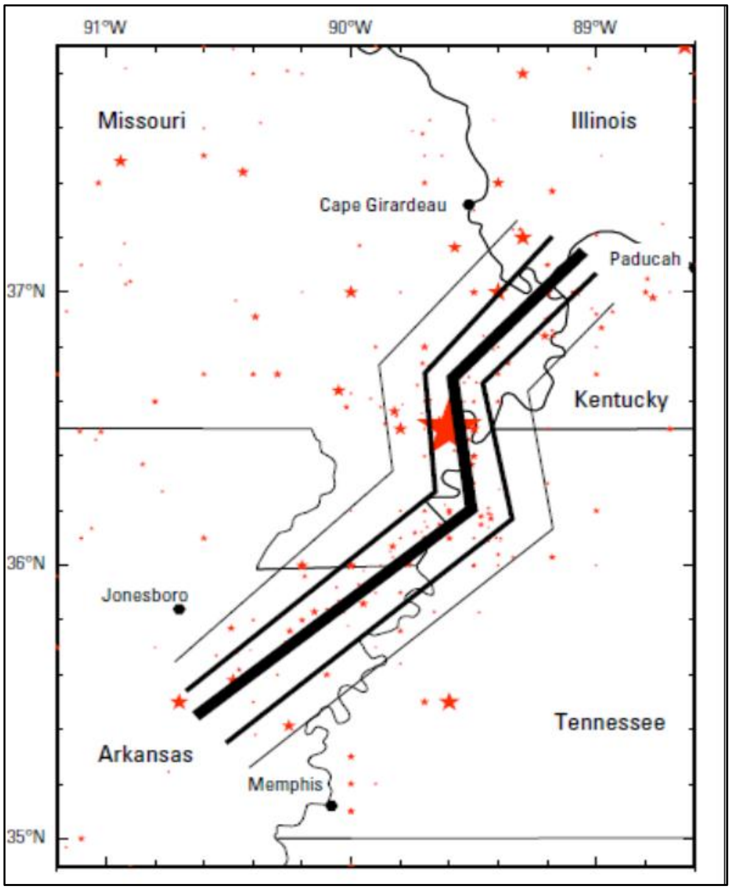

Figure 12. Historical seismicity (M≥3) and locations of the modeled New Madrid hypothetical faults. Relative weights assigned to the hypothetical faults shown by line width. Size of red stars indicates relative size of earthquake (Petersen and others, 2008).

CUSSO provides a test site for verification and calibration of weak and strong motion propagations in thick sediments. Preliminary results show that velocity models produced from the P-wave walkaway soundings, P-wave arrival of earthquake recordings, and downhole P-wave suspension measurements at CUSSO are comparable; however, the S-wave suspension log model underestimates the velocity compared to the models derived from S-wave walkaway soundings and S-wave arrival of earthquake recordings. Significant sediment disturbance in the borehole annulus is speculated to have affected the accuracy of the S-wave suspension log, whereas the saturated condition of the soft sediment at depth made the downhole P-wave measurements less susceptible to the sediment disturbance.

5. References Cited

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.

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.

Haskell, N.A., 1953, The dispersion of surface waves on multilayered media, Bulletin of the Seismological Society of America, 43, 17–34.

Horton, S., 2012, Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake, Seismological Research Letters, v. 83, p. 250–260.

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.

Wang, Z. (compiler), 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 National Conference on Earthquake Engineering, April 18-22, 2006, San Francisco, CA, Paper no. 416.

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., ed., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: *Geological Society of America Special Paper 425*, p. 363–373.

Wang, Z., 2008, Understanding seismic hazard and risk: A gap between engineers and seismologists, **the 14th World Conference on Earthquake Engineering**, October 12-17, 2008, Beijing, China, Paper No. **S27-001.**

Wang, Z., 2011, Seismic Hazard Assessment: Issues and Alternatives, Pure and Applied Geophysics, 168: 11–25.

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 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., and E.W. Woolery, 2006, Recordings from the Deepest Borehole in the New Madrid Seismic Zone, *Seismological Research Letters*, **77**: 131–136.

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

Wang, Z., and M. Zhou, 2007, Comment on "Why Do Modern Probabilistic Seismic-Hazard Analyses Often Lead to Increased Hazard Estimates?" by Julian J. Bommer and Norman A. Abrahamson, *Bulletin of Seismological Society of America*, **97**: 2212–2214.

Wang, Z., B. Shi, and J. Kiefer, 2005, Comment on "How Can Seismic Hazard around the New Madrid Seismic Zone Be Similar to that in California?" by Arthur Frankel, *Seismological Research Letters*, **76**: 466–471.

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.

Woolery, E.W., and Z. Wang, 2010, Toward construction of the central United States Seismic Observatory and calibration site: Defining the geologic site model, Report to the United States Geological Survey, NEHRP Award 08HQGR0094, 33p