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

April 2009–September 2012

Final Report

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Contract Report 5

Series XII, 2013

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Introduction

The seismic-hazard maps produced by the U.S. Geological Survey (Frankel and others, 1996, 2002; Petersen and others, 2008) showing the 2 percent probability of peak ground acceleration being exceeded in 50 yr, or about once in 2,500 yr, show high ground motion in western Kentucky, the Jackson Purchase Region in particular (Fig. 1). These maps have assigned the Jackson Purchase Region a seismic hazard that is similar to or even higher than for San Francisco or Los Angeles, Calif. For example, the predicted peak ground acceleration at the Paducah Gaseous Diffusion Plant is about 1.0 g. These high ground-motion estimates resulted in a high design requirement (0.8 g PGA) for a landfill at the Paducah Gaseous Diffusion Plant, which made it difficult for the U.S. Department of Energy to obtain a permit from State regulators to construct the landfill (Wang and Woolery, 2008; Beavers, 2010). They 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 economic development issue in western Kentucky.

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 (Wang and others, 2003). Initially, the main focus was to install a temporary dense seismic network with seven short-period stations (i.e., ARKY, BAKY, BLKY, LAKY, LVKY, VSAP, and WIKY) 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 in the area.

The effort was enhanced and expanded with support from the U.S. Department of Energy (phase I) through the Kentucky Consortium for Energy and the Environment 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 them, and operate and maintain the seismic network in the Jackson Purchase Region. Wang (2005, 2006, 2007, 2008, 2011), Wang and Ormsbee (2005), Wang and others (2005), Wang and Zhou (2007), Wang and Woolery (2008), and Wang and Cobb (2012) published summaries of the study. The most significant accomplishment during this period (2003–07) was the drilling and logging of a 594-m-deep borehole for the Central United States Seismic Observatory (CUSSO) (Fig. 3) at site VSAS (Fig. 2), funded by grants from the U.S. Department of Energy through the Kentucky Consortium for Energy and Environment, with supplemental funding from the Kentucky Geological Survey and the U.S. Geological Survey (Woolery and Wang, 2010; Wang and others, 2012).

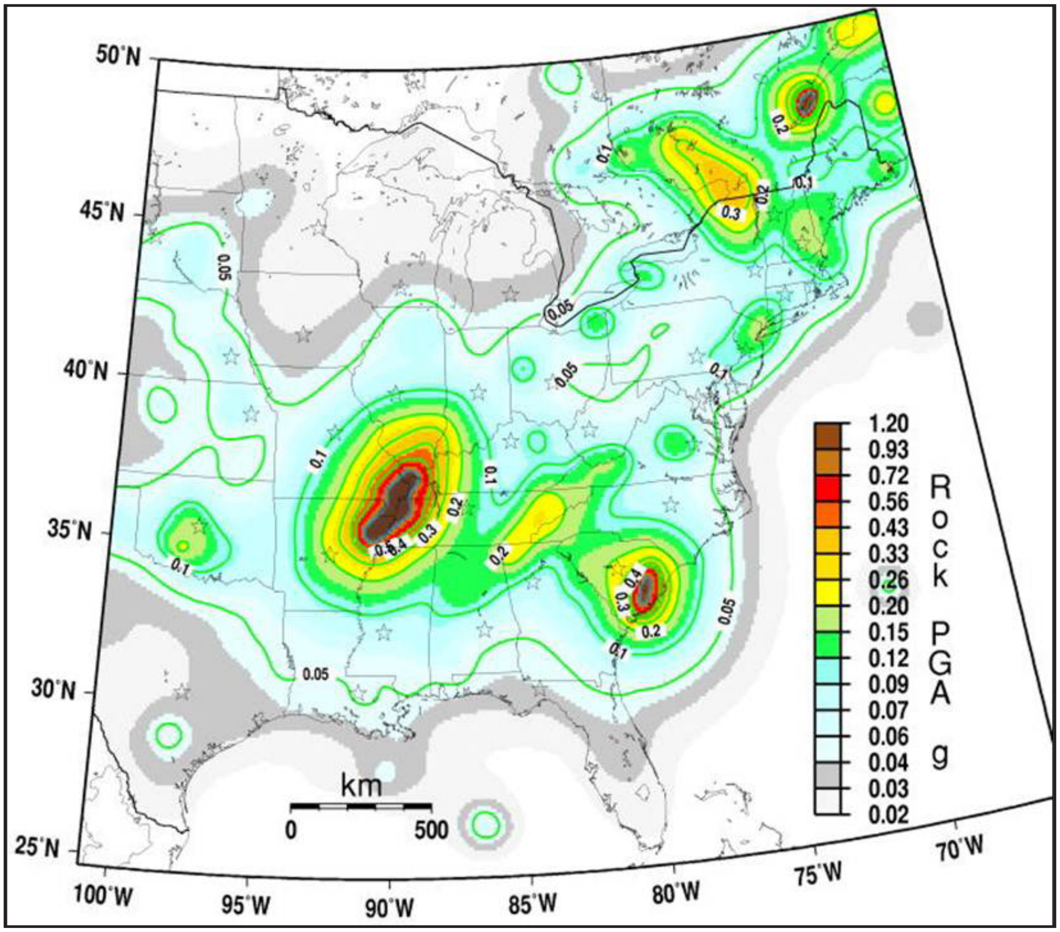

Figure 1. Peak ground acceleration (percent g) with 2 percent probability of exceedance in 50 yr on rock. From Petersen and others (2008).

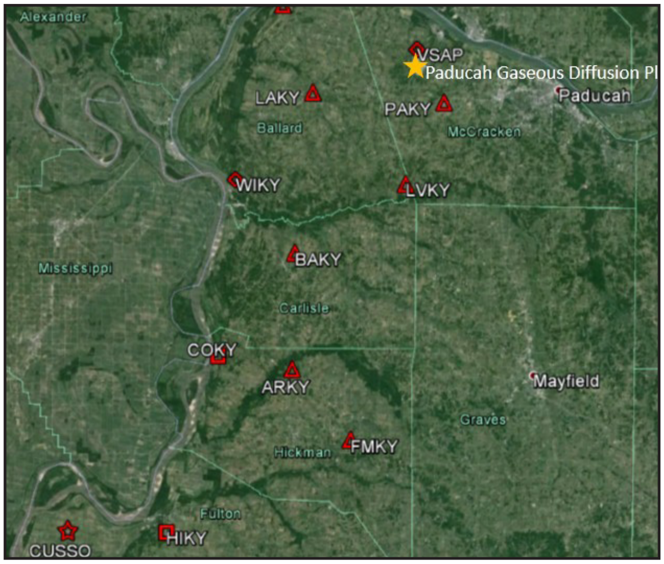

Figure 2. Seismic network in the vicinity of the Paducah Gaseous Diffusion Plant. Triangle = short-period stations, diamond = short-period and strong-motion station, square = strong-motion station.

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). Before the hole was cased, 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 the underlying black clay. The sand and cemented sand correlate with the Claiborne Formation, and the underlying clay correlates with the Wilcox Formation. A distinctive change is also evident in the gamma-ray 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, and 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 lithologic differences and a distinctive change in the gamma-ray log. The boundary between the Wilcox Formation and the underlying Porters Creek Clay is at approximately 396 m below the surface, and is relatively easy to identify

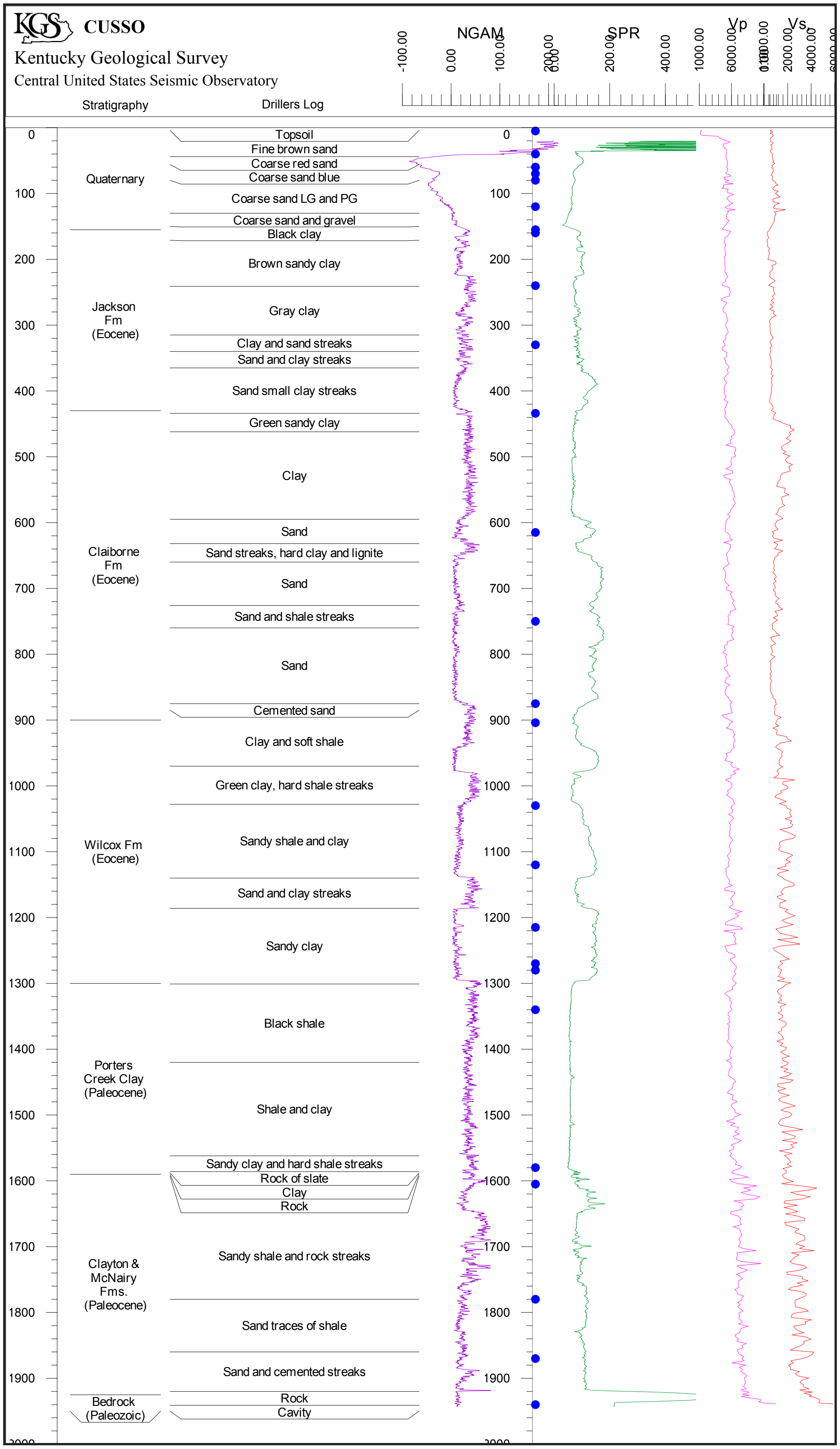

Figure 3. Geologic and geophysical logs from CUSSO.

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-ray 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 the Clayton and McNairy Formations with the underlying Paleozoic bedrock (limestone) is approximately 585 m below the surface, as shown on the gamma-ray, spontaneous-potential, and sonic logs (Fig. 3).

This report summarizes phase II of the operation and maintenance of the seismic network in the vicinity of the Paducah Gaseous Diffusion Plant, (Fig. 2), particularly the installation and operation of CUSSO, with support from the U.S. Department of Energy through the Kentucky Consortium for Energy and Environment, between 2009 and 2012.

Operation and Maintenance of the Network

As shown on Figure 2, seven short-period stations, including VSAP and WIKY, were installed in the vicinity of the Paducah Gaseous Diffusion Plant 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 at LAKY and ARKY malfunctioned in June 2011 and June 2012, respectively. Stations ARKY, BLKY, and LAKY were removed due to lack of funds.

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 Kinematrics FBA-23 strong-motion sensors[1] (Fig. 5).
2. 30 m—Kinematrics strong-motion sensors.

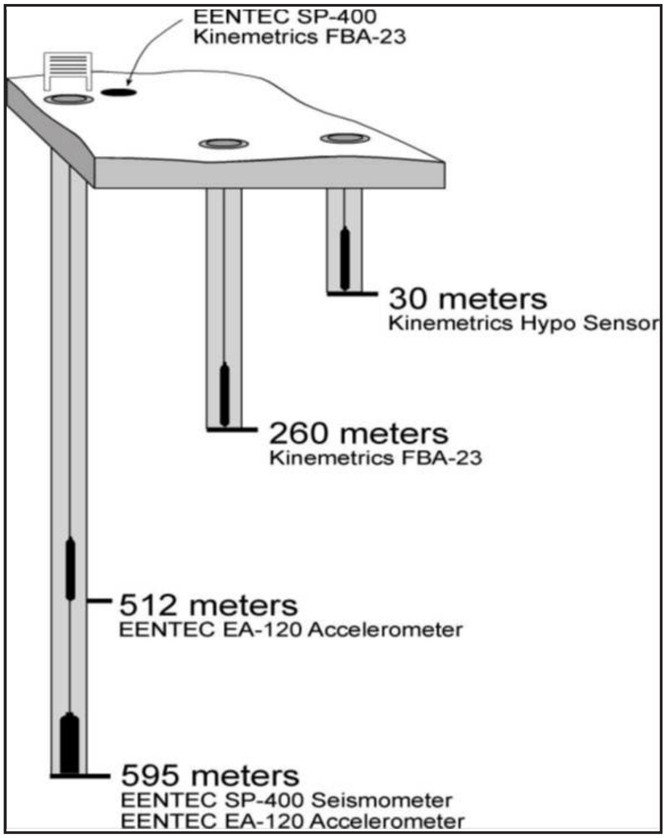

Figure 4. Instrumentation layout at CUSSO.

3. 260 m—Kinematrics FBA-23 strong-motion sensors.
4. 512 m—EENTEC EA-120 strong-motion sensors.
5. 595 m—EENTEC SP-400 broadband and EA-120 strong-motion sensors.

The recorder is the Kinemetrics Granite 36-channel system (Fig. 6). Installation of the EENTEC EA-120 sensor at 512 m and the EENTEC EA-120 and SP-400 sensors at 595 m was the most difficult. The sensors were put in place in September 2009 and operated until July 2010, when the sensors at 595 m were found to be not working. The sensors were removed in August 2010, and some of the wires in the cable were short-circuited by high water pressure. A replacement cable was purchased and the sensors were reinstalled in December 2010. The sensors at 595 m malfunctioned again in July 2011 and were removed in August 2011. However, the sensors were not retreated because the lock for the sensors at 512 m failed. The sensors at 512 m were

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[1] The use of manufacturer and trademark names does not constitute an endorsement of the product by the Kentucky Geological Survey or the University of Kentucky.

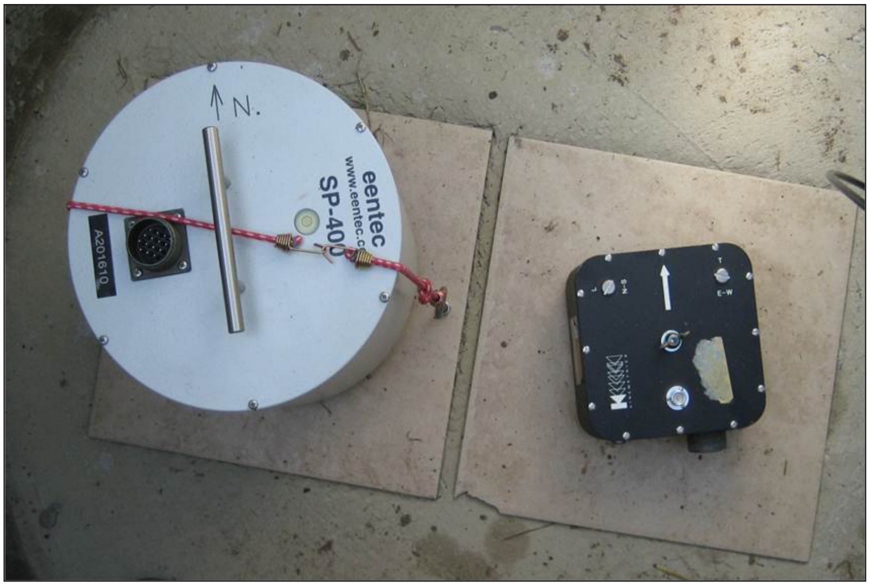

Figure 5. Free-field SP-400 broadband and FBA-23 strong-motion sensors at CUSSO.

retreated in May 2013, but the sensors at 595 m could not be retreated and were left at the bottom of the hole. Replacement strong-motion and short-period sensors were reinstalled at the bottom of the hole in June 2013. The sensors at the bottom are not functioning properly because they were short-circuited by high water pressure. Currently, the sensors at free surface, 30 m, and 260 m are in operation.

Data Analysis

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 one earthquake occurred in the vicinity of the Paducah Gaseous Diffusion Plant between January 1, 2009, and September 30, 2012. 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 earthquake.

Between September 2009 and July 2010 and between December 2010 and July 2011, many local, regional, and global earthquakes were recorded, in particular the 2010-11 central Arkansas earthquake swarm (Horton, 2012) and the March 11, 2011, Japan earthquake (M 9.0). Figure 10 shows the velocity recordings at CUSSO from the largest event (M 4.7) of the central Arkansas earthquake swarm (Horton, 2012). The recordings from CUSSO were used to calculate P- and S-wave velocities. The average P- and S-wave 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 record-

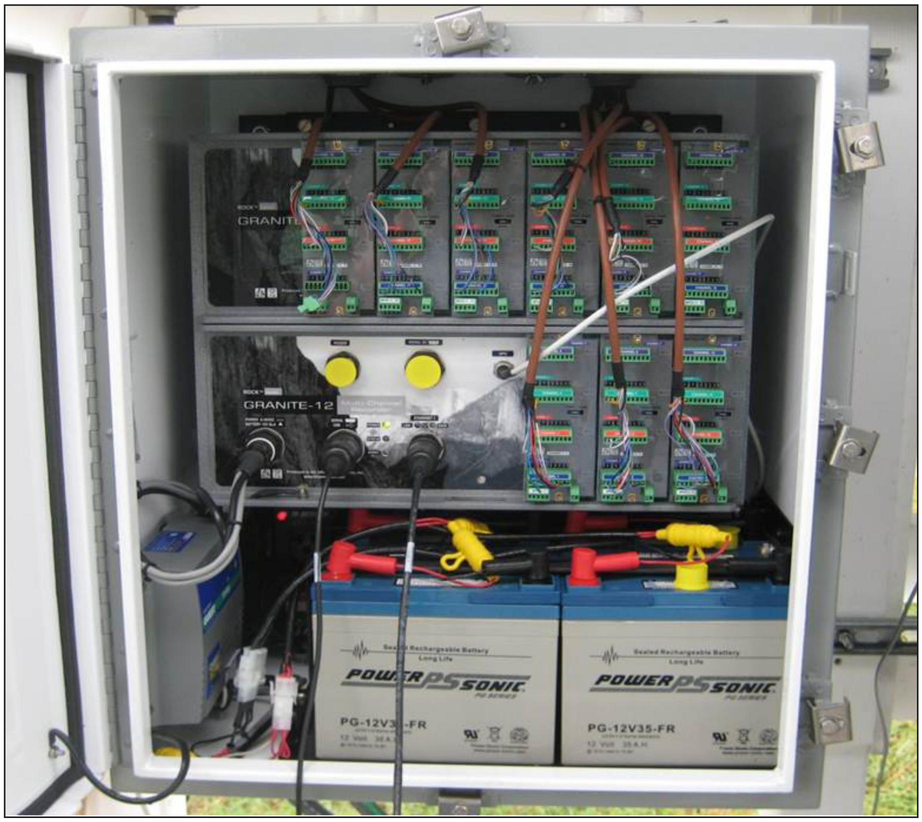

Figure 6. Granite 36-channel recorder for CUSSO.

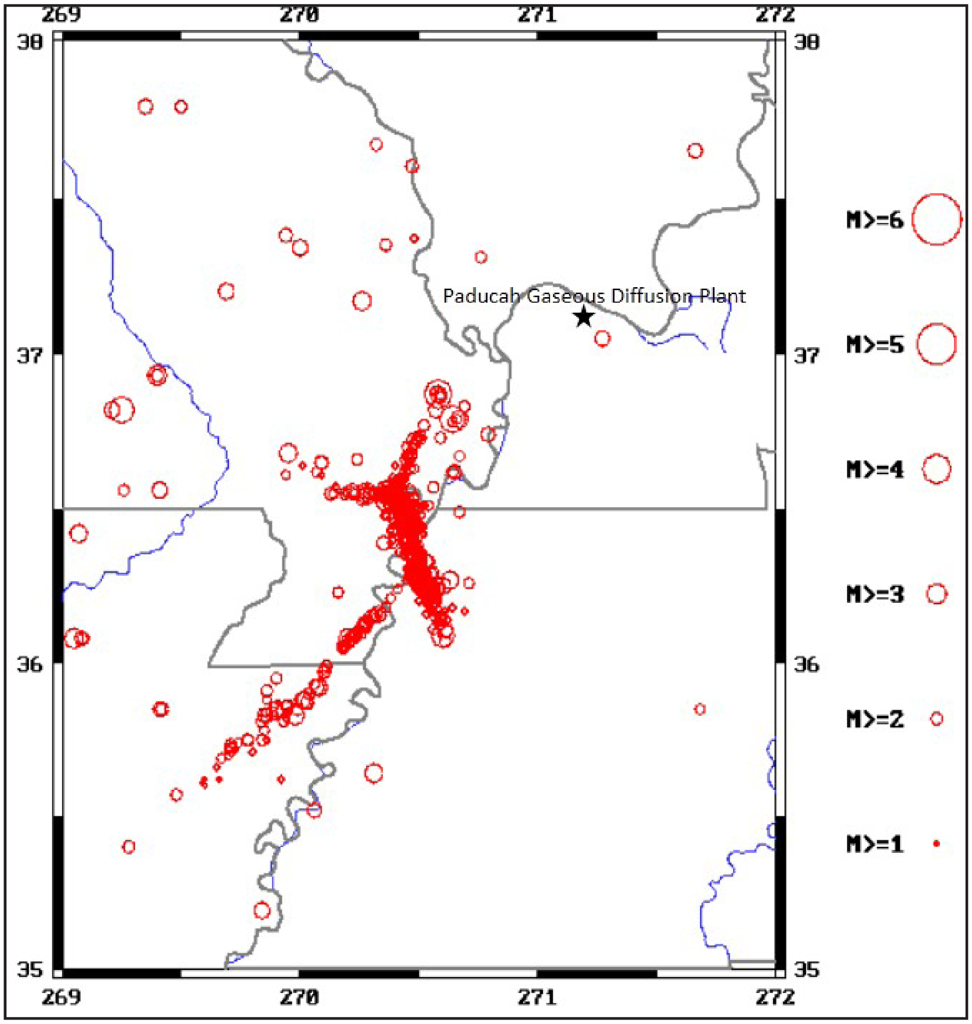

Figure 7. Locations of earthquakes occurring in the New Madrid Seismic Zone between January 2009 and September 2012.

ings is similar to those from walkaway soundings and 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 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, the significant sediment disturbance in the borehole annulus and immediate vicinity may have 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 with simulated velocity 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 Figure 11, the simulated velocity time history is quite similar to the observed velocity time history.

Summary

Ten years of operating a dense seismic network is beginning to provide critical preliminary data on locations and depths of earthquakes in the Jackson Purchase and the vicinity of the Paducah Gaseous Diffusion Plant. But this 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 Paducah Gaseous Diffusion Plant 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 seismic-hazard assessments, particularly those on which the national seismic-hazard maps were based (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 with a dense seismic network is important for the health and safety of the

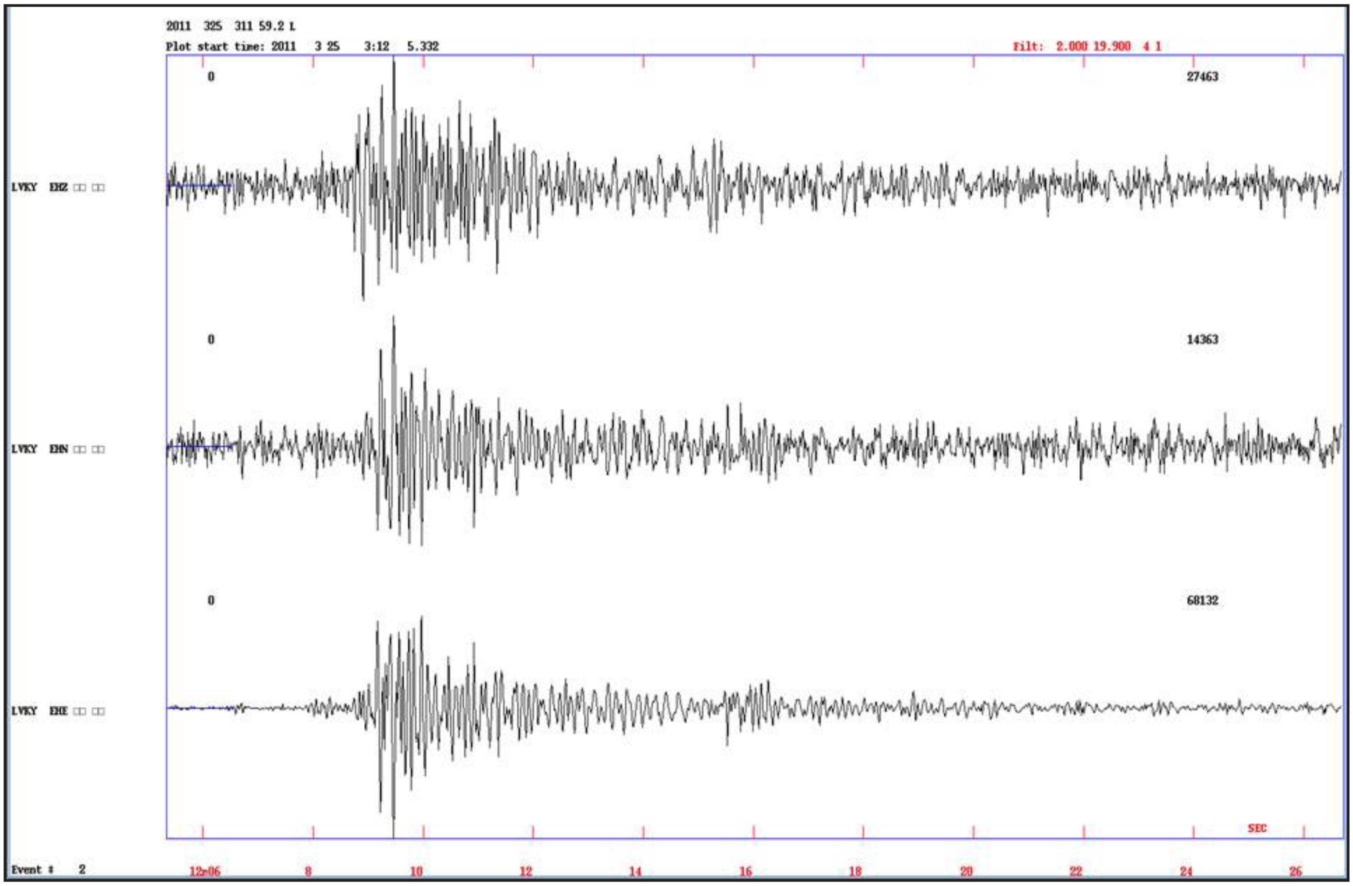

Figure 8. Velocity recordings at station LVKY from the March 25, 2011, earthquake.

citizens of western Kentucky, as well as for the economic development of the state.

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 most likely 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.

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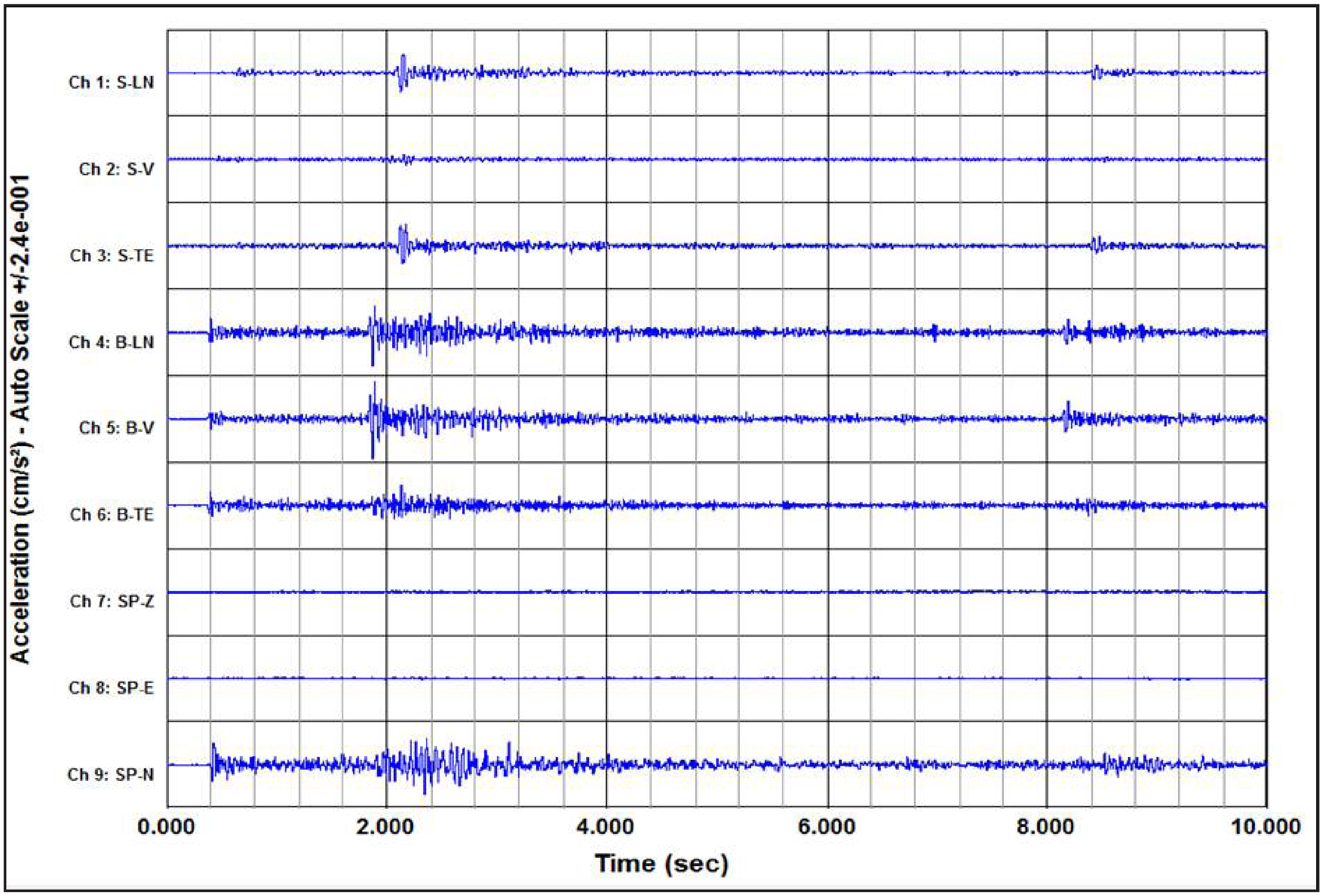

Figure 9. Acceleration records of the March 25, 2011, earthquake at station VSAP.

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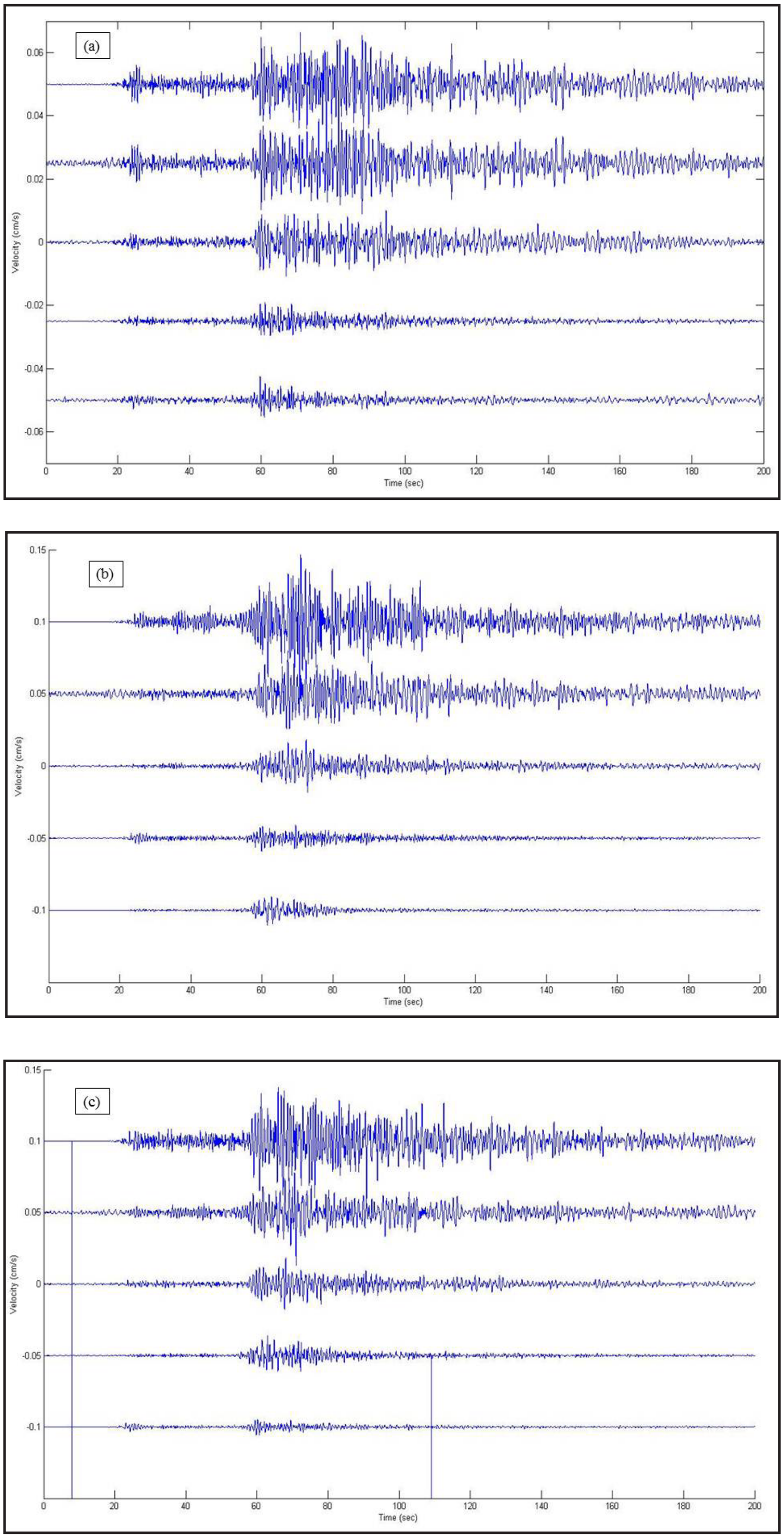

Figure 10. Velocity recordings from strong-motion sensors at CUSSO from the largest event (M 4.7) of the 2010-11 central Arkansas earthquake swarm. (a) Vertical components. (b) Horizontal component 1. (c) Horizontal component 2.

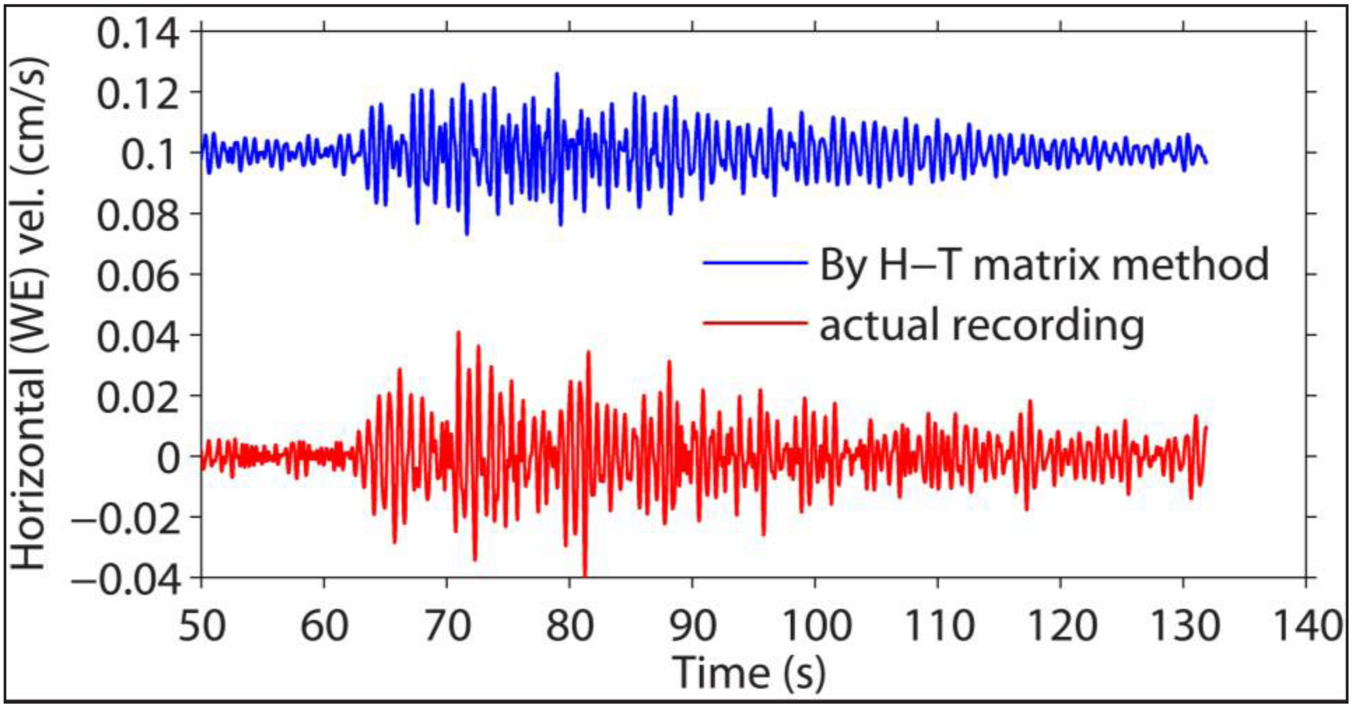

Figure 11. Comparison of actual and 1-D simulation of horizontal (east-west) S-wave velocity.

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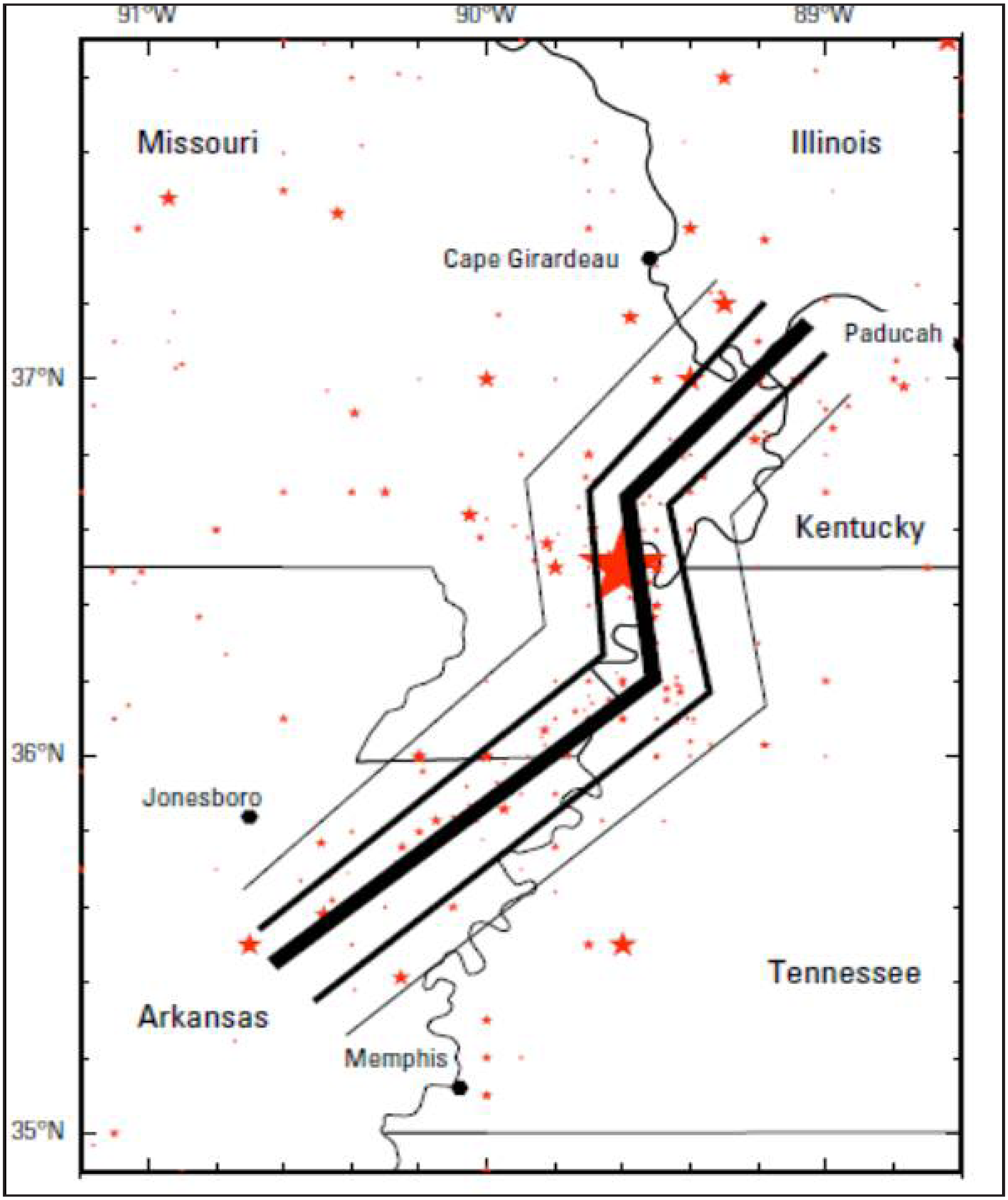

Figure 12. Historical seismicity (M ≥ 3) and locations of the modeled New Madrid hypothetical faults. Relative weights assigned to the hypothetical faults shown by line width. Size of red stars indicates relative size of earthquake. From Petersen and others (2008).