Structure and Seismicity of the Wabash Valley Seismic Zone
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Final Report

Gary L. Pavlis, Michael W. Hamburger, Kevin Eagar, and Jiedi Wu
Department of Geological Sciences, Indiana University,Bloomington IN 47405
(pavlis@indiana.edu , hamburg@indiana.edu, jiwu@indiana.edu)
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Introduction

In the past decade our understanding of earthquake hazards in southern Indiana has been profoundly changed through results from paloeseismology studies. Hundreds of liquefaction features that are believed to be the result of local earthquake ground motion were systematically surveyed and examined by Obermeier *et al.* (1991, 1992) and Munson *et al.* (1993, 1994) along river banks and exposures of late Pleistocene and Holocene sediments. This evidence indicates the lower Wabash Valley area has experienced repeated earthquakes with magnitude of 6.7 or larger during Holocene times. While the historical and instrumental records show that although the seismicity rate is much lower than a typical plate boundary region, activity is by no means zero. Nuttli's (1979) historical records show that numerous felt events occurred in this region prior to modern network recording. In the combined historical and instrumental record at least seven events with than $m_b \geq 5$ have occurred in the region (Nuttli, 1979, 1983; Taylor et al., 1989; Kim, 2003).

In spite of the clear evidence that the Wabash Valley Seismic Zone (WVSZ) represents a significant seismic risk, the area has not received a level of seismic monitoring consistent with the threat. While the New Madrid region has been heavily instrumented, with station densities higher than most of California, the WVSZ has consistently remained at the fringe of the national seismic monitoring infrastructure. This has limited the quality and quantity of data available to appraise seismic risk in the region. In this project we are addressing this problem by using two underutilized, seismic data sets that provide new constraints on this problem.

1. We are analyzing data acquired by the Indiana PEPP educational seismic network (Figure 1). The Indiana PEPP network (Hamburger and Pavlis, 2003; see http://www.indiana.edu/~pepp) began as an education and outreach effort as part of the national seismology education and outreach program called the Princeton Earth Physics Project (PEPP); see Hamburger & Taber, 2003). PEPP's original goal was to link science teachers and university groups doing seismology research to form a national network of seismic stations operated in schools. We have held regular workshop with teachers at participating schools since 1996 to form a strong working collaboration with teachers in 22 schools with 28 active teachers. An important element of this project is utilizing the data these teachers have helped us collect for a useful scientific purpose. Until now the primary purpose of the network was educational. Support from this project is helping us extend the research objectives of the PEPP network and provide an important focus for high school students and teachers involved in the network.

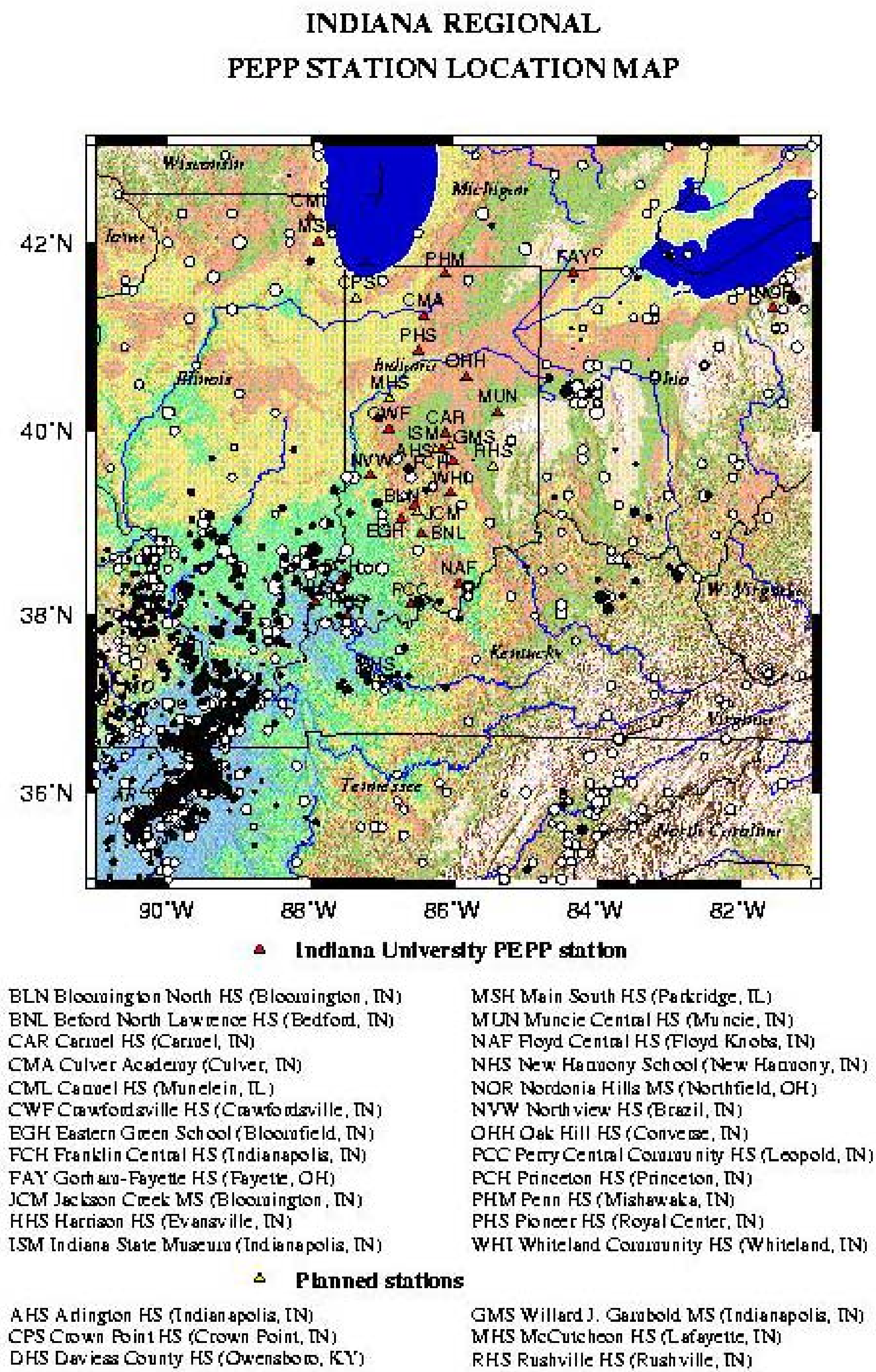

Figure 1. Stations of the Indiana PEPP network.

2. We used data from a temporary network of seismic stations deployed in 1995-1996 as part of a collaborative experiment focused on detecting and locating small earthquakes within the

WVSZ (Figure 2). The results provided new constraints on seismic hazards in the WVSZ (Pavlis et al., 2002), but as in most experimental programs there were numerous research questions that justified further work on these data.

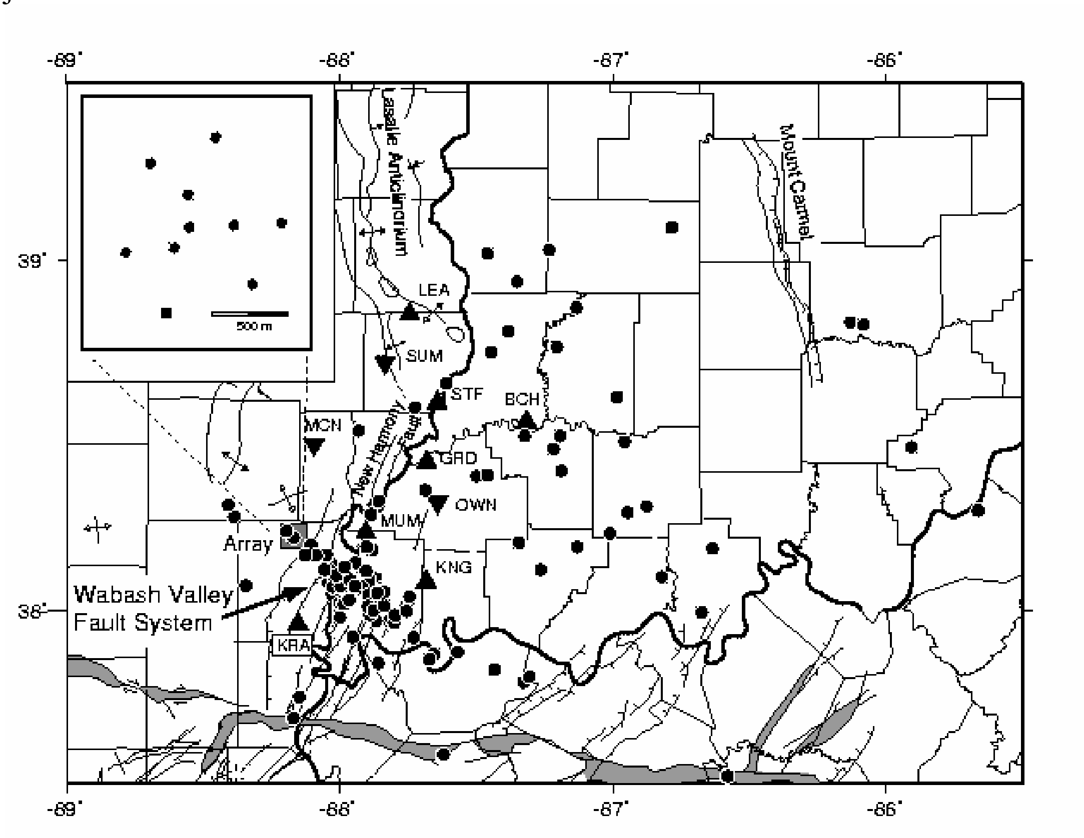

Figure 2. Seismicity results of 1995-1996 Wabash Valley experiment (from Pavlis et al., 2002). Circles are events identified as earthquakes. Triangles show the location seismic stations that operated in triggered mode. (Inverted triangles used geophone strings for noise reduction instead of single sensors.). The inset square shows the geometry of a phased array deployed in southeastern Illinois (location shown by shaded square).

This report summarizes the results of four projects completed on these data under this grant: (1) teleseismic P wave tomography for the Illinios Basin region; (2) a detailed analysis of microearthquakes in the "New Harmony cluster" in southwestern Indiana (Figure 2); (3) performance analysis of the PEPP network; and (4) an educational research collaboration analyzing mining and quarry explosions in the southern Illinois Basin. These projects define individual sections in the remainder of this report.

Teleseismic P-wave Tomography

Wu (2004) completed the first ever tomographic inversion of the lower crust and upper mantle beneath the Illinois Basin. She utilized data from teleseismic earthquakes recorded by the PEPP network (Figure 1) and from the MOMA experiment (Fouch et al., 2000). Key results of this work are:

1. The data suggest that seismic velocities the upper mantle beneath central Indiana are slightly higher than that to the southeast and north (Figure 3). Because the lower velocities correlate with the Illinois and Michigan basins, respectively, and the higher velocities correlate with the basement arch between them, Wu (2004) suggested that

these regional-scale geologic structures could have been controlled by variations in upper mantle strength.

2. Analysis of near-surface velocities indicates a relatively low-velocity uppermost mantle beneath the seismically active part of the WVSZ (-0.5% relative to neighboring areas of Indiana and Illinois). This velocity anomaly appears to extend from the base of the crust to at least 180 km depth, although the resolution with these data make the vertical extent of this feature unclear.
3. A detailed analysis of the resolution of this tomographic model (Wu, 2004) indicates that both the magnitude of the velocity variations and the vertical location of the variations seen in Figure 3 are poorly constrained. With the existing data set, we can, however, document a systematic difference in average lithospheric properties between central Indiana and the neighboring basins.

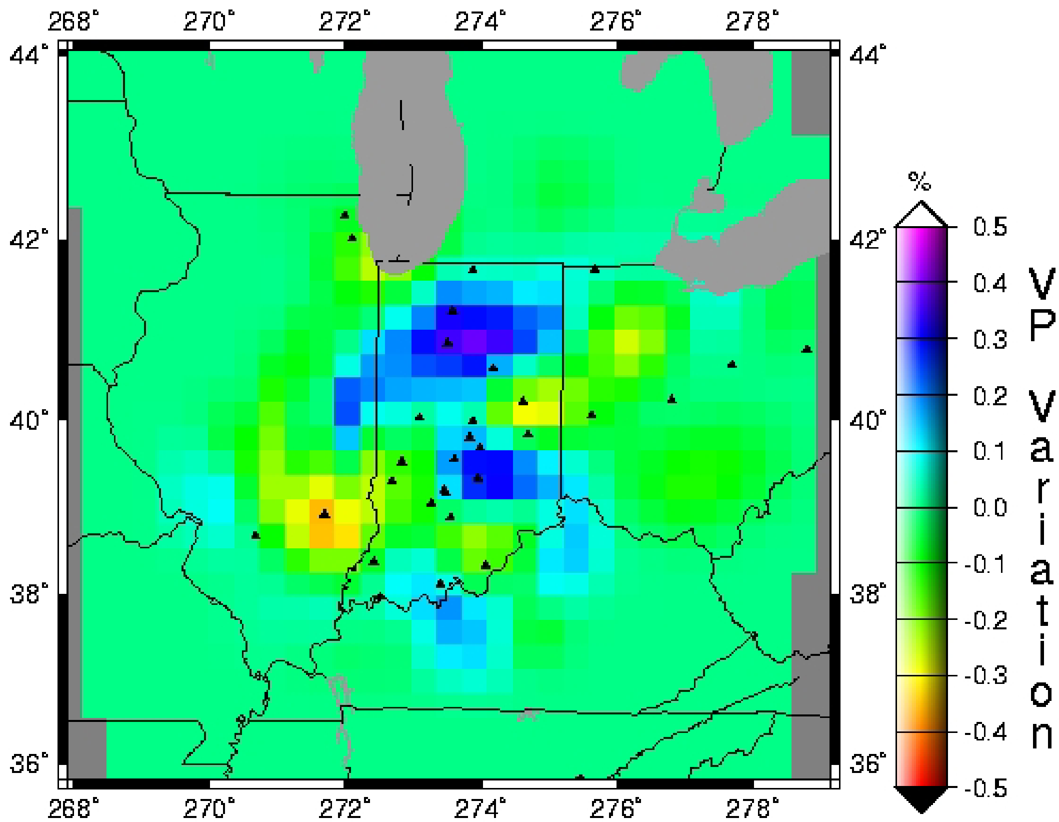

Figure 3. P wave tomography result for a depth slice at 180 km from Wu (2004). Stations are shown as black triangles on this map. Colors show P velocity variations as a percentage perturbation from the initial layer velocity.

Analysis of the New Harmony Cluster

We undertook a focused study of an unusual feature in the seismicity of the Wabash Valley seismic zone that we will refer to as the New Harmony Cluster (Pavlis et al., 2002). This feature was discovered during data processing of the 1995-1996 Wabash Valley experiment. It is defined by the cluster of events near the Wabash River (near the Indiana-Illinois state line) between the stations KRA and MUM (Figure 2). Pavlis et al. (2002) noted that the events in that cluster showed a remarkable similarity in waveforms. Because of this observation they argued that the New Harmony Cluster was probably much smaller in size than Figure 2 would suggest and the scatter in those locations was due mainly to location errors. We aimed to test this hypothesis and obtain more insight on this feature through a focused study of these events. In order to examine these events, we completed an exhaustive data processing effort, including: (1) retrieval of all array data from our archive and reformatting into a unified database; (2) array processing of the data for an additional 109 days of network operation using the same procedures described in the Pavlis et al. (2002) paper: array processing of the continuous data from the phased array to produce semblance versus time plots; running a specialized detector we developed to identify potential events (during interactive processing we skipped events that were clear mining explosions); running an interactive array processing procedure to measure P and S wave slowness vectors and construct array beam signals for all three components of the array; (3) merging the array beam data with data from the triggered stations (Figure 2); and (4) locating these events using the dbgenloc program (Pavlis et al., 2004).

The new catalog produced by this procedure yielded a total of 657 events that were identified as possible earthquakes. The overall catalog shows a similar spatial pattern to that shown in Figure 2. The events define a strong concentration of events in the New Harmony cluster and a fairly random distribution of events elsewhere. To test the hypothesis that most of the events were tightly clustered we separated events of the New Harmony Cluster from the rest of the catalog. To do this we scanned all the array beam records for signals that had the shape we had previously learned to recognize as diagnostic of this cluster. We identified 537 events by this procedure, mostly recorded only on the phased array only. We found only 8 waveforms with observable signals on any of the triggered stations. This observation underscores the value of the phased array in studying low-level seismicity associated with intraplate seismic zones.

To improve the consistency of P and S picks from the array beam traces we utilized a cross-correlation method with results illustrated in Figure 4. We selected the event with the largest amplitude as a master trace for cross-correlation and used a time-domain method to align all traces to the nearest sample. We also utilized a novel complex-valued cross-correlation to align the S wave data described in the published paper on this topic by Eagar et al. (2006). Figure 4 compares signal alignment based on the original, hand-picked data with the results after cross-correlation using conventional time-domain cross-correlation for the vertical data and the complex-valued cross correlation on the horizontals for the S wave data. This figure demonstrates the remarkable similarity of waveforms and the success of the correlation procedure for P and S waves. It is important to recognize that the results for the S phase using the horizontal components were good, but somewhat less consistent due to the lower signal-to-noise ratio that characterized the horizontal component data. A bigger ambiguity discussed by Eagar et al. (2006) is an ambiguity in the absolute position of what should be picked as the S wave arrival (S' and S'' in Figure 4). The relative timing of this phase cannot be resolved from the data alone and is critical for determining the absolute position of the cluster when the phased data alone are considered. Eagar et al. (2006) resolve this issue with a careful analysis of data a handful of signals associated with these events recorded by triggered stations. We argued that the time marked as S' yields an absolute location more consistent with the triggered data than the earlier arrival labeled S'' in Figure 4.

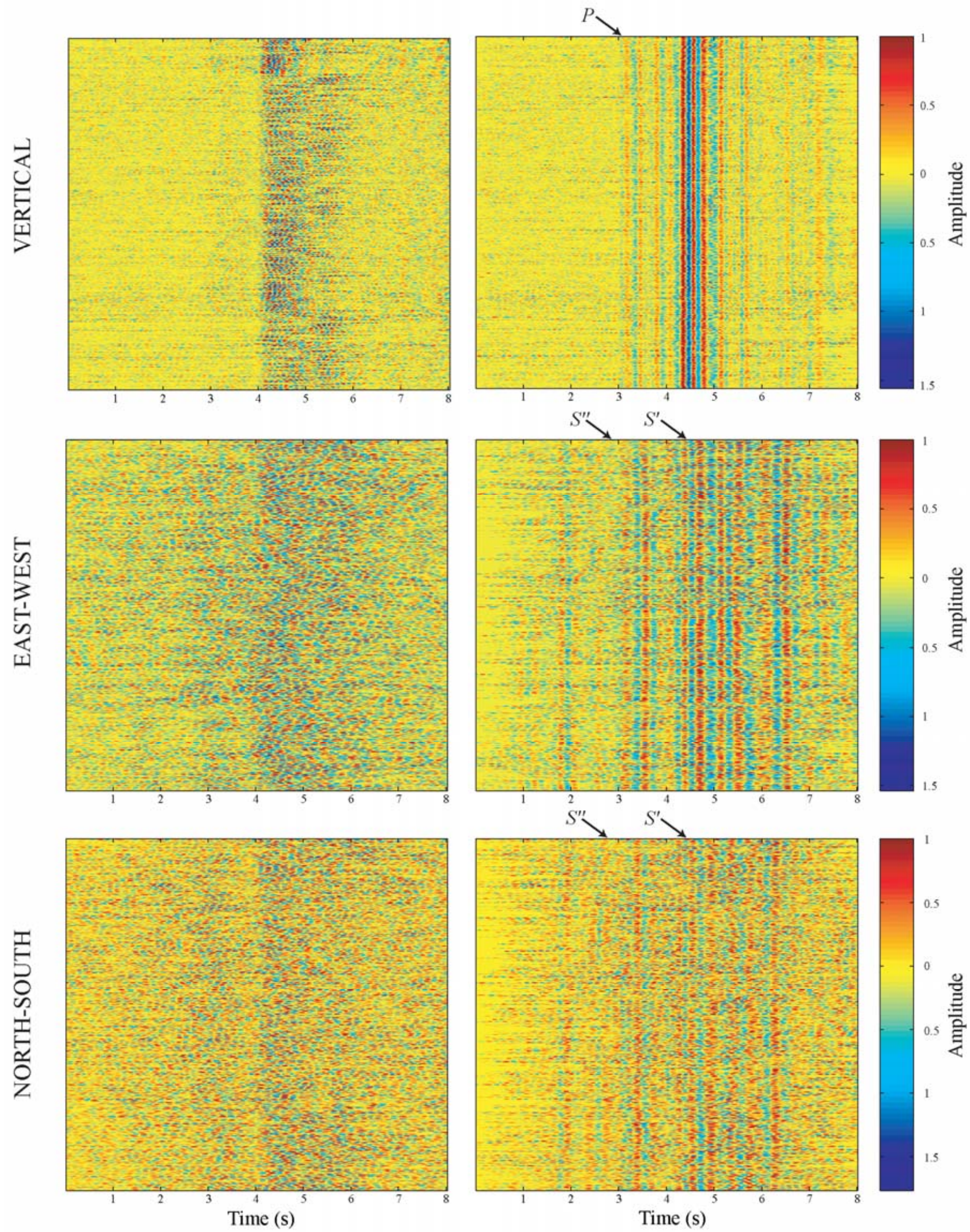

Figure 4. Image displays of amplitude on the beam traces of the New Harmony cluster earthquakes on each of the three components. The seismograms are arranged in chronological order with the earliest event in the sequence at the top. Left plots show x-axis alignment based on the original hand-picked P and S arrivals. Plots on the right hand side have been aligned by cross-correlation. S' and S'' are two feasible picks for S discussed in detail by Eagar et al. (2006). (Figure from Eagar et al. (2006)).

The revised picks were used to relocate the events from the New Harmony Cluster with the results shown in Figure 5. That figure also shows the final location results in a framework of oil and gas wells in the region. In Eagar et al. (2006) we used this association to support the hypothesis by Pavlis et al. (2002) that these events were induced by human activity. We argued here that the most likely human activity to explain this cluster is oil and gas production. We note here that Eagar et al. (2006) present two other lines of evidence that support this observation: (1) Synthetic seismograms computed from well-constrained velocity models for the Illinois Basin provide strong evidence these events are located within the sedimentary section. This is in contrast to earthquakes seen in this region that have all been located below the sedimentary section and show very different waveforms. (2) We produced very accurate magnitude estimates of these events by a relative rms amplitude method tied to an absolute standard by synthetic seismograms. We found the entire cluster (537 events) spanned a magnitude range of only about 1 magnitude unit. This is completely inconsistent with the normal magnitude-frequency relation for earthquakes.

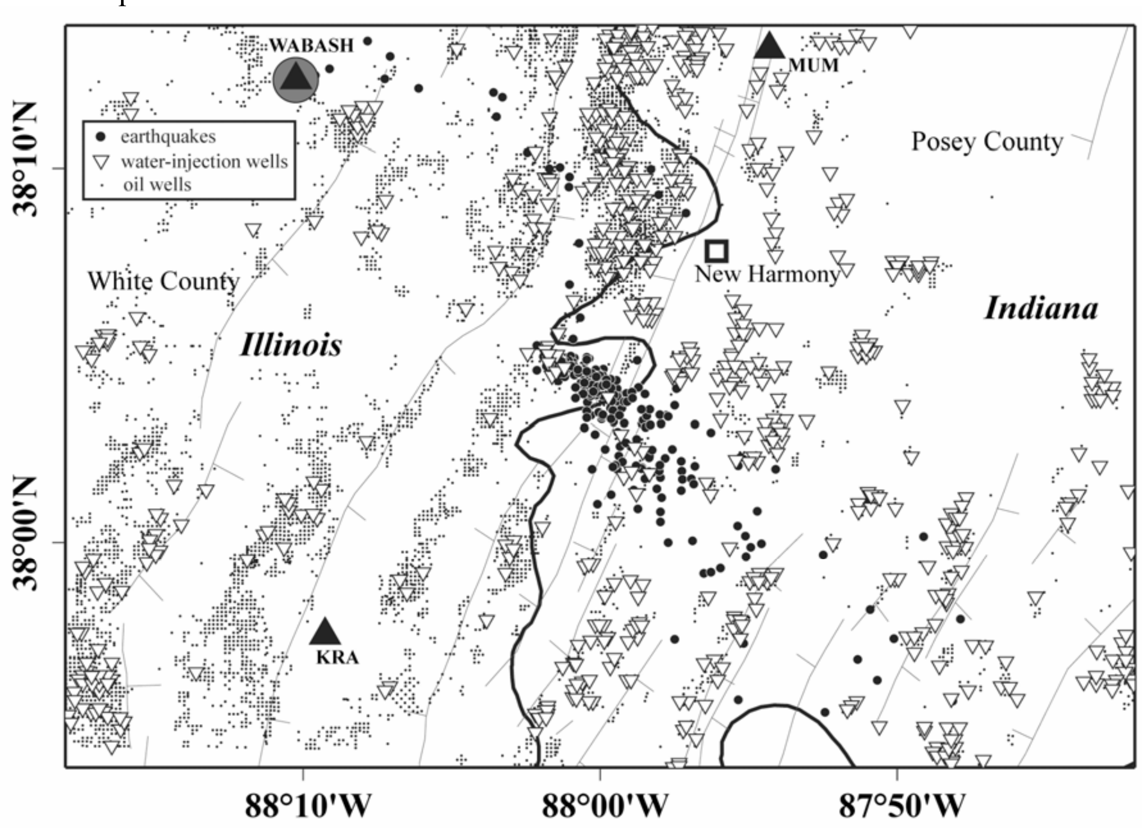

Figure 5. Relocated New Harmony Cluster event locations relative to oil wells and water-injection wells. Earthquake locations are shown as larger solid circles, oil wells as dots, and water-injection wells as inverted triangles. Solid triangles are triggered seismic stations that were used to constrain the absolute location of these events. The station labeled WABASH is the location of the phased array that provided most of the data for this study. (Figure from Eagar et al. (2006)).

The results of this analysis have important implications for earthquake hazards assessment for this region. Figure 6 shows this result in comparison to related catalogs. If we treated the New Harmony cluster events as earthquakes, the projected seismicity level is a factor of about 5 times that estimated by other data (Pavlis et al., 2002). In contrast, if we treat all the

New Harmony events as anomalous we get an estimate consistent with longer term monitoring results, including those from the PEPP network analysis, as discussed below.

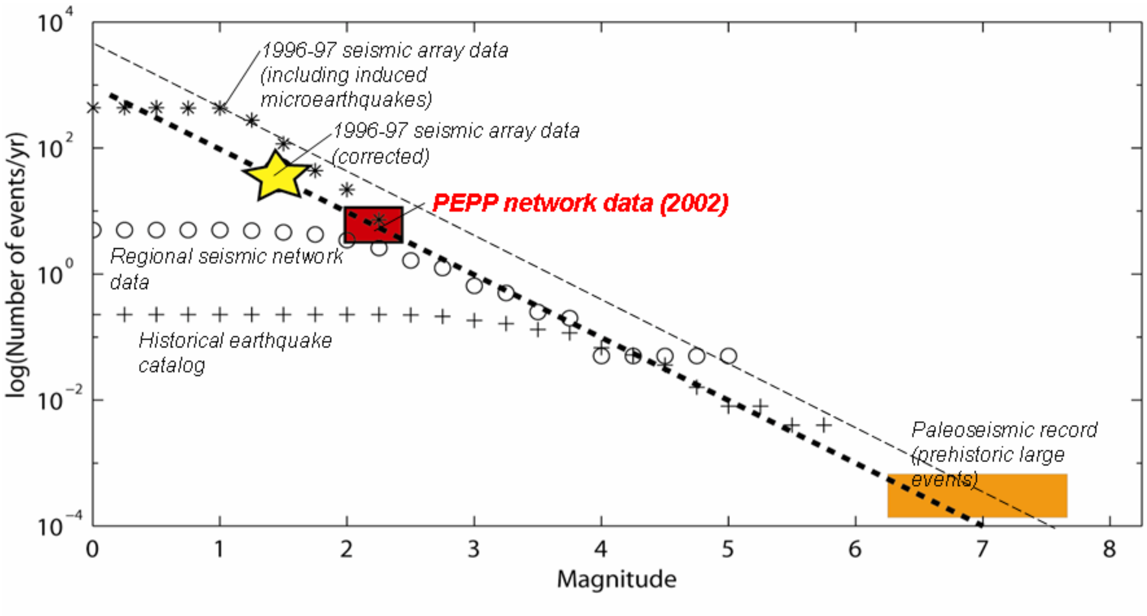

Figure 6. Magnitude-frequency estimates for the Wabash Valley region. This figure is an update of a similar figure found in Pavlis et al. (2002). It shows the relations of two results from this study in the context of paleoseismic, historical, and instrumental catalogs for the same area. The asterisks show magnitude-frequency results that would have been projected had New Harmony cluster events been included in the catalog while the yellow star shows the results of the 1996 data set excluding these events (i.e., assuming they are induced by human activity). The asterisk results are based on the earlier magnitude estimates of Pavlis et al. (2002). If we used the more accurate magnitude estimates used in Eagar et al. (2006) almost all the New Harmony events would fall near magnitude 1. The red box shows the range of a single data point on this curve provided from the related study of the PEPP network data described in this report.

PEPP Network Detection Analysis

The final phase of this project involved an exhaustive examination of data from the PEPP network (Figure 1). Our primary objective was to appraise seismicity levels in Indiana through a careful quantification of events detected by the PEPP network. This required care in ensuring that we were detecting all possible events, in discrimination of earthquakes and mining/quarrying blasts, and quantifying the detection threshold of the network.

The approach we used to study this problem was a careful, visual scanning of one full year of continuous data. This approach was necessary as attempts to utilize automated detections from the Antelope real-time system showed serious problems. The primary reason for this is that a large fraction of events detected by this network are mining explosions from coal and aggregate mines. Significant numbers of events were clearly being missed due to the fact that signals generated by mining explosions in this region are commonly dominated by Rayleigh waves in the 0.5 to 2 Hz band. Because these signals propagate at a low velocity compared to P and S (group velocity near 2 km/s), detectors tuned to P and S moveout times do not work well. We concluded it was necessary to carefully scan the data to search for all events and to manually classify the events into four categories: (1) local earthquakes, (2) regional earthquakes, (3) teleseismic earthquakes, and (4) local/regional mining explosions.

We scanned the first 143 days of data in 2002 and the nighttime hours (0000 – 1200 UTC) of the remaining days of 2002. Events were classified by a three step procedure. First, the data were visually scanned with the Antelope program dbpick (http://www.brtt.com). Based on previous experience reinforced by synthetic seismograms we computed for the paper by Eagar et al. (2006) we used a first-order discrimination of most explosions based on surface waves. That is, explosions in the Illinois Basin, which are always detonated at or near the Earth's surface, strongly couple into high frequency Rayleigh and Love waves formed by a strong waveguide floored by the Knox formation (a carbonate with velocities larger than many crystalline rocks). These surface waves propagate large distances and often are the only observable phase. They are, however, readily identified by dispersion of the waveforms and most are very easy to identify when seen on multiple stations. Several students and high school teachers participated in this exercise. They marked clear explosions with a unique pick flag, clear teleseismics with another flag, and ambiguous events with another. These results were double checked by one of the PIs. Remaining ambiguous events and teleseisms were then fully processed by associating with regional and national catalogs, and manually locating events not associated with any catalogs. The results net results of this process are summarized in figures 7 and 8.

The results shown in Figure 7 can be summarized as a simple colloquial phrase: Finding earthquakes in Indiana is like looking for a needle in a haystack. Of 4358 events we identified by this process only 5 were possible local earthquakes. Of these only two can be unambiguously identified as local earthquakes (the mainshock of the 2002 Darmstadt earthquake and a single aftershock). The other three events are somewhat ambiguous with low signal-to-noise conditions on all observing stations. Figure 8 and Figure 6, however, reinforce that our procedures are robust in discrimination of earthquakes from explosions. Figure 8 shows that telseismic events and regional events occur randomly throughout the day while events identified as explosions occur exclusively during daylight hours. Figure 6 shows that the actual numbers of events we observed in this time period are consistent with the magnitude-frequency relations estimated from other studies.

In Figure 6 we have reduced this entire time-consuming analysis to a single point on the magnitude-frequency plot. With such a small number of events (2-5) it is meaningless to plot the results on a magnitude-frequency distribution. Since the plot represents cumulative numbers of events over a certain size, however, we can add a further constraint on the magnitude-frequency distribution. The upper and lower limits of the box in Figure 6 are defined by the range in the number of events we counted (2 to 5) normalized by the time period of data we scanned. The range on the x-axis, however, comes from a different analysis. Rather than use the magnitude of the smallest event observed, we elected to cast the problem in terms of the detection threshold of the network. If the detection threshold of any network is known, the cumulative count of events with magnitude higher than the detection threshold is an unbiased estimate of the total seismicity above the threshold. Thus an estimate of the detection threshold can help us put a count of 2 to 5 earthquakes in a more solid quantitative foundation.

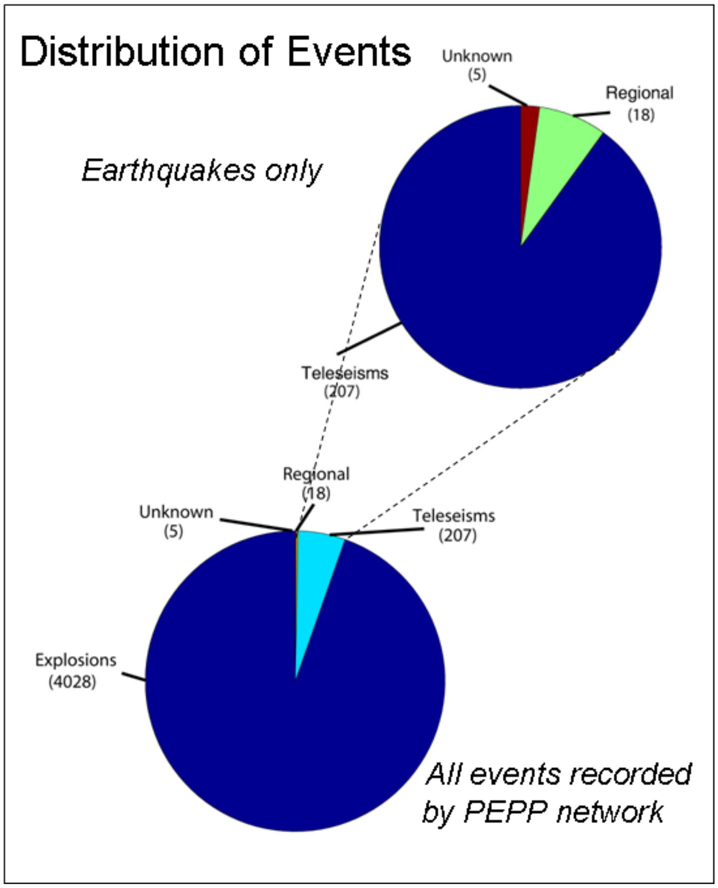

Figure 7. Event counts for visually scanned data from PEPP network data from 2002. We present this here as two pie charts. The bottom chart shows the tiny fraction of earthquakes of all kinds relative to mining explosions. The upper pie chart shows that the fraction of local earthquakes relative to local and regional events is also small. Approximately one event in 1000 recorded by the PEPP network is a local earthquake.

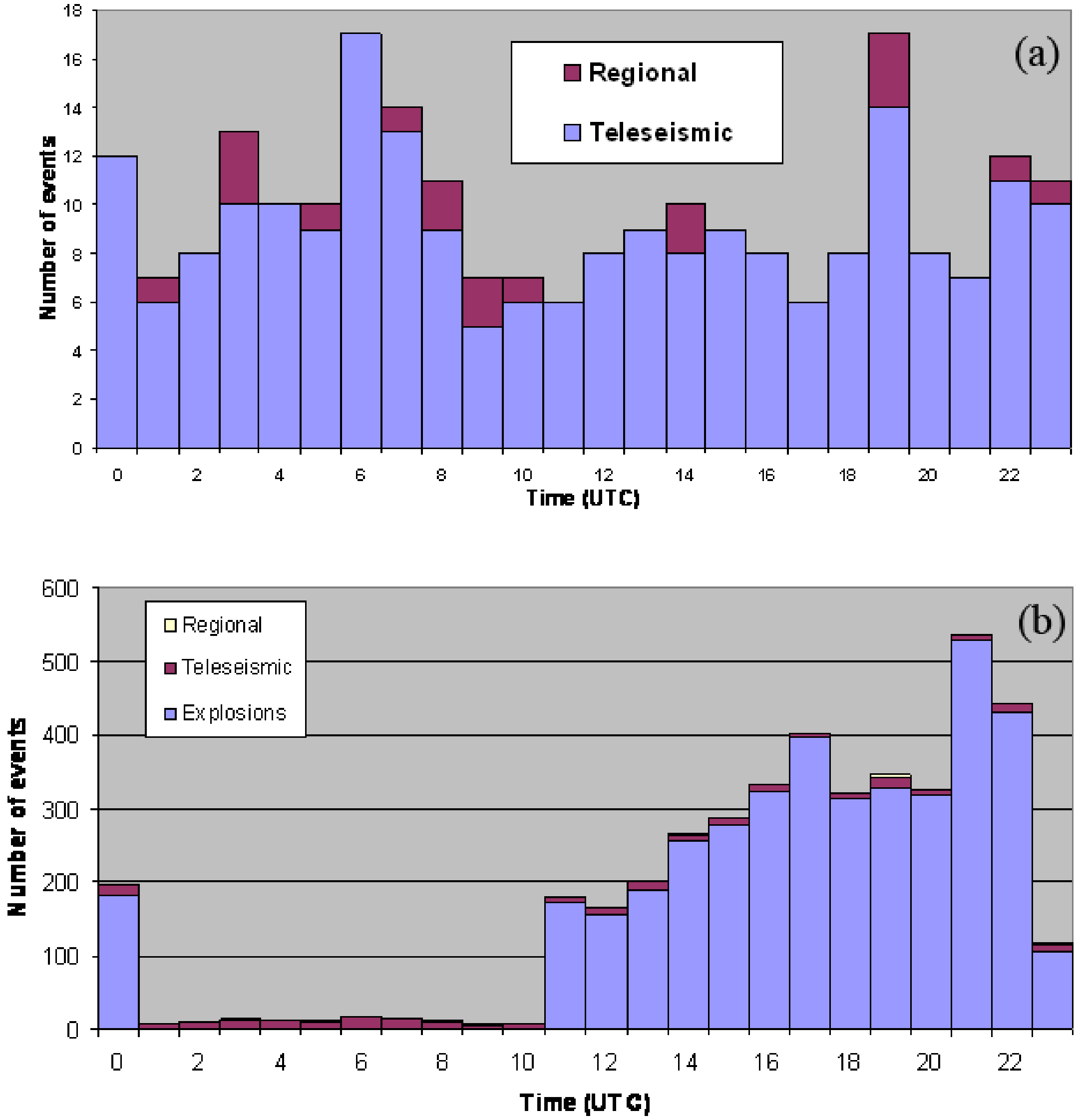

Figure 8. Histograms of event types versus time of day identified from PEPP network data. (a) is a stacked histogram of local, regional, and teleseismic earthquakes and (b) is a similar plot including events identified as mining explosions. These figures show that earthquake occurrence time is random while explosions are recorded only during daylight hours.

To address this issue we developed two methods to quantify the detection threshold for the PEPP network. The first is based on a projected signal-to-noise condition from a suite of known, instrumentally recorded earthquakes in the region, as illustrated in Figures 9 and 10. We assembled data from the PEPP network for all felt earthquakes in the region from 1999 to 2006. We made a signal-to-noise measurement using the graphical technique illustrated in Figure 9. For this purpose we used the PC program WinQuake to allow two teachers working with us (see below) to make the measurements more easily. The product of these measurements was a set of signal-to-noise measurements for each of the stations that recorded each of the earthquakes plotted in Figure 10. Because local magnitude scales by the log of the peak amplitude measured on each station, we can project the minimum earthquake magnitude associated with each event that would have yielded a workable P and S phase. For the projection we assumed a phase was detectable and could be used in analysis at a signal-to-noise level of 2. For each of the events plotted in Figure 10 we then produced two magnitude estimates. The "Detection threshold" is defined as the minimum magnitude at which the earthquake would been seen on two or more seismic stations with one of the phases (typically S) with a signal-to-noise ratio of 2 or larger. In practice, this is the likely magnitude at which an event would be detected by a network operator during a routine scan. We define "Location threshold" as the projected magnitude where four distinct phases would be visible with a signal-to-noise ratio greater than 2, i.e., the minimum that would allow both reliable detection and a reasonable estimate of earthquake position. Figure 10 shows that the location threshold for the PEPP network is between 2 and 2.5 for most of the state of Indiana. The detection threshold estimates range from 1.3 to 2.2 for the same region. The location threshold range was used to conservatively define the limits of the red box on the x axis in Figure 6.

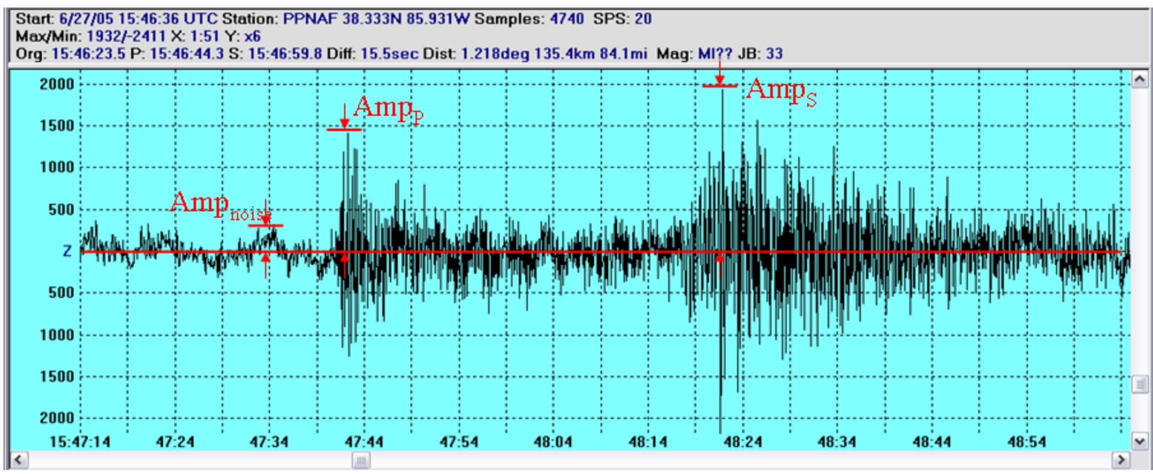

Figure 9. Illustration of signal-to-noise measurement made from felt events recorded by the PEPP network. The noise amplitude is nominal peak amplitude while we measured a true peak amplitude for P and S. These measurements were made on both raw data and data filtered through a standard analysis band of 0.5 to 5.0 Hz.

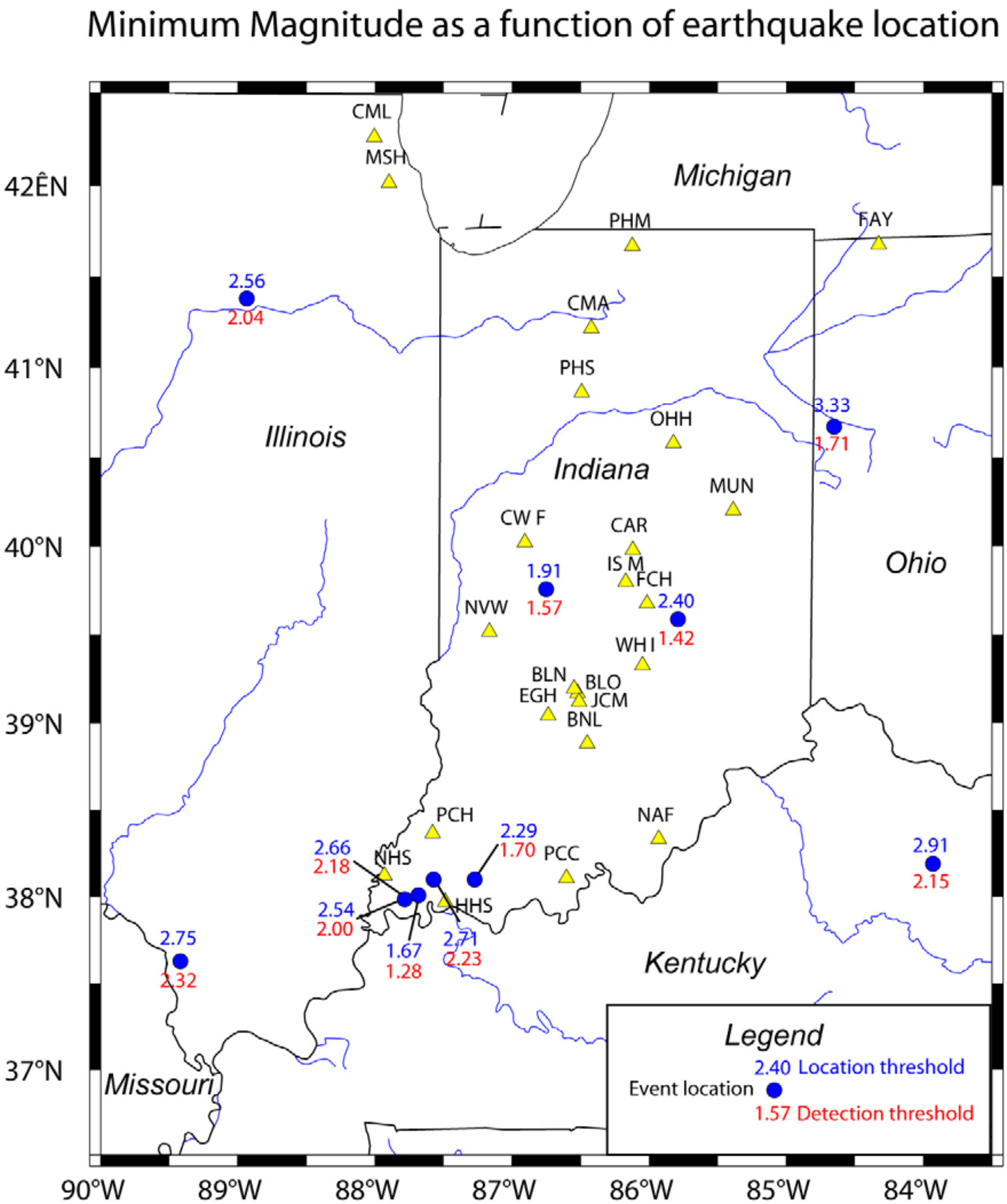

Figure 10. Detection and location threshold estimates obtained from felt events recorded by the PEPP network. Yellow triangles are the location of PEPP stations that were used for this analysis. Blue circles are the epicenters of events analyzed. The two threshold measurements plotted are described in the text of this report.

We used a second method using regional events to extend our detection estimates to regional distances. For this purpose we examined all regional events in the ANSS catalog from 2002. We examined PEPP network data visually from time windows around the projected P and S arrival times from these events. Data from the network were graded from “A” to “F”, as summarized in Table 1 below. Figure 11 plots these events along with their grade as a function of distance. Notice that this data set is dominated by events from New Madrid at epicentral distances of approximately 300-400 km. The key observation is that even at 300 km distance we missed no events larger than magnitude 2.5. This confirms that our signal-to-noise detection threshold of around magnitude 2 for events inside the network is reasonable. This provides additional constraints on the lower magnitude edge of box drawn in Figure 6. At far regional distances (1000-2500 km), the magnitude threshold increases to magnitude 3-3.5.

Table 1. Classification of events recorded by the ANSS network.

Event Classification	Description
A	P and S easily visible at all stations
B	Visible at most stations with P and/or S
C	Visible at about ½ stations or only one phase visible
D	P and/or S faintly visible at some stations
F	Not visible at all

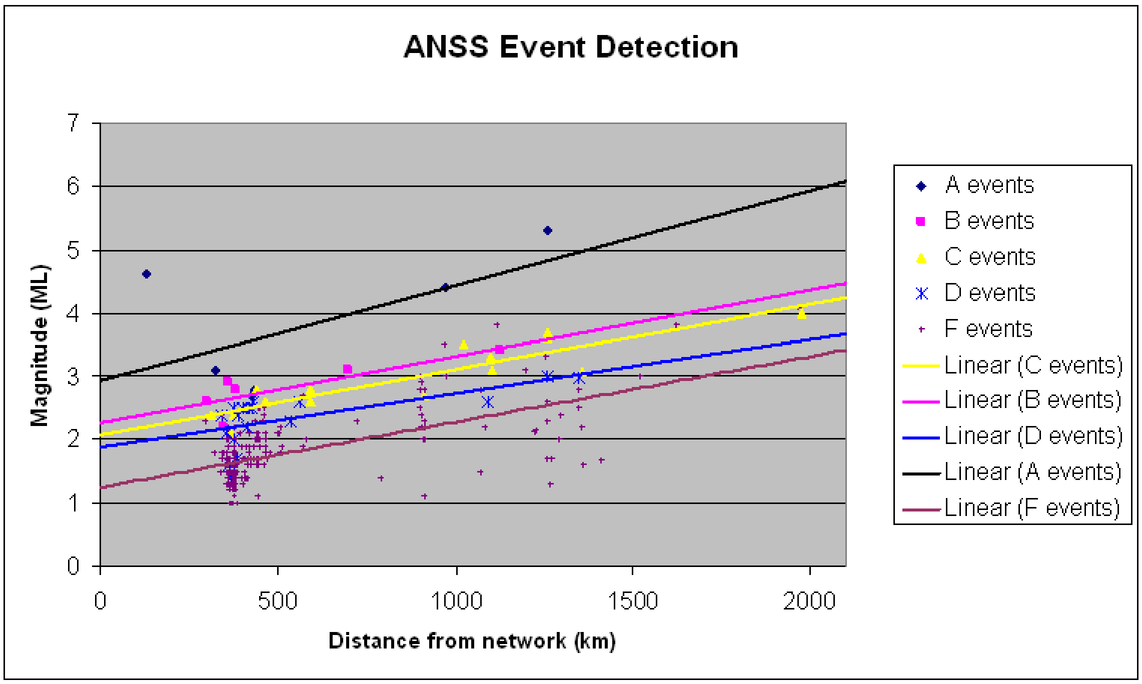

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Figure 11. Results of regional event detection analysis. Each event we examined is plotted as one symbol with the x axis representing epicentral distance from the center of the PEPP network and the y axis defined by magnitude for that event tabulated in the ANSS catalog. The symbol color and type is determined by a grade we assigned to signals recorded by the PEPP network. F events are not seen at all while A events are seen at all stations. The lines are a linear fit to the data with a common grade. They confirm our grading scheme is consistent with detection quality and show, as expected, that detection threshold increases with epicentral distance. The data from distances under 500 km are dominated by events in the New Madrid region.

Education and Outreach

A unique aspect of the PEPP network is that it is not just a network of seismic instrumentation but also a network of science and education professionals interested in seismology education and outreach. Over the past 10 years we have established a strong collegial relationship with one or two teachers in each of the schools shown in Figure 1. A very important element of this project is that it provides a research focus for our teacher partners. To retain their interest and the interest of their students it is important that they see these data being used for scientific research. Our work on this project has helped greatly in this way. In addition, we have two ongoing programs that have enhanced the educational impact of this project.

1. For the past 6 years we have been running a special program aimed at top middle and high school science students we call the IU-PEPP Earthquake Science Symposium. This program aims to provide these students a research experience with state-of-the-art seismic data. Teachers act as research advisors and mentors to small groups of students. The students attend a fall and/or spring research symposium. The fall symposium stresses training, while the spring symposium is more aimed at student presentations on independent research project. (see for example http://www.indiana.edu/~pepp/workshops/2003_04student/SpringPictures.htm)
2. With support from this project we invited six teachers to work as 'PEPP Research Fellows' (three in the summer of 2004 and three in the summer of 2006). The main objective of this program was to provide these teachers some real-life research experience in seismology that would improve their ability to teach science in general and earthquake science in particular. For this reason the projects they undertook were focused on problems they could readily transport to working with students. Since most of the seismic events we see are explosions (Figure 7) the first group of teachers (summer 2004) all elected to work with explosion data. Two of them (Michael Kelley [Harrison HS, Evansville, IN] and William Combs [Crawfordsville HS, Crawfordsville, IN]) worked with travel-time data from a set of mining explosions with known locations. The locations had been obtained in earlier student projects and through direct on-site measurements by Kelley. They produce a useful set of travel time curves for P, S, and Rg phases measured in a set of narrow frequency bands. The third teacher, Ewa Shannon (Crown Point HS, Crown Point, IN), worked with amplitude data from the same set of ground-truth explosions. She developed empirically determined amplitude decay curves for Rg that she used to develop a 'pseudomagnitude' scale based on Rg (it remains a 'pseudomagnitude' as we do not yet have an independent calibration method to equivalence these to a local or regional earthquake magnitude scale). She compared pseudomagnitude estimates to known blasting parameters (total shot size, shots per hole, and shot size per hole) and found poor correlation between the pseudomagnitude and any of these parameters. She concluded that local blasting practice and differences in local site characteristics had a larger effect than any of the tabulated blasting parameter. The conclusion is consistent with similar results from nuclear monitoring research directed at discrimination of chemical explosions. The scientific results of this experiment, as well as results from other PEPP Fellows' work, were presented at the Fall AGU meeting in San Francisco (Combs et al, 2004; Sayers, 2004; Pavlis and Hamburger, 2004). The second group of teachers (Lowell Bailey, Bedford-North Lawrence High School; Jim Lindsey, Mooresville High School; and Steve Webb, Brescia College) did most of the data analysis for the detection threshold work described above (Figures 7 to 11). There work was presented at the fall 2006 AGU meeting (Webb et al., 2006). We are currently working on finalizing a version of a written paper on this work we expect to submit for publication in *Seismological Research Letters*.

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