43328 Vol 2

OSM

OFFICE OF SURFACE MINING
RECLAMATION AND ENFORCEMENT
TECHNICAL REPORT/1994

INVESTIGATION OF DAMAGE TO STRUCTURES IN THE M^cCUTCHANVILLE-DAYLIGHT AREA OF SOUTHWESTERN INDIANA

Volume 2 of 3

Part II: Geologic and Unconsolidated Materials in the McCutchanville-Daylight Area.
Part III: Blast Design Effects on Ground Vibrations in McCutchanville and Daylight, Indiana from Blasting at the AMAX, Ayrshire Mine.
Part IV: Vibration Environment and Damage Characterization for Houses in McCutchanville and Daylight, Indiana.
Part V: Racking Response of Large Structures from Airblast, A Case Study.
Part VI: Investigation of Building Damage in the McCutchanville-Daylight, Indiana Area.

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Office of Surface Mining Reclamation and Enforcement

Part VI

Investigation of Building Damage in the McCutchanville-Daylight, Indiana Area.

U. S. DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

INVESTIGATION OF BUILDING DAMAGE IN THE McCUTCHANVILLE-DAYLIGHT, INDIANA AREA

by

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Contract No. EF68-I491-13797

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1993

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INVESTIGATION OF BUILDING DAMAGE IN THE McCUTCHANVILLE-DAYLIGHT, INDIANA AREA

ABSTRACT

The U.S. Geological Survey, along with the U.S. Army Corps of Engineers and the U.S. Bureau of Mines is assisting the Office of Surface Mining in conducting an investigation of building damage in the McCutchanville-Daylight area near Evansville, Indiana. The investigation is a consequence, in part, of claims by a number of property owners that the damage is a result of blasting at a nearby surface coal mine. This report describes the USGS portion of the investigation.

The USGS investigation included: (1) a review of the historical seismicity, the earthquake ground motion that has historically affected Evansville, together with estimates of ground motion that might be experienced from earthquakes hypothesized for the future and a probabilistic assessment of ground motion; (2) ground motion and dynamic-response investigations aimed at understanding the characteristics and nature of ground shaking; and (3) an assessment of the observed damage based on field investigations. Ground motion was recorded at a number of locations and considerable other soil data were obtained during the course of this investigation.

Fifty-two houses were inspected for damages. Thirty-three houses were located in the McCutchanville-Daylight area and nineteen were located in an area remote from the blasting. The nineteen remote area houses were used as a control group and established a non-blast-related level of damage. The thirty-three houses located in McCutchanville-Daylight consisted of thirteen houses in which the owners believed damage was caused by blasting and twenty companion houses in which the owners either did not claim or did not believe there was blast-related damage. All of the owners of the houses inspected in the McCutchanville-Daylight area reported feeling blasts. The damages in the twenty non-complainant houses was, for the most part, similar to that in the remote area. The damage in many of the thirteen complainant houses was more than what would be expected in a house due to normal use and aging.

An OSM analysis of blasting vibrations during the period 1986 to 1992 led to upper bound estimates of vibrations in the Daylight area of 0.39 in/sec (about 1.0 cm/sec) and in the McCutchanville area of 0.17 in/sec (about 0.4 cm/sec). A 1987 earthquake caused peak particle velocities at stations near Daylight ranging from 0.13 to 0.44 in/sec (0.33 to 1.12 cm/sec). There was reported damage in Evansville from this earthquake. These vibrations are smaller than previously reported levels of peak-particle velocities causing major damage.

Most of the major damage in the complainant houses is believed to be soil related in origin and some mechanisms are suggested. The major mechanism is thought to associated with poor drainage of water in the loess around houses. The lesser damage cannot be explicitly explained, it is similar in nature to that seen in the remote area which is not blast related. It is possible that some of this slight damage could be vibration related since both site and resonance effects appear to be sufficient to cause threshold damage. These effects do not appear to be large enough to cause major damage unless there are some other conditions present which, when combined with vibration effects, cause large stress levels.

INTRODUCTION AND OBJECTIVES

The U.S. Geological Survey (USGS), along the with U.S. Army Corps of Engineers Waterways Experiment Station (WES), and the Bureau of Mines (BOM) is assisting the Office of Surface Mining (OSM) in conducting an investigation of building damage in the McCutchanville-Daylight area, located just north of Evansville, Indiana. The investigation is a consequence, in part, of claims by a number of property owners that the damage is a result of blasting at a nearby surface coal mine. This report documents the USGS portion of the investigation. The WES investigations are described by Hadala and Peterson (1993) and Chiarito (1993). The BOM investigations are described by Siskind and others (1990) and Siskind and others (1992).

The principal objectives of this part of the overall study are to describe and characterize the observed damage in the McCutchanville-Daylight, Indiana area (see Figure 1 for location), to describe the characteristics of ground shaking due to mine blasts and earthquakes and, if possible, to determine the cause of the observed building damage. To accomplish these objectives, the USGS investigation included: (1) a review of the historical seismicity, the earthquake ground motion that has historically affected Evansville, together with estimates of ground motion that might be experienced from earthquakes hypothesized for the future and a probabilistic assessment of ground motion; (2) ground-motion and dynamic-response investigations aimed at understanding the characteristics and nature of ground shaking in the area; and (3) an assessment of the observed building damage based on field investigations.

EARTHQUAKE-RELATED GROUND SHAKING AT EVANSVILLE, INDIANA AND VICINITY

INTRODUCTION

Consideration must be given to the possibility of building damage resulting from the occurrence of earthquakes in any comprehensive evaluation of ground vibration hazard in and around Evansville. Historically, Evansville has been shaken by earthquake ground motion and building damage has occurred. Accordingly, possible historical earthquake building damage must be considered in reviewing the known building damage in the McCutchanville-Daylight area. The potential for future earthquake building damage is also reviewed.

The objectives of the following discussion are to: (1) evaluate the historical earthquake record at Evansville; (2) estimate historical earthquake shaking at Evansville based on the historical record; and, (3) estimate the future earthquake shaking potential at Evansville assuming possible large shocks in the Mississippi Valley and on the basis of a probabilistic model of earthquake occurrence in the central United States. The probabilistic assessment of ground motion takes into account all possible earthquake sources that might affect Evansville.

In evaluating the seismic hazard, use is made of the historical seismicity of the United States as it affects Evansville. This seismicity is based on the earthquake data, catalogs and publications developed and maintained by the USGS, probabilistic models of earthquake occurrence, and scenario (deterministic) evaluations of future, possible earthquake effects at Evansville.

EARTHQUAKE HAZARD AND RISK ASSESSMENT

The location of all instrumentally located earthquakes in the vicinity of Evansville from 1942 through mid-1992 (Engdahl and others, 1991 and U.S.G.S. Preliminary Determination of Epicenters - computer data base in Golden, CO) are shown in Figure 2. The locations of historical earthquakes with maximum Modified Mercalli intensities (MMI, see Table 1 for description of the scale) of V or greater within 450 km of Evansville that occurred from 1811 through 1990 are shown in Figure 3. Table 2 gives the parameters of these earthquakes, the MMI of each earthquake at Evansville and a brief description of the damage if it was significant. Generally, data on the spatial distribution of intensity associated with relatively minor earthquakes of this type are obtained by postcard surveys distributed over a wide area by the National Earthquake Information Center of the USGS in Golden, Colorado. The individual postcards are rarely kept, however the intensity data on the postcards is summarized and appears in the serial USGS publication *United States Earthquakes*. The exact location of the damage, when it is reported for small cities, is generally not given.

The two most relevant historical earthquakes (Table 2 and Figure 3) for this study that have affected Evansville are the maximum MMI VI shocks of 1968 and 1987. These earthquakes caused intensities of VI at Evansville. In particular, the 1968 shock caused damage to the Federal Building: "Two ornament columns on building dislodged. About 4 square feet of plaster fell from third floor ceiling Small objects fell. ......". At another location there was a press report that a chimney fell on an old house and at still another location that bricks loosened on an old church and a wall threatened to collapse. Throughout the city : "...plaster cracked and broke ...". An alternate interpretation of the 1968 damage at Evansville might be that damage approaching the intensity VII level occurred. The 1987 earthquake resulted in the cracking of "chimneys, sidewalks, and streets". The cracking of streets and sidewalks may be indicative of some degree of soil liquefaction or differential compaction. A soil failure such as liquefaction depends on the type of soil, level of the water table, and the magnitude and duration of ground shaking.

While the postcard surveys do not contain direct reports of damage in the McCutchanville-Daylight area, it is entirely possible that there was some. In fact, as discussed later, some damage was reported by owners in the remote area during the house inspection phase of this project. Several homeowners in the McCutchanville-Daylight area reported feeling earthquakes.

Figure 4 shows the distribution of intensity of shaking at Evansville based on the historical record of earthquake occurrences. This distribution of shaking was obtained by using the locations of historical earthquakes and either attenuating the ground motion intensity from the earthquake epicenter to Evansville using isoseismal maps developed for each earthquake in question or using actual reports of damage in Evansville (for recent earthquakes). Thus it should be noted that the intensities of VII and VIII shown as occurring at Evansville are all associated with the 1811-1812 series of shocks in the New Madrid region of Missouri (listed in Table 2). These intensities are projected intensities since their actual occurrence at Evansville is not known. This does not mean, however, that intensities of this degree or greater will not be experienced in the future. As already pointed out, the important historical ground shaking at Evansville in terms of the present study are those associated with the earthquakes of 1968 (MMI of VI) and 1987 (MMI of VI), and to a lesser extent, the earthquake of 1990 (MMI of V).

The 1987 earthquake (Table 2) with M_S 4.6 (surface wave magnitude), at a distance of 89 km, caused intensity VI damage in Evansville and also triggered instruments at a number of coal mine monitoring stations, including four in the Daylight area (Figure 1). Street and others (1988) have summarized the peak particle velocities at each station. Peak particle velocities at the four stations near Daylight ranged from 0.33 to 1.12 cm/sec (0.13 to 0.44 in/sec) for the horizontal components and 0.10 to 0.23 cm/sec (0.04 to 0.09 in/sec) for the vertical components. The subsurface material was not identified for the sites, so any effect of site response is not known. There were no instrument recordings in Evansville where the damage reported in Table 2 was documented. However, since it is more distant from the earthquake epicenter, it is likely that the peak-particle velocities would have been smaller than those recorded in the Daylight area, assuming similar site conditions. Thus it would appear that in this area damage can occur at peak-particle velocities in the range of those recorded in the Daylight area. A stronger earthquake occurring in 1968 (Table 2) with M_W 5.27 (moment magnitude), at a distance of 72 km, was felt by many and caused damage to the Federal Building in Evansville. Apparently there were no recordings for this stronger earlier event.

Figures 5, 6, and 7 represent a simulation of the distribution of intensity that might be expected in Evansville in the event of the occurrence of earthquakes with M_S magnitudes of 8.6, 7.6, and 6.7 in the New Madrid seismic zone of southeast Missouri (Hopper, 1985). These isoseismal maps of hypothetical, but possible, future earthquakes attempt to take into account the amplifying effect of the near surface soils and rocks beneath Evansville.

Figures 8 and 9 present a different measure of possible future ground motion in the central United States based on a slightly different approach. These ground motion values (spectral response acceleration at 0.3 and 1.0 second periods, 5 percent damping, 10 percent probability of being exceeded in 50 and 250 years) are based on a probabilistic model of earthquake occurrence used in the development of national ground motion maps for the seismic design provisions of building codes (Algermissen and others, 1991; Building Seismic Safety Council, 1992; Algermissen and Leyendecker, 1992). The principal value of these maps in the present study is to provide a comparative assessment of the expected spectral response acceleration in 50 and 250 years at Evansville with other sites in the central United States. The expected equal hazard spectrum in 50 years at Evansville based on probabilistic ground motion calculations at 12 ground motion periods from 0.1 to 4.0 seconds is shown in Figure 10. Two spectra are shown, one without variability in spectral acceleration attenuation and fault rupture length included, and the other with variability in these two parameters included. Equal hazard spectra means that there is an equal probability that all spectral acceleration amplitudes used to represent the spectral shape are equally likely to occur.

Response spectral acceleration curves such as that in Figure 10 are very useful. Given such a response spectrum, once a buildings' natural period (the natural period is the reciprocal of the natural frequency) is known, the response of a particular building may be determined from the curve. This approach avoids the necessity of calibrating specific building types to ground vibration parameters such as peak-particle velocity (PPV) or acceleration. Because the spectral values are increasing for short periods, low-height, stiff structures (small natural periods, high natural frequencies) would probably be more susceptible (relatively) to minor damage than taller structures. However, if a large earthquake of the order of M_S 8.0 should occur in the New Madrid seismic zone, damage to a wide range of building types (generally, the taller the building, the larger the natural period) would probably occur as suggested by Figure 5.

The preceding review of the historical seismic activity affecting Evansville, a determination of the intensity distribution of shaking at Evansville, (Figure 4) the simulation of ground motion that would result from the occurrence of earthquakes in the New Madrid Seismic Zone, and the probabilistic modeling of ground motion all are in agreement with regard to the ground motions that have been experienced at Evansville in the past.

The probabilistic assessment of future earthquake ground shaking in Evansville indicates that Evansville can expect to sustain scattered architectural damage in the future. If large earthquakes occur in the New Madrid Seismic Zone of southeastern Missouri, it is probable that the city and surrounding area would also experience scattered structural damage to buildings.

GROUND-MOTION AND DYNAMIC-RESPONSE INVESTIGATIONS

INTRODUCTION

The purpose of measuring ground motions and site parameters for this program was to attempt to locate areas showing different ground response characteristics, particularly areas of high ground response anomalies. The ground motion measurement program was planned such that ground motions were recorded both at sites near buildings that experienced damage and near buildings with no history of reported damage. The investigations at various sites were intended to provide additional quantitative data relevant to the ground motion shaking characteristics of these sites.

GROUND-MOTION MEASUREMENTS AND DATA PROCESSING

Ground motions resulting from blasting at open-pit coal mines were recorded with portable digital seismic systems at 24 sites (Figure 11, Table 3). The seismic systems used triaxial velocity-sensing transducers that have a natural period of 0.62 sec and are damped at 60 percent of critical. The data were digitally recorded on magnetic tape at 100 samples per second per channel.

Between two and six seismic systems were installed at temporary locations for each phase of the field operations. The seismometers were leveled, oriented, and calibrated for each event using standardized techniques (Carver and others, 1986). Generally the procedure for recording the induced vibrations from some known event is to manually start all data recorders at least 15 min before the expected arrival of the induced vibrations and to record for at least 15 min after the event. However, due to the lack of advance information on precise blast times, either a system internal triggering algorithm based on expected vibration amplitude was used to turn on the recorders or an intelligent guess was made as to the blast time based on listening to the mine operators' radio transmissions. Due to the lack of accurate blasting times, only a limited number of multiple site combinations were recorded in the McCutchanville area (Table 4).

A minimum of 30 seconds of pre-event and 60 seconds of post-event data were included with each seismic record. Data transferred from the field tapes were stored on a VAX computer disk at the USGS office in Golden, CO and transferred as required to a personal computer for inspection and analysis. The data were reduced to analog seismograms plotted on similar amplitude and time scales for inspection, selection of time windows, and further analysis. Because ground-shaking damage is due principally to horizontal wave motion (Hays, 1969), only the horizontal ground vibration data were fully analyzed. The frequency band of the spectral analysis was limited to a 0.5-18 Hz band-width because the seismic systems are not well calibrated below 0.5 Hz. The error in calibration is greater than 5 percent below 0.5 Hz. At frequencies above 18 Hz, a signal-to-noise ratio greater than 10 is required, the ratios for the system used were less than this. The center of the frequency band chosen for analysis is near the natural frequency of most of the houses in the area under study.

The recorded vibration data were processed using spectral analysis software developed for a PC-compatible computer by the USGS (Cranswick and others, 1989). A 10-sec time window of digitally recorded ground-shaking data for events of interest was selected for analysis. The window was tapered using a whole-cosine bell (Hamming window) before being transformed by a standard Fast Fourier Transform (FFT) program. It was not necessary to normalize spectral amplitudes for the window length because all spectra in this study were derived from time series of identical duration (10 sec). Several of the tests use spectral ratios as a comparison technique. The spectral ratio, R, is calculated by:

$$R_{i,j,m} = (F_{i,j,m})/(F_{r,j,m})$$

where F = Fourier amplitude spectrum, i = site index, j = frequency band index, m = horizontal component, and r = reference site. The frequency bandwidths (index) used for the analysis are 0.5-1 Hz, 1-3 Hz, 3-5 Hz, 5-7 Hz, 7-9 Hz, 9-11 Hz, 11-13 Hz, 13-15 Hz, 15-17 Hz and 17-19 Hz. In this report, the average of the Fourier spectra for two horizontal components at the site being evaluated ($F_{i,j,m}$) and the average for the two components at the reference site ($F_{r,j,m}$) are obtained and the spectral ratio is then computed.

The spectra and spectral ratios were smoothed for display and comparisons using a moving-average window with a Hamming taper and width of 0.15 Hz. Tests were also conducted to determine the extent of variability in the spectral ratios. Possible sources of variation are instability in the seismic systems, seismometer-ground coupling, source directivity, and differential attenuation effects. Tests indicate the largest difference in spectral ratios from repeated recordings of mine blasts is 0.6 log units, indicating good repeatability from blast to blast at the same site (King and others, 1990)

Seismic data from two closely-spaced ground sites will have a certain variation in time-histories because of slight differences in the seismic recording systems, coupling difference between the seismometer and the ground, difference in the soil at the sites, and variance in the read-out. Based on past calibrations and experience with the equipment used in this study, it is believed the amplitude variance between seismic systems is less than 5 percent and the contribution from differences in the soils and seismometer ground coupling may add an additional 10 percent to the total variance. A conservative estimate of the maximum spectral ratio variation due to these differences is approximately 15 percent (Carver, et al, 1986).

ATTENUATION TESTS

Induced ground motion amplitudes are dependent on the source function, transmission path, and the site response. The effects of source function and site response can be minimized by having the recording sites located on a minimum of soil and by recording the same event at each site. The ground motion amplitude difference at sites located on bedrock, at similar azimuths from the source, and at different distances from the source will be mainly due to geometric spreading of the seismic signal and energy absorption by the propagation materials, taken together this is referred to as signal attenuation. Attenuation of the induced ground motion from the mine to McCutchanville was evaluated using Array No. 1, consisting of Sites GER and COR (Figure 12). The sites were located on limestone, at similar azimuths from the present mine blasting, and were approximately 5 and 8 km respectively from the mine.

Using a power-law function, an attenuation exponent of -2.04 was derived from the recorded particle velocities induced by the mine blasts as recorded at sites GER and COR in the frequency bandwidth under study (Figure 13). The $D^{-2.04}$ function where D = distance from the blast, compares favorably with a similarly derived distance exponent of -1.7 from the Centralia, Washington mine blasts (King and others, 1990). Attenuation of the frequencies in the ground motions that are similar to the natural frequencies of the sites or the buildings in question is of more concern than the attenuation of the peak-particle amplitude. The spectra derived from the vibration time-histories are shown on Figure 14. The distance attenuation exponents of specific band-widths were calculated as shown in Figure 14B for bandwidths of 0.5 to 1.5, 1.5 to 3, 3 to 5, 5 to 7, 7 to 9, 9 to 11, 11 to 13, and 13 to 15 Hz.

The attenuation functions that were determined from the measurements indicate that the transmission of the blast ground vibration energy to the study area would not result in ground motion anomalies (either high or low). This study indicates that the amplitude of the frequency band-width near the natural frequencies of the houses (discussed later) attenuated more rapidly than the peak-particle velocity (see Figure 14).

TOPOGRAPHIC AND SITE-RESPONSE EFFECTS

The difference in the induced ground motion amplitude at the upland or ridge top sites as compared to the sites in the lowland or valley is the summation of several factors: the variability in the field equipment, the coupling of the seismometer to the ground, distance from the blast, site response, and topographic effects. Since the seismometers' azimuths and distances from the blasts are approximately the same, the primary factors that cause a difference in the ground motions at the sites are a summation of the topographic and site effects. Since all of the topographic study sites are underlain by soil, and it is impossible to directly separate the effects of the underlying soil column (site response) and the topographic location. Accordingly, both effects are discussed in this section, first topography and then site effects.

Topographic Effects

Many investigators such as Phillips and Aki (1990), Herrmann (1986), Dowding (1986), and Tucker (1989) have studied the effects of topography on ground motion. Three instrument arrays (Nos. 2, 3, and 4) were deployed to examine the possible topographic effects of the hills in McCutchanville on the ground motion. Array No. 2 consisted of two sites (STA and HAD, Figure 15) located approximately 2-3 km from the mine blasting and has an elevation difference (approximate elevations were obtained from topographic maps) of approximately 130 feet. Array No. 3, shown in Figure 15, is approximately 5 km from the mine blasting and consists of three sites on or near the ridge tops (GRE, MCC, and ARN) and one site in a shallow valley (HEI). The elevation difference of this set ranged from 75 to 90 feet. Array No. 4 consisted of two sites (FRI and AIR, Figure 15) which had an elevation difference of 55 feet.

Figure 16 shows the seismograms, spectra and horizontal spectral ratios from the topographic investigation for Array No. 2 (sites STA and HAD). Comparisons were made between the valley site and the higher elevation site by (1) determining the peak-particle PPV ratio by dividing the PPV for site STA into the PPV for site HAD and (2) determining the spectral ratio by dividing the spectra from the induced ground motion at the valley site into the spectra from the induced ground motion at the higher elevation site using the procedure described earlier in the section on data processing.. These ratios are summarized in Table 5. The PPV ratios are independent of frequency. Since the spectral ratios are frequency dependent, both a ratio and its frequency are given in the table. The spectral ratios give an indication of the frequencies (6-8 and 10-12) that are more prominent at the higher elevations. The seismograms and spectra shown on Figure 16 use the same amplitude, time, and frequency scales to allow visual comparison of the recorded ground motion.

The same type of data for Array No. 3 is shown in Figure 17 and for Array No. 4 is shown in Figure 18. The ratios for both of these arrays are also tabulated in Table 5. The data indicate that the PPV at site HAD (the higher elevation) is greater than site STA by a maximum factor of 2.5 (Table 5). The horizontal spectral ratios indicate that the greatest difference is in the 10-12 Hz frequency band-width.

The difference in the source distance in Array No. 2 topographic data set is less than 0.1 km and is considered insignificant. However, the average difference in distances from the sites to the blast location for Array No. 3 topographic data set is 0.3 km which may result in amplitude variation due to attenuation of the signal. Normalizing the recorded ground motion amplitudes at the sites in this array to site HEI is accomplished by using the attenuation function with a power of -2.04 (as previously discussed) and the formula:

$$(\text{hill } D^{-2.04} - \text{valley } D^{-2.04})/(\text{valley } D^{-2.04})$$

where D=the distance to the blast. Normalization by the source to distance attenuation factor shows that the ground motion amplitude at GRE is reduced by 4 percent, ARN is reduced by 9 percent, and MCC is reduced by 13 percent in amplitude to be directly compared with site HEI. Once the distance attenuation factor is removed from the recorded ground motion amplitudes, the remaining difference in amplitude is a summation of the topographic and site effects (Table 5). Figure 17 shows Array No. 3 seismograms and spectral ratios at similar amplitude, time, and frequency scales but they have not been corrected by the attenuation function. Similarly, seismograms and spectral ratios are shown in Figure 18 for Array No. 4 (sites FRI and AIR).

The horizontal PPV ratios show a difference due to a summation of effects from topography and site response at the lower elevation sites to the higher elevation sites by a factor of 1.4 for ARN, 1.3 for MCC, 1.2 for GRE and 2.0 (average of 1.5 and 2.5) for FRI (Table 5). A similar comparison (ratio) was made with the spectra derived from the same ground shaking data. The spectral ratios show a larger amount of spectral energy in the 4-6 Hz, 6-8 Hz, and the 16-18 Hz frequency band-widths at the higher elevation sites.

Site-Response Effects

Methods for deriving ground-response values and for mapping ground motion hazards have evolved from a number of projects including the areas of Las Vegas, Nevada, San Francisco and Los Angeles, California, the Wasatch Front area in Utah, and Olympia-Seattle, Washington (Murphy and Hewlett, 1975; Borcherdt and Gibbs, 1976; Rogers and others, 1979; Hays and King, 1982; King et al, 1990, 1991). In general the method consists of deriving spectra from ground-shaking time-histories (seismograms) for sites underlain by soils and a standard reference site located on bedrock. Spectral ratios are derived by dividing the soil site spectra by the standard site spectra. If the source, distance, azimuth and general topographic position can be held constant, then the primary cause of difference in ground shaking between the site on rock (reference) and a study site will be due to the subsurface differences of the site under investigation; that is, site response.

Two sites were found on bedrock and at the same approximate azimuth and distance from the blasts as the other study sites. Both sites COR and GER (Figure 12) are located on limestone and were also used for the attenuation study (Array No. 1).

Spectral ratios were calculated at the sites GRE, WOF, KIN, MCC, ARN, EFF, FRI, and FIN, using the reference site COR (Array No. 5, Figure 19). The recorded seismograms of these sites are shown with similar amplitude and time scales for visual comparison in Figure 20. Figure 20 shows examples of comparisons of the spectra from the data recorded at the reference site (COR) with spectra from data recorded at sites ARN and MCC. The spectra were then ratioed (Figures 21 and 22). Table 6 gives a summary of the PPV and spectral ratios that have been normalized for distance-to-source differences. The horizontal PPV ratios range from 1.3 at FIN to 3.8 at ARN. The spectral ratios indicate a peak site response is within the 6-8 Hz frequency band-width at all sites except for FIN and FRI which have peak spectral ratios in the 8-10 Hz frequency band-width (Table 6). These site response frequencies compare well with those calculated from the bore-hole shear measurements (Table 7, discussed later under site tests).

Spectral ratios were calculated at the Array No. 6 sites (Figure 23): STA, ENG, and HAD relative to the reference site GER. The recorded seismograms and spectral ratios are shown in Figure 24. The horizontal PPV ratio of this data set shows a maximum ratio of 2.6 at the HAD site (Table 6). The spectral ratios of the HAD and ENG sites to the rock site show a peak site response in the 12-14 Hz bandwidth. The STA site (located in the valley) indicates a low response at 5 and 13 Hz that also compares well with the natural soil frequency calculated from the bore-hole measurements (Table 7).

The site response study indicates that the sites underlain by soil have a **PPV** amplification factor of approximately 2-4 over the ground motion on rock and that most of the frequencies of the higher response spectral ratios are in the 6-8 or 8-10 Hz frequency band-width. The frequency of the larger values of the spectral ratios indicate the natural frequency of the soil columns. The natural frequencies indicated from the spectral ratios agree well with the calculated natural frequencies determined from the bore-hole tests discussed later.

Summary

In this study the effects of topography on the induced ground motion must be considered along with the site response study. In general, the topographic study suggests an amplification of the peak-particle ground motion in the upland areas compared to the lowland areas by a factor of 1.2 to 2.5 and more seismic energy in the 4-6, 6-8, and 10-12 Hz frequency band-widths. This would suggest an amplification at those frequencies in the highlands or, conversely a deamplification at those frequencies in the valleys or, a possible combination of both relative to a standard site underlain by rock. However, the site response study at some of the same sites evaluated for topographic effects (HAD, GRE, MCC, FRI) show that the site response due to the soil column is greater than the topographic response. Therefore, logic suggests that the topographic effects of this area are much less compared to the site effects. This conclusion is reinforced when rock site COR is compared to site ARN, which is 10 feet lower. However, site ARN is significantly higher in response. A comparison of sites HAD and GER (Table 6) leads to a similar finding.

SITE TESTS

Nineteen holes were bored using an auger drilling system and the soil profile was logged. Thirteen of the holes were augered to bedrock. Eleven of these were located at complainant houses, one at valley site STA and one at hilltop site HAD. Eight of the holes were located at non-complainant houses. These eight holes were augered to depths of about 2 1/2 feet below the bottom of the foundations. Where possible, samples of bedrock (shale or limestone) were recovered from the 13 holes augered to bedrock by split-spoon sampling at the bottom of the hole. In each case a standard 140 pound standard penetration test (SPT) was also made at the bottom of the hole to confirm the resistance. The SPT at the bottom of each bore hole was greater than 30 blows per foot. The bore-holes were cased with PVC pipe which was grouted in the hole.

Additional tests included natural gamma logging and both compressional and shear wave velocities. These data are shown in Figure 25. The down-hole seismic data were analyzed on a PC-compatible computer using a refraction analysis program. The natural gamma logging helped to define the boundary between the alluvium material and the bedrock. The system measures the natural gamma radiation from the substratum, which usually indicates the presence or absence of clay. Fine material such as clay will shift the base line to the right (higher count/sec) and the coarser sediments that usually have less natural radiation will shift the base line to the left (Figure 25).

The shear and compressional wave velocities were measured at the bore hole sites by positioning a triaxial downhole seismometer at 1 meter incremental depths in the cased bore holes. A shear-wave was generated at the surface by horizontally hitting a plank with a sledge hammer. A compressional wave was generated by vertically hitting a steel plate. The methods are described in detail by Crice (1986). Previous investigations into site response have found that the site amplification of ground motion increases as the shear-wave velocity decreases and that the amplification usually occurs at sites that are underlain by a thick sequence of material that has a shear-wave velocity below approximately 150 m/s (Borcherdt, 1970; Rogers and others, 1985; King and others, 1990). The bore-hole test results did not show any significant thickness of material that have low shear-wave velocities. Ten of the sites have an average shear-wave velocity range from 202 m/s at BOE to 318 m/s at STA (Table 7). Only three sites have shear-wave velocities below 200 m/s (HAD at 165 m/s, CHR at 188 m/s, and RIC at 189 m/s) but these were still in excess of 150 m/s. Therefore, none of the test holes indicate an anomalous subsurface condition that would cause an area of unusual high ground response.

The approximate average soil frequency can be calculated by the following formula (Richart and others, 1970): soil period = (0.25 x average shear wave velocity)/ (thickness of the soil layer). The calculated natural frequency (Table 7) of the soil ranged from 4.8 Hz at the site of deepest low velocity material (17.5 m deep at STA) to 8.3 Hz. at the site of shallowest low velocity material (5.3 m at HAD).

SITE-COMPARISON STUDIES

Several pairs of sites were chosen for comparison studies (Figures 26 and 27). Each pair consisted of (1) a site at which the home owner had made an official complaint due to suspected vibration damage and (2) a house that was adjacent to or in close proximity to the complainant house which, to our knowledge, had not made an official damage complaint. In the later section of this report on building damage, these are respectively referred to as Category 1 and Category 2 houses. For each pair of sites, an attempt was made to select a non-complainant house within a few hundred meters of the complainant house, each located on similar geology and topography.

It was not possible to have all sites optimally paired. For instance, at the complainant site EFF a land-use permit could not be obtained for a companion. Other site pairs were instrumented but no data were collected due to conflicting blast and field operations schedules. The site pairs for which comparison data were obtained are: BOH-MIL, FRI-EDD, MCC-ARN, OSB-ROS, KIN-WOF, and FIN-COX. Addresses and names associated with the three letter codes are listed in Table 8. Figures 26 and 27 show the locations of the sites. The recorded ground motions are from locations or sites approximately 15-30 feet from the structures. These recording locations, which are believed to be far enough away from the structures so as not to be influenced by their presence, are referred to as "free-field" sites.

Figure 28 shows the recorded seismic time-histories at the companion free-field sites. The amplitudes are all on the same vertical scale so that they can be visually compared. The time scales are also the same in order to show variations in the duration of the vibrations. The duration of vibrations induced by the blasts at a site can be compared by measuring the time or duration that the induced vibrations exceeds a set level such as 3 dB or 40 percent above the ambient background. Inspection of the paired vibration time-histories show less than a 1 sec difference in duration (Figure 28). Peak-particle velocities are compared by dividing the recorded ground motion values at the companion non-complainant site into the PPV at the complainant site. The difference at most of the paired sites is 30 percent or less (Table 8). Larger differences were recorded at complainant sites FRI and FIN for a maximum PPV ratio of 1.6 in the N-S direction at FIN and a ratio of 1.5 in the E-W direction at FRI.

The ground motion comparison study between complainant and non-complainant sites shows that the induced ground motions at all paired sites except two agree in maximum peak particle amplitude within 30 percent. The 30 percent difference should not be considered significant since approximately 15 percent of the difference may be due to the factors previously discussed.

BUILDING-RESPONSE MEASUREMENTS

Important parameters in the analysis of vibration-induced damage to building structures are the natural resonant frequency of the building and the amount of vibration amplification that will be caused by the building. Given a particular type of structure, the natural frequency is primarily dependent on the height and secondarily on other factors. The procedure for obtaining these parameters consisted of installing portable horizontal seismometers on the top and at the midpoint of bearing walls of the structure. The seismic systems used to determine the natural frequencies of 21 houses and the structural amplification factors at two houses were the same as those used to record ground motion. The natural frequency of the structure is determined by recording the induced motion into the building by body movement of a person in close synchronization with the structure's approximate natural frequency (King, 1969; King and Carver, 1988). The measured natural frequencies are shown in Table 9. Reliable data could not be obtained from some of the buildings' long-axis direction due to the stiffness of the buildings. However, past experience has shown that the recorded frequencies of the long-axis of 1- to 3-story houses are usually the 2nd mode of the natural frequency and are within 8 Hz of the short-axis first mode natural frequency (King, et al., 1991).

The natural frequencies of the short-axis of the 1-2 story houses range from 5.6 to 10.5 Hz. which is similar to the natural frequencies of 1-2 story buildings tested in other areas (King et al., 1991). The natural frequencies of the comparison houses were not greatly different from the natural frequencies of the complainant houses. All were within 2-3 Hz of each other as shown Table 9. Where data are available for comparison houses, the data have been paired in Table 9. Comparison data were not obtained for the six houses at the bottom of the table.

A structure will amplify induced vibrations that are near the structure's natural frequency. Vibration data induced by mine blasting were recorded in the attics of two houses (Figure 29). The ratio of the peak-particle velocity motion at the free field sites to the attic sites in the horizontal plane indicates that the buildings are amplifying the induced motion by about 4-4.5 times and have an increase in vibration duration of approximately 4 seconds compared with ground motion at the adjacent free-field site.

Testing of the natural frequencies of the houses indicates that the houses are sensitive to frequencies within the 5.6 to 10.5 Hz bandwidth. In general, when comparison houses were available, the natural frequencies of the non-complainant house was not significantly different than the complainant houses. It is important to note that the site frequencies in Table 7 are similar to the natural frequencies of the houses in Table 9. Table 10 illustrates the similarity. The houses with frequencies that are particularly close to the site frequencies are shown shaded. This condition may result in amplification of the vibrations experienced by the houses.

Testing of structural vibration amplification indicates that the 2-story structures amplify the peak-particle ground motion by a factor of 4 to 4.5 which is normal for houses of that size (FRI and FIN, Figure 29). However, the FRI house did show two notable resonances. The vibration amplification was nearly equal in both horizontal axes. This is perhaps not surprising since the natural frequencies are about the same. Normally a structure will have a different amplification along each axis since the natural frequencies are usually different. Also, the vertical axis of the FRI house indicated an amplification factor of approximately 3. Most structures have very low amplification in the vertical axis. These amplifications suggest that the Harris house might be more sensitive to vibrations than normal.

BUILDING DAMAGE

INTRODUCTION

Fifty-two houses were inspected in the vicinity of Evansville to obtain data for use in the determination of possible causes of damage. The inspections were of a walk-through type. Overall crack patterns were inspected in order to determine possible mechanisms causing problems. Detailed crack documentation such as pattern marking and width measurements were beyond the scope of the work. Analytical studies of structural response and resistance were done by Chiarito (1993 - The Chiarito report was not complete at the time of preparation of this USGS report). Soil evaluations were done by Hadala and Peterson (1993).

Inspections were conducted on three categories of houses located in the McCutchanville-Daylight area and a remote area west of Evansville. The three categories are:

Category 1

Complainant, McCutchanville-Daylight area	Formal complaints were made by the owners and/or occupants of these houses located in an area where blasts were felt.

Category 2

Non-complainant, McCutchanville-Daylight area:	Formal complaints were not made by the owners and/or occupants of these houses located in an area where blasts were felt.

Category 3

Non-complainant, Remote area:	Formal complaints were not made by the owners and/or occupants of these houses located in an area where blasts were not felt.

Category 1 and 2 houses are listed in Table 11, their locations are shown in Figures 26 and 27. Category 3 houses are listed in Table 12. The general location of the remote area is shown in Figure 1. Permits for inspection of the structures in the three categories were obtained by the Office of Surface Mining. The actual sample was affected by the desire to "match up" with houses in Category 1 and by the necessity that all houses inspected would require homeowner approval. Homeowners were very cooperative in this respect, nonetheless exact matches were not always possible.

In general damage descriptions are given in Tables 11 and 12 in the following manner:

Exterior - A brief description of damage or conditions outside the house.

Foundation - A brief description of damage or conditions related to the basement, crawl space, and/or slab on grade as appropriate.

Interior - A brief description of damage or conditions related to the interior finish surfaces inside the house.

BACKGROUND ON STRUCTURAL PERFORMANCE

Structural performance depends on the demand placed on the structure by the environment (*loads*) and the capacity (*resistance*) of the structure to resist the demand. These two aspects are discussed below in further detail along with damages.

Loads

Load is a general term that includes effects on a structure from causes such as snow, wind, earthquake, and environmental changes such as temperature or humidity variation. The loads impose a demand on a structure which, in turn, must have the capacity to resist the demand or damage will occur. The load or loads actually experienced by a building may be larger than the ones considered in the design or the loads may never have been considered in design. Often design for one loading may also be sufficient to provide limited resistance for another one that was not explicitly considered. For example, normal design for wind might provide a limited resistance to vibrations. Normal wind design would not necessarily be expected to provide resistance for vibrations such as those caused by large earthquakes, unless that effect was explicitly considered.

Structural Resistance

If the resistance of a structure is less than the demand placed on it, damage or possibly collapse will occur. The extent of the damage depends on how much the load effects exceed the capacity. The resistance of a structure may change with time. For example, weathering may result in deterioration of materials such as brick (some brick are more weather resistant than others). Such deterioration may simply show as slight wear or, in severe cases, may result in loss of capacity (due to a reduction in size or strength) to resist forces caused by loads such as those resulting from wind or earthquake.

The construction practice in the McCutchanville-Daylight area seems to be to use little or no reinforcement in the basement or foundation walls or concrete slabs. This is the case in many areas in the eastern U.S. It is not acceptable practice in areas of expansive soils or in earthquake areas. It is assumed that the practice in the McCutchanville-Daylight area is generally acceptable. Otherwise, it is expected that there would be more complaints about structural performance and that some of the more severe problems found during inspections would have been more widespread.

There is no simple way of determining how closely the houses were built in accordance with local requirements or whether there was any inspection during construction. Some of the houses were apparently built by a contractor while others involved at least some of the owner's participation in construction. Because of this, quality of construction can not normally be evaluated.

Damage

It is not necessarily true that simple observation of damage will reveal the cause. Frequently more than one factor contributes to the damage, for example load demand caused by a combination of vibration-induced stresses imposed on top of existing settlement stresses might be sufficient to induce cracking, when neither condition alone would be enough to do so. It is the total stress level, regardless of cause, that results in the damage. More often than not, the magnitude of imposed load needs to be known in order to separate the stresses due to various effects. The issue is complicated by the fact that there are cracks present in virtually all structures, usually in the more brittle materials (such as plaster, wallboard, or concrete). Such cracks are frequently found in areas of stress concentration (such as in the corners of openings for doors or windows). Under normal circumstances in a well-designed and well-built structure these cracks will hardly be noticed. Some cracks may be noticeable only during specific seasons as a consequence of humidity and temperature changes. Though possibly annoying, they are rarely of consequence to the overall performance of a structure.

SOILS

The ability of a soil to support a structure plays a crucial role in performance of the structure. Investigation of the soils in the McCutchanville-Daylight area was included as part of this overall investigation. The soil investigations were conducted by WES (Hadala and Peterson, 1993). They concluded:

Compaction due to vibration - "The torsional shear tests conducted on samples from three different sites offered no evidence to suggest the existence of any kind of collapse mechanism or creep mechanism caused or triggered by sustained low level vibration. The specimens essentially behaved visco-elastically in the tests conducted. This eliminates soil structure collapse or creep due to sustained vibration from the list of possible causal mechanisms for the observed building distress."

Settlement - "Because pre-consolidation pressures are substantially more than the bearing pressure, one should not expect large settlements." Hadala and Peterson calculated settlements on the order of 0.18 in at the center of a foundation slab and a differential settlement on the order of 0.07 in. Settlements observed at a number of houses were much larger than this, indicating some other cause than normal settlement.

Bearing capacity - "Bearing capacity failure is therefore not a reasonable scenario for the footing size and load in the base case and the soils encountered in the subsurface investigations."

Expansive soil - They found that the correlation between bowed-in walls and expansive clay at depths shallower than the bottom of the wall was not good. The expansive soil is generally too deep in the profile to produce severe wall loads. However, in a personal communication with Hadala (March 18, 1993), he did believe there was a correlation of severe damage with the presence of expansive clay anywhere in the soil profile.

Hadala and Peterson did not rule out vertical differential heave due to expansive soil, piping or slope creep. They also mention other possibilities such as earthquake, thermal cycling of the superstructure, and frost action in the foundation.

SUMMARY OF INSPECTIONS OF CATEGORY 1 AND 2 HOUSES

Thirteen Category 1 and twenty Category 2 houses were inspected. They are listed in Table 11. Their locations are shown in Figures 26 and 27. Companion houses are identified in the table by grouping and by their category number. Houses in Category 1 are a sample of the population of complainant houses in the McCutchanville-Daylight area. Category 2 houses were selected to obtain damage data for houses in the same vicinity as the complainant houses that constitute Category 1. When possible, each house in Category 1 was matched with a nearby house in Category 2. Attempts were made to match structural type, foundations, and site conditions. Exact matches in all of these parameters were not always possible due to variations in geology and construction type. A brief description of the construction of each building is provided in Table 11 along with a brief description of damage and the soil profile.

Most homeowners said that the severe damage did not appear until cast blasting was started in 1988. All of the homeowners of the houses inspected in Categories 1 and 2 felt the blasting, some described it as severe. Two of the Category 1 homeowners described some specific cracks as resulting from specific blasting events. The vibration levels that occurred during these blasts are not known. It is not doubted that the homeowners felt the blasting nor is there any argument about the presence of damage, in some cases severe.

The Category 1 structures were damaged to widely different degrees. Some of the Category 1 structures that were severely damaged, had companions (Category 2) with little or no damage. For example, the McCutchan house had extensive wide cracking in the floor slab and masonry veneer whereas its companion, the Zinn house was judged to have minor damage.

In general the damage in the Category 1 houses inspected was more than one would normally expect in well-constructed houses subjected to normal seasonal variations with no foundation problems. Much of the more severe damage such as stair-stepped cracking in exterior veneer and cracked basement floor slabs resembled damage related to foundation problems. Unfortunately, vibration damage can also produce similar crack patterns.

Most of the Category 2 houses had damage that was no worse than that found in the Category 3 houses. Although one of the houses in Category 2, the Palmer house, had damage that was as bad as some of the structures in Category 1.

It would normally be expected that if damage was a consequence of foundation problems, it would occur in the first five or ten years in the life of the structure. Since many of the severely damaged structures were built in the 1950's and 1960's, such problems should have occurred prior to 1988, barring any unusual circumstances. Some of the possibilities are discussed.

A number of the houses produced information that illustrate possible sources of the damage found during the inspections. Because the houses are different and are on different foundations, there may be no single explanation for all of the damages observed.

McCutchan/Zinn - The basement slab of the McCutchan house has a crack about one-half inch wide (actual width varies) running the full length of the slab. There is no differential vertical displacement across the crack as might be expected if the problem were due to expansive soil. The crack does appear to have been spread apart, which would be consistent with movement downslope. The basement block wall next to the garage is cracked (on the order of 1/4 in wide) and the blocks are displaced, indicative of inward movement of the wall. There is soil missing from behind the wall as could be seen when viewing through a large crack in the masonry joints. The owner said dirt has washed through these cracks into the basement. The owner also said he had drilled a hole through the garage slab on the other side of the wall and there appeared to be a void under the slab. Thus the soil, which is loess at this depth may flow readily when moisture penetrates through it. Cracks in the exterior brick veneer also appear consistent with downhill movement. A marble placed on the bedroom floor in one corner rolled in the direction of apparent downhill movement. The Sinn house, on similar soil but with no basement, had only a few hairline cracks.

Kinney/Wolff - The basement damage in the Kinney house, which is located on a slope, is similar to that observed in the McCutchan house. There was evidence of poor drainage around the basement wall that is most severely damaged. The cracks in the basement slab appeared to be spread apart with little vertical differential displacement. The companion house, which also had a full basement had only hairline cracks. The drainage appeared better around it. Soils profiles were not available at either location.

Fink/Condict - Both of these houses had damage but in portions of the Fink house the damage was severe. There was no major damage at the Condict house although there were cracks in the basement and water stains on the basement walls. The was severe damage at the Fink house which is discussed below.

In the Fink house the ground showed signs of settlement, particularly around the perimeter of the foundation walls. Brick walkways around the house were uneven. The garage slab was severely cracked, being displaced over a foot next to a doorway entering the house. There was no evidence of reinforcement in the garage slab. There was a sink hole that was present along one foundation wall, a foot or so in diameter. Mrs. Fink said that a flower pot had disappeared down the sink hole.

Examination of the crawl space adjacent to the foundation wall by the sink hole showed that exterior soil had literally washed into the crawl space. This sediment transport is referred to in this report as "soil flow." The flow pattern was traceable to the sink hole outside the house. The missing flower pot was found in the crawl space. This could be one reason the basement is damp. Step footings[1] were visible in the crawl space. One such step in the footing was located at the sink hole. There was a vertical crack in the foundation wall at the step and the footing appeared to be discontinuous at the step.

There was a long steel beam in the crawl space which supported the floor joists. In addition to the end supports for the beam, there were two intermediate concrete block supports. The steel beam was supported on the top of the concrete blocks by a single brick at each support. These bricks were crushed. This steel beam, which is losing support, lines up with vertical cracks in the brick veneer outside the house. This house shows the susceptibility of the loess material around the house to piping. It also points to possible bad construction since this is one house where plans were available and these called for steel plates rather than bricks. The natural frequency of this house was a close match to the site frequency.

Since the garage slab was severely damaged, the basement was closely examined in the area adjacent to the garage. A small, unexacavated room was found in the basement adjacent to the garage. The purpose of the room is not known. Although virtually inaccesible, the area inside the room was visible. Two of the full-height block walls separated the room from the rest the basement. The third wall was part of the exterior wall of the house while the fourth wall was common with the garage. This fourth wall was supported on step footings similar to the type seen in the crawl space. As in the crawl space there was a crack at the step in the wall and there appeared to be soil movement under the wall. There were soil deposits visible on the floor of the room. The floor plans of the house, dated June 8, 1951 (made available by Mrs. Fink), show drain tile running under the garage slab in the area of severe displacement. Since this tile carried part of the drainage water from the roof and away from the house, it is possible that this was the source of water to transport soil from underneath the slab.

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[1] A stepped footing supports the bottom of a wall at different elevations. In this case, the top of the wall is at a constant elevation, whereas the height of the wall varies around the crawl space. The variation of the wall height change is abrupt, like a step. The concrete footing which supports the wall steps up or down with the bottom of wall it supports.

Effinger/No Companion - The damage at the Effinger house was severe. One long (about 60 feet) unreinforced block wall was bowed in to the extent that the owner had braced it, fearing collapse. There appears to be no expansive soil to act as the source of the pressure against the wall. The slope of the ground outside the wall is such that it appears almost certain that water would penetrate alongside the wall and possibly exert lateral pressure. However, there is little evidence of water stains on the inside of the wall. The source of the pressure is not evident at this time and may not be possible to explain without excavating the area outside the wall. There is some moisture that does come inside in one corner where the floor slab is cracked. The exterior brick veneer above this area is cracked.

Greenfield/Palmer - Both houses had basements or partial basements. There were depressions observed by others in the yard of the Greenfield house but none were seen in the crawl space nor were any observed at the Palmer house. The brick veneer at the wing of the Greenfield house with a full basement had large cracks in the joints. There was also interior damage. The owner of the Greenfield house said the house was undamaged when he purchased it. He also pointed to some cracks which he associated with a particular blast.

The Palmer house, built on a slope, had both interior cracking on the finish surfaces and exterior cracking in the masonry veneer. The stair-step nature of the exterior cracking in this house was typical of what is usually found due to differential settlement.

Boettcher/Ogg - Some of the same flows of loess seen at the Fink residence were seen in the crawl space at the Boettcher residence. The Boettcher house was severely damaged while the Ogg house across the street had only two hairline interior cracks. Both of these would be expected to be exposed to similar vibration environments, whether from mine blasting or earthquakes. This difference in damage points to some other cause of damage in the Boettcher house. The foundation of the full basement portion of the Boettcher house, which is believed to be in loess appears to be moving downhill (both vertically and laterally) with respect to the crawl space portion of the house. Damage in the basement was reported to have started in the 1950's.

Harris/Deutsch/Halwes - The Harris house has both interior and exterior damage while the companions had only minor damage. The Harris house has a basement under part of the house and a crawl space under the remainder. A second story was added to the central part of the house. The Halwes had no basement and the Deutsch house had a small partial basement in the center of the house.

Mrs. Harris keeps an extensive log of cracking in her residence. She has marked cracks by progress and date. She states that the cracks were not present when she purchased the house around 1988. It was then that she started feeling blasts and thus started keeping records. Mrs. Harris has reported new cracks on more than one occasion during recent blasting. She also pointed to fallen fragments of material below cracks as evidence of continuing crack movement.

One crack extension in the Harris house that occurred during the period of blasting was documented by someone by other than Mrs. Harris. This occurred during the 1990 BOM study. Siskind and others (1990) conducted crack monitoring during their investigation. In OSM house 107 (Harris house) there was one ceiling crack extension that was not under inspection but it did pass through a mark placed to identify a nearby crack tip that was under observation. The largest PPV during the period when this extension occurred was 0.031 in/sec. The largest PPV at this house during the monitoring period was 0.06 in/sec, which produced no change.

During one USGS inspection of this house, one crack was found that predated marked cracks in the same general area where cracks were marked. This was a diagonal crack behind a cabinet. The crack could be traced from behind the cabinet into the painted wall area above the cabinet. The crack, discovered by accident, could not be easily seen there since it had been painted over and the paint bridged the crack. While this does not prove, and is not intended to prove, that all of the cracks were present at an earlier time, it does indicate that there has been some process going on in the past that caused some cracking. There was also repointing of joints near the bedroom windows.

The crawl space area was examined from the inside. One portion of the foundation wall had a horizontal crack in the joint of the concrete block wall. A downspout was located on the outside near the crack. There was a sump pump in the crawl space, it was dry during the inspections of the crawl space. A sump pump in the basement had water in it. It is not known if this crawl space was part of the original house or if it was part of a modification. It is known that the area was shown as existing on a set of plans dated February 11, 1984 (made available by Mrs. Harris). This set of plans was prepared for modifications of the first story and for the addition of the second story.

The Harris house had a natural frequency relatively close (within 30 percent) to the site frequency. There was also evidence of relatively high structural amplification in this house. Accordingly, vibrations would likely be more noticeable in this house as compared with one that was not close to the site frequency The site frequency at the companion houses are not known. However, the natural frequency of the Deutsch house is almost twice as large as the Harris house so it probably does not match the site response.

Osborne - This house had a full basement. During construction, water pressure was sufficient to collapse one basement wall at the house prior to attachment of the superstructure. This indicates that, at least at this location, the lateral pressure on the walls can be significant.

Richey/Stevens/Heil - The Richey house had two basements with a crawl space between them. One basement wall is bowed in although not as much as at the Effinger house. This resulted in the exterior masonry, which was supported on it, to fall off. There were many cracks in the masonry on the exterior of the house. There were claims of damage at the Richey house as early as 1985 (Gerst, January 13, 1985; Donan, October 2, 1985; Franklin, November 15, 1985; S. Bhatacharya, 1986). The site frequency and natural frequency of the Richey house are very close together.

The Stevens house had a full crawl space and, like the Richey house, had wood panelling inside. There were hairline cracks present in the masonry block. The occupant said that the floor sloped and that sticking of doors and windows was a common. The occupant also described the sudden appearance of holes on the property. One of these apparently required several cubic yards of dirt to fill it

The Heil was close to the other two houses but was near the bottom of the hill, unlike the other two which were on the top of the hill. The house had a full basement. Wood panelling was used in the first floor living area. There were a few hairline cracks but little else that could be observed.

Christensen/Klausmeir/Board - The Christensen house had moderate to severe interior damage while the companions had very little damage. The Christensen house has a basement that was apparently added at some time after original construction. The companions had no basement.

The bedroom in the Christensen house where damage was most apparent (but not the only area with damage) had a water bed located in it. The floor gave the impression of sloping towards the middle of the room. The floor joists supporting the floor loads in this room could be examined in the basement. The end bearing area of the joists (area of the joists resting on supports) appeared to be partially crushed, as evidenced by bulging of the sides of the joists.

The natural frequency of this house closely matched the site frequency, indicating a possible sensitivity to blast vibrations. Of the damages inspected, the cracking on the interior walls of this house appeared to most closely resemble vibration damage and was more extensive than would normally be expected in a house subjected to normal use.

Zimmerman/Shelton/Daugherty - The Zimmerman house had a full basement as did the Daugherty house. The Shelton house had a crawl space. There was no damage at the Shelton house and only minor cracking at the Daugherty house.

There were hairline cracks in the basement slab and the basement walls of the Zimmerman house. There were also cracks in the exterior masonry veneer. The interior of the house had hairline cracks and some evidence of nail pops (loose nails fastening wallboard to the wood studs). On the initial 1991 USGS visit to the Zimmerman house, Mrs. Zimmerman produced a photo report documenting damages in which there were photos of damage resembling that at the 1991 inspection (A copy of this report in not available but it is believed to have been prepared by Amax Mine in 1985 at the request of Mrs. Zimmerman). Mrs. Zimmerman stated that the blasting was bothering her much earlier than 1988.

Norton/LeCocq - Both of these houses have full basements. The most severe damage at the Norton house is to a three-stall garage which has an unreinforced concrete slab on grade. The concrete slab is cracked and vertically displaced in one corner of the garage. There is clear evidence of poor drainage around the garage in the area of most damage.

There are some cracks in the basement of the LeCocq house. The owner attributes these to causes other than blasting, but he was emphatic that in spite of having no damage complaint, the blasts were very bad from an annoyance standpoint.

SUMMARY OF INSPECTIONS OF CATEGORY 3 HOUSES

Nineteen Category 3 houses were inspected, these houses are listed in Table 12. A brief description of the construction of each building is provided in the table. These houses were used as a control group. The remote area (see Figure 1) was selected to match as closely as possible the site conditions for Categories 1 and 2, but to be so remote as to preclude any damage from the mine blasting. Damage observed in the remote area was believed likely to have resulted from causes other than blasting.

The presence of some damage was not unusual even in the Category 3 structures. Typical damages included cracks around door and window openings and ceiling cracks. In two instances the owners said specific cracks were a consequence of earthquakes. Additionally there were some damages that, according to owners, resulted from poor drainage around houses. Once drainage problems were corrected, the problems stopped. However, with one exception (Neale) which has a known cause of faulty construction, the damage was not as severe as some of the structures in Category 1, although not much different from most structures in Category 2.

DISCUSSION OF FACTORS AFFECTING DAMAGE

Vibration Levels and Exposure - As stated earlier, the PPV that were produced by blasting during the period of highest complaints are not known. The largest vibrational levels measured by USGS at the USGS-monitored sites were on the order of 0.05 cm/sec (0.02 in/sec), much smaller than those that occurred during other periods of observation (discussed later). It is not assumed that these other observation periods were typical of the period of cast blasting. However the small amplitudes and lack of information hinders reaching conclusions about the damage potential based solely on the amplitudes of our measurements.

Siskind and others (1990) recorded maximum peak-particle velocities in the Daylight area of about 0.1 in/sec (0.25 cm/sec) in the Daylight area and 0.06 in/sec (0.15 cm/sec) in the McCutchanville area during the course of their investigation. The highest PPV observations in McCutchanville were in the frequency range of 4 to 5 Hz. The McCutchanville PPV was found to be high relative to the large blast-to-structure scaled distances.

Eltschlager and Michael (draft, 1993) provided an analysis of blasting ground vibrations during the period 1986 to 1992. They estimated maximum vibrations in the Daylight area of 0.39 in/sec (about 1.0 cm/sec) and in the McCutchanville area of 0.17 in/sec (about 0.4 cm/sec). They considered this an upper bound on the vibration levels. Review of their draft report indicates that these do not seem to be unreasonable PPV levels, although they are subject to revision.

The 1987 earthquake discussed earlier resulted in peak particle velocities at four stations near Daylight ranging from 0.33 to 1.12 cm/sec (0.13 to 0.44 in/sec) for the horizontal components and 0.10 to 0.23 cm/sec (0.04 to 0.09 in/sec) for the vertical components. These measurements were larger than those recorded by Siskind and others in their 1990 investigation. There was damage in Evansville that resulted from this earthquake.

Presumably similar houses subjected to similar vibration levels would have similar damages, barring any other differences. This was not usually the case. The companion houses of Boettcher/Ogg, Christensen/Klausmier/Board, and Harris/Deutsch/Halwes illustrate this point. The Boettcher/Ogg pair is the clearest example since they both have partial basements. This is not the case in the other companion houses.

Existing Damage Criteria - Siskind and others (1990) contains the figure that is shown as Figure 30 in this report. The current BOM safe-blasting peak-particle velocity (PPV) envelope is shown in the plot along with data used to establish the envelope. Two things should be noted in the figure: (1) there is a lot of scatter in the data and (2) the threshold damages (the data, not the envelope for safe PPV) are approaching the PPV levels estimated by Eltschlager and Michael (draft, 1993). While it is believed that much of the damage can be explained by soils problems (discussed later) for the major damage, it is not so certain about the lesser damage (such as hairline cracks), which appears to be similar to that found in the threshold damage category.

While there are problems with using peak-particle velocities to monitor blasting, as long as the guidelines are estabiashed (or calibrated) based on structures that are in the area being monitored, the approach should be reasonably satisfactory. If structural types are different from those used for the basic calibration, accuracy will suffer.

Building Natural Frequency and Site Frequency - The houses which had their natural frequencies and the site frequencies measured have been tabulated in Table 10. There is a clear overlap of the two frequencies. When this occurs, vibrations will be more noticeable. It does not necessarily mean that if the vibrations are more noticeable that there will be more damage. The match between building and site frequencies are close in most instances (within 30 percent for Harris, Fink, Zinn, Osborn, Boettcher, Richey, and Christensen). Two of the houses (Fink and Christensen) had natural frequencies that were within 10 percent of the site frequencies. Vibrations at these locations would probably be more noticeable than the others. The Fink and Harris houses also show structural amplification.

Sediment Transport - In reviewing the soil profiles in Table 11, there is a correlation of damage with the presence of loess. Evidence of water flow through the soil and erosion by soil movement (sediment transport) was present at the Fink and Boettcher house. This is referred to as soil flow in this report, whether referring to sediment transport on the surface or through the mass of material. When soil flow occurs through the material, the resulting erosion is similar to piping. In the Fink case there was clear evidence of undermining the foundation walls. At the Boettcher house, there was also clear evidence of soil flow on the surface but the evidence of undermining is more subjective. However, the apparent downward movement of the basement wing of the house is consistent with removal of subsurface material. There also appears to be movement of soil through one wall of the McCutchan house.

Expansive soil - As stated earlier, Hadala and Peterson found that the correlation between bowed-in walls and expansive clay at depths shallower than the bottom of the wall was not high. The expansive soil is generally too deep in the profile to produce severe wall loads. Hadala (March 18, 1993) later indicated he did believe there was a correlation of severe damage with the presence of expansive clay anywhere in the soil profile. While this correlation does appear to exist, it is thought to be more a statistical correlation than a physical relationship. The sediment transport mechanism seems to provide more of a physical explanation of much of the most severe damage. It is also believed that this mechanism would take a longer time to occur than expansive soil damage and thus would seem to be more consistent with the time of damage mentioned by most complainants.

Slope Movement - The spreading deformation of the basement floor slabs at the McCutchan and Kinney houses suggests possible slope movement. The results of level loop surveys done by Siskind and others (1990) also suggests this possibility.

Time of Initial Damage - Some of the damages occurred prior to the period of cast blasting. Damages in the Boettcher house started in the 1950's. There were claims of damage at the Richey house as early as 1985. The Zimmerman house had damages around 1985 that resembled those present during inspection in 1991. There was at least some damage at the Harris house that occurred prior to the painting that was done before the house was purchased by the Harris family.

Continuing Damage - A number of the owners indicated that damage is continuing. Mrs. Harris, through her record keeping provided some documentation. One crack extension was observed during the 1990 BOM study.

Construction Features - The simpler shaped houses with a crawl space (usually Category 2 houses), had less damage than more complex-shaped houses with basements. Some of the houses have gone through one or more structural modifications, such the Richey and the Harris houses. The inspections and the soils information, suggest that houses with crawl spaces are less susceptible to the soil flow phenomenon believed to be responsible for the most severe damages.

Conclusions - With the evidence currently available it is believed the root cause of the severe damage is related to soils, primarily soil flow and slope movement. There is clear evidence that water flows through the soil and that the soil flows. This does not explain all damages and in some cases it only suggests an alternative cause.

It is not believed that the vibration levels that occurred in the McCutchanville-Daylight area were large enough to explain the most severe damage observed without some other contributing factors. Even if the historical data for severe damage were in error by as a factor of two (for example) it would not explain the severe damages. However, it is not clear if the hairline crack type of damage was or was not caused by blasting, since many structures may have this type of cracking from normal conditions. The PPV amplitudes estimated by Eltschlager and Michael (1990) may have been sufficient, considering the scatter of data, for this type of damage to occur. Particularly if site response and resonance effects are considered.

It is also possible that pre-existing conditions, related to soil problems, caused high stress levels in the houses. Blasting stresses superimposed on top of these could have been the "straw that broke the camel's back". The same argument could be made that the 1987 earthquake might have done the same thing. However, this is not as consistent with damage claims and with some evidence of continuing damage.

SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate, document, and if possible suggest the causes of observed building damage in the McCutchanville-Daylight area near Evansville, Indiana. Several Federal agencies (USGS, WES, BOM) are involved in the study. This USGS report is based on three main areas of investigation: (1) a review and assessment of the effects of historical seismicity on the Evansville area and the potential for damaging earthquake ground motion in the future, (2) ground motion and soil investigation of the observed damage area to attempt to quantify the cause of the damage, and (3) an assessment of the observed damage based on field investigations. The following conclusions summarize our findings. These conclusions are based on the USGS portion of the investigation and portions of the BOM, OSM, and WES studies as noted. It is important to recognize that the USGS portion of the study did not include structural analysis of the houses and that the results of the analytical studies done by WES were not available at the time of the final writing of this report.

Fifty-two houses were inspected for damages. Thirty-three houses were located in the McCutchanville-Daylight area and nineteen were located in an area remote from the blasting. The nineteen remote area houses were used as a control group and established a non-blast-related level of damage. The thirty-three houses located in McCutchanville-Daylight consisted of thirteen houses in which the owners believed damage was caused by blasting and twenty companion houses in which the owners did not claim blast-related damage. All of the owners of the houses inspected in the McCutchanville-Daylight area reported feeling blasts. The damages in the twenty non-complainant houses was, for the most part, similar to that in the remote area. The damage in many of the thirteen complainant houses was more than what would be expected in a house due to normal use and aging.

EARTHQUAKES - The known levels of ground shaking in Evansville during the 1968 and 1987 earthquakes could have caused damage consistent with the observed damage to houses in existence at the times of these earthquakes, but this cannot be confirmed with the present data base. It is recognized that these dates precede the period in which the homeowners believe much of their damage occurred. It is also possible that other small earthquakes near the study area may have occurred, but were not officially noted by the federal and state seismic networks.

ATTENUATION - The attenuation functions that were derived indicate that the transmission of the blast-induced ground-vibration energy to the study area did not produce a high ground-motion anomaly in the study area.

TOPOGRAPHIC AND SITE-RESPONSE EFFECTS - In this study the effects of topography on the induced ground motion must be considered along with the site-response study. In general, the topographic study suggests an amplification of the peak-particle ground motion in the upland areas compared to the lowland areas. However, the site response study at some of the same sites evaluated for topographic effects show that the site response due to the soil column is greater than the topographic response.

SITE TESTS - The bore-hole test results did not show any significant thickness of material that have low shear-wave velocities. Therefore, none of the test holes indicate an anomalous subsurface condition that would cause an area of unusual high ground response.

SITE COMPARISONS - The ground motion comparison study between complainant and non-complainant sites shows that the induced ground motions at all paired sites except two agree in maximum peak-particle velocity within 30 percent.

BUILDING RESPONSE - Testing of the natural frequencies of the houses indicates that the houses are sensitive to frequencies within the 5.6 to 10.5 Hz bandwidth. In general, when comparison houses were available, the natural frequencies of the non-complainant house was not significantly different than that of the complainant houses. It is important to note that the range of site frequencies is similar to the range of natural frequencies of the houses. The houses with frequencies that are particularly close to the site frequencies are the Fink and Christensen houses. These houses may be especially susceptible to resonance conditions.

GROUND-VIBRATION LEVELS - It must be noted that the blast induced vibration amplitudes documented in the test area during this USGS study were too low to cause discernable damage. However, an OSM study of ground vibrations found levels that could, when considered in conjunction with site response and resonance effects have caused minor cracking. This damage would not have appeared much different than that observed in the remote area.

BUILDINGS INSPECTED - Thirteen Category 1, twenty Category 2, and nineteen Category 3 buildings were inspected. Damage was found in all three categories of houses but the damage to Category 1 houses (complainant houses in the McCutchanville-Daylight area) was more severe. In Category 1, many of the structures that were severely damaged had companions with little or no damage. A few of the houses in Category 2 had damage that was as severe as some of the structures in Category 1.

The presence of some damage is not unusual even in the Category 3 structures. However, with one exception which had a known cause of faulty construction, none of the damage was as severe as the damage to most of the structures in Category 1.

CAUSE OF DAMAGE - With the evidence currently available it is believed the root cause of the severe damage is related to soils, primarily soil flow and slope movement. There is clear evidence that water flows through the soil and that the soil flows. This mechanism can account for differential settlement, slope movement, and undermining.

It is not believed that the vibration levels that occurred in the McCutchanville-Daylight area were large enough to explain the most severe damage observed without some other contributing factors. It is possible that pre-existing conditions related to soil problems caused high stress levels in the houses. Blasting stresses superimposed on top of these could have been the "straw that broke the camel's back".

Damage in the slight-to-moderate category is more difficult to assess since the appearance of such damage is similar to that caused by normal wear and tear such as that caused by temperature and humidity changes. Vibration is a more likely candidate in those houses where the site frequency is a close match with the natural frequency of the house.

The damage in the Christensen house most closely resembles that caused by vibration, both in appearance and severity. This house natural frequency is also close to the site frequency. This judgement is complicated by the fact that the walls in which the most severe damage is present are supported by floor joists which have some support problems. Actual vibration levels and detailed structural calculations would clarify the evaluation.

BLASTING CRITERIA - It was not the purpose of this study to review blasting criteria. However, a few comments are made here on two matters that came up several times during this investigation.

(1) *Vibration Monitoring* - While there are limitations with using peak-particle velocities (as compared to the more sophisticated response spectral velocity) to monitor blasting effects on structures, as long as the guidelines are established based on structures that are in the area being monitored, the approach should be satisfactory, as long as adequate consideration is given to potential scatter in data.

(2) *Vibration Annoyance* - As stated earlier, it is not believed that the vibration levels that occurred in the McCutchanville-Daylight area were large enough to explain the most severe damage observed without some other contributing factors. However, most owners of Category 1 houses do associate their damage with the cast blasting, which they considered more noticeable than other types. All of the homeowners of the houses inspected in Categories 1 and 2 said they felt the blasting, with some Category 1 owners describing it as severe. Even some homeowners in Category 2 houses described the blasting during the cast-blasting period as severe, both in frequency of occurrence and amplitude, in spite of the fact that they did not believe they had blast-related damage. This suggests that there should be consideration of including requirements related to human perception, as well as damage levels, in establishing blasting criteria.

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I Not felt--or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy, or heavily loaded trucks. Sensation like heavy body striking building, or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V Felt indoors by practically all, outdoors by many or most; outdoors direction estimated. Awakened many, or most. Frightened few--slight excitement, a few ran outdoors. Building trembled throughout. Broke dishes, glassware, to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instance, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

VI Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks, chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.

VII Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amount charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes,embankments, often for long distances. Few, if any (masonry), structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earth completely out of service.

XII Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfall, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward in the air.

Table 1. Modified Mercalli Scale of 1931.

Year	Date-Time (GMT)			Lat °N	Long °W	Mag[1]	Ref[1]		MM I_o[2]	Ref[3]	Dist km	Epicentral location		MMI at Evansville	References[4]
1811	*12*	*16*	*08:15*	*35.400*	*90.400*	*7.20*	*FA*	*NU*	*11*	*SRA*	*382*	*AR*	*New Madrid, Mo.*	*Evansville in VII area.*	*Street, 1981*
1811	*12*	*16*	*14:15*	*35.400*	*90.400*	*7.00*	*FA*	*NU*	*11*	*SRA*	*382*	*AR*	*New Madrid, Mo.*	*Evansville in VII area.*	*Street, 1981*
1812	*01*	*23*	*15:00*	*36.300*	*89.600*	*7.10*	*FA*	*NU*	*11*	*SRA*	*259*	*MO*	*New Madrid, Mo.*	*Evansville in VII area.*	*Street, 1981*
1812	*02*	*07*	*09:45*	*36.500*	*89.600*	*7.30*	*FA*	*BAR*	*11*	*SRA*	*244*	*MO*	*New Madrid, Mo.*	*Evansville in VIII area.*	*Street, 1981*
1827	07	05	11:30	38.000	87.500	5.00	FA	SG	6	SRA	6	IN	New Harmony	Evansville in IV–VI area.	Street and Green, 1984
1838	06	09	14:45	38.500	89.000	-	-	-	7	SRA	139	MO	Saint Louis	Evansville in IV–VII area.	Street and Green, 1984
1843	01	05	02:45	35.500	90.500	6.00	FA	FAR	8[5]	SRA		AR	N.E. Arkansas	Evansville in V area.	*Hopper, ed., 1985*
1857	10	08	10:00	38.700	89.200	5.30	FA	BAR	7	SRA	165	IL	Centralia	IV. a slight shock. A few awakened but generally unnoticed.	Street and Green, 1984
1865	08	17	15:00	36.000	89.500	5.30	FA	BAR	7	SRA	279	TN	Memphis	Evansville outside felt area.	Street and Green, 1984
1876	09	25	06:00	38.500	87.800	4.70	FA	BAR	6	SRA	62	IL	Friendsville	No information on Evansville.	Docekal, 1970
1876	09	25	06:15	38.500	87.700	4.70	FA	BAR	7	SRA	60	IN	Vincennes	V–VI. Awakened, alarmed people all over town, some ran into streets. [V]	Street and Green, 1984
1883	01	11	07:12	37.000	89.200	4.70	FA	SG	6	SRA	181	KY	Paducah	III. Felt by many.	Street and Green, 1984
1883	04	12	08:30	37.000	89.200	-	-	BAR	6	SRA	181	IL	Cairo	No information on Evansville.	Docekal, 1970
1886	09	01	02:51	32.900	80.000	7.02	Mw	BOL	10	SRA	887	SC	Charleston	Evansville in IV area.	Bollinger, 1977
1887	02	06	22:15	38.700	87.500	4.70	FA	BAR	6	SRA	81	IN	Vincennes	V. Two distinct shocks. Lasted about 10 sec. So violent as to awaken soundest sleepers.	Street and Green, 1984
1887	08	02	18:36	37.200	88.500	5.20	FA	SG	6	SRA	119	IN	Jasper, Ind.; Mill Creek, Ill., Russellville, Ky.	IV–V. Slight. Windows and doors rattled. People went into the streets.	Street and Green, 1984
1891	*07*	*27*	*02:28*	*37.900*	*87.500*	*4.00*	*FA*	*SG*	*6*	*SRA*	*9*	*IN*	*Evansville*	*VI–VII. Alarmed everyone. People fled to street. Dishes and lights broken, furniture overturned all over the city. One wall in a hotel collapsed.*	*Street and Green, 1984*
1891	09	27	04:55	38.250	88.500	5.50	FA	SG	7	SRA	88	IL	Mount Vernon	V. Alarmed entire city.	Street and Green, 1984
1895	10	31	11:08	37.000	89.400	6.20	FA	BAR	9	SRA	195	MO	Charleston	V. Alarmed entire city.	Street and Green, 1984

Table 2. Effects of Historical Earthquakes at Evansville, Indiana (37.97°N, 87.56°W). Earthquakes in italics may have caused damage (MMI ≥VI) at Evansville. The 1968 and 1987 earthquakes affecting Evansville have been shown shaded.

Year	Date-Time (GMT)			Lat °N	Long °W	Mag[1]	Ref[1]		MM I_o[2]	Ref[3]	Dist km	Epicentral location		MMI at Evansville	References[4]
1899	04	30	02:05	38.500	87.400	4.50	FA	SG	7	SRA	60	IN	Greencastle, Princeton, Vincennes	VI. Hundreds ran from their homes but no damage was done.	Street and Green, 1984
1903	02	27	00:21	37.800	89.300	4.80	FA	BAR	7	SRA	154	IL	Carterville, Grand Towers, Murphysboro	IV–V. Badly frightened some.	Street and Green, 1984
1903	11	04	19:14	36.500	89.800	4.80	FA	SG	7	SRA	257	MO	New Madrid	III. A slight shock was felt.	Street and Green, 1984
1905	08	22	05:08	37.200	89.300	4.80	FA		6	SRA	176	IL	Cairo	IV–V. Felt perceptibly all over the city.	Street and Green, 1984
1909	09		09:45	39.800	87.200	5.40	FA	SG	7	SRA	206	IN	Covington, Princeton	V. Pictures swayed on walls, houses creaked.	Street and Green, 1984
1917	04	09	20:52	38.100	90.200	5.00	FA	BAR	7	SRA	232	MO	DeSoto	III. Felt a vibration for 8 seconds.	Street and Green, 1984
1921	03	14	12:15	39.500	87.500	4.50	FA	SG	6	SRA	170	IN	Terre Haute	Felt.	Street and Green, 1984
1922	03	22	22:29	37.400	89.400	4.20	FA	SG	7	SRA	174	MO	Illmo	Evansville outside felt area.	Street and Green, 1984
1922	03	23	02:20	37.400	89.400	4.50	FA	SG	6	SRA	174	MO	Illmo	IV. Some heard dishes in closets rattle.	Street and Green, 1984
1922	11	27	03:31	37.800	88.500	4.50	FA	BAR	7	SRA	85	IL	El Dorado	V. Slight shocks. Shook windows and dishes. A few pictures fell off walls.	Street and Green, 1984
1925	04	27	04:05	38.200	87.800	4.80	FA	BAR	6	SRA	33	IL	Carmi	V–VI. Lasted 30 sec. Dishes crashed to floor. [V]	Street and Green, 1984
1925	09	02	11:56	37.900	87.200	4.70	FA	SG	6	SRA	33	KY	Henderson, Owensboro	V. Moved furniture.	Street and Green, 1984
1934	08	20	00:47	37.000	89.200	4.30	FA	BAR	7	SRA	181	IL	South Ill.; Rodney, Mo.	Evansville outside felt area.	Neumann, 1936
1937	03	09	05:44	40.470	84.280	4.90	FA	DG	8	SRA	397	OH	Anna	Felt.	Neumann, 1940
1955	04	09	13:01	38.232	89.785	4.30	FA	DG	6	SRA	197	IL	West of Sparta	Evansville outside felt area.	Murphy and Cloud, 1957
1958	11	08	02:41	38.436	88.008	4.40	FA	DG	6	SRA	65	IL	Illinois–Indiana border	V. Dishes, tables and chairs moved. Alarmed many.	Brazee and Cloud, 1960
1962	06	27	01:28	37.700	88.500	5.5	mb	GS	5	PDE	77	IL	South Illinois	Not felt anywhere in Indiana.	Lander and Cloud, 1964
1965	08	14	13:13	37.226	89.307	3.44	Mw	STT	7	SRA	175	IL	Tamms	Local shock at Tamms.	Docekal, 1970

Table 2 continued. Effects of Historical Earthquakes at Evansville, Indiana (37.97°N, 87.56°W). Earthquakes in italics may have caused damage (MMI ≥VI) at Evansville. The 1968 and 1987 earthquakes affecting Evansville have been shown shaded.

Year	Date-Time (GMT)			Lat °N	Long °W	Mag[1]	Ref[1]		MM I_o[2]	Ref[3]	Dist km	Epicentral location		MMI at Evansville	References[4]
1968	*11*	*09*	*17:01*	*37.911*	*88.373*	*5.50*	*Mn*	*SLM*	*7*	*SRA*	*72*	*IL*	*South-central Illinois*	*VI. In Federal Building two ornamental columns dislodged. Four square feet [.4 m²] of plaster fell from third floor ceiling. A chimney fell on an old house. Plaster cracked and broke throughout the city. On an old church building bricks loosened and a wall threatened to collapse.*	*Coffman and Cloud, 1970*
1974	04	03	23:05	38.549	88.072	4.36	Mw	STT	6	SRA	78	IL	South Illinois	V.	Coffman and Stover, 1976
1977	01	03	22:56	37.583	89.714	3.60	Mn	DG	6	SRA	195	MO	Cape Girardeau	No information on Evansville.	Coffman and Stover, 1979
1983	05	15	05:16	38.770	89.570	4.40	Mn	GS	6	GS	197	IL	South Illinois	II.	Stover, 1987
1984	06	29	07:58	37.700	88.470	4.10	Mn	GS	6	SRA	86	IL	South Illinois	No information on Evansville.	Stover, 1988
1987	*06*	*10*	*23:48*	*38.713*	*87.954*	*5.10*	*Mn*	*SLM*	*6*	*GS*	*89*	*IL*	*Illinois*	*VI. Chimneys, sidewalks, and streets were cracked. A few items shaken off store shelves.*	*U.S. Geological Survey, unpub. data, Oct., 1991*
1990	09	26	13:18	37.165	89.577	4.80	Mn	BLA	6	GS	199	MO	Cape Girardeau region	V. A few knicknacks broken.	U.S. Geological Survey, unpub. data, Oct., 1991

1 FA Magnitude from felt area.
Mw Moment magnitude (N-m) by formula of Hanks and Kanamori (1979).
Mn M_n magnitude from Nuttli (1973b).
Ms M_s magnitude from Bath (1966) or Gutenberg (1945).
mb m_b magnitude from Gutenberg and Richter (1956).
NU Computed according to Nuttli, 1973a.
BAR Computed according to Barstow and others, 1981.
SG Computed according to Street and Green, 1984.
BOL Computed according to Bollinger, 1986.
DG Computed according to Dewey and Gordon, 1984.
STT Computed according to Street and others, 1975.
HRN Computed according to Herrmann, 1979.
SLM Computed according to Saint Louis University, Saint Louis, Mo.
GS Computed according to National Earthquake Information Center, U.S. Geological Survey (and predecessor agencies), Golden, Colo.
BRK Computed according to Seismological Station, University of California, Berkeley, Calif.
BLA Computed according to Virginia Polytechnic Inst. and State University, Blacksburg, Va.

2 The intensity listed from the SRA and PDE catalogs is the maximum intensity reported on land, in the United States. In the central United States this is usually the same as the maximum intensity, MMI_o, assigned for the earthquake.

3 Reference for the information in all columns to the left of this column
SRA National Earthquake Information Center (NEIC), Earthquake Data Base System (EDBS), computer files of the State Seismicity File. The SRA catalog contains magnitudes ≥2.5 and is current through 1985.
PDE National Earthquake Information Center (NEIC), Earthquake Data Base System (EDBS), computer files of the Preliminary Determination of Epicenters listings published by the National Earthquake Information Service (NEIS). Searched from 1986 to present.

4 Reference for the epicentral location and *MMI* at Carbondale.

5 SRA's maximum MMI_o of VII for this earthquake has been changed to VIII as in Nuttli, 1981.

Region included:

$MMI_o \geq$ VI	within 200 km of Evansville	$MMI_o \geq$ VII	within 300 km of Evansville
$MMI_o \geq$ VIII	within 450 km of Evansville	$MMI_o \geq$ IX	within 650 km of Evansville
$MMI_o \geq$ X	within 950 km of Evansville	$MMI_o \geq$ XI	within 1400 km of Evansville

Table 2 continued. Effects of Historical Earthquakes at Evansville, Indiana (37.97°N, 87.56°W). Earthquakes in italics may have caused damage (MMI ≥VI) at Evansville. The 1968 and 1987 earthquakes affecting Evansville have been shown shaded.

SITE CAT.[1]	SITE NAME	SITE CODE	OSM I.D.	ADDRESS	ARRAY NUMBER [2]							
					1	2	3	4	5	6	C	f
1	Kinney	KIN	114	8915 Baumgart Rd.					5		C	f
2	Wolff	WOF	114A	9001 Baumgart					5		C	f
1	McCutchan	MCC	108	9435 Baumgart Rd.			3		5		C	f
2	Zinn	ZIN	108A	9455 Baumgart Rd.								f
2	Arnold	ARN		9325 Baumgart Rd.			3		5		C	
1	Effinger	EFF	201	1624 Swope Lane					5			f
	No Companion											
1	Harris	FRI	107	8304 Whetstone				4	5		C	f
1	Harris	FRA	107	Attic of Harris house								f
2	Deutsch	EDD	107A	2271 Maple Lane							C	f
2	Halwes	HAL		2200 Maple Lane							C	f
1	Fink	FIN	301	9120 Petersburg Rd.					5		C	f
1	Fink	FIA	301	Attic of Fink house								f
2	Condict	CON	301A	9200 Petersburg Rd.							C	
1	Greenfield,	GRE	302	8010 Petersburg Rd.			3		5			f
2	Palmer	PAL	302A	8101 Petersburg Rd.								
1	Boettcher	BOE	113	8216 Petersburg Rd.								f
2	Ogg	OGG	113A	8219 Petersburg Rd.								f
2	Lavallo	LAV		8416 Petersburg Rd.								
1	Gorbett	GOR	316	11345 Browning Rd.								
	No Companion											
1	Hoover	HOO	118	2225 Kansas Rd.								
	No Companion											
1	Zimmerman	ZIM	103	10991 N. Green River Rd.								f
2	Shelton	SHE	103A	10801 N. Green River Rd.								
2	Daugherty	DAU		10901 N. Green River Rd.								
1	Norton	NOR	104	13145 N. Green River Rd.								f
2	LeCocq	LEC		13421 N. Green River Rd.								

Table 3. Station and inspection site locations.

SITE CAT.[1]	SITE NAME	SITE CODE	OSM I.D.	ADDRESS	ARRAY NUMBER [2]							
					1	2	3	4	5	6	C	f
1	Bohrer	BOH	105	4949 Daylight							C	f
2	Miller	MIL		5101 Daylight							C	
1	Osborne	OSB	421	2400 Schlensker Rd.							C	f
2	Rozanski	ROZ	421A	2530 Schlensker Rd.							C	f
1	Richey	RIC	202	15101 Cemetery Rd.								f
2	Stevens	STE	202A	15045 Cemetery Rd.								
2	Heil	HEL		15056 Cemetery Rd.								f
1	Christensen	CHR	115	Route 3, Box 257 Baseline Rd.								f
2	Klausmeir	KLA	115A	6604 Baseline Rd.								
2	Board	BOA		6616 Baseline Rd.								
	Wayman	WAY		8300 Petersburg Rd.								f
	Engelhardt	ENG		10150 N. Green River Rd.						6		
	Cox	COX		9202 Petersburg							C	
	Rock Site	COR		On Cox property, see Figure 12	1				5			
	Valley Site	AIR		Northeast end of airport, see Figure 15				4				
	Rock Site	GER		On Summer Hill Drive, see Figure 12	1					6		
	HADI Shrine Temple	HAD		On OASIS property of Hadi Shrine Temple, Evansville Industrial Park, see figure 15		2				6		
	Stahl	STA		5416 Kansas Road, see Figure 15		2				6		
	Valley Site	HEI		1820 Heinlin Road, see Figure 15			3					

1 Locations listed for Site Category 1 or 2 were all inspected for building damage.
2 Stations listed as Array Number1 were used to evaluate attenuation.
Stations listed as Array Numbers 2, 3, and 4 were used to evaluate topographic effects.
Stations listed as Array Numbers 5 and 6 were used to evaluate site response effects.
Stations listed as Number C were used to compare companion sites.
Stations listed as Number f were used to measure natural frequency of buildings and for structural amplification.

Table 3 continued. Station and inspection site locations.

EVENTS[1]	STATIONS[2]										
mo/day - hr:min	FRI	FRA	AIR	EDD	CON	HAL	COR	COX	FIN	FIA	GRE
10/21 - 25[3]	X										X
10/31 - 11/11[3]	X										
11/13 12:10	X	X	X								
11/15 08:25	X	X	X	X							
11/16 13:00	4.8	4.8	4.7	4.8		4.8	4.6				
11/16 13:12	4.7	4.7	4.7	4.8		4.7	4.6				
11/16 13:24	4.6		4.6			4.7	4.5				
11/18 08:45	X		X				X	X	X	X	
11/19 03:28							X	X	X	X	
11/19 11:02	4.6				4.53		4.4	4.5			
11/19 11:10	4.6				4.5		4.4	4.44			
11/19 13:25							X	X			
mo/day - hr:min	COR	MCC	ARN	KIN	WOF	HEI	EFF	MIL	BOH	ZIN	GRE
11/21 13:21	4.3	4.8	4.9	5.1	5.0	5.1	5.2				5.0
11/22 11:36								1.4	1.6	4.5	
11/22 11:45								X	X	X	
11/22 13:15								X	X		
mo/day - hr:min	COR	ROS	OSB					MIL	BOH		
11/26 15:46		X	X								
11/27 14:12	5.3	3.2	3.3					2.5	2.6		
11/27 14:23	5.3		3.3					2.4	2.5		
11/27 14:34	5.3	3.2	3.3					2.4	2.5		
11/27 16:29	X	X	X					X	X		
11/30 13:23			3.3					2.4	2.4		
12/03 09:37			X					X			
12/04 13:35			3.2					2.3	2.4		
12/04 16:25			X					X			
12/05 16:20			X					X	X		
12/06 10:21			X					X	X		
12/06 16:29			X					X	X		
12/07 10:09			X					X	X		
mo/day - hr:min	COR	GER	ENG	HAD	STA						
12/13 10:51	X	X	X	X	X						
12/13 10:58				X	X						

[1] Unless otherwise indicated, numbers designate the month/day-hour:min (military time). All dates are in 1991.
[2] Numbers are distance in miles to the source. X = distance not scaled.
[3] Numbers indicate the range of days over which an event was recorded. The specific day, hour, and minute are not available.

Table 4. Station recording times.

STATION CODE	ELEV. (feet)	DIST. (km)	PEAK-PARTICLE VELOCITY RATIO [1, 2]			HORIZONTAL SPECTRAL RATIO [3]	
			Vertical Component	Horizontal North-South Component	Horizontal East-West Component	Ratio[1]	Frequency Range, Hz
ARRAY NO. 2							
STA	380	4.1	Valley Reference Site			Valley Reference Site	
HAD	510	4.1	2.5	1.6	2.5	3.4	10 - 12
						2.5	6 - 8
ARRAY NO. 3							
HEI	390	8.2	Valley Reference Site			Valley Reference Site	
GRE	465	8.0	(1.2)	(1.2)	(1.2)	3.6	6 - 8
MCC	440	7.7	(1.7)	(1.3)	(1.3)	2.1	6 - 8
ARN	480	7.9	(2.1)	(1.4)	(1.4)	2.5	4 - 6
ARRAY NO. 4							
AIR	410	7.4	Valley Reference Site			Valley Reference Site	
FRI	465	7.4	2.1	1.5	2.5	3.2	16 - 18
						2.1	4 - 6

[1] Ratios are relative to the appropriate valley reference site.
[2] Numbers in ( ) have been corrected by the distance attenuation factor.
[3] Spectral ratios are based on the average of the two horizontal components prior to computing the ratio. Spectral ratios are not corrected for the slight differences in distance to mine blasts.

Table 5. Summary of topographic data.

STATION CODE	ELEV. (feet)	DIST. (km)	PEAK-PARTICLE VELOCITY RATIO [1, 2]			HORIZONTAL SPECTRAL RATIO [3]	
			Vertical Component	Horizontal North-South Component	Horizontal East-West Component	Ratio[1]	Frequency Range, Hz
ARRAY NO. 5							
COR	490	7.0	Rock Reference Site			Rock Reference Site	
GRE	465	8.0	(1.3)	(3.4)	(3.5)	6.7	6 - 8
WOF	430	8.0	(1.3)	(3.2)	(3.0)	3.3	6 - 8
KIN	425	8.2	(1.4)	(3.0)	(3.3)	3.3	6 - 8
MCC	440	7.7	(1.2)	(2.6)	(3.7)	4.3	6 - 8
ARN	480	7.9	(1.3)	(3.4)	(3.8)	4.1	6 - 8
EFF	435	8.3	(1.4)	(3.7)	(3.2)	4.7	6 - 8
FRI	465	7.1	(1.0)	(2.6)	(2.6)	5.0	8 - 10
FIN	470	7.1	(0.9)	(1.3)	(2.1)	9.2	8 - 10
ARRAY NO. 6							
GER	520	4.1	Rock Reference Site			Rock Reference Site	
STA	380	4.1	0.4	1.6	0.9	2.2	5, 13
ENG	395	4.1	1.2	1.6	1.7	4.9	12 - 14
HAD	510	4.1	1.1	2.6	2.3	6.8	12 - 14

[1] Ratios are relative to the appropriate rock reference site.
[2] Numbers in ( ) have been corrected by the distance attenuation factor.
[3] Spectral ratios are based on the average of the two horizontal components prior to computing the ratio. Spectral ratios are not corrected for the slight differences in distance to mine blasts.

Table 6. Summary of site response data.

Site name	Code	Bore - hole Depth, m	Average Shear Wave Velocity, m/s	1 m - Depth Shear Wave Velocity, m/s	3 m - Depth Shear Wave Velocity, m/s	Soil Natural Frequency , Hz
Zinn	ZIN	9.6	250	160	194	6.9
McCutchean	MCC	13.0	263	187	197	5.1
Fink	FIN	10.2	210	122	147	5.8
Effinger	EFF	14.4	303	173	219	5.4
Harris	FRI	13.4	266	166	194	5.1
Greenfield	GRE	11.4	238	169	238	5.4
Boettcher	BOE	8.0	202	158	202	6.4
Hadi Oasis	HAD	5.3	165	155	190	8.3
Stahl	STA	17.5	318	116	118	4.8
Zimmerman	ZIM	9.9	227	143	133	5.9
Christensen	CHR	6.8	188	164	158	7.2
Osborne	OSB	7.3	207	167	187	8.6
Richey	RIC	6.6	189	184	180	7.3

Table 7. Bore-hole shear wave data.

SITE CATEGORY - SITE CODE	OWNER	ADDRESS	PEAK PARTICLE VELOCITY RATIO Category 1 Site/Reference Site		
			Vertical	Horizontal North-South	Horizontal East-West
1 - FRI	Harris	8304 Whetstone Rd.	1.2	1.1	1.1
2 - HAL	Halwes	2200 Maple Lane	Reference Site		
1 - FRI	Harris	8304 Whetstone Rd.	0.9	0.7	1.5
1 - EDD	Deutsch	2271 Maple Lane	Reference Site		
1 - FIN	Fink	9120 Old Petersburg Rd.	1.3	1.6	1.2
2 - CON	Condict	9200 Old Petersburg Rd.	Reference Site		
1 - MCC	McCutchen	9435 Baumgart Rd.	Data Not Available		
2 - ZIN	Zinn	9455 Baumgart Rd.	Data Not Available		
1 - MCC	McCutchen	9435 Baumgart Rd.	0.7	0.7	1.0
2 - ARN	Arnold	9325 Baumgart Rd.	Reference Site		
1 - OSB	Osborn	2400 Schlensker Rd.	0.9	1.1	0.9
2 - ROS	Rozanski	2530 Schlensker Rd.	Reference Site		
1 - KIN	Kinney	8915 Baumgart Rd.	1.0	0.9	1.3
2 - WOF	Wof	9001 Baumgart Rd.	Reference Site		
1 - BOH	Bohrer	4949 Daylight Dr.	1.1	0.9	1.0
2 - MIL	Miller	5101 Daylight Dr.	Reference Site		

Table 8. Comparisons of Site Category 1 and 2 buildings. Category 1 (complainant) sites are shown shaded.

SITE CATEGORY - SITE CODE	OWNER	ADDRESS	BUILDING NATURAL FREQUENCY, Hz	
			Short Axis	Long Axis
1 - FRI	Harris	8304 Whetstone Rd.	7.1	7.2
2 - HAL	Halwes	2200 Maple Lane	7.3	9.8
1 - FRI	Harris	8304 Whetstone Rd.	7.1	7.2
1 - EDD	Deutsch	2271 Maple Lane	9.3	13.8
1 - FIN	Fink	9120 Old Petersburg	5.6	6.5
2 - CON	Condict	9200 Old Petersburg	No Data	No Data
1 - MCC	McCutchen	9435 Baumgart Rd.	9.7	No Data
2 - ZIN	Zinn	9455 Baumgart Rd.	8.3	14.6
1 - MCC	McCutchen	9435 Baumgart Rd.	9.7	No Data
2 - ARN	Arnold	9325 Baumgart Rd.	8.9	No Data
1 - OSB	Osborn	2400 Schlensker Rd.	10.5	14.5
2 - ROS	Rozanski	2530 Schlensker Rd.	8.6	No Data
1 - KIN	Kinney	8915 Baumgart Rd.	6.2	7.8
2 - WOF	Wof	9001 Baumgart Rd.	8.6	16.5
1 - BOH	Bohrer	4949 Daylight Dr.	7.6	10.1
2 - MIL	Miller	5101 Daylight Dr.	No Data	No Data
1 - BOE	Boettcher	8216 Petersburg Rd	7.2	8.6
2 - OGG	Ogg	8219 Petersburg Rd.	8.6	No Data
1 - RIC	Richey	15101 Cemetary Rd.	6.6	No Data
2 - HEL	Heil	15050 Cemetary Rd	7.9	8.6
1 - NOR	Norton	13145 N. Green River	9.3	8.6
1 - EFF	Effinger	1624 Swope Lane	8.7	9.9
1 - GRE	Greenfield	8010 Petersburg Rd.	9.3	13.6
1 - ZIM	Zimmerman	10991 N. Green River	9.9	No Data
1 - CHR	Christensen	257 Baseline Rd.	6.8	No Data
2 - WAY	Wayman	8300 Petersburg Rd.	8.9	No Data

Table 9. Comparison of housing sites and building response tests. Where companion data are available, the Category 1 building is shown shaded.

SITE CATEGORY - SITE CODE	OWNER	SITE FREQUENCY Hz	BUILDING NATURAL FREQUENCY, Hz	
			Short Axis	Long Axis
1 - FRI	Harris	5.1	7.1	7.2
1 - FIN	Fink	5.8	5.6	6.5
1 - MCC	McCutchen	5.1	9.7	No Data
2 - ZIN	Zinn	6.9	8.3	14.6
1 - OSB	Osborn	8.6	10.5	14.5
1 - BOE-	Boettcher	6.4	7.2	8.6
1 RIC	Richey	7.3	6.6	No Data
1 - EFF	Effinger	5.4	8.7	9.9
1 - GRE	Greenfield	5.4	9.3	13.6
1 - ZIM	Zimmerman	5.9	9.9	No Data
1 - CHR	Christensen	7.2	6.8	No Data

Table 10. Comparison of natural frequencies for sites and buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 McCutchan 9435 Baumgart Rd. MCC/108	Built in 1967 One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Numerous wide cracks in veneer, with some displacement of brick in the walls. Foundation - Stair step cracks visible in walls. Severe crack running full length of basement slab. Interior - Nail pops and hairline cracks in wallboard in the first story.	BORING 108 0-4 ft B horizon and loess 4-5 ft colluvium 5-9 ft weathered shale, expansive- 2.5 tons/sqft >10 ft firm shale a. Large velocity mismatch at 13 ft (compressional), 4 ft, 9 ft (shear wave). b. The colluvium may be the source of water permeability c. The weathered shale shows slickensides d. Foundation is probably in weathered shale. e. One corner of foundation could be on firm shale (uphill side).
2 Zinn 9455 Baumgart Rd. ZIN/108A	Built in 1972. One-story wood frame with all brick veneer. Drywall finish. Partial crawl space and concrete slab. Unreinforced concrete block walls in crawl space.	Exterior - Few hairline cracks. Foundation - None. Interior - Few hairline cracks.	BORING 108A 0-2 ft fill? 2-7 ft B horizon and loess 7-8 ft colluvium 8-10 ft weathered shale - very expansive >10 ft shale a. A velocity change at 13-14 ft (compressional) a shear wave velocity change at 10-11 ft. b. Foundation is probably in the loess.
2 Arnold 9325 Baumgart Rd. ARN	Built in 1940's. One-story wood frame with stone veneer. Plaster on sheet rock finish. Partial basement with crawl space. Unreinforced concrete block walls.	Exterior - One small crack visible in stone wall, which the owner believed appeared in the 1980-89 time period. Foundation - None. Interior - Few small cracks in breakfast room ceiling.	
1 Kinney 8915 Baumgart Rd. KIN/114	Built in 1969. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Cracking on exterior walls. Posts on the front porch are loose sometimes. Evidence of poor drainage is evident around the downspout on the uphill side of house, particularly in corner where considerable damage is present on the inside basement wall of the house. Foundation - Basement slab has a large North-South crack. Block walls have both horizontal and stairstep cracks. Interior - Cracking visible throughout.	
2 Wolff 9001 Baumgart WOF/114A	Built in 1945. One-story wood frame with all stone veneer. Plaster on sheet rock finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Few hairline cracks. Foundation - Few hairline cracks. Interior - Few hairline cracks.	

Table 11. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Fink 9120 Petersburg Rd. FIN/301	Built in 1953 Two-story wood frame with all brick veneer. Plaster on sheet rock finish. Partial basement with walkout and with crawl space Unreinforced concrete block l	Exterior - Diagonal, horizontal, and vertical cracks were present around openings on the south wall. Other cracks were also present on the exterior. The ground showed signs of settlement, particularly around the perimeter of the foundation. The garage slab was severely cracked, being displaced over a foot next to the house. There was no evidence of reinforcement in the garage slab. Foundation - Cracks were present in all walls in the basement. Many ceiling tiles were displaced. The basement was damp and sometimes wet. Examination of the crawl space showed that exterior soil had literally washed into the crawl space. The flow pattern was traceable to the "sink hole" outside the house. Step footings were visible in the crawl space. One such step was located at the "sink hole." There was a vertical crack at the step and the footing appeared to be discontinuous at the step. Bricks supporting a steel beam supporting the upper stories were crushed. This steel beam, which is losing support, lines up with vertical cracks in the veneer outside the house. Interior - Cracks were present in the first and second floor although not severe. The biggest problem seemed to be sliding doors and windows that no longer worked well. There were openings between boards in the hardwood floor. Nails were working their way out of the floor.	BORING 301 0-8.5 ft small B Horizon and loess 8.5-11 ft colluvium, high permeability 11-14 ft weathered shale. >14 ft shale, siltstone. a. A moderate compressional velocity change is located at approximately 8-9 feet and at 11-12 ft. b. No expansive soils were found by the lab tests. c. Foundation is thought to be in the loess. d. It is thought that the shale (14') is an aquatard, the colluvium is the possible "pipe" to carry loess away from the foundation if a source of water can be found.
2 Condict 9200 Petersburg Rd. CON/301A	Built in early 1930's. Two-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement. Unreinforced poured concrete walls.	Exterior - A few cracks were found in the veneer around one window. Foundation - Numerous cracks were present in the basement walls with evidence of moisture penetration from the outside. Interior - A few ceiling and wall cracks were found. There was one crack in a patio floor.	
2 Cox 9202 Petersburg Road COX	Not Inspected		

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Effinger 1624 Swope Lane EFF/201	Built in 1980. One-story wood frame with all brick veneer. Drywall finish. Full basement. Unreinforced concrete block walls.	Exterior - Large horizontal and stairstep cracks are visible near doorways and windows. Foundation - Stairstep cracking present in corners with moisture on the slab in the northwest corner. The slab was also cracked in this corner. The entire north basement wall (about 60 ft) was bowed with cracks present in many of the mortor joints. Although the slab on the ground outside this wall was sloping inwards, possibly providing a path for moisture buildup, the wall did not appear water stained. Interior - Cracks present in walls throughout much of the upstairs. Cracking did not appear as bad as might have been anticipated given the degree of damage observed outside and in the basement.	BORING 201 0-9 ft B horizon and loess 9-11 ft colluvium and expansive (it took 2.1 tons/sf to contain it). 11-14 ft weathered shale, not expansive >14 ft shale a. No large velocity changes in the compressional wave, a possible large velocity change at 9 ft in shear wave. b. Foundation is probably in loess and/or colluvium. c. It is possible that the foundation is on different materials as a 2nd bore hole further away from the foundation showed a greater thickness of weathered shale and less colluvium.
No Companion			
1 Harris 8304 Whetstone FRI/107	Built in 1953 with 2nd story added in 1984. There may have been a modification between these two dates Two-story wood frame with stone veneer. Drywall finish. Partial basement with crawl space. Unreinforced poured concrete in main basement with unreinforced concrete block walls in part of basement and crawl space.	Exterior - Cracks present in mortor joints around the house. Foundation - Cracks are present in the both the poured concrete walls and the block walls of the basement. A few horizontal cracks were noticed in the crawl space area near the location oa an outside downspout. These cracks would have been noticed by an inspector. Stair step cracks visible in workshop walls. The slab was also cracked in this room. Mrs. Harris keeps track of crack growth by marking and dating and dating them. Interior - Cracks were present in many of the walls of the first story as were nail pops. Some were present in second story but to a lesser. degree.	BORING 107 0-7 ft B horizon and loess (nonexpansive clay and silt) 7-8 ft Colluvium. Probably nonexpansive. >8-9 ft Competent shale. a. 14 ft first significant velocity change in compression wave. b. 9 ft velocity change in shear wave velocity. c. No expansive clays at this location were found in the lab tests.--no tests in the 7-9 ft interval. d. Strange gamma log kick at 7 ft. e. Foundation thought to be on different material; that is, the center may be on competent shale where as each end may be located on the colluvium.
2 Deutsch 2271 Maple Lane ED/107A	Built in early 1950's. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Partial basement with crawl space. Unreinforced concrete block walls.	Exterior - Vertical cracks were present in the veneer between the bottom of the windows and top of the basement/crawl space on three sides of the house. On the east face cracks were as wide as 1/4 in. Foundation - None. Interior - One minor crack in the ceiling.	f. Companion house bore hole shows expansive weathered shale 8-12 ft depth which is probably below the foundation level.
2 Halwes 2200 Maple Lane HAL	Built in 1953. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full crawl space. Unreinforced concrete block walls.	Exterior - Two minor cracks below windows on the east and west side of house. A crack was present in the floor slab of a screen porch that was added. Foundation - None. Interior - Few ceiling cracks in the center of the house.	

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Greenfield 8010 Petersburg Rd. GRE/302	Built in 1961. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Partial walkout basement with crawl space. Unreinforced concrete block walls.	Exterior - The area around the north basement shows severe cracking. The owner spoke about depressions in the yard. Foundation - The basement walls had cracks, none were seen in the crawl space. Interior - The owner showed cracks in several rooms. The room on the north side was the most severe. The owner associated some cracks in the kitchen specifically with a blast. He said the house was inspected prior to purchase and the cracks were not there.	BORING 302 0-4 ft B horizon and loess. 4-6 ft weathered shale (no knowledge on expansiveness) 6-9.5 ft clayey shale, borderline expansive. 9.5-11.5 ft very expansive clay. >11.5 ft shale, siltstone, silty shale-unnamed Shelborn (sp) member just below the West Franklin. a. No significate compressional velocity changes in the upper 20 ft. Velocities show constant increase with depth. b. Many vertical (2-3+'deep) water drainage holes found down hill from house and lawn continued to shift level. c. Desiccant of clay, (cracks) is possible mechanism for concentration of ground water flow and erosion of holes. d. Foundation is in/on clay.
2 Palmer 8101 Petersburg Rd. —/302A	Built in 1950's. One-story wood frame with all brick and stone veneer. Plaster on sheet rock finish. Full basement. Unreinforced concrete block walls.	Exterior - Numerous severe stairstep and horizontal cracks were seen around the house. Foundation - Minor cracking was found. Interior - A number of ceiling and wall cracks were found throughout the house.	k. Companion house foundation is probably on shale at 8 ft depth. (The top of an underground storage tank may have been erroneously recorded as shale.)
1 Hoover 2225 Kansas Rd. —/118	Built in 1901 with major modifications. Two-story wood frame with wood siding. Original plaster on wood lath, more recent drywall finish. Partial basement with crawl space. Unreinforced brickwalls.	Exterior - None. Foundation - None. Interior - Hairline cracks the in first and second story walls and ceiling.	
No Companion			
1 Gorbett 11345 Browning Rd. —/316	Built in 1980. Two-story wood frame with all brick veneer. Drywall finish. Full basementwith walkout. Unreinforced concrete block walls.	Exterior - None. Foundation - Minor crack in slab. Interior - Minor crack inthe joint around the fireplace. The owner pointed out that soil had washed out from under the driveway slab on several occasions and that there had been modifications to the drainage to try to prevent this.	
No Companion			

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Boettcher 8216 Petersburg Rd. BOE/113	Built in late 1950's. One-story wood frame with all brick veneer. Plaster on sheet rock finish/wood panelling. Partial walk-out basement with crawl space. Unreinforced concrete block walls.	Exterior - Long, wide cracks were found in the walls of the North-South wing of the L-shaped house. Foundation - Wall cracks and slab cracks were obvious in the basement. This pattern plus the exterior cracks indicate a rotation of this wing East-West wing with respect to the North-South wing. Interior - Rooms were panelled over the basement area of most severe damage. The panelling prevented seeing any interior damages.	BORING 113 0-5 ft B horizon and loess 5-8 ft Colluvium mix 8-9 ft weathered shale, marginal expansive >10 ft competent shale. a. Compressional velocity change at 9+-ft. b. Foundation lower part in loess, upper part on weathered shale.
2 Ogg 8219 Petersburg Rd. OGG/113A	Built in 1949. One-story wood frame with 50%stone veneer. Plaster on sheet rock finish. Partial walkout basement with crawl space. Unreinforced concrete block walls.	Exterior - None Foundation - None. Interior - One small crack was found.	c. Companion house foundation is on shale with slightly expansive weathered shale above.
2 Lavallo 8416 Petersburg Rd.	Built in ?? Two-story wood frame with all brick veneer. Plaster on sheet rock and drywall finish. Full basement. Unreinforced concrete block walls.	Exterior - Cracks were present around openings in the older part of the house Foundation - Basement walls had numerous cracks in the older part of the house. Interior - Hairline cracks were present in the drywall and plaster finish.	
2 Wayman 8300 Petersburg Road WAY	Not Inspected		
1 Osborne 2400 Schlensker Rd. OSB/421	Built in 1955. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement. Unreinforced concrete block walls. Attached garage with block walls.	Exterior - Cracks were visible in the veneer. Foundation - A few cracks were visible in the basement walls. Interior - Cracks above doors and windows were present throughout the house. Ceiling cracks were also present.	BORING 421 0-7 ft B horizon plus loess (reworked?) nonexpansive clays. 7-8 ft Stoneline material; sd, lean clay, good permeability, good down slope (gravity) drainage. 13 blow count. 9-12 ft weathered shale, moderate expansive (less than McCutchan) 26 blow count. 12 ft competent shale. a. 9 and 12 ft - good compressional wave velocity changes. b. Foundation is probably in the weathered shale layer.
2 Rozanski 2530 Schlensker Rd. ROZ/421A	Built in 1early 1950's. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement. Unreinforced concrete block walls.	Exterior - Minor. Foundation - A few cracks were present around windows. Interior - Cracks were present around doors and in the ceiling.	c. Companion house bore hole samples showed no weathered shale, Stoneline is at 8 to 12, shale at 12'.

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Richey 15101 Cemetery Rd. RIC/202	Built in 1967 with modifications in 1983. One-story wood frame with stone veneer. Wood panel finish. Partial basement with crawl space. Unreinforced concrete block walls.	Exterior - Many cracks were present and evidence of severe damage. Foundation - Large cracks were present in the basement. Could not tell about the extensive crawl space. Interior - Wood panelling prevented inspection.	BORING 202 0-5 ft B horizon plus clay/loess--nonexpansive. 5-9 ft weathered shale ? - expansive material. 9-10 ft weathered mix of materials, -colluvium? 10 ft West Franklin material (Ls, etc.) 10 ft good compressional wave velocity change at 9-11'. a. Foundation. The north foundation may be on loess and the south part of the foundation may be on the weathered shale. b. Basement wall is at same level as the expansive weathered shale.
2 Stevens 15045 Cemetery Rd. STE/202A	Built around 1970. One-story wood frame with partial brick veneer. Wood panel finish. Full crawl space. Unreinforced concrete block walls.	Exterior - Hairline cracks. Foundation - None. Interior - Wood panelling prevented inspection. Floor slopes and doors and windows stick.	c. Companion house bore hole samples do not show the weathered shale layer. The subsurface material goes from loess to colluvium to shale.
2 Heil 15056 Cemetery Rd. HEL/—	Built around 1970. One-story wood frame with all brick veneer. Wall panel finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Few hairline cracks. Foundation - Few hairline cracks. Interior - Wood panelling prevented inspection.	
1 Christensen Route 3, Box 257 Baseline Road CHR/115	Construction date not known. One-story wood frame with all brick veneer. Drywall finish. Partial basement with crawl space. Unreinforced concrete block walls.	Exterior - Cracks were visible both in the veneer and around the corners. Vertical cracks were present along the chimney. Foundation - There were cracks and signs of some movement of upper story floor beam supports. Some of the floor beams under the master bedroom showed signs of compression bulging at the ends. Interior - Considerable cracking was evident in the walls in the first story. These cracks were particularly bad on the walls in the master bedroom. The floor gives the impression of sloping inward in this room. There is a water bed in the room.	BORING 115 0-7.5+-ft B horizon plus loess. 7.5-10 ft Nonexpansive weathered shale? 10 +- ft Bedrock ? sc/silt/sh interbedded (Shelburn Fm sp.?) a. 8 and 11 ft - good velocity shifts in compressional waves. b. Subsurface formations are located in the Shelburn fm sequence below the West Franklin Ls. c. Foundation thought to be in nonexpansive weathered shale.
2 Klausmeir 6604 Baseline Rd. —/115A	Construction date not known, probably around 1970. One-story wood frame with brick veneer below window. Drywall finish. Full crawl space. Unreinforced concrete block walls.	Exterior - Hairline cracks in block walls. Foundation - See above. Interior - None.	d. Companion house is on similar material in the upper 9 ft.
2 Board 6616 Baseline Rd.	Built One-story wood frame with mostly aluminum siding. Full crawl space. Unreinforced concrete block walls.	Exterior - None Foundation - None Interior - Minor	

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Norton 13145 N. Green River Rd. NOR/104	Unknown construction, remodelled in 1966. One-story wood frame with 50% brick veneer. Plaster on sheet rock finish. Full basement. Unreinforced concrete block walls.	Exterior - Hairline cracks on the exterior. Foundation - Hairline cracks on walls and floor. Interior - Hairline cracks. The most severe damage was present in the block walls and slab in a separate building which was a three stall garage. All were severely cracked. Much of the damage appeared associated with a drainage problem around the building. There was no evidence of reinforcement in the severely cracked garage slab.	
2 LeCocq 13421 N. Green River Rd.	Built in 1981. One-story wood frame with all brick veneer. Drywall finish. Full basement. Unreinforced concrete block walls.	Exterior - None. Foundation - Hairline crack in one corner in the walls and floor slab. Evidence of some moisture penetration. Appeared well-drained outside. The owner believes it is associated with water supply lines. This bears watching and the owner appears to be doing so. Interior - Few hairline cracks.	
1 Zimmerman 10991 N. Green River Rd. ZIM/103	Built in 1974. One-story wood frame with all brick veneer. Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Cracks were present on many walls. Foundation - Both walls and floor slab were cracked. Interior - Nail pops and cracks were present throughout the first story living area.	BORING 103 0-7+-ft Dry, B horizon plus some loess. 7-17 ft moist, silts and clays - no evidence of expansive clays from the samples. 17-20 ft good compressional wave velocity change. 17+- ft probable shale contact 14' clay squeezed in the hole at this depth?? a. Foundation thought to be in loess.
2 Shelton 10801 N. Green River Rd. SHE/103A	Built in 1989. One-story wood frame with all brick veneer. Drywall finish. Full crawl space. Unreinforced concrete block walls very close of crawl space walls.	Exterior - None. Foundation - None. Interior - None.	b. Companion house is on very similar material in the upper 9 ft.
2 Daugherty 10901 N. Green River Rd. DAU/—	Built in 1968. One-story wood frame with all brick veneer. Plaster on sheet rock finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Few hairline cracks. Foundation - Few hairline cracks. Interior - Few hairline cracks.	

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME/ADDRESS USGS ID/OSM ID	DESCRIPTION OF BUILDING	DAMAGE	SITE CONDITIONS
1 Bohrer 4949 Daylight BOH/105	Built in 1966. One-story wood frame with all brick veneer. Plaster on sheet rockfinish. Full basement. Unreinforced concrete block walls.	Exterior - Some cracks were present in exterior veneer. Foundation - A horizontal crack was present along one wall of the basement. This may be where the block size changes since it was about at the ground line. Interior - Some cracks and nail pops were present in the interior finish surface.	
2 Miller 5101 Daylight MIL/—	Built in 1955. One-story wood frame with all brick veneer. Plaster on metal lath finish. Full crawl space. Unreinforced concrete block walls.	Exterior - Severe cracking in the sidewalk and driveway. Foundation - None Interior - A few cracks were visible	

Damage Descriptions

Exterior - A brief description of damage or conditions outside the house.
Foundation - A brief description of damage or conditions related to the basement, crawl space, and/or slab on grade as appropriate.
Interior - A brief description of damage or conditions related to the interior finish surfaces inside the house.

FOUNDATION/SUBSURFACE SUMMARIES FROM OCT. 13-16 MEETING IN BLOOMINGTON, ID.
Interpretations by: Ned Bleuer and Don Eggert, Indiana Geological Survey, Paul F. Hadala, US Army Corps of Engineers, Bernard Maynard, Office of Surface Mining, Ken King, U.S.G.S.

NOTE: Bore holes at homes went to depth of hard drill resistance; at companion house to a depth of 9 foot. All depths are estimates.

Table 11 continued. Category 1 and 2 buildings.

SITE CATEGORY NAME ADDRESS	DESCRIPTION OF BUILDING	DAMAGE
3 Niemeier 6800 New Harmony Rd.	Built in 1963. One-story wood frame will all brick veneer. Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Hairline cracks in brick planter walls. Few cracks in brick around door of walkout basement. Foundation - None. Interior - None.
3 Berendes 6801 New Harmony Rd.	Built around 1930. Two-story wood frame will all brick veneer. Plaster on wood lath finish. Full basement with walkout. Unreinforced poured concrete walls.	Exterior - Two masonry walls by driveway entering below grade garage are being pushed in by soil pressure. Foundation - Cracks in west and south walls. Cracks have been sealed and show no sign of movement. Interior - Hairline cracks above doors and ceiling in a few rooms.
3 Smock 6819 New Harmony Rd.	Built in 1968. One-story wood frame will all brick veneer. Plaster on sheet rock finish. Partial basement with walkout and crawl space. Unreinforced concrete block walls.	Exterior - Some heaving of driveway slab. Some surface spalling of brick due to weathering. Foundation - Two floor-to-ceiling vertical cracks. Interior - Few cracks around two doors. Few cracks in ceiling. Diagonal crack near fireplace. Previous owner said it appeared after an earthquake.
3 Franks 6904 New Harmony Rd.	Built in 1987. One-story wood frame will all brick veneer. Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - None Foundation - None Interior - None
3 Niehaus 7120 New Harmony Rd.	Built in 1953., 2nd story added in mid 60's. Two-story wood frame will all brick veneer. Plaster on sheet rock and drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - None Foundation - Hairline cracks in basement Interior - No cracks in first story. Minor cracks in one room on second story.
3 Boughton 7200 New Harmony Rd.	Built around 1940. One-story wood frame will brick veneer and aluminum siding over wood. Plaster on sheet rock finish. Partial basement with crawl space. Unreinforced poured concrete walls.	Exterior - Minor crack in concrete at entry. Slight movement of steps. Foundation - One vertical crack in basement. Interior - Interior was mostly papered. Owners said this was done because of cracks in the plaster. Owners did not feel the cracks were serious.
3 Neale 9800 Upper Mount Vernon Rd.	Unknown construction. Owner bought in 1979. One-story block construction with brick veneer on front. Finish surface was paneling and concrete block with a mortar coating for a finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Hairline cracks on the exterior blocks in corners, stair step type. Large cracks in exterior veneer. This happened because the veneer was erroneously attached by supporting on the sidewalk instead of the foundation walls. Foundation - Few hairline cracks in corners. Interior - Few hairline cracks. Block wall is coated with a layer of mortar. Some hairline cracks which may be in the coating are present.

Table 12. Category 3 buildings.

SITE CATEGORY NAME ADDRESS	DESCRIPTION OF BUILDING	DAMAGE
3 Goebel 9808 Upper Mount Vernon Rd.	Built in late 1950's. One-story wood frame will stone veneer and vinyl siding. Drywall finish. Full crqwl space. Unreinforced concrete block walls.	Exterior - Two vertical cracks in back. Stair stepped cracks in north wall. Foundation - None. Interior - One crack in a bedroom. Others rooms were papered.
3 Feller 6924 Little Schaeffer Rd.	Built in 1971. One-story wood frame will all brick veneer. Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Slight pulling away of front stoop. Foundation - Slight stairstep crack in basement on one wall. One horizontal crack in a joint 2 courses down. Slight bulging. Interior - None.
3 Lamb 7201 Little Schaeffer Rd.	Built in 1954. One-story wood frame will all brick veneer. Plaster on sheet rockfinish. Partial basement with walkout and crawl space. Unreinforced concrete block walls.	Exterior - Stair step around window in NE corner, probably bad drainage. Also stair step on NW corner. Foundation - None. Interior - Few in one bedroom and the hall around windows and doors.
3 Arhelger 7212 Little Schaefer Rd.	Built in 1966. One-story wood frame will all brick veneer. Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Vertical crack below window on east wall. Foundation - Some horizontal in north wall near NW corner. Interior - One crack below a window, 2 or 3 in ceiling.
3 Humphrey 2917 Koressel Rd.	Built in 1975. One-story wood frame will all brick veneer. Drywall finish. Full basement. Unreinforced concrete block walls with pilasters.	Exterior - Two horizontal cracks above garage door and window. Foundation - Stairstep crack in northwest corner wall. Some slab cracks. Hairline crack on east wall, about eye level. One vertical hairline crack on the south wall. Some evidence of moisture leakage. Interior - Crack in living room around fireplace. The owner said the fire was too hot. Few cracks in hallway walls.
3 Warren 8480 Hogue Rd.	Built in 1958. One-story wood frame will all brick veneer. Plaster on wood lath finish. Partial crqwl space with slab. Reinforced concrete walls in crawl space.	Exterior - One cracked brick that occurred when a joist was being replaced. Foundation - None. Interior - Few cracks around one door and window. Few in ceiling.
3 Kares 8518 Hogue Rd.	Built in 1950's. One-story wood frame will all brick veneer. Plaster on sheet rock finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - Some masonry joint cracks on brick supporting front porch. Foundation - A hairline crack was present the 3rd course down. This was in the joint where the block size in the basement wall decreases from 8" to 4" in order to accomodate the brick veneer. Stair step cracks on each wall. One long crack in the floor. All cracks were hairline. Interior - Few cracks around windows. Cracks were typical at the corners of openings for heating vents. One ceiling crack in one bedroom.

Table 12 continued. Category 3 Buildings.

SITE CATEGORY NAME ADDRESS	DESCRIPTION OF BUILDING	DAMAGE
3 Helfrich 9401 Hogue Rd.	Built in 1910, extensively remodelled in 1980's. Two-story wood frame will 75% brick veneer. Drywall finish. Partial basement with walkout and crawl space. Unreinforced brick walls.	Exterior - One crack below second-story window above bay window. Foundation - None. Interior - None.
3 Effinger 8112 Marx Rd.	Built in 1957 add on in 1980. One-story wood frame will all brick veneer. Add on is vinyl siding Drywall finish. Full basement with walkout. Unreinforced concrete block walls.	Exterior - One vertical crack below window on east wall. Some cracks in block wall on south face. Foundation - Finished, could not tell if cracks were present. Interior - Few cracks in the living room. One in ceiling in hall.
3 Bauer 2324 Diefenbach Rd.	Built in 1940. One-story wood frame will aluminum siding over wood. Plaster on sheet rock finish. Full basement. Unreinforced concrete block walls.	Exterior - Few hairline cracks. Foundation - Lots of cracks due to a previous moisture problem which the owner corrected. Perimeter drains were added inside and out and the basement was waterproofed. This has solved the problem. Lots of slab cracks, mostly on the surface. Interior - Vertical crack in fireplace masonry. Horizontal crack at second floor level in stairwell. It was said to be getting worse. A few cracks were above doors and in the ceiling in the upstairs area.
3 Kelley 2623 Diefenbach Rd.	Built in 1954, attic finished later. One-story wood frame will all brick veneer. Plaster on sheet rock (drywall in attic) finish. Full crawl space. Unreinforced concrete block walls.	Exterior - Front stoop pulled away slightly. Foundation - None. Interior - Few hairline cracks in the bedroom. Worst cracks were in the entrance way. Wall cracks were particularly noticeable around an arched door. Some were associated with an earthquake in the 70's. The owner also considered some cracks in a breakfast room wall earthquake related.
3 Bender 8520 W. Chapel Rd.		Bender Exterior - Hairline crack above double car garage. Foundation - A full-length horizontal crack was present on the south wall. Interior - None.

Damage Description

Exterior - A brief description of damage or conditions outside the house.
Foundation - A brief description of damage or conditions related to the basement, crawl space, and/or slab on grade as appropriate.
Interior - A brief description of damage or conditions related to the interior finish surfaces inside the house.

Table 12 continued. Category 3 Buildings.

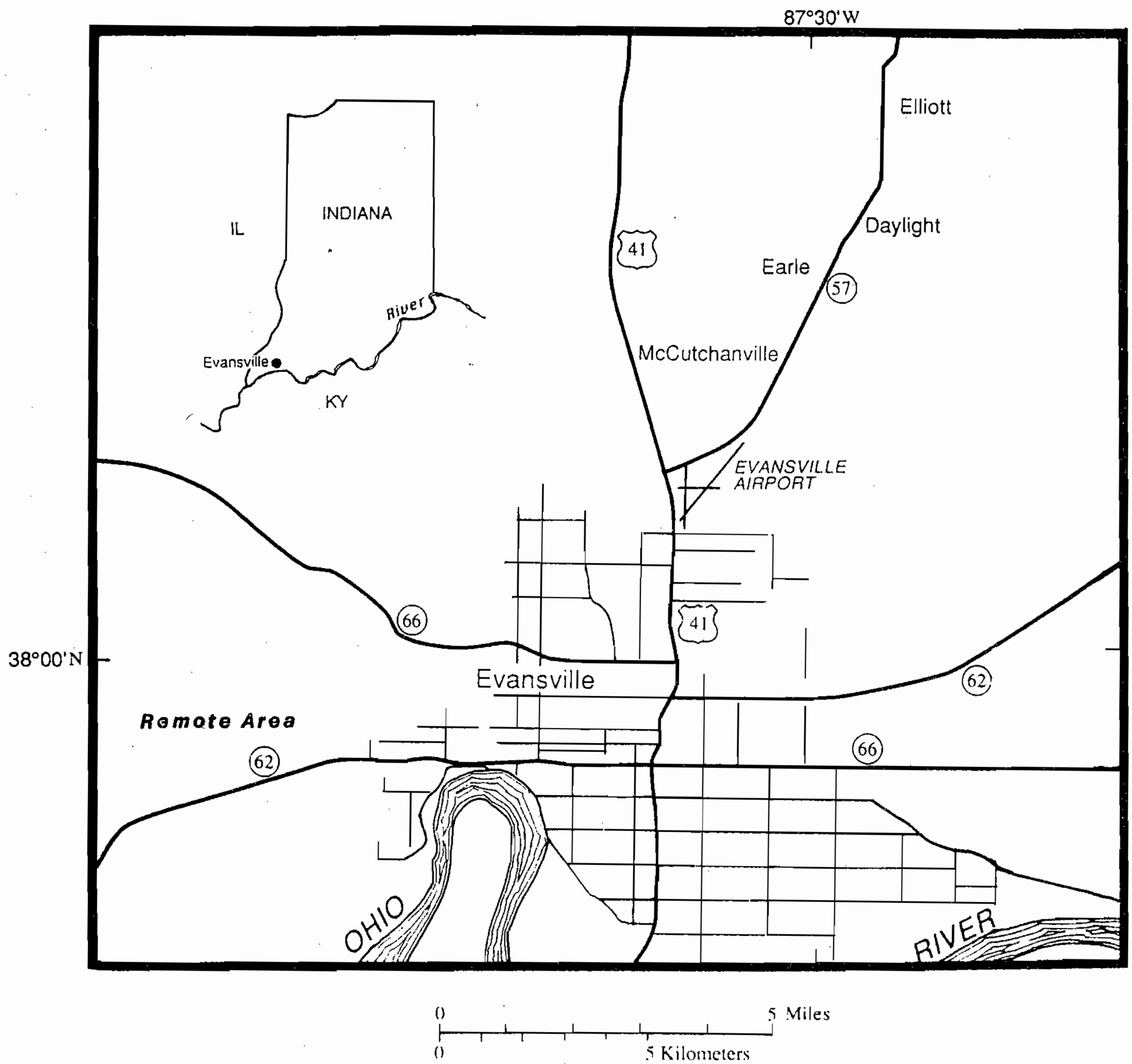


Figure 1. Location of the McCutchanville-Daylight and remote study areas.

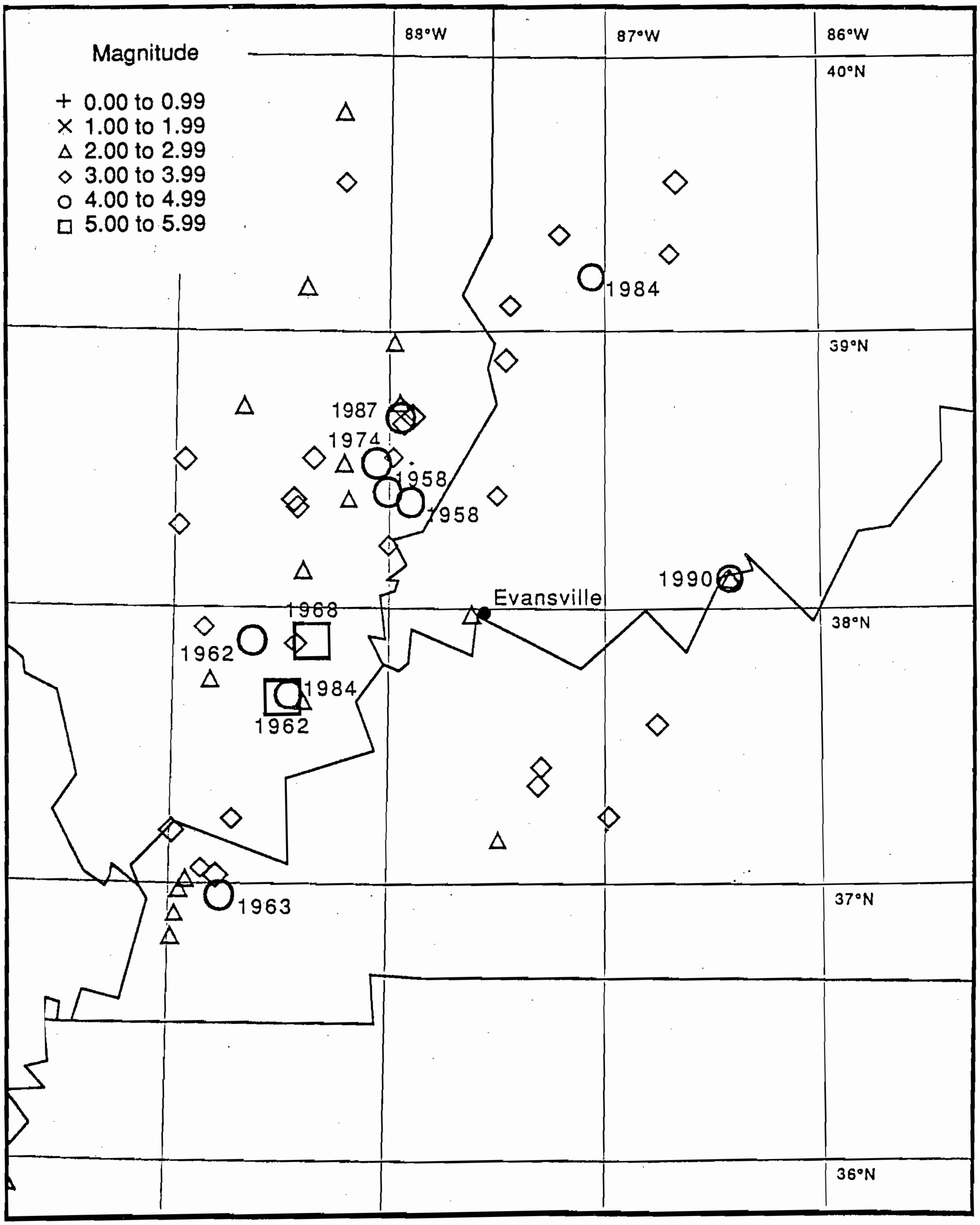


Figure 2. Instrumentally located earthquakes, 1942 through mid-1992 (Engdahl and Rinehart, 1991 and Preliminary Determination of Epicenters, USGS, NEIC computer data base).

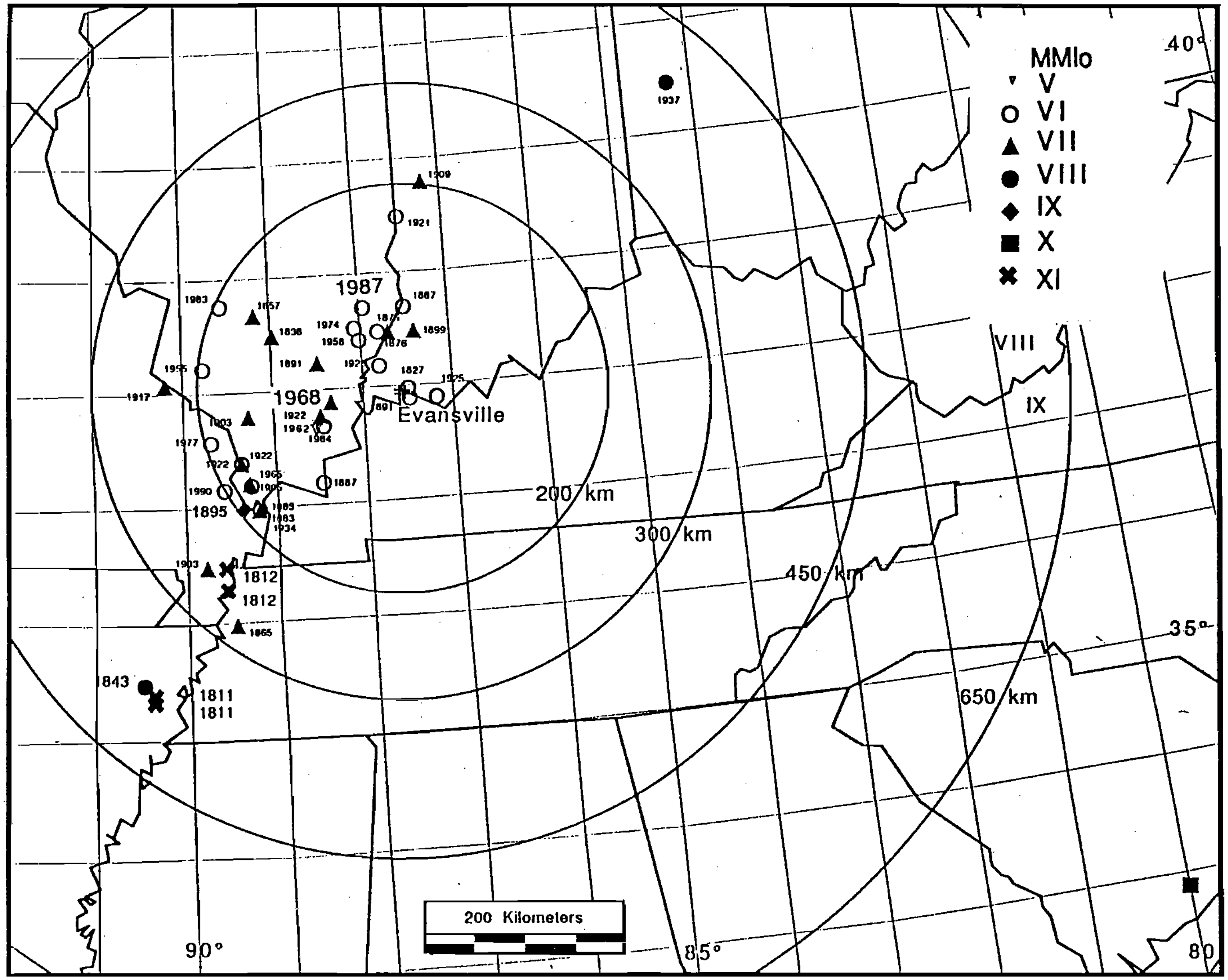


Figure 3. Earthquakes with maximum Modified Mercalli intensities of V or greater affecting Evansville, Indiana, 1811 - 1990.

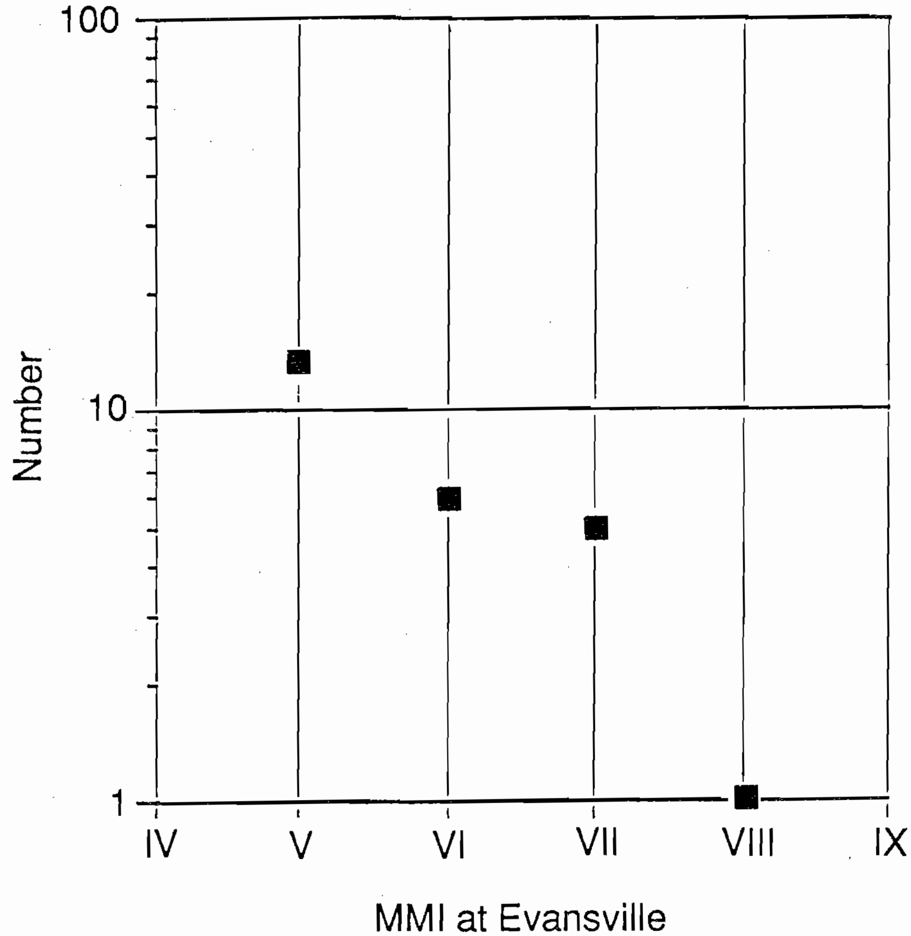


Figure 4. Distribution of Modified Mercalli intensities affecting Evansville, Indiana. Derived from a review of the seismic history of the United States.

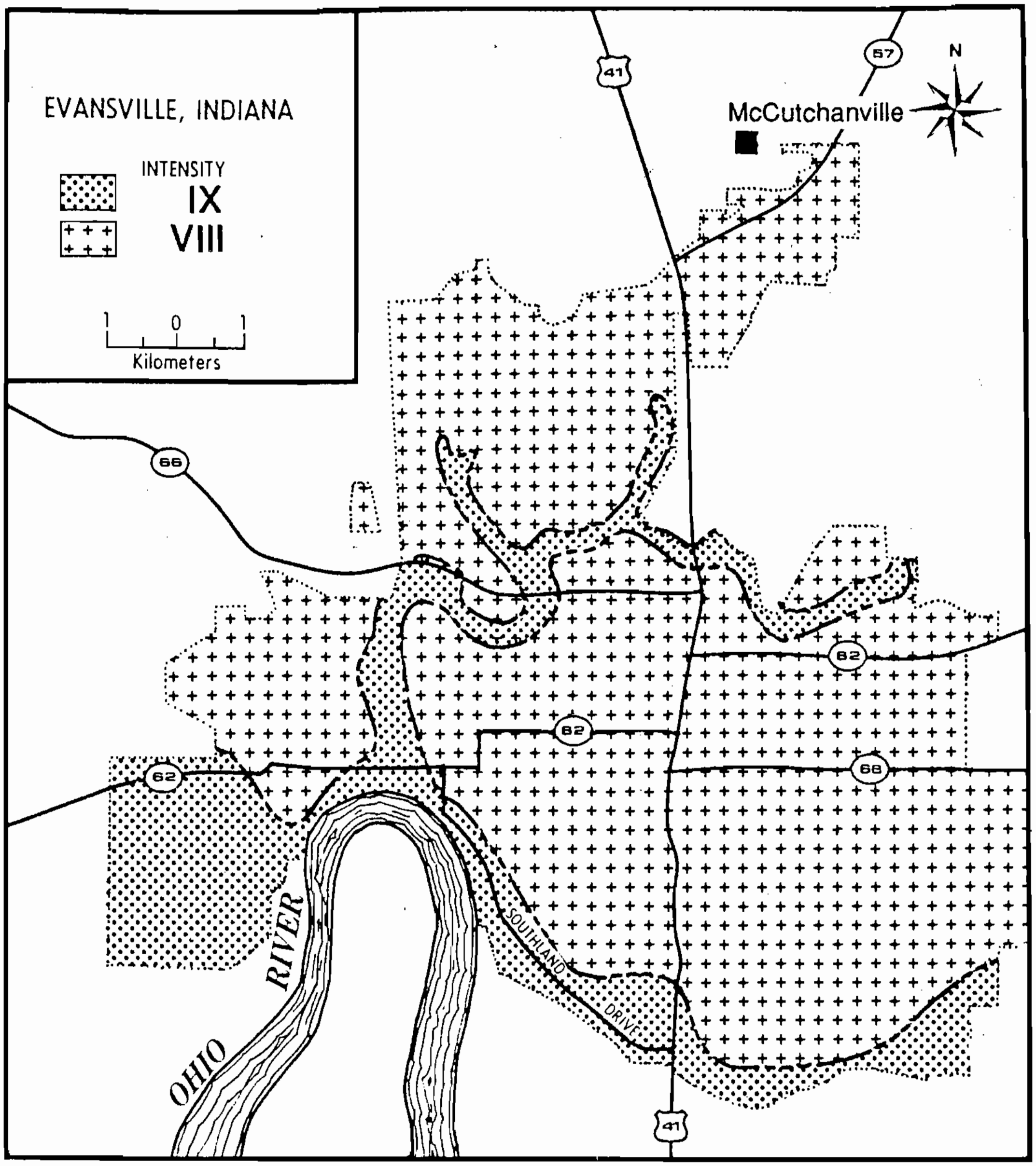


Figure 5. Map of hypothetical maximum Modified Mercalli intensities for Evansville, Indiana, for a magnitude M_S 8.6 earthquake anywhere in the New Madrid Seismic Zone (after Hopper, 1985).

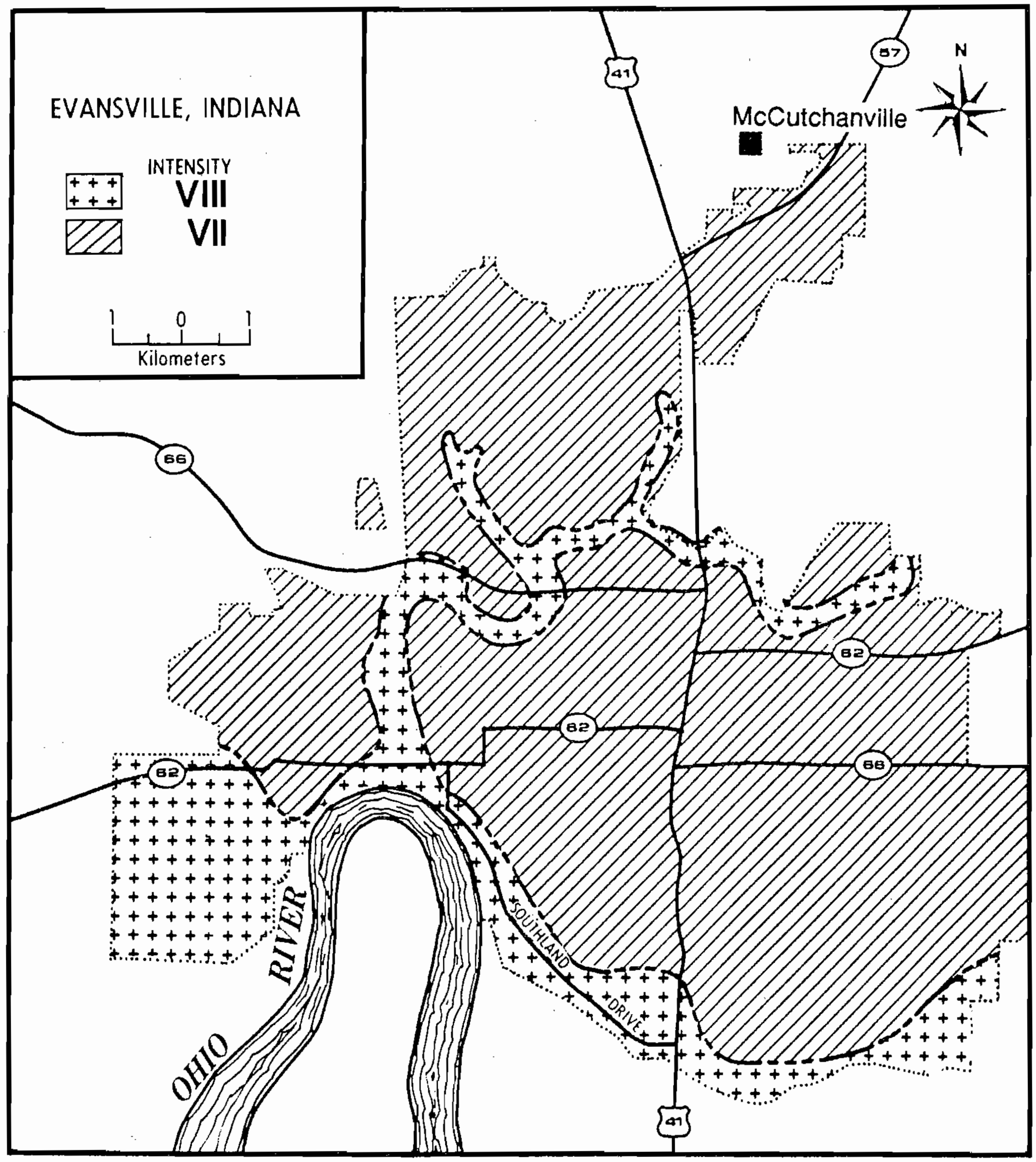


Figure 6. Map of hypothetical maximum Modified Mercalli intensities for Evansville, Indiana, for a magnitude M_S 7.6 earthquake anywhere in the New Madrid Seismic Zone (after Hopper, 1985).

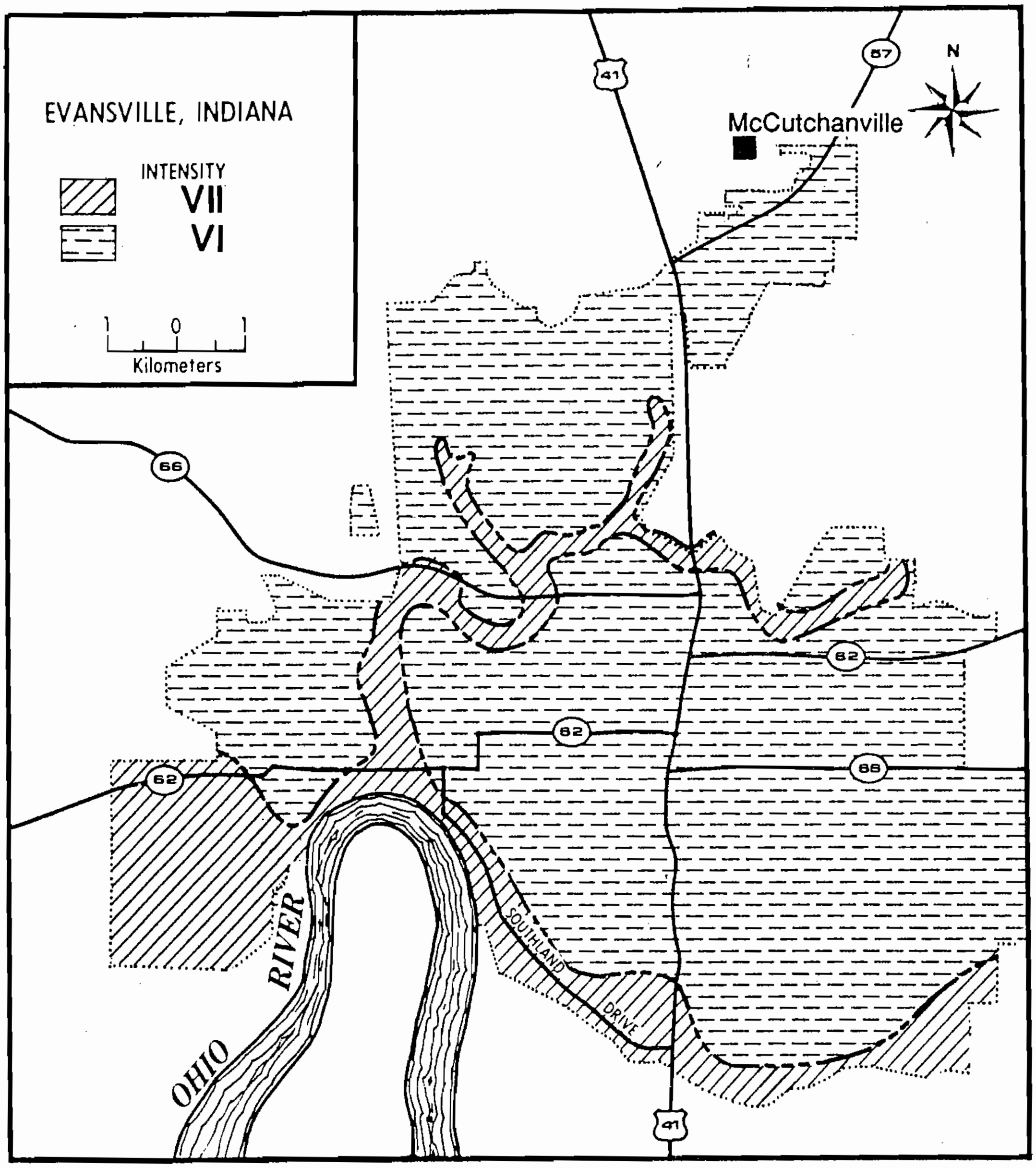
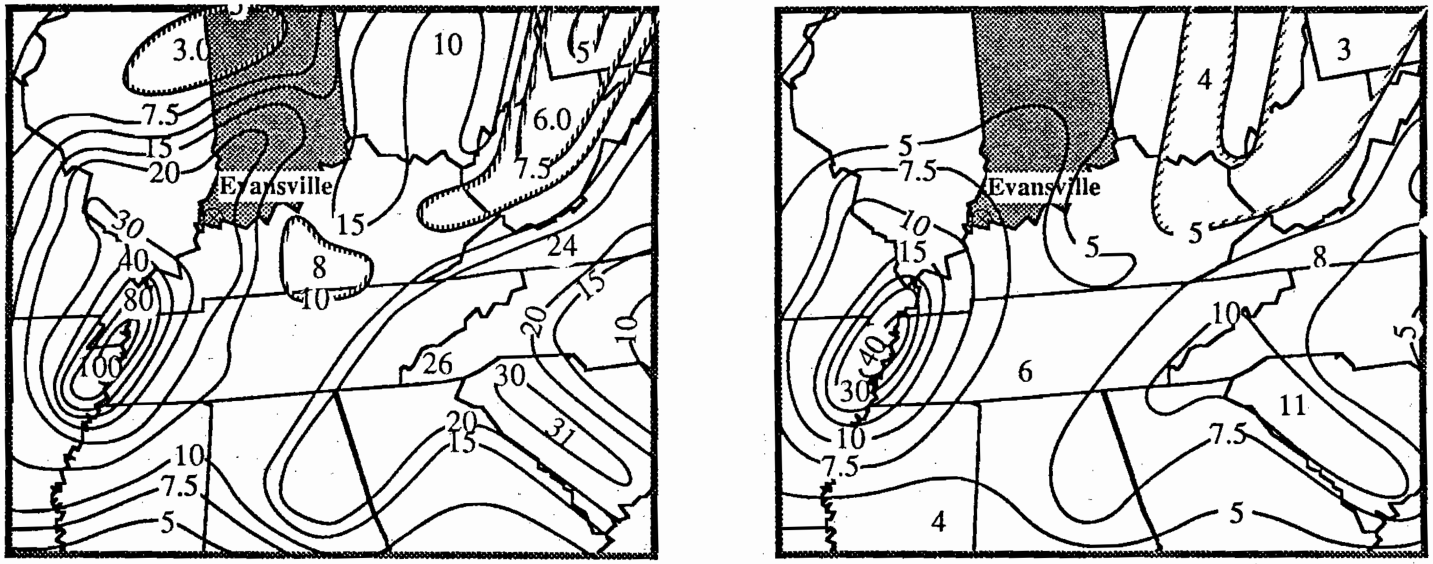
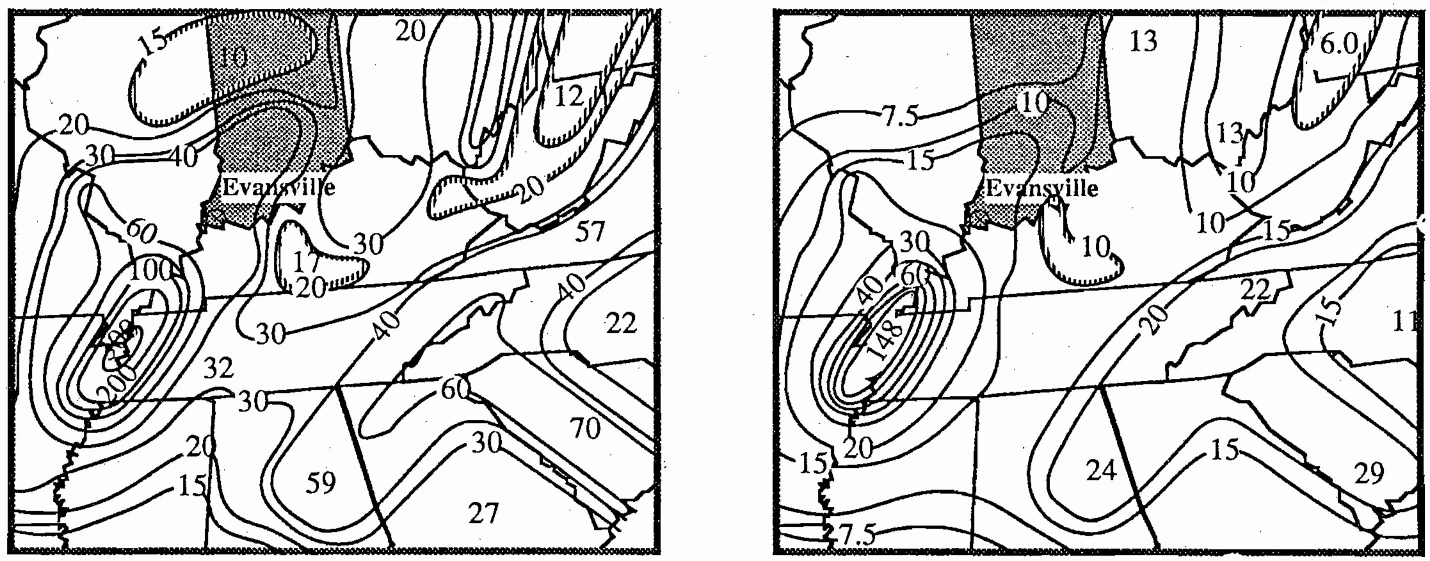


Figure 7. Map of hypothetical maximum Modified Mercalli intensities for Evansville, Indiana, for a magnitude M_S 6.7 earthquake anywhere in the New Madrid Seismic Zone (after Hopper, 1985).



0.3 Second Period　　　　1.0 Second Period

Figure 8. Maps of spectral response acceleration for the central United States at a 0.3 sec and 1.0 sec periods with 5 percent damping. Values are for a 10 percent probability of exceedance in a 50 year exposure period. The contours are given in percent of the acceleration of gravity. Surface reference material is S_2 (Building Seismic Safety Council, 1992).



0.3 Second Period

1.0 Second Period

Figure 9. Maps of spectral response acceleration for the central United States at 0.3 sec and 1.0 sec periods with 5 percent damping. Values are for a 10 percent probability of exceedance in a 250 year exposure period. The contours are given in percent of the acceleration of gravity. Surface reference material is S_2 (Building Seismic Safety Council, 1992).

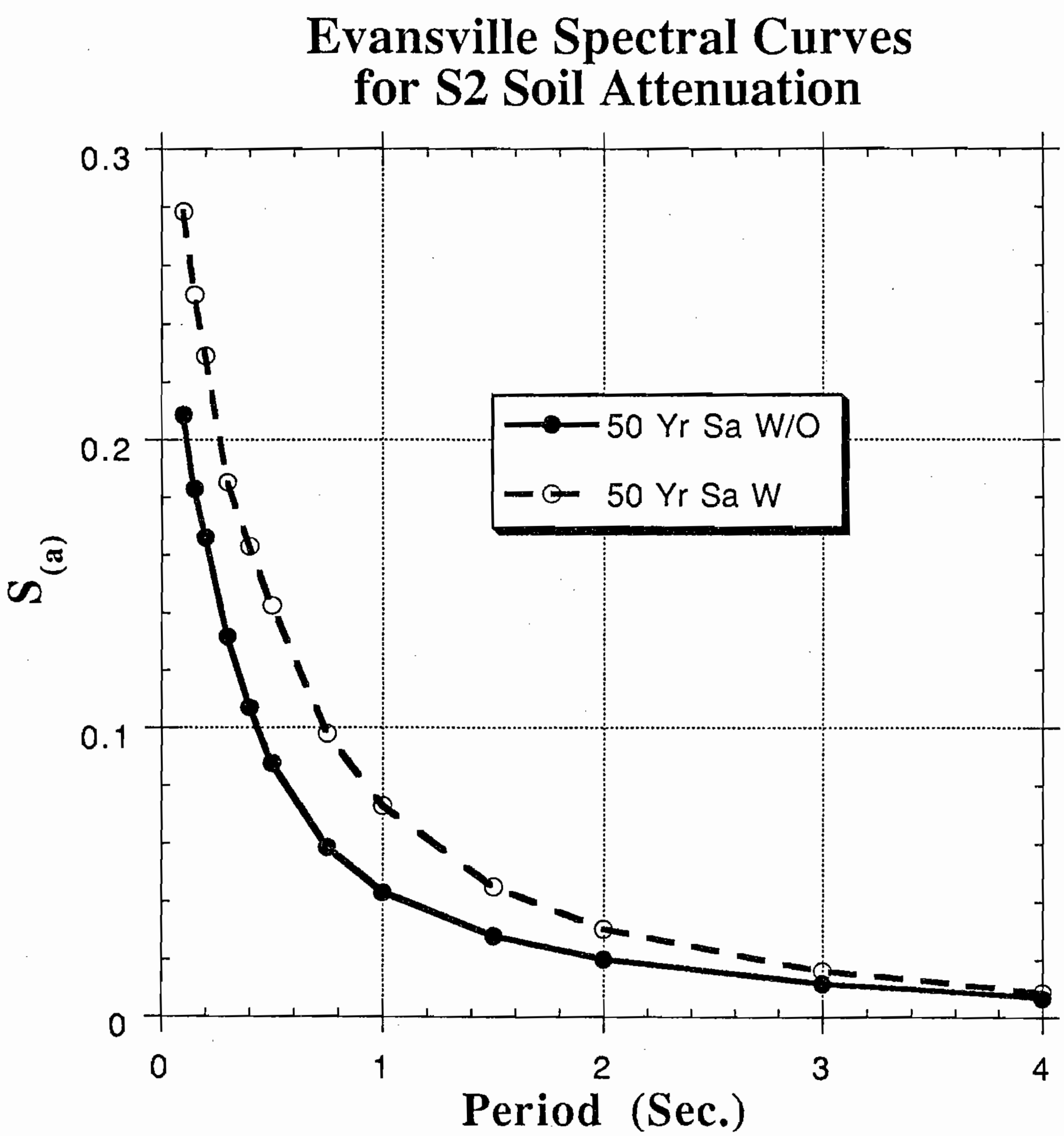


Figure 10. Equal hazard response spectra with 5 percent damped spectral response acceleration (as a fraction of gravity) for Evansville, Indiana. Spectral values are for a 10 percent probability of exceedance in a 50 year exposure period. The contours are given in percent of the acceleration of gravity. The surface reference material is S_2 (Building Seismic Safety Council, 1992).

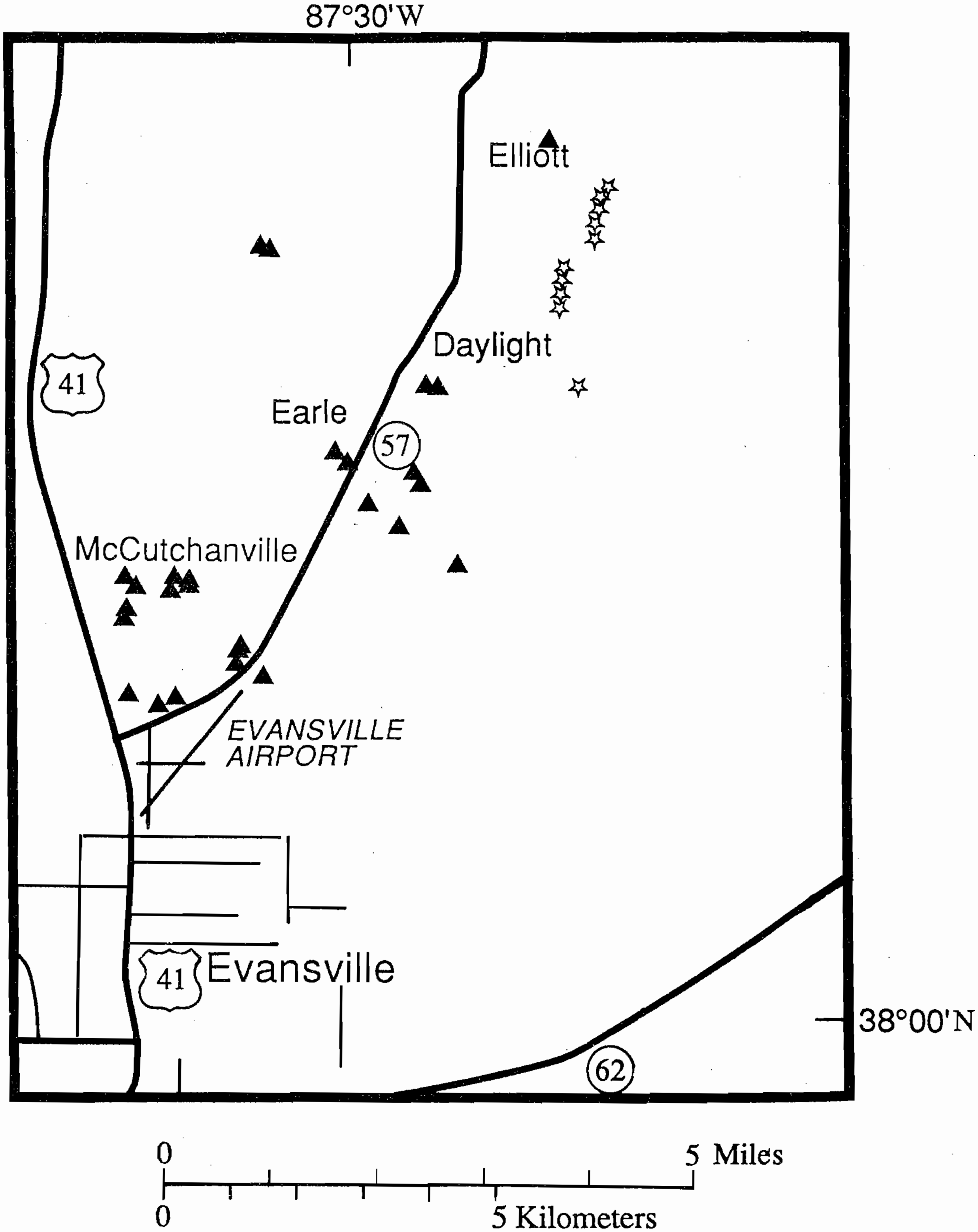


Figure 11. Locations of the mine blasts are denoted by open stars, locations of seismic recording sites denoted by solid triangles.

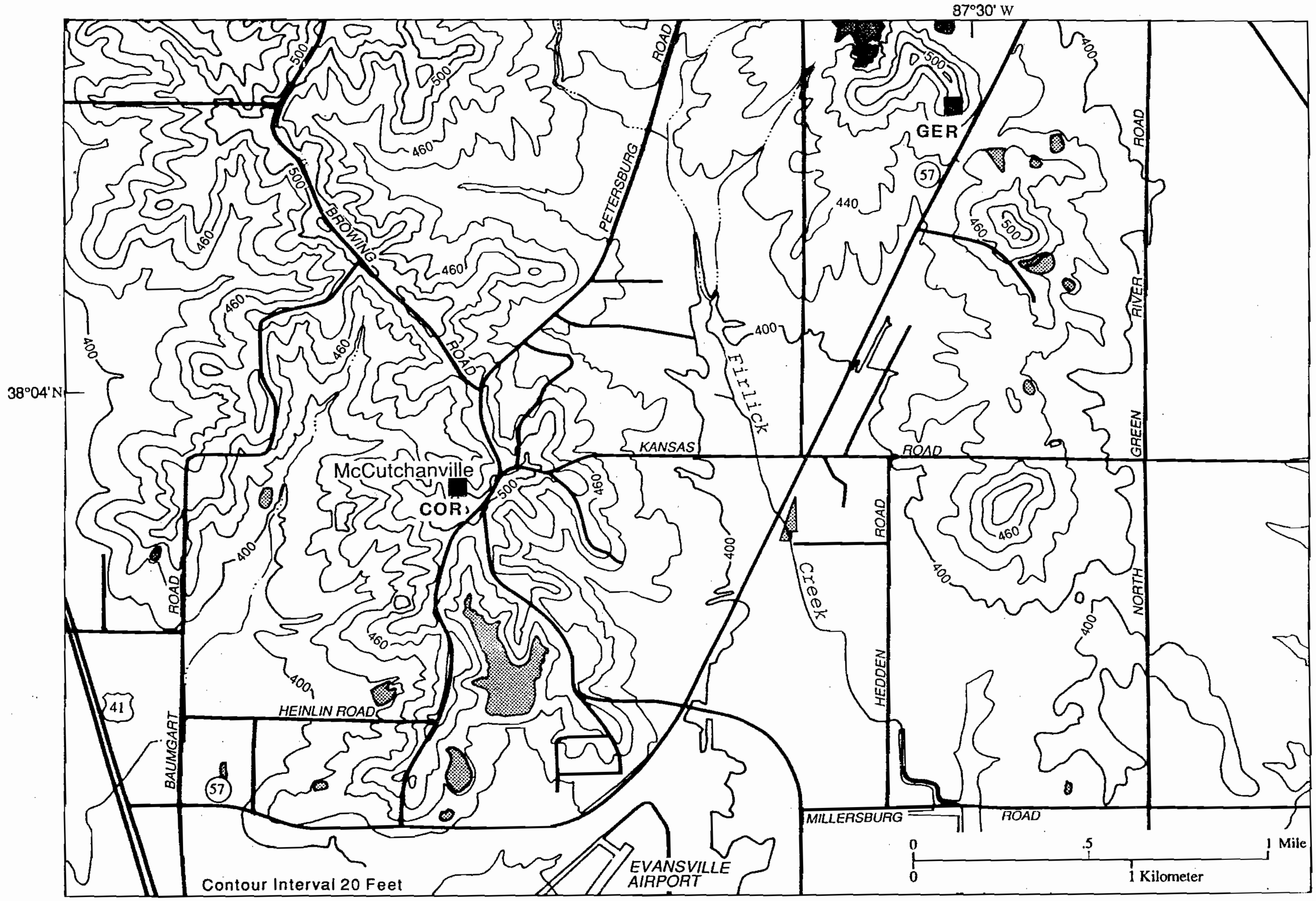
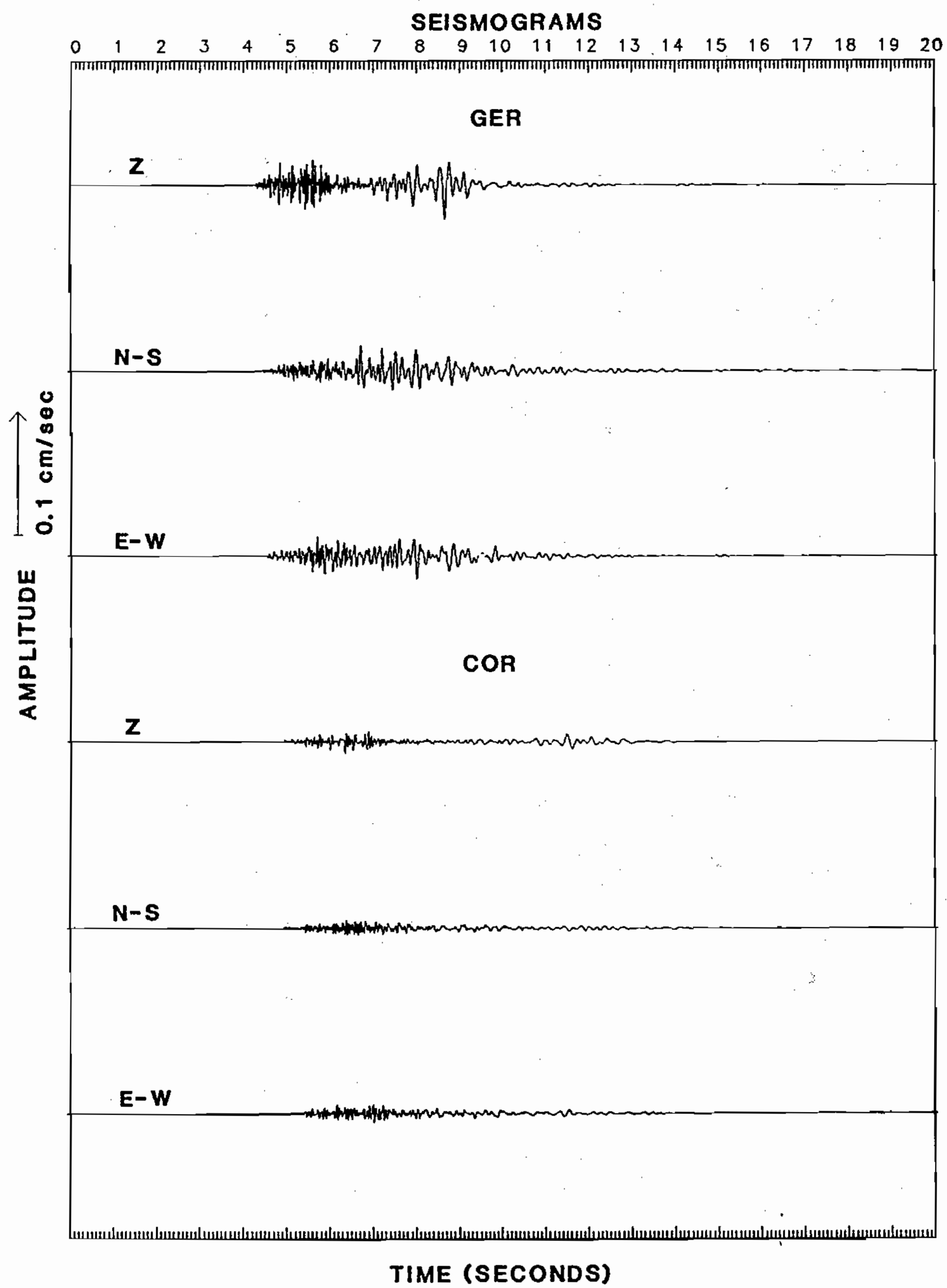


Figure 12. McCutchanville study area. Array Number 1 is denoted by solid squares.



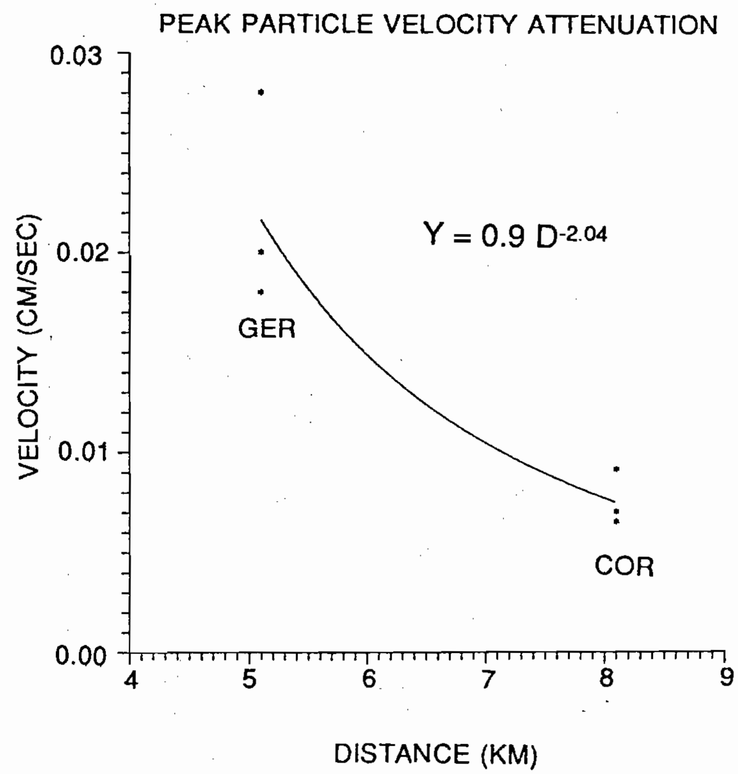
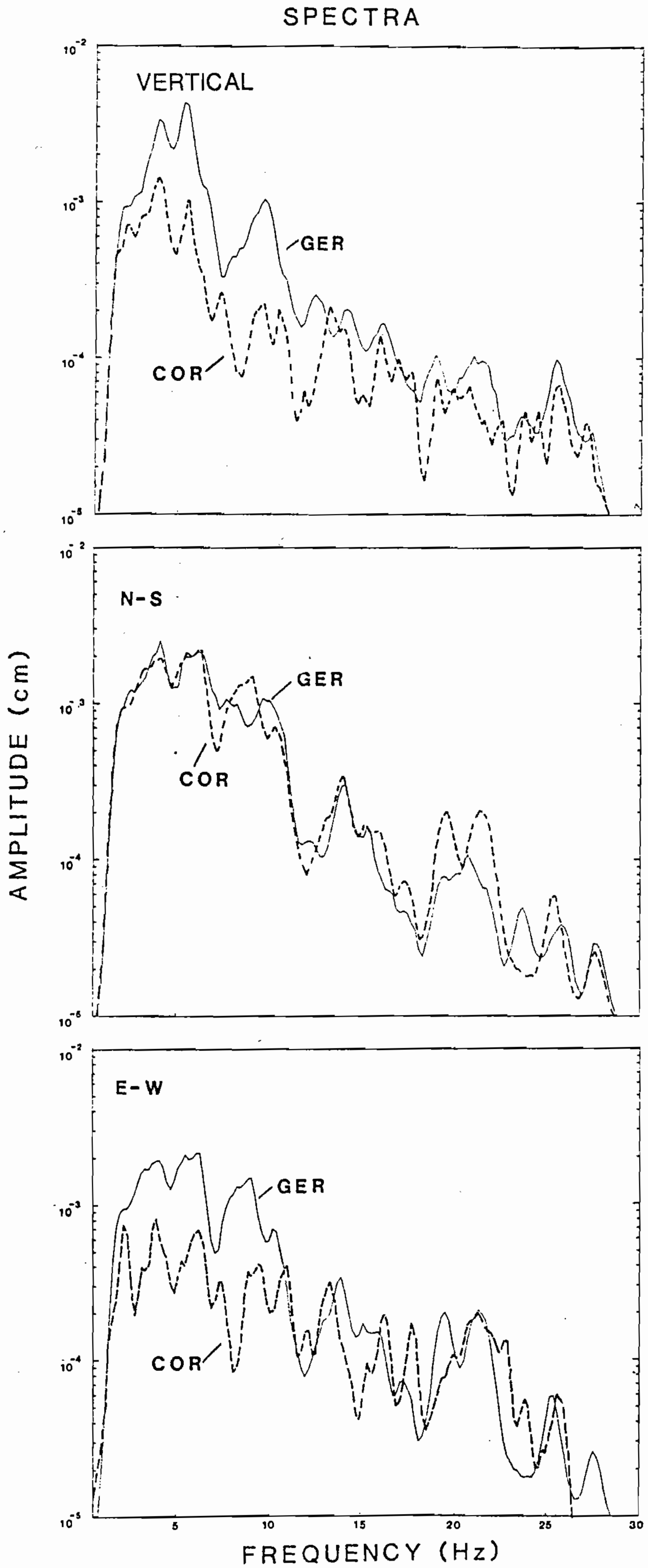
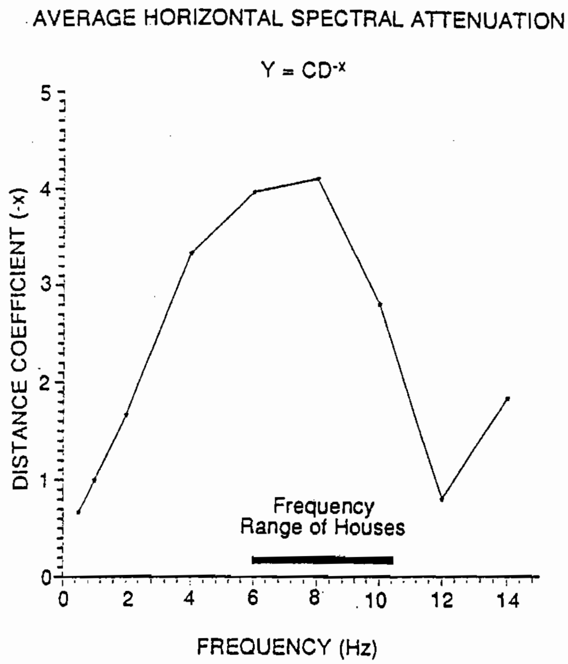


Figure 13. Seismograms and graph showing ground motion attenuation.





B. Spectral attenuation functions derived from $Y = CD^{-X}$
Where:

Y = maximum spectral amplitude at n frequency
C = constant
D = distance to mine blast
X = distance attenuation coefficient

Figure 14. Spectra and spectral attenuation functions for Array No. 1. The horizontal bar in Figure B shows the bandwidth of the natural frequencies of the houses.

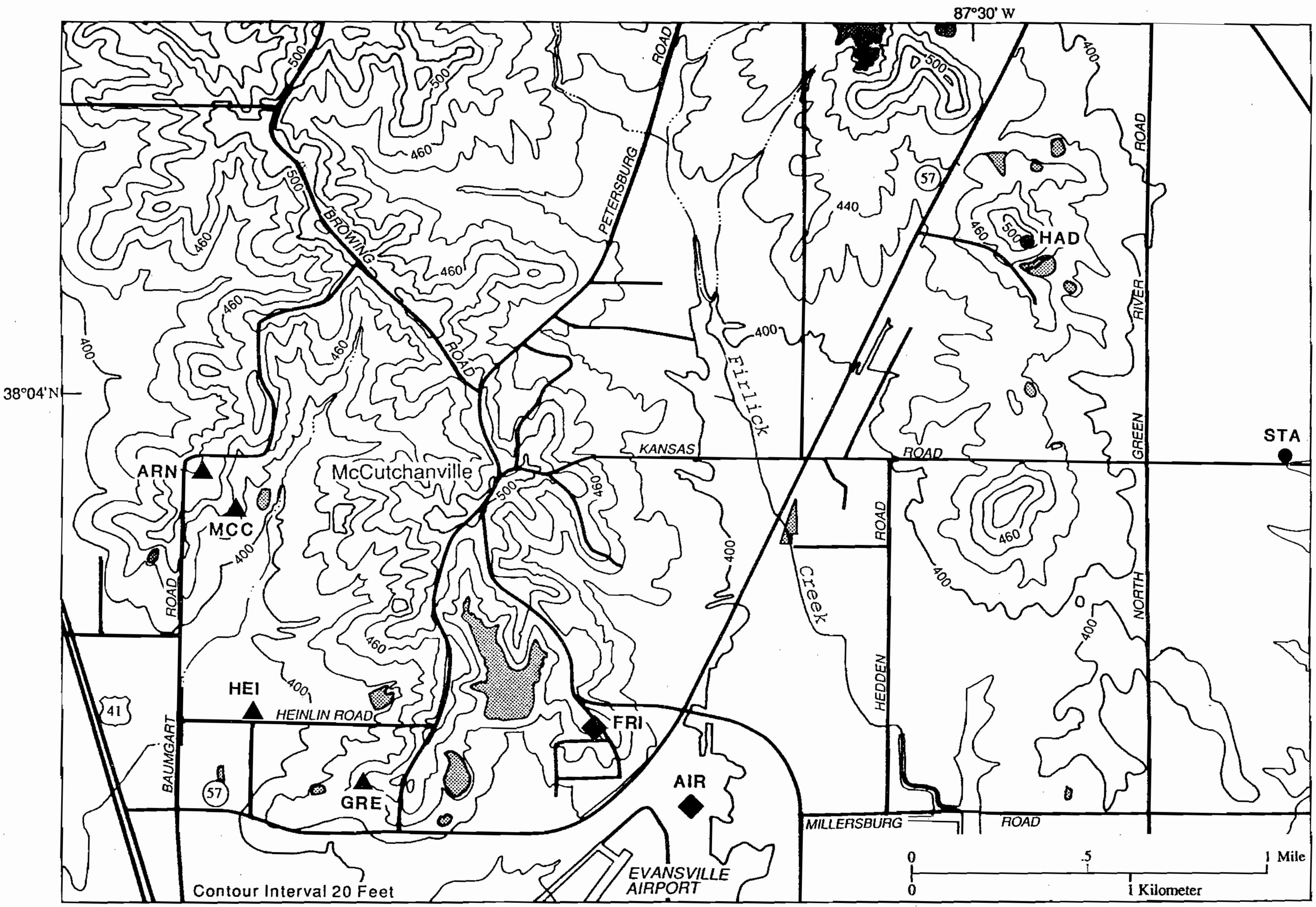


Figure 15. McCutchanville study area. Array Numbers 2, 3, and 4 are denoted by solid circles, triangles, and diamonds respectively.

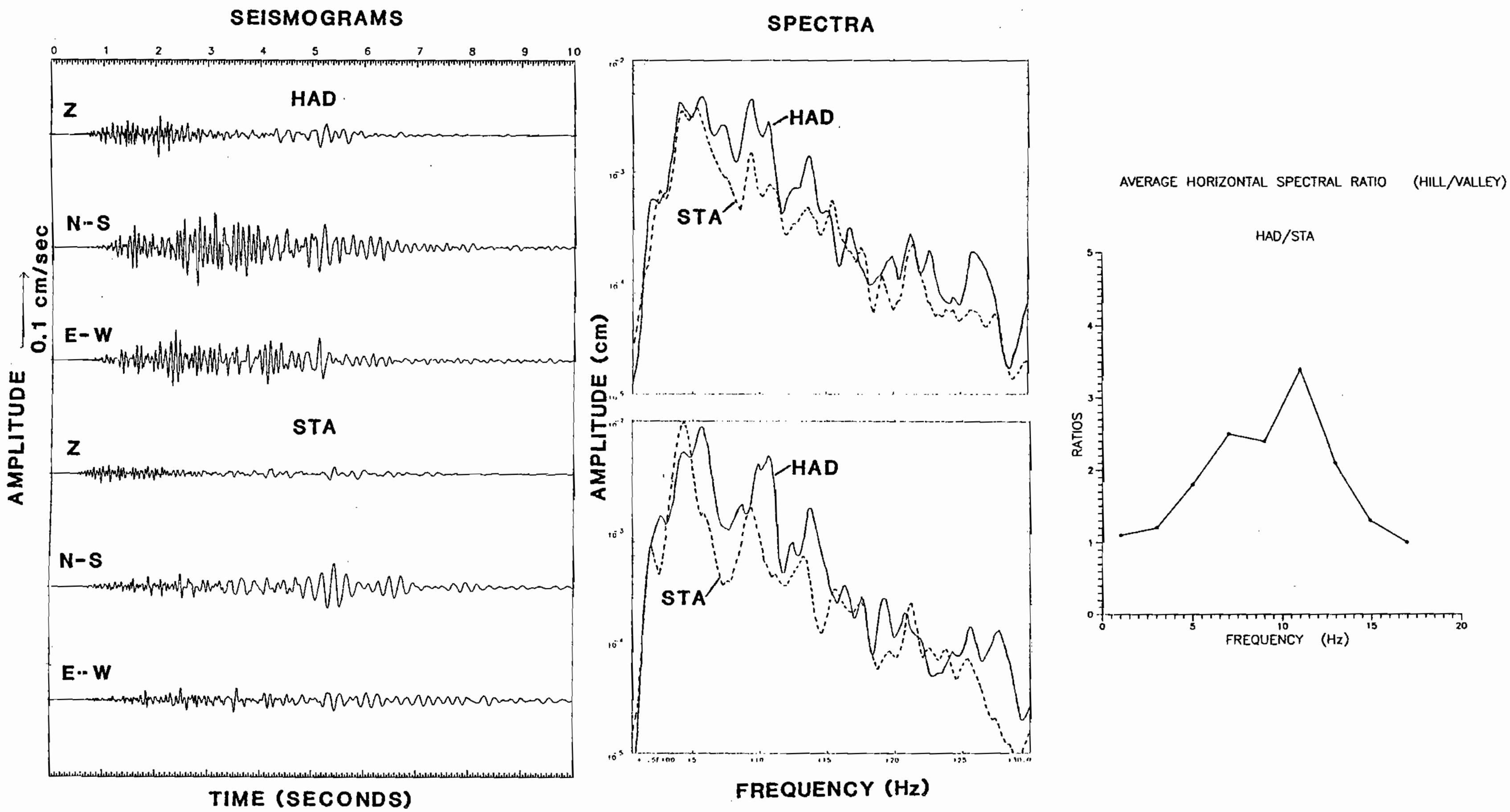


Figure 16. Seismograms and derived horizontal (N-S, E-W) spectra and the derived horizontal spectral ratios showing the difference between the valley site (STA) and the upland (HAD) site in Array No. 2.

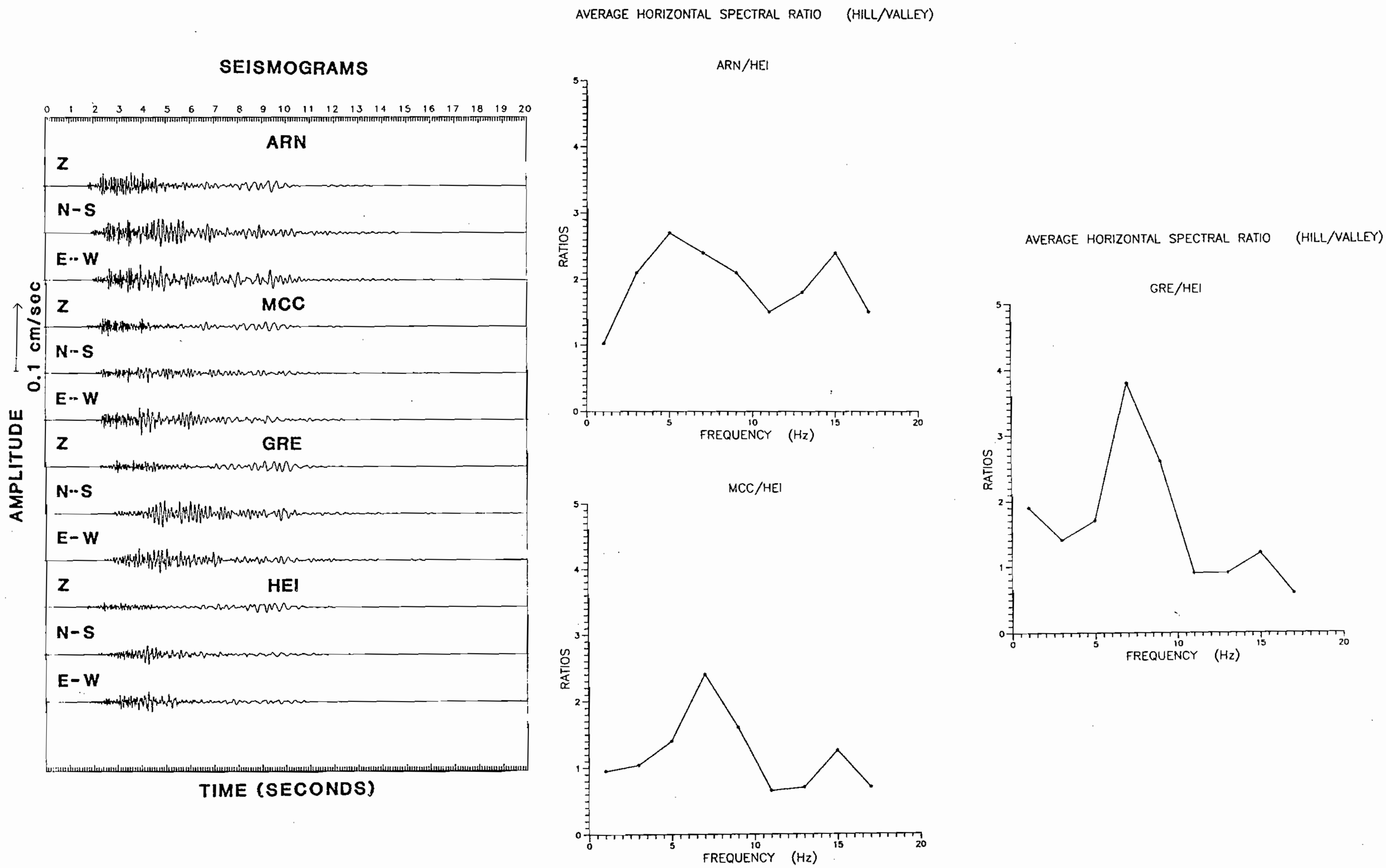
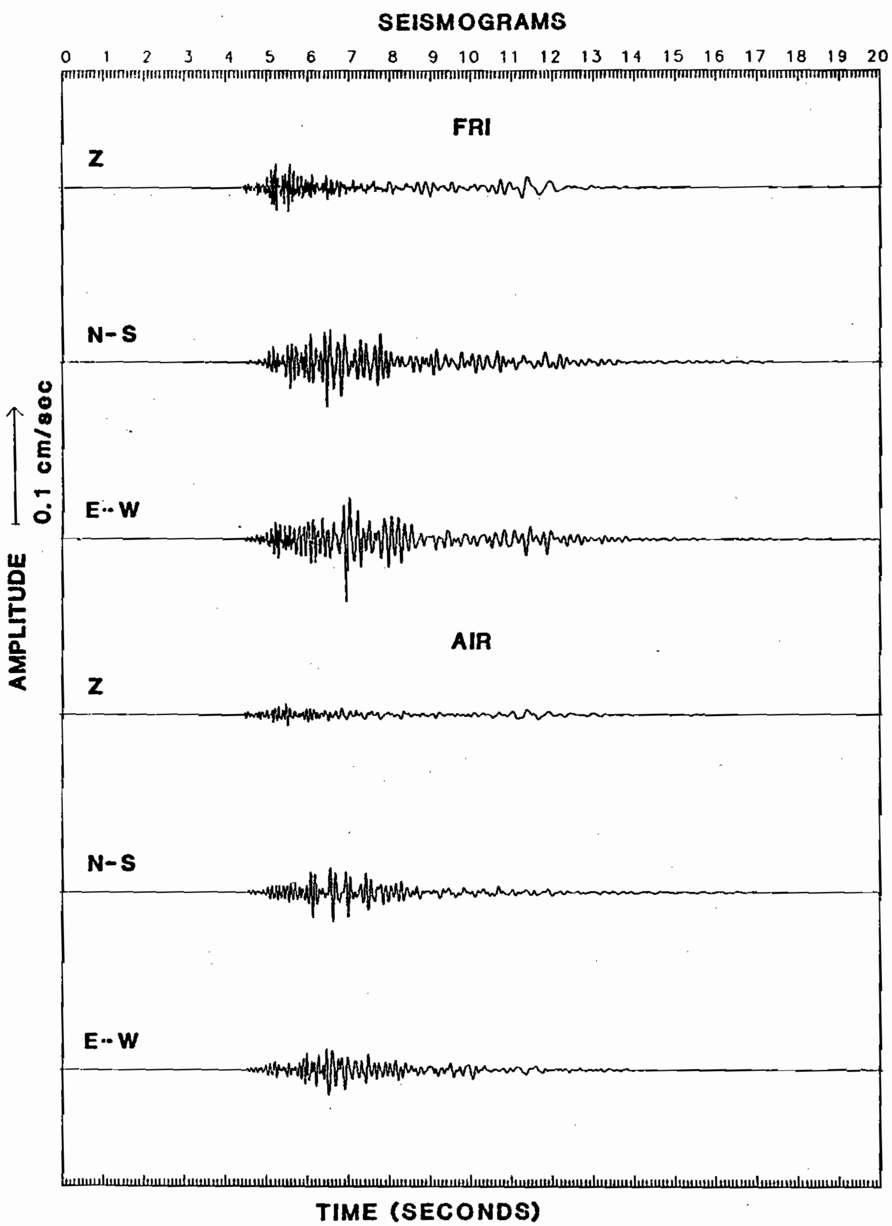


Figure 17. Seismograms and derived spectral ratios showing the differences between a site located in the valley (HEI) and the sites located in the upland areas (GRE, MCC, ARN) in Array No. 3.



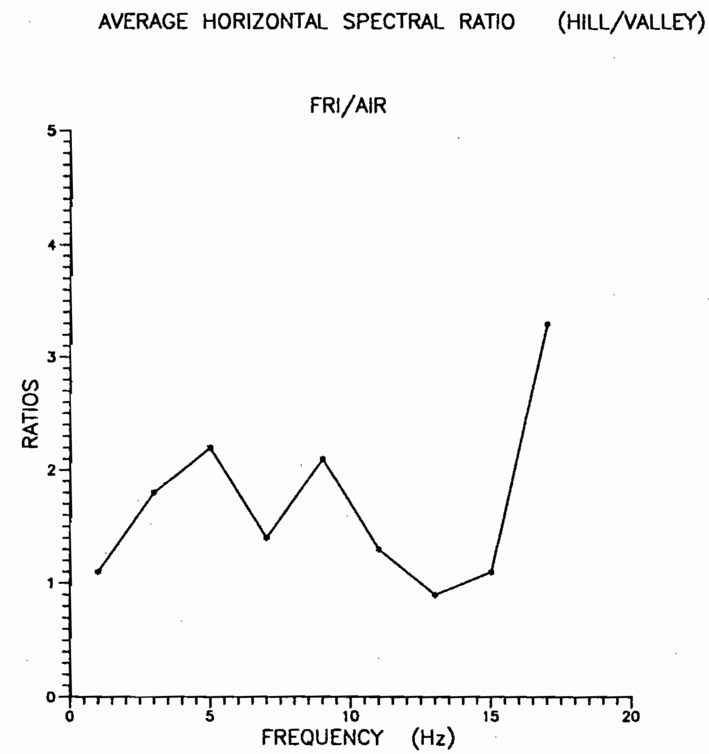


Figure 18. Seismograms and derived spectral ratios showing the difference between a lowland (AIR) and an upland (FRI) site in Array No. 4.

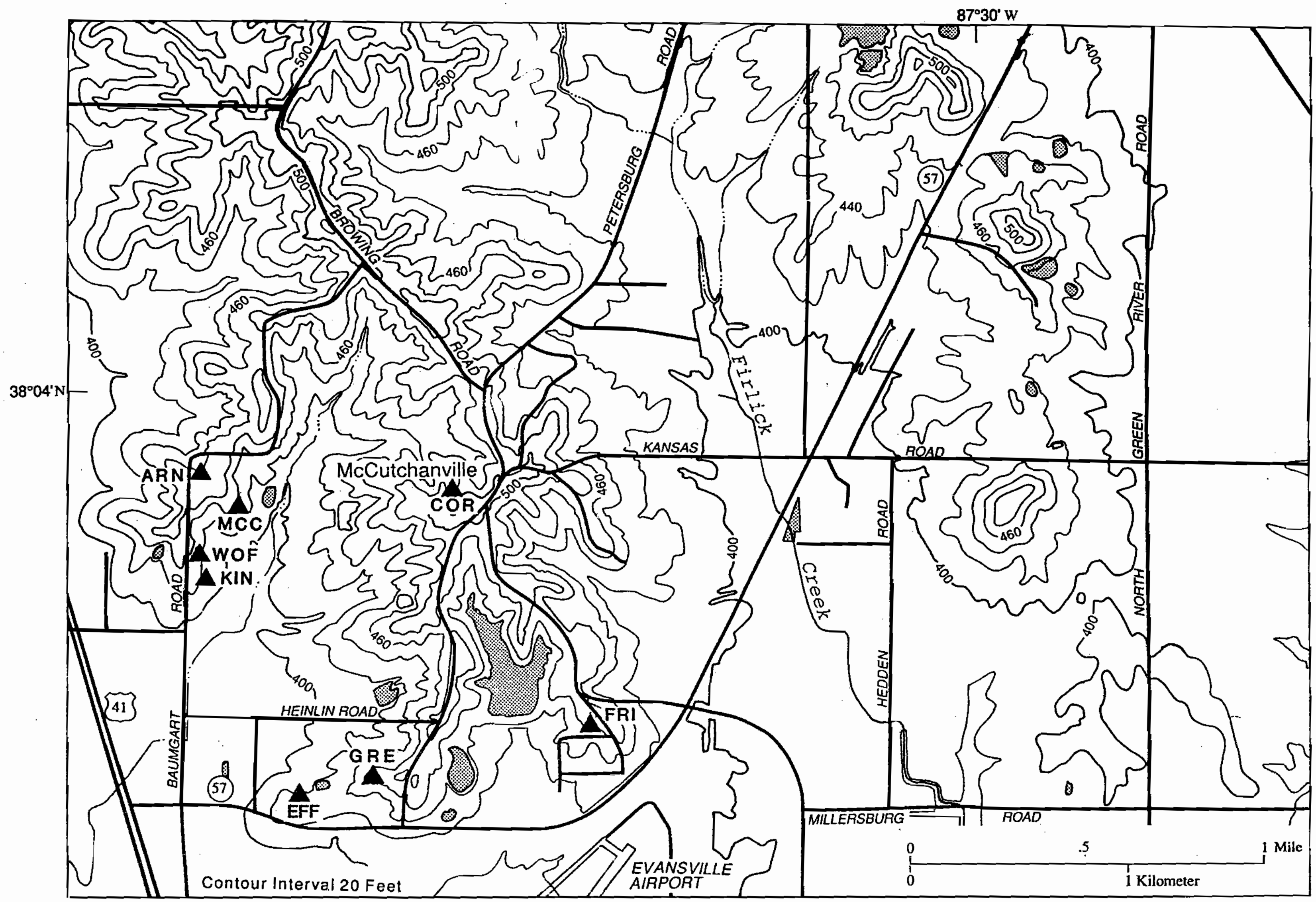


Figure 19. McCutchanville study area. Array Number 5 is denoted by solid triangles.

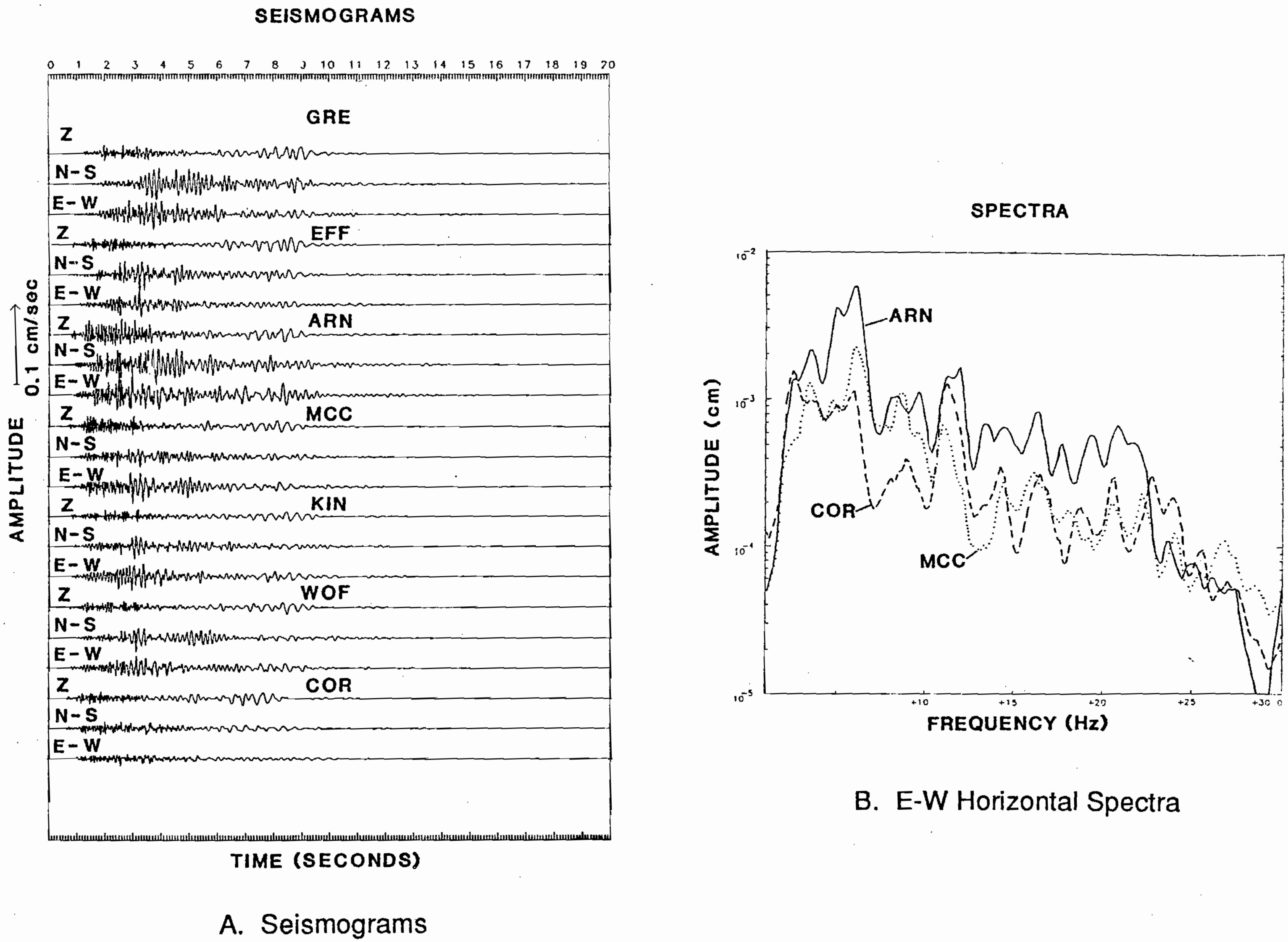


Figure 20. Seismograms and derived spectra showing difference between a site located on rock compared to sites located on a soil column, Array No. 5.

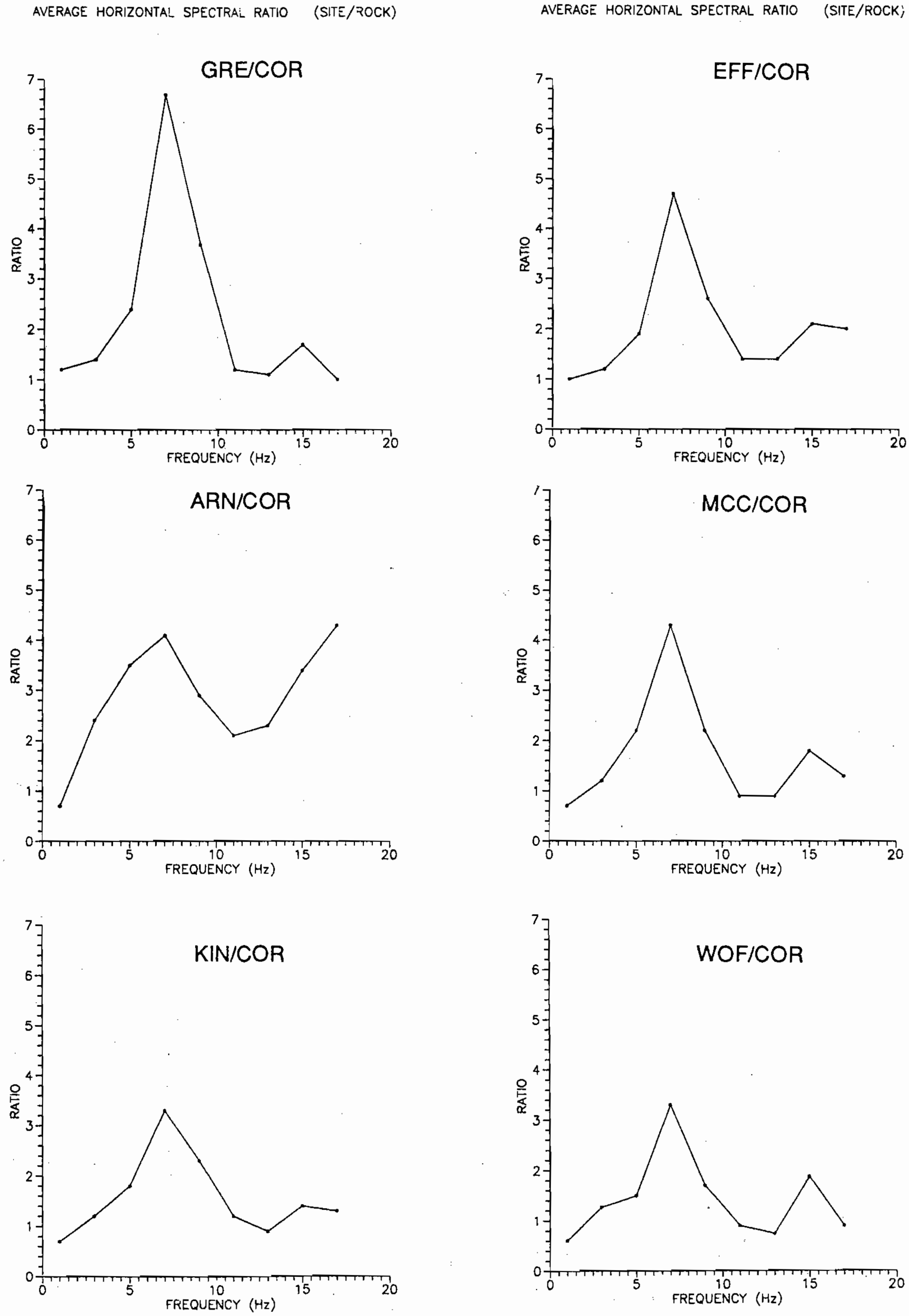


Figure 21. Spectral ratios derived from seismograms at study sites compared to a site on rock (COR), Array No. 5. Ratios are not corrected for the slight differences in distances to the mine blasts.

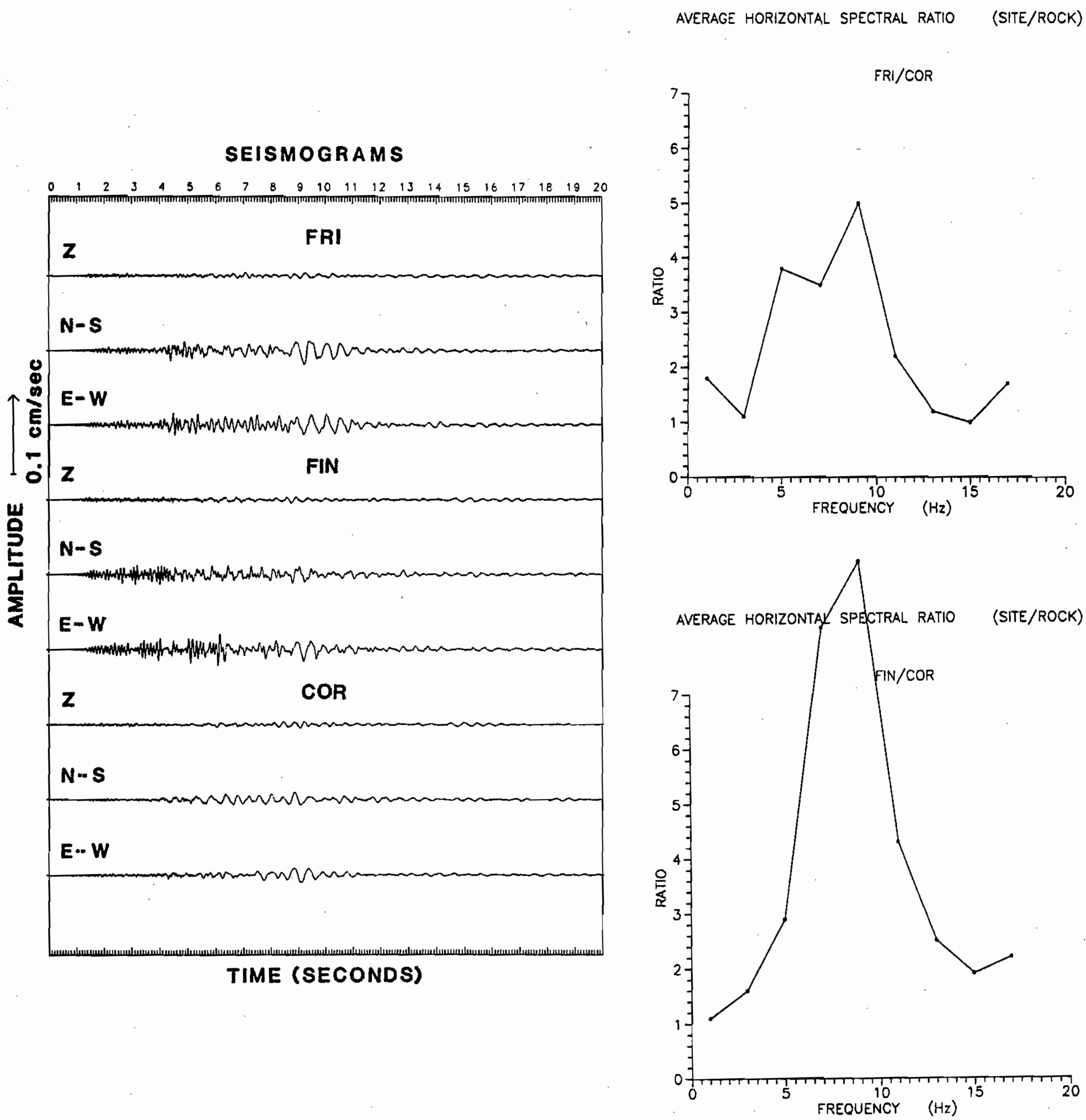


Figure 22. Seismograms and derived spectral ratios showing frequency selection by the study sites, Array No. 5. Ratios are not corrected for differences in distances to mine blasts.

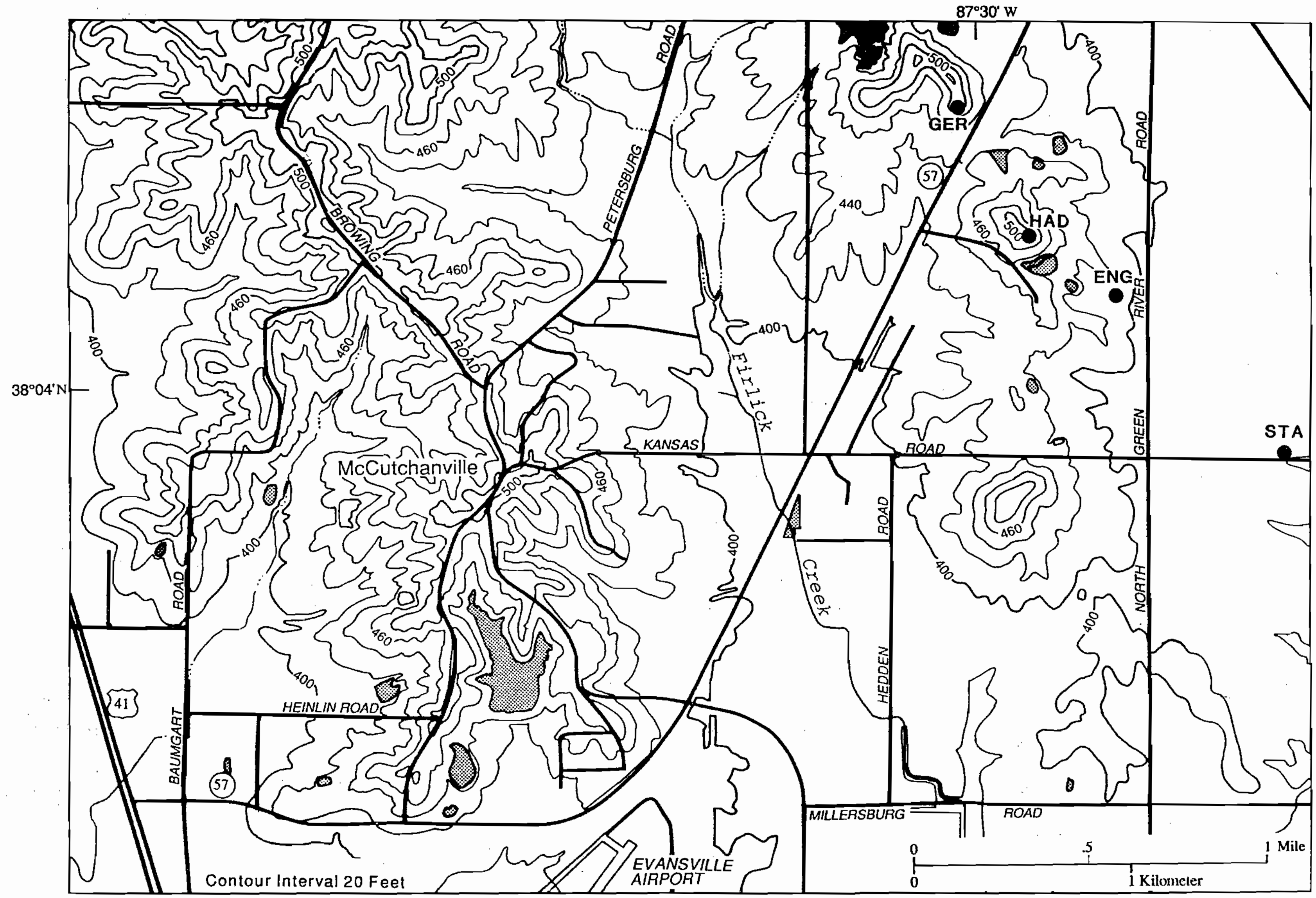


Figure 23. McCutchanville-Daylight area. Array Number 6 is denoted by solid circles.

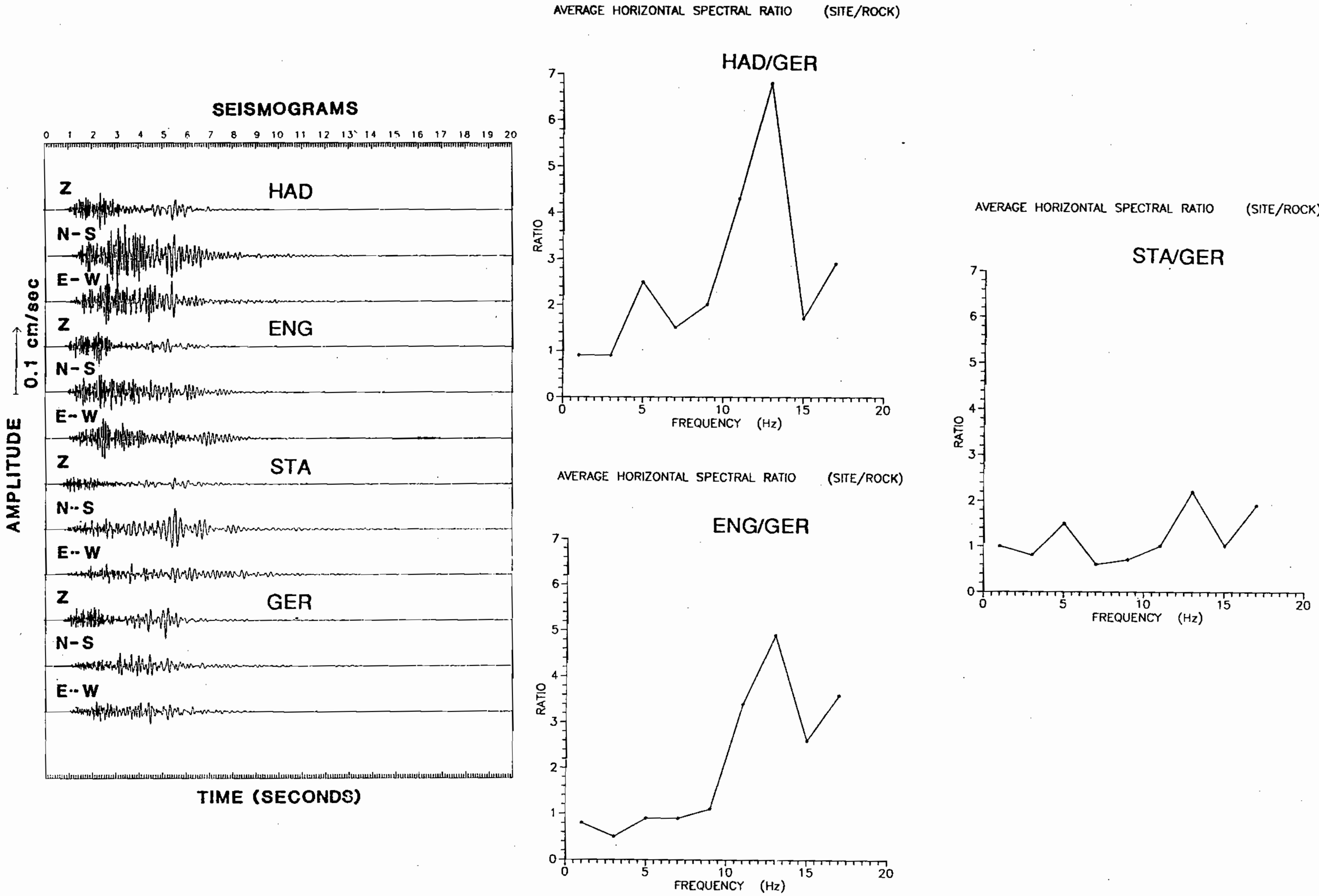


Figure 24. Seismograms and derived spectral ratios showing frequency selection by the study sites, in Array No. 6. Ratios are not corrected for the slight difference in distances to the mine blast.

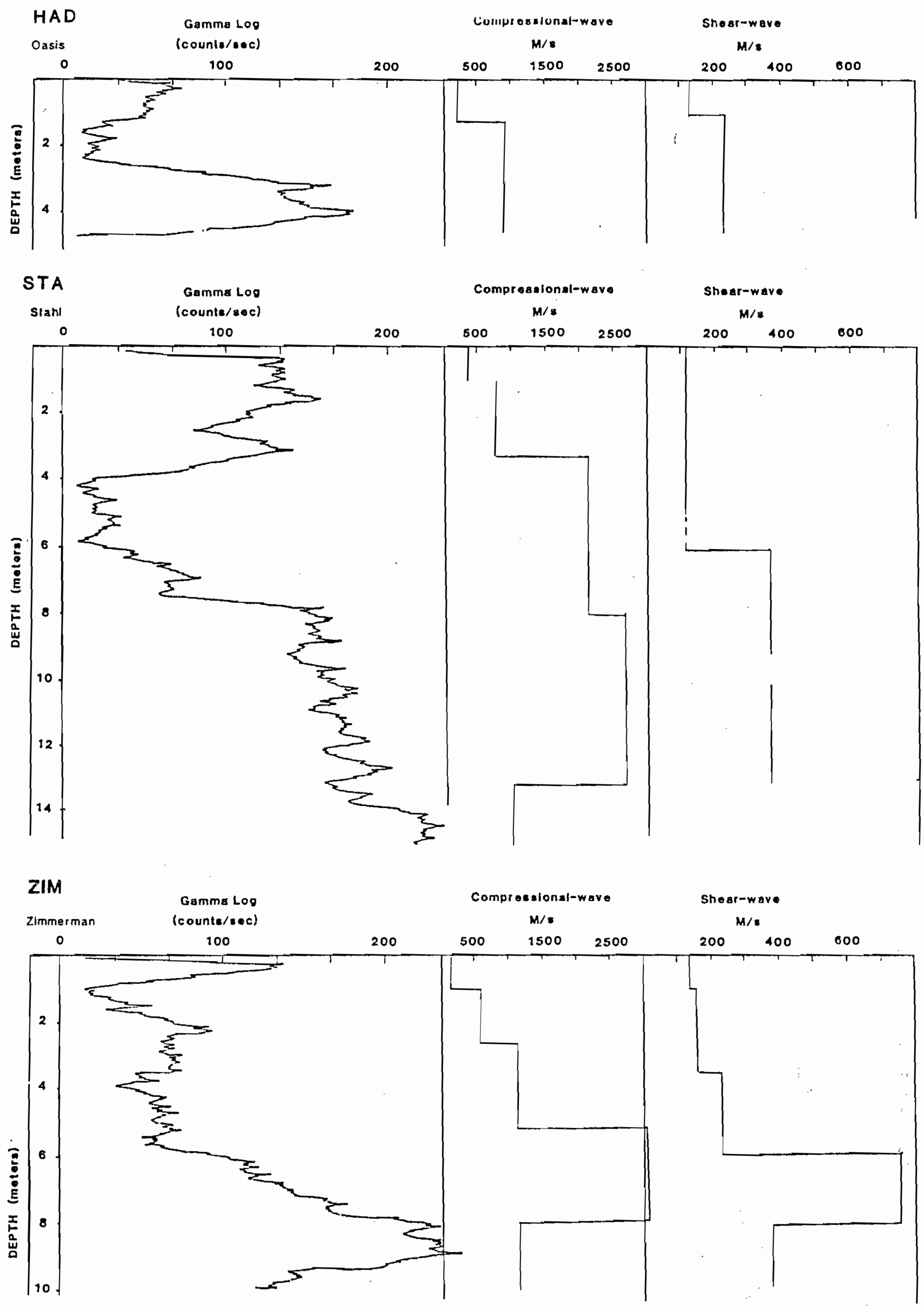


Figure 25. Bore-hole data for gamma logs, compression wave velocity, and shear wave velocity.

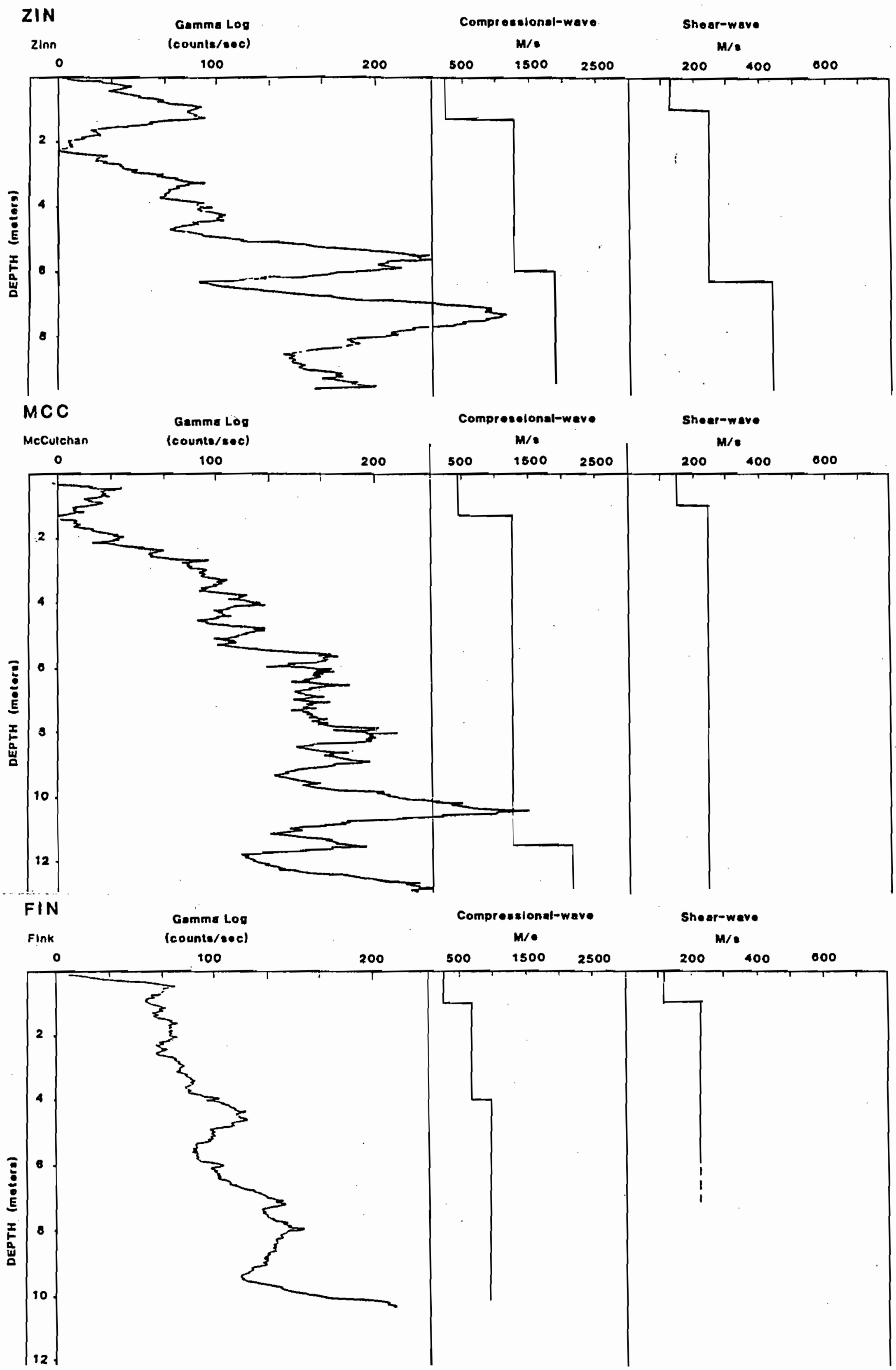


Figure 25 continued. Bore-hole data for gamma logs, compression wave velocity, and shear wave velocity.

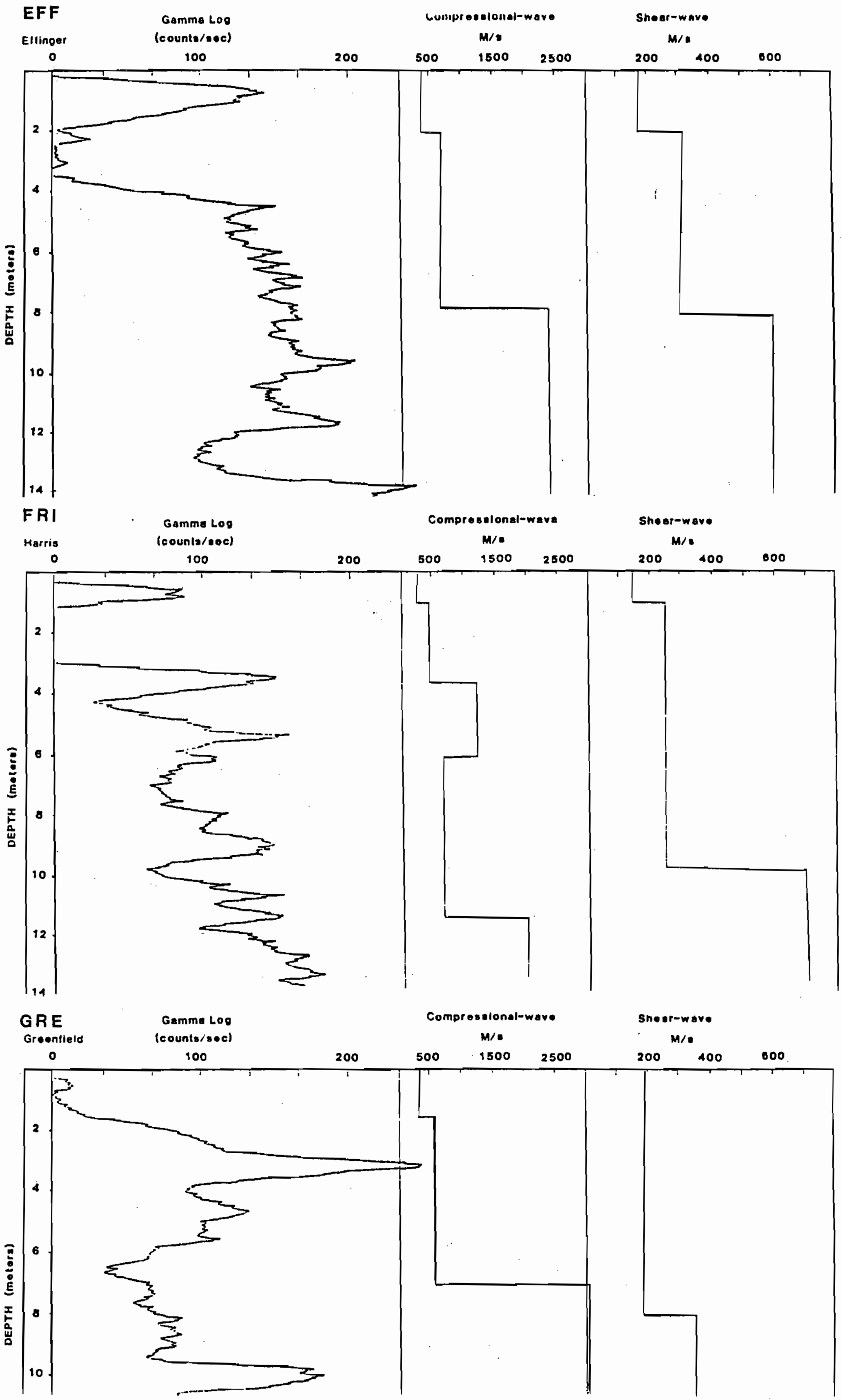


Figure 25 continued. Bore-hole data for gamma logs, compression wave velocity, and shear wave velocity.

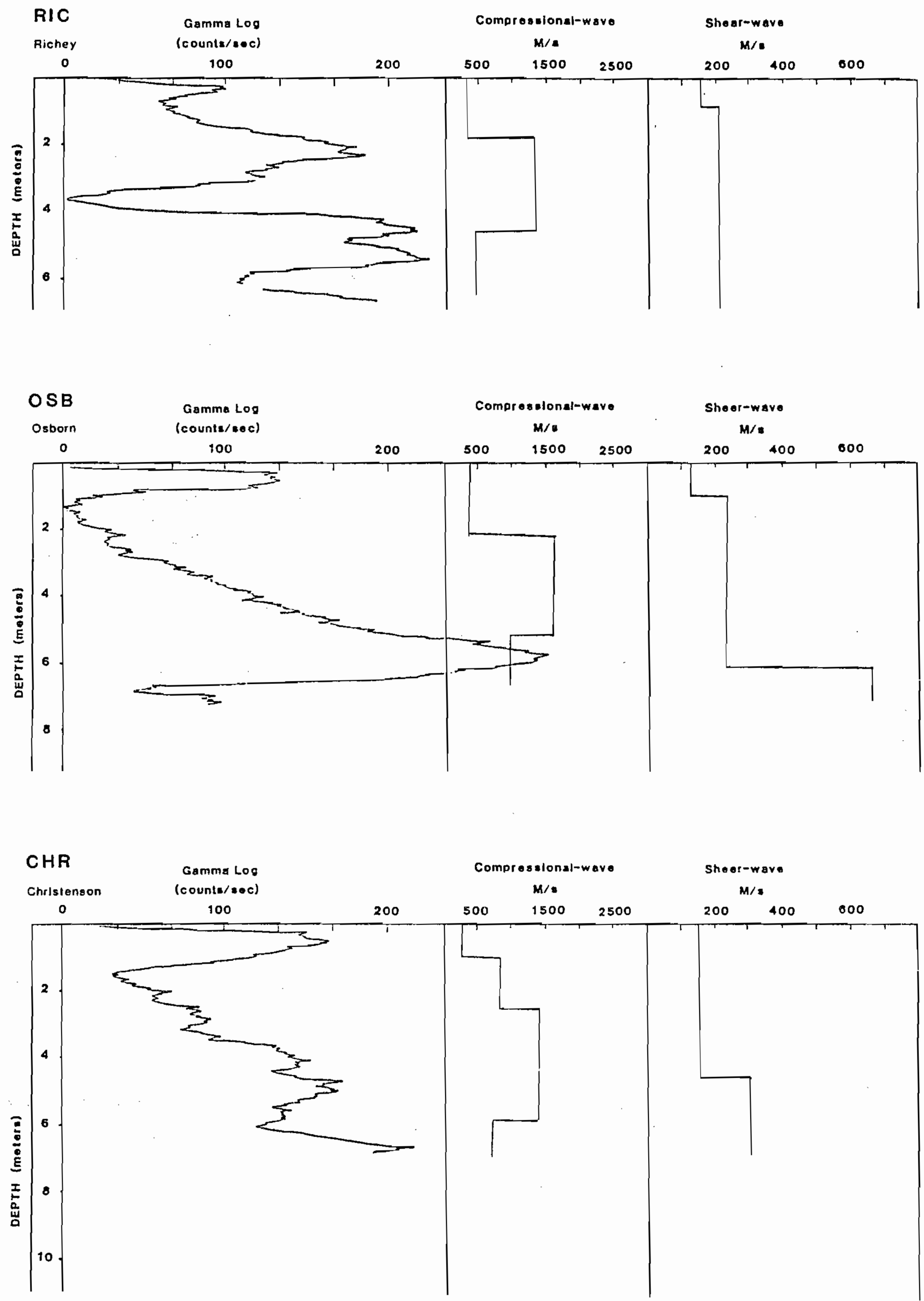


Figure 25 continued. Bore-hole data for gamma logs, compression wave velocity, and shear wave velocity.

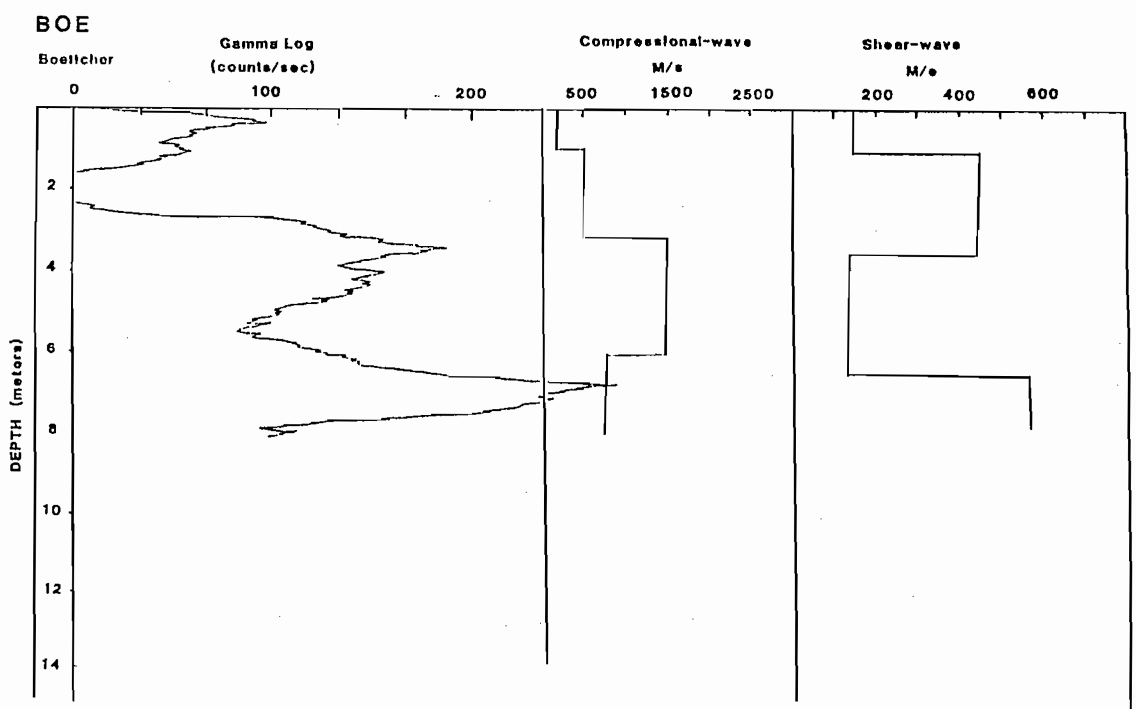


Figure 25 continued. Bore-hole data for gamma logs, compression wave velocity, and shear wave velocity.

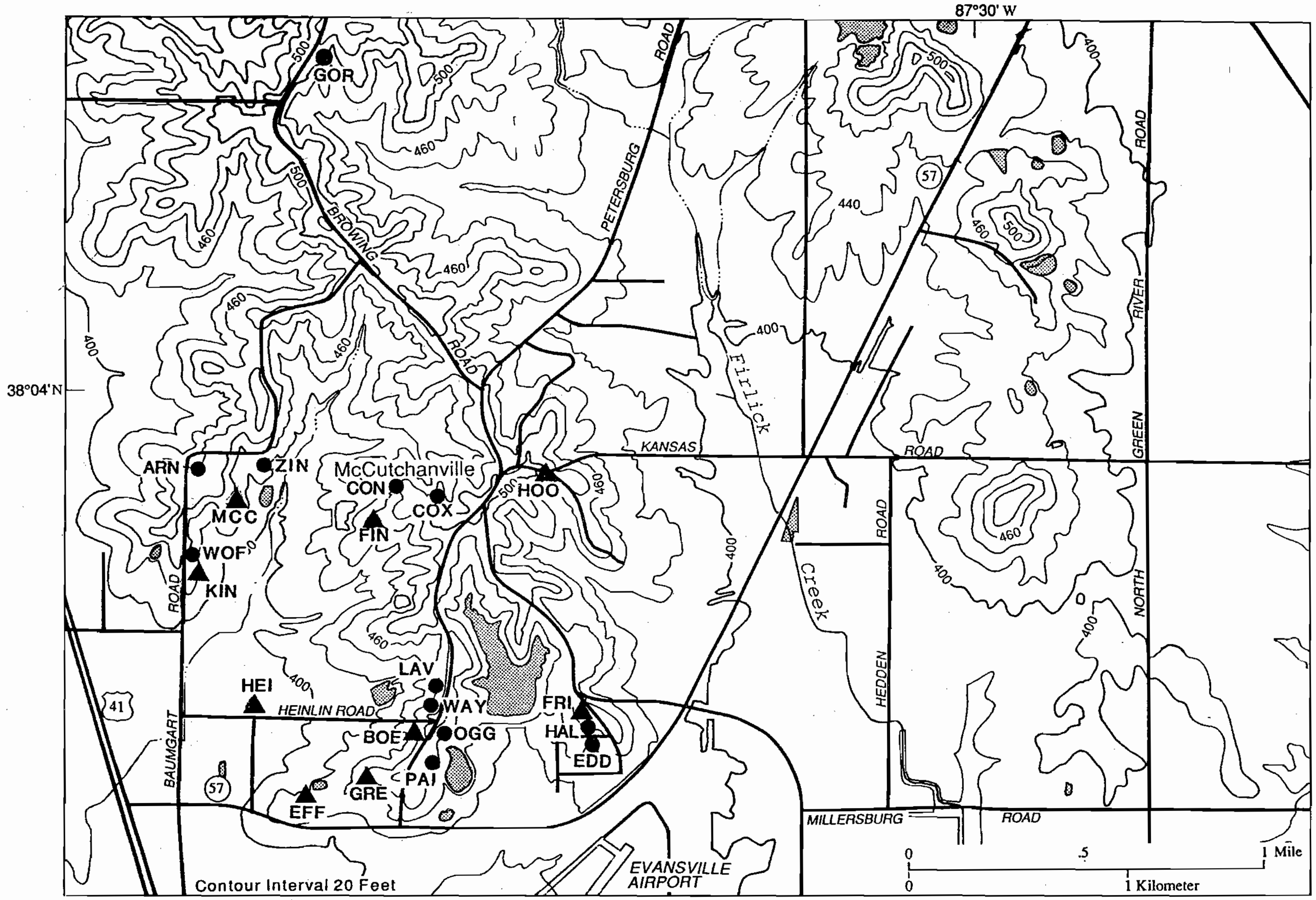


Figure 26. McCutchanville study area. The houses used in the inspection program, comparison study, and building frequency studies are shown. Complainant houses are denoted by solid triangles and the non-complainant houses are denoted by solid circles.

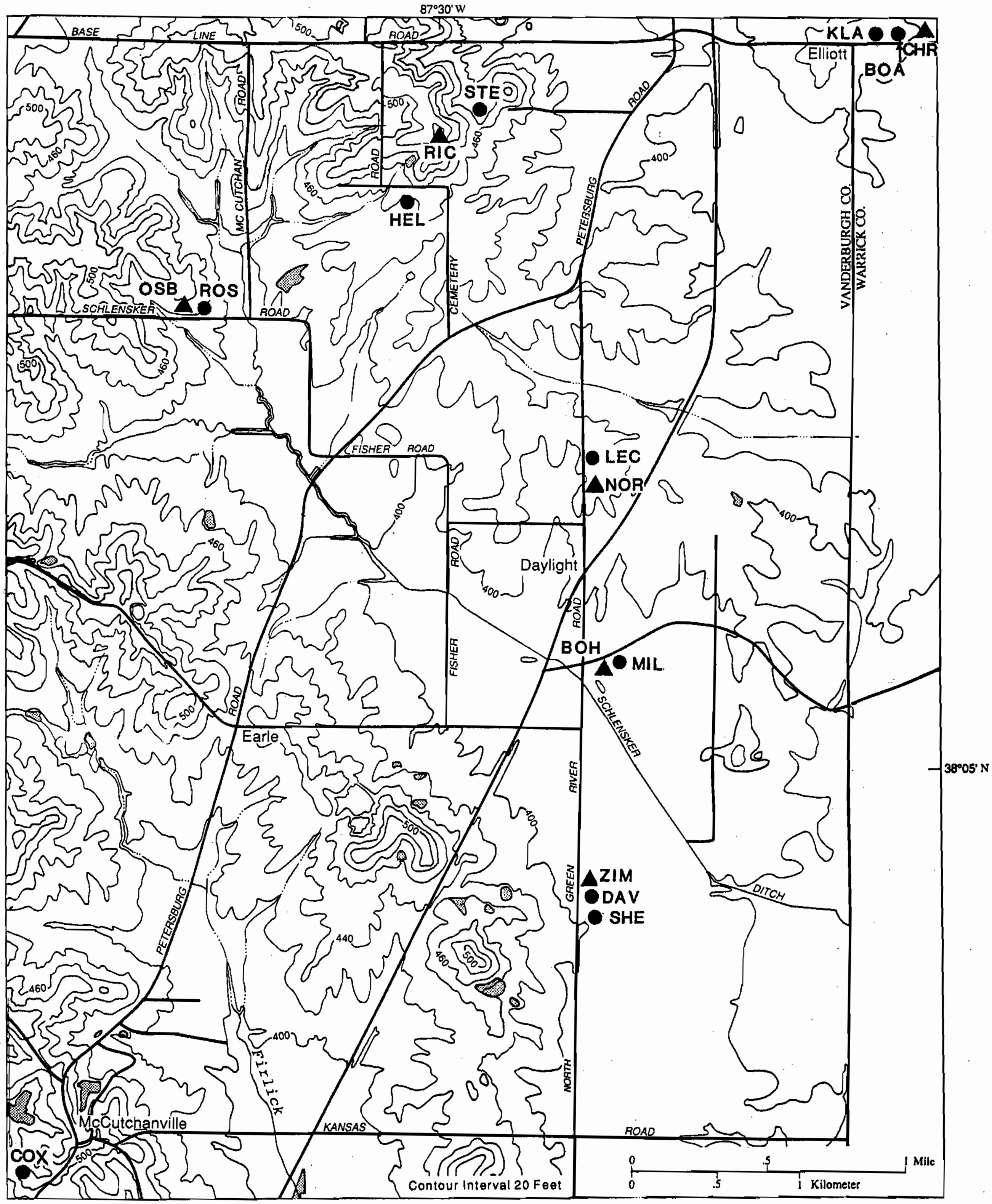


Figure 27. Daylight area. The houses used in the inspection program, comparison study, and building frequency studies are shown. Complainant houses are denoted by solid triangles and the non-complainant houses are denoted by solid circles.

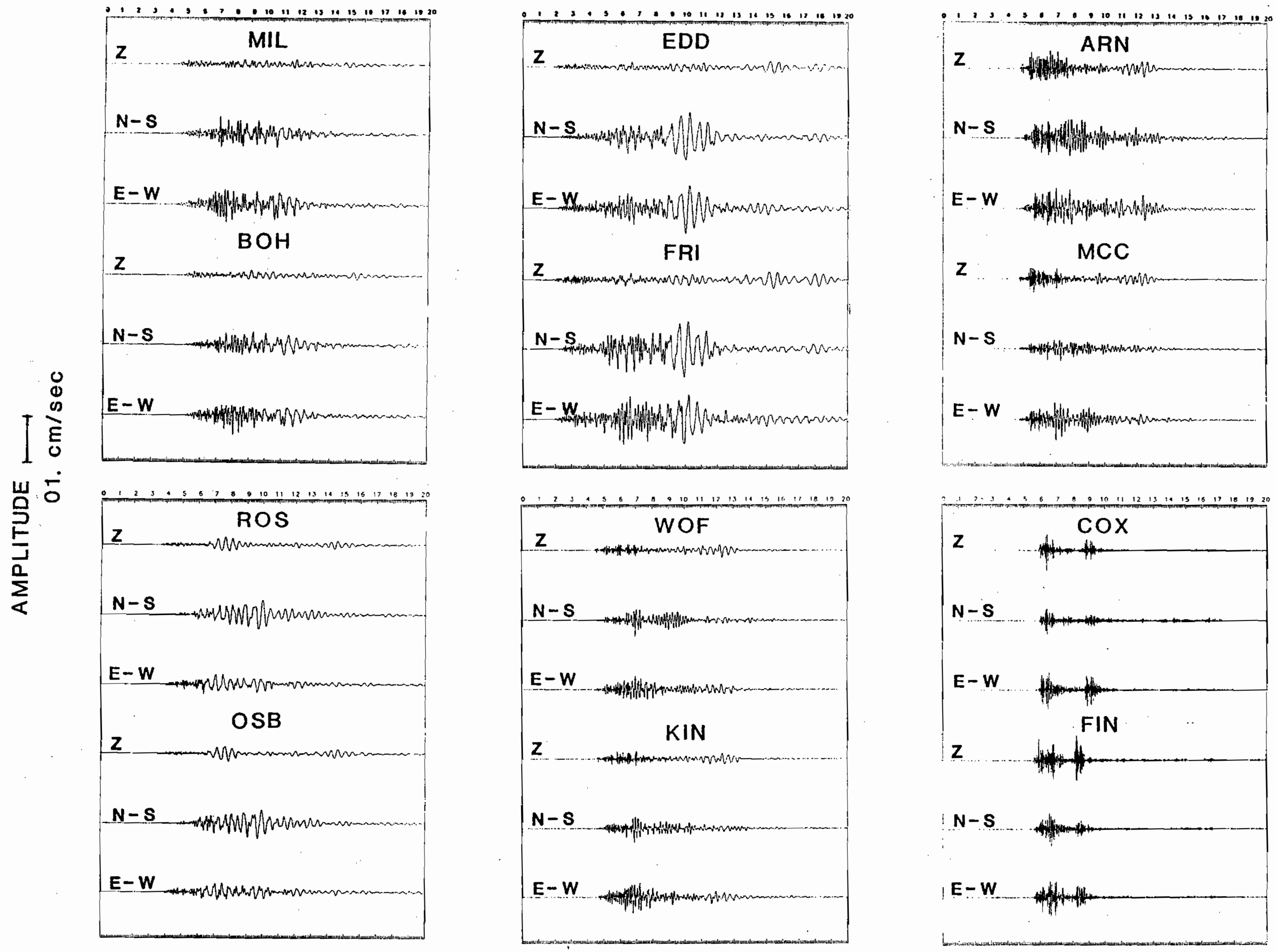


Figure 28. Seismograms at the comparison sites. All amplitudes and time scales are identical for comparisons. BOH, FRI, MCC, OSB, KIN, and FIN are the complainant sites.

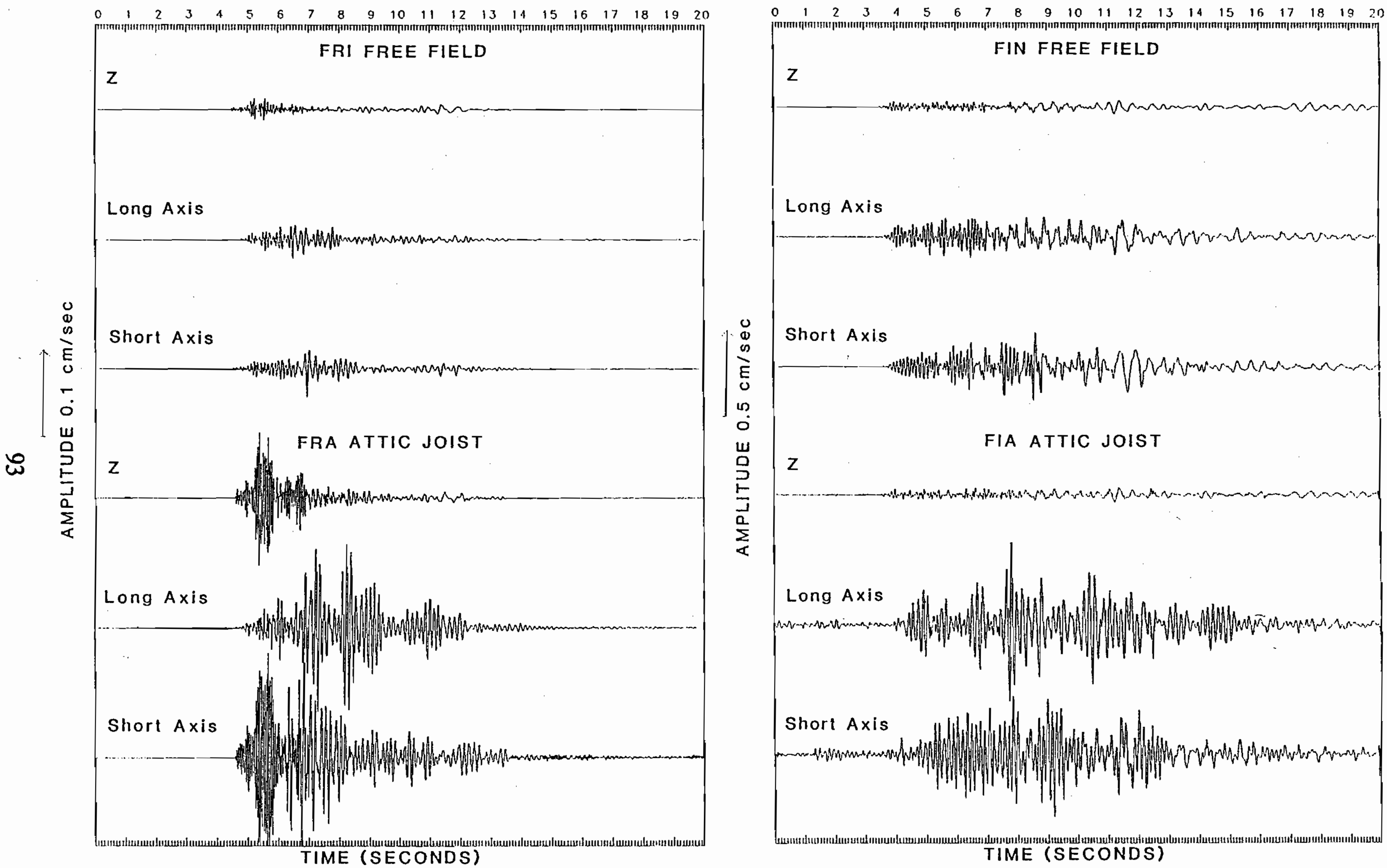


Figure 29. Seismograms comparing vibrations at free-field with the attics of two complainant homes.

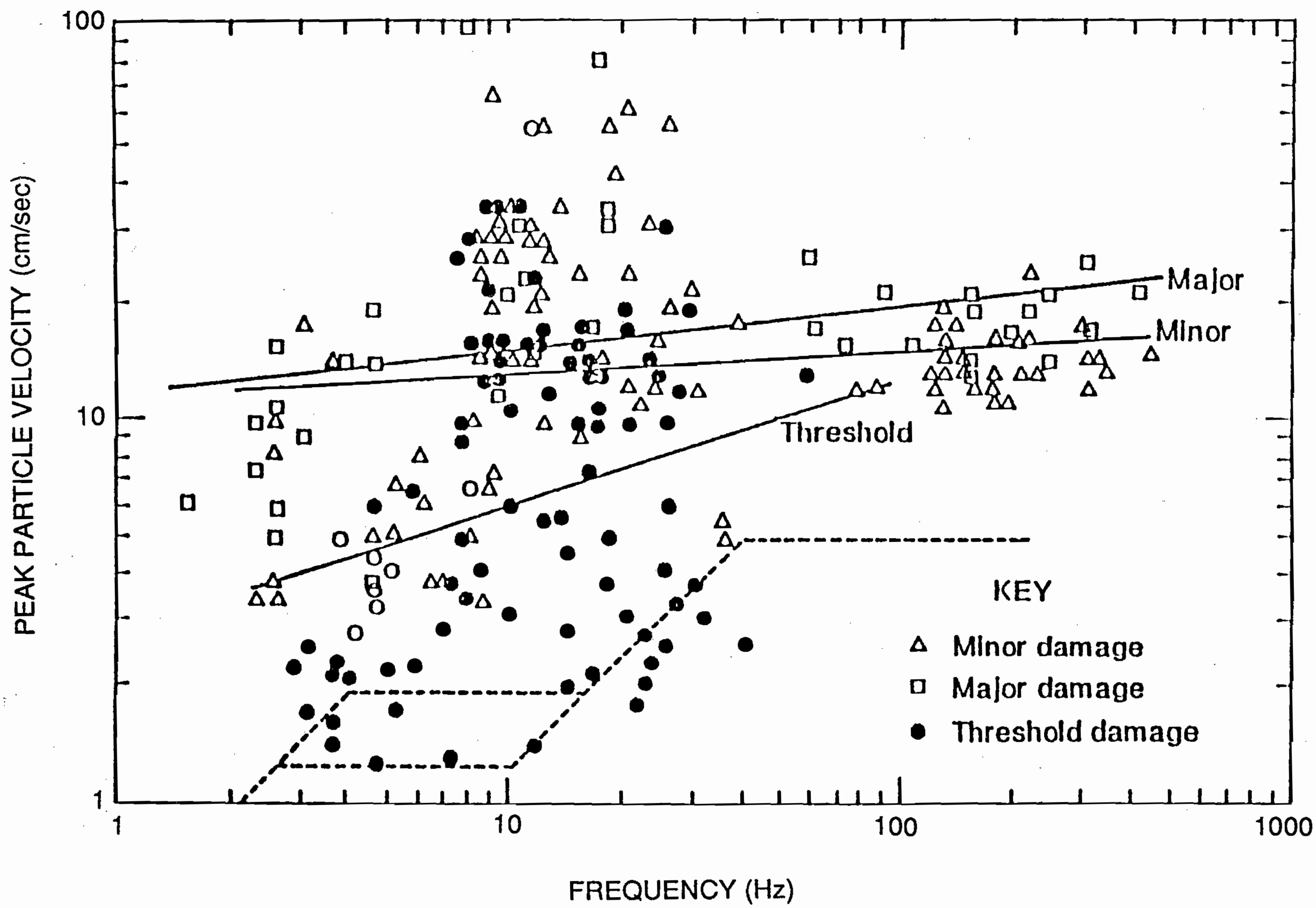


Figure 30. Envelope of safe peak-particle velocities from Bureau of Mines RI 8507 (Siskind and others, 1980). The envelope is based on a combination of velocity and displacement. The envelope and summary of vibration damage data is from Siskind and others (1990).

*U.S. GOVERNMENT PRINTING OFFICE: 1994-509-349/00006