FINAL TECHNICAL REPORT

Shear-wave Velocity of the Post-Paleozoic Sediments in the Upper Mississippi Embayment: Collaborative Research between the University of Kentucky and the University of Memphis

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Element : I

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ABSTRACT

Realistic determination of site response and modeling of earthquake induced ground motions in the upper Mississippi Embayment can not be accurately achieved without a reliable P- and S-wave velocity model for the embayment soils/sediments. We have demonstrated from 15 selected sites in the upper embayment that a reliable P- and S-wave velocity model can be achieved by combining data from seismic reflection/refraction profiles, existing deep well-logs, in-situ measurements of shallow Vp and Vs, existing geological models, and arrival time differences between the direct S and converted Sp waves from the bottom of the unlithified sedimentary basin. Because there are significant lateral velocity and structural variations in the unlithified sediment within the embayment, a representative 3-D velocity structure for the embayment can only be established via extensive high-resolution measurements of velocity structures in the region. For example, the lack of systematic measurements in previous S-wave models creates an oversimplification such that lateral velocity variations (especially at shallow depth) are undetected. Consequently, more measurements will be needed to fully develop a reliable 3-D velocity model.

In this investigation, the University of Kentucky performed (1) seismic P-wave and SH-wave reflection/refraction soundings, (2) data analysis and correlations with drill hole logs, and (3) modeling of the P-wave seismic reflections to the bedrock, and SH-wave velocities at selected broadband and short-period seismic station sites to a depth of ~400 m. The University of Memphis performed (1) the compilation of arrival time differences between the direct S and S-to-P converted waves from the bottom of the sediments beneath each selected seismic station (e.g. Chen et al., 1996), (2) the inversion of S-wave velocities of the deeper (>400 m) sediments beneath the selected seismic stations. This report discusses the results from the University of Memphis tasks.

NONTECHNICAL SUMMARY

This study demonstrates that well-constrained seismic p- and s-wave velocity models of the Post-Paleozoic unlithified sediment in the Upper Mississippi Embayment can be derived by integrated geophysical methods. The thickness of the sediments varies from a few meters near the edges of the Embayment, to several hundreds of meters near the center. These sediment deposits are expected to have a profound influence on the ground motions in the area as a result of a damaging earthquake in the New Madrid seismic zone. Knowledge of the sediment shear-wave velocities allows researchers to assess the hazard posed by earthquakes, as well as recommend mitigation strategies.

INTRODUCTION

The Upper Mississippi Embayment, as described by Toro et al. (1992), is a large wedge-shaped syncline that dips to the south, and is filled with several tens to several hundreds of meters of unlithified, post-Paleozoic sediments (Fig. 1).Underlying the embayment, and aligned approximately with its axis is the New Madrid seismic zone, which Cramer (2001) estimated is capable of producing large (> M7) earthquakes at mean-recurrence intervals of 498 years. The effects of the unlithified embayment sediments on ground motions from a damaging earthquake are poorly understood because of the lack of instrumental records, and a lack of reliable S-wave velocity data for the deeper (> 100 m) sediments. The sediments in the embayment, as well as the subsurface topography of the bedrock could have a significant effect on the earthquake ground motions in the area. S-waves propagating upward through thick layers of unlithified sediments are apt to be amplified and induce resonance at selected frequencies. Resonance can also be set up in a sediment-filled basin if the S-waves are incident to the edge of the basin, and the width of the basin is comparable to its depth (Frankel, 1994).

P- and SH-wave seismic reflection and refraction data have been acquired at 16 sites (Fig. 2). The sites were chosen for a reasonable spatial distribution, nearness to drill holes that penetrated into bedrock, and nearness to seismograph stations from which earthquake travel-time differences between the direct S- and top-of-bedrock converted Sp-waves are known. In addition, existing drillhole data, P- and SH-wave seismic reflection/refraction data, and earthquake travel-time differences between the direct S- and top-of-bedrock converted Sp-waves were used to estimate the S-wave velocities of sediments across the study area.

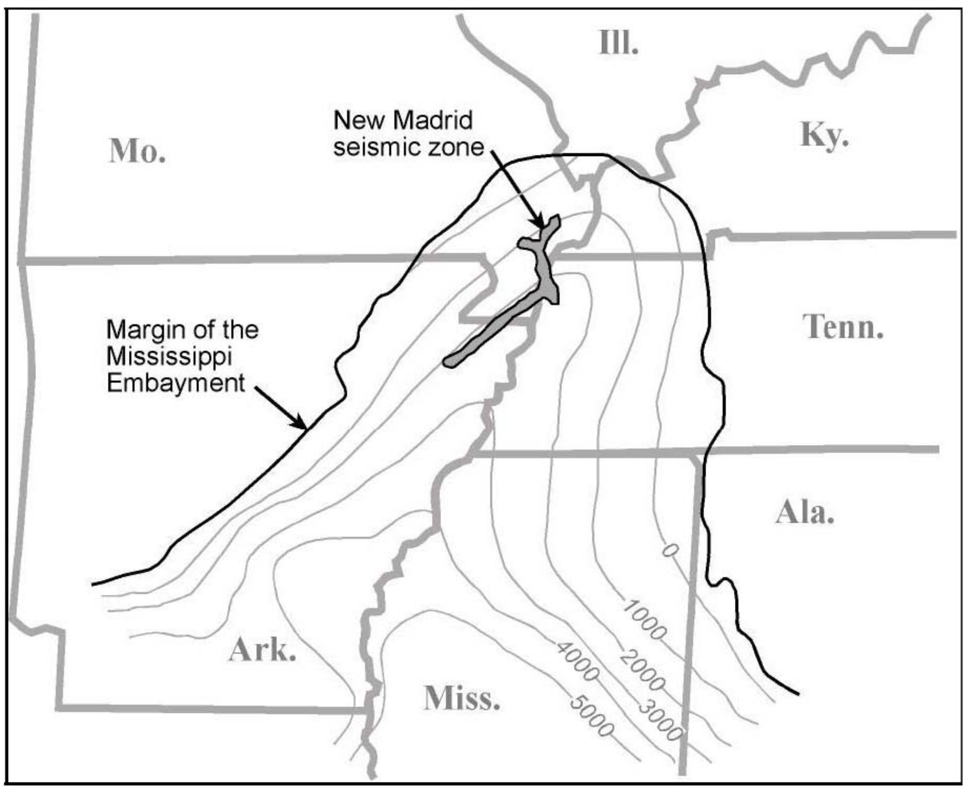

Figure 1. The upper Mississippi embayment has sediment thickness in excess of 600 meters. The contours shown represent feet below mean sea level.

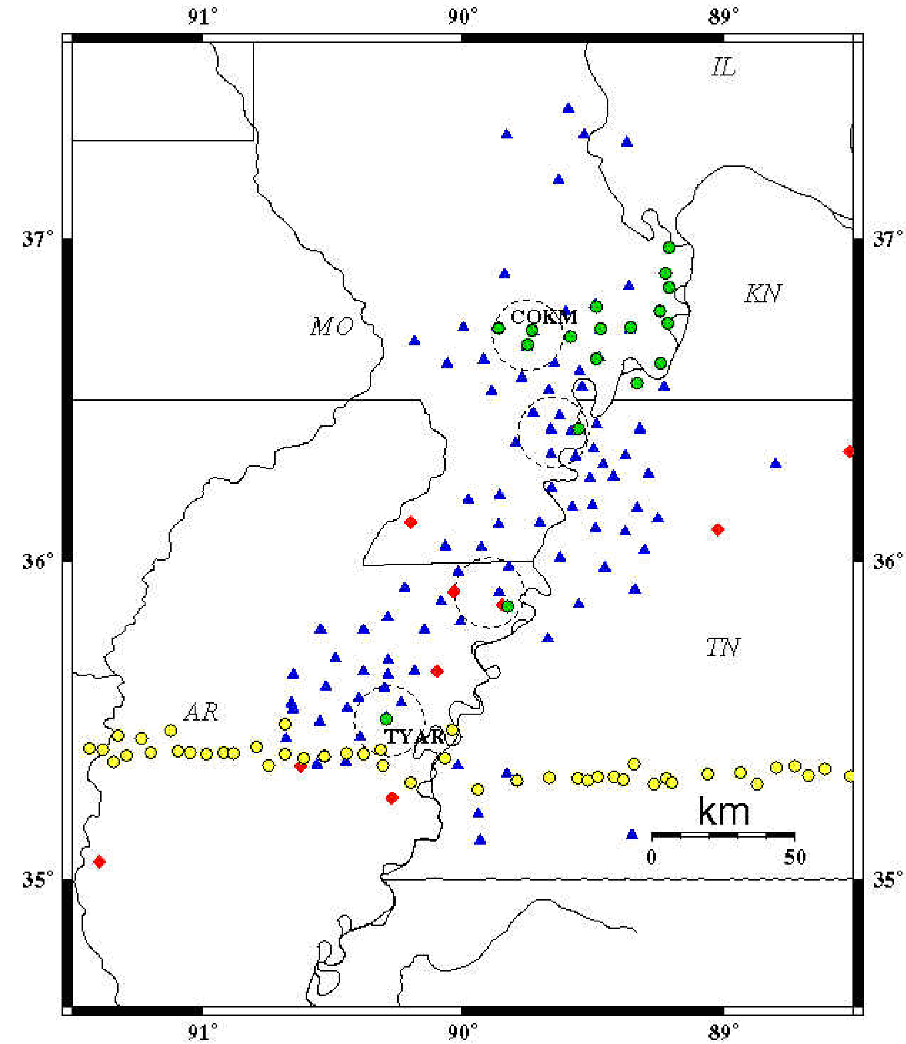

Figure 2. Map showing CERI seismic station locations (solid blue triangles) and deep wells/well-logs (solid orange diamonds). Open yellow circles along an east-west orientation are the locations where seismic profiles are available at the University of Kentucky from previous experiments. Dashed large circles around TYAR, COKM, and two other deep well sites are the clusters of sites done during the current project. Additional P- and S-wave seismic profiles are also collected at northern upper Mississippi embayment near Kentucky, Tennessee, and Missouri border (solid green circles) where thickness of sediments is relatively thin (200~300 meters).

PREVIOUS STUDIES

The early results of a few seismic refraction lines defined a layer of 0.65 km thickness and Vp=1.8 km/sec was introduced to represent the sediments in the Upper Mississippi Embayment (e.g. Mooney et al., 1983; Andrews et al., 1985) where the S-wave velocity of the sedimentary layer was determined under an assumption of Vp/Vs = 3.21 from similar sediments elsewhere. From a 1-D velocity inversion of 3-component PANDA data in the central NMSZ region, Yang

(1992) and Chiu et al. (1992) provided the first estimation of an average S-wave velocity of 0.6 km/sec for the sedimentary layer which leads to a Vp/Vs = 3.0.

It has long been recognized from deep wells and from seismic refraction profiles that thickness of the sediments in the Mississippi Embayment region increases toward the south and center of the basin (e.g. Mooney et al., 1983; Andrews et al., 1985; Dart, 1992). From their study of the converted seismic waves occurred from the bottom of the sediments, Chen et al. (1994) and Chen et al. (1996) concluded that the non-vertically incident P- and S-waves from any NMSZ earthquake will not only incident to the surface almost vertically but also will generate large amplitude converted waves across the interface between the overriding sediments and the underlying Paleozoic basement. In their modeling of surface wave dispersion using Vp, Vs and thickness information of the sediments from adjacent well logs, Dorman and Smalley (1994) concluded that the sediments in the embayment serve as an excellent wave-guide to excite very efficient surface waves from earthquakes inside the embayment than that from outside. Based on the relationship between basin resonance and the thickness of basin fill, Bodin and Horton (1999) estimated an average S-wave velocity of 834 m/sec and 960 m thickness for the post-Paleozoic sediments beneath Memphis area. The Post-Paleozoic sediments in the embayment have basically been characterized as a layer or subdivided into many horizontal layers with an average S-wave velocity inside each layer.

Using the previously determined average Vp=1.8 km/sec (e.g. Mooney et al., 1983; Andrews et al., 1985) and thickness of the sediments from nearby deep wells (e.g. Dart 1992), Chen et al. (1996) were able to estimate the variations of average S-wave velocities of the sediments in the ranges from 0.45 to 0.67 km/sec beneath the 40 PANDA stations in the central NMSZ. They concluded that the region of higher S-wave velocity could be correlated to thicker and more compact sediments. Pujol et al. (1997) pointed out that P- and S-wave velocity of the sedimentary section is not a constant from a JHD analysis of earthquake data. Liu et al. (1997) shows significant differences on shallow P- and S-wave velocity profiles of the sediments from in-situ measurements at Shelby Forest, Tennessee; Marked Tree, Arkansas; and Risco, Missouri.

Combining data from well-logs and from some shallow seismic profiles, Mihills (1998) and Mihills and Van Arsdale (1999) were able to subdivide the Post-Paleozoic sediments into layers based on lithology. Gao (1999) and Gao et al. (2001) combined well-log information (Dart, 1992), the geological model of Mihills (1998) and Mihills and Van Arsdale (1999), the in-situ measurement of shallow S-wave velocity information at Marked Tree (Liu et al., 1997), the shallow P- and S-wave velocity information from a few nearby seismic reflection/refraction profiles provided by the University of Kentucky, and the arrival time differences between the direct S and the S-to-P (i.e., S- and Sp-waves) converted waves to determine first a representative 8-layer P-wave velocity model and then inverted for the deeper S-wave velocities of the sediments.

The results of Gao (1999) and Gao et al. (2001) provided the first reliable estimation of 3-dimensional P- and S-wave velocity model for the embayment sediment; this has improved the hypocentral locations for NMSZ earthquakes. These data have limited shallow P- and S-wave velocity information, and are from a small area in the central NMSZ, however. In addition, lateral variations of the upper most two sedimentary layers were not accounted for in the modeling. This may significantly affect the determination of S-wave velocities for deeper sedimentary layers.

NEHRP CONTRIBUTIONS

The joint research demonstrated that the integration of SH- and P-wave velocity measurements, times, drill hole depths, seismic sections, and sonic logs, can provide a well-constrained P- and S-wave velocity model of the post-Paleozoic sediments for ground motion modeling throughout the Upper Mississippi Embayment. Knowledge of the deeper sediments is critical to ground motion modeling (Anderson et al. 1996). In addition, major impedance boundaries within the post-Paleozoic sediments in the Upper Mississippi Embayment will significantly benefit the linearity/nonlinearity study of the ground motions throughout the region.

INVESTIGATIONS UNDERTAKEN

During the current USGS project support that started on March 1, 2002, the UK and UoM team have conducted seismic reflection and refraction profiles adjacent to two CERI seismic network stations, a few deep well-sites, and a few sites of shallow sediments in the upper Mississippi Embayment (Figure 1). Short seismic reflection and refraction profiles using P- and SH-wave sources were conducted at these sites. The P-wave source was powerful enough to observe strong reflection from the bottom of the sediments even at the southern most sites where the thickness of sediments is around 800 meters. However, the S-wave hammer source was used to sample only the uppermost ~100 meters of sediments. The experiment was designed to demonstrate that P-wave velocity model for the sediments beneath a seismic station can be determined from the analysis of traditional seismic reflection and refraction profiles. Nearby deep wells with geological and sonic logs can provide critical information to constrain the interpretation and to validate the results from the P-wave profile. Therefore, a well-defined P-wave velocity profile for the entire sediment section and shallow S-wave velocity profile beneath each site have been determined. Details about seismic data and seismic line interpretation can be found in the final technical report from the University of Kentucky for the same award number.

We have inspected all seismograms since 1995 at the CERI stations near each site of seismic profile. The arrival time differences Δt_{S-S_p} between the direct S and the S-P converted waves (Sp) from the bottom of the sediments are measured from each seismogram. Since the velocity contrast between the bottom of sediments (Vp≈2.2 km/sec) and the underling Paleozoic rocks (Vp≈6.0 km/sec) is extremely high, the direct S and the converted Sp waves are likely to incident to surface stations near vertically in spite of epicentral distances, depths, and azimuths of earthquakes. Therefore, the arrival time differences Δt_{S-S_p} observed at each site from earthquakes of various depths, azimuths, and epicentral distances are almost a constant which can be determined from a simple least square fitting. The S-wave velocity model for deeper sediments can thus be preliminarily determined from a simple linear inversion of Vp/Vs ratio for the sediments using Vp model, shallow Vs model, and Δt_{S-S_p} as the *priori* information.

RESULTS

Figures 3a and 3b show the representative P- and SH-wave seismic profiles, respectively, that are being collected and processed. Strong layered interface inside the sediments can be clearly identified. Comparisons of these seismic data with nearby well log data (Figure 4) often found agreement of major horizons within 5%; however, in a few instances mists of a little more than 10% was observed. A powerful MiniVib source to be used in the future will significantly enhance the strength of seismic signals to improve the resolution and accuracy. Because velocity contrast across the bottom of the sediments is the strongest among all the sedimentary interfaces, and P-wave sources have the capacity to sample the entire section of sediments, clear reflections from deep interfaces including the top of the Paleozoic bedrock can be identified and analyzed (Figure 3a).

The S-wave hammer source was used to sample the very near surface interfaces shallower than ~100 meters (Figure 3b). In the remaining period of the current project, we are planning to use MiniVib S-wave source to improve the sampling depth of the S-wave. Figure 5 shows a summary of the interpreted shallow S-wave velocity profile for a few selected sites in the upper Mississippi Embayment. The shallow S-wave velocity models show very significant lateral variations and very slow S-wave velocity near the surface, most probably due to the existence of water in the shallow sediments. Depths of the top three interfaces are somewhat consistent but the difference of interval S-wave velocity between different sites increases at deeper depths.

Figure 6 shows two interpreted Vp profiles beneath the TYAR station near Marked Tree, Arkansas where abundant converted waves are observed from local NMSZ earthquakes. The two Vp profiles include one from the interpretation of seismic profile (red line) and the other from interpolation of the nearby deep well-logs (blue line). It is apparent that the interval P-wave velocity and major interfaces inside the sediments from the two P-wave profiles are very consistent with minor differences which indicate that a reliable P-wave model for the sediments is possible from seismic reflection and refraction profiles.

Figure 7 shows a typical 3-component seismogram recorded at one of the CERI seismic station. Clear S and P-to-S converted wave arrivals can be identified from the two horizontal components (top two traces). The P and S-to-P converted waves can be easily identified on the vertical component (bottom trace). The arrival time difference between the direct and the converted waves (Δt_{S-S_p}) for each site is a constant from earthquakes of various epicentral distances and azimuths which varies, however, between different sites (Figure 8). Since Δt_{S-S_p} is proportional to the thickness of sediments beneath each site, a simple 1-D linear inversion of Vp/Vs ratio can be achieved to determine the S-wave velocity model for the deeper sediments using the P-wave model, the shallow S-wave model, and the Δt_{S-S_p} observations as the *priori* information. The resultant S-wave velocity model for the selected site is shown in Figure 6 (green line) which satisfies the observed Δt_{S-S_p} and other relevant information at this site. In the future experiment using MiniVib or other powerful S-wave source, we should be able to determine the S-wave velocity model for the entire thickness of sediments from the seismic profile. Results of S-wave model obtained from the 1-D linear Vp/Vs inversion should be supplemental to that determined from the seismic profiles.

Since the sedimentary basin in the upper Mississippi Embayment is characterized by very significant vertical and lateral velocity structural variations, a systematic research similar to the one presented here over many sites in the area is the only effective and reliable approach to achieve a realistic 3-dimensional model of the sedimentary basin.

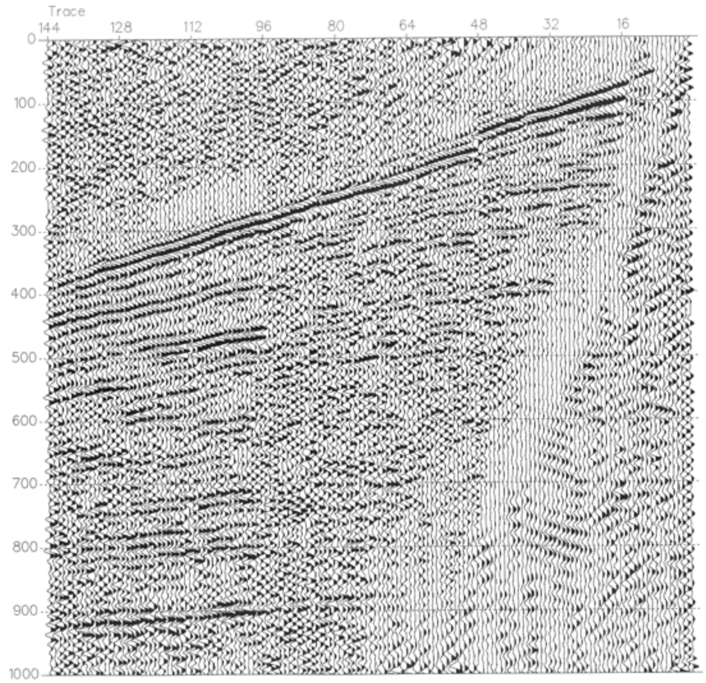

Figure 3a. Example of a processed P-wave sounding near station TYAR. Time, in milliseconds, is represented on the vertical axis. The trace spacing is 4 meters. The bedrock intercept is at approximately 860 ms.

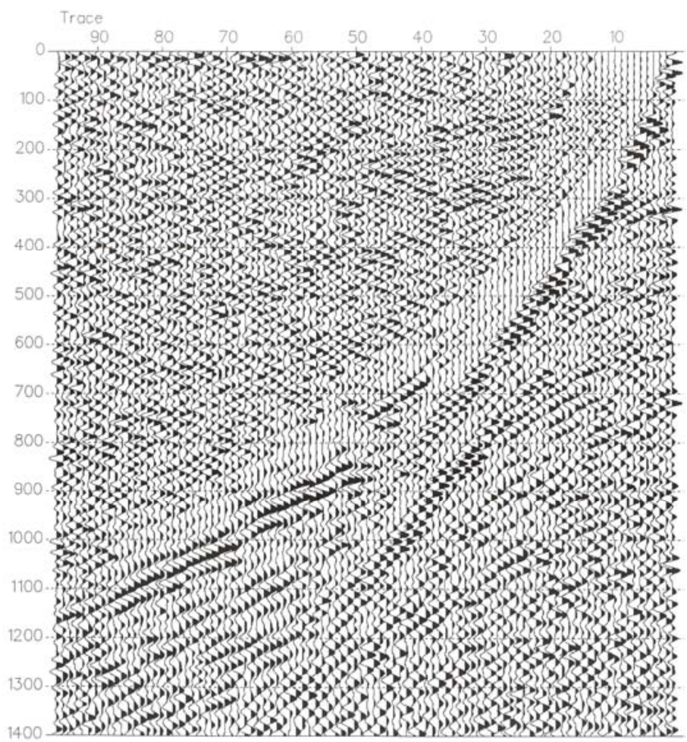

Figure 3b. Example of a processed SH-wave sounding near station TYAR. Time, in milliseconds, is represented on the vertical axis. The trace spacing is 4 meters. Only shallow reflectors can be seen.

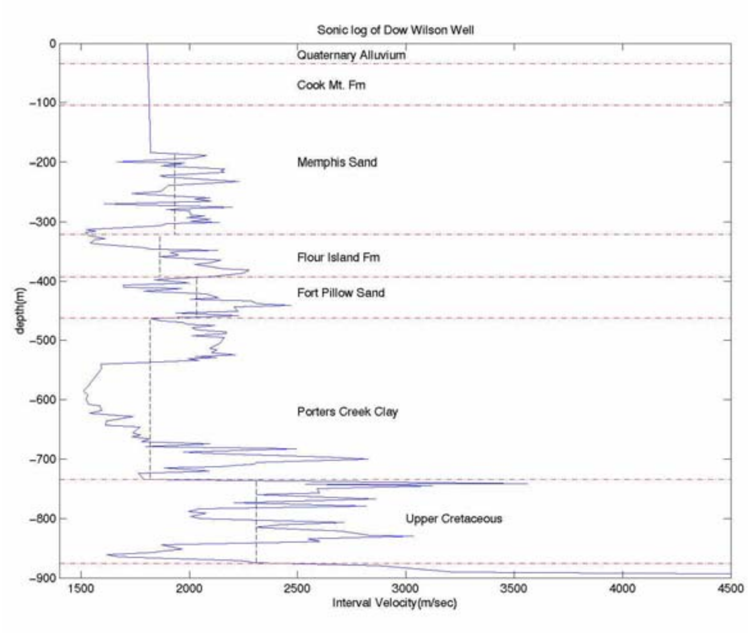

Figure 4. Example of sonic log from the Dow Wilson #1 (AR31) well. Layer boundaries (dashed-dot line) are also shown. Interval velocities shown are digitized from the original record with some errors removed.

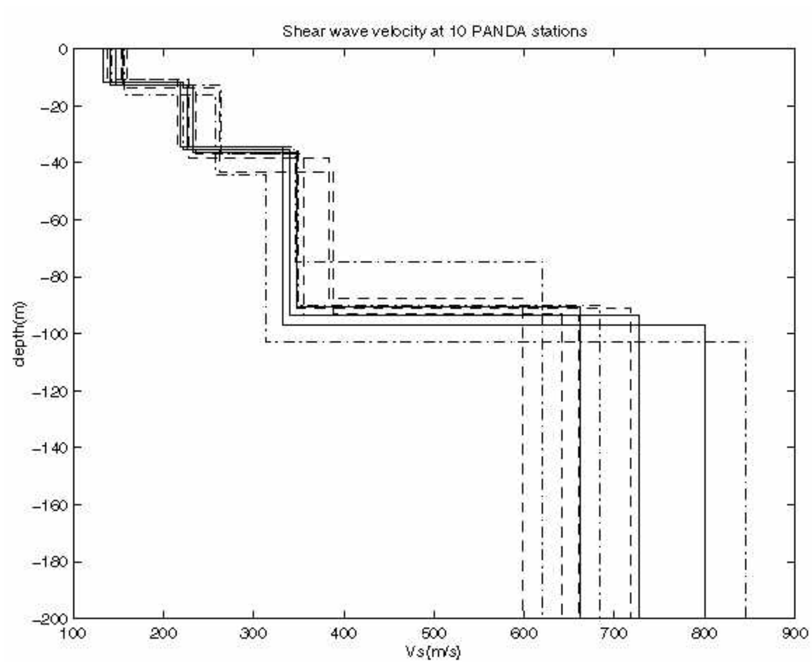

Figure 5. Shallow shear-wave velocity profiles from seismic reflection/refraction lines at various sites showing that shear-wave velocities are slower than the speed of sound in the upper most 100 meters of sediments. The top three interfaces are consistent but not the interval S-wave velocity at deeper depth.

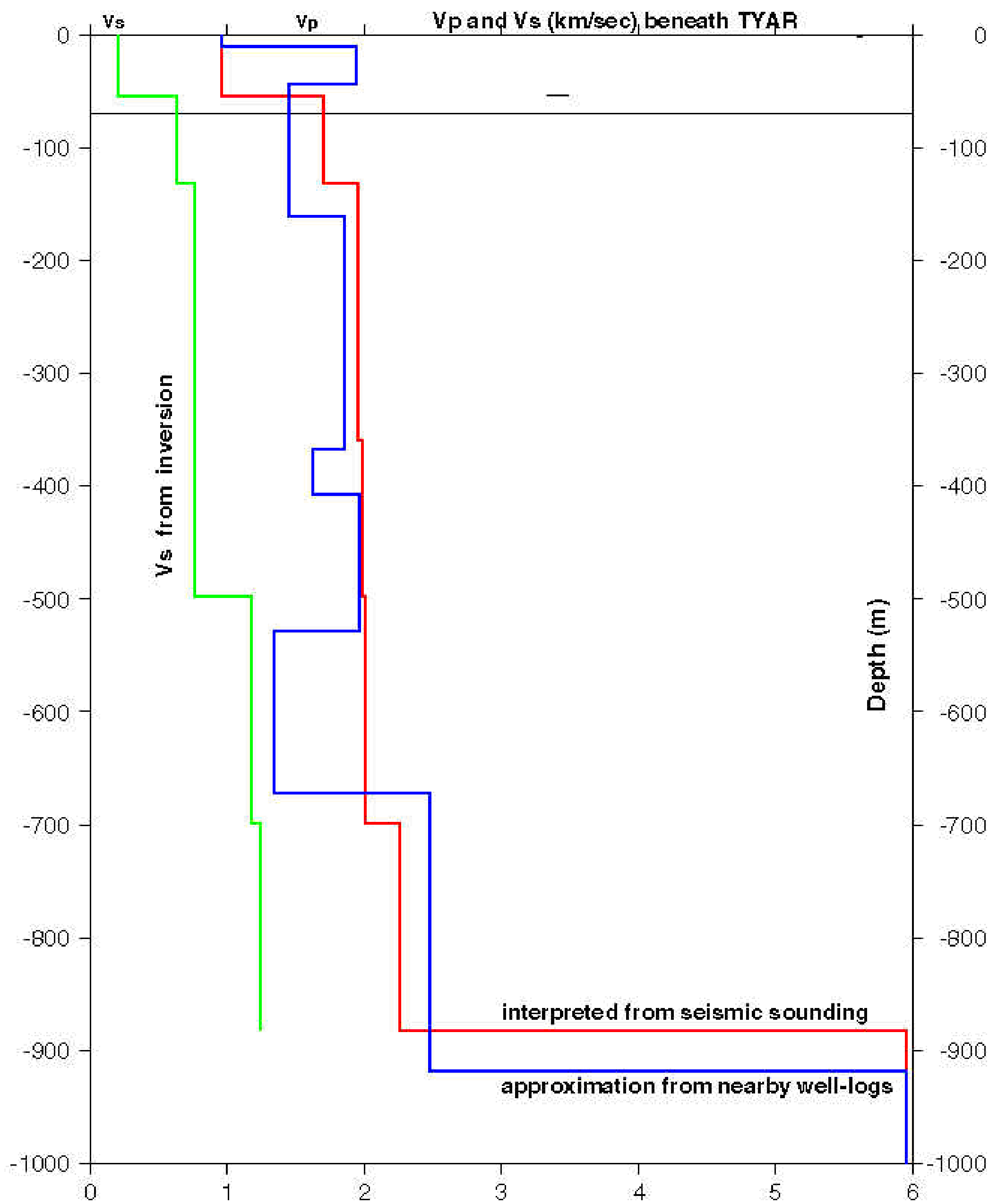

Figure 6. Vp and Vs as a function of depth beneath station TYAR. The red Vp profile is interpreted from a seismic sounding (Figure 3b) and the blue Vp profile is interpolated and extrapolated from nearby well logs. Layer boundaries and interval velocities determined from seismic sounding are consistent with those from nearby well logs within reasonable error ranges. We are currently in the process of re-interpretation of nearby well logs and will try to correlate them with the observed Vp from seismic soundings. The Vp/Vs ratio for each layer can be inverted from a linear inversion using the Vp model, the shallow Vs, and the arrival time difference between the direct S and converted Sp waves (Δt_{S-S_p}) as the *priori* information. Thus, Vs profile (green line) can be determined from the resultant Vp and Vp/Vs information obtained.

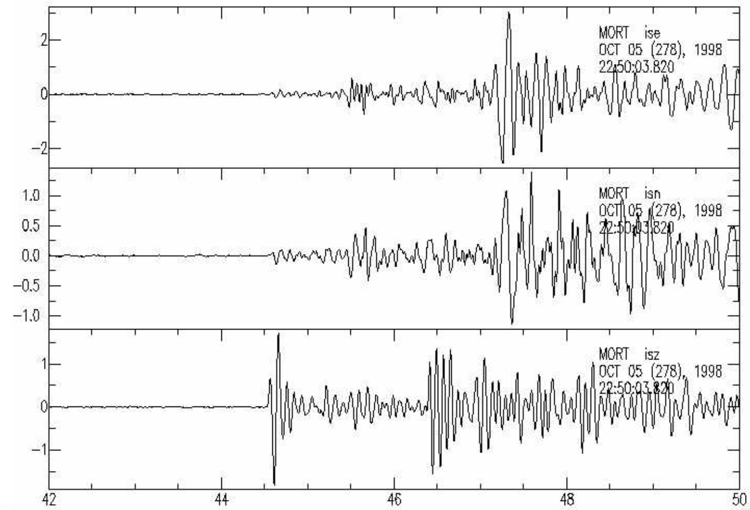

Figure 7. Typical 3-component seismograms at a CERI seismic station (MORT) showing the direct P and the converted Sp waves on the vertical component (bottom) and the direct S and the converted Ps waves on the two horizontal components (top two traces).

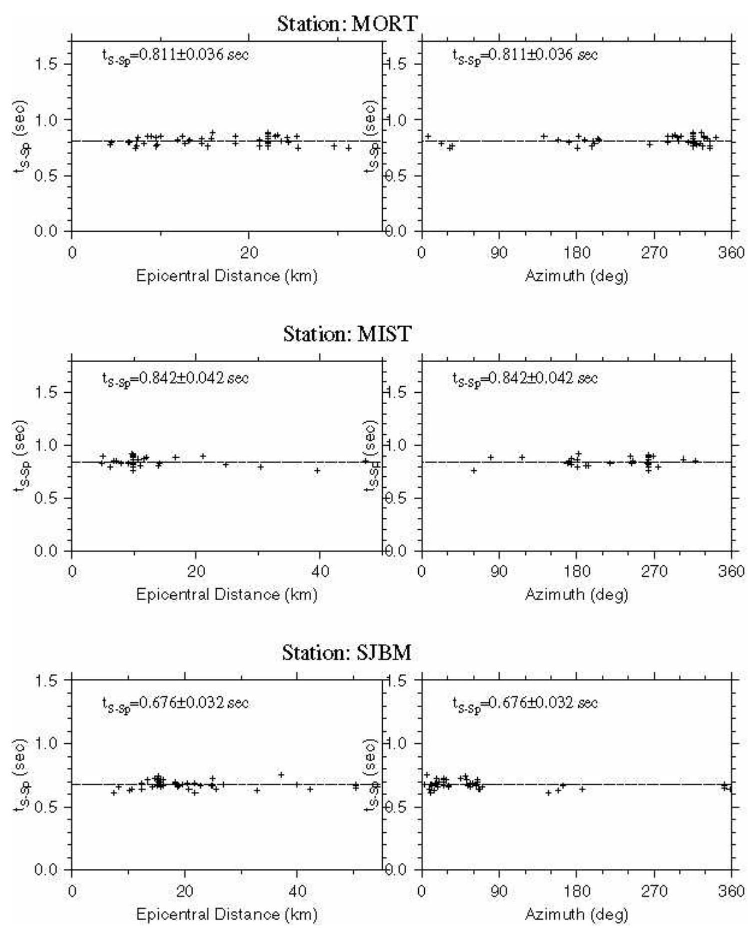

Figure 8. Plots of travel time differences (Δt_{S-S_p}) between the direct S and converted Sp waves versus depth and azimuth of earthquakes from CERI regional seismic network stations showing that Δt_{S-S_p} is a constant for every station but are different between stations.

REPORTS PUBLISHED

This is the first year of the project and is supposed to accomplish a few test sites adjacent to logged deep wells to validate the resultant velocity model. Thus, no report has been published so far. Preliminary results of related research have been presented in the SSA and ESSSA meetings. They include:

A single-event relocation of local earthquakes in the NMSZ using a 3-D Vp and Vs crustal velocity model, Chiu, J.M., H. Chen, J. Pujol, S.C. Chiu, and M. Withers, presented in the 97th SSA annual meeting, held at Victoria, Canada, April, 2002, **SRL**, 73(2), 216.

A New earthquake catalog for the New Madrid seismic zone using a preliminary 3-dimensional Vp and Vs structural model, Chiu,J.M., H. Chen, J. Pujol, S.C. Chiu, and M. Withers, presented at the **74th annual ES-SSA meeting** held October 2002 at Boston College, Western, MA.

Preliminary study of Pn velocity and Moho geometry beneath the NMSZ in the central US, Kim, K.H., J.M. Chiu, S.C. Chiu, and M. Withers, presented at the **74th annual ES-SSA meeting** held October 2002 at Boston College, Western, MA.

DATA AVAILABLE

Seismic data from the reflection and refraction profiles are available in SEGY format by contact Edward Woolery at the University of Kentucky (woolery@uky.edu). Local earthquake seismograms in AH format and converted wave information in ASCII format can be obtained by contact Jer-Ming Chiu at the University of Memphis (chiu@ceri.memphis.edu).

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