FINAL TECHNICAL REPORT

TOWARD CONSTRUCTION OF THE CENTRAL UNITED STATES SEISMIC OBSERVATORY AND CALIBRATION SITE: DEFINING THE GEOLOGIC SITE MODEL (PART 2)

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ABSTRACT

The Central United States Seismic Observatory (CUSSO) consists of an array of vertical strong motion accelerometers and medium period seismometers that penetrate 585 m into the Mississippi Embayment sediments and terminate into the top of Paleozoic bedrock. The array is located near the central segment of the New Madrid Seismic Zone. The thick unlithified sediment overburden has the potential to influence earthquake ground motions; understanding how these sediments affect ground motion is the overall goal of the CUSSO array. Part 2 of the associated geological model, however, characterizes the Quaternary sediment and includes nine SH-wave refraction surveys totaling approximately 4.3 km, as well as two common-midpoint reflection surveys totaling 0.8 km. These data were collected within a 1 km radius of the CUSSO borehole in order to characterize the dominant Quaternary-aged seismic stratigraphy. Three units are identified in the SH-wave refraction surveys; the deepest is correlated to a Tertiary (Eocene) clay unit with two overlying Quaternary sands. Specific stratigraphic correlation with the borehole log suggests that the Quaternary is composed of a lower coarse sand and gravel, overlain by coarse sand. The Tertiary clay correlates with the Jackson Formation. These results along with those from the previous deep stratigraphic investigation provide a complete geologic model (Quaternary to top-of-Paleozoic bedrock) based on acoustical impedance for CUSSO and a 1-km radius. In addition, a set of faults were discovered at the site during the initial deep seismic stratigraphy investigation. The northeast-southwest striking, sub-parallel faults extend above Paleozoic bedrock and clearly displace the base of the Quaternary and most likely the intra-Quaternary sand and gravel horizon. Additional investigation, including ground-penetrating-radar and/or invasive trenching is required to evaluate the latest extent of the deformation.

NONTECHNICAL SUMMARY

The thick Mississippi embayment sediment deposits are expected to alter the ground shaking characteristics of an earthquake. Estimating the ground motions of earthquake engineering interest in these thick deposits is problematic, however. To address these issues, we have constructed a geologic model around a seismic observatory that penetrates the 585-m-thick sediment overburden near the central segment of the New Madrid seismic zone. The existing borehole observatory houses instrumentation beneath, within, and atop a 585-m sediment overburden, and will allow the effects deep sediments have on earthquake ground motions to be characterized. An earlier investigation characterized and defined the deeper sediment horizons around the observatory. Consequently, this study focuses on characterizing the thickness and geometric variation, as well as dynamic properties of the shallow Quaternary sediment. Previously discovered faults were also imaged and found to extend across the base of the Quaternary sediment. Combined with the previous results the fundamental components are available to construct 1- and 3-D ground motion models in order to validate the geotechnical techniques currently being used to estimate ground-motion response at deep sediment sites throughout the Mississippi embayment.

INTRODUCTION

The thick sediment overburden of the New Madrid seismic zone (NMSZ), located in the northern Mississippi embayment (Fig. 1), is expected to produce earthquake site effects. The physical properties and configuration of these soil/sediment deposits can give rise to ground motions that consist of a complex mixture of source, path, and site effects: including 3D effects (e.g., Anderson et al., 1996; Bard and Chavez-Garcia, 1993). The only truly reliable way of separating an earthquake's source and path effects from the site effect is to simultaneously record the earthquake with downhole (i.e., bedrock) and surface recorders (Field et al., 1998). Consequently, the University of Kentucky has installed a seismic borehole observatory, the Central United States Seismic Observatory (CUSSO) that penetrated the thick Mississippi embayment soil/sediment deposits (585 m) and terminated 8 meters into Paleozoic bedrock near the most active segment of the New Madrid seismic zone. Geographically, CUSSO is located in the community of Sassafras Ridge, Kentucky, at coordinates N 36º33.139', W 89º19.784'. The location of the site is typical of what Toro et al. (1992) referred to as Embayment Lowlands (i.e., floodplains) that cover much of the northern embayment (Fig. 2).

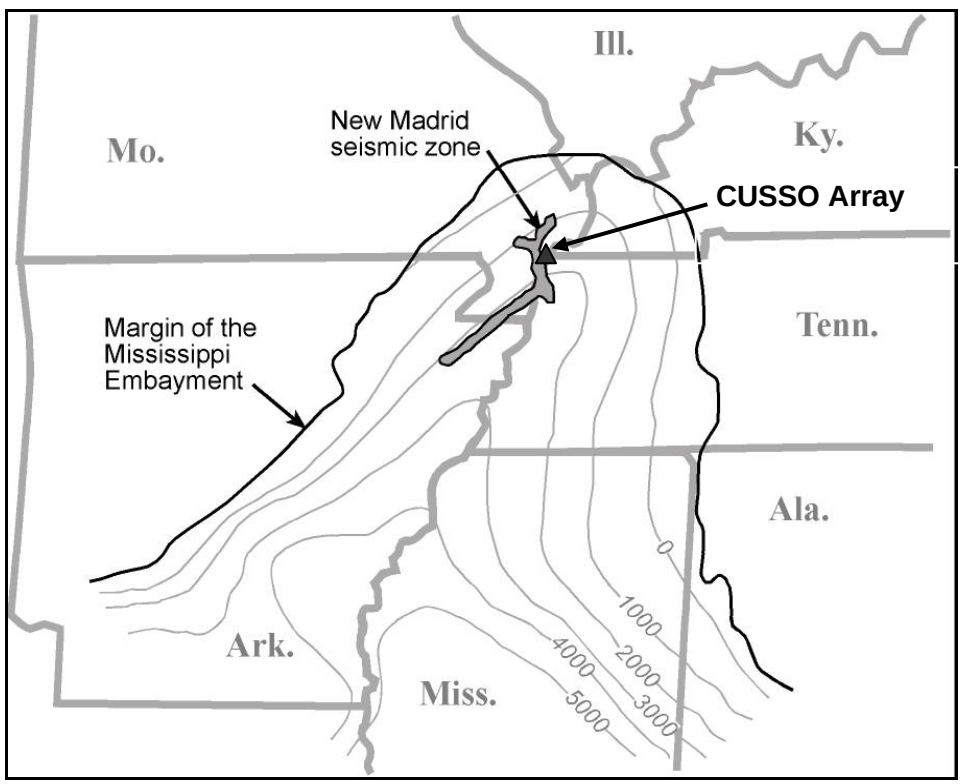


Figure 1. Location of the CUSSO in the central segment of the New Madrid seismic zone. The contours show sediment thickness in feet below mean sea level.

As part of the construction of the seismic observatory, the subsurface geologic configuration around the site (e.g., 1 km radius) requires definition in order that 3-D ground-motion

researchers can construct accurate response models for comparison with the observational data. In the initial phase of this study, we collected and processed a series of north- and east-oriented common-midpoint (CMP) reflection surveys, as well as utilized sections of favorably oriented proprietary lines in order to image and characterize the subsurface configuration in an approximate 1 km radius of the observatory site. These profiles interpreted four major subsurface impedance boundaries, designated zones 2-5. These zones represented the tops of the site's deeper stratigraphic horizons (i.e., Paleocene, Cretaceous and Paleozoic). The previous study did not assign a zone 1 because the aperture of those acquisition arrays precluded us from sampling the uppermost (i.e., Quaternary) sediment. The initial investigation also defined abrupt lateral anomalies produced by structural and/or sedimentological features that might affect the ground-motion spatial coherence. This included three north-east oriented high-angle faults.

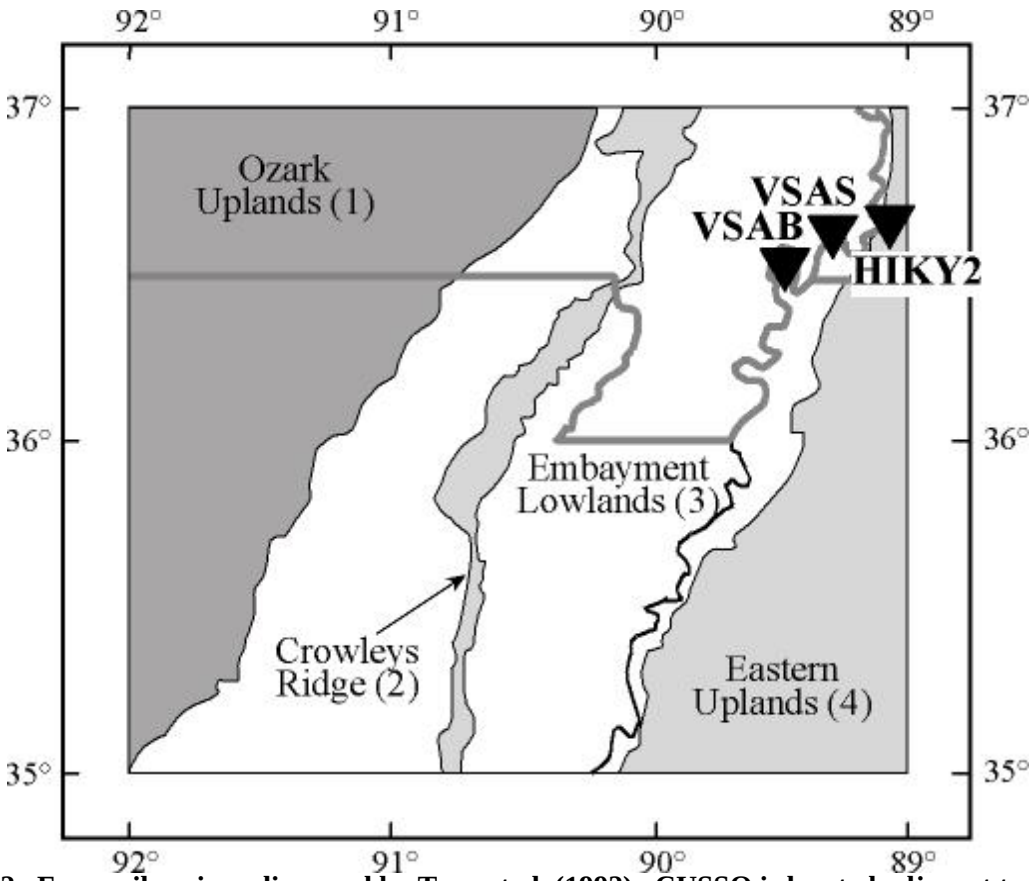


Figure 2. Four soil regions discussed by Toro et al. (1992). CUSSO is located adjacent to the vertical accelerometer array VSAS, and is situated between existing strong-motion stations VSAB and HIKY2.

The objectives for this investigation were to complete the sampling of the near-surface stratigraphic horizons (Quaternary) and evaluate the near-surface extent of the previously identified faults. Specific tasks and goals for this investigation were:

1. Collect SH-wave refraction profiles coincident with previous P-wave surveys to generate

seismic velocities and depths/elevations for the major impedance intervals within the Quaternary stratigraphic section.

2. Acquire a higher-resolution near-surface seismic-reflection image coincident with the location of an interpreted fault from the deeper phase 1 P-wave investigation in order to assess the near-surface extent of the deformation.
3. Depth migrate the phase 1 data sets in to provide more readily usable results.
4. Integrate the Quaternary seismic intervals with the previously defined Tertiary-Paleozoic intervals to construct a complete velocity model for the CUSSO site.

Central United States Seismic Observatory :

A combination of strong-motion accelerometers and medium-period seismometers are currently installed at varying depths within the 1,950-foot (594 meter) borehole comprising the Central U.S. Seismic Observatory (CUSSO) in Fulton County, KY (Fig. 3). The borehole penetrated the entire soil/sediment overburden (586 m) and was terminated 8 meters into limestone bedrock. The four strong-motion accelerometers at CUSSO will provide the direct measurement of strong-motion propagating from the bedrock through the soil column to the surface and allow us to evaluate how various segments of the soil column alters the characteristics of strong motions propagation. The medium period seismometers (0.06 - 50 Hz) will also provide direct measurements of the sediments effects on seismic wave propagation and along with the accelerometers provide a means for calibrating free-field stations in the region.

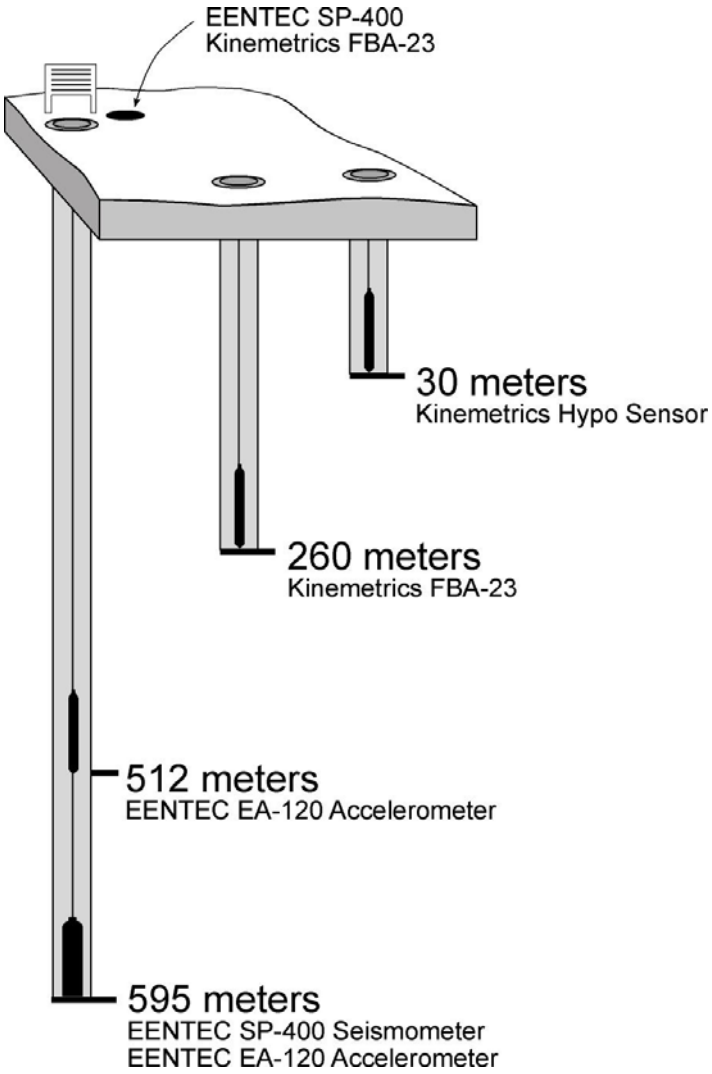


Figure 3. Schematic layout of the CUSSO instrumentation and depths below ground surface. Future instrumentation will include 120° fanned surface accelerometer array.

GEOLOGICAL SETTING

General Tectonic:

The study area is located in the North American Precambrian craton that was described by Heigold and Kolata (1993) as a collage of tectonic terranes that formed by lateral accretion to preexisting continent prior to 1600 Ma (Fig. 4). The northern part of the Mississippi Embayment lies within the Eastern Granite-Rhyolite tectonic province (Bickford et al., 1986) of this cratonic collage. The Eastern Granite-Rhyolite Province is bounded by the Western Granite-Rhyolite Province and Central Plains Province to the west, the Penokean Province and Midcontinent Rift System to the north, and the Grenville Front to the east. The southern boundary is defined by the Late Precambrian cratonic margin. Large-scaled geological and geophysical investigations (i.e., Burke and Dewey, 1973; Ervin and McGinnis, 1975; Hildenbrand et al., 1977, 1985; Kane et al., 1981; Mooney et al., 1983; and Thomas, 1991) have defined the Mississippi Embayment as the

site of a Late Precambrian–Early Paleozoic rift complex, called the Reelfoot Rift. Aeromagnetic and gravity surveys (e.g., Kane et al., 1981) defined the Reelfoot Rift as an approximately 70-km-wide by 300-km-long northeast-trending basement depression, which extends from the southern cratonic margin into the Eastern Granite-Rhyolite Province, where it is truncated by an east–west-trending graben (Rough Creek Graben) near the northern embayment boundary (Soderberg and Keller, 1981; Keller et al., 1983; Drahovzal et al., 1992). The Reelfoot Rift has a linear trend with nearly parallel sides over its length. Kane et al. (1981) estimated the depth of the graben to be over 2 km relative to the top of the surrounding magnetic basement.

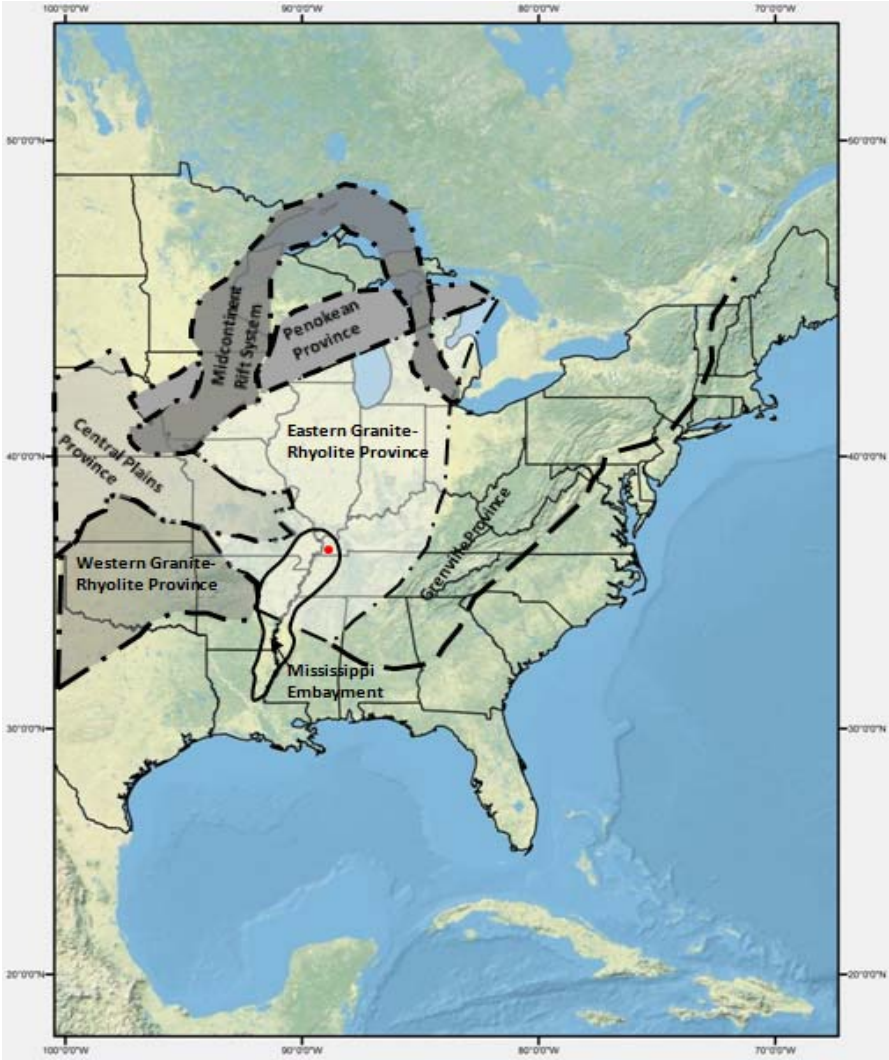


Figure 4. Tectonic provinces of the central and eastern United States (after Bickford et al. 1986). The CUSSO site is located approximately at the red-filled circle.

Site Stratigraphy:

The upper Mississippi embayment is a south-plunging synclinal trough characterized by gently dipping post-Paleozoic sediments that thicken to the south. The depth to the Paleozoic bedrock at the CUSSO site is approximately 586 m based on the results of the mud-rotary drilled borehole. The drill rig initially advanced a 15 inch (381 mm) diameter borehole through the alluvium cover to a depth of 150 ft (45.7 m) below ground surface. The second phase of drilling telescoped down to a 10 inch (254 mm) diameter boring that was extended through the remaining poorly lithified sediment, terminating 8.6 meters into limestone bedrock. The cuttings were collected at the well head and saved for stratigraphic interpretation at the Kentucky Geological Survey's Well Sample and Core Library. Prior to casing the hole, electrical, sonic velocity (P- and S-wave) and deviation logs were acquired. The cutting-based picks were constrained by e-logs, and the overall stratigraphic interpretation is shown in Figure 5.

The contact between the surficial alluvium and the underlying Jackson Formation is interpreted to be at 155 feet (47.2 m) below the surface at an elevation of 135 feet (41.1 m) msl. This boundary marks a distinct lithologic change between the overlying coarse sand and gravel and underlying black clay. There is also a distinctive change in the gamma and spontaneous potential logs (Fig. 5). Reported palynomorph assemblages in the Jackson Formation represent deposition in a continental lacustrine environment, however some marine forms are also present in some localities (Olive, 1980).

The contact between the Jackson Formation and the underlying Claiborne Formation was placed approximately 430 feet below the surface at elevation -140 feet (-42.6 m) msl. A lithologic change was interpreted from the driller's log, as well as the electric logs. Lithologically, the underlying green sandy clay of the Claiborne Formation is glauconitic and evidence for marine environment deposition. There was also a significant change in the electric logs as further evidence for a stratigraphic boundary.

The boundary separating the Claiborne Formation and the underlying Wilcox Formation is approximately 900 feet (274.3 m) below the surface at elevation of -610 feet (-185.9 m) msl. The contact was interpreted from litholigic differences and a distinctive change in the gamma log. The sand and cemented sand is correlative with the Claiborne Formation, and the underlying clay is correlative with the Wilcox Formation.

The Wilcox Formation is separated from the underlying Porters Creek Clay at approximately 1300 feet (396 m) below the surface at elevation -1010 feet (-307.8) msl, and is relatively easy to identify lithologically and geophysically. The Porters Creek Clay is a distinctive, thick sequence of clay and underlies the sandy clay lithology of the Wilcox Formation. This lithologic change is also evident in the gamma and spontaneous potential logs.

The contact between the Porters Creek Clay and the underlying Clayton and McNairy Formations is approximately 1590 feet (484.6 m) below the surface or at an elevation of -1290 feet (-393.2 m) msl. Lithologically, there is distinct contrast between the overly clays and the underlying sand and clays of the Clayton and McNairy formations. This lithologic distinction is exhibited well by the spontaneous potential log (Fig 5).

The Clayton and McNairy Formations boundary with the underlying Paleozoic bedrock is approximately 1925 feet (586.7 m) below the surface at elevation -1625 feet (-495.3 m). The contact is clearly exhibited by the gamma and spontaneous potential logs (Fig. 5). The limestone is likely Mississippian in age, but the exact age and formation is equivocal.

There are three industry wells near the CUSSO site on Sassafras Ridge in the Bondurant Quadrangle. The stratigraphic tops of the formations are listed on the Bondurant GQ, and the driller's logs are available via the Kentucky Geological Survey oil and gas database. These holes include KGS oil and gas record numbers 8740, 8741, and 8742. Record number 8740 is approximately 2.4 km southwest of Sassafras Ridge. Record number 8741 is approximately 4.0 km east, and record number 8742 is approximately 3.6 km south of Sassafras Ridge, respectively. Figure 6 shows an example of the seismo-stratigraphic correlation south of the site along the Tennessee border.

Stratigraphic interpretations from the CUSSO hole were correlated with the stratigraphic interpretation of the nearby deep-holes. The elevation for the top of the Jackson Formation is relatively consistent in all the holes. The Claiborne Formation is hard to distinguish from the Jackson Formation, therefore that stratigraphic interval is not identified in the 3 holes near the Sassafras Ridge hole. The Wilcox Formation is varies in thickness and is deposited on an irregular surface; however the elevation of this formation on Sassafras Ridge is consistent with the other deep-holes given the regional dip of the strata in this part of the Mississippi embayment. The elevation of the top of the Porters Creek Clay, Clayton and McNairy Formations, and Paleozoic bedrock are all relatively consistent with elevations in nearby boreholes.

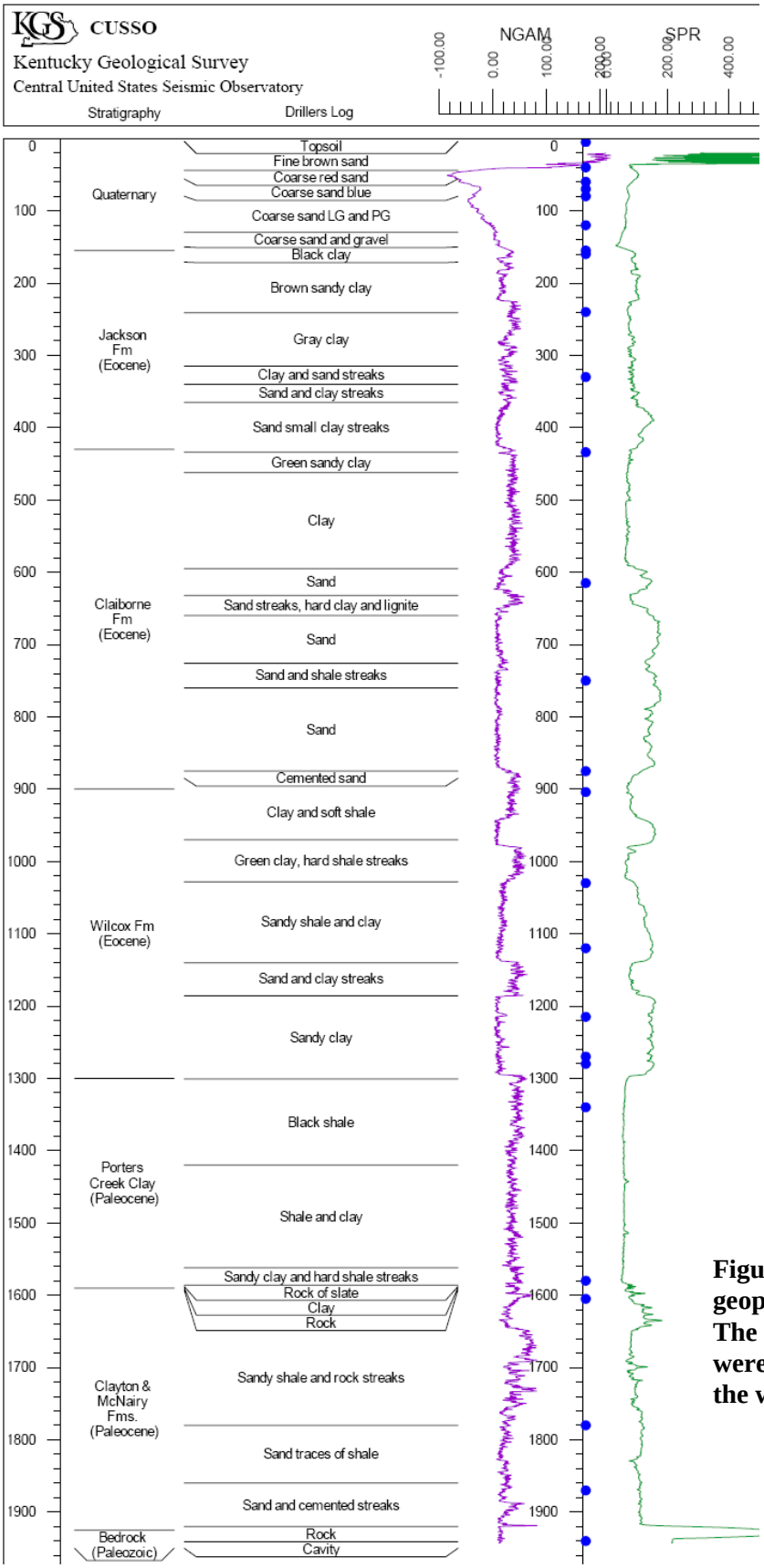
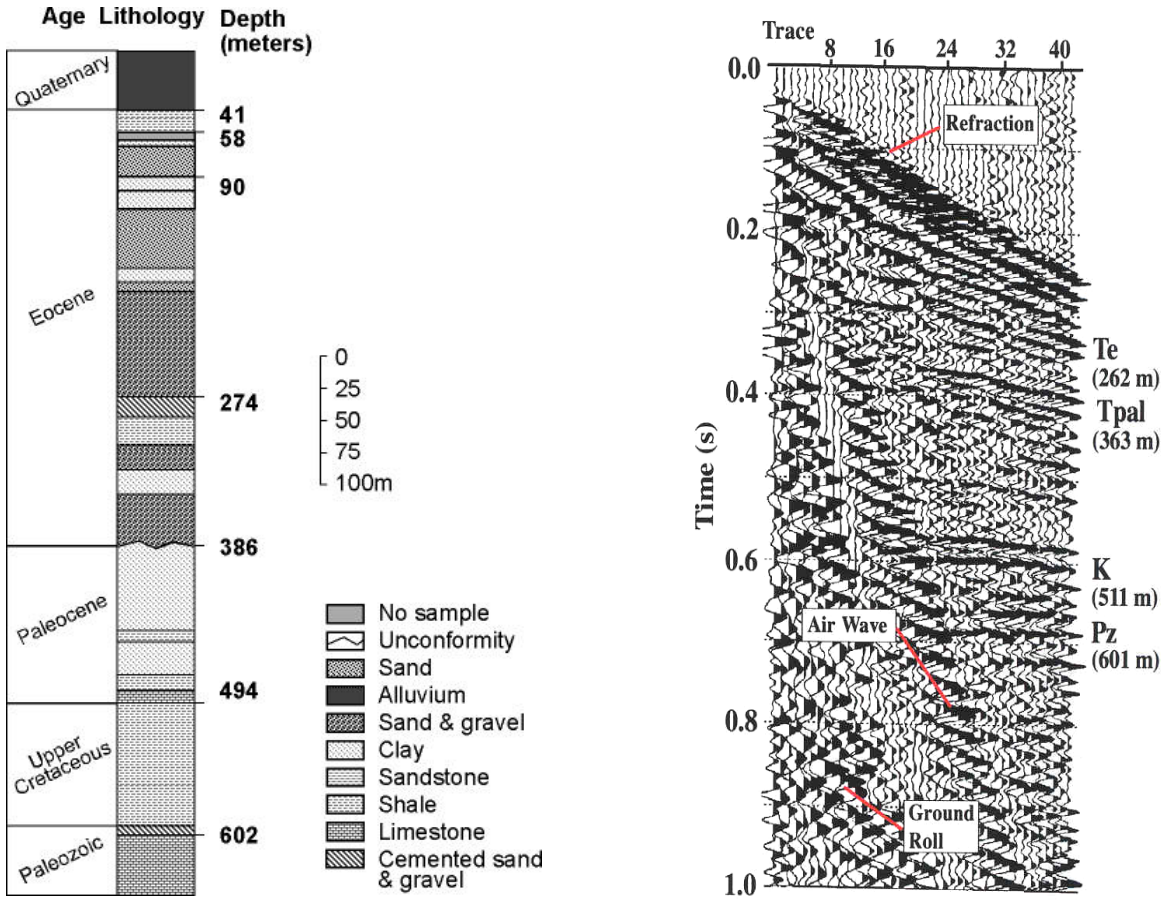


Figure 5. Stratigraphic and geophysical well log interpretations. The stratigraphic interpretations were made from cuttings collected at the well head.



a b

Figure 6. a) Stratigraphic correlation of the major geologic boundaries ~10 km south of CUSSO at the Kate Wright no. 1 well, b) A seismic P-wave sounding acquired ~5 km south of the site along the Tennessee border demonstrating seismo-stratigraphic correlation with the Kate Wright information.

RESULTS

Seismic-Refraction Survey Acquisition and Processing:

A 48-channel Geometrics StrataVisor seismograph was used to collect the seismic refraction data. The seismograph has a dynamic range of 120db and stores data on an internal hard drive. The seismograph has two takeout cables to connect geophones. The cables have 24 takeouts each, allowing for a maximum of 48 geophones to be connected at one time. Two different types of geophones were used for collecting seismic-refraction data. Table 1shows the acquisition parameters for the refraction lines.

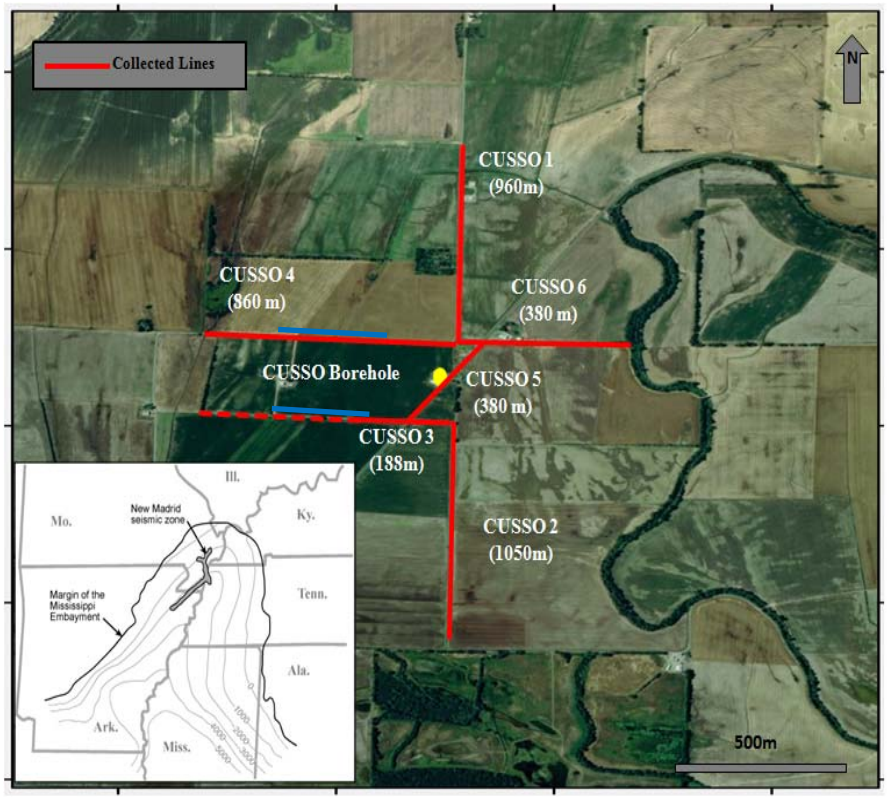


Figure 7. Locations of seismic profiles for the Part 2 investigation. The CUSSO borehole is in the center (yellow circle). The red lines are the refraction lines that run along existing roadways surrounding the CUSSO borehole. The blue lines are reflection profiles collected above previously interpreted faults.

Shear Wave Refraction Acquisition Parameters					
	CUSSO 1	**CUSSO 2**	**CUSSO 4**	**CUSSO 5**	**CUSSO 6**
Date of Survey	4/16/12	3/14/12	3/13/12	6/20/12	6/21/12
Source Type	4 lb. hammer	4 lb. hammer	4 lb. hammer	4 lb. hammer	4 lb. hammer
Source Deployment	5-10 times per station	5-10 times per station	5-10 times per station	5-10 times per station	5-10 times per station
Geophone Frequency	30 Hz SH-wave	30 Hz SH-wave	30 Hz SH-wave	30 Hz SH-wave	30 Hz SH-wave
Sample Rate	0.25 ms	0.25 ms	0.25 ms	0.25 ms	0.25 ms
Acquisition Filters	Low: 15 Hz High: Off Notch: 60 Hz	Low: 15 Hz High: Off Notch: 60 Hz	Low: 15 Hz High: Off Notch: Off	Low: 15 Hz High: Off Notch: 60 Hz	Low: 15 Hz High: Off Notch: 60 Hz
Source Stations	56	70	56	21	21
Geophone Interval	4 m	4 m	4 m	4 m	4 m
Geophone Group Channels	2 X 24	2 X 24	2 X 24	2 X 24	2 X 24
Offset	±48 m	±48 m	±48 m	±48 m	±48 m
Record Length	2,000 ms	2,000 ms	2,000 ms	1,024 ms	1,024 ms
Site Surveyed	Sassafras Church Road	Running Slough Road	State Highway 971	State Highway 94	Cotton Gin Road
Total Profile Length	956 m	1050 m	860 m	380 m	380 m

Table 1. Acquisition parameters for 4-m CUSSO full refraction lines.

The surveys were conducted using 30 Hz horizontally polarized (SH-wave) geophones. The geophones were leveled and oriented orthogonal to the direction of wave propagation. The seismic shear waves were generated using 4-lb and 10-lb hammers. The hammers were struck against an orthogonally oriented steel H-pile relative to the direction of wave propagation for SH-wave production surveys. In order to enhance the first-arrival signal, multiple stacks (or hammer blows) were made at each shotpoint. In order to minimize P-wave contamination, the acquisition polarity was changed 180° on the seismograph and the direction of the hammer swing, thus providing constructive interference for SH-wave generation and destructive interference for any inadvertent P-waves.

The refraction data acquisition needed to be rolled-along in order to produce a refraction profile that had equivalent coverage as the previous deeper CMP profiles. A roll-along is done by laying out 48-channel geophones and collecting the data at specific geophones, usually 1, 12, 24, 36, 48, and offsets, if needed. After the initial line is collected, the first 24 geophones are picked up and moved ahead of the remaining 24 geophones. Example geometric stationing for a roll-along line is shown in Table 2. The roll-along allows for an extended profile and for overlap and redundancy in the subsurface source-to-receiver ray-path coverage if performed one cable at a time, reducing residual error of the continuous velocity model (Chiemeke and Osazuwa, 2009).

The refraction models were created using the SeisImager software suite that include the modules Pickwin (ver. 4.2.0.0) for picking first arrivals (and dispersion curves) and Plotrefa (ver. 2.9.1.9) for the velocity inversion. A time-term inversion method was used which inverts the first-arrivals by using linear-least squares and delay time analysis (Diabiase, 2004; OYO Corporation, 2009). The three major steps needed for creating a velocity model (Fig. 8) are: first-break picking, velocity and layer assignment, and final inversion. How accurate the final inversion model is depends heavily on the accuracy of the first break picking.

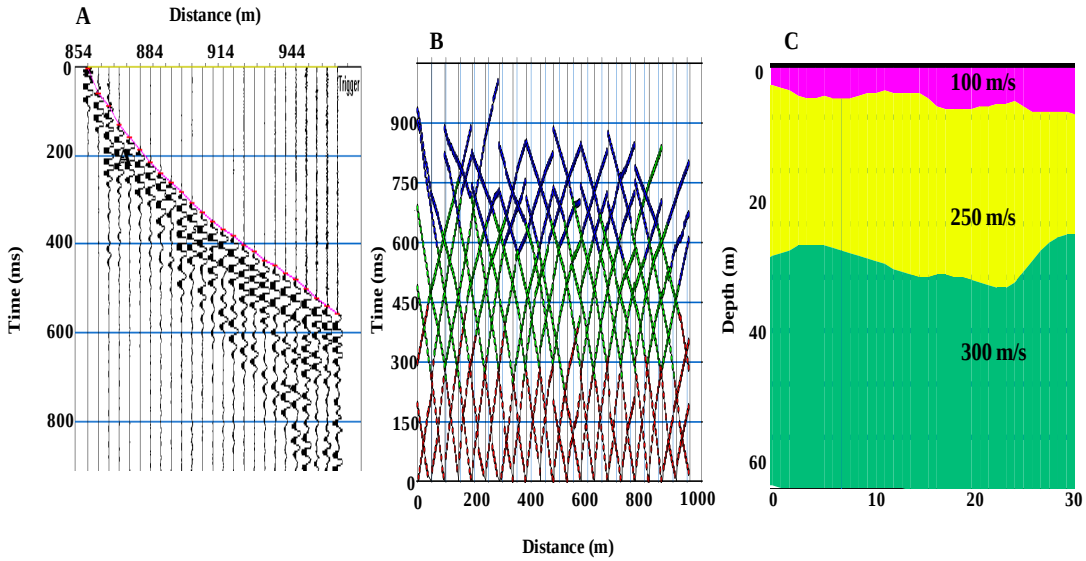


Figure 8. The 3 steps in the refraction process. (a) first-break picks, (b) travel time curve assignment, and (c) time-term inversion velocity model.

	Offset (-48m)	Geophone 1	Geophone 12	Geophone 24	Geophone 36	Geophone 48	Offset (+48m)
First 48 m	-48	0	48	96	144	192	240
First Roll Along (24 m)	48	96	144	192	240	288	336
Second Roll Along (24 m)	144	192	240	288	336	384	432
Third Roll Along (24 m)	240	288	336	384	432	480	528
Fourth Roll Along (24 m)	336	384	432	480	528	576	624
Fifth Roll Along (24 m)	432	480	528	576	624	672	720
Sixth Roll Along (24 m)	528	576	624	672	720	768	816
Seventh Roll Along (24 m)	624	672	720	768	816	864	912
Eighth Roll Along (24 m)	720	768	816	864	912	960	1008
Ninth Roll Along (24 m)	816	864	912	960	1008	1056	1104

Table 2. Geometry parameters for a 48-channel survey with four additional 24 m roll-along segments.

Refraction Models

The CUSSO refraction lines focus on the Quaternary and upper Eocene seismic boundaries. The five 4 m surveys consisted of 21 to 70 source locations with two to nine roll-alongs. The energy source locations were at geophones 1, 12, 24, 36, and 48. Additional shot-points were located 48 m off the ends of the geophone array. Lines 1, 2, and 4 are 956, 1050, and 860 m in length, respectively. Both lines 5 and 6 are 380 m in length.

The velocity model for Line 1 (Fig. 9a) contains three distinct velocity layers. The first layer has an average thickness of 16 m and a velocity of 160 m/s. The second layer has an average thickness of 25 m and a velocity of 275 m/s. Both the first and second layers correlate to Quaternary sediments. The third layer has a velocity of 406 m/s and corresponds to upper Eocene sediments. The velocity difference between the two layers that corresponds to Quaternary sediments may be caused by the transition from coarse to fine sands in the Quaternary or the level of compaction of the sediments.

The model for Line 2 (Fig.9b) shows approximately 35 to 45 m of Quaternary sediments overlying the top of the Eocene. The first layer has an average 15-m thickness and 131 m/s velocity. The second layer has an average 17-m thickness and a 285 m/s velocity. The third layer has a velocity of 402 m/s and correlates to Eocene sediments. Although slightly southwest of the Line 1, all three layers are relatively consistent between the two lines.

The Line 4 (Fig. 9c) model has an average of 45 m of Quaternary sediments overlying the Eocene sediments. The first layer has an average thickness of 17 m and velocity a of 149 m/s. The second layer has an average thickness of 27 m and a velocity of 243 m/s. The third layer has a velocity of 349 m/s, slightly lower than the thrid layer in the previous models, but correlates in depth to upper Eocene sediments. All three last layers velocites for this east-west line are slightly lower than expected based on depth and may be caused by a subtle lithologic change.

Line 5 was adjacent to the borehole (Fig. 9d). The first Quaternary layer has an average 12-m thickness and a 181 m/s velocity. The second layer has an average thickness of 18 m and a velocity of 210 m/s. The third layer has an average 294 m/s velocity. The second and third layers correlated to Quaternary sediments and likely represent a subtle transition between Quaternary and upper Eocene sediments.

The model for Line 6 (Fig.9e) line has a first layer with an average thickness of 13 m and a velocity of 160 m/s. The velocity for this layer is consistent with the other profiles at this average depth. The second unit ranges in thickness between 18 and 34 m, and the velocity associated with this layer is 210 m/s and closely corresponds with the second layer for Line 5. The third layer has a velocity of 304 m/s correlates with the Eocene Jackson Formation (see Fig. 5).

All lines have a first layer with similar velocity and thickness. The velocity ranges between 131 m/s and 181 m/s with an average 15 m depth. The second layer has a velocity range between 210 m/s and 310 m/s. The third layer has a velocity range between 349 and 406 m/s as interpreted in lines 1, 2, and 4. Figure 10 shows an averaged composite layer interpretation for the CUSSO refraction models.

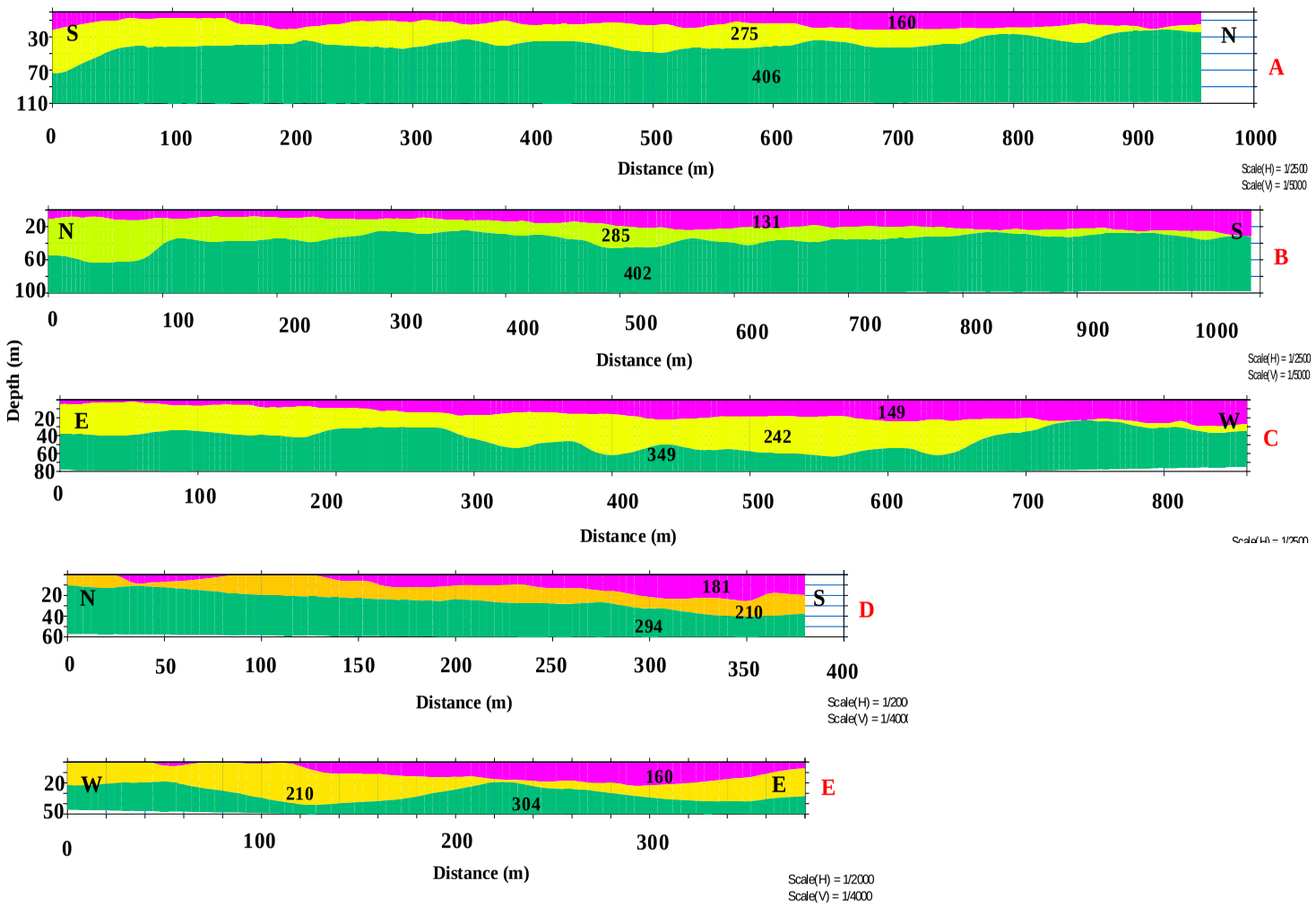


Figure 9. Inverted refraction models. The vertical array correspond to CUSSO lines 1, 2, 4, 5, and 6, respectively.

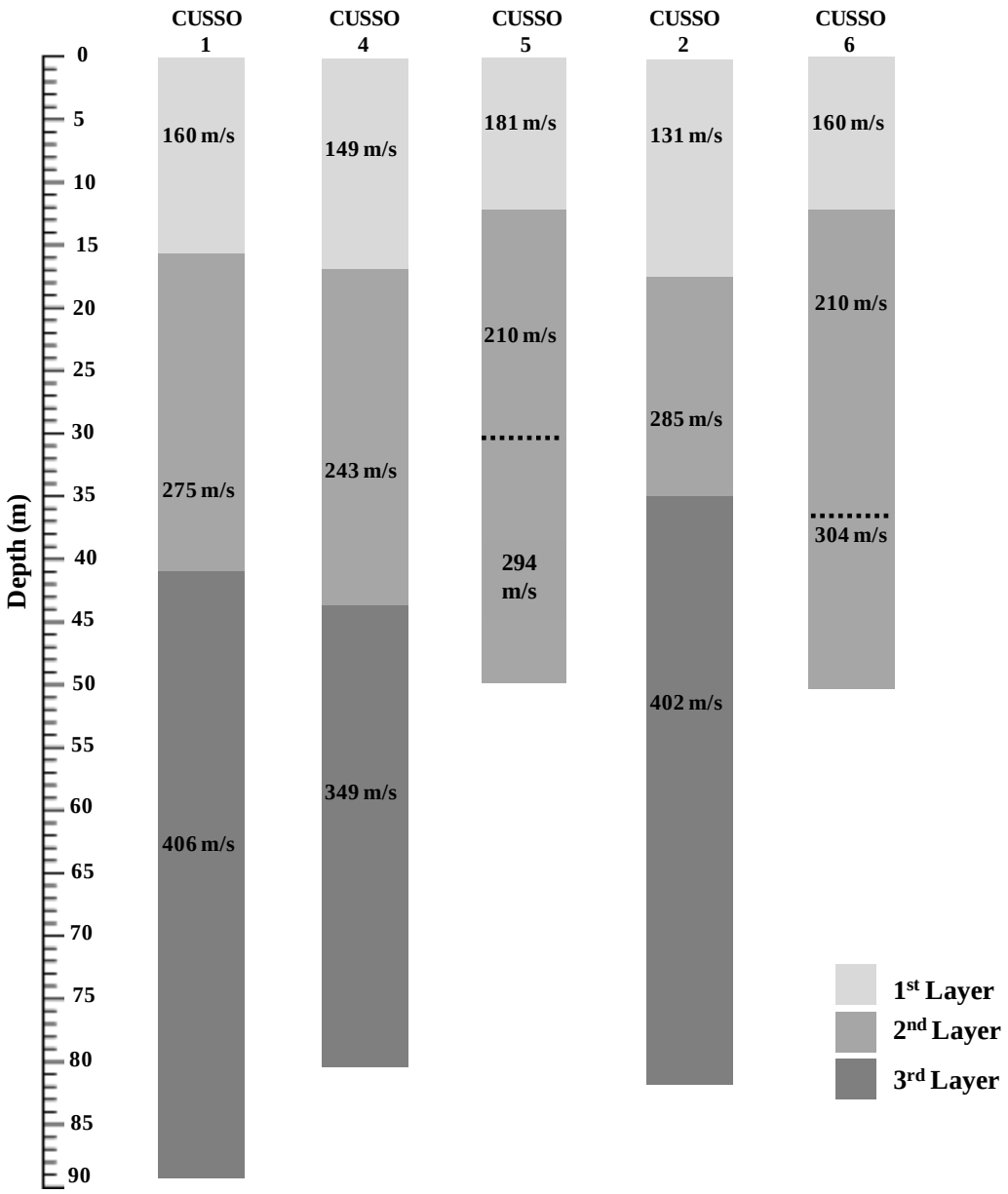


Figure 10. Averaged composite refraction models from the rolled-along surveys. Three major velocity zones are interpreted. The first and second layers correlate with Quaternary fine and coarse sand deposits and third with an upper Eocene clay (i.e., Jackson Formation).

P- and SH-Wave Seismic Reflection Surveys:

Conventional P-wave and SH-wave seismic-reflection common midpoint surveys (CMP) were collected at two locations that transect a projected fault strand imaged in the phase 1 investigation. The original seismic-reflection surveys were acquired at a 10 meter group interval and 110 meter near-offset, an array aperture too wide to confidently resolve features shallower than approximately 125 m below ground surface. Two-meter group intervals, as well as and 50-m and 2-m near-offsets were applied to the phase 2 P- and SH-wave surveys, respectively. The original CUSSO lines 3 and 4 provided the best targets for the follow-up surveys (Fig. 11). SH-wave reflection data were collected across the target area on line 4, and P-wave reflection data were collected over fault projection on line 3. The SH-wave data were collected first, but the data quality was anomalously poor; we attributed this to the unusually high attenuation that the extreme drought conditions created in the near-surface materials. Prior SH-wave soundings in the immediate vicinity during normal ground conditions exhibited much better data quality. P-wave data were subsequently acquired on line 3 and yielded very good data quality; however, the drought had subsided and the ground conditions were normal for this survey (Fig. 12). Although the data quality is less than was expected, the image was not unusable (Fig. 13).

All data were collected with a 48-channel Geometrics StrataVisor seismograph using two inline spreads of 24 Mark Products 30-Hz and 40-Hz geophones for the SH- and P-wave surveys, respectively. The prior seismic walkaway sounding in the area indicated that an optimal recording window for the Quaternary section could be obtained by using a 2-m shot and geophone group spacing. The shear-wave energy source was a 1.8-kg sledgehammer for impact and an H-pile with a weight of approximately 70 to 80 kg, including the weight of the hammer swinger and the beam section. The H-pile flanges were placed and struck perpendicular to the geophone spread and the direction of SH-wave propagation. The H-beam flanges were also placed in prepared slit trenches to resist movement and improve the energy couple with the ground. Seismograph polarity reversals and impacts of the sledgehammer on both sides of the energy source enhanced the SH-wave energy and degraded any P-wave contamination. Six vertical stacks were applied at each shot point (i.e., 3 positive and 3 negative).

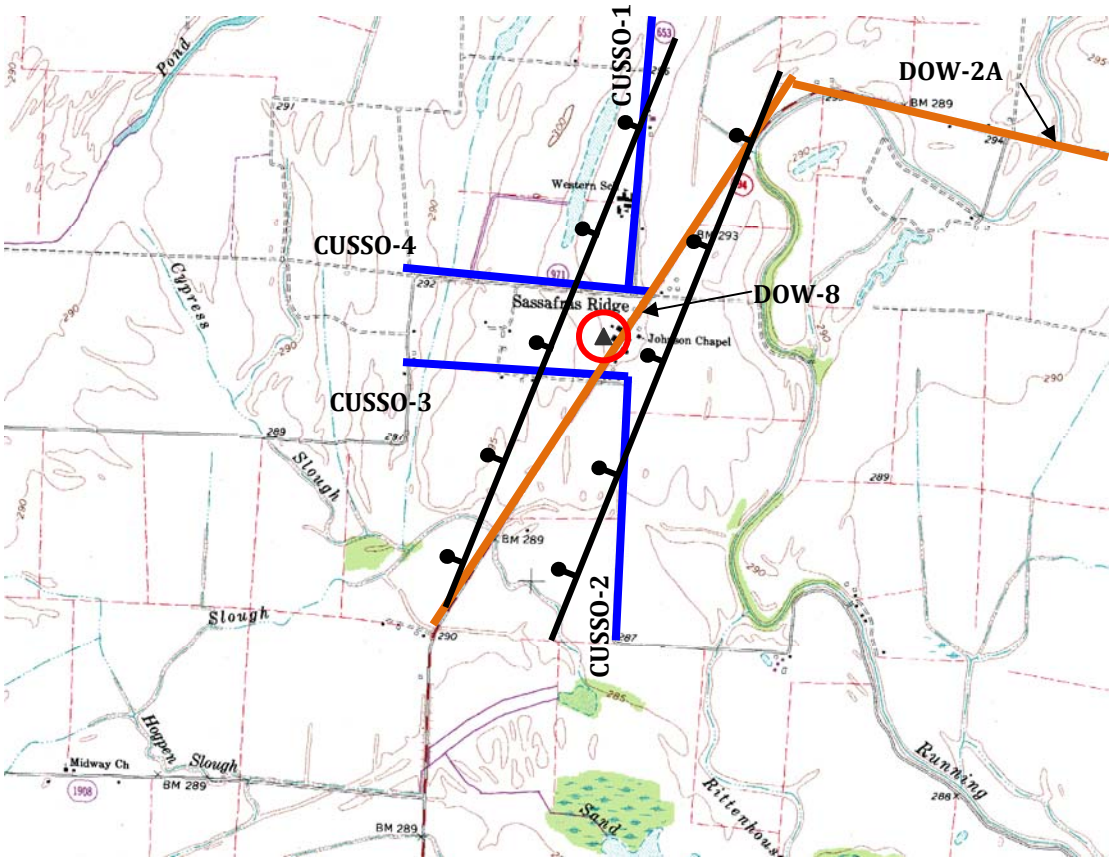


Figure 11. The original Part 1 location of the seismic profiles relative to the CUSSO site is shown. The blue lines are UK collected surveys and the brown lines are proprietary lines provided to the university by Apache Corporation. The black triangle inside the red circle is the CUSSO deep borehole. The black lines are the fault interpretations associated with the lines. The balls are on the down throw. Clear fault images on CUSSO lines 3 and 4 were selected for further imaging using a narrower acquisition array aperture in order to better evaluate the near-surface extent.

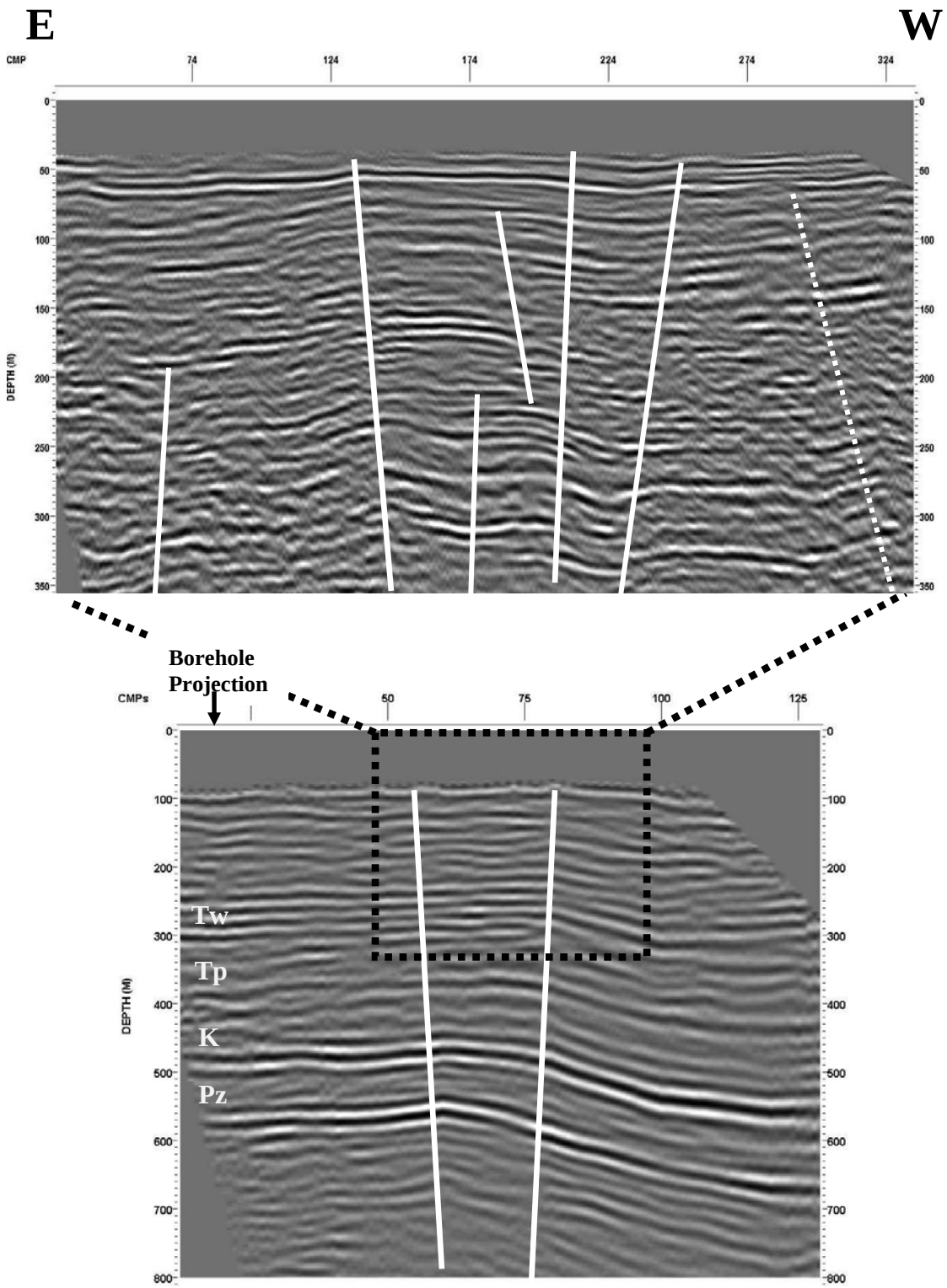


Figure 12. The original phase 1 CMP image (CUSSO Line 3) at bottom and the higher- resolution image exhibiting increased near-surface detail at the top.

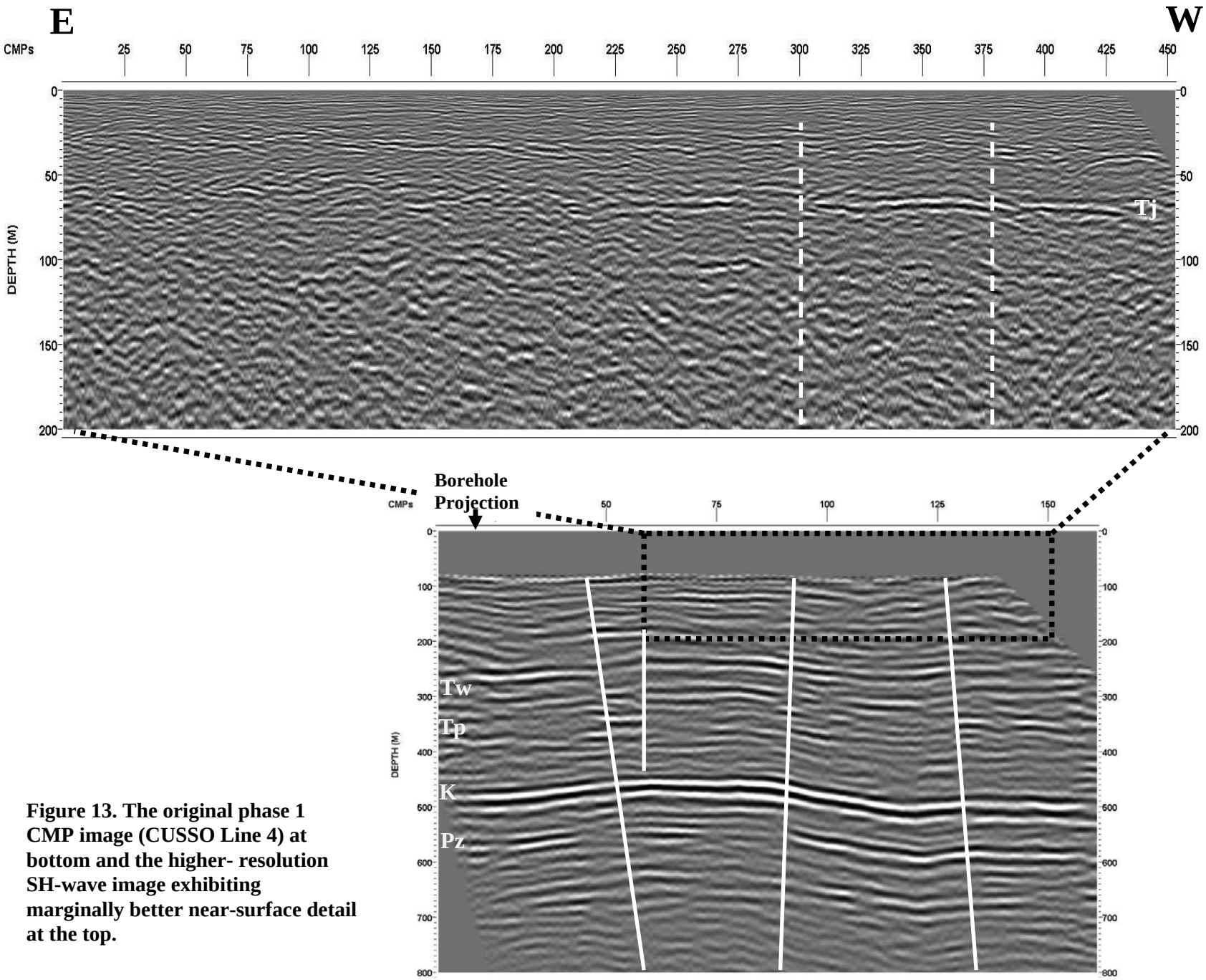


Figure 13. The original phase 1 CMP image (CUSSO Line 4) at bottom and the higher- resolution SH-wave image exhibiting marginally better near-surface detail at the top.

The SH-wave and P-wave reflection data were processed (and reprocessed phase 1 data) on a Pentium-based microcomputer using the commercial signal-processing software Vista 12.0. Shallow-reflection processing procedures were considered to improve the prestack quality of the desired reflected signals in the raw field data. Each profile was processed individually, but all the area-based parameters (e.g., band-pass filter, time-variant scaling, and deconvolution) were identical for uniformity. A general processing flow-chart (Fig.14) was designed for all CMP reflection after preprocessing tests. Optimization of the processing parameters was made throughout the preprocessing tests in order to minimize pitfalls. The preprocessing tests included band-pass filter, f-k filter, deconvolution type and operator length, and depth migration smoothing parameters.

All structural interpretations on the profiles were defined by: (1) offset reflectors, (2) abrupt termination of relatively strong reflection horizons, and (3) changes in reflector apparent dip. Noticeable sediment thickening on the downthrow of interpreted faults can also be a structural indicator. Temporal continuity of an anomaly was used to discriminate between structure and erosion or soft-sediment deformation features.

The original CUSSO Line 3 is an east–west-oriented 12-fold profile shown in Figure 12. The survey was collected along the nearly flat-lying edge of Cheshire farm road, south of the CUSSO borehole. The trace spacing for the phase 1 line is 5 meters. The two most prominent impedance boundaries on the profile are from the tops of the Cretaceous and Paleozoic bedrock. Although the reflections above the K horizon have more discontinuous characteristics, two of them are relatively coherent across the profile. These horizons are interpreted as the Paleocene Porters Creek Clay and Eocene Wilcox. This interpretation is based on elevation correlations associated with the adjacent borehole log. A distinct vertical offset across the K and Pz reflectors is seen near trace number 65. The higher-resolution phase 2 image suggests that the fault extends above the uppermost Eocene, displacing the base of the Quaternary. The K and Pz horizons show approximately nearly 75 meters of vertical displacement across this zone. The structure has a positive “flower” feature, broadening into the nearer surface.

The original CUSSO Line 4 is an east–west-oriented CMP profile collected along KY971, just north of the CUSSO borehole (bottom Fig. 13). The profile has a trace spacing of 5 meters. The two most prominent impedance boundaries on both profiles are again from the tops of the Cretaceous and Paleozoic bedrock horizons. The reflections above the K horizon are more discontinuous than the K or Pz; however, two of them are relatively coherent across the profile. These are interpreted as the Paleocene Porters Creek Clay and the Eocene Wilcox. This interpretation is based on the correlation with the adjacent borehole log. Changes in reflection dip and vertical elevation across the K and Pz horizons near trace numbers 45 and 90 are interpreted as thin horst block. The Paleocene and Eocene horizons are also affected. The K and Pz appear to have nearly 75 meters of offset. The SH-wave image resolves the top of the Eocene Jackson Formation (base of the Quaternary) at approximately 60 meters and a weaker relatively discontinuous intra-Quaternary sand/gravel (likely) horizon at approximately 35 meters. The fault clearly displaces the Jackson and possibly the intra-Quaternary horizon. There is a pronounced westward thickening of the Quaternary sediment above the sand/gravel horizon.

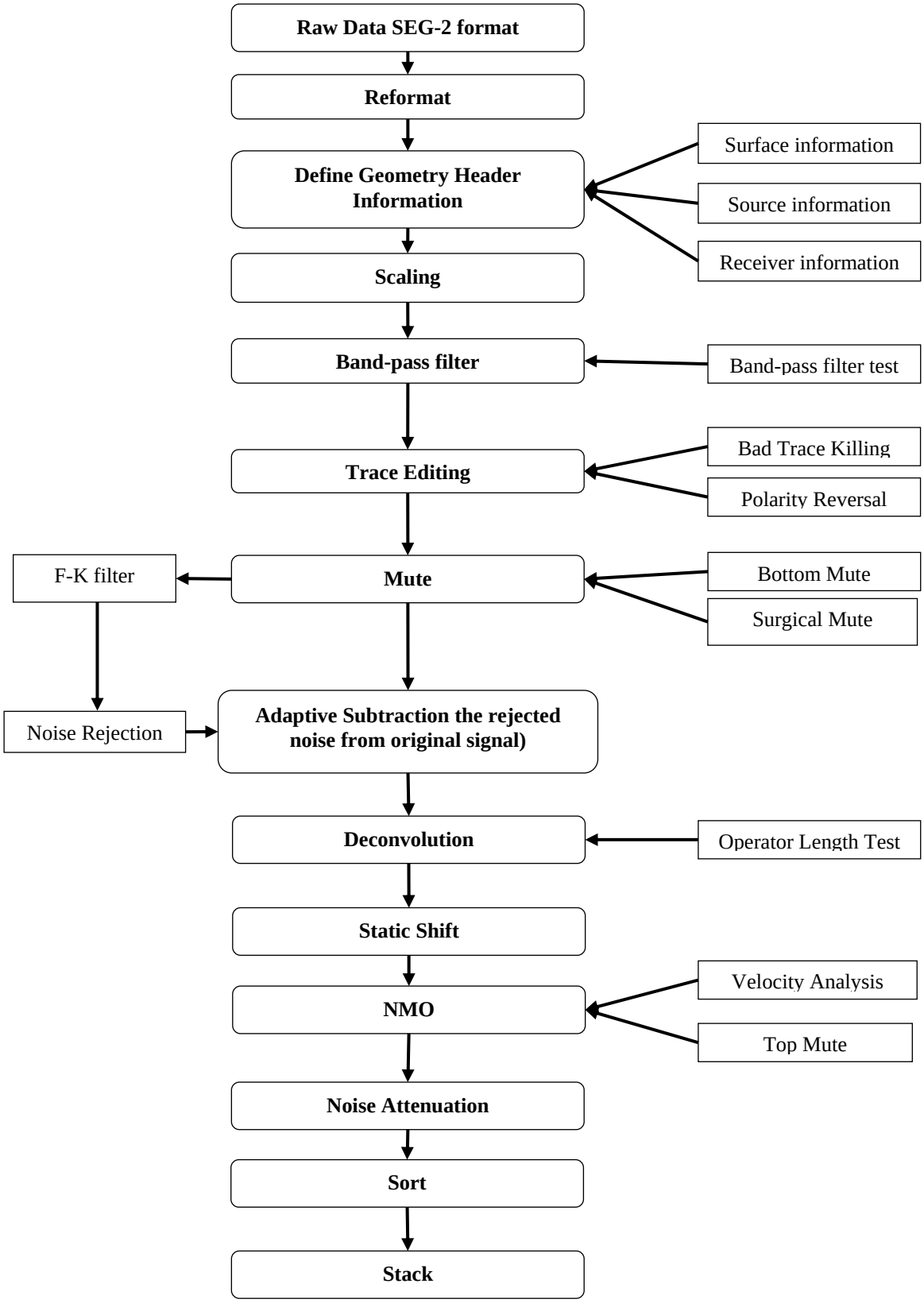


Figure 14. A generalized seismic-reflection data processing flow-chart

BIBLIOGRAPHY

Anderson, J.G., Y. Lee, Y. Zheng, and S. Day (1996). "Control of strong motion by the upper 30 meters." *Bulletin of the Seismological Society of America*, Vol. 86, pp.1749–1759.

Baker, G.S. (1999). Processing near-surface seismic-reflection data: A primer, *Soc. of Explor. Geophy., Course Notes Series No. 9*, Roger Young ed., 77 p.

Bard, P.-Y., and F.J. Chavez-Garcia (1993). "On the decoupling of surficial sediments from surrounding geology at Mexico City." *Bulletin of the Seismological Society of America*, Vol. 83, pp. 1979–1991.

Bickford, M.E., Van Schmus, W.R., and Zietz, I., 1986, Proterozoic history of the midcontinent region of North America: *Geology*, v. 14, p. 492–496.

Burke, K., and Dewey, J.F., 1973, Plume generated triple junctions—Key indicators in applying plate tectonics to old rocks: *Journal of Geology*, v. 81, p. 406–433.

Chiemeke, C.C., and Osazwa, I.B., 2009, An improved technique for static correction in high resolution shallow seismic reflection data using difference in reflection times, *Journal of the Environment*, v. 5, p. 72-79.

Drahovzal, J.A., Harris, D.C., Wickstrom, L.H., Walker, K., Baranoski, M.T., Keight, B., and Furer, L.C., 1992, The east continental rift basin—A new discovery: *Special Publication 18, Series XI, Cincinnati Arch Consortium*, 25 p.

Diabiase, R., 2004, Seismic refraction analysis of sediment fill in cyclone graben, needles district canyonlands national park, *Eighteenth Annual Keck Research Symposium in Geology* Proceedings, 11.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot rift—Reactivated precursor to the Mississippi embayment: *Geological Society of America Bulletin*, v. 86, p. 1287–1295.

Field, E.H., S. Krammer, A.-W. Elgamal, J.D. Bray, N. Matasovic, P.A. Johnson, C. Cramer, C. Roblee, D.J. Wald, L.F. Bonilla, P.P. Dimitriu, and J.G. Anderson (1998). "Nonlinear site response: Where we're at (A report from SCEC/PEER seminar and workshop)." *Seismological Research Letters*, Vol. 69, pp. 230–234.

Hamilton, R.M. , and M.D. Zoback (1982). "Tectonic features of the New Madrid Seismic Zone from reflection profiles." McKeown, F.A., and L.C. Pakiser, eds., Investigations of the New Madrid, Missouri, Earthquake Region, U.S. Geological Survey Professional Paper 1236, pp. 55–82.

Heilgold, P.C., and Kolata, D.R., 1993, Proterozoic crustal boundary in the southern part of the Illinois Basin: Tectonophysics, v. 217, p. 307–319.

Hildenbrand, T.G., 1985, Rift structure of the northern Mississippi Embayment from the analysis of gravity and magnetic data: Journal of Geophysical Research, v. 90, p. 12607–12622.

Hildenbrand, T.G., Kane, M.F., and Stauder, W., 1977, Magnetic and gravity anomalies in the northern Mississippi embayment: U.S. Geological Survey Miscellaneous Field Studies Map MF-914.

Hildenbrand, T.G., Kane, M.F., and Hendricks, J.D., 1982, Magnetic basement in the upper Mississippi Embayment region, a preliminary report, *in* McKeown, F.A., and Pakiser, L.C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-I, p. 39–52.

Hildenbrand, T.G., Langenheim, V.E., and Heigold, P.C., 1994, Geophysical setting of the northern Reelfoot Rift and southern Illinois Basin: Proceedings of the Illinois Basin Energy and Mineral Resources Workshop, U.S. Geological Survey Open-File Report 94-298, p. 18–20.

Hildenbrand, T.G., and Hendricks, J.D., 1995, Geophysical setting of the Reelfoot rift and relations between rift structures and the New Madrid seismic zone: U.S. Geological Survey Professional Paper 1538, 30 p.

Kane, M.F., Hildenbrand, T.G., and Hendricks, J.D., 1981, Model for the tectonic evolution of the Mississippi Embayment and its contemporary seismicity: *Geology*, v. 9, p. 563–568.

Keller, G.R., Lidiak, E.G., Hinze, W.J., and Braile, L.W., 1983, The role of rifting in the tectonic development of the midcontinent, USA: *Tectonophysics*, v. 94, p. 391–412.

Mooney, W.D., Andrews, M.C., Ginzburg, A., Peters, D.A., and Hamilton, R.M., 1983, Crustal structure of the northern Mississippi Embayment and a comparison with other continental rift zones: *Tectonophysics*, v. 94, p. 327–348.

Odum, J., W.J. Stephenson, K. Shedlock, and T.L. Pratt (1998). Near-surface structural model for deformation associated with the February 7, 1812, New Madrid, Missouri, earthquake, *Geol. Soc. Am. Bull.* 110, 149–162.

OYO Corporation. (2009). SeisImager Manual Version 3.3 [Computer program manual]: OYO Corporation.

Schweig, E.S., F. Shen, L.R. Kanter, E.A. Luzietti, R.B. VanArsdale, K.M. Shedlock, and K.W. King (1992). Shallow seismic reflection survey of the Bootheel lineament area, southeastern Missouri, *Seism. Res. Lett.* 63, 285–295.

Seismic Image Software, Ltd., 1995, VISTA 7.0 notes.

Sexton, J.L., and P.B. Jones (1986). Evidence for recurrent faulting in the New Madrid seismic zone from mini-sosie high-resolution seismic data, *Geophysics.* 51, 1760–1788.

Sodenberg, R.K., and Keller, G.R., 1981, Geophysical evidence for a deep basin in western Kentucky: *American Association of Petroleum Geologists Bulletin*, v. 65, p. 226–234.

Steeples, D.W., and Miller, R.D., 1990, Seismic reflection methods applied to engineering, environmental, and groundwater problems, *in* Ward, S.H., ed.: *Geotechnical and Environmental Geophysics Volume 1*, Society of Exploration Geophysicists, Investigations in Geophysics, v. 5, p. 1–30.

Stephenson, W.J., J.K. Odum, R.A. Williams, T.L. Pratt, R.W. Harrison, and D. Hoffman (1999). Deformation and Quaternary faulting in southeast Missouri across the Commerce geophysical lineament, *Bull. Seism. Soc. Am.* 89, 140–155.

Thomas, W.A., 1991, The Appalachin-Ouachita rifted margin of southeastern North America: *Geological Society of America Bulletin*, v. 103, p. 415–431.

Toro, G.R., J. Silva, R.K. McGuire, and R.B. Herrmann (1992). Probabilistic seismic hazard mapping of the Mississippi Embayment. *Seism. Res. Letters* 63, 449-475.

Ventosa, S., LeRoy, S., Haurd, I., Pica, A., Rabeson, H., Ricarte, P., and Duval, L. (in press). Adaptive multiple subtraction with wavelet-based complex unary Wiener filters, *Geophysics*.

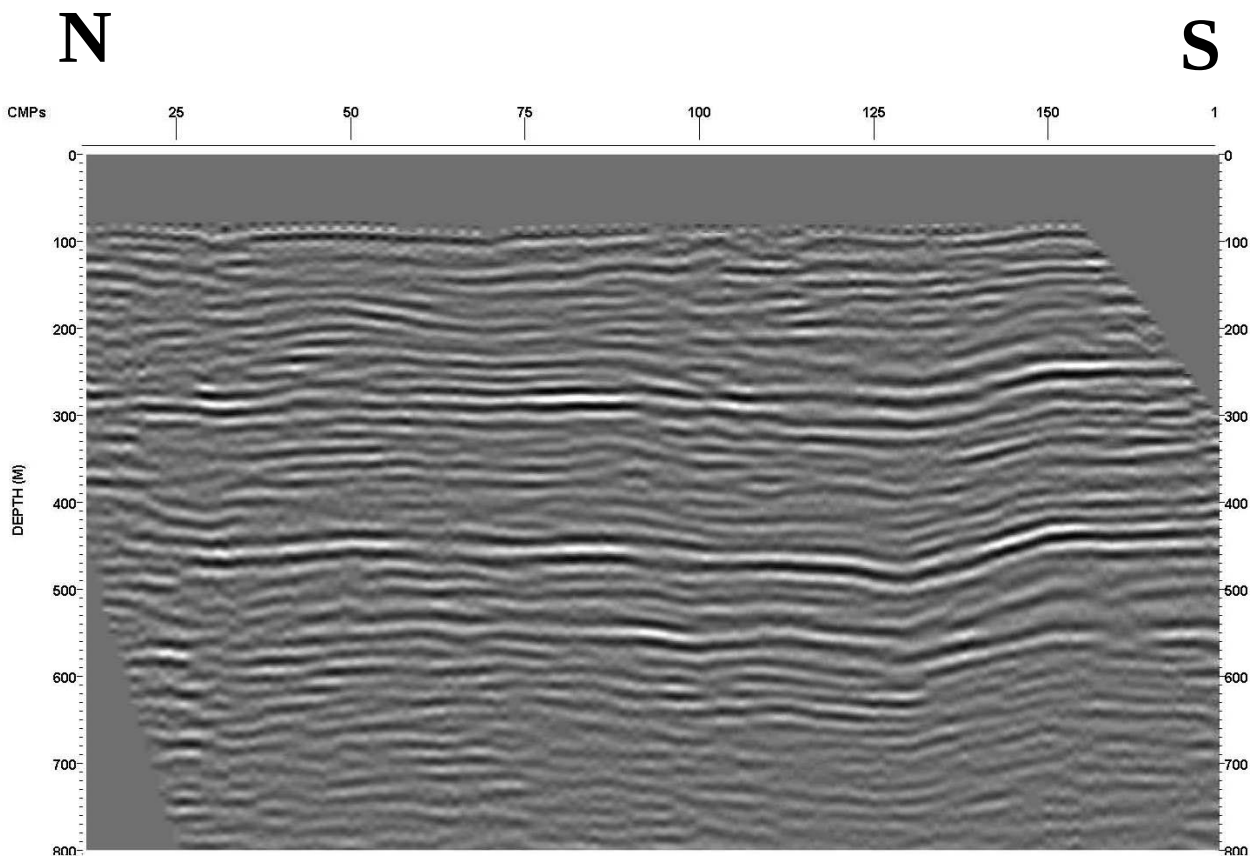
Williams, R.A., E.A. Luzietti, and D.L. Carver (1995). High-resolution seismic imaging of Quaternary faulting on the Crittenden County fault zone, New Madrid seismic zone, northeastern Arkansas, *Seism. Res. Lett.* 66, 42–57.

Woolery, E., R. Street., J. Harris, and Z. Wang (1999). "Neotectonic structure in the central New Madrid Seismic Zone: Evidence from multi-mode seismic-reflection data." *Seismological Research Letters*, Vol. 50, pp. 554–576.

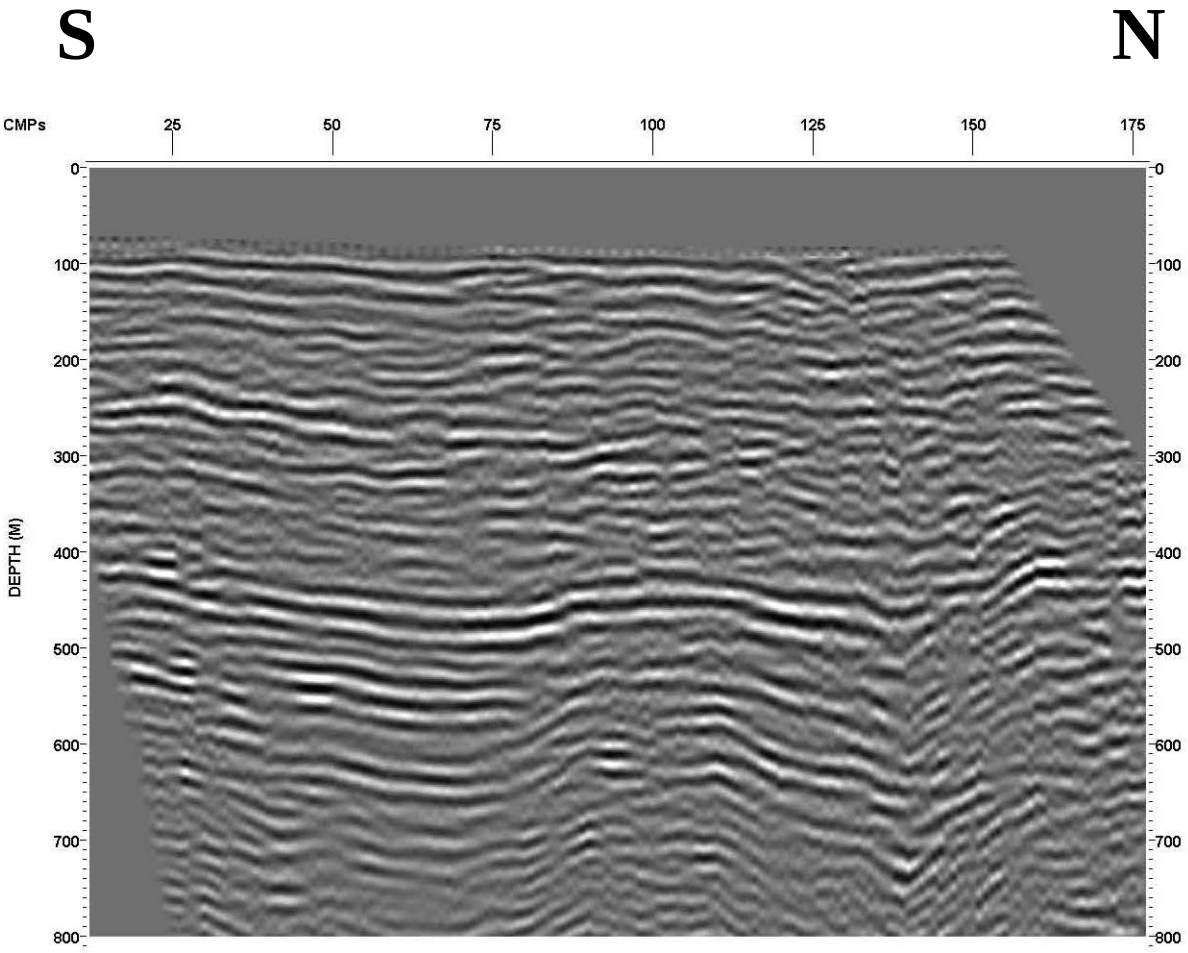
Woolery, E., Z. Wang, R. Street, and J.B. Harris (1996). A P- and SH-wave seismic investigation of the Kentucky Bend scarp in the New Madrid seismic zone, *Seism. Res. Lett.* 67, 67–74.

Woolery, E., R. Street, Z. Wang, and J. Harris (1993). Near-surface deformation in the New Madrid seismic zone as imaged by high resolution SH-wave seismic methods, *Geophys. Res. Lett.* 20, 1615–1618.

Appendix



Depth migrated CUSSO Line 2.



Depth migrated CUSSO Line 1.

The recorded seismic data is stored at the University of Kentucky in standard format and available upon request. Requests for information can be directed to:

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