FINAL TECHNICAL REPORT

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CHARACTERIZING THE GEOMETRY AND TIME OF DEFORMATION OF THE MEEMAN-SHELBY FAULT, NEAR MEMPHIS, TN

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ABSTRACT

A 10 km-long high-resolution seismic reflection profile was acquired in the summer of 2010 in West Memphis, AR to constrain the location and character of the Meeman-Shelby Fault (MSF), near Memphis, Tennesse, in the Central US. The fault, previously identified by a marine reflection survey as deforming the base of the Quaternary alluvium and the recent sediments along the Mississippi River, is a ~45km-long structure that strikes N25ºE and dips west-northwest ~80º, exhibiting an up-to-the-west sense of motion, with a possible right-lateral strike-slip component.

The survey imaged the fault at the predicted location, confirming the trend and character of the previously identified feature. At the fault, the top of the Paleozoic and Upper Cretaceous units are folded and display an elevation of ~56 and ~42 m respectively at the crest of the fold. The fold propagates to the Tertiary sediments and the top of the Paleocene is warped up ~21 m, and deformation is visible up to 380 m from the surface. Consistently with the other locations where the MSF was imaged, the fault dips ~80° to the west and shows an up-to-the-west sense of motion.

The MSF is the best documented fault close to Memphis yet discovered, and exhibits a recurrent fault history. Understanding its slip history and characteristics is therefore crucial for seismic hazard assessment in the region.

INTRODUCTION

Despite continuing studies in geodesy, seismology, and paleoseismology in the mid-continent/Mississippi Embayment area, there remains a paradox regarding the documented series of relatively large seismic events and the apparent low rates of deformation. As both modeling and observational studies improve, a variety of approaches are beginning to bear fruit. A promising hypothesis proposed to solve the apparent paradox is that deformation may be focused in different areas at different times, and that the present seismicity might not reflect the long-term behavior of the fault system in the Central US. Mounting evidence, mainly from paleoseismological studies, strongly suggests that the seismicity might have been migrating at least during the Holocene, although specific structures responsible for seismogenic faults other than the NMSZ system are not well documented.

In order to test the hypothesis of migrating faults, a pilot study conducted in the summer of 2008 collected 300 km of high-resolution seismic marine reflection data along the Mississippi river, from Caruthersville, MO, to Helena, AR (Magnani and McIntosh, 2009). The pilot study was a collaborative effort between NEHRP and the NSF/Tectonics program. The data identified with unprecedented resolution the existence of areas of deformation and faulting involving Quaternary sediments, several of which outside of the NMSZ. Among the imaged structures, the one identified along the Mississippi river just 10 km northwest of downtown Memphis, TN is the focus of this study. The 2008 river

profile crosses the structure at a minimum of three locations that align along a ~60 km-long NE-SW striking trend (Magnani and McIntosh, 2009, Hao et al., in press) (Fig. 1). The structure is characterized by a large ~60 m-high (at the top of Cretaceous), asymmetric anticline bounded to the east by a fault that displaces the Paleozoic, Mesozoic and Cenozoic sediments, including the Holocene deposits of the river alluvium. The imaged structure is interpreted as the southern continuation of the Meeman-Shelby Fault (MSF) (Williams et al., 2001). No seismicity is observed today along this fault, although the deformation of Quaternary deposits suggests that the fault has been active recently. The length and the Quaternary activity of this fault suggest that it might pose a more serious seismic hazard to Memphis than the NMSZ itself.

The goal of this project was therefore to image the onshore continuation and verify the northeast trend of the MSF across the segment between two river crossings. The acquired high-resolution reflection seismic data was used to locate the fault and help the characterization of the structure (style of faulting, geometry, history of deformation, etc.). The results of this study provide an opportunity to bracket the activity of the fault in time and to obtain age, amount of motions in the last events as well as recent slip rates through dating of key horizons by trenching, coring and geologic studies.

REGIONAL SETTING AND STRATIGRAPHY

Our study area is located in the Mississippi Embayment, along the southeastern margin of the failed Paleozoic Reelfoot Rift (Figure 1). The embayment is filled by gently southward dipping unconsolidated Cretaceous, Tertiary and Quaternary sediments topped by the Mississippi River alluvium (Stearns, 1957, Van Arsdale, 2009, Hardesty et al., 2010). The thickness of the unconsolidated sediments is ~1km near Memphis (Van Arsdale and Ellis, 2004), and reaches ~2 km to the south, where the embayment merges with the Gulf Coastal Plain. The lower boundary of the embayment section is marked by an unconformity of Cretaceous sequences on lower Paleozoic rocks.

The shallow (to ~1.5 km depth) stratigraphy of the study area consists predominantly of unconsolidated or semiconsolidated sediments, deposited both in marine and continental environments.

The Ordovician limestones and dolomites at the base of the stratigraphic column are separated from the overlying Upper Cretaceous marls and sandy limestones by a regional unconformity (Figure 2), recording extensive denudation that removed all the late Paleozoic and early Mesozoic strata [Van Arsdale, 2009; Thomas, 2010]. Another unconformity separates the Upper Cretaceous section from the Tertiary units, consisting of the Paleocene Midway Group (clays), the Paleocene-Eocene Wilcox Group (sands and clays), and the Eocene Claiborne Group (sands, silts and clays) [Saucier, 1994; Parrish and Van Arsdale, 2004; Velasco et al., 2005; Csontos, 2007; Van Arsdale, 2009]. Additional secondary unconformities within the Tertiary units record the Paleocene regression and the Eocene marine transgression from the south. At the top of the stratigraphic

sequence, the Quaternary sediments lie unconformably over the Eocene Claiborne Group.

The stratigraphy used for the interpretation of the seismic profiles (Figure 2) was derived from regional stratigraphic studies (Fisk, 1944; Saucier, 1994; Luzietti et al., 1995; Parrish and Van Arsdale, 2004), as well as interpretations of three well logs of self-potential, resistivity, and Gamma ray located in proximity of the seismic lines (Figure 1). Time to depth conversion of seismic profiles was performed using a P-wave velocity model derived from the Wilson 2-14 Well sonic log (Figure 1) (Langston, 2003).

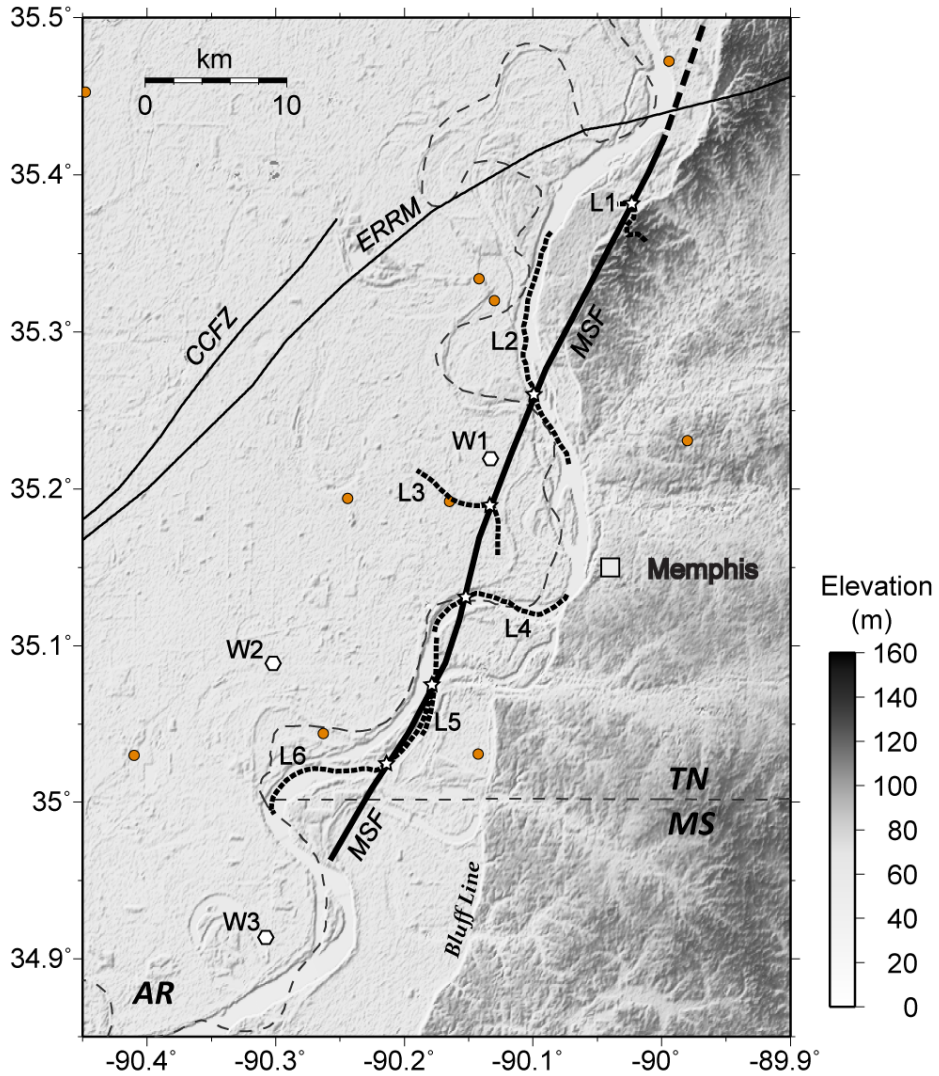

Figure 1. Topography map of the study area showing the extent of the MSF (heavy black line) as imaged by the 2010 land seismic reflection profile (L3) (this study), 4 seismic profiles from 2008 Mississippi River Project (L2, L4-6), and the 2001 USGS seismic survey (L1). CCFZ: Crittenden County Fault Zone; ERRM: East Reelfoot Rift Margin (from Hildenbrand and Hendricks, 1995). Orange dots show seismicity in the area (CERI New Madrid Earthquake Catalog 1974-2012, M0.1-8). White stars show surface projections of the MSF. Hexagons show the location of the boreholes used to calibrate the interpretation (for stratigraphy, see Figure 2).

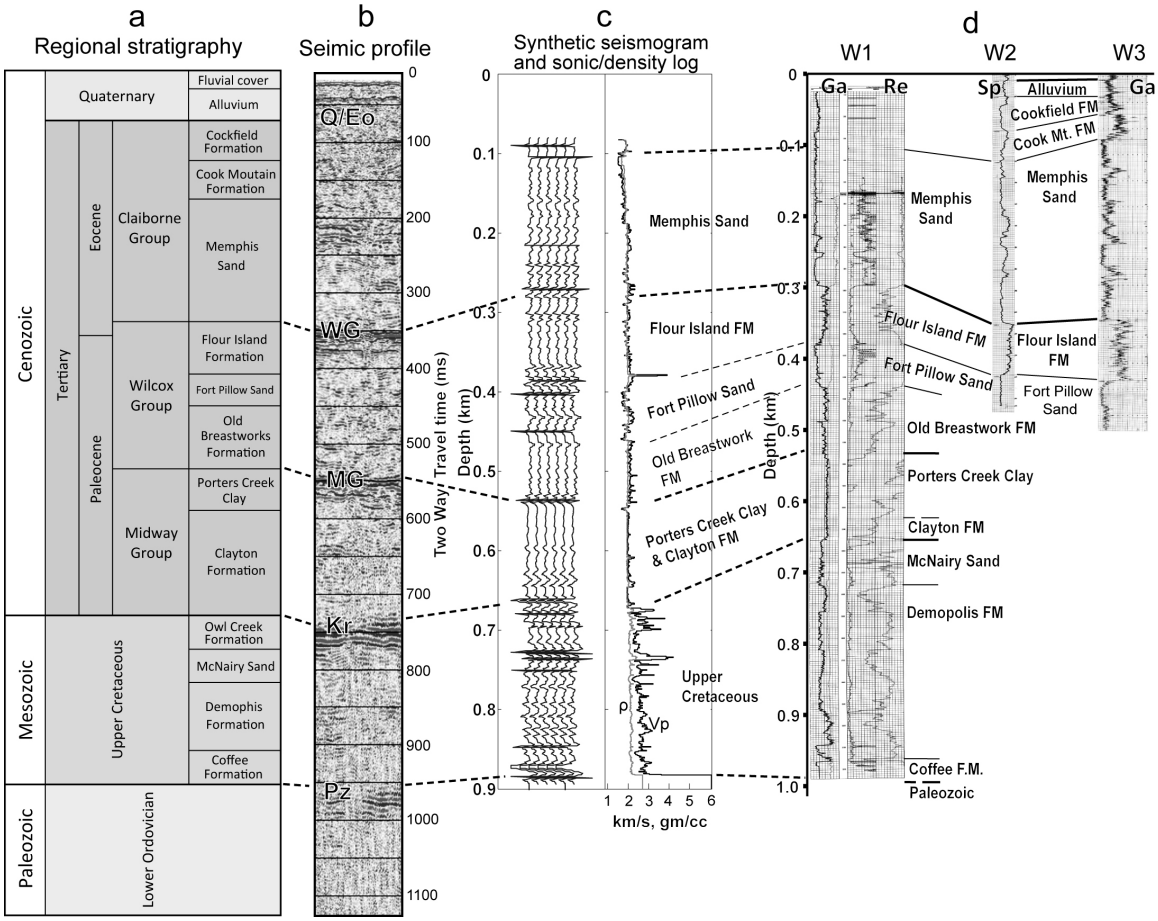

Figure 2: (a) Regional stratigraphy of the unconsolidated sediments in the Mississippi Embayment with formation names, and (b) correlation with seismic data in the study area, (c) with the synthetic seismogram (left) derived from the Wilson Well 2-14 sonic log (right), and (d) with three local well logs (W1: Gamma ray and resistivity; W2: self-potential; W3: Gamma ray). The stratigraphy column was derived from studies in this region [Saucier, 1994; Luzietti et al., 1995; Parrish and Van Arsdale, 2004] and modified according to the interpretations of the well logs in (d). The P-wave velocity model for time-to-depth conversion of the seismic profiles was derived from the Wilson Well 2-14 sonic log in (c) [Langston, 2003].

DATA ACQUISITION AND PROCESSING

The Mississippi River Project in 2008 imaged the MSF at three river crossings. To constrain the extension of the MSF on land and verify the northeast trend of the fault revealed by the marine data we carried out a high-resolution land seismic reflection survey between two river crossings, near West Memphis, Arkansas (Figure 1). We chose to acquire the land profile on the Mississippi river floodplain rather than on the region covered by the Upland Complex ("bluffs"), because the lack of the Quaternary loess layer overlying the Pleistocene and Tertiary strata on the floodplain is usually associated with increased energy penetration and good data quality (Williams et al., 2001).

The acquisition parameters (**Table 1**) for the land survey were designed to be reproduce as much as possible those used for the Mississippi River Project (Magnani and McIntosh, 2009) to facilitate the comparison between the two datasets. The parameters were also similar to those used for the 2001 USGS survey (Williams et al., 2001), which identified the MSF north of Memphis and imaged the unconsolidated sediments to a depth of ~1 km. The only difference between the 2010 and the 2001 land surveys was a reduced receiver interval (5 m instead of 10 m), which resulted in a higher fold in the CDP domain.

The profile was acquired using the 9990 kg Mini Vibe "Thumper" (Figure 3) provided by the Network for Earthquake Engineering Simulation (NEES) at the University of Texas at Austin as a seismic source. The Mini Vibe is a high-frequency Vibroseis capable of a peak force of 26.7 kN over a 17-225 Hz range of frequencies, and has been successfully employed in several locations of the Mississippi Embayment to image the unconsolidated sediments from the Paleozoic to the Quaternary (Williams et al., 2008). The recording system (consisting of 12 Geometrics Geodes for a total of 144 active channels) (Figure 4) was kindly provided by the USGS Near Surface Imaging Group in Golden, CO. A 12 s-long linear upsweep with frequencies of 20-220Hz and a listening time of 14 s resulted in fully correlated shot records of 2 s. A group interval of 5 m and a source interval of 10 m translated into a nominal CDP fold of 36 and a CDP interval of 2.5m. A minimum of two shots were recorded and vertically stacked at each shot location to increase the S/N ratio and reduce random noise. The parameters selected for this study have the advantage to achieve both high spatial and temporal resolution.

Table 1. Comparison of acquisition parameters

Parameters	2008 Mississippi River Project	2001 USGS survey	2010 MSF land survey
Source	Airgun, Sercel Mini GI/15/15 in^3, 13.79 MPa	Three 46-km earth tamper	9990 kg Mini Vibe, 20-220 Hz, 12 s, upsweep
Shot interval	2-6.5 m	10 m	10 m
Receiver type, cable length, n. channels	75m-long, 24 channels	28 Hz 3C, 590 m-long, 59 channels	40 Hz vertical, 720 m-long, 144 channels
Receiver interval	3.125 m	10 m	5 m
Min offset	3-6 m	10 m	10 m
Sampling interval	0.5 ms	1 ms	1 ms
Samples per trace	3000	1000	2000 (correlated)
Stacking fold	6-16	29.5	36
CDP interval	1.6 m	5 m	2.5 m
Survey line length	300 km	4.5 km	10 km

Figure 3: The Network for Earthquake Engineering Simulation (NEES) 9990-kg Mini Vibe "Thumper" executing a sweep during the seismic survey.

Figure 4. One of the Geometrics Geode data digitizers in the field. The equipment was kindly provided by the USGS Near Surface Imaging Group, Golden CO.

Figure 5: Surveying the stations along the spread. The survey was performed using a Trimble GeoExplorer GPS with a postprocessed differential accuracy of ~10 cm.

The seismic data were analyzed using a tested processing flow (**Error! Reference source not found.**) for high-resolution land seismic reflection data in the unconsolidated sediments of the Mississippi Embayment. Survey data, acquired in the field (Figure 5) were processed to an accuracy of ~10 cm and used to apply a crooked line geometry and perform CDP binning. After Vibroseis correlation, which resulted in 2 s-long fully correlated traces, noisy traces were edited out of the dataset, and two clean shot gathers at each shot station were stacked to enhance the S/N ratio. This step proved especially effective in suppressing the random ambient noise, such as the incoming traffic along the nearby road (Figure).

In order to more accurately constrain the deformation history of the MSF, data were depth converted after normal moveout (NMO) correction and stacking using a P-wave velocity field derived from the Wilson Well sonic log (Langston, 2003). The 2D velocity field was derived by projecting the time-converted Wilson Well 1D velocity function on the seismic profiles and calibrating the key regional seismic markers/reflectors.

Table 2. Processing flow of the land seismic reflection data

Data Format	Convert from SEGY to ProMAX format
Vibroseis Correlation	Total correlated trace length: 2000 ms
Trace Editing	Remove noisy traces, edit reverse polarity
Shot Gather Formation	Vertical Stacking of two shot gathers into one
Geometry Assignment	Crooked line geometry with 2.5 m bin size
Frequency Filter	10-24-150-177 Hz (Ormsby minimum phase), 60 Hz Notch
Top Mute	Remove direct and refracted arrivals
Internal Mute	Remove data within surface wave cone
Air Wave Energy Attenuation	Air wave velocity: 348 m/s
CDP Sorting	Sort to CDP domain
Velocity Analysis	Supergather formation with 3 CDPs
NMO Correction	100% stretch mute
Frequency Filter	10-24-150-177 Hz (Ormsby minimum phase)
Amplitude Gain	AGC with a 150 ms window length
Eigenvector Filter	0-60% eigenimage accepted
CDP stack	36 fold nominal
Time-Variant Frequency Filter	0-70 ms: 45-55-150-177 Hz; 150-550 ms: 30-45-150-170 Hz; 700-2000 ms: 10-24-140-160 Hz (Ormsby minimum phase)
Time-to-depth conversion	2D P-wave velocity model derived from the Wilson 2-14 well sonic log

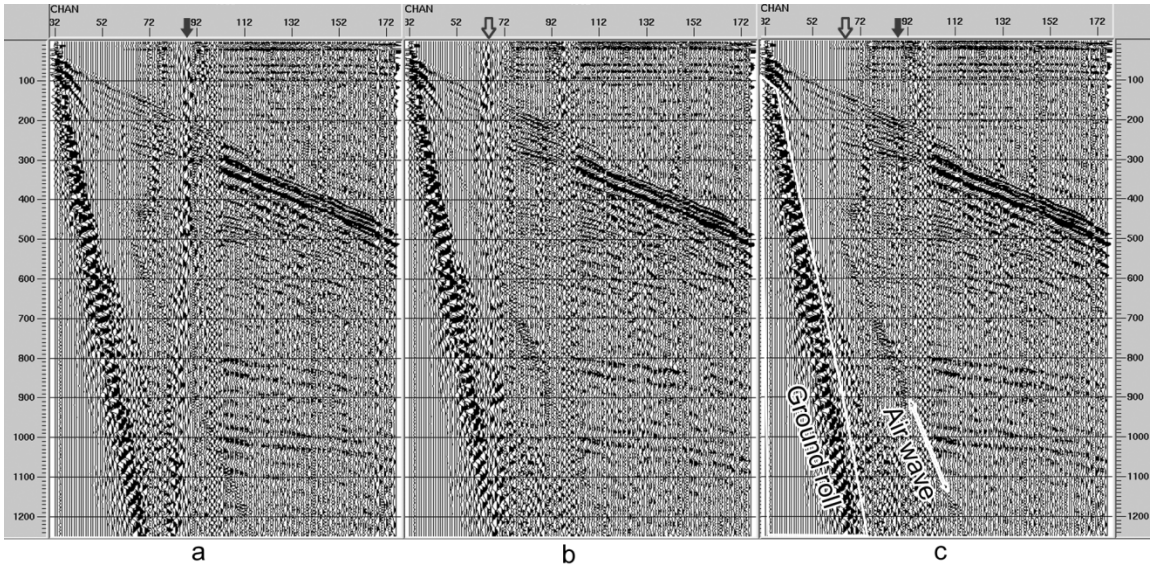

Figure 6: Examples of shot gathers acquired as part of the land survey showing the correlation/vertical stacking process at a single shot point. (a) First shot gather after Vibroseis correlation and bandpass filter (10-24-150-177 Hz); (b) second shot gather acquired at the same shot point and with identical processing; (c) vertical stacking of the two shot gathers. Traffic noise (marked by the solid and hollow vertical arrows at the top of the gathers) has been effectively attenuated after stacking. Reflectors are visible from 200-1100 ms. Clear reflectors between 800-900 and 1000-1100 ms are interpreted as the top of the Upper Cretaceous sediments and the top of the Paleozoic rocks, respectively. Ground-roll noise is visible as a high-amplitude, low-frequency energy at near offsets. The air wave energy is visible as the high frequency, low velocity (335 m/s) linear arrival.

INTERPRETATION

The 10 km-long profile (**Figure**) successfully imaged the MSF at the predicted location, showing reflectors of the top of the Paleozoic section and the top of the Upper Cretaceous sediments folded ~51 and ~42 m, at a depth of ~10.4 and ~0.8 km respectively, at the MSF around shotpoint 1600. The top of the overlying Paleocene Wilcox Group appears warped up ~21 m. At this location, the MSF dips ~80° to the west and shows an up-to-the-west sense of motion. Also the consistent increase of offset with depth/age suggests a prolonged activity throughout the Cenozoic and possibly the Late Cretaceous. A fault showing an up-to-the-east sense of motion is imaged along the profile ~1.7 km west of the MSF (shotpoints 2200-2400), forming a gentle anticline together with the MSF. We speculate that the anticline, as well as the two faults that bound it, could be the upper portion of a compressional strike slip system (flower structure) which merges at depth in light of the N80°E compressional regional stress field (Zoback and Zoback, 1980; Grana and Richardson, 1996).

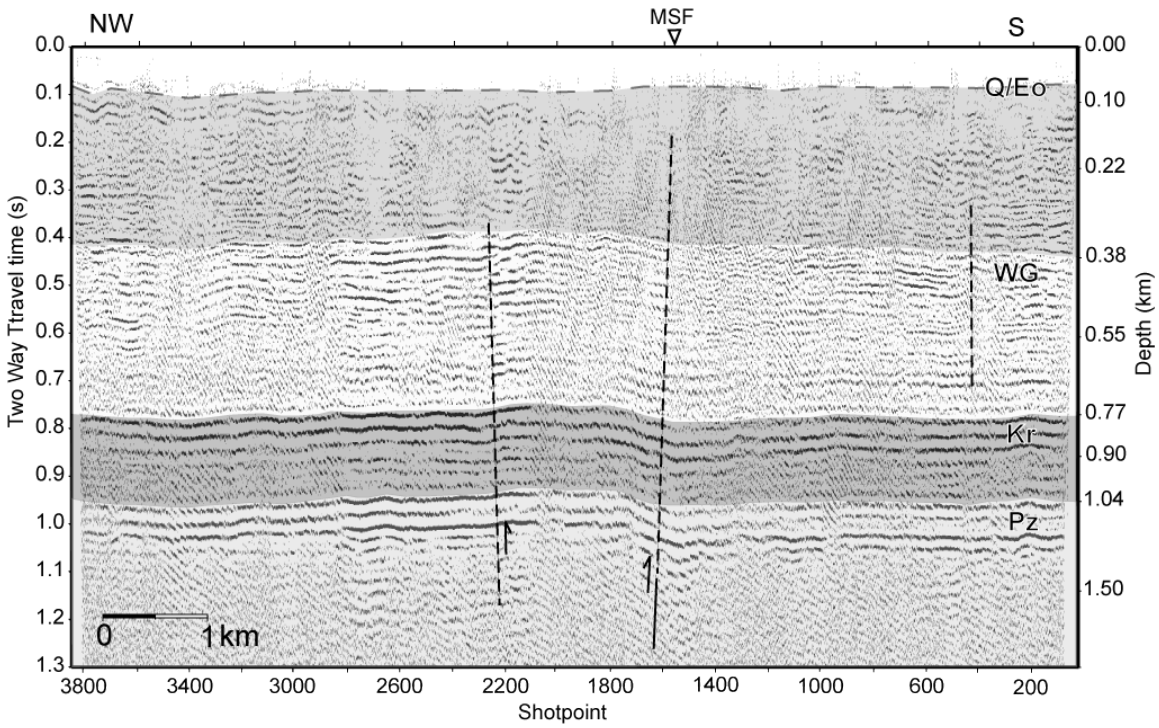

Figure 7: Seismic profile and interpretation of the land seismic reflection survey of the MSF. Black solid and dashed lines indicate interpreted faults on the two-way traveltime (TWT) seismic profile with estimated values of depth based on time-to-depth conversion labeled on the right of the profile. Pz, Paleozoic; Kr, Cretaceous; WG, Paleocene-Eocene Wilcox Group; Q/Eo, Quaternary-Eocene unconformity. The MSF label and the triangle at the top of the profile show the surface projection of the MSF as identified by the alignment of multiple crossings of the fault along the Mississippi river and a location on land (see Fig 1 for locations). The Q/Eo boundary is extrapolated from nearby boreholes.

DISCUSSION AND CONCLUSIONS

The 2010 land seismic survey, together with the 2001 USGS land seismic survey and the 2008 Mississippi River Project, provided a total of 6 seismic profiles to constrain the location and geometry of the MSF (Hao et al., in press). The locations where the fault has been identified align along a linear trend for ~45 km, striking N25°E (**Figure 1**). The fault shows a consistent up-to-the-west sense of displacement and a dip of ~80°.

The observed increase in amount of deformation with age along the MSF from the recent sediments to the Paleozoic units in the seismic profiles is consistent with a prolonged activity of the fault that spans from the Quaternary back to the Late Cretaceous.

Cumulative deformation of the MSF at the top of Paleozoic unit, the top of Cretaceous unit, and the top of Wilcox Group are 57, 42, and 21 m, respectively. Vertical displacement for each of the three stratigraphic units are 14, 21, and 21 m, respectively. The net slip for each profile was calculated from the vertical slip using 80° dipping angle and an assumed average rake of 132° derived from the

two nearby focal mechanism solutions (Chiu et al., 1997; Hao et al., in press). Net slips were averaged with the results from the other seismic profiles and divided by corresponding time periods, resulting the slip rates for the Late Cretaceous, the Paleocene, the Eocene, and the Quaternary are 0.0022, 0.0010, 0.0004, and 0.2154 mm/yr, respectively (**Table 3**) (Hao et al., in press). These values are comparable with those calculated for structures associated with the active Reelfoot Fault system (Van Arsdale, 2000) and corroborate the evidence for an increase in strain rates during the late Quaternary.

Table 3. Estimates of deformation and slip rate of the MSF

Cumulative deformation (m)						**Vertical deformation (m)**					**Average net slip (m)**	**Time span (Myr)**		**Vertical slip rate (mm/yr)**
Reflector	L2	L3	L4	L6	Mean	L2	L3	L4	L6	Mean				
Top Q	-	-	-	-	-	28	-	-	-	28.0	38.0	LPls-Ho*	0.13	0.2154
Q/Eo	28	-	-	-	28	19	21	19	12	17.8	24.1	Eocene	45	0.0004
Top WG	47	21	19	12	25	14	21	26	17	19.5	26.5	Paleocene	20	0.0010
Top Kr	61	42	45	29	44	66	14	26	23	32.3	43.8	Late Kr	15	0.0022
Top Pz	127	56	71	52	77	-	-	-	-	-	-	Paleozoic		-

Note: L3 is the 2010 land seismic reflection survey line of the MSF (this study). L2, L4, and L6 represent the survey lines of the 2008 Mississippi River Project. * Late Pleistocene to Holocene.

Source scaling estimates (Wells and Coppersmith, 1994) suggest that the 45 km-long MSF is capable of generating a M6.9 earthquake if rupturing in one event. The seismic potential of the MSF coupled with the evidence for an increase in fault activity during the late Quaternary as well as its proximity (only 9 km) to Memphis suggest that the MSF could present a higher seismic threat to Memphis than the NMSZ itself.

PRESENTATIONS AND PUBLICATIONS

The data acquired as part of this study were presented at numerous regional and national meetings. The student supported by the study (Yanjun Hao) was awarded the AGU Best Student Presentation Award at the 2011 AGU Fall meeting in San Francisco presenting the results of this study.

Below is a list of presentation and publications resulting from this project:

Y. Hao, M.B. Magnani, K. McIntosh, B. Waldron, L. Guo, High-Resolution Marine and Land Seismic Reflection Imaging of the Meeman-Shelby Fault, near Memphis, Tennessee, Tectonics, in press.

Y. Hao, M.B. Magnani, L. Guo, K. McIntosh, 2012, History of Deformation Along the Meeman-Shelby Fault near Memphis, Tennessee, EOS Trans, AGU Fall Meeting, San Francisco, CA.

M.B. Magnani, McIntosh, K.D., *Guo, L.* and *Hao, Y.*, 2012, Distribution of long-term Quaternary Deformation and Correlation with Pre-existing Tectonic Structures in the Central US, EOS Trans. AGU, Fall Meet. Suppl., Abstracts.

Y. Hao, M.B. Magnani, L. Guo, J.K. Odum and D.M. Worley, 2011, Characterizing The Geometry and History of Deformation of The Meeman-Shelby Fault (Central U.S.), SSA Annual Meeting, April 2011, Memphis, TN.

Magnani, M.B., Spatial and Temporal Distribution of Deformation in the Central US from High-Resolution Reflection Data, Seismological Society of America Meeting, Memphis, April 13-15, 2011, SRL, v. 82, 2.

Y. Hao, M.B. Magnani, L. Guo, 2011, Characterizing the Geometry and History of Deformation of the Meeman-Shelby Fault near Memphis, TN, EOS Trans, AGU Fall Meeting, San Francisco, CA.

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