FINAL TECHNICAL REPORT

Award Number 08HQGR0089

TOWARD AN UNDERSTANDING OF THE LONG-TERM DEFORMATION IN THE MISSISSIPPI EMBAYMENT: COLLABORATIVE RESEARCH WITH THE UNIVERSITY OF MEMPHIS AND THE UNIVERSITY OF TEXAS

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ABSTRACT

The Central U.S. hosts one of the most active intraplate seismic areas in the world, the New Madrid seismic zone (NMSZ). Here the high level of historic and instrumental seismicity clashes with the subdued topography of the Mississippi Embayment, minimal geodetic vectors and a puzzling lack of substantial deformation in the post Late-Cretaceous sediments. To explain this apparent paradox it has been proposed that the seismicity in the NMSZ is either 1) very young (at least in its present form), 2) episodic, or 3) migrates throughout a broad region.

To test these hypotheses and to understand how deformation is partitioned within the Mississippi Embayment, we collected 300 km of high-resolution seismic reflection and chirp data along the Mississippi River from Helena, Arkansas to Caruthersville, Missouri. The data image a portion of the embayment outside the area of influence of the NMSZ in a region where evidence is mounting of a seismic source, predating the NMSZ, for which no corresponding structure has yet been identified.

The seismic survey exploited the advantages of marine acquisition (time effective, low cost) using a 245/245 cm^3 (15/15 in^3) mini-GI airgun fired at 13.790 MPa (2000 psi), a 24-channel 75 m-long active streamer, with 3.125 m group and 9 m nominal shot interval. The high quality data image the Cretaceous and younger sedimentary section, from the top of the Paleozoic unconformity to the Quaternary deposits.

The acquired data identified with unprecedented resolution the existence of three areas of deformation and faulting involving Quaternary sediments. Two of these areas lie outside the NMSZ, confirming the hypothesis that recent (Quaternary) deformation is not limited to the area of present seismicity, but it extends beyond the NMSZ. The data show that seismicity has migrated spatially within the embayment, suggesting that the long-term seismic activity in this area might extend over a broader region than previously suspected.

INTRODUCTION

The New Madrid Seismic Zone, located in the Central U.S., is one of the most studied intraplate seismic zones in the world and by far the most active in the U.S. east of the Rocky Mountains. In this area, in the winter of 1811-1812, more than 2000 km from the nearest plate boundary, three large earthquakes of estimated magnitude 7.2- 8.1 (Nuttli, 1982; Johnston and Nava, 1985; Johnston, 1996; Hough et al., 2000) are thought to have ruptured in rapid succession the Reelfoot fault and two associated faults to the north and south. The exact locations of these events are still controversial due to the fact that the only evidence of surface rupture is along the Reelfoot fault. The historical seismicity pattern constrains the location of present deformation to four main arms, extending from west of Memphis, TN, into southern Missouri for more than 200 km (Fig 1).

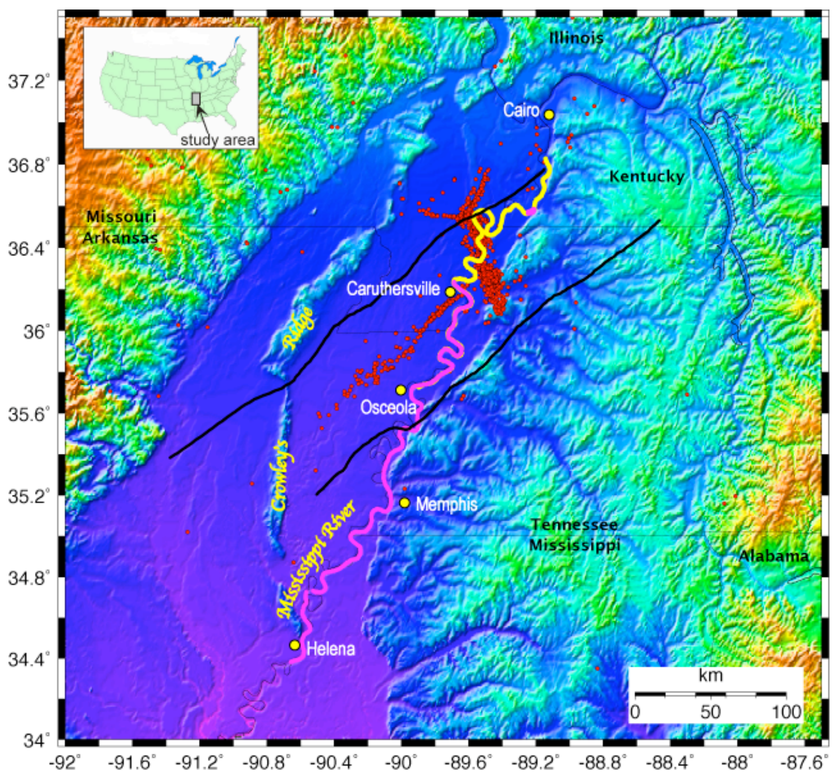

Figure 1. Topography map of the Mississippi Embayment (Central U.S.) showing the location of the Mississippi "Moonwalk" seismic survey (pink solid line) acquired along the Mississippi River. The profile overlaps with the 1981 USGS river acquisition (yellow line). The epicenters of earthquakes recorded from 2000 to present with magnitudes greater than 1.0 (red dots) define the New Madrid Seismic Zone (NMSZ). Solid black lines show the boundaries of the Paleozoic Reelfoot rift buried beneath the Mississippi Valley sedimentary cover and inferred from aeromagnetic data (Hildebrand, 1985).

Estimates of the recurrence interval for large NMSZ earthquakes are mainly provided by paleoseismological data, which indicate that seismic events in the NMSZ capable of generating widespread soil liquefaction have occurred in the past 5000 yr with a recurrence rate of ~500 yr in late Holocene (Tuttle et al., 2002, Tuttle et al., 2005). Alternative recurrence models based on the response of the Mississippi River meander pattern to subsurface deformation suggest that the NMSZ might rupture every 1000 yrs (Holbrook et al., 2006), although this methodology is not sensitive to small reverse-slip or large strike-slip ruptures. Estimates of the age of the NMSZ, based on the Gutenberg-Richter relation, suggest that the NMSZ has been active for at least 2000 years and it could be as old as 64,000 years (Pratt, 1994; Mitchell et al., 1991; Russ, 1982; Gomberg and Ellis, 1994). Pratt (1994) calculates that modern seismicity levels should produce ~ 0.11 cm/yr of horizontal slip, which paired with the suggested age of the NMSZ predicts an amount of deformation that should have a significant topographic signature and a distinct counterpart in subsurface structures. Instead, seismic reflection profiles show small cumulative fault offsets and mild deformation in the post Late Cretaceous sediments (Hamilton and Zoback, 1982, Nelson and Zhang, 1991), corroborating the geodetic data that show that motion vectors are less than 1 mm/yr in the NMSZ with greater values across the Reelfoot thrust fault-scarp (up to ~2.7 ± 1.6 mm/yr) and that velocities decay to levels not different from zero in the far field (Smalley et al., 2005, Calais et al., 2005). Reconciling these controversial observations in a unifying model applicable to the Central US intraplate seismicity has been the focus of a heated scientific debate that has involved researchers as well as policy-makers, as the solution of this paradox has major implications for earthquake hazard policy.

One of the hypotheses proposed to reconcile the available data suggests that the present, historical and prehistorical pattern of seismicity does not reflect the long-term behavior of the faults in the Central US (e.g., Coppersmith, 1988; Pratt, 1994; Langenheim and Hildebrand, 1997; Harrison and Schultz, 2002; Stein and Newman, 2004, Calais and Stein, 2009), but that the seismicity may spatially shift throughout a broad region and seismically "activate" and "deactivate" different fault systems at different times. The stresses imparted by plate margin forces (including the remnants of the ancient Farallon slab as suggested by Forte et al. (2007)), and generated within the plate (e.g. regional loads and/or mantle convection tractions) are causing the NMSZ to "turn on" today, but the hypothesis assumes that the seismicity in a certain area is transient and will eventually migrate to a different fault or system of faults at the continental (Central US) or regional (Mississippi Embayment) scale.

Present earthquake hazard calculations assume that large future earthquakes will occur where small earthquakes are occurring today and where large historical earthquake have occurred. Perhaps the most critical consequence of spatially and temporally migrating seismicity in intraplate settings is that the risk of occurrence of large magnitude earthquakes extends beyond the limits of the presently active areas. The disastrous May 2008 M7.8 earthquake that struck the Sichuan region in China, has possible similarities to activity that could occur on the NMSZ - it was located in the interior of a continent and it occurred on a fault with little recent seismicity in an area that was not expected to suffer seismic activity of such magnitude (Kirby et al., 2008). In the Mississippi

Embayment evidence is mounting that during the Holocene seismic activity extended beyond the limits of the NMSZ and that different portions of the embayment have experienced large earthquakes that do not correlate with historical or prehistorical NMSZ seismic events. Most of this evidence is based on paleoseismological studies of liquefaction features caused by violent ground shaking during large earthquakes (Tuttle et al., 2006; Cox et al., 2001; Al-Shukri et al., 2005), but the seismogenic faults associated with these structures have not been identified. What is emerging, after 50 years of research and investigations in the Mid-Continent and in other intraplate regions, is that the present seismicity does not reflect the long-term behavior of continental interiors, but that the tectonic evolution is the result of the interaction between all the faults of this complex system. The mechanisms that guide these interactions cannot therefore be understood by focusing uniquely on those faults that are historically seismogenic, but requires an approach that includes the intricate network of faults that are quiescent today. This task is particularly challenging in the Mississippi Embayment, as most of the faults are concealed under the Mississippi Embayment sediments and very few of them have a morphological expression.

In an effort to identify the relatively large faults in the region, in the summer of 2008 we acquired a 300 km long marine reflection profile along the Mississippi River (Mississippi Moonwalk Project), from Caruthersville, MO to Helena, AR (Fig. 1). The project, which was a pilot study to test the feasibility of marine acquisition along the Mississippi River, collected high resolution data of unprecedented high quality that successfully imaged the embayment sedimentary cover to a depth of ~1 km, mapping the Paleozoic, Mesozoic and Cenozoic stratigraphy.

STUDY AREA

The Mississippi Embayment (Fig. 1) is a trough filled with Late Cretaceous and Cenozoic clastic sediments, which lie unconformably on Late Cambrian to Ordovician sedimentary rocks and a Precambrian crystalline basement. The area is a long-lived, fundamentally weak zone in the North American plate and has been the location of repeated crustal extension, compression and continental rifting since at least the Late Proterozoic, with several episodes of reactivation and magmatic activity (Burke and Dewey, 1973; Ervin and McGinnis, 1975). The Reelfoot rift, today buried under the Mississippi Valley sediments, represents the backbone of the embayment (Hildebrand, 1985). The rift is a Late Proterozoic or Early Paleozoic crustal feature that was reactivated during the Late Paleozoic and uplifted in the Cretaceous. Today the top of the crystalline basement is displaced more than 2 km along the rift margins (Kane et al., 1981). NMSZ seismicity is hosted within the rift structure (Fig. 1) and features two dextral-slip north-east trending arms connected by a left-stepping (Reelfoot thrust restraining bend) reverse-slip arm (Chiu et al., 1992). The magnitude of the historic earthquakes and the level of background seismicity make this area the most active seismic zone in the Central U.S. and an enigmatic feature that appears to defy plate tectonic theory.

The Mississippi Embayment and the NMSZ have been extensively studied for several decades, mostly due to the notorious 1811-1812 events, but also because the thick sedimentary rocks of this region have attracted natural gas and oil exploration. Early efforts focused on the crustal structure of the embayment, mostly in the area of active deformation. The 70-80 km-long Reelfoot rift structure was identified by aeromagnetic and gravity data in the northern Mississippi Embayment (Hildebrand et al., 1977, 1982), while seismic refraction (Mooney et al., 1983) and COCORP deep reflection studies (Nelson and Zhang, 1991) modeled the velocity and imaged the structure of the ~39 km thick crust, revealing the presence of a high velocity lower crustal layer ("rift pillow") coincident with the Reelfoot rift. Vibroseis surveys imaging the Precambrian crystalline basement and part of the unconsolidated sediments across the area of the NMSZ provide evidence for reactivation of older faults (Hamilton and Zoback, 1982; Sexton and Jones, 1986), suggesting a long slip history that extends back to the Late Cretaceous (Van Arsdale, 2000) and possibly to the Precambrian (Cox et al., 2001). Dozens of high-resolution land seismic reflection surveys were carried out in the last three decades (e.g. Luzietti et al., 1992; Schweig et al., 1992; Sexton and Jones, 1986; Williams et al., 2001). The surveys targeted the unconsolidated sedimentary section, from the top of the Paleozoic to the Tertiary. Very few (Odum et al., 1995) successfully imaged the top of the Tertiary and the Quaternary alluvium, thus the analysis of recent deformation from these projects is limited.

Mostly due to high cost and long acquisition times required for land seismic surveying, the majority of the aforementioned high-resolution seismic reflection surveys are short profiles (~5 km max) targeting specific areas where faulting and recent deformation were inferred based on available constraints. Only one seismic survey (USGS, 1981) attempted a regional profile (Fig 1), exploiting the presence of the Mississippi River across the NMSZ (Shedlock and Harding, 1982). The USGS 1981 river profile acquired 240 km of marine seismic reflection data from Wickliffe, Kentucky, to Osceola, Arkansas, using a single Bolt 40 cu. in. airgun and a 12-channel, 120 m-long streamer (Table 1). The survey successfully achieved consistent penetration of 0.5 – 0.8 s two-way travel time (TWTT) and imaged with fairly good continuity the top of the Paleozoic and the Cretaceous section and intermittently the Tertiary sediments (Fig 2). Based on these reflectors, the profile documents several apparent crossings of the Reelfoot thrust, thanks to the meandering of the river, as well as crossing of the Cottonwood Grove fault and the New Markham fault. Unfortunately the USGS 1981 river acquisition image of the upper sedimentary section is only sporadic and it is not possible to separate the Tertiary activity from the recent movement along the identified faults. The most important contribution of this pioneering effort was to demonstrate the feasibility of marine seismic reflection data acquisition along the river, in spite of the challenging environment and technical difficulties.

THE "MISSISSIPPI MOONWALK" PROJECT

The project, which acquired the descriptive name of Mississippi Moonwalk, was essentially a pilot study to determine whether high-quality seismic reflection data could be acquired in the Mississippi River. The idea is attractive because marine seismic acquisition is cost effective relative to land work and largely avoids many of the pitfalls of land seismic including statics problems and source-generated noise such as "ground roll". However, as noted above, the previous attempt at Mississippi River seismic acquisition by the USGS in 1981 had mixed results. Most importantly, that data set generally did not provide good images of the shallow section (Eocene-Quaternary), which precludes any attempt to document recent faulting associated with ongoing deformation.

To improve our ability to image the post-Cretaceous section we used a significantly different geometry than the previous work (Table 1) and also used an advanced seismic source that had been previously unavailable. The primary change in geometry was to reduce the nearest source-to-receiver offset from 60 m to ~3 m. This reduced our aperture but ensured that we would record reflections rather than refractions from the shallow subsurface. For our seismic source we used a mini-GI airgun rather than a single chamber airgun. The GI airgun uses two chambers (a **G**enerator and an **I**njector) and applies a delay to the release of the second chamber such that it prevents the air bubble produced by the first chamber from collapsing. This process significantly reduces the bubble pulse, leaving a cleaner, sharper source signature, which is essential for shallow, high-resolution imaging. Although we were certain that the mini-GI source would improve the shallow imaging, we were concerned that it may not provide sufficient energy to also image the deeper Cretaceous and Paleozoic strata. Fortunately this did not prove to be a problem as we consistently recorded reflections from these horizons across almost all segments surveyed (Fig 2).

Parameters	Moonwalk Survey	1981 Survey
Streamer: # channels/length	24 channels/75 m	12 channels/120 m
Streamer group interval	3.125 m	10 m
Near trace source/receiver offset	3 to 6 m	61 m
Shot interval	9 m	5-10 m
Sample interval	0.5 ms	0.5 ms
Samples per trace	3000	2000
Stacking fold	8	6 to 12
CDP interval	3 m	5-10 m
Airgun Make/Size	Sercel Mini GI/ (15/15) in.^{3}	Bolt / 40 in.^{3}

Table 1. Comparison between parameters used during the 1981 USGS Mississippi River acquisition (Shedlock and Harding, 1982) and the parameters for the Mississippi Moonwalk river survey.

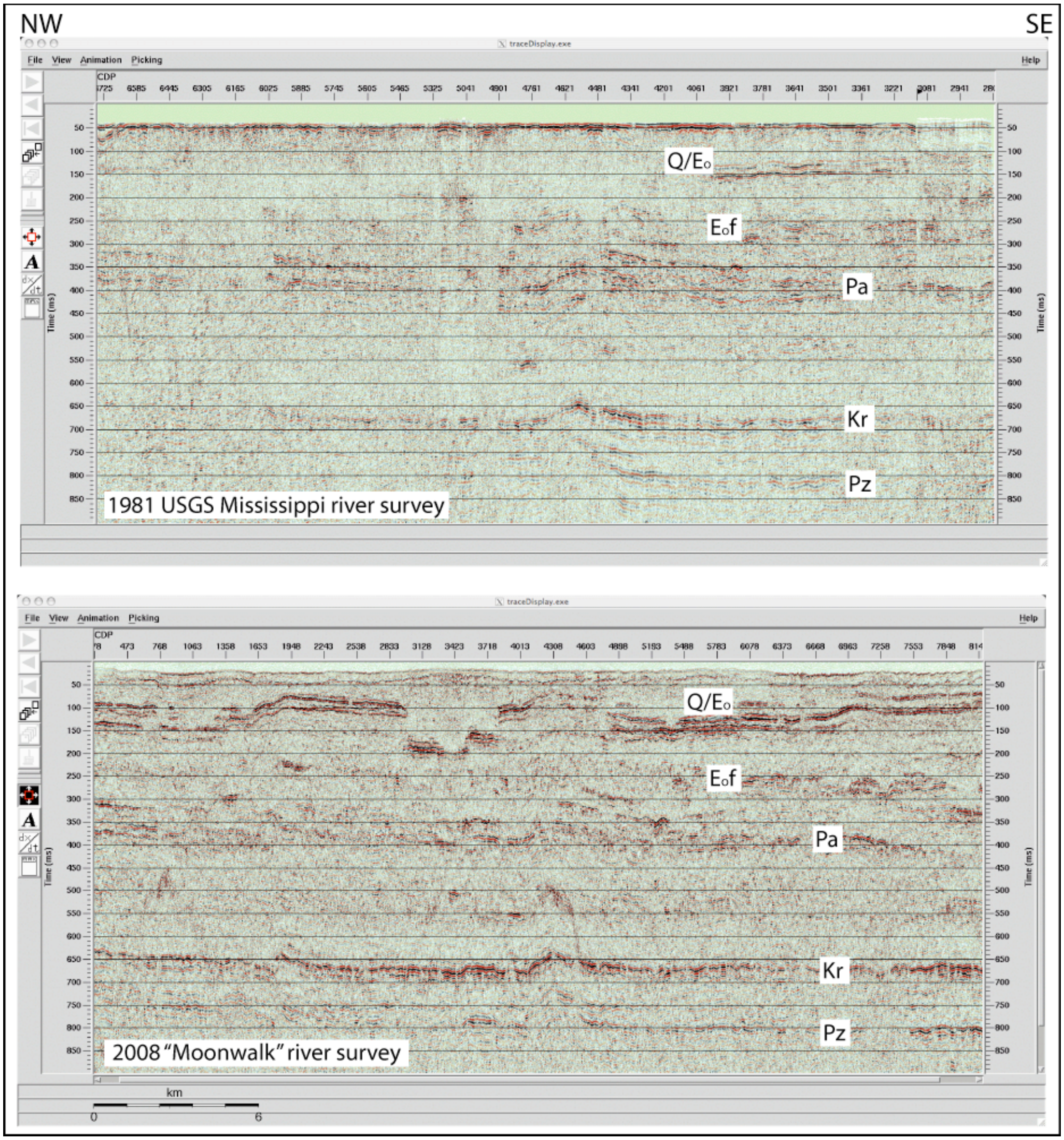

Figure 2: Comparison between the 1981 USGS survey (top) and the 2008 "Moonwalk" survey (bottom) along the portion of the Mississippi River at Caruthersville, MO (location of profile shown in Fig 3a). Q/E_0: Quaternary-Eocene unconformity; Eof: Eocene Flour Island formation; Pa: Paleocene Porters Creek Clay; Kr: top of Cretaceous; Pz: Top of Paleozoic.

There are two other reasons for our success in the pilot project: 1) more channels in the hydrophone streamer, leading to denser spatial sampling, and, 2) a lower-noise environment. Our streamer has 24 channels over 75 m of active section, resulting in 3.125 m group spacing. This means that we typically have spatial sampling at either 1.6 or 3.125 m when sorted to common midpoint gathers, as opposed to 5 or 10 m CMP spacing for the 1981 USGS project. This denser sampling makes a difference when tracing the extent of reflection segments and identifying whether strata are folded or faulted. The lower noise environment is due to the "Moonwalk" geometry and progression. By facing upriver but under a slow controlled drift downriver, we were able to reduce our speed through the water and, consequently, the noise that results from it. Our speed through the water was generally only 3-5 km/hr going downriver. In contrast, we would have had to travel at 10-11 km/hr to make the same progress going upriver. This is likely the reason we were able to image the entire section despite using a relatively small seismic source.

Notably, the data quality deteriorates over the southern leg of our survey, due primarily to fine-tuning the survey methodology. Our initial plans for the seismic acquisition involved navigating the Mississippi River upstream, starting in Helena, Arkansas. After the first three days of testing, we identified an appropriate geometry of acquisition and proceeded to move to the northern end of the profile (Caruthersville, MO) and drift downstream. Due to time constraints the southern leg of the profile was not surveyed again.

Using this procedure we collected ~300 km of high-quality data, from Caruthersville, MO, to Helena, AR, overlapping for ~100 km with the USGS 1981 profile from Caruthersville to Osceola. A comparison of the two surveys acquired in the same portion of the river (Fig. 2) reveals that we were able to illuminate with continuity the sedimentary cover of the embayment from the Cenozoic and Mesozoic clastic sediments to the Late Cambrian and Ordovician sedimentary rocks, a depth of ~ 1.2km. The detailed image of the Tertiary/Quaternary unconformity, corresponding to the contact between the Eocene Upper Claiborne clay layer and the Mississippi River alluvium, documents with unprecedented high-resolution the recent deformation.

RESULTS

The ~300 km long profile clearly identified three main areas of Quaternary deformation (Fig. 1). The northernmost corresponds to the Cottonwood Grove dextral strike-slip fault, the southernmost arm of the active seismic zone (Fig 3). Here the sedimentary section is deformed (faulted and folded) at several locations suggesting that the single fault (the Cottonwood Grove fault) identified by the seismicity at middle crustal depths (~5-12 km) branches upsection to form a flower structure (Fig. 3c) that accommodates the deformation along the southernmost arm of the seismicity. The data along this profile also image a 3 km-wide, ~90 m-deep channel, eroded through the base of the Quaternary section, into the Eocene sediments (Magnani et al., 2008). This scour is exceptionally deep for the Mississippi Valley, and we infer that it is the result of erosion and sedimentation associated with glaciations and deglaciation floods. If so, these structures represent an invaluable tool to date relative events along the active seismic zone. The pilot survey also imaged two areas of Quaternary deformation outside the NMSZ (Magnani et al., in prep), one located north of

Osceola, at about river mile (RM) 818 (Fig. 4), the second is located only ~10 km

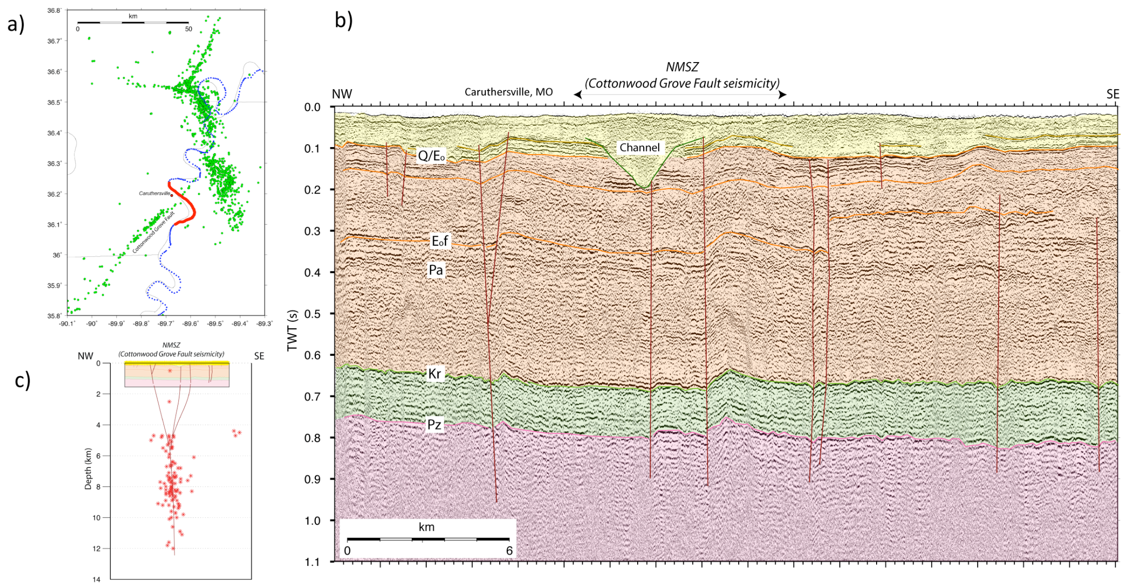

Figure 3: Seismic reflection profile acquired as part of the Mississippi Moonwalk seismic survey across the Cottonwood Grove fault. a) location map of the profile (in red) along the Mississippi River, showing the NMSZ 2000-2008 seismicity (green dots); b) interpreted reflection profile. Labels as in Fig 2; c) crustal section along the reflection profile showing the seismicity of the Cottonwood Grove fault (red stars) projected onto the river profile.

north of downtown Memphis, TN (Fig. 5) at ~RM746.

The structure imaged north of Osceola is a previously unknown fault that displaces the top of the Paleozoic and Cretaceous sediments and propagates through the Cenozoic layers up to the Tertiary/Quaternary unconformity that separates the Eocene sediments from the Quaternary deposits of the Mississippi River (Fig. 4). The fold associated with the fault is a narrow structure with ~ 43 m relief at its crest for the top of the Paleozoic and ~36 m relief for the top of Cretaceous. The amount of offset and shortening of this structure appears to increase with depth, suggesting a prolonged activity throughout the Tertiary and the Quaternary. Because we observe this fault only at this location along the river (i.e. the fault does not appear to cross the river to the north or south), we suggest that the fault strikes NW-SE, with up-to-the-north sense of displacement and dips steeply to the north. A similar structure at this exact point along the river was suggested by Heyl and McKeown (1978), based on changes in the river geomorphic conditions. The authors attribute the anomalous meander pattern of this reach to an increased local gradient imposed by a tectonic structure with comparable strike and displacement as the fault imaged by the reflection data. Considering that the changes in meander pattern along this portion of the river occurred after 1821 (i.e. after a meander cutoff just north of the location of the fault imaged by the seismic data) (Fisher and Schumm, 1993; Bragg, 1977), the data would indicate that the fault was active in the past ~250 yr.

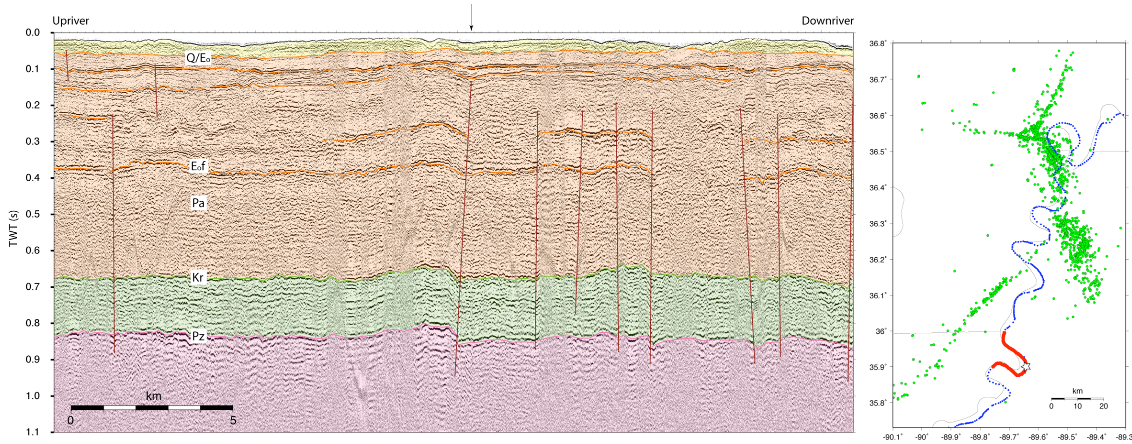

Figure 4: (Left) Interpreted seismic reflection profile acquired as part of the 2008 Mississippi Moonwalk seismic survey imaging a newly discovered fault (marked by vertical arrow) that displaces the unconsolidated sediments from the top of the Paleozoic to the Quaternary alluvium. (Right) Location map of the profile (in red) along the Mississippi River showing NMSZ 2000-2008 seismicity (green dots), and the location of the imaged fault (star) along this stretch of the Mississippi River.

The area of deformation imaged about 10 km northwest from downtown Memphis is better constrained than the new fault north of Osceola. Here the seismic reflection profile images a fault that offsets the tops of the Paleozoic and Cretaceous layers to the Tertiary/Quaternary unconformity (Figure 5a and 5b). The fault dips steeply to the NNW and shows an up-to-the-northwest sense of displacement. The structural relief at the crest of the fold is ~70 m at the top of the Paleozoic and ~60 m at the top of the Cretaceous section. The amount of deformation appears to decrease through the Tertiary section, but the unconformity at the bottom of the Quaternary section is still visibly deformed and folded consistently with the deeper structure. The relief at the crest of the anticline of the Eocene/Quaternary unconformity is ~50 m. Unfortunately the internal geometry of the Quaternary deposits is masked by the presence of strong water bottom multiples and it is not possible to resolve with clarity the youngest limit of the age of deformation associated with this fault. All that can be concluded from the imaged section is that the fault has been active at least during the Quaternary. Additionally, the decrease in the amount of offset from the Cretaceous to the Tertiary reflectors suggests recurrent fault movements since the Mesozoic and throughout Tertiary/Quaternary time. A second structure is imaged 26 km downriver that is very similar to the northern feature: a NW steeply dipping fault visibly deforms the top of the Cretaceous and the Tertiary sediments with a top-to-the-west displacement (Figure 5c). At this location neither the tops of the Paleozoic nor the shallow unconformity are clearly imaged, likely owing to lack of signal penetration in the first case (the Paleozoic deepens to the south with a regional slope of 0.05%), and to water bottom multiple noise in the second case. To the south, 10 km downriver from this fault, a third fold and fault are visible (Figure 5d), more subdued than the previous two structures, but with a similar displacement and dip. No clear reflector corresponding to the Eocene/Quaternary unconformity is traceable beneath the water bottom multiple.

The three folds/faults mapped along the profile align along a straight trend that strikes N25E. The sense of displacement and the dip of the structures observed at the three locations are consistent with an almost vertical reverse fault with an up-to-the-west motion that offsets the Paleozoic and Cretaceous sedimentary rocks and folds the Tertiary deposits. Where visible, the Quaternary alluvium is clearly deformed, revealing that this fault has been active at least during the Quaternary, although older tectonic activity cannot be ruled out. The Mississippi River crosses again the southern projection of the fault at two additional locations, and although undulating Paleozoic and Cretaceous reflectors are traceable, the structure cannot be identified with certainty, as the quality of the seismic data degrades to the south. To the north, the fault appears to coincide approximately with the drop in topography that separates the modern Mississippi River floodplain from the Mississippi River bluffs, where 15 m of Quaternary loess overlies the Pleistocene and Tertiary clastic deposits. Here, on the floodplain deposits and along the northern projection of the fault imaged by us along the river, Williams et al. (2001) imaged the Meeman-Shelby Fault (MSF). The MSF shows a striking similarity with the fault we imaged 15 km to the south, exhibiting the same sense of displacement (top-to-the-west), the same fault attitude (steeply dipping to the west) and even comparable amounts of displacement across the fault for the Paleozoic and Cretaceous sections (70 m and 40 m respectively). Because the survey at the MSF was designed to target the deeper horizons (Paleozoic and Cretaceous reflectors), the geometry of acquisition was not ideal to image the shallow section. As a result, the Tertiary section is visible only up to the top of the Paleocene and no reflections are recorded from the base of the alluvium. The data therefore do not provide information about the Quaternary history of deformation for this fault at this location.

Considering the similarity of the two structures, their close distance and the fact that they align along the same trend, we feel confident that the new fault imaged along the Mississippi River north and south of Memphis represents the southern continuation of the MSF fault imaged 15 km to the north. The fault therefore appears to be a ~60 km-long continuous structure, at least within the portion imaged by the 2008 Mississippi River profile and the USGS 2001 survey, although it is possible that the fault propagates both to the north and to the south.

The strike of the newly imaged southward extension of the MSF is generally consistent with several major known structures in the Mississippi Embayment (Figure 1). The fault is located at the southern edge of the Eastern Reelfoot Rift Margin (ERRM), a southwest trending zone of faulting that is interpreted to bound the Proterozoic Reelfoot rift (Hildebrand, 1985). The ERRM might have been reactivated in Late Wisconsin-Early Holocene (Cox et al., 2001; 2006) with a reverse, dextral-slip sense (Chiu et al., 1997) along the Mississippi River bluff line north of the MSF. The ERRM is inferred to extend southward to Arkansas under the Mississippi River deposits and connect to the Crittenden County fault zone (CCFZ), (Crone, 1992; Luzietti et al., 1992), a basement controlled structure that appears to have been reactivated as a reverse fault displacing Paleozoic and Cretaceous rocks with an up-to-the-west offset. Tertiary and possibly Quaternary (up to Holocene) deformation has been proposed for this fault.

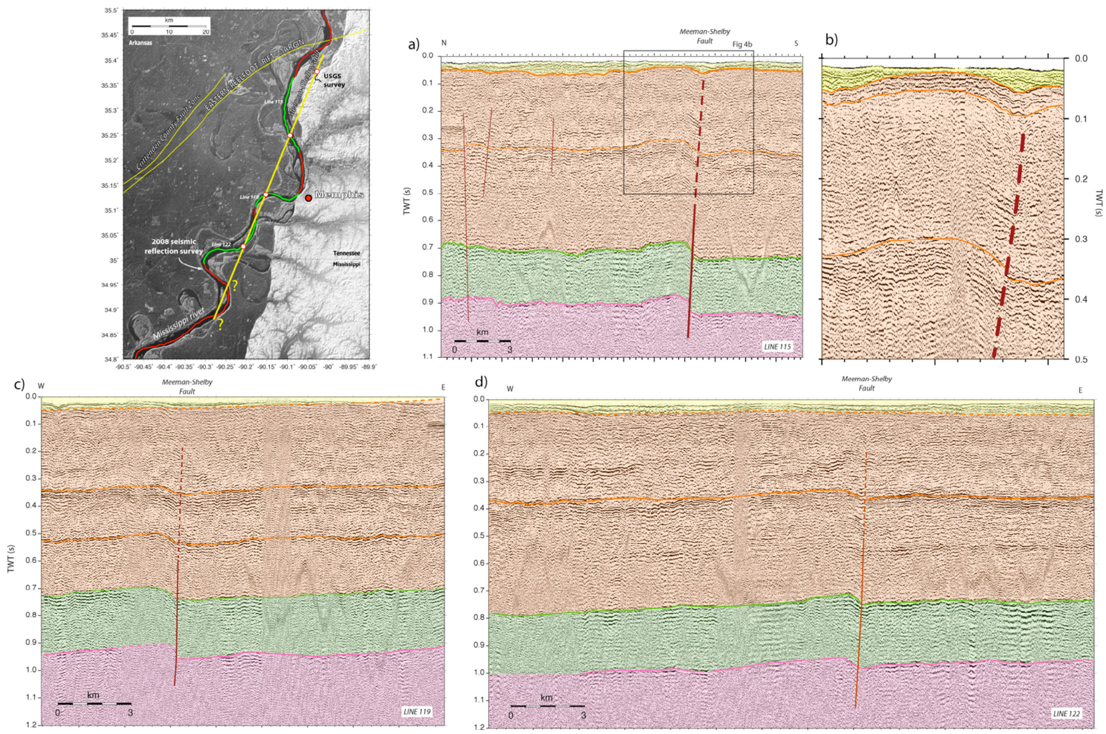

Figure 5: a) seismic profile recorded along the Mississippi River as part of the 2008 river survey showing one of the three crossings of a 60 km-long fault that offsets the Paleozoic (pink) and Cretaceous (green) reflectors at 900 and 700 ms TWT respectively, and folds the Tertiary (orange) and Quaternary (yellow) sediments (see Figure 3 for stratigraphy); b) at 50 ms (TWT) the reflector marking the base of the Quaternary alluvium (unconformity between the Eocene and the Quaternary deposits) appears folded in a consistent way with the underlying structure; c) and d) show the two Mississippi River seismic profiles imaging additional crossings of the MSF downriver from profile in a). Exact locations of seismic profiles are shown on the location map.

It is not possible to ascertain if there is a relationship (past or present) between the MSF, the CCFZ and ERRM. We do not know if and how these faults interact (or have interacted), and if there are mechanisms of stress transmission between them. The 2008 river seismic acquisition provided continuous coverage of a large portion of the embayment and seismic images of unprecedented resolution. Because the MSF shows tectonic activity at least during the Quaternary, this fault is a suitable candidate for the seismic source responsible for the liquefaction features observed in Marianna, Arkansas and dated as 5,000 and 7,000 years old (Holocene) (Tuttle et al., 2006). At its closest location, the fault runs ~10 km north of downtown Memphis and crosses the Mississippi River, major highways and railroads. Considering that a ~60 km-long upper crustal fault is capable of generating a M7 earthquake (Wells and Coppersmith, 1994; Ellsworth, 2003), this fault might pose a greater threat to Memphis than the NMSZ itself.

AQUIFER CONSIDERATION

A second utility of our survey, beyond gaining a better understanding of intraplate tectonics and redefining the seismic hazard for the region, is the ground water, primarily the Tertiary and Quaternary aquifers. Ground water is the primary and, in some instances, the sole source of potable drinking water. Relied upon heavily by agriculture, municipalities and industry, ground water in the Mississippi Embayment is withdrawn from three prolific aquifers: the Mississippi River alluvium, the Memphis/Sparta (Middle-Lower Claiborne) aquifer and the Fort Pillow (Wilcox) aquifer in large amounts (Hutson et al., 2004). In an effort to ascertain the long-term sustainable yield and quality of the Tertiary and younger ground-water system, Congress funded a regional effort through the Environmental Protection Agency (EM#27274464). An outcome from this ground-water effort was the need to quantify the exchange of waters between the aquifers through breaches in or thinning of the aquitards that separate them (see Upper Claiborne clay (Q/E_o) and Flour Island (E_of) in figures 3-5).

The Flour Island aquitard separates the lower Fort Pillow aquifer from the Upper Memphis/Sparta aquifer. Because of the depth of the Flour Island (between 300 and 400 ms), mapping of this unit is readily identified on the seismic sections (see E_of in Figures 2-5). Unfortunately consistent identification of the Q/E_o contact along the survey is not possible. We hoped that the Chirp could resolve shallower stratigraphy of the upper 10m and therefore extend the seismic marine survey into the Holocene deposits. Water bottom reverberations and low signal strength of the Chirp has made it difficult to interpret the shallow markers with continuity. Further investigations with a more appropriate high-frequency source would be needed to image the Eocene/Quaternary unconformity, especially at Memphis and to the north, were the Upper Claiborne shallows. Along the portion of the river at Memphis (RM 750-735), the Chirp resolved an intermittent reflective boundary suspected of being the Upper Claiborne contact (Figure 6). Further investigation of this data with supplemental geologic controls will determine the validity of this surface interpretation.

Resolving the integrity of the aquitards from the seismic reflection data has proved to be a difficult task, because the absence of reflectors can be ascribed both to an aquitard breach and loss of signal (Figure 6). However, the fact that faulting of the Wilcox-Claiborne contact (E_of) is observed on the acquired multichannel seismic data is important for assessing inter-aquifer exchange. Anomalously high concentrations of Na and Cl in the Lower Claiborne-Wilcox aquifer in southern Arkansas and northern Louisiana have been attributed to upwelling of waters along faults (Bryant et al., 1985; Kresse and Clark, 2009). The Mississippi River survey identified faulting of this unit along the 300 km long profile. Thanks to this information ground-water scientists can monitor the geochemistry of ground water proximal to these faults as indicators of inter-aquifer exchange, and vice versa water chemistry can be used as a proxy for the presence of faulting. Such exchange is important in quantifying ground-water reserves and assessing water quality

CONCLUSIONS

The 2008 seismic acquisition in the Mississippi River demonstrated that techniques adapted for this environment result in significant improvements in data quality. The key adaptations include 1) downriver progression to achieve a low-noise recording environment, 2) use of a mini-GI airgun for cleaner source signature, 3) short near-trace offset to record shallow reflections, and 4) more recording channels for denser spatial sampling. Our acquisition approach allowed us to image shallow, Quaternary strata as well as the deeper Eocene, Cretaceous, and Paleozoic units. Deformation that we observe in these strata of various ages can be used to locate the distribution of deformation in this region and also contribute to the deformation history.

The 2008 river seismic acquisition provided continuous coverage of a large portion of the embayment and seismic images of unprecedented resolution. The data revealed the existence of at least two main zones of prolonged deformation throughout the Cenozoic showing activity as recent as the Quaternary.

The presence of large faults characterized by Tertiary and Quaternary deformation in areas outside the NMSZ supports a scenario where protracted and continuous deformation in the Mississippi Embayment (and possibly in the Central U.S.) is accommodated along faults distributed across a large area rather than along individual, isolated faults. In this scenario the NMSZ faults are only some of the structures that have been active in this region and are the system along which deformation is presently occurring.

The results of this study reconcile the small geodetic vectors observed in the mid-continent, with the occurrence of large magnitude earthquakes, and with the lack of substantial deformation localized along the presently active fault system. Unlike at plate boundaries, where plate motion dominates the fault loading process and concentrates the deformation along a localized system of faults, the faults in the Mississippi Embayment and in the mid-continent are loaded slowly, as indicated by the GPS vectors, and stresses imparted by other mechanisms may prevail, with the result that in the long-term, the deformation is accommodated by a complex system of faults and distributed across a larger region. Identifying the network of faults and establishing when they were active is the key to unraveling the mechanisms of stress transfer that control the interaction between faults and the spatio-temporal pattern of earthquakes in intraplate regions.

The success of this project suggests that the techniques used here are effectual and efficient in further defining the zones of recent faulting, and in improving seismic hazard assessment in the greater Mississippi Embayment area. Additionally this study stresses the need for investigations in an area larger than the presently seismically active zone.

Two manuscripts describing and discussing the results of this study are in preparation, and will be submitted to Nature Geoscience and to Journal of Geophysical Research.

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