Final Technical Report

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"Intraplate Earthquakes in the central-eastern United States: An integrated seismological and geodynamic study"

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Non-technical Summary

The project is to use seismology and geodynamic modelling to understand lithospheric structure and stress evolution in the New Madrid Seismic Zone (NMSZ) and other parts of the central-eastern US. We have completed 1) a 3D viscoelastic model of stress evolution following the 1811-1812 NMSZ large earthquakes, 2) a regional scale geodynamic modelling of lithospheric stress distribution in central and eastern US, 3) preliminary integration of seismological studies and dynamic modelling on intraplate earthquakes in the CEUS; 3) a Pn tomography and anisotropy structure in central and eastern US, and 4) a joint teleseismic and local P wave tomography of the lithospheric structure under the New Madrid seismic zone. Our results indicate the NMSZ is associated with a local, NE–SW trending low-velocity anomaly in the lower crust and upper mantle, and in central and eastern US, the intraplate seismic zones are localized around high-velocity structures. Our models predict stress concentration near lithospheric rheological boundaries. Our modelling also show that the NMSZ is likely in a stress shadow from stress release by the large 1811-1812 earthquakes; significant stress has transferred to southern Illinois and eastern Arkansas, capable of producing some damaging earthquakes there.

Technical Report

Summary: We studied intraplate earthquakes in the New Madrid seismic zone and other part of central and eastern US by seismic imaging of the lithospheric and upper mantle structure and numerical modelling of stress distribution and evolution. These studies have led to four publications. Studies have continued beyond the funded period, and we have another three publications directly stemmed from this project. This technical report focuses on the four projects directly funded by this grant.

Abstract

The Central-Eastern United States (CEUS) is located within the stable North American continent. Although the overall seismicity in the CEUS is low compared with that of the tectonically active western US, there are numerous seismic zones in the CEUS that are associated with some of the most devastating historic events in this country, including the three M=7-7.5 events in 1811-1812 in the New Madrid Seismic Zone (NMSZ), and the 1886 Charleston South Carolina event (Mb=6.6-6.9). Whereas intensive studies in the past decades have greatly expanded our knowledge of seismic history in the CEUS, the cause of earthquakes in these intraplate seismic zones remains poorly understood.

We combined passive-source seismic imaging with geodynamic modeling to investigate the lithospheric structure and geodynamics controlling the seismicity in the CEUS. The investigation is conducted on two spatial scales: a local-scale study focused on the NMSZ, and a regional-scale study focused on the CEUS. For the NMSZ, we used available P-wave travel time data and available waveform data to refine the structure of the lower crust and the mantle lithosphere. In particular, the seismic imaging showed a low velocity zone under the NMSZ, but no clear evidence for the existence of the "rift pillow", and rift zones in CEUS have no clear correlation with lithospheric mantle structures. Systematic numerical experiments suggested that the NMSZ remains in a stress shadow from the stress release by the large 1811-1812 events, and much stress has transferred to southern Illinois and eastern Arkansas. The integrated seismic and geodynamic studies suggest that stress tends to concentrate around lithospheric rheological boundaries, which is consistent with the spatial correlation between seismic zones in CEUS and the seismically inferred boundaries of the cratonic lithosphere.

1. Introduction

The central-eastern United States (CEUS), defined broadly as the region east of the Rocky Mountains, is located in the middle of the North America plate where Cenozoic crustal deformation is minimal. However, both historic earthquakes and instrument-recorded earthquakes are abundant in the CEUS (Fig. 1). The best-known historic events include the three large shocks (M=7-7.5) that occurred in the New Madrid seismic zone (NMSZ) over a three-month period between 1811-1812, and the 1866 Charleston, South Carolina earthquake (M~6.5-7.0). Numerous recent events (e.g., 06/18/2002 Evansville, Indiana, 04/29/2003 Fort Payne, Alabama, etc.) serve as fresh reminders that earthquake hazard is a significant issue in the CEUS. Because of the large population centers near these seismic zones, a repeat of the large New Madrid or the Charleston events would be catastrophic.

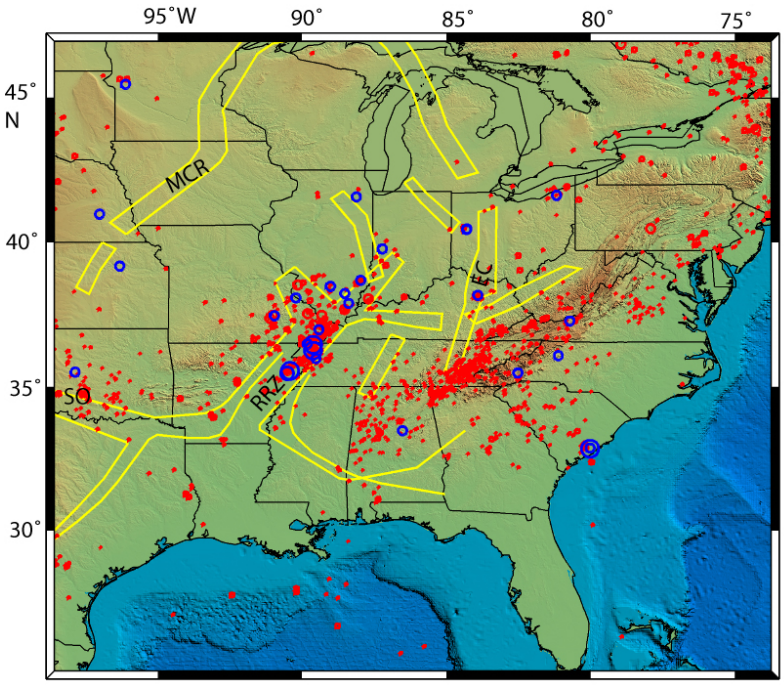

Figure 1. A map of historical (blue circles) and instrumental (red circles) seismicity of the central and eastern U.S. The circle sizes are scaled by earthquake magnitude. The yellow lines are the approximate boundaries of failed rifts within this region. RRZ- Reelfoot Rift Zone; MC – Midcontinent Rift; SO – South Oklahoma Aulacogen; EC- East Continent Rift.

Despite the pressing need for a better understanding of the potential hazards of intraplate earthquakes, the mechanics of intraplate earthquakes remain poorly understood. Intraplate earthquakes cannot be readily explained within the framework of plate tectonics theory, and the typical long recurrence interval, usually hundreds to thousands of years, make it difficult to study the intraplate earthquake cycle. Recognizing that many of the seismic zones are near the ancient rifts in the CEUS, it has been suggested that the rifts represent weak zones within the stable continental crust where stress accumulates and triggers earthquakes [*Johnston and Kanter*, 1990; *Johnston*, 1996]. However, not all rifts are seismically active. The Mid-continent rift system (Fig. 1), for example, is one of the most prominent rifts in the CEUS, but it is essentially aseismic. Fundamental questions regarding the physics of intraplate earthquakes in the Central and Eastern U.S. include: 1) What causes earthquakes within the stable North American continent? Do earthquakes occur in these zones because crust there is too weak, or because some aspects of the CEUS lithospheric structure caused stress concentration and amplification in these zones? 2) How might the large historic events have influenced the stress field in the CEUS? Where are the most likely places for the next big hit? What controls the recurrence intervals of intraplate earthquakes?

We addressed these questions using an integrated seismological imaging and geodynamic modeling. The investigation will be conducted on two spatial scales: a local-scale study focused on the NMSZ, and a regional-scale study focused on the CEUS. For the NMSZ, we used available P-wave travel time data to resolve 1) the existence and nature of the "rift pillow" under the NMSZ, and the ductile shear zones speculated in previous models, and 2) the mantle lithospheric structure that may have given raise to the uplifted surface heat flow in the NMSZ. We developed a three-dimensional (3-D) finite

element model with spatially variable viscoelastic rheology and realistic fault geometries for NMSZ.

2. Background

2.1. Seismotectonic setting of the central-eastern United States

The United States east of the Cordillera is located in the middle of the North American plate. This region is generally referred to as the stable North America where Cenozoic deformation is minimal. Historic and modern seismicity are generally scattered, with some concentration around numerous zones of a few hundreds of kilometers in dimension (Fig. 1). Major seismic zones include [*Dewey et al.*, 1989]:

1) *The New Madrid seismic zone and the Mississippi Embayment*: this was the site for the three large events (M ~ 7-7.5) occurred in the winter between 1811 and 1812 [*Hough et al.*, 2000; *Johnston and Schweig*, 1996]. Paleoseismological studies indicate that at least two major earthquakes may have occurred around the year 900 and 1400. Modern instrument has recorded more than 2500 events since 1977.

2) *Amarillo- Wichita uplift and Anadarko basin*: Moderate seismicity has been recorded in the southern Oklahoma and the Texas panhandle [*Gordon*, 1983]. Holocene fault scarps indicate earthquakes of magnitude greater than 6.5 [*Madole and Rubin*, 1985]. The largest historical event, occurred near El Reno, Oklahoma, on April 9, 1952, had a magnitude of 5.0 [*Gordon*, 1983].`

3) *Southern Valley and Ridge:* Modern seismicity in the southern Appalachians is concentrated beneath the Valley and Ridge province, near the western edge of that part of the Appalachians. The largest historical earthquake in this region was the magnitude 5.8 Giles County, Virginia, earthquakes of May 31, 1897 [*Nuttli et al.*, 1979].

4) *South Carolina Coastal Plain:* The best-known event in this region was the destructive (M~ 6.5-7.0) event that occurred near Charleston, South Carolina, on August 31,1886 [*Nuttli et al.*, 1979]. Paleoseismological studies indicate at least two prehistoric earthquakes in the past 3000 years [*Obermeier et al.*, 1985; *Talwani and Cox*, 1985].

5) *New England and the St. Lawrence River Valley:* Earthquake epicenters in central New England, upstate New York, and adjacent Canada form a northwest-trending belt of seismicity, usually called the Boston-Ottawa zone [*Diment et al.*, 1972; *Sbar and Sykes*, 1973]. The largest historic earthquake in the U.S. part of the Boston-Ottawa zone was probably the Cape Ann, Massachusetts, earthquake of 1755 (M~6, [*Street and Lacroix*, 1979]. Further north in the St. Lawrence River valley, numerous events with magnitude 6-7 have been recorded.

The stress field in the CEUS is characterized by a nearly horizontal, NE to E-striking axis of maximum compressive stress [*Herrmann*, 1979; *Sbar and Sykes*, 1973; *Zoback*, 1989]. The uniformity of stress-tensor orientation over a broad area of the CEUS suggests that the stress field arises from forces that drive or resist plate motions. Previous studies have pointed to ridge-push and/or drag forces at the base of the North American plate as the most likely sources of the midplate stress field [*Richardson and Solomon*, 1979; *Zoback and Zoback*, 1989]. The nature and role of the basal shear under the North American plate are the subject of numerous recent studies [*Bokelmann*, 2002; *Silver and Holt*, 2002].

In the central US, most large earthquakes occurred at or near the sites of ancient rifts (Fig. 1). Some of these buried, ancient rifts correlate with active fault zones at the surface. For example, the southern Indiana arm is overlain by the Wabash Valley fault zone, which appears to connect with the New Madrid zone. The southern Oklahoma rift corresponds with the frontal-fault system of the Wichita Mountains. In the eastern US, the seismic zones seems spatially associated with ancient faults developed when eastern United States was near the plate boundaries [*Dewey et al.*, 1989], or faults that may be related to transform fracture zones in the Atlantic ocean floor [*Sykes*, 1978]. This association may be due to the old zones of deformation containing numerous unhealed faults, some of which are favorably oriented to slip in response to the current stress field [*Sbar and Sykes*, 1973; *Sykes*, 1978]. Alternatively, the old rifts and near-plate-boundary regions may concentrate seismicity by virtue of an anomalous bulk property within the crust or upper mantle, such as higher than average porosity [*Costain et al.*, 1987] or greater ductility below the seismogenic layer [*Zoback*, 1983]. One major objectives of this investigation is to refine the lithospheric structure and understand how why some of these rifts are seismogenic while others are not.

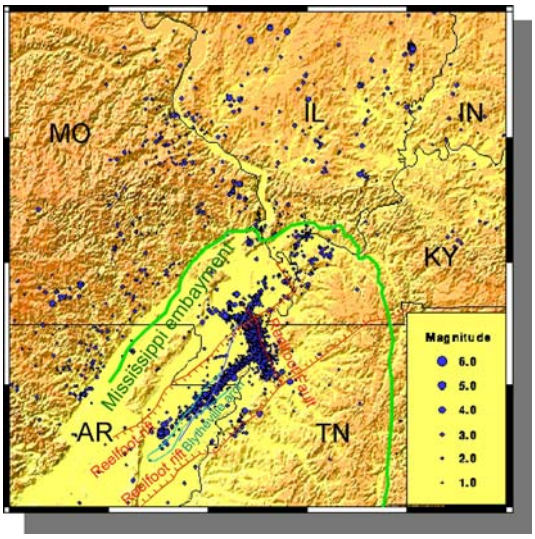

Figure 2. A map showing the outline of the New Madrid Seismic Zone and the associated instrumentally recorded seismicity. The outline of the Mississippi embayment is shown in green.

2.2 The New Madrid Seismic Zone

Our local-scale study will focus on the NMSZ, the most seismically active and the best studied seismic zone in the CEUS. The NMSZ has been the subject of intensive studies; the local geology has been discussed in detail by numerous authors [*Atkinson and others*, 2000; *Ervin and McGinnis*, 1975; *Fuller and Magill*, 1958; *Hough et al.*, 2000; *Johnston and Schweig*, 1996]. The brief summary here is to highlight the major features important for understanding the geodynamics of this region.

Seismotectonic setting: As shown in Fig. 2, the NMSZ is located within the Reelfoot Rift Zone (RRZ), which is part of a failed rift system originated in Late Proterozoic to Early Cambrian and reactivated in the Mesozoic [*Ervin and McGinnis*, 1975]. The seismicity delineates three major segments of the NMSZ (Fig. 2): the two northeast trending segments dominated by right-lateral strike-slip, and the northwest trending

segment where seismic events exhibit mainly reverse mechanisms. Seismicity in the NMSZ reflects major basement structures in this region. The southern segment of seismicity is largely within the Blythveille Arch, identified as an upwarp of Paleozoic strata within a ~10-15 km wide zone that widens to the northeast and is roughly centered on the axis of the RRZ [*Crone et al.*, 1985]. The axial fault zone is perhaps the most important feature within the RRZ. The initial nucleation of the 1811-1812 sequence was probably on the axial fault [*Johnston and Schweig*, 1996]. The Reelfoot fault, associated with the northwest trending seismic segment, is the only seismogenic fault in the NMSZ with clear surface expression. Paleoliquefaction studies [*Johnston and Schweig*, 1996; *Saucier et al.*, 1987; *Tuttle et al.*, 2002] indicate that in addition to the 1811-1812 events, there were at least two strong ground-shaking earthquakes: one around AD 900, and another around AD 1400.

Crustal and Lithospheric structure: The upper crust (~10 km) in the NMSZ contain low-velocity bands that clearly coincide with the NW trending and NE trending segments of seismicity [*Al Shukri and Mitchell*, 1987; *Vlahovic et al.*, 2000; *Vlahovic and Powell*, 2001]. Potential field data indicate a positive gravity anomaly under the RRZ, which was interpreted as a "rift pillow" of mafic intrusion in the lower crust [*Hildenbrand*, 1985]. This high-density body is also indicated by reflection and teleseismic data [*Al Shukri and Mitchell*, 1987; *Mooney et al.*, 1983], although the resolution was greatly limited by the available data. There are some tentative indications that a lower velocity zone corresponding to the RRZ may have extended into the mantle lithosphere [*Al Shukri and Mitchell*, 1987]. However, the image of lithospheric structure under the NMSZ remains unclear.

Crustal Deformation: Based on minor topographic relief and shallow sounding measurements and assuming that all movement on the Reelfoot fault was dip-slip, Mueller et al. [1999] estimated 2 mm/yr of strike-slip motion parallel to the major NE- trending fault system. Recent GPS studies within the NMSZ estimate a uniform strain rate of ~0+0.1 rad/yr or ~.07+.14 rad/yr for a smaller network centered over the seismicity. Measured horizontal site velocities relative to a stable North American reference are generally less than a few millimeters per year, and at most sites, the uncertainties are considerably larger than the estimated velocities [*Newman et al.*, 1999]. This suggests that the deformation rate within the NMSZ may not differ from that of the surrounding region. This is corroborated by deformation rates of less than a few nanostrain/yr estimated for a larger region from a permanent national wide-aperture continuous GPS network [*Atkinson and others*, 2000]. Thus the drive for the continued seismicity in the NMSZ remains puzzling, and the slow strain rates are difficult to reconcile with paleoliquefaction data that suggest a ~500 year recurrence interval of earthquakes comparable to the large 1811-1812 events.

3. Objectives of this project

The overarching objective of the this investigation is to gain a better understanding of the lithospheric structure and the underlying geodynamics that control the intraplate earthquakes in the CEUS. For the regional-scale study of the CEUS, major questions to be addressed include:

1) *What controls the distribution and evolution of deviatoric stresses within the CEUS crust*? The regional stress field in the CEUS, characterized by a rather uniform NE to E-

striking maximum compressive stress, is consistent with the forces driving the North American plate (Richardson et al., 1979; Zoback and Zoback, 1981). However, the driving forces alone cannot explain the concentration of deviatoric stresses in the seismic zones in the CEUS. Variations of the physical properties and rheology of the lithosphere may affect crustal stress field. Whereas there is a strong correlation of large intraplate earthquakes in the central US with ancient rifts [*Johnston et al.*, 1998], many earthquakes in eastern US do not have a clear link to any known fault systems. In this work we will use seismic imaging to refine the lithospheric structure in the CEUS, and 3-D dynamic modeling to explore the major factors causing stress concentration in these seismic zones.

2) *Are the seismic zones in CEUS dynamically coupled? How would earthquakes in CEUS cause stress migration*? Recent studies of earthquakes in California and Alaska have shown that a large earthquake may cause significant stress migration into neighboring faults and trigger earthquakes there. Could similar stress migration occur in the intraplate seismic zones? Can a large event trigger earthquakes in the neighboring seismic zones? After all, the large historic events in the CEUS are known to have sent shocks thousands of kilometers away because of effective transmission of elastic energy through the relatively strong basement rocks. With the refined lithospheric structure of the CEUS, we will explore the earthquake-triggered stress migration and potential dynamic coupling among the seismic zones in the CEUS.

For the local-scale investigation focused on the NMSZ, major questions to be addressed including the following:

1) *What caused earthquakes to be concentrated in the NMSZ and surrounding regions*? The NMSZ is located within the Reelfoot rift, presumably a weak zone that fails more easily than the surrounding crust. However, not all ancient rifts in the CEUS are seismogenic. What makes the RRZ unique? Numerous factors have been proposed as the major cause of stress buildup in the NMSZ, including the “rift pillow” [*Grana and Richardson*, 1996; *Pollitz et al.*, 2001], the ductile weak zone under the RRZ [*Kenner and Segall*, 2000; *Stuart et al.*, 1997], and thermal weakening [*Liu and Zoback*, 1997]. We will use seismic imaging to better resolve the existence and nature of the rift pillow and the mantle lithospheric structure that may have given raise to the anomalously high heat flow in the NMSZ. We will use 3-D geodynamic modeling to test the dynamic effects of these structures and investigate the effects of the speculated viscous weak zones in the lower crust on stress evolution in the NMSZ region.

2) *What is the impact of the 1811-1812 large events on stress evolution in the NMSZ and surrounding regions*? *Where would be the most likely places in this region to be hit by the next big one?* Intraplate seismogenic faults are of finite length, surrounded by strong stable crust. After stress relieve by a large quake, it remains unclear how stress re-accumulates within the fault zone, given that the deviatoric stresses would be supported by the strong surrounding crust. Our preliminary modeling results (see below) indicate that after the 1811-1812 events, stress re-accumulation within the NMSZ would have lagged behind that in southern Illinois and eastern Arkansas, consistent with the distribution of most moderate events since 1811-1812.Whereas time-prediction for intraplate earthquakes is extremely difficult if at all possible, the combined seismic imaging and 3-D dynamic modeling will provide an improved space-prediction of future large earthquakes in the areas surrounding the NMSZ.

4. Main Results

We have addressed these questions by integrating seismological imaging with geodynamic modelling. These studies have led to four publications. Studies have continued beyond the funded period, and we have another three publications directly stemmed from this project. The following report focuses on the four projects directly funded by this grant.

4.1. Stress evolution following the 1811-1812 large earthquakes in the New Madrid Seismic Zone, Li, Q., Liu, M., and Sandvol, E., 2005, Geophysical Research Letters, v. 32, p. 1-4.

In this study we simulated the evolution of Coulomb stress and strain energy in the NMSZ and surrounding regions following the large 1811–1812 events in a three-dimensional viscoelastic finite element model. The results show that much of the stress and strain energy released by the large 1811–1812 events has migrated to southern Illinois and eastern Arkansas, consistent with the seismicity distribution including a dozen moderate-size (M > 5) earthquakes occurred in this region since 1812. This inherited strain energy in these areas is capable of producing damaging (M = 6–7) earthquakes today (Fig. 3).

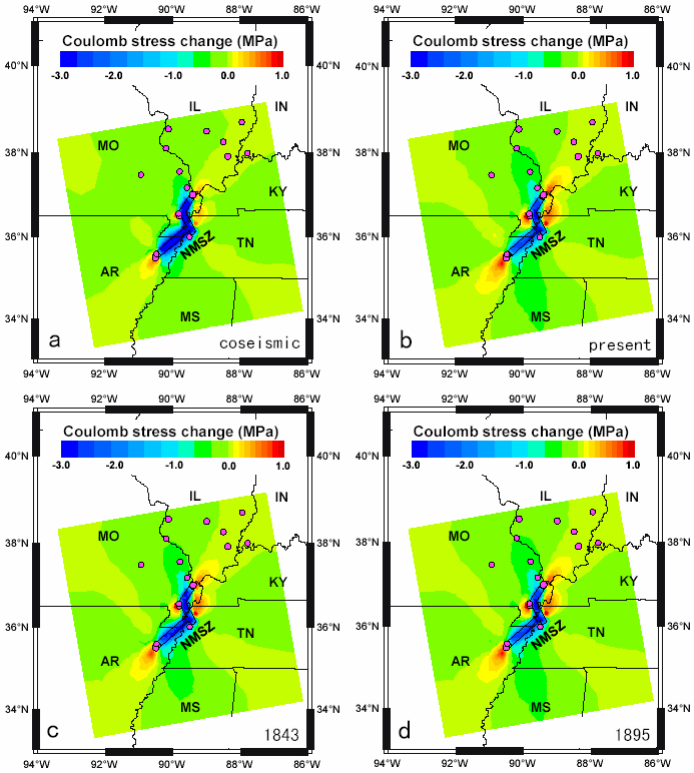

Figure 3. (a) Predicted coseismic Coulomb stress change (for an optimally oriented fault plane) during the 1811-1812 earthquakes in the NMSZ. (b) Predicted Coulomb stress change 200 years after the 1811-1812 events. (c) Predicted Coulomb stress change after the 1843 Marked Tree, Arkansas earthquake. (d) Predicted Coulomb stress change after the 1895 Charleston, Missouri earthquake. The red dots are the major earthquakes (M>5) since 1812 [*Stover and Coffman*, 1993].

4. 2. Stress evolution and seismicity in the central-eastern United States: Insights from geodynamic modeling, Li, Q., Liu, M., Zhang, Q., and Sandvol, E., 2007, *in* Stein, S., and Mazzotti, S., eds., *Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues*, Volume 425: Geological Society of America Special Paper, p. 149-166, doi: 10.1130/2007.2425.

In this study we investigated how stress evolves in interplate and intraplate faults, and the spatial collation between intraplate seismic zones in central and eastern US and stress states in the lithosphere. We find that large intraplate earthquakes can significantly increase Coulomb stress and strain energy in the surrounding crust. We contrasted stress evolution following intraplate and interplate earthquakes. We find that for intraplate earthquakes, the inherited strain energy may dominate the local strain energy budget for thousands of years following main shocks, in contrast to interplate seismic zones, where strain energy is dominated by tectonic loading. We find that the intraplate seismicity in central and eastern US is spatially correlated with the major rheological contrasts within the lithosphere (Fig. 4).

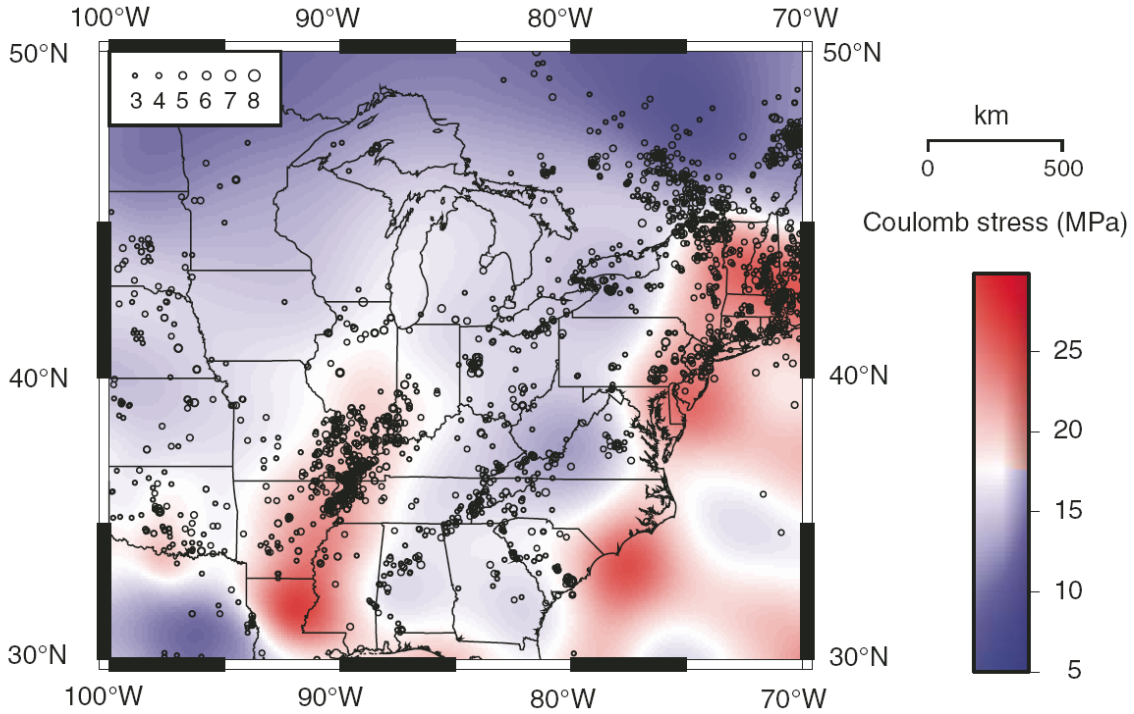

Figure 4. Calculated optimal Coulomb stress in central and eastern US. Note the spatial correlation between seismicity and regions of high Coulomb stress. In this model the Coulomb stress variations are associated with changes of lithospheric thickness inferred from seismological data.

4.3: Lithospheric Velocity Structure of the New Madrid Seismic Zone: A Joint Teleseismic and Local P Tomographic Study, Zhang, Q., Sandvol, E., and Liu, M., 2009, Geophys. Res. Lett, v. 36, p. doi:10.1029/2009GL037687.

In this study we combined teleseismic and local P wave data to image lithospheric structure under the New Madrid seismic zone. The enigmatic seismicity in the New Madrid Seismic Zone (NMSZ) has been attributed to some abnormal lithospheric structure, including the presence of dense mafic intrusions and a low-viscosity lower crust. However, the area's detailed lithospheric structure remains unclear. We inverted 2,056 teleseismic P and 12,226 local P first arrival times from a recent nine-year dataset to infer the lithospheric velocity structure beneath the NMSZ. Our results show that the seismically active zone is associated with a local, NE–SW trending low-velocity anomaly in the lower crust and upper mantle, instead of high-velocity intrusive bodies proposed in previous studies. The low velocity anomaly is on the edge of a high-velocity lithospheric block, consistent with the notion of stress concentration near rheological boundaries. This lithospheric weak zone may shift stress to the upper crust when loaded, thus leading to repeated shallow earthquakes (Fig. 5).

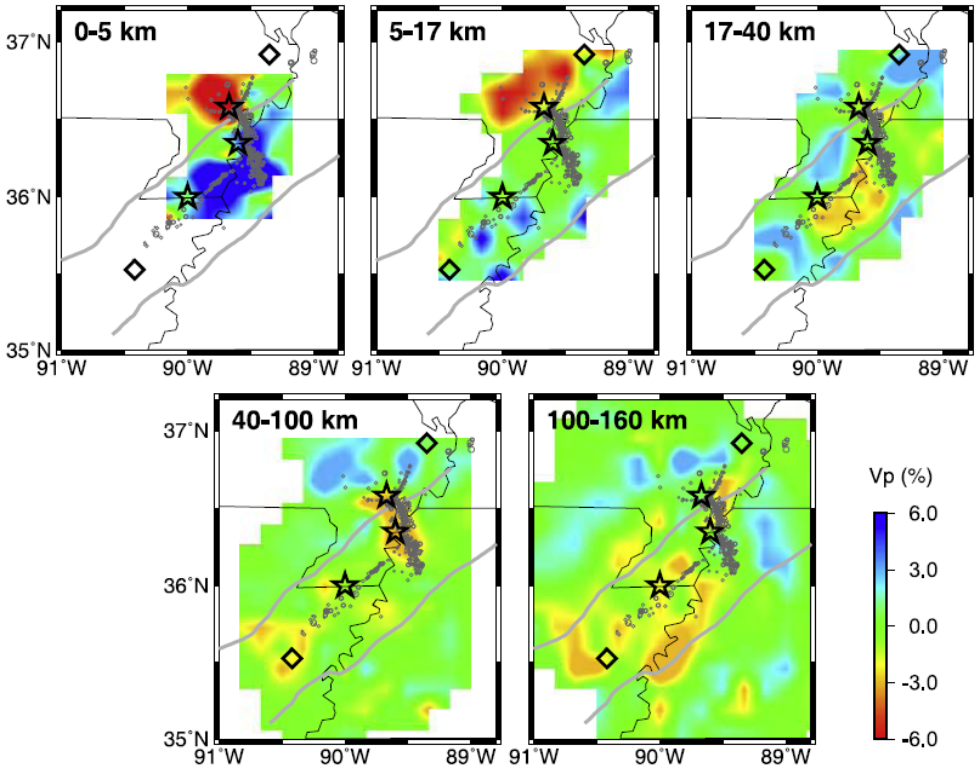

Figure 5. Lithospheric P velocity structure for the NMSZ. First P arrivals of 2,056 teleseismic phases and 12,226 local phases were used for the joint inversion. Stars show the estimated epicenters of the 1811–1812 large events. Diamonds show the estimated locations of the 1843 Marked Tree, Arkansas earthquake and the 1895 Charleston, Missouri earthquake. Thick grey lines delineate the boundaries of the Reelfoot rift.

4. 4. Tomographic Pn Velocity and Anisotropy Structure in the Central and Eastern United States, Zhang, Q., Sandvol, E., and Liu, M., 2009, Bulletin of the Seismological Society of America, v. 99, p. 422-427.

In this study we used a total of 19,166 Pn phase readings as well as hand-picked arrivals to map the velocity and anisotropy structure of the lithospheric mantle in the central and eastern United States (CEUS). Our Pn tomographic model shows a broad region of very fast velocity under the North American craton (the northern CEUS) and significant lateral variations within the rest of the CEUS. The surface locations of the major intraplate seismic zones are near the edges of high-velocity anomalies, which is consistent with the notion that stress accumulation and hence focused deformation are likely to occur at the rheological boundaries around the rigid lithospheric root. However, the ancient rifts show no clear correlation to the low-velocity anomalies in the lithospheric mantle. Our Pn anisotropic model shows a complex pattern of fast directions with an overall north–south trend in the CEUS that may reflect the preserved fabrics of the cratonic lithosphere. Nonetheless, high Pn anisotropy seems to wrap around the high-velocity blocks, which may indicate local deformation around the rigid blocks (Figs. 6-7).

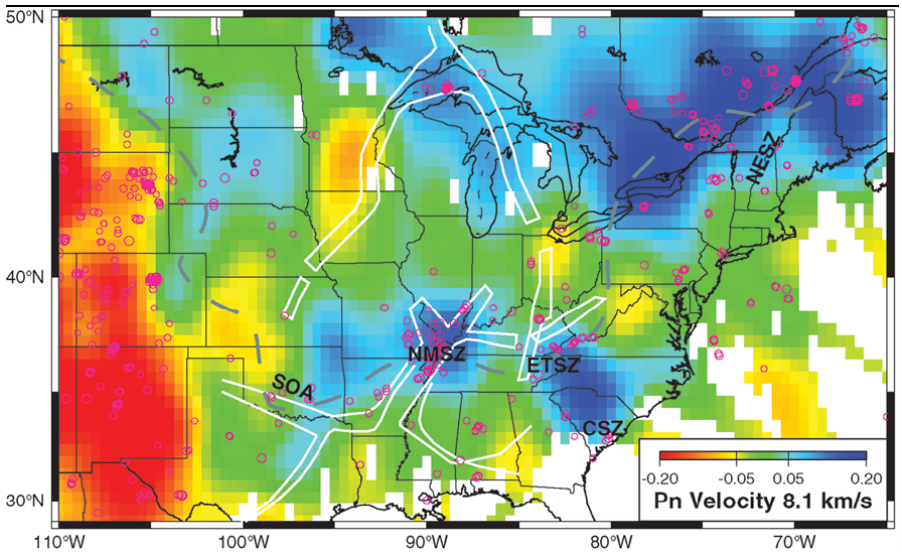

Figure 6. Pn velocity variations obtained from the inversion of travel-time data for the CEUS. The dashed gray line delimits the+0:1 km/sec contour of the high-velocity lithosphere in the NA04 model at 110 km depth for comparison. Note that main intraplate seismic zones (NMSZ, ETSZ, CSZ, and NESZ) are near the margins of the high-velocity anomalies.

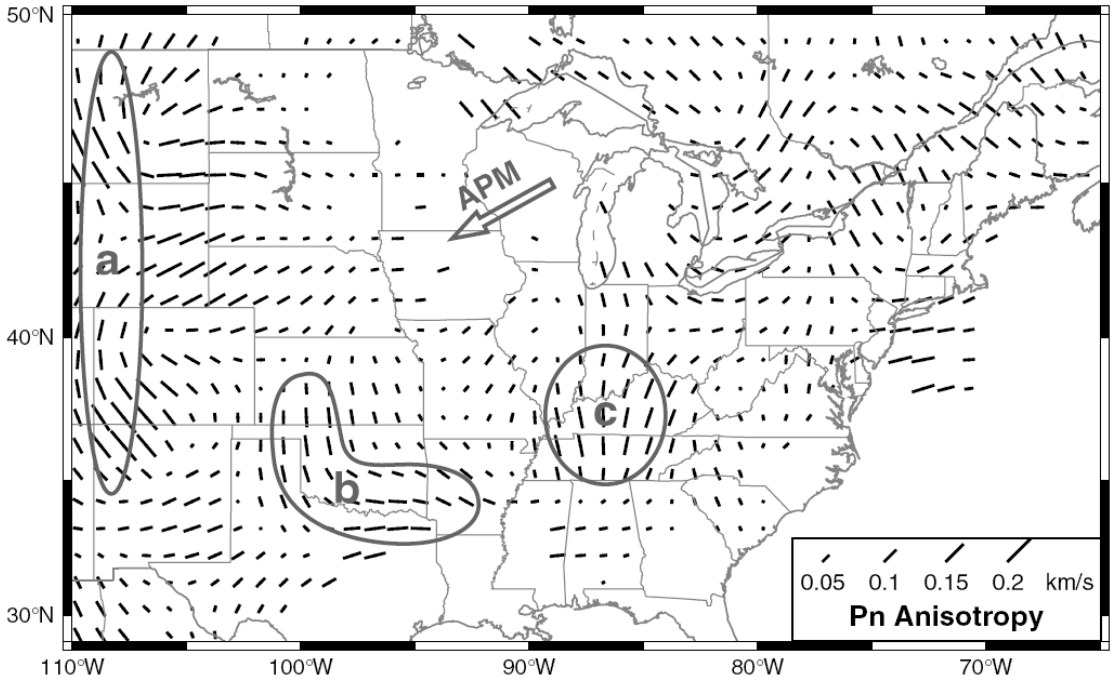

Figure 7. Pn anisotropy model for the CEUS. This model was created by simultaneously inverting for Pn anisotropy and velocity. Only cells with more than 10 counts were plotted. The strikes of the vectors show the fast directions, and their lengths are proportional to the amount of anisotropy. The large arrow gives the absolute plate motion (APM) of North America. Circled areas a, b, and c are where strong anisotropy occurs, which may indicate focused deformation.

5. Work stemmed from this study

We studies have been continuing after the funded period. In particular, we have been investigating the cause of the episodic, temporally clustering, and spatially migrating earthquakes in central and eastern US, with three more papers published to date.

6. Publications Resulted from this grant

Li, Q., Liu, M., and Sandvol, E., 2005, Stress evolution following the 1811-1812 large earthquakes in the New Madrid Seismic Zone: Geophysical Research Letters, v. 32, p. 1-4.

Li, Q., Liu, M., Zhang, Q., and Sandvol, E., 2007, Stress evolution and seismicity in the central-eastern United States: Insights from geodynamic modeling, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues, Volume 425: Geological Society of America Special Paper, p. 149-166, doi: 10.1130/2007.2425.

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