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4 Crustal signatures of the tectonic development of the North American midcontinent

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6 Austin J. McGlannan¹ and Hersh Gilbert
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14 Department of Earth Atmospheric and Planetary Sciences
15 Purdue University
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24 Corresponding author address:
25 Hersh Gilbert
26 550 Stadium Mall Drive
27 West Lafayette, Indiana
28 47901
29 email: hersh@purdue.edu
30 phone: 765-496-9518
31
32
33

34 ¹present address:
35 Department of Geology and Geophysics
36 Louisiana State University
37 Baton Rouge, LA 70803
38

Abstract: The stable eastern portion of the North American continent offers an excellent environment to study the tectonic development of intra-continental structures. The midcontinent of North America formed by the accretion of Proterozoic terranes, and has since experienced episodes of deformation during the subsidence of the Illinois Basin and uplift of the Ozark Plateau. Rifting also initiated in eastern North America, but extension did not continue and arms of failed rifts extend across the region. The New Madrid Seismic Zone, situated within a portion of the failed Reelfoot Rift, represents an active zone of intraplate seismicity. Analyzing the structure of the crust and upper mantle within the midcontinent will therefore provide insight into the factors that lead to intraplate deformation. Using data from over 180 Transportable Array seismic stations, we calculate receiver functions to investigate the crust and upper mantle of the midcontinent. At close to 40 km thick, the crust of the New Madrid Seismic Zone is thinner than the surrounding areas outside of the Reelfoot Rift and Rough Creek Graben. The Illinois Basin cannot be characterized by a single crustal structure, as crust near 50 km thick in the central portion of the basin thins to between 40 and 45 km thick towards the northern and southern portions of the basin. Discontinuities within the crust and upper mantle are prominent in and around the New Madrid Seismic Zone and mark locations of crustal modification and underplating. Comparing changes in crustal structure to the distribution of Bouguer gravity anomalies, the presence of positive gravity anomalies suggest that higher density crust plays a role in maintaining low surface elevations within the Reelfoot Rift. Conversely, a negative gravity anomaly in an area of thinner crust within the Ozark Plateau supports the need for low-density crustal material to influence the uplift of the plateau.

1. Introduction

Investigating crustal structure over continental scales has proven useful for determining the manner in which the crust records continental evolution through terrane accretion and modification by subsequent tectonic events. Continental-scale crustal thickness variations coincide with both the boundaries of terranes that accreted together and physiographic boundaries that mark the limits of particular styles, or episodes, of deformation. Crustal structure observations within North America using EarthScope USArray Transportable Array data have been generated through a variety of techniques that identified changes in crustal structure that align with physiographic boundaries. These changes in crustal thickness occur over distances that range from localized variations that align with specific tectonic features to broad-scale trends that extend over 1000's of km. The EarthScope Automated Receiver Survey (EARS; Crotwell and Owens, 2005) displays areas of thin crust between 30 and 40 km thick in the tectonically active western portion of North America, while thicker crust that is mostly greater than 40 km thick lies within the more stable eastern North America (**Figure 1**). Additionally, thickened crust along the Grenville Front and Appalachian fold-thrust belt (**Figure 1**) illustrate patterns of crustal modification during earlier episodes of shortening within the eastern half of North America.

The amplitudes of azimuthally dependent receiver function arrivals recorded by USArray stations also exhibit differences between tectonic provinces (Schulte-Pelkum and Mahan, 2014). By relating these azimuthally variable receiver function arrivals to the presence of either crustal anisotropy or dipping interfaces, the alignment of their spatial variability with province boundaries suggests changes in the strain history of the crust between provinces. Areas of the crust that experienced greater amounts of strain that produced an anisotropic crustal fabric would be expected to possess receiver functions with larger azimuthally varying amplitudes. Clear

differences in the amplitudes of azimuthally varying receiver function signals align with tectonic boundaries, such as the Rocky Mountain Front and the Appalachian-Ouachita belt (**Figure 2**), which also correspond to locations of dramatic changes in crustal thickness (compare **Figures 1 and 2**).

A smaller scale of heterogeneity can also be identified based on changes in the relative amplitude of the azimuthally varying receiver function signal between the Illinois Basin, Ozark Plateau, and Reelfoot Rift (**Figure 2**; Schulte-Pelkum and Mahan, 2014), which appears to relate to intracontinental deformation and the formation of these epiorogenic features. Although the lateral extent of domes and basins within the midcontinent is sufficient for them to exhibit differing signatures in large-scale crustal structure maps, additional insights into the processes responsible for the evolution of these structures can be gained by investigating their lithosphere structure at a more focused scale (e.g. Hopper et al., 2013). The tectonically stable North American midcontinent provides an excellent setting to study how extension and mafic intrusions associated with the Reelfoot Rift, the formation of the Ozark Plateau, and subsidence of the Illinois Basin, changed the crust (**Figures 1 and 2**).

The Nd- (Neodymium) line (**Figures 1 and 3**) marks the eastern limit between the Paleoproterozoic Mazatzal province (> 1.55 Ga) and the Mesoproterozoic Granite Rhyolite province (< 1.55 Ga) (Whitmeyer and Karlstrom, 2011). This midcontinent structural boundary allows for investigating terrane accretion and the response of terranes to later episodes of deformation. A sharp transition in long-wavelength depth integrated magnetic susceptibility aligns with the Nd-line, where the Mazatzal Province is characterized by higher susceptibility while the Mesoproterozoic province possesses lower susceptibility (Ravat, 2007). However, the magnetic signal at shorter wavelengths indicates no contrast between the terranes (Ravat et al.,

2009) and instead reflects near-surface features such as plutons, the depth to basement, and faulting in the crystalline basement (Hildenbrand et al., 2002). While the contrast in long wavelength magnetic susceptibility suggests differing structural characteristics between these two Proterozoic crustal blocks at depth, the lack of a contrast in the short wavelength magnetization suggests that whatever contrast these blocks possess at depth does not extend to the shallower crust (Ravat et al., 2009).

The extensive and regular sampling of the Transportable Array, facilitates measuring changes in crustal structure across the midcontinent of North America (**Figures 1 and 3**). Constructing cross sections by common conversion point (CCP) stacking receiver function waveforms, as presented here, facilitates identifying discontinuities within and beneath the crust. Heterogeneous structures in the crust and upper mantle provide insight into the tectonic development of the region, and can be identified viewing receiver function waveforms in this manner even though such variations may not be apparent in crustal thickness maps. The sampling of the Transportable Array is well suited for investigating changes in crustal structure across terrane boundaries or between physiographic provinces with dimensions that exceed 100's of km.

Understanding the crustal characteristics and dynamics that allow for the formation of intracratonic structures also contributes to our understanding of seismic hazards and the conditions responsible for creating economic resources in a continental interior. Ore deposits in the Ozark Dome and the oil trapped in anticlines and domes within the Illinois Basin both serve as examples of economic resources resulting from the tectonic evolution of the midcontinent (Leach and Rowan, 1986; Appold and Wenz, 2011). The sedimentation patterns and drainage systems of the Mississippi and Ohio Rivers, which both flow through arms of the failed Reelfoot Rift (Braile et al., 1986); also appear to have been influenced by the tectonic evolution of the

region. An improved understanding of midcontinent tectonics therefore provides insight into the origins of these hazards and resources.

Geodynamic models require constraints on the crustal structure of the midcontinent (e.g., Hansen et al., 2013; Becker et al., 2014; Porter et al., 2014). Comparing crustal thicknesses to Bouguer gravity anomalies and surface topography helps refine our understanding of the lateral and depth extent of processes responsible for shaping continents. We seek to investigate the manner in which rifting, uplift, subsidence, and volcanism modified the North American lithosphere in the midcontinent along the boundary of the Mazatzal Province, and why it remains a locus of intraplate seismicity.

2. Tectonic History

North America grew as Proterozoic and Paleozoic terranes accreted onto Archean cratonic cores. Following the addition of the Mesoproterozoic Province to eastern Laurentia, widespread volcanism between 1.48 – 1.35 Ga intruded granites, which have been characterized as anorogenic, into the crust of proto-North America (Whitmeyer and Karlstrom, 2011). The Missouri Gravity Low, which trends from the northwest to the southeast across central Missouri (**Figure 3**), may be linked to granitic intrusions and mark the location of batholith emplacement (e.g., Hildenbrand et al., 1996). The supercontinent Rodinia then grew during the Grenville orogeny between 1.3 and 0.9 Ga (Whitmeyer and Karlstrom, 2011), but was subsequently fragmented by widespread extension, which produced several failed rifts between 0.62 and 0.55 Ga (Braile et al., 1986) (**Figure 1**).

The Reelfoot Rift, which trends northeast from the Mississippi Embayment into Missouri, southern Illinois, and western Kentucky (**Figures 1 and 2**), is an example of a failed rift that formed during the late Precambrian and early Cambrian. The Reelfoot Rift, in combination with

arms extending into southern Indiana, along the boundary between Missouri and Illinois, and along the Rough Creek Graben make up the four armed rift complex of the New Madrid Seismic Zone (**Figure 2**; Braile et al., 1982). Extension within the Reelfoot Rift modified the crust of the continental interior through normal faulting, crustal attenuation, and the emplacement of mafic material at the base of the crust. The New Madrid Seismic Zone then formed in the resulting weakened crust. Small cumulative fault offsets measured within post-Cretaceous sediments of the Mississippi Embayment (Hamilton and Zoback, 1981) indicate increasing slip rates on faults within the Reelfoot Rift by four orders of magnitude from the Pleistocene to the Holocene (Van Arsdale, 2000).

Encompassing the northern portion of the Reelfoot Rift complex, the Illinois Basin extends to the north and east from the New Madrid region over much of Illinois, western Kentucky, and southwestern Indiana (**Figure 1**). The mechanism by which cratonic basins form remains poorly understood. Attempts to describe the formation of cratonic basins, such as the Williston, Michigan, or Illinois Basins (**Figures 1 and 2**), have attributed subsidence to contraction following thermal doming (Haxby et al., 1976; Sleep et al., 1980), lower crustal eclogitization (Fowler and Nisbet, 1985), or excess mass in the lower crust (e.g., Burke and Dewey 1973; McGinnis et al., 1976; DeRito et al., 1983). Negative buoyancy resulting from crustal modification by the Reelfoot Rift has been suggested to be responsible for the evolution of the Illinois Basin (e.g., DeRito et al., 1983; Braile et al., 1986; Kolata and Nelson, 1990a). However, seismically identified stratigraphic relationships at depths below the Late Cambrian Mt. Simon formation in the central portion of the basin indicate the presence of material interpreted to have originated from a Proterozoic rhyolitic caldera complex (McBride et al., 2003). These sequences would have been deposited prior to the opening of the Reelfoot Rift, which may mean that the

Reelfoot Rift actually contributed to a secondary stage of the development of the Illinois Basin (McBride et al., 2003; Bedle and van der Lee, 2006). In such a scenario, the Centralia sequence would be the product of a Proterozoic caldera or rift that formed the proto-Illinois Basin, which would have then been modified by the Reelfoot Rift during the Phanerozoic (McBride et al., 2003). The southern extent of the Illinois Basin reaches the Pascola arch, which was uplifted during the Cretaceous and produced the current oval shape of the basin.

In addition to basins resulting from subsidence, provinces that have been uplifted, such as the Ozark Plateau, are also present in the midcontinent. Mesoproterozoic felsic igneous rocks and plutons comprise the Ozark Plateau (e.g. Hildenbrand et al., 1996), which covers much of southern Missouri and northern Arkansas. The St. Francis Mountains in southeastern Missouri mark one of the few exposures of the rocks that comprise the granite-rhyolite provinces. Marshak et al., (2005), describe the Ozark Plateau as a low-density crustal block bounded by faults. Reactivation of bounding faults during compressional tectonics in the late Paleozoic allowed for its uplift (Brown and Marshak, 2004; Marshak et al., 2005). Liang and Langston, (2009) suggest that the Ozark Uplift may be a relic feature of a phase of active rifting given its geometry and thin, to non-existent, sedimentary layers. However, contrary to expectations for a rift origin to the Missouri batholith, the area lacks mafic volcanic material, leading to suggestions of a plume origin for the uplift of the Ozark Plateau (Hildenbrand et al., 1996).

3. Previous Investigations

The Phanerozoic strata covering the basement geology of the midcontinent presents challenges towards unraveling its tectonic evolution, making geophysical observations necessary for investigating its crustal architecture. The development and geographical extent of the Reelfoot Rift has been investigated through gravity and magnetic studies in concert with seismic

observations. Synthesizing geological and geophysical data, Ervin and McGinnis (1975) interpret the tectonic framework of the Mississippi Embayment and related its formation to the presence of the buried late Precambrian Reelfoot Rift. However both hotspot activity (Cox and Van Arsdale, 1997) and the opening of the Gulf of Mexico have also been suggested to be responsible for subsidence in the Mississippi Embayment.

Anomalous high crustal wave speeds towards the northern portion of the Mississippi Embayment correlate with regions of elevated gravity (**Figure 4**) and magnetic anomalies and have been interpreted to result from intruded mafic rift pillows during Precambrian to Cambrian extension (Braile et al., 1986). The combined locations of positive Bouguer gravity and magnetic anomalies, observations from seismic reflection studies, and the distribution of seismicity within the New Madrid seismic zone all served as evidence for a connection between the formation of the Illinois Basin and the Reelfoot Rift (Braile et al., 1986). Seismic refraction observations also identified an anomalously thick layer with high wave speeds in the lower crust beneath the Reelfoot Rift from Memphis, Tennessee, to St. Louis, Missouri (Catchings, 1999), possibly marking intrusive mafic material that entered the crust during extension in the Reelfoot Rift. The presence of such an anomalous layer supports earlier models (e.g., DeRito et al., 1983) that an uncompensated mass in the lower crust originating from a failed rift initiated subsidence that led to the formation of the cratonic Illinois Basin (Braile et al., 1982; 1986).

However, COCORP (Consortium on Continental Reflection Profiling) seismic observations within the St. Louis arm of the Reelfoot Rift did not identify rift and graben structures, which raises the question of whether this arm indeed formed by rifting, or does it possess a signature of crustal alteration that predates the Reelfoot Rift (Kolata and Nelson, 1990b) High crustal shear wave speeds (V_s) throughout the Reelfoot Rift and Ozark Plateau revealed by ambient noise

tomography led to suggestions that both provinces result from earlier rifting episodes (Liang and Langston, 2009), with the Ozark Plateau representing a dome associated with active rifting while the Reelfoot Rift would have resulted from passive rifting. Both teleseismic body and surface wave studies using data from the Transportable Array recognized the presence of reduced velocities extending to depths near 200 km beneath the Reelfoot Rift (Pollitz and Mooney, 2014; Chen et al., 2014). Zones of reduced velocities have also been identified in the crust (Chu and Helmberger, 2014) and upper mantle (Bedle and van der Lee, 2006; Chu et al., 2013) extending away from the Reelfoot Rift towards the eastern portion of North America. These low velocity zones do not correspond to known surface geology and have been attributed to metasomatism of the continental lithosphere or the presence of primitive mantle material resulting from past plume or subduction activity (Bedle and van der Lee, 2006; Chu et al., 2013; Chu and Helmberger, 2014).

Changes in crustal thickness appear to occur at terrane boundaries, such as between the thinner crust of the Yavapai (~40-45 km) province and the thicker Mazatzal (~45-50 km) crust in the area of Nebraska, Kansas, Iowa, and Missouri (**Figure 1**). However, previous investigations have found that crustal thicknesses only vary a small amount across the Nd-Line. Crustal thicknesses between ~42 to 50 km have been identified for the midcontinent of North America within the Granite Rhyolite Province and 46 to 50 km within the Mazatzal Province (**Figure 1**; e.g., Li et al., 2002; French et al., 2009; Crotwell and Owens, 2005). Particularly notable for an area with limited variations in surface elevation, abrupt changes in crustal thicknesses have been reported by these previous studies, such as those between the 40 km thick crust in southern Illinois and 45 km thick crust near St. Louis (**Figure 1**; e.g., Li et al., 2002). The crust appears to thin within the Mississippi Embayment (**Figure 1**). However reverberations of seismic waves in the thick

sedimentary material of the embayment complicate their signal, which hinders identifying the Moho.

4. Receiver Function Analysis

To investigate crustal structure we calculate receiver functions, which utilize *S*-waves produced by mode conversions of teleseismic *P*-waves that encountered seismic discontinuities beneath the stations used to investigate the midcontinent (e.g., Phinney, 1964; Langston, 1977; Owens et al., 1984). Migrating the differences in arrival times between these *P*-waves and the converted *S*-waves produced at a discontinuity allows for estimating the depth of the discontinuity where the converted wave originated. The amplitude and pulse width of the converted phases are sensitive to the contrast in seismic velocities and densities across the discontinuity and the depth interval of the discontinuity. This investigation focuses on the thickness of the crust and discontinuities within the crust. Our study utilizes recordings from over 280 teleseismic earthquakes that occurred between June 2010 and December 2013 and were recorded on 183 broadband seismic stations spanning between Missouri and eastern Indiana. To eliminate complications from teleseismic *P*-waves interfering with the outer core, we limited our events to those that occurred at distances between 30 and 96 degrees away from each station. Long period signals were removed from the seismograms using a high-pass four-pole Butterworth filter with a corner frequency of 0.02 *Hz*. Visually inspecting each set of three-component seismograms facilitates eliminating poor quality data with a low signal-to-noise ratio or traces that have been contaminated by other spurious signals. Receiver functions were then calculated using an iterative time-domain deconvolution approach (Ligorria and Ammon, 1999) with only traces satisfying a variance reduction cutoff of $\geq 70\%$ retained for further analysis. The receiver functions presented here were calculated using a low-pass Gaussian filter with *a* values of 2.5, corresponding to a ~ 1.2 *Hz*, and 5, corresponding to ~ 2.5 *Hz*.

269 Determining the depth of the discontinuities at which converted phases at particular arrival times
270 originated depends on the assumed values of V_P and V_P/V_S . We use a V_P of 6.6 km/s based on
271 average crustal velocities obtained from refraction results (Catchings, 1999). A V_P/V_S value of
272 1.785 was used based upon finding the V_P/V_S value that would lead the arrival times of direct P_{dS}
273 and PpP_{dS} reverberation phases to migrate to the same depth for the Moho discontinuity across
274 the majority of the study area (e.g. Brennan et al., 2011; Frassetto et al., 2011). Using the S -wave
275 model of Benson et al. (2009) we correct for shallow lateral variations in crustal shear wave
276 speeds and account for low seismic wave speeds within basins using sediment thickness from
277 CRUST1.0 (Laske et al., 2013) while migrating receiver function arrival times to depths. Tracing
278 the ray paths of the receiver functions through a grid of sampling bins and stacking together
279 traces sampling a common location allows for constructing a receiver function CCP volume.
280 Here we follow the CCP stacking approach described by Gilbert (2012) and a grid of bins
281 distributed across the study area that extends over an area 750 km in the north-south direction
282 and 1000 km from east to west.

283 After testing the coherence of CCP stacks calculated for a range of bin sizes, the bins used in this
284 investigation are spaced by 45 km in the north-south and east-west directions and have a radius
285 between 45–135km based on sampling density to ensure sufficient sampling of each bin (**Figure**
286 **3**; e.g., Owens et al., 2000). Averaging together data that can sample the crust as far as 90 km
287 apart causes our stacks to not be sensitive to smaller scale variations, which would require
288 sampling by more closely spaced stations. Rays that pierce a common location are stacked
289 together to produce the average receiver function for each bin (**Figure 3**). Bootstrap resampling
290 the receiver functions within each bin ensures that spurious traces did not dominate the CCP
291 stacks. We gathered 100 realizations of random sets of the traces within each bin to determine

the mean and standard deviation of the bootstrap stacks. Examining the stacks in this manner permits us to limit our interpretation to significant receiver function arrivals.

From these stacked receiver functions, the Moho depth is picked by finding the maximum amplitude in the 20 to 60 km depth range. Using the distribution of the maxima of all 100 of the bootstrap stacks in the 20 to 60 km depth range provides an estimate of the uncertainty in the crustal thicknesses associated with the depth interval of receiver function peaks. Uncertainties associated with picking receiver function peaks for the $a = 2.5$ receiver function stacks range from <1 km to >5 km, depending on its width and amplitude. Bins for which the standard deviation of the distribution of Moho picks exceeds 3 km are not included for constructing our crustal thickness map. For stacks with multiple peaks in this depth range, we pick the peak that would make the most laterally continuous Moho. Additional visual inspection of the Moho picks helps identify and remove other spurious picks.

The standard deviation limit, and the requirement that each bin must be sampled by at least 40 traces to be considered reliable, results in measurements from 290 out of a possible 391 bins contributing to the construction of our crustal thickness map (**Figure 5**). In addition to uncertainties resulting from picking receiver function arrivals, uncertainties in the assumed values for V_P and V_P/V_S also influenced our crustal thicknesses. Assuming a crustal thickness of 45 km, as has been measured in the region, increasing or decreasing V_P/V_S by 5% would change the measured crustal thickness by ~ 5 km and a 5% change in V_P would change the crustal thickness measurement by closer to 2 km. Although the use of constant values for V_P and V_P/V_S across much of the crust for our study ignores velocity heterogeneities that can be present throughout the crust in our study area, such heterogeneities would need to be especially pronounced to affect crustal structure variations of the scale observed here.

Our receiver function stacks include arrivals at mid- and sub-crustal depths. The origin of such phases needs to be carefully inspected to determine whether arrivals are direct converted phases or erroneously migrated phases resulting from converted S -wave reverberating in shallower layers. Analyzing the moveout, or the variability in arrival times as a function of ray parameter, of receiver function arrivals facilitates determining whether arrivals display positive moveout as expected for a direct phase, or if they display negative moveout, as would be the case for a reverberation phase (**Figure 6**; Gurrola et al., 1994; Wilson et al., 2003). An example moveout plot illustrates that positive arrivals closely follow the predicted arrival times for direct arrivals at the Moho and mid-crustal depths (**Figure 6**). Observing arrivals at times of 7 and 10 s after the P -arrival that follow predictions for both the PpP_{ds} and $PsP_{ds} + PpS_{ds}$ reverberation phases produced at a depth of 19 km provides confidence that the arrivals near a time of 2.5-3 s after the P -arrival indeed correspond to a direct phase from 19 km. In addition to this shallow mid-crustal phase, we also observe later arrivals that follow the predicted arrival times for direct and reverberation phases from mid-crustal discontinuities at greater crustal depths. Comparing the arrival times of direct and reverberation phases to predictions for assumed V_P and V_P/V_S values allows for identifying a model that can fit observations. The agreement between the observed and predicted receiver function arrivals for direct and reverberation phases corresponding to 57 km depth provides confidence that the signals observed at stations Q42A, Q43A, and Q44A indeed migrate to the same depth based on an average crustal V_P/V_S of 1.785 (**Figure 6**).

5. Observations

Crustal thicknesses within the region vary from less than 40 km to more than 50 km, with 44 km thick crust underlying the majority of the region (**Figure 5**). Across the midcontinent of North America, we do not observe a correlation between crustal thickness and surface elevations or that single patterns in crustal thickness characterize each of the provinces across the region. No clear

difference in crustal thickness is apparent between the Mazatzal and Granite Rhyolite provinces across the Nd-line, where crustal thickness appears to be similar across the boundary.

The amplitudes of receiver function arrivals corresponding to the Moho vary along the Nd-line (**Figure 7**). The Moho is marked by multiple receiver function arrivals in the area of the Nd-line within the Illinois Basin (**Figure 7C**), which may be a relic of crustal modification during an accretionary event or magmatism associated with Granite Rhyolite emplacement. However, diminished Moho arrivals near the Nd-line in the central portion of the study area do not continue to the southwest where a similar Moho arrival appears across the Nd-line within an area of thickened crust in the Ozark Plateau (**Figure 7D**). Just as crustal thicknesses do not remain consistently on either side of the Nd-line, the amplitudes of receiver function arrivals from the Moho also fluctuate. However, in contrast to other terrane boundaries across the eastern portion of North America, the Nd-line does not appear as a major boundary of crustal structures in the midcontinent.

Although clear changes in crustal thickness can be identified between the Ozark Dome, Reelfoot Rift, and Illinois Basin, crustal thicknesses also vary within each of these regions. The zone of thickest crust identified here, which reaches more than 55 km thick, is located on the boundary of the Illinois Basin and Ozark Plateau. Areas where the crust thins to < 40 km lie within the Reelfoot Rift and Mississippi Embayment region of Arkansas (**Figure 5**). Regional faults, including the Ste. Genevieve, Cottage Grove, and Wabash Valley align with changes in crustal thickness (**Figure 5**), which highlights a link between changes in crustal structure and surface deformation. Crustal thickness variations within the EARS dataset do not similarly reflect this scale of variability that correlates with these faults.

In select locations, the observations presented here possess a similar pattern to the crustal thickness values within the EARS database. Both studies identify thinner crust, which is near 40 km thick in southwestern Missouri towards the area of the Ozark Dome (**Figures 1 and 5**). However, while the EARS data exhibits a pattern of thicker crust that reaches 50 km or more along a swath extending to the northeast of the Ozark Dome towards southern Indiana, this is an area in which we identify crust that remains between 40 and 45 km thick. We also identify zones where the crust remains less than 45 km thick in central Missouri and in the northern parts of the Illinois Basin (**Figure 5**), neither of which appear as areas of thin crust in the EARS dataset (**Figure 1**).

The presence of multiple discontinuities within the crust and upper mantle of the Illinois Basin offers a potential explanation for why some of the crustal thickness observations presented here differ from the EARS dataset. Receiver functions stacks that possess mid- or sub-crustal arrivals in addition to the Moho signal can lead to spurious results from automated approaches, such as the H- κ stacking used by EARS. Differences in crustal thicknesses values between EARS and those measured here highlight the utility in examining the raw receiver functions themselves and their stacks to observe whether the arrival identified by EARS to be significant does indeed correspond to the Moho.

5.1 New Madrid Seismic Zone and Reelfoot Rift

Multiple receiver function arrivals mark the mid-crust near a depth of 25 km and the Moho close to 45 km beneath the Reelfoot Rift and Rough Creek Graben (**Figures 7A and 7B**). A positive receiver function arrival at mid-crustal depths indicates an abrupt increase in crustal wave speeds, which likely corresponds to material added to the crust by the Reelfoot Rift. The receiver function arrival marking the Moho beneath the rift at a depth of ~45 km displays diminished

amplitudes underneath the mid-crustal arrival (**Figure 7A**). Incorporating high velocity material into the lower crust (e.g., Catchings, 1999) would also reduce the impedance contrast between the crust and mantle and result in a smaller amplitude receiver function arrival than those for areas with an average Moho impedance contrast. Previous refraction and gravity investigations also identified mid-crustal discontinuities within the Reelfoot Rift and similarly proposed that they result from magmatic emplacement of dense high velocity material into the crust, which produced the positive gravity anomaly (e.g., Braile et al., 1986; Catchings, 1999).

The Rough Creek Graben, Southern Indiana, and St. Louis arms of the New Madrid Rift complex (Braile et al., 1986) do not exhibit a single continuous crustal thickness (**Figure 5**). While crust between 40 and 45 km thick extends across much of the Rough Creek Graben and Southern Indiana arms of the rift (**Figure 7B**), the St. Louis arm intersects a region where the crust thickens to > 50km along the border between Missouri and Illinois. Crustal thicknesses along the western boundary of the Reelfoot Rift thin relative to the surrounding Illinois Basin and Ozark Plateau.

The area of the rift that possesses crust between 40 and 45 km thick coincides with elevated Bouguer gravity in the location where Missouri, Illinois, and Kentucky meet (**Figures 4 and 5**). The lateral extent of the crustal structure that appears thinned in response to extension within the Reelfoot Rift does not extend far beyond the region of the positive gravity anomaly. The extent of thin crust suggests that crustal modification by the Reelfoot Rift is confined to the area at the southern end of the Illinois Basin. If this is the case, a process other than rifting, such as modification by a mantle plume, must be responsible for producing low lithospheric velocities across the broader region where they have been identified spanning from the central to the eastern United States (Chu and Helmberger, 2013; Chu et al., 2014).

Changes in crustal thickness in the area of the Reelfoot Rift appear related to the locations of surface faults, suggesting that these faults extend across much of the crust. The northward limit of thinner crust within the Reelfoot Rift reaches the Cottage Grove fault in southern Illinois (**Figure 5**). The thinner crust of the Reelfoot Rift appears to be acting as a zone of weakness (e.g., Liu and Zoback, 1997) as it contains much of the New Madrid Seismic Zone, while the thicker crust of the surrounding areas do not appear to be deforming in a similar manner.

5.2 Illinois Basin

As surface elevations diminish along the transition between the Ozark Plateau to the Illinois Basin the crust thickens from ~40km to 50km (**Figures 5 and 7C**). An increase in Bouguer gravity accompanies this change in crustal thickness between the plateau and southern portion of the Illinois Basin (**Figures 4 and 5**). In contrast to expectations based upon Airy isostasy, the thickest crust we measured in the midcontinent lies along the western margin of the Illinois Basin, directly beneath the Mississippi River. Both the southward decrease in crustal thickness and increased Bouguer gravity anomaly occur near the latitude of the Cottage Grove fault in southern Illinois. The crust thins to close to 40 km in the southeastern portion of the Illinois Basin to the south of the Cottage Grove fault. However the surface elevations do not dramatically change at the location of the Cottage Grove fault. Identifying thinner crust and a positive Bouguer gravity anomaly in the area south of the Cottage Grove fault supports hypotheses that involve the addition of dense material to the crust and mantle during extension within the Reelfoot Rift (e.g., Braile et al., 1986; **Figure 7C**).

The presence of receiver function arrivals from mid-crustal discontinuities becomes evident when viewing the crustal structure of the Illinois Basin in cross section (**Figure 7C**). Arrivals at depths from 20 to 30 km within the Illinois Basin serve as clear examples of these mid-crustal

discontinuities. The northward dipping arrivals closely align with the location of a northward dipping interface identified by a refraction profile that sampled the same area and attributed the interface to the top of a layer of high wave speed material in the lower crust that thickens to the south (Catchings, 1999). These arrivals indicate that the area where the Reelfoot Rift has modified the crust reaches as far north as the positive gravity anomaly extends in southern Illinois (**Figure 7C**).

Previous seismic investigations identified heterogeneous crustal (Chu and Helmberger, 2014) and upper mantle (Bedle and van der Lee, 2006; Chu et al., 2013) structures within and surrounding the region of the Illinois Basin. These studies attributed the presence of heterogeneous seismic velocities to activity associated with earlier episodes of subduction and volcanism. The mid-crustal arrivals within the Illinois Basin may also be influenced by crustal imbrication during terrane accretion or the magmatic addition of material to the crust during the emplacement of granites that characterize the Granite-Rhyolite provinces.

The location where the sedimentary layers that fill the Illinois Basin reach their greatest thickness surrounds the Cottage Grove fault (McBride et al., 2003), which aligns with where thicker crust to the north thins to the south. In this configuration crustal thickness variations do not correlate with changes in the structure of the basin. Instead, variable crustal structure within the Illinois Basin suggests that the formation of the basin reflects the cumulative effects of multiple events. Crustal modification due to rifting may have been the dominant factor leading to subsidence in the southern Illinois Basin, while other process, possibly including the formation of a caldera (McBride et al., 2003), were responsible for crustal subsidence further to the north.

5.3 Ozark Plateau

Crustal thicknesses range from close to 40 km to > 50 km within the Ozark Plateau. The zone of increased elevations within the Ozark Dome marks a topographically distinct feature within the Ozark Plateau, yet possesses some of the thinner crust within the Ozark Plateau at just ~42 km thick (**Figure 7D**). A zone of thickened crust straddling the Missouri-Illinois border extends from the northwestern corner of the Ozark Plateau. The western edge of the location of this zone of crustal thickening nearly coincides with the Ste. Genevieve fault and the Cottage Grove fault marks the southern boundary of thicker crust (**Figure 7D**). The area of anomalously thickened crust flanks the eastern margin of the Missouri Gravity Low, which is characterized by a ~-50 to -60 mGal Bouguer gravity anomaly (**Figures 4 and 5**).

Crust less than 45 km thick lies along a northwest to southeast oriented band that lies parallel to the gravity low across central Missouri (**Figures 4 and 7D**). Comparing the locations of the extent of thin crust in Missouri to the location of the negative gravity anomaly reveals that although the two anomalies both possess a northwest to southeast trend, the zone of thin crust is offset to the east relative to the minimum values of the negative gravity anomaly (**Figure 7D**).

Observing an offset between crustal structures and Bouguer gravity anomalies indicates that factors other than variations in the thickness of constant density crust, in which a more negative anomaly would correspond to thicker crust (e.g., Robinson and Coruh, 1988), must be responsible for producing the observed anomaly. Instead, lateral density variations in which particularly low-density material comprises the area of thinned to normal thickness crust offers an explanation for how a gravity low would be present in an area of reduced crustal thicknesses.

On a regional-scale, the location of the Missouri Gravity Low lies near an area of elevated degree-1 azimuthally varying receiver function amplitudes (**Figure 2**), which differs from its

474 surroundings and would be consistent with a change in pattern of deformation between the Ozark
475 Plateau and its neighboring provinces.

476 A relationship between the northwest to the southeast trending Missouri Gravity Low and the
477 emplacement of a batholith in a region of thin crust is consistent with a plume origin to the
478 batholith, which may have also contributed to the uplift of the Ozark Plateau. By attributing the
479 Missouri Gravity Low to a low-density batholith, Hildenbrand et al., (1996) suggested a plume
480 origin for the uplift of the Ozark Plateau. Alternatively, if the batholith responsible for the
481 Missouri Gravity Low formed by a mechanism that would have also created high-density mafic
482 residuum, the removal of that residuum may have driven uplift in the Ozark Plateau, as has been
483 proposed to explain other uplifted regions such as the Colorado Plateau (Beghoul and Barazangi,
484 1989).

485 5.4 Subcrustal arrivals

486 The pattern of crustal thinning towards the southern end of the Illinois Basin appears to be
487 accompanied by the emergence of a subcrustal layer in the upper mantle. Low amplitude receiver
488 function arrivals at depths greater than the Moho beneath the Reelfoot Rift may correspond to
489 material that underplated onto the base of the crust (**Figures 7A and 7C**). Refraction surveys of
490 the New Madrid Rift Complex have also identified evidence for layering in the upper mantle
491 based on a discontinuity at a depth near 60 km (Catchings, 1999). Detecting this arrival below
492 the Moho in the same location of a positive Bouguer gravity anomaly suggests that it may relate
493 to high-density material that underplated the crust during rifting. Evidence for underplated
494 material has also been identified beneath the Baikal Rift zone and Donbas Basin, and has been
495 interpreted to result from substantial magmatic intrusions into the crust (Thybo and Artemieva,
496 2013). Upper mantle layering may also result from subduction related (e.g., Bedle and van der

Lee, 2006) or magmatic (e.g., Chu et al., 2013) processes, which have both been suggested to cause heterogeneous upper mantle seismic velocities in the midcontinent.

6. Summary

The seismic images presented here provide insight into crustal structure spanning a Mesoproterozoic convergent margin where juvenile crustal blocks attached to Paleoproterozoic crust along eastern Laurentia. Continental rifting appears to have modified the lithosphere by producing a zone of thinned crust within the Reelfoot Rift and Rough Creek Graben. Additionally, discontinuities within the crust and upper mantle at depths just below the Moho within the Illinois Basin suggest locations of intrusions or underplated material resulting from rifting. We identify evidence for crustal layering within much of the crust of the Illinois Basin, as mid-crustal discontinuities appear to continue northward from the Reelfoot Rift throughout the basin. The structure of the Ozark Plateau differs from its adjacent province, as it does not possess similar mid-crustal or subcrustal arrivals. The coincidence of thin crust and a negative gravity anomaly can be explained by low-density crust in the Ozark Plateau, which may have also contributed to the uplift of the plateau.

Previous studies of the New Madrid Seismic Zone identified evidence of crustal thinning and layering due to magmatic activities leading to the intrusion of high velocity material during rifting. The receiver function images presented here for the Reelfoot Rift similarly reveal a large amplitude mid-crustal receiver function arrival marking the top of a layer of increased lower crustal seismic wave speeds. The correlation of this large amplitude mid-crustal arrival at the southern end of the Illinois Basin (**Figures 7A and 7C**) with the extent of the increasing Bouguer gravity anomaly and a subcrustal arrival supports a link between the development of the Illinois Basin and the addition of dense material to the crust during rifting. However, the variability in

crustal thicknesses within the Illinois Basin suggests that instead of the basin resulting from a single tectonic event, a number of events may have each modified the crust and the Illinois Basin represents an accumulation of their effects.

Our receiver function images indicate changes in crustal thickness over short distances that coincide with a zone of faults in the midcontinent. Thin crust towards the southern end of the Illinois Basin thickens in a position that aligns with the Cottage Grove fault system. The thickened crust of the central Illinois Basin continues westward into the Ozark Plateau, where its western limit lies along the Ste. Genevieve fault zone (**Figure 5**). A connection between changes in crustal thickness and surface faults highlights the important role that crustal structure plays in influencing deformation in the midcontinent.

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696

697 **Figure Captions**

698 **Figure 1:**

699 Map of crustal thickness estimates for the contiguous United States from the EARS dataset.
700 ([http://ears.iris.washington.edu/stationLatLonBox.csv?minLat=28.0&maxLat=52.0&minLon=-](http://ears.iris.washington.edu/stationLatLonBox.csv?minLat=28.0&maxLat=52.0&minLon=-125.0&maxLon=-65.0)
701 [125.0&maxLon=-65.0](http://ears.iris.washington.edu/stationLatLonBox.csv?minLat=28.0&maxLat=52.0&minLon=-125.0&maxLon=-65.0), accessed June 24th, 2015). Filled circles mark station locations with their
702 color corresponding to crustal thickness values ranging from values of 30 km or less shown as
703 red, to 55 km or greater, shown as purple. Locations of terrane boundaries and other structures
704 (after Whitmeyer and Karlstrom, 2007) to the east of the Rocky Mountain Front (RMF labeled
705 gray dashed line) are presented as thick red lines with terrane names noted. The location of the
706 Nd-Line, discussed in text, is labeled and shown as a dashed blue line striking from the
707 northeastern to the southwestern portion of the map. Locations of the Midcontinental Rift and
708 other failed rifts are presented as filled red polygons stretching across the central portion of the
709 United States. Abbreviations include T. H. O. Trans Hudson Orogeny; G-R Granite Rhyolite
710 Province; M. E. Mississippi Embayment. Maps shown in **Figures 3-5** correspond to the focused
711 study area in the box outlined by the white and black dashed line.

712 **Figure 2:**

713 Background colors represent the relative amplitude of degree-1 azimuthally variable signals of
714 radial and tangential receiver functions from Schulte-Pelkum and Mahan (2014). See text for
715 description. Areas for which the azimuthally varying signal possesses larger amplitudes relative
716 to their total signal are shown as red (values correspond to amplitude of degree-1 receiver
717 function signals relative to their total amplitude). Conversely, the purple and blue colors
718 correspond to areas in which the amplitude of the degree-1 signal is lower relative to the total the
719 signal. Transparent white polygon outlined by dashed black line notes the locations of the arms
720 of the New Madrid Seismic Zone based on Braile et al., (1982). Note that the location of the

seismic zone corresponds to failed rifts in the northern end of the Mississippi Embayment in **Figure 1**. Dashed black lines note locations of intercontinental basins (I.B. Illinois Basin; M.B. Michigan Basin; W.B. Williston Basin). Uplifted cratonic blocks (O. D. Ozark Dome) are outlined by red and white dashed lines. The Rocky Mountain Front (RMF) Appalachian fold-thrust belt (AFB) are noted as gray dashed lines. Locations of rifts, basins, and uplifts in **Figures 1 and 2** are after Marshak and Paulsen, (1997). Maps shown in **Figures 3-5** correspond to the focused study area in the box outlined by the white and black dashed line.

Figure 3:

Focused map of geological provinces within the United States midcontinent presenting the location of stations comprising the Transportable Array (red triangles) in study area outlined black and white outlined box in **Figures 1 and 2**. Blue diamonds mark bin center points. Piercing point locations of where receiver functions sample at a depth of 44 km are presented as green points surrounding each station. The extent of a sampling bin with a radius of 45 km extending across southern Indiana is plotted as a light red circle outlined in black. The Nd-line is plotted as a pink dashed line running from northeastern Indiana through southern Missouri, which marks the boundary between the Mazatzal Province to the northwest and the Granite Rhyolite Province to the southeast. The perimeter of the Illinois Basin outlined in blue extends across the Nd-line. A dashed orange line outlines the northern end of the Mississippi Embayment (Miss. Emb.). Within the Mississippi Embayment lies the Reelfoot Rift (RFR), which is outlined in red and extends into the southern end of the Illinois Basin. To the west of the Reelfoot Rift lies the Ozark Dome (O.D.) outlined in green. Three black triangles in western Illinois mark the locations of stations Q42A, Q43A, and Q44A (west to east) that contribute data to the moveout plot presented in **Figure 6**. Solid black lines labeled A-D correspond to the locations of cross sections presented in **Figure 7**.

Figure 4:

Map of Bouguer gravity acquired from the Pan American Center for Earth and Environmental Studies website (Keller, 2005; PACES; http://irpsrvgis08.utep.edu/viewers/Flex/GravityMagnetic/GravityMagnetic_CyberShare/).

Elevated gravity anomalies (shown as red colors) located at the southern end of the Illinois Basin in the Reelfoot Rift. Locations of negative gravity anomalies (shown as blue and purple) are located within the Ozarks in Missouri and are more negative along the Missouri Gravity Low. Gray lines note the locations of regional faults within the area: CG – Cottage Grove fault, Du – Du Quoin monocline, RC – Rough Creek Graben. SG – Ste. Genevieve, and WV – Wabash Valley Fault Zone. Solid white lines labeled A-D correspond to the locations of cross sections presented in **Figure 7**.

Figure 5:

Map presenting crustal thickness within the midcontinent measured by this study. Blue colors indicates regions of thicker crust, which reach a maximum value >55 km along the Illinois-Missouri border. The thinnest crust found here is <40 km within the Reelfoot Rift of southeast Missouri and eastern Arkansas. Other patches of thin crust are also present along the perimeter of the study area in eastern Kansas and northern Illinois. Contours at an interval of 5 km overlay the colors indicating crustal thicknesses. Note the extent of thickened crust on the boundary between the Illinois Basin and Ozark Plateau is largely confined within the area outlined by the Ste. Genevieve and Cottage Grove faults and the Du Quoin monocline. Fault locations presented in the same manner as in **Figure 4**. Small black circles note the locations of CCP stacking bins that contribute crustal thickness estimates used to make this map. The crustal thickness values and the receiver function stacks used to generate this crustal thickness map will be made available as

a supplementary document and through the IRIS Earth Model Collaboration webpage (<http://ds.iris.edu/ds/products/emc-earthmodels>).

Figure 6:

Receiver function moveout plot for TA stations Q42A, Q43A, and Q44A located in the area of thickened crust in Illinois in western Illinois. Locations of these stations are noted as black triangles in **Figure 3**. Red colors correspond to positive receiver function amplitudes while blue colors indicate negative receiver function arrivals. Receiver functions, calculated here with using a low-pass Gaussian filter with an $a = 5$, are sorted by ray parameter to identify whether the variations of arrival times for specific phases increase or decrease along expected moveout curves. Predicted arrival times for direct and reverberation phases originating at depths of 19, 33, 43, and 57 km are presented. The moveout curves have been calculated for a 1-D model in which $V_P = 6.6$ km/s and $V_P/V_S = 1.785$. Curves are presented for the direct P_{ds} (black) and PpP_{ds} (blue) and $PsP_{ds} + PpS_{ds}$ (pink) reverberation phases. Positive moveout, in which arrivals times increase with increasing ray parameter, marks direct arrivals while negative moveout, with an opposite slope, would be expected for reverberation phases. The depth of predicted moveout curves in km are noted along the right side of plot. Note the potential for interference between direct and reverberation phases.

Figure 7:

(A-D) Cross sections of CCP receiver function stacks across the study area. The mean receiver and its standard deviation determined through bootstrap resampling are plotted as black and blue lines respectively. Locations of the cross sections are plotted as lines A-D in **Figures 3 and 4**. Surface elevations and Bouguer Gravity anomaly (blue in mGal) are plotted along the top of the stacks. (A) East-west cross section sampling the Ozark Plateau (OP), Mississippi River (MR), and Reelfoot Rift (RFR). Sub-crustal arrivals are visible in this cross section at depths ~60 km.

792 **(B)** Northeast-southwest cross section spanning the Southern Indiana (SI) and Rough Creek
793 Graben (RCG) arms of the Reelfoot Rift and the Illinois Basin (IB). **(C)** North-south cross
794 section from the northern Illinois Basin (IB), across the location of the Nd-line, to the northern
795 edge of the Reelfoot Rift (RFR). **(D)** Cross section sampling the Ozark Plateau (OP), the
796 Missouri Gravity Low (MGL), the Mississippi River (MR), and the Illinois Basin (IB). Note the
797 offset of the MGL relative to the location where the crustal thickness decreases.

Figure #1

McGlannan and Gilbert, Figure #1

Figure #2

McGlannan and Gilbert, Figure #2

Figure #3

McGlannan and Gilbert, Figure #3

Figure #4

McGlannan and Gilbert, Figure #4

Figure #5

McGlannan and Gilbert, Figure #5

Figure #7