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Fossil flat-slab subduction beneath the Illinois basin, USA

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Abstract

The Illinois basin is one of several well-studied intracratonic sedimentary basins within the North American craton whose formational mechanisms and subcrustal structure are not well understood. We study the *S*-velocity structure of the upper mantle beneath the Illinois basin and its surrounding area through seismic tomography. We utilize continental scale waveform data of seismic S and surface waves, enhanced by regional earthquakes located near the Illinois basin. Our 3D tomographic model, IL05, confirms the existence of a slow *S*-velocity structure in the uppermost mantle beneath the Illinois basin region. This anomalously slow region exists from the base of the crust to depths of ~90 km, and is slower than the North American cratonic average by about 200 m/s. This anomalous uppermost mantle beneath the Illinois basin is underlain by a faster lithosphere, typical of the surrounding craton, to depths of ~200 km. Excluding the formation of the Reelfoot Rift, this area of North American has been stable for over 1.0 Gy. Thus, we do not expect thermal anomalies from before that time to persist into present day *S*-velocity anomalies and we consider a delamination origin as an explanation of Illinois basin subsidence unlikely. We cannot rule out that the slow mid-lithosphere beneath the Illinois basin is caused by an uppermost mantle enriched by a deep, but weak plume. We attribute the slow mid-lithosphere to the presence of either oceanic, hydrous crust, or, a relatively cool mantle wedge with preserved hydrous minerals in the Illinois basin's uppermost mantle, related to a fossilized flat subduction zone.

Keywords: Seismic tomography; Illinois basin; Upper mantle; *S*-wave velocity

1. Introduction

The Illinois basin is an oval-shaped intracratonic sedimentary basin, which covers parts of southern Illinois and Indiana, western Kentucky, Tennessee, and Missouri (Fig. 1). The shallow structure of this basin has been well defined from drill core studies (Buschbach and Kolata, 1990) and active source seismic studies (Braile et al., 1981; Braile et al., 1986; Catchings, 1999; McBride and Kolata, 1999; McBride et al., 2003). These data provide constraints that allow the separation of the crustal and mantle structures' effects on seismic waveforms during tomographic inversions. In this study, we utilize S and surface waveforms from local earthquakes to test whether the separation of the effects of crustal heterogeneities from seismic waveforms improves imaging of the upper mantle *S*-velocity structure beneath the Illinois basin. In addition, we evaluate the possibility of improving seismic waveform tomography on regional scales by incorporating crustal constraints. In this paper, we consider possible links between the imaged subcrustal *S*-wave velocity anomaly beneath the

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basin and mechanisms of basin formation, and interpret the Illinois basin to be underlain by a fossilized flat subduction zone that was active in the Mesoproterozoic.

1.1. Subsidence mechanisms of intracratonic basins

Sedimentary basins that exist within the stable, cratonic, interiors of continents, away from plate margins are called intracratonic basins. There exist several such basins on the North American continent, among them: the Hudson basin in Canada; the Illinois basin; the Michigan basin; and the Williston basin along the Canadian–US border (Fig. 2). Despite much study, the formational mechanisms of this class of sedimentary basins remain widely debated. This is well summarized by Catacosinos et al. (1996), who emphasized that after years of inquiry, basin researchers remain divided on the driving mechanisms of intracratonic basin formation. Currently, some basin researchers believe there are no uniform driving mechanisms responsible for intracratonic basin formation and development, while others primarily believe that the processes of basin formation and evolution are directly related to the stress fields incurred from plate tectonics. It has also been pointed out that basins tend to reoccur at the same sites (Sloss, 1991), which implies that there may exist some such heterogeneity within the lithosphere of these basins to cause the reactivation of subsidence through time. Fortunately, evidence for understanding the basinal history can be gleaned from both the sedimentary record and through using geophysical methods to perform remote sensing of crustal and mantle mineralogical and thermal alterations.

We find that the upper mantle *S*-velocity structure differs between the North American intracratonic basins as modeled by the 3D tomographic model NA04 (Van der Lee and Frederiksen, 2005), as shown in Fig. 3. When comparing the Williston, Hudson Bay, Michigan, and Illinois basins, only the Illinois basin shows an anomalously slow uppermost mantle structure. This suggests that some intracratonic basins, but not all, may be related to observable heterogeneities within the upper mantle.

Two hypotheses have been presented to explain the formation of the Williston basin. Gerhard et al. (1991) suggested that the Williston basin formed as either a craton-margin or a continental shelf basin, and later became an intracratonic basin during deformation of the Cordilleran orogeny, and as continental crust was added on to the west during accretion. Conversely, Baird et al. (1995) suggest that crustal root from the Hudson orogeny

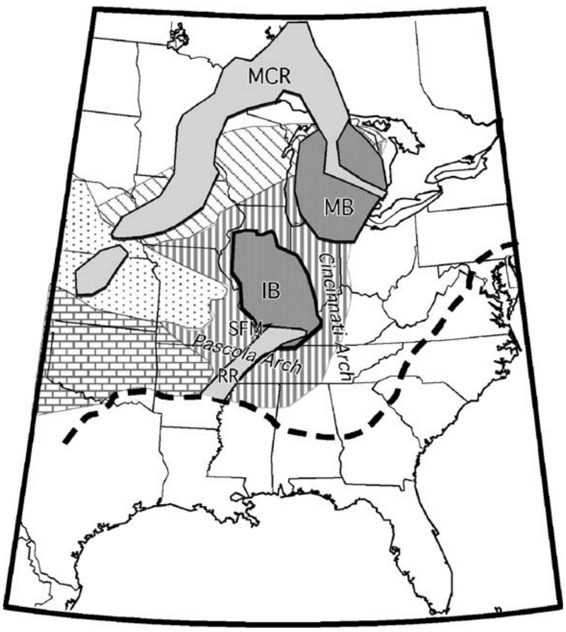

Fig. 1. Major tectonic provinces and Precambrian basement of the mid-continent United States. MCR = Mid-continent Rift; MB = Michigan basin; IB = Illinois Basin; RR = Reelfoot Rift and Rough Creek Graben. The thick dashed line represents the Late Precambrian cratonic margin. The diagonally filled area, the Penokean Province (1890–1830 Ma); the stippled area represents the Central Plains Province; the vertically shaded area the eastern granite–rhyolite province (1450–1480 Ma); and the bricked area represents the western granite–rhyolite province (1340–400 Ma) (modified from Bickford et al., 1986).

transformed to eclogite causing subsidence of the basin. In either case we would not expect to observe a heterogeneous *S*-velocity structure beneath the Williston basin, as Gerhard et al. (1991) hypothesis does not involve upper mantle participation, and in the case of Baird et al. (1995), eclogite is seismically indistinguishable from mantle peridotite (Helffrich et al., 1989).

To the northeast of the Illinois basin, separated by the Cincinnati arch, lies the Michigan basin, the most similar of the three other major North American intracratonic basins to the Illinois basin. The formation of the Michigan basin is not as well understood as that of the Williston basin. Current theories have the Michigan basin developing as a rift basin over the 1.1 Ga Midcontinent rift system (Hinze, 1963; Van Schmus and Hinze, 1985). Throughout the Phanerozoic, the development and subsidence of these two geographically close basins has been related. Both the Illinois and Michigan basins experienced a period of thermal subsidence during the Cambrian (Sleep and Sloss, 1978). The Illinois and Michigan basins were further linked during the Appalachian orogeny, as overthrusting allowed sediments from the Appalachians to accumulate in the two basins. Interestingly, despite some similarities between the Illinois and Michigan basin's more recent subsidence episodes, the upper mantle *S*-velocity structure differs (Fig. 3); suggesting that the upper mantle structure observed beneath the Illinois basin may be the result of a Proterozoic event.

1.2. Geologic and tectonic setting of the Illinois basin

It is most often suggested that the Illinois basin began as a rift basin over the Reelfoot Rift, forming in the late Proterozoic concurrent with the breakup of Rodinia (Keller et al., 1983; Braile et al., 1986). In the Late Proterozoic, the New Madrid rift complex, which includes the Reelfoot Rift, attempted to open to the south of the current position of the Illinois basin. The rift extension ended by the Late Cambrian (Braile et al., 1982). During the Paleozoic, the Illinois basin experienced thermal and isostatic subsidence (Heidlauf et al., 1986; Kolata and Nelson, 1991; Bond and Kominz, 1991), with increasing subsidence rates in the late Mississippian (330–323 Ma) through Early Permian (290–256 Ma) (Kolata, 1991). In the Early Permian, the basin experienced extension as Pangaea broke apart, resulting in the uplift of the Pascola Arch at the southern edge of the Illinois basin, establishing the basin's current oval shape (McKeown et al., 1990).

While it is probable that the Reelfoot Rift did play a role in the Phanerozoic evolution of the Illinois basin, recent evidence suggests it might not have been the initial formational mechanism of the basin. Sequence stratigraphy (Pratt et al., 1992; McBride, 1999; McBride et al., 2003) and reflection profiles (McBride and Kolata, 1999) have recently noted an episode of localized subsidence and/or volcanic accumulation before deposition of the Cambrian sedimentary layers laid down within the Illinois basin

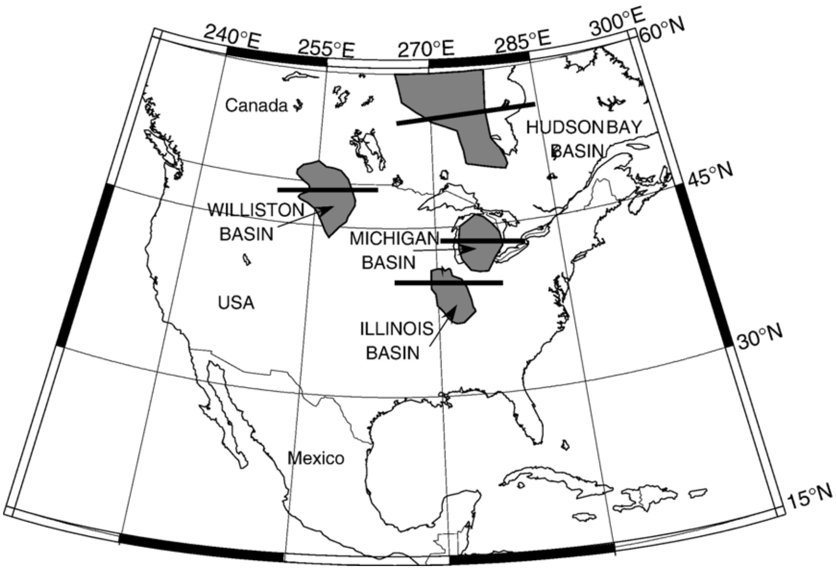

Fig. 2. Locations of major intracratonic basins within North America (Sleep, 1971; Sleep, 1976; Sleep and Sloss, 1978; Gerhard et al., 1982). Thick lines through each basin show map-view of cross sections shown in Fig. 3.

during extension of the Reelfoot Rift. This demonstrates that the Illinois basin region was operating as a sedimentary basin before Reelfoot Rift extension (McBride and Kolata, 1999). Based on faulting and sedimentation patterns, McBride et al. (2003) proposed that the northern portion of the Illinois basin might be related to a Proterozoic caldera or rifting complex, possibly responsible for the emplacement of the uppermost basement beneath the Illinois basin region, the eastern granite–rhyolite province. Thus, McBride et al. (2003) show that the Illinois basin is the result of two primary formational episodes: initially as a Proterozoic basin overlying either a rhyolitic caldera complex or a rift, with the depositional center shifting further south during the extensional rifting of the Reelfoot Rift in the late Precambrian.

1.3. Previous S-velocity studies

The propagation velocity of *S*-waves in the crust and upper mantle is proportional to the thermal, mineralogical, and compositional states of the lithosphere. The three-dimensional *S*-velocity structure underneath the Illinois basin has been previously modeled in continental-wide (Grand, 1994; Van der Lee and Nolet, 1997; Godey et al., 2003; Van der Lee and Frederiksen, 2005) and global scale (Woodhouse and Dziewonski, 1984; Laske and Masters, 1998; Boschi and Ekstrom, 2002; Grand, 2002; Li and Romanowicz, 1996) three-dimensional tomographic models. We find that the global models are not detailed enough to show variation within the North American craton. On the other hand, the regional model NA00 (Van der Lee, 2002) imaged a mid-lithosphere zone of low velocities underneath the Illinois basin. In this study, we investigate this anomalous mid-lithosphere zone and enhance a recent regional model, NA04 (Van der Lee and Frederiksen, 2005), with data that are particularly sensitive to the crust and uppermost mantle beneath the Illinois basin region.

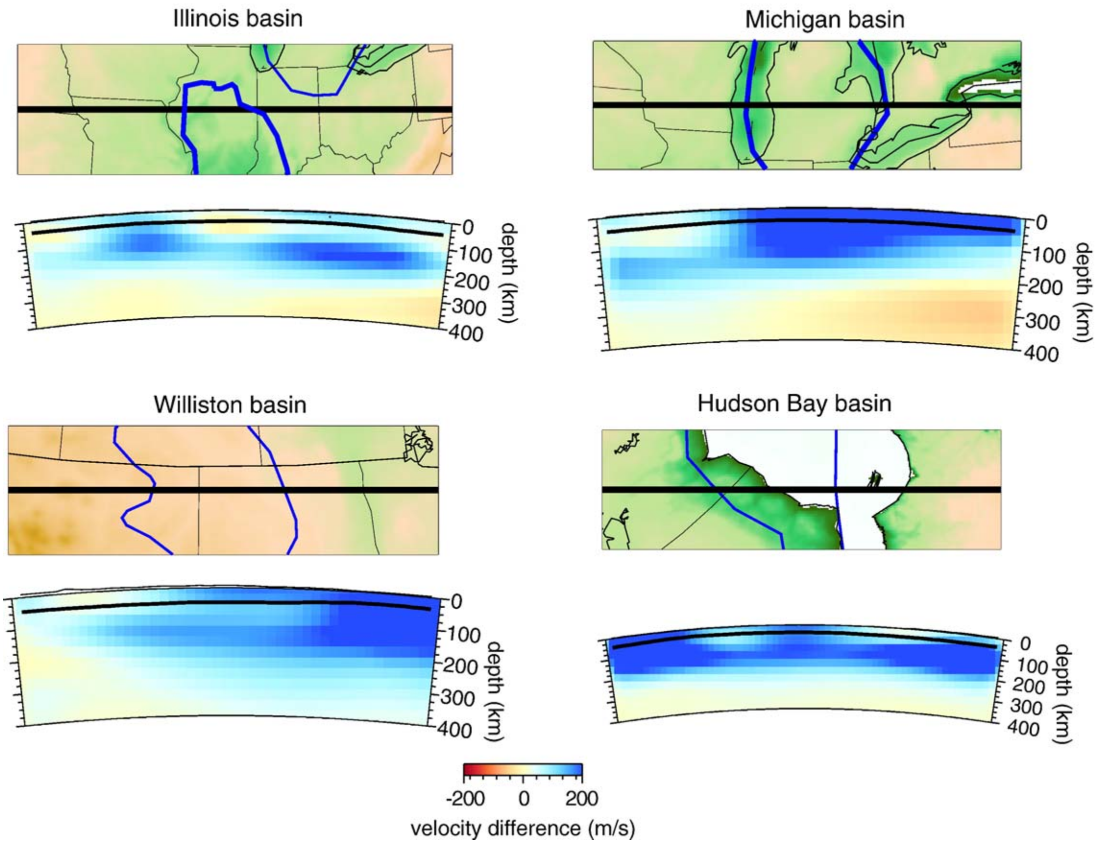

Fig. 3. Upper mantle structure beneath intracratonic basins in the United States, as determined by model NA04 (Van der Lee and Frederiksen, 2005) and model IL05. Shown are the Illinois basin, Michigan basin, Williston basin, and Hudson Bay basin. In the map view projection each basin is outlined in blue. The velocity scale depicts the velocity difference from the 3D model with the 1D earth model, MC35, as shown in Fig. 4. Note that a low velocity region only exists in the uppermost mantle beneath the Illinois basin, and not beneath the other North American intracratonic basins.

2. Methods

Fundamental and higher mode waveforms were inverted to image the three-dimensional upper mantle *S*-velocity structure under the Illinois basin region. We applied the method of Partitioned Waveform Inversion (PWI) (Nolet, 1990; Van der Lee and Nolet, 1997), to the waveforms. PWI derives linear constraints on the average velocity structure along each station-event path through the non-linear waveform fitting of regional S and surface waves. After these constraints are derived from all selected seismograms, PWI involves completing a damped linear inversion for the three-dimensional *S*-velocity structure. For this we combined the existing constraints with constraints from the newly fitted Illinois basin waveforms. The 3D model is relative to a 1D reference model, MC35, which is based on PEM-C (Dziewonski et al., 1975), with the upper mantle set to a constant *S*-velocity of 4.5 km/s down to 210 km. The resultant three-dimensional *S*-velocity model is parameterized with linear interpolation between nodes in a Cartesian grid; and the laterally varying Moho depth is parameterized, with linear interpolation between nodes, on a spherical grid of triangles. The distance between nodes in the z-direction is 60 km, and the distance in the x- and y-directions is 100 km.

Two one-dimensional background models, also adapted from PEM-C, were created for this study. A background model was created for both the northern Illinois basin (IL43n) and the southern Illinois basin (IL43s). A comparison of these background models is shown in Fig. 4. In these background models, the upper mantle high and low velocity zones in PEM-C were replaced by a constant upper mantle *S*-velocity of 4.5 km/s down to the depth of 210 km. The crustal structure in PEM-C was also replaced. Instead, both IL43 models incorporate five crustal layers: a 4 km thick lower crust; a 35.5 km middle crust; a thin sandstone layer; a limestone layer; and a sediment layer. These upper-crust depths are an average of the Illinois basin's northern and southern crustal layers, as determined from drill cores (Buschbach and Kolata, 1990). In IL43n and IL43s, we used *P*-velocities, *S*-velocities and crustal densities for each middle- and lower-crustal layers, and the depth to the Mohorovicic discontinuity as determined by Catchings (1999) and Braile et al. (1981) from seismic reflection and refraction surveys and Bouger gravity anomaly studies.

3. Data

Due to the low seismicity of the target area, waveforms from relatively small mid-continent earthquakes were used. We collected vertical component seismograms for regional station-event pairs for which the great circle ray path intersects near the vicinity of the Illinois basin (Fig. 5). Ray paths that intersected the Illinois basin were fitted with either IL43n or IL43s, dependent on individual path. Event-station paths that did not intersect the Illinois basin were fitted with MC35, as were ray paths for which greater than 50% of the path was outside the basin. Data from eleven mid-continent events (Table 1) were fitted in this study. We collected seismic data from the Incorporated Research Institutions for Seismology (IRIS). The earthquake source parameters used in this study were taken from the USGS National Earthquake Information Center (NEIC) catalogue, the Lamont-Doherty Earth Observatory (LDEO) (Kim, 2003; Horton et al., 2005), or from Harvard's Centroid Moment Tensor Solution (CMT) (Dziewonski et al., 1983). The hypocenter depth was taken from NEIC, and the origin time, latitude and longitude was taken from the International Seismological Center (ISC), when available. In cases the ISC had not yet published origin times and locations, this information was obtained from NEIC. As ISC and NEIC epicenters have associated uncertainties, we tested how this would affect the waveform fits, and found that a variance in depth (±7 km) only affects the

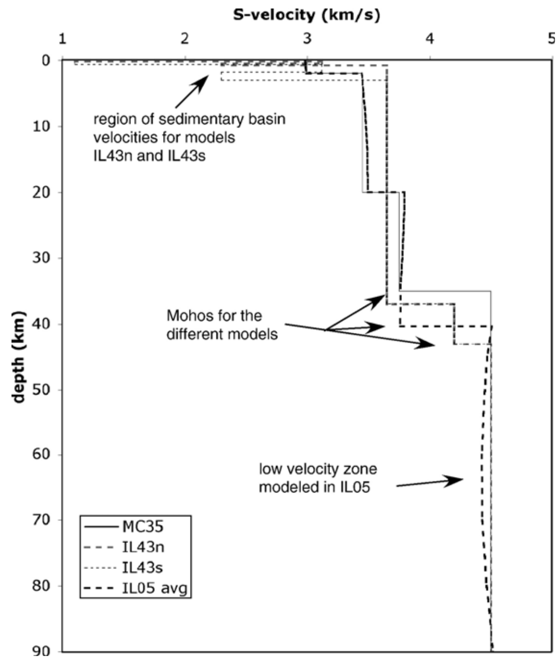

Fig. 4. The upper 90 km of the lithosphere for 1D *S*-velocity models MC35, IL43n, and IL43s used as the starting models in the waveform fitting process. Also shown is the 1D model of the averaged IL05 Illinois basin region.

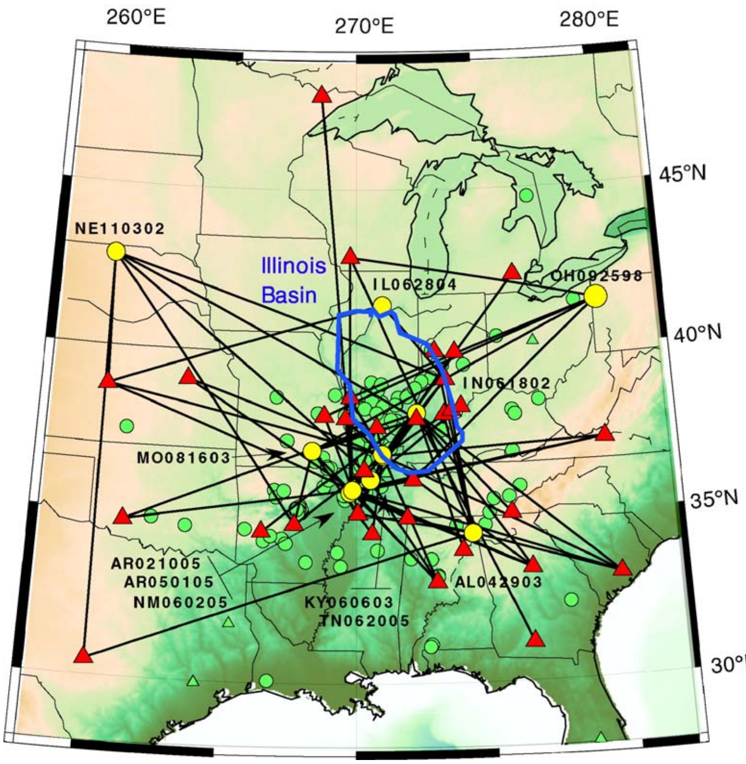

Fig. 5. Event-station paths for waveforms fitted in the IL05 inversion. Events used in this study are shown as yellow circles. Seismic events over Mb3.0 that occurred since 1974 are shown as small green circles. The red triangles are seismic stations from which data were used in this study. Black lines connecting the events and stations represent the raypaths for data used. Small green triangles represent other nearby permanent seismic stations that are currently deployed. The Illinois basin is outlined in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amplitude of the low velocity anomaly, not its polarity. After retrieval, each seismogram was deconvolved from its instrument response and checked for quality. A time window was interactively set for each seismogram so that both the fundamental and higher mode waveforms would be fit.

4. Results

The averaged velocity structure of waveforms fit using IL43n, IL43s, or MC35 were inverted for a 3D structure in a damped linear inversion along with the constraints from model NA04 (Van der Lee and Frederiksen, 2005). The resultant 3D tomographic model, IL05, confirms the existence of a slow *S*-velocity structure in the uppermost mantle beneath the Illinois basin region (Figs. 6 and 7). This anomalously slow region exists from the base of the crust to depths of ~90 km, and is slower than a cratonic average by about 200 m/s. The slow uppermost mantle beneath the Illinois basin is then underlain by a faster lithosphere typical for of the surrounding North American craton to depths of ~200 km (Fig. 6). Tomographic imaging tends to widen and subdue velocity anomalies, particularly small anomalies. Therefore, the 90 km is to be regarded as an upper limit for the actual thickness of this low-velocity anomaly. However, if the actual anomaly is thinner, its velocity contrast is approximately proportionally stronger. An east–west transect of the Illinois

Table 1
Mid-continental North American events used in this study

Event ID	Origin time	Latitude	Longitude	Depth (km)	Mb	Ms
AL042903	08:59:39.07	34.4940	−88.6290	19.6	4.4	4.3
AR021005	14:04:54.00	35.760	−90.250	15.5	4.1	3.9
AR050105	12:37:32.00	35.83	−90.15	9.7	4.1	4.1
IL062804	06:10:52.60	41.4400	−88.9500	9.0	4.5	3.5
IN061802	17:32:12.50	38.1490	−87.6630	18.0	5.4	4.6
KY060603	12:29:34.00	36.8700	−88.9800	2.5	3.9	3.4
MO081603	05:09:23.06	37.0055	−91.6911	5.0	3.9	3.9
NE110302	20:41:58.70	42.7988	−99.8651	5.0	4.2	3.9
NM06025	11:35:11.00	36.150	−89.470	15.0	3.7	4.0
OH092598	19:52:51.51	41.4444	−80.3388	5.0	4.8	4.2
TN062005	12:21:42.00	36.91	−89.00	3.5	3.7	3.9

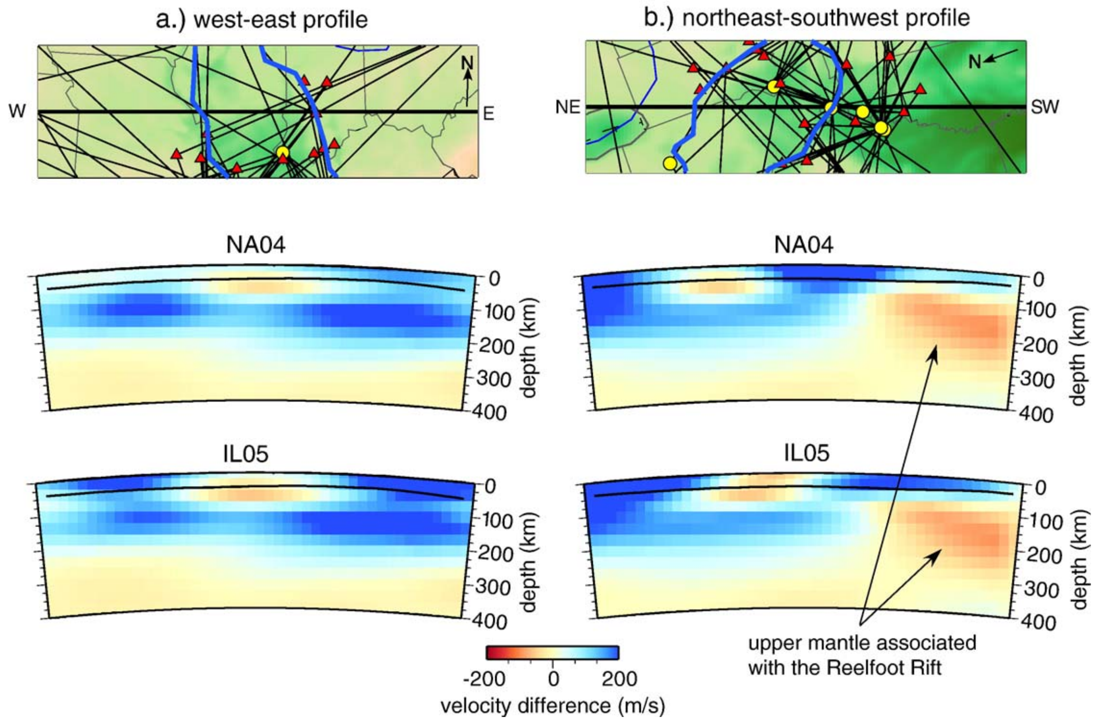

Fig. 6. This figure shows upper mantle *S*-velocity relative differences for the 3D models from the reference 1D background model, MC35. From top to bottom are a map view of the area being transected, with the ray paths of stations and events used in this study and the Illinois basin outlined in blue, the direction of North is indicated in the upper right corner of each map. Below those are cross-sections through the two models: NA04 and IL05 (Illinois events fitted with IL43n, IL43s, and MC35 background models as well as NA04 constraints). a) an west–east transect along the 39th parallel. b) a northeast–southwest transect that roughly aligns with the Mississippi River. All four cross-sections show the low velocity region beneath the Illinois basin in the uppermost mantle, and b) shows the slow upper mantle structure attributed to the Reelfoot Rift.

basin at latitude 39°(Fig. 6a) shows that the upper 90 km of the Illinois basin has a slower *S*-velocity than what exists outside of the basin. This is also demonstrated in a northeast–southwest transect (Fig. 6b). The seismically slower, warm upper mantle beneath the Reelfoot Rift (Goes and Van der Lee, 2002) also is imaged in Fig. 6b. Here we note that the upper mantle beneath the Reelfoot Rift is distinctly separate from the slower *S*-velocity anomaly beneath the Illinois basin. It has been hypothesized that the seismicity in the southern Illinois basin is linked to the northward extent of the inferred warm upper mantle related to the Reelfoot Rift and New Madrid Seismic Zone. As we observe a distinction between the coherent fast lithosphere beneath the southern Illinois basin and the slower upper mantle related to the Reelfoot Rift, we suggest that the Reelfoot Rift does not currently propagate north beneath the basin, and rule out this hypothesis.

Slices of *S*-velocity models NA04 and IL05 are also plotted at 60 km, and 100 km depths as shown in Fig. 7. It is observed that at shallower depths, the Illinois basin has slower modeled *S*-velocities than its immediate surrounding region, with maximum velocity differences centered in the central Illinois basin, near the south-central border of Illinois and Indiana. At a 60 km depth, we observe that IL05 models slower upper mantle anomalies than NA04. Beneath 100 km depth, differences between the two models' upper mantle velocity structures are minimal.

4.1. Resolution tests

We performed several resolution tests to verify the robustness of IL05 (Fig. 8), and to demonstrate that the observed anomaly is not an artifact. To do so, we tested the ability of the IL05 data set to retrieve a synthetic structure, similar to what we observe in the Illinois basin. We first created a synthetic crust and upper mantle *S*-velocity structure with a slower upper lithosphere to 90 km depth surrounded by a faster lower lithosphere (Resolution Test A in Fig. 8). Fig. 8 shows two profiles for this resolution test, demonstrating the ability of the IL05 data set to retrieve a synthetic structure consisting of a slow crust and uppermost mantle above a fast lithosphere. We then assumed a fast,

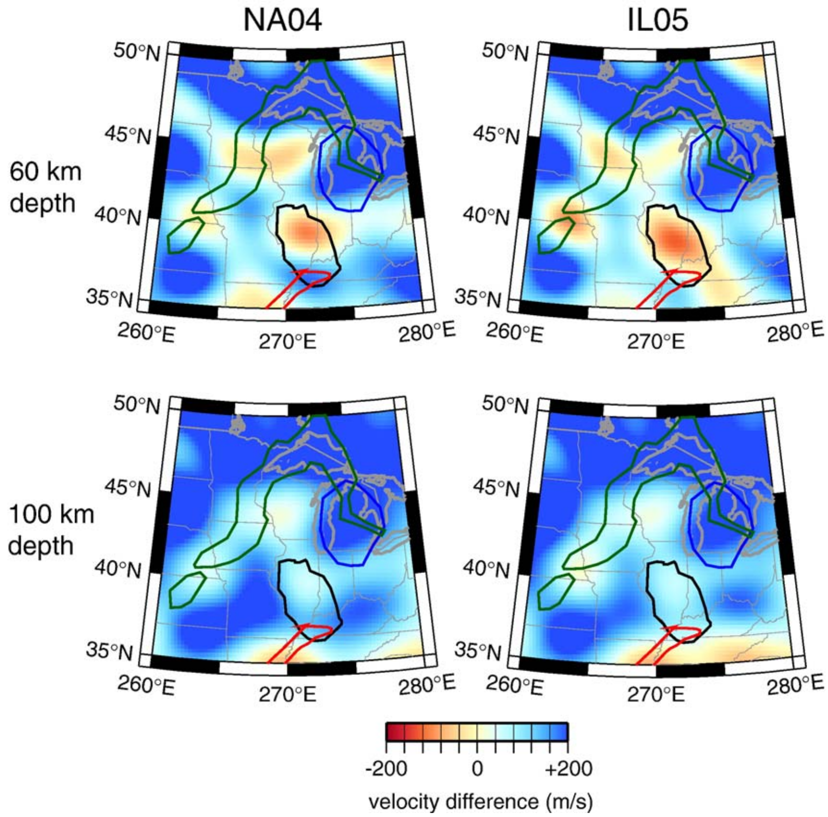

Fig. 7. This figure shows slices of the upper mantle *S*-velocity at constant depths of 60 km and 100 km, for two models: NA04, and IL05 (Illinois events fitted with IL43 models and the NA04 constraints). The Illinois basin is outlined in black, the Michigan basin is outlined in blue, the mid-continent Rift is outlined in green, and the Reelfoot Rift in red.

solid lithosphere, as can usually expected in an old cratonic region, such as the area surrounding the Illinois basin (Resolution Test B in Fig. 8). We chose to test such a structure, in order to see if the IL05 data set contained gaps which would model a slower upper- and mid-lithosphere in the presence of a homogeneous fast lithosphere. As seen in Fig. 8, the IL05 constraints model no such gap, as the resolution test images a solid fast lithosphere as the output model. By this method, we demonstrate that no artificial zones of low velocities are imaged using the IL05 data set, and that the *S*-velocity anomaly modeled in the mid-lithosphere is real.

4.2. Predicted traveltimes

To further test and compare the 1D models with IL05, we collected P and S arrival times from smaller magnitude events that occurred within or very close to the Illinois basin, including the events used in the creation of the model IL05. Using only seismic stations and their waveforms that had ray paths almost entirely within the Illinois basin, we compared the traveltimes predicted from the models to the observed arrivals of the primary *S*-wave. To calculate traveltimes, we used the TauP Toolkit (Crotwell et al., 1999), which required a 1D input velocity model. To represent the 3D model IL05, we calculated an average 1D model of the entire Illinois basin region, which is shown in Fig. 4.

For these ray paths, which intersected the region below the Illinois basin, IL05 predicted the *S*-wave arrival time better than the two 1D models, MC35 and IL43s (Fig. 9). The IL43s S-arrivals match the observed arrivals better than MC35, but not as well as the 1D model based on IL05. This test of model IL05, employing independent local traveltime data, demonstrates that IL05 is a viable three-dimensional model for the Illinois basin structure.

4.3. Predictive capability

A posteriori synthetic seismograms were calculated for the three-dimensional models NA04 and IL05 in order to further evaluate the reliability of the differences in *S*-velocity structure observed between the 3D models.

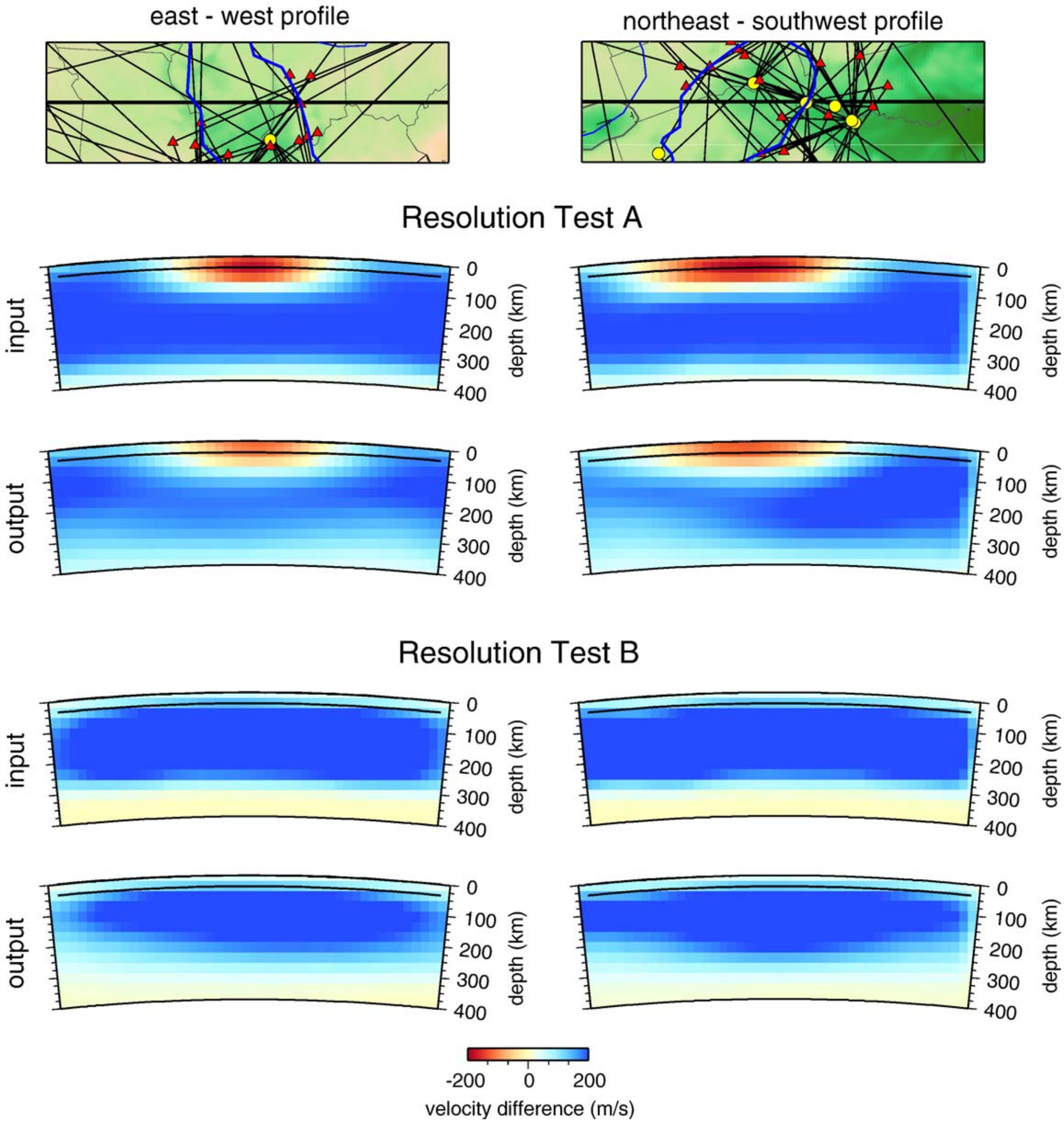

Fig. 8. Resolution tests performed on model IL05. The input panels show two resolution tests. Resolution Test A assumes a synthetic slow upper- and mid-lithosphere beneath the Illinois basin, surrounded by a faster, more typical, cratonic lithosphere; which is retrieved by the model constraints. Resolution Test B assumes a homogeneous, typically cratonic lithosphere, which is retrieved. The output panels show how these structures would be imaged after an inversion using the IL05 data set.

These synthetic waveforms were compared to waveforms from the regional earthquakes used in this study. Fig. 10 displays waveforms calculated with different three-dimensional models for several event-station paths. These synthetic seismograms were calculated using mode summation of the 1D averaged earth structure from the source to the receiver as modeled in each of the three-dimensional models. As shown in Fig. 10, for the event KY060603, model IL05 shows an improvement in phase over NA04, while neither models the amplitude well. While we are not attempting to match amplitudes, the amplitude difference is probably due to the energy radiation pattern of the seismic event. For event AR050105, again, the IL05 synthetics match the observed waveform more accurately than NA04. The consistently better predictive capabilities of model IL05 over model NA04 demonstrates that improvements in modeling local earth structure can be obtained by incorporating smaller,

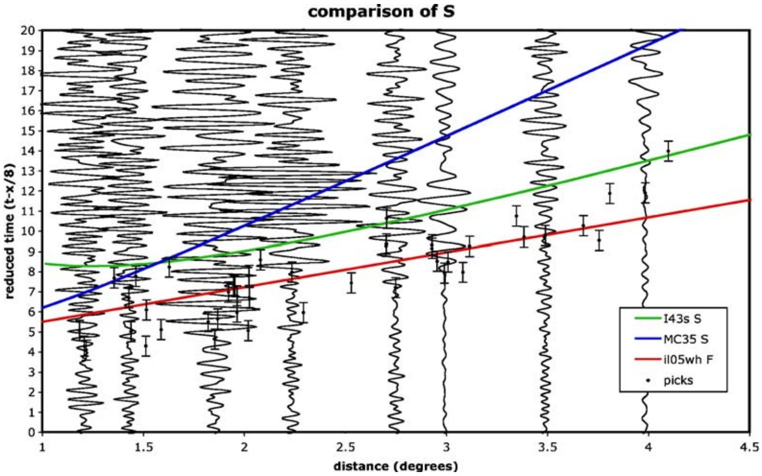

Fig. 9. Record section plot showing some of the waveforms (grey) used in the traveltime study. *S*-wave arrival picks and error bars for all waveforms analyzed are shown as black circles. Predicted traveltimes for different 1D models are shown: MC35 (blue), IL43s (green), and IL05 averaged over the Illinois basin (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regional earthquakes, and that the mid-lithosphere velocity anomaly is required in the model in order to fit the data.

4.4. MC35 test

Another test was performed to determine how the addition of *a priori* knowledge of regional crustal velocity structure affects model results. TM15 is the 3D *S*-velocity model that was calculated when the waveforms were fit with precisely the same method as used in NA04, using MC35 as a background one-dimensional model. When compared to NA04 and IL05, TM15 models a faster crust, but the upper mantle anomaly remains. We also computed predictive waveforms, which further show that using a regional crustal structure in the waveform fitting process, as done to create IL05, does slightly improve the final three-dimensional model in its predictive capability (Fig. 11). Thus, using regional, smaller earthquakes, and more representative crustal structures does improve the resultant three-dimensional *S*-velocity models, as shown by the predictive capability of IL05 over TM15. We find that incorporating smaller regional data sets with larger continental-sized data sets does prove to be a useful technique in imaging smaller regions within the continent.

5. Discussion

Over the last 25 years many hypotheses have been presented that attempt to explain the formational mechanisms of the Illinois basin. Sleep et al. (1980) proposed that Illinois basin subsidence was the result of a single, local, thermal subsidence event in the Late Cambrian through Early Mississippian. Braile et al. (1986), among others, suggested that the Illinois basin began its formation as a rift-basin over the Reelfoot Rift in the late Precambrian. Another theory (Heidlauf et al., 1986) suggested that the Illinois basin formed initially through fault-controlled subsidence from the Late Precambrian through Late Ordovician and then developed further through thermally controlled subsidence from the late Ordovician through the Middle Mississippian. Unfortunately, none of these hypotheses satisfactorily explain the nearly oval uppermost mantle *S*-wave velocity anomalies observed in our seismic studies; nor, do they account for the Mesoproterozoic deposition of layered sequences (Pratt et al., 1992; McBride and Kolata, 1999; McBride et al., 2003), for which the deposition center of these Mesoproterozoic sequences is centered in east-central Illinois and west-central Indiana. In addition, the Heidlauf et al. (1986) hypothesis does not account for the observed second episode of Illinois basin subsidence that lasted from the Middle Mississippian through the Early Permian. Interestingly, this Proterozoic deposition center is centered directly above the slowest region of the seismic anomaly imaged by IL05.

A possible source of error into the waveform fitting process would be a large anisotropic signal within the mantle fabric of the Illinois basin study region. But, the *S*-wave anisotropy within the Illinois basin has been found to be relatively small (Gaherty, 2004); thus, the *S*-velocity results observed in our tomographic study cannot be attributed to anisotropic errors in our waveform fitting process.

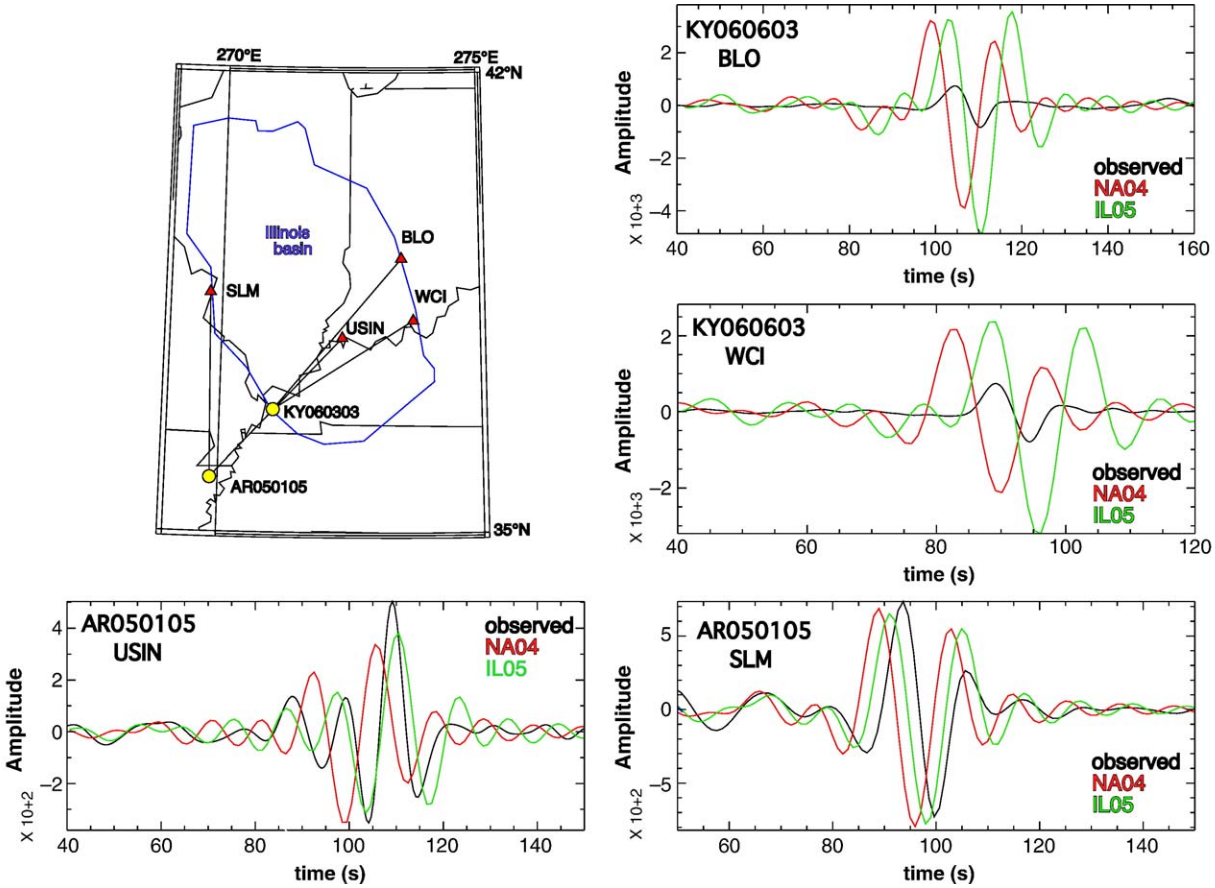

Fig. 10. Seismograms calculated for the June 06, 2003 Kentucky earthquake (KY060603) received at stations BLO in Bloomington, IN, and WCI in Wyandotte Cave, IN; as well as seismograms for the May 01, 2005 Arkansas earthquake (AR050105), received at stations SLM in St. Louis, Missouri, and USIN at the University of Southern Indiana. Raw waveform data is in black, NA04 in red, and IL05 in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The appearance of the *S*-velocity anomaly in our tomographic model demonstrates that there is a definite difference in the upper mantle structure inside and outside the Illinois basin. In general, low *S*-velocities, such as those imaged in the mid-lithosphere beneath the Illinois basin, are attributed to thermal anomalies and/or compositional differences between this region and the surrounding North American cratonic lithosphere.

Heat flow measurements can provide us with information about the temperature within the lithosphere below the Illinois basin. Blackwell and Richards (2004) show that observed heat flow within the Illinois basin is minimally elevated as compared to outside the basin. The isolation of the anomaly suggests that potentially warm mantle material from beneath the Reelfoot Rift has not been carried to the Illinois basin mantle. Heat from thermal events associated with formation of the basin more than one billion years ago would have completely dissipated away over this long period. These three considerations suggest that our modeled *S*-velocity anomaly is the result of a compositional and or/ mineralogical anomaly in this region of the mid-lithosphere.

5.1. Upper mantle compositional anomaly

Other evidence for compositional/mineralogical upper mantle heterogeneity beneath the Illinois basin region has been detected during seismic reflection studies (McBride, 1999). Using reprocessed seismic reflection data, McBride (1999) found dipping reflectors in the sub-Moho mantle beneath the Illinois basin. These types of seismic reflections are typically ascribed to compositional or mineralogical differences within the mantle fabric. For example; upper mantle reflectors have been attributed to several mechanisms associated with several types of heterogeneities within the upper mantle; (1) subduction

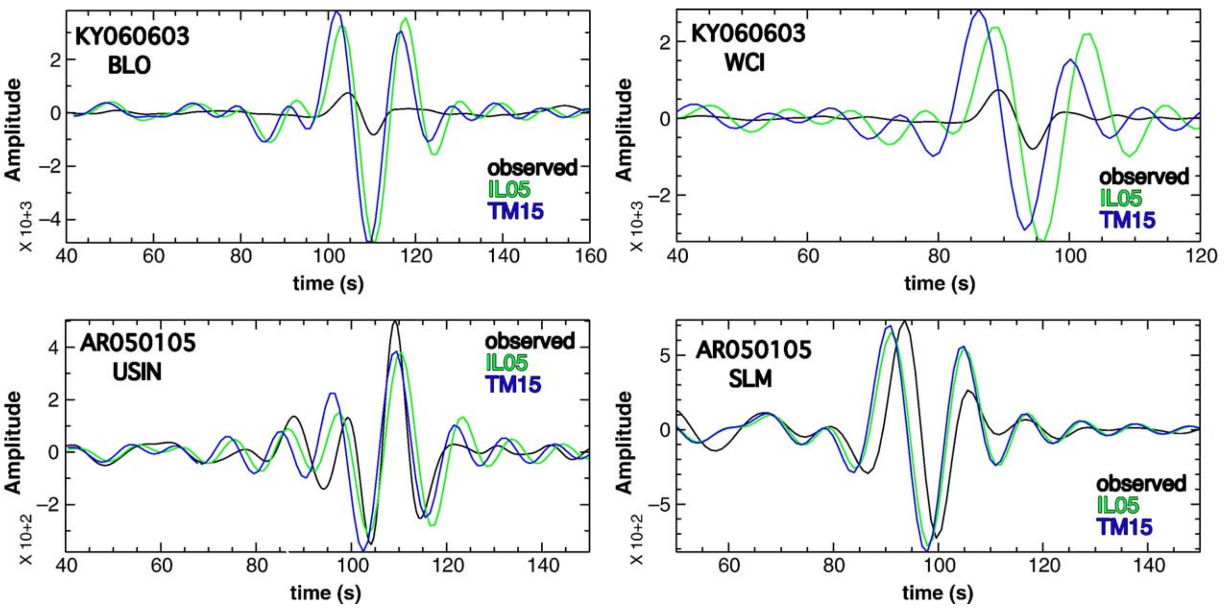

Fig. 11. Synthetic seismograms calculated for the same events and stations as shown in Fig. 10. Raw waveform data is in black, IL05 in green, and TM15 in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

remnants; (2) mafic intrusions in the upper mantle; (3) alterations in the rheological environments within the lithospheric mantle; (4) lithospheric thinning (McGeary and Warner, 1985; Warner and McGeary, 1987; Lie et al., 1990; Snyder and Flack, 1990; Calvert et al., 1995; Caress, 1995; Knapp, 1996; Cook et al., 1999; Balling, 2000; Yang, 2003). Since the Illinois basin region was once located on the southern edge of Laurentia, the sub-Moho dipping reflectors observed by McBride (1999) may represent heterogeneity in the upper mantle in the form of a fossilized subducted slab, as terranes subducted beneath and accreted onto the edge of the continent during the Proterozoic (Okure, 2005). However, alternative explanations have been offered for the unusual mantle reflectors in the form of lithospheric alteration/delamination caused by its interaction with deep mantle material brought up by a weak plume (McBride and Kolata, 1999; McBride et al., 2003; Okure, 2005). The nature of the plume would be weak in view of the geologically inferred degrees of melting (Menuge et al., 2002; McBride et al., 2003). And, as we model a deep cratonic lithosphere beneath the anomaly, we rule out lithospheric delamination, as proposed by McBride (1999) to explain the sub-Moho reflectors beneath the Illinois basin.

5.2. Subduction or mantle plume?

A deep mantle plume could refertilize the mid-lithosphere in depleted elements, such as Fe. The effects of Fe on *S*-velocity are disputed, but they are not negligible (Jordan, 1979; Lee, 2003), as Fe enrichment works to lower the *S*-velocity (β). At the same time, the Fe enrichment would increase the density of the refertilized lithosphere, possibly explaining a +200 to +250 mgal residual compositional gravity anomaly over the Illinois basin region, deduced by Kaban et al. (2003). Using $d\beta/dMg\#$ relations from Jordan (1979) and Lee (2003) and a drastic Mg# drop of eight, we find that Fe-enrichment of the uppermost mantle cannot account for more than half of the observed *S*-velocity anomaly in the Illinois basin region. This failure of iron enrichment to explain our *S*-velocity anomaly enhances the probability that some of the seismic slowness may be caused by the presence of hydrogen in the mantle. This hydrogen could have been brought up by the same refertilizing deep plume and would also work to lower the *S*-velocity, mostly through its enhancement of attenuative properties (Karato and Jung, 1998).

The basement rock of the Illinois basin region, the eastern granite–rhyolite province, is a region of undeformed and unmetamorphosed Mesoproterozoic igneous rocks, which are believed to have formed due to the melting of the lower crust (Hoppe et al., 1983; Bickford et al., 1986; Lidiak et al., 1993; Van Schmus et al., 1996). A recent geochemical isotopic and trace element analyses of the eastern granite–rhyolite province (Menuge et al., 2002), found that it is most likely that the magmas that formed this province were primarily formed by partial melting of preexisting crustal rocks in a back-arc setting rather than a plume setting. Menuge et al. (2002) attributed the heat source for the melting of the lower and middle crust to the thinning and extension of the lithosphere within the continental back-arc setting, which eventually led to the emplacement of the eastern granite–rhyolite province, possibly through the rhyolitic caldera complex as proposed by McBride et al. (2003). Subduction, however, in general tends to deplete the over-riding mantle through partial melting of the mantle wedge, as triggered by dehydration of the subducting oceanic crust. This depletion (including dehydration) process would ultimately yield a seismically fast mantle, which we do not observe. But if subduction beneath the Illinois basin region occurred at relatively flat dip angles, potential slab dehydration in the flat zone would not have triggered partial melt and dehydration in the overlying shallow and relatively cold mantle (Kay and Kay, 1993; James and Sacks, 1999). Furthermore, wet oceanic crusts that are subducted to uppermost mantle depths would contain hydrous metabasalts, which have significantly lower *S*-velocities than typical mantle peridotite (Peacock, 1993; Helffrich, 1996; Connolly and Kerrick, 2002). If the flat subduction zone fossilized in such a state, the average uppermost mantle velocities that we image should reflect the average elastic properties of a mixture of continental lithosphere, which is possibly somewhat hydrated, with subducted oceanic, hydrated crust, which would provide the bulk of the *S*-velocity lowering conditions that we infer beneath the Illinois basin. We thus suggest that the imaged low *S*-velocity in the mid-lithosphere beneath the Illinois basin most likely represents a fossil flat-slab subduction zone.

5.3. Fossil flat subduction

The observed IL05 anomalous feature must be related to compositional and/or mineralogical difference in the mantle fabric. With abundant evidence that this region was a subduction zone in the Proterozoic, it is most likely that the modeled mid-lithospheric seismic anomaly can be explained by the presence of an unusual crust–mantle mixture related to a fossil subduction zone.

Shallowly subducted oceanic crust would likely be hydrous, and at the mid-lithospheric depths, would be in the form of seismically slow hydrous metabasalts, such as lawsonite blueschist and lawsonite eclogite (Helffrich, 1996; Connolly and Kerrick, 2002). The seismic velocity contrasts (~7% slower) of such metabasalts with mantle peridotite (Helffrich, 1996; Connolly and Kerrick, 2002) imply that about 15% of the inferred crust–mantle mixture beneath the Moho would be of a hydrous crustal composition. The remaining 85% of the anomalous region would then be of a mantle peridotite composition. As our anomalous zone is roughly 50 km thick, roughly 15% of it would correspond to a layer with a thickness of 7–8 km, which is close to the thicknesses of the present oceanic crust. Thus, if oceanic lithosphere subducted at a sufficiently shallow dip angle for its crust to remain hydrous, and subsequently was incorporated into the lithosphere of the over-riding plate, our seismic observations would be accounted for. Alternatively, our observations would also be accounted for if the subducted crust hydrated the overlying mantle, reducing its *S*-velocity without generating partial melt, thus trapping the water in the mantle lithosphere. Therefore, based on our seismic model, IL05, in the context of other geophysical and geochemical studies, we propose that the upper mantle beneath the Illinois basin contains a fossil flat subduction zone.

Whether or not this upper mantle heterogeneity or its possible cause, in the form of a flat subduction zone, is related to the original formation of the intracratonic Illinois basin remains an open question. Studies of present or recent flat subduction zones may constrain how subcontinental mantle is modified by the flat-subduction process, and which of these modifications has potential for longevity and/or basin formation.

6. Conclusion

Employing seismic tomography techniques and combining local with regional waveform data, we confirm a mid-lithospheric region (sub-Moho to about 90 km) beneath the Illinois basin region with *S*-velocities about 200 m/s slower than for the surrounding North American craton. This low *S*-velocity anomaly is resolved and is not found beneath other major North American interior cratonic basin. It is possible that the likely cause of the anomaly is somehow responsible for the original formation of the Illinois basin in the Proterozoic, and thus differed from the mechanisms that caused the other North American intracratonic basins to form. However, we cannot rule out that our observations are unrelated to basin formation.

We find that we cannot explain this seismically slow region through elevated mantle temperatures. We rule out the hypothesis of a delamination origin for Illinois basin subsidence. While we cannot rule out a potential deep-mantle plume, we do not deem the scenario likely in the context of geological, geochemical, and other geophysical studies of the region. We find that the anomaly is most straightforwardly explained by an unusual crust–mantle mixture, where either 1.) oceanic crust became incorporated in the mantle of an over-riding plate during a Proterozoic episode of flat-slab subduction, or 2.) a relatively cool mantle wedge is preserved with hydrous minerals. In either case a flat dip-angle is necessary to avoid slab dehydration and associated partial melting of the mantle, which would deplete the mantle and eventually result in a seismically fast lithosphere. Thus, we conclude that the upper mantle beneath the Illinois basin region most likely represents a fossilized flat subduction zone, which may or may not be related to the subsidence of this intracratonic basin.

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