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# Upper mantle surprises derived from the recent Virginia earthquake waveform data

Risheng Chu *, Don Helmberger, Michael Gurnis

*Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*

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A B S T R A C T

Recent high resolution regional waveform modeling reveals that the lithosphere beneath the North American craton is subdivided into an upper nearly uniform layer and a lower layer with a high velocity gradient. The boundary occurs at about a depth of 115 km and is responsible for 8° discontinuity in seismic record sections that is often observed in craton environments. Unexpectedly, we find seismic velocities in the lower layer significantly reduced along a corridor from the New Madrid rift zone to Virginia. This reduced velocity in the lower lithosphere may be associated with a possible historic hotspot activity. We also find a well developed X-discontinuity that we model as a ∼3% increase in *P* velocity starting at a depth of ∼290 km. These anomalous features transition into a nearly 1D craton structure to the north with a strong low-velocity anomaly just above the 410 discontinuity along an east–west boundary. The latter two features may be relics of structures formed from the descending Farallon plate between Late Cretaceous and Early Tertiary.



## 1. Introduction

Although the lithosphere–asthenosphere boundary (LAB) plays an essential role in plate tectonics, it proves difficult to image (see review by Fischer et al., 2010). As the extensive US Array Transportable array (TA) moves across the United States, we are gaining enormous insight into the complexity of both continental lithosphere and upper mantle compared to the Pacific Basin (Tan and Helmberger, 2007). Their results support the earlier studies by (Gaherty et al., 1999) that argues for a fairly uniform structure beneath the Pacific Basin with relatively thin lithosphere (80 km) overlaying a strong low-velocity layer (Fig. 1A), although this remains somewhat controversial (Ritzwoller et al., 2004). However, the upper-mantle structure beneath the Pacific displays strong anisotropic features, as widely accepted (Nettles and Dziewoski, 2008).

In contrast to the simplicity of the Pacific lithosphere and upper mantle, tomographic studies of western United States from TA data reveal a large range of complex structures where the upper-mantle structure appears to have more vertical than horizontal layering (e.g. Schmandt and Humphreys, 2010). Using regional *P*-wave data, (Chu et al., 2012a) revealed that the lithosphere thickness is relatively thin with the lowest velocities in the mantle occurring at shallow depths (110 km) (Fig. 1B), similar to earlier studies using SH-waveform data (Grand and Helmberger, 1984). The latter study derived two 1D models, TNA for the tectonic region west of the Rocky Mountain Front and SNA for the stable North American craton. SNA has a thick lithosphere (180 km). The large difference in lithosphere thickness regionally may explain why hotspot tracks are quite evident beneath the Pacific and western United States (Hawaiian chain and Snake River Plain) and less evident for the eastern United States.

The TA is now in the midwest US where the structure is close to 1D and the triplicated waveform data is better behaved (Chu et al., 2012b). The events used in their study are plotted along with the recent Virginia event (Fig. 2). The deep Quebec event had a relatively strong *sP* phase which was used to model the upper-mantle triplications. By stacking the data, excluding stations in Texas, they observe a simple 1D structure displaying a strong CD branch and a late AB branch extending beyond 25° indicating a low-velocity layer near a depth of 200 km, compatible with the SNA model (Fig. 1A). Three smaller earthquakes were used to investigate the lithosphere structure. A mid-lithosphere discontinuity was found at about 115 km (Fig. 1B). This two-layer lithosphere structure produces an 8° discontinuity (Thybo and Perchuc, 1997), where $P_n$ from the upper lithosphere gives way to *P* from the lower lithosphere. In short, *P*-waveform modeling reveals distinct lithosphere structures beneath the North American craton. Moreover, if the low-velocity layer below 180 km in model CR is associated with the LAB, the lower lithosphere structure could track the temporal emplacement of kimberlites as suggested by Heaman et al. (2004).

* Corresponding author. Tel.: +1 626 395 2439.
*E-mail addresses:* chur@gps.caltech.edu, risheng.chu@gmail.com (R. Chu).

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Unfortunately, reference models used in tomographic inversions do not contain lithosphere structure which is probably the most important feature in defining plate structure. However, it appears that regional modeling of body waves with their horizontal ray paths has advantages on detecting the LAB over teleseismic vertical ray paths, commonly used in tomography and receiver function studies in defining the uppermost mantle and lithosphere structure. But modeling seismic data involving regional triplications proves difficult, especially in tectonic provinces.

Besides the LAB and well-studied discontinuities near 410 and 660 km, there are many reports of a sporadic X discontinuity near the depths of 250–350 km. This discontinuity has been observed mainly beneath continents (Massé, 1973; Xu et al., 1998), subduction zones (Revenaugh and Jordan, 1991; Zhang and Lay, 1993; Kelly and Schmerr, 2010), and perhaps the Pacific super swell (Bagley and Revenaugh, 2008; Deuss and Woodhouse, 2002). Seismic studies indicate a *P*-velocity increase of about 2% across the X discontinuity (Massé, 1973). Several mechanisms have been proposed to explain this discontinuity, including a phase change from orthorhombic to monoclinic pyroxene (Woodland, 1998; Zhang et al., under revision), forsterite plus water to enstatite plus phase *A* transition in old plate subduction zones (Revenaugh and Jordan, 1991), forsterite plus periclase to anhydrous phase *B* (Ganguly and Frost, 2006), and coesite to stishovite or exsolution of stishovite from clinopyroxenes with excess silica (Williams and Revenaugh, 2005). These mechanisms are related to chemical and/or thermal variations in the upper mantle.

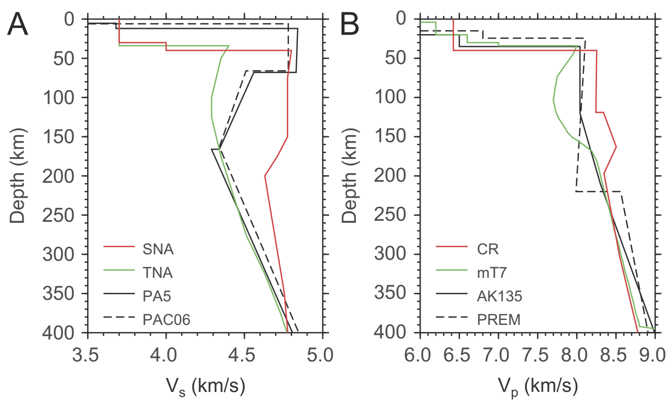


**Fig. 1.** 1D upper-mantle *S*- and *P*-velocity structures. (A) Comparison of *S*-velocity models for the Pacific Basin, PAC06 (Tan and Helmberger, 2007) and PA5 (Gaherty et al., 1999), and western (TNA) and eastern (SNA) North America (Grand and Helmberger, 1984). (B) Comparison of *P*-velocity models for the Basin and Range (mT7) (Chu et al., 2012a), the North American craton (CR) (Chu et al., 2012b), and two commonly used global average models PREM and AK135 (Dziewonski and Anderson, 1981; Kennett et al., 1995).

## 2. Data and modeling results

In this report we examine the TA dataset produced by the 08/23/2011 Mw 5.6 Virginia event (Fig. 3). An example of the *P* waveforms is displayed in Fig. 4 along the two azimuthal profiles at 10.5° and 13.5°. Because the earthquake radiated strong *P* waves and weak *S* waves at these azimuths, we have concentrated only on the vertical *P*-waveform displacements. Although we will discuss a more definitive method of determining the initial arrival times later, here we present visual (hand picked) estimates based on velocity records (red crosses, Fig. 4), similar to the initial arrivals used in travel-time tomography. The differences in travel times are pronounced with the stations within the New Madrid rift zone being especially late at the azimuths of about 280°. Note the differences in frequency content along paths to the west. Thus, we subdivided the data along profiles with Profile I having the earliest arrivals and II the latest (ditto for azimuths).

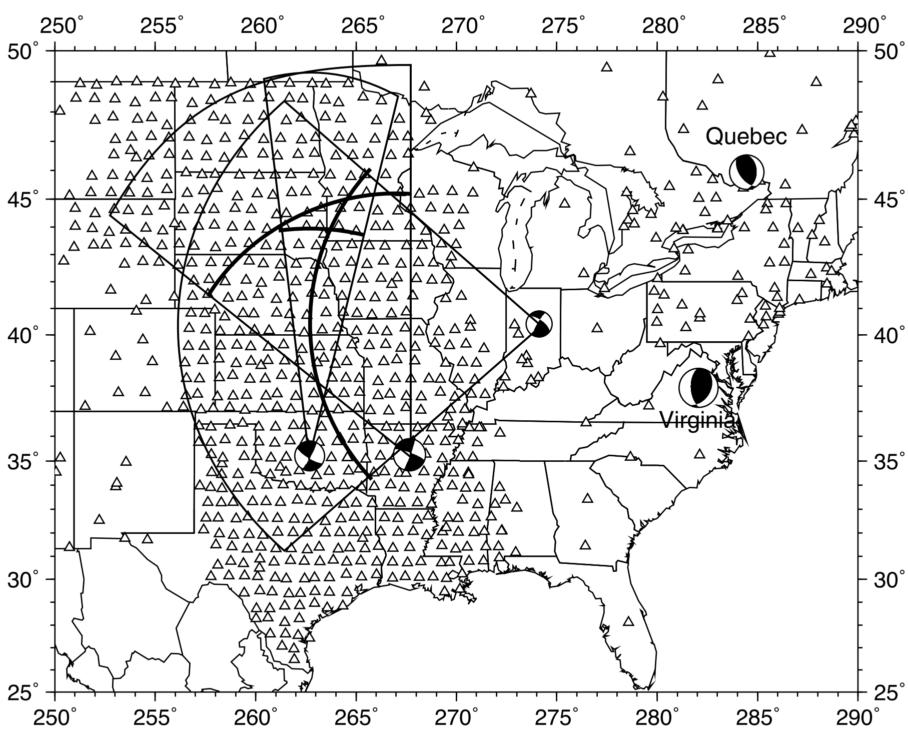


**Fig. 2.** Map of regional earthquakes and seismic stations (triangles) used to derive upper-mantle structures beneath the Midwestern United States. The fan plots display the station coverage provided by three regional earthquakes used to derive the lithosphere structure (Chu et al., 2012b). The thick lines denote the crossover of $P_n$ and *P*, indicating the 8° discontinuity, supporting the CR model displayed in Fig. 1.