Hidden hotspot track beneath Eastern United States

Risheng Chu, Wei Leng, Don V. Helmberger, and Michael Gurnis
Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

More than two thirds of surface hotspots associated with volcanism can be explained by the interaction between a moving plate and deep-seated mantle plumes. Most of these hotspot tracks are observed on oceanic or thin continental lithosphere. Although there are not many traditional hotspot tracks on old continents, there are diamondiferous kimberlites indicative of deep mantle origins. This poses the question that there could be many more hotspot tracks beneath old continental regions than suggested by the record of surface volcanism. Here we show that seismic waveforms recorded by USArray from a recent Virginia earthquake reveal an unexpected linear, lower lithosphere seismic anomaly extending from Missouri to Virginia without a clear relationship to surface geology. This east-west corridor has P velocity reduced by 2.1% along with high attenuation and crosscuts prominent regional features suggesting a link to plate motions. We suggest that a thermal plume-like upwelling interacting with the base of the continental lithosphere can produce the requisite seismic signal. A Late Cretaceous kimberlite in Kentucky, dated 75 Ma, pins a hotspot track that bends northward beneath Virginia. Seismic data indicates that the lower lithospheric anomaly along this northeastern segment is even stronger than the east-west segment, supporting such a hypothesis.

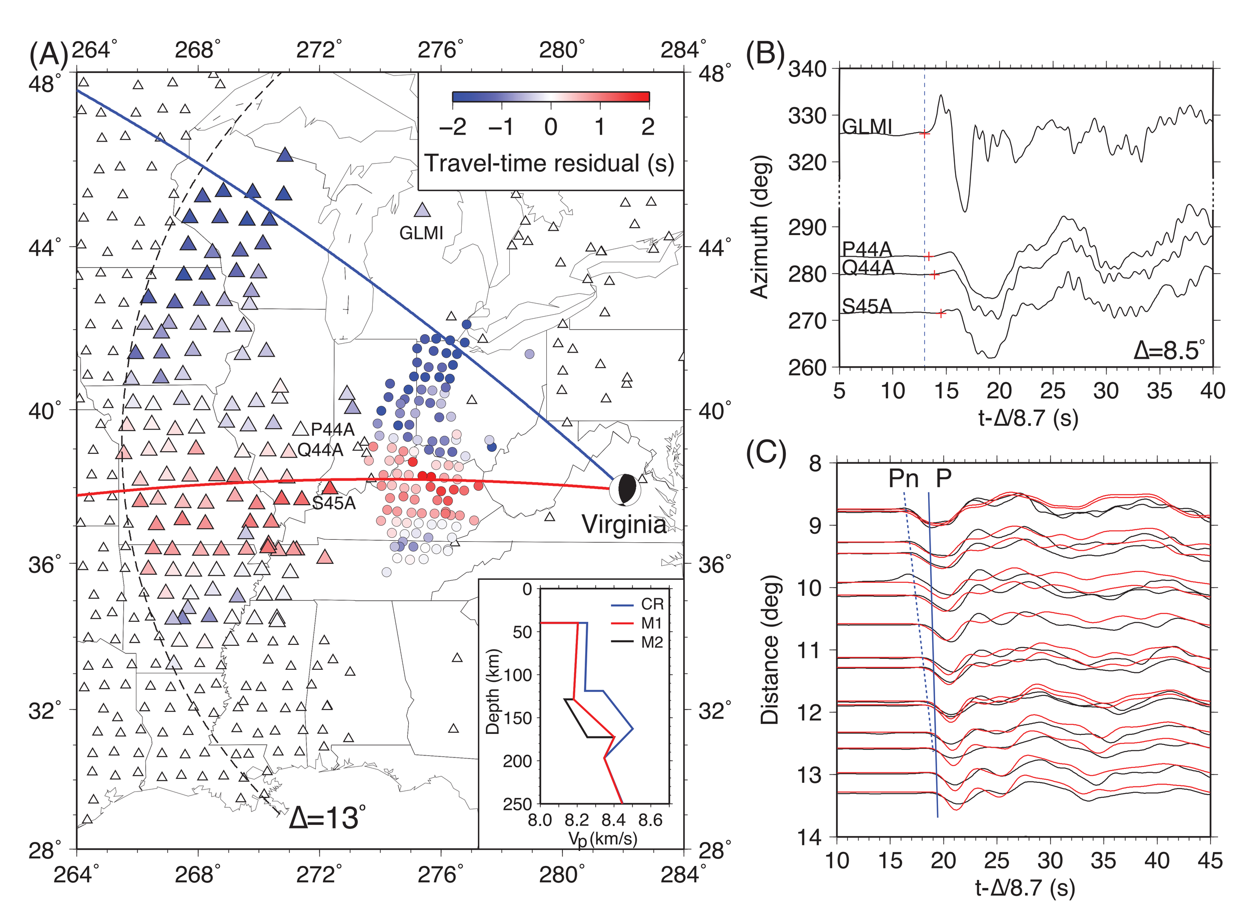

Fig. 1. Summary of seismic observations of the Virginia earthquake recorded by the TA stations (triangles). (A) The recordings along the red profile are broad and late with deficient short-period energy, compared to those along the blue profile (e.g. Q44A vs. GLMI in Fig. 1B). Both the travel-time residuals (color triangles) and the ratio of long-period and short-period amplitudes multiplied by the travel-time residuals (colored circles at the midpoints) delineate an east-west corridor. The model M1 (red in the inset) predicts good waveform fits for the corridor (Fig. 1C). The synthetics (red) display the interferences between Pn, traveling in the upper lithosphere, and delayed P in the lower lithosphere.

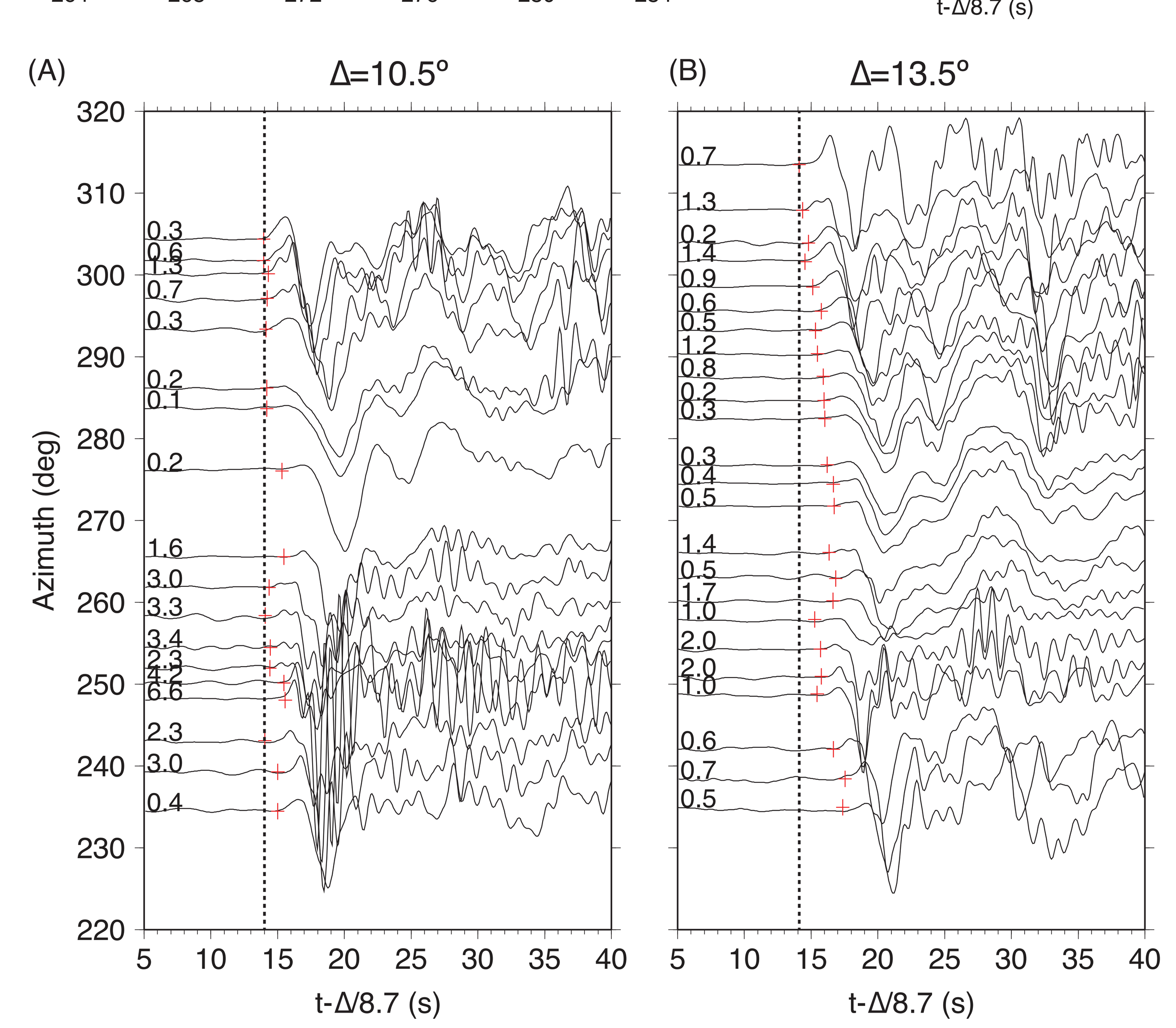

Fig. 2. Unfiltered vertical displacement recorded by TA from the Virginia earthquake at distances of 10.5° and 13.5°, respectively, as plotted in azimuth. The data is broken into distance intervals of 0.5° and the waveforms are plotted using a reduced velocity of 8.7 km/s. Red crosses denote hand-picked arrival times. Numbers above each waveform correspond to the amplitude ratio of short period (0.5-2.0 s) to long period (2.0-100 s). Note the short-period depletion near azimuths of 280°.

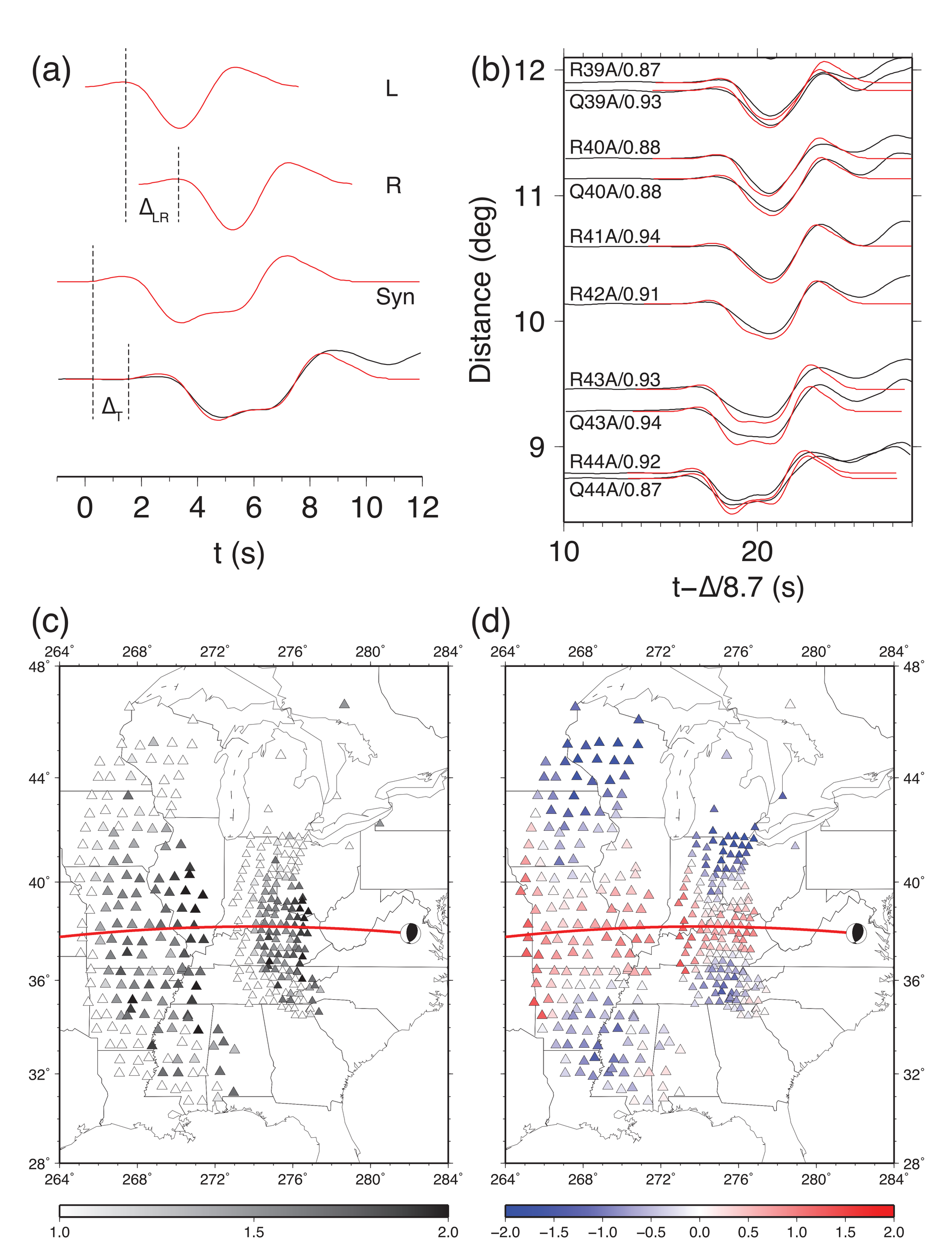

Fig. 3. Summary of multipath analyses. The methodology is reviewed in (a). The broadened waveforms can be estimated by two pulses with a splitting time Δ_T (a). Starting with the source time function, we search for the differential time Δ_{LR} and amplitude ratio C between the two pulses to fit the observed waveform broadening. The travel-time residual Δ_T is obtained by cross-correlating the synthetic waveform with the observation. Some examples are given in (b) with large separations at the smaller distances. The fits are measured with the cross-correlation given after station names. The results are displayed in (c) and (d). Because these delays are accumulative we also have included the values at the midpoints indicated by the small triangles. The red line denotes the proposed hotspot track.

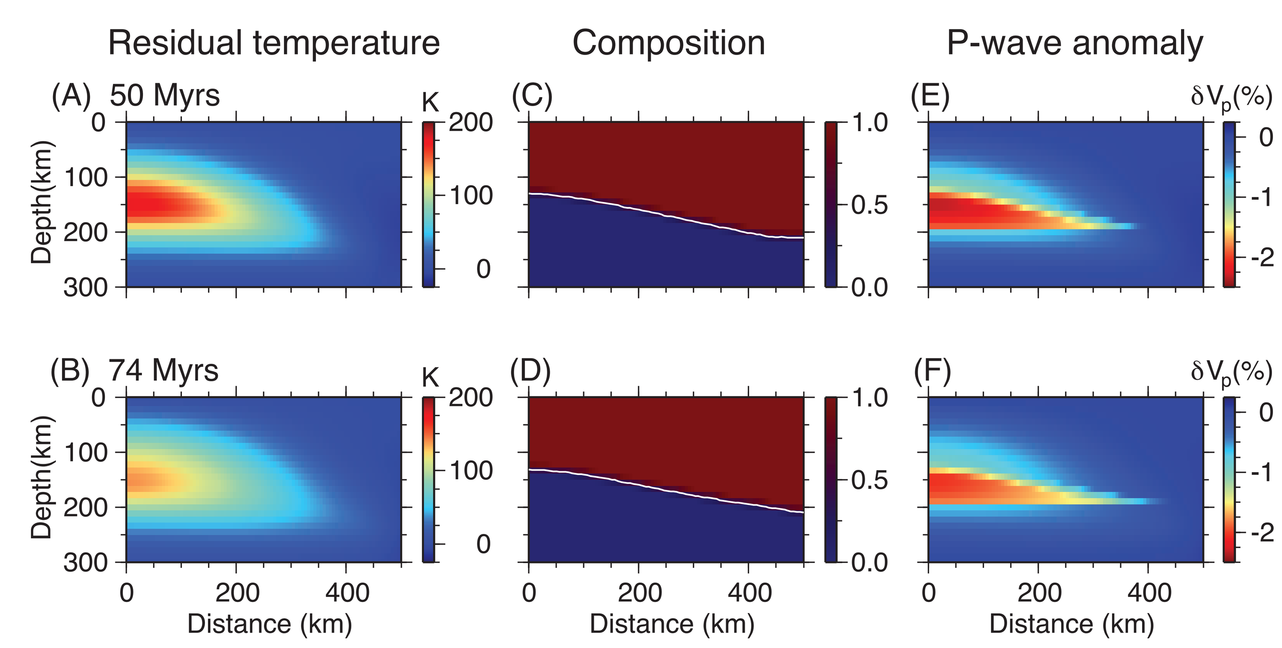

Fig. 4. (A) and (B) show the residual temperature (i.e. after horizontally averaged values subtracted) for the ponded plume material beneath the lithosphere after evolving for 50 Myrs and 74 Myrs. (C) and (D) show compositional fields with C=1 for lithosphere and C=0 for asthenosphere, corresponding to (A) and (B). The white lines show the compositional interface with C = 0.5. (E) and (F) show the P-wave anomalies from combined effects of temperature and composition. The x-axis label "Distance" represents the radial distance from the center of the plume.

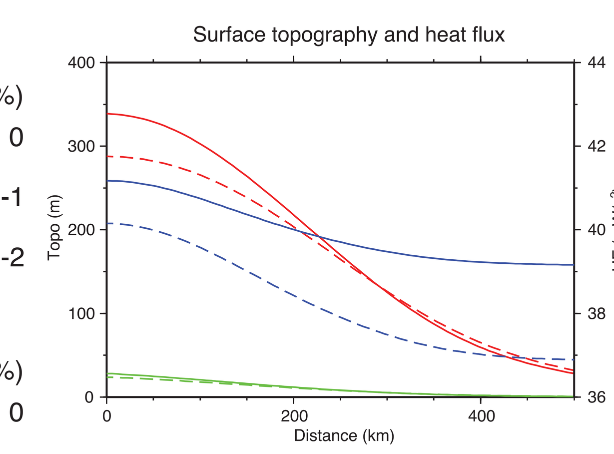

Fig.5 Topography without (red) and with (green) elastic forces together with heat flux (blue) at the surface for the ponded plume material after evolving 50 Myrs (solid) and 74 Myrs (dashed). The topography with elastic forces are computed with elastic lithospheric thickness Te = 200 km, Young's modulus E = 70 GPa, and Poisson's ratio v = 0.25.

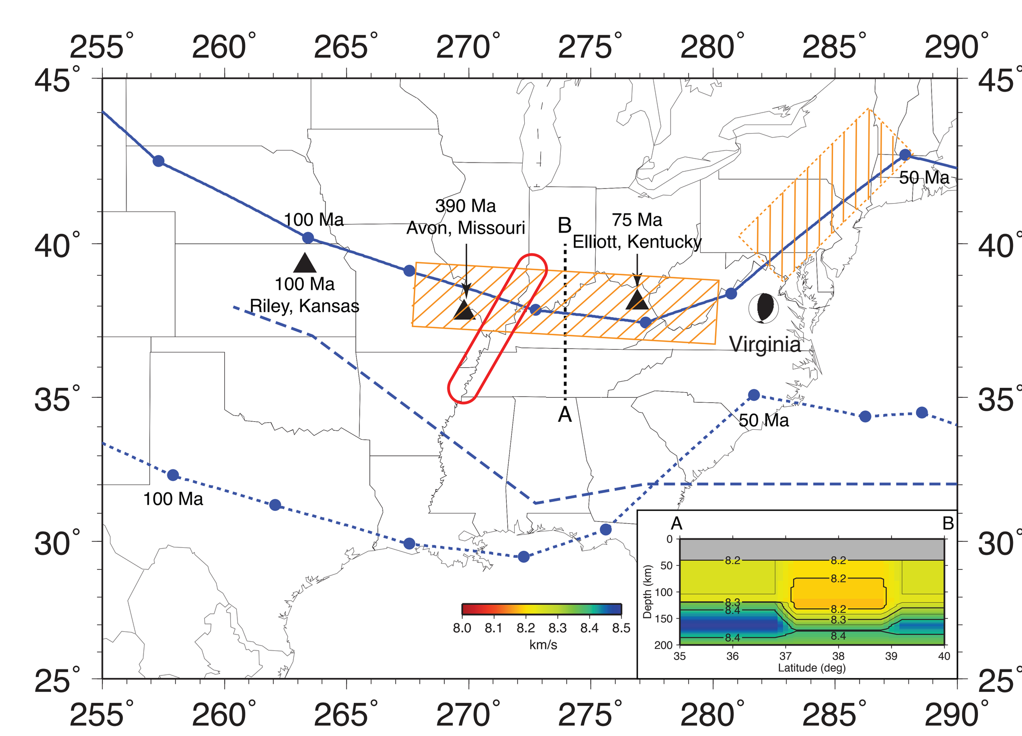

Fig. 6. Relationship of hidden lower lithosphere tracks, motion path of North American plate relative to the asthenosphere (blue lines), and surface features. Seismic anomalies are denoted by rectangular boxes. The inset shows a 2D north-south cross-section of seismic velocities for the east-west track with the lower lithosphere mostly eroded. The two tracks in the south are paths connecting to Bermuda; the dotted path is reconstructed using Seton et al., [2012] and the dashed path is taken from Cox and Van Arsdale [2002]. The red line is the boundary of the New Madrid rift complex. Black triangles denote kimberlite intrusions with age labeled.

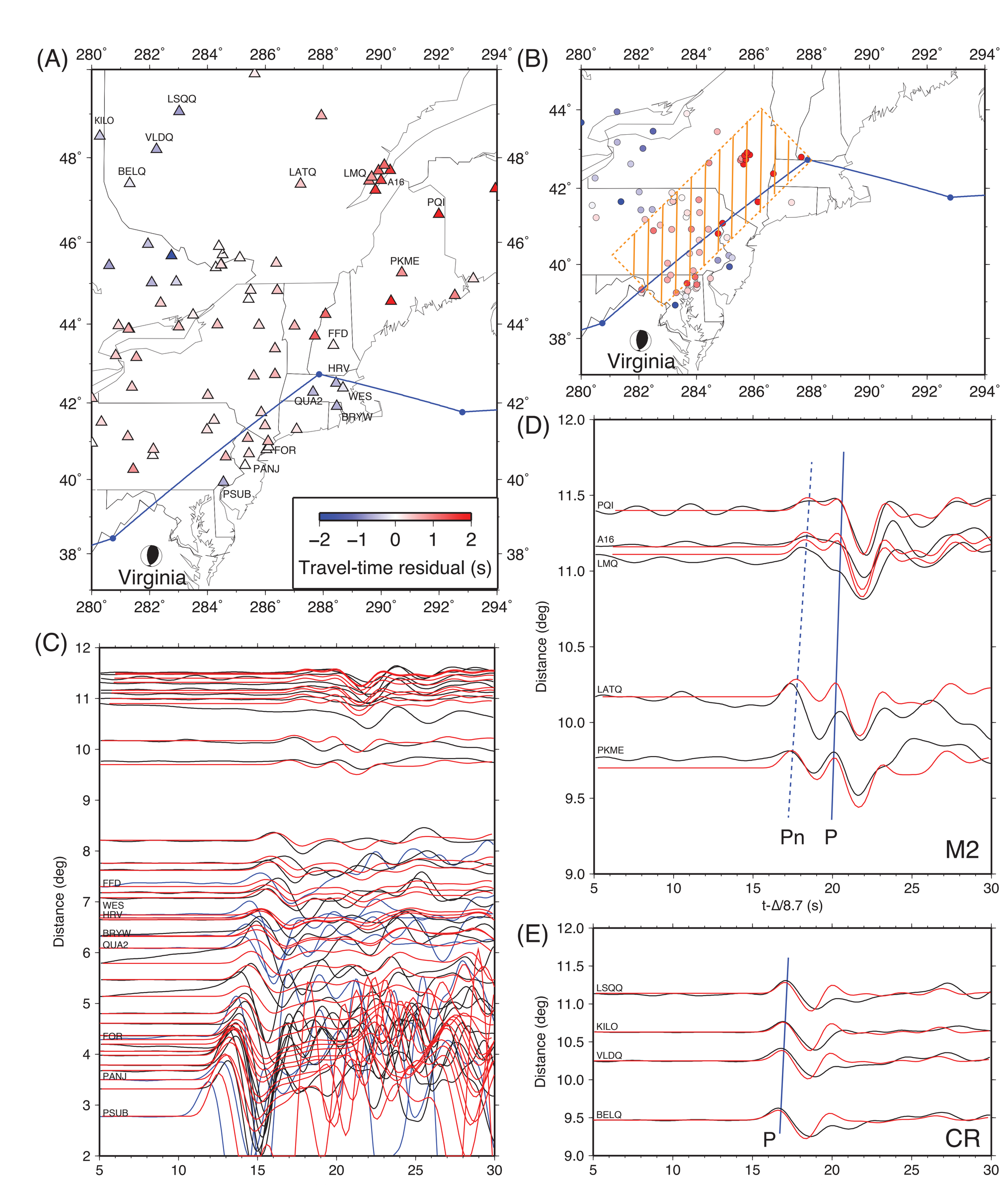

Fig. 7. Presentation of data and modeling along the northeast corridor. The travel-time delays relative to CR predictions and the product of Δt and long-period/short-period ratio are shown in (A) and (B), respectively. The blue line denotes the proposed hotspot track. The fits of data (black) and synthetics (red) for northeastern stations are shown in (C), filtered to 2-100 s. The velocity model is III displayed in Fig. 1. Waveforms between 9° and 12° are enlarged in (D) indicating two arrivals, Pn and P denoted by dotted and solid blue lines, respectively. For comparison, waveform fits for stations to the north, which are similar to CR, are shown in (E) with a single P arrival. The uncertainty is greater than the east-west section in Figure 1 because of lack of station density. However, the existing data along the corridor clearly displays a delayed P onset relative to paths along the northern direction indicative of a low velocity corridor.

References:

1. Chu, R., W. Leng, D. V. Helmberger, M. Gurnis. Hidden hotspot track beneath Eastern United States, Nature Geoscience, under review.
2. Chu, R., D. V. Helmberger, M. Gurnis. Upper mantle surprises derived from the recent Virginia earthquake waveform data, Earth Planet. Sci. Lett., in press.

Acknowledgment:
We thank the Gordon and Betty Moore Foundation for financial support.
(Email: chur@gps.caltech.edu)