# The NAA as Observed with S Wave Travel Times from Two Very High-Quality Teleseisms

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Summary: We use observations of S wave differential travel time anomalies of two very high-quality teleseisms, together with forward modeling with a simple earth model, to elucidate the basic properties of the Northern Appalachian Anomaly (Schmandt and Lin, 2014), a strong low-velocity zone beneath southern New England.

Selection of Teleseisms. Using the U.S. Geological Survey's Comprehensive Earthquake Catalog (ComCat), we identified two large teleseismic earthquakes: Earthquake 1, a magnitude 6.6 event near Etchropo, Mexico (occurring at 17:54:54 on 2013/10/19); and Earthquake 2, a magnitude 6.9 event near Kamariotissa, Greece (occurring at 09:25:02 on 2014/05/24). Hypocentral and origin time information were downloaded from the database and retained for later use. The back-azimuths from these events to a reference point at (45°N, 72°W) in northeastern North America are 55.1° and 251.5°, respectively. These directions are nearly anti-parallel. The corresponding body wave propagation paths do not cross the continent margin of Eastern North America, and hence should be unaffected by the poorly-known asthenospheric structure beneath the westernmost Atlantic Ocean.

Methods. We downloaded broadband seismic time-series, instrument responses and station coordinates from the Incorporated Research Institutions for Seismology's (IRIS's) Data Management System (DMS) for all stations in Northeastern North America that recorded the two earthquakes. Stations included, among others, those of the Transportable Array, the Canadian Seismic Network, the Lamont-Cooperative Seismic Network, the New England Seismic Network. The radial-component seismograms were interpolated to a uniform sampling interval of 0.01s, corrected for instrument response, band-pass filtered between 0.03-0.10 Hz, and windowed around the S-wave arrival time, as predicted by the AK135 earth model. Differential travel-times between pairs of stations were computed via cross-correlation and converted to a differential travel time anomaly $\Delta T_S$ by subtracting the differential time predicted by AK135 and removing the overall mean.

S Wave Differential Travel Time Anomalies. The Northern Appalachian Anomaly (NAA) is clearly depicted as a prominent region of late arrivals centered beneath southern New England (Figure 1). The amplitude of the anomaly is about $-6$ s relative to the cratonic region of central North America (e.g. Indiana). Profile E-F (Figure 1C), which is coastline-perpendicular, depicts the anomaly as smooth and with a width of about 400 km. Clear parallax is observed, with the center of the differential travel time anomaly of Earthquake 2 (with waves from the southwest) being displaced ~230 km in the direction N50°E from that of Earthquake 1 (with waves from the northeast).

Simple Forward Model. We modeled the differential travel time anomalies by ray tracing through a simple earth model consisting of a vertically-stratified reference model, adapted from AK135, with a superimposed Gaussian-shaped anomaly. Rays are started at 400 km depth with the azimuth and angle of incidence predicted by AK135, and propagated to the surface by solving the ray equation using second order Runga-Kutta integration. A single Gaussian, centered at 200 km depth, with a peak amplitude of $-0.75$ km/s, and standard deviations of 400, 300 and 100 km in the east-west, north-south and vertical directions, respectively, roughly fits the observations (Figure 2). This result confirms the findings of Skryzalin et al. (2015), who also analyzed parallax from teleseisms. The Gaussian shape poorly fits two aspects of the data: the parallax direction is predicted to be N65°E, which is 15° more easterly than is observed; and the flanks of the differential travel time anomaly decays with distance much faster than is observed. We have not been able to find any simply-shaped anomaly that exactly reproduces the observed parallax direction. One possibility is that the NAA has a more complicated shape than is apparent in the data; another is that some unmodeled aspect of wave propagation (e.g. anisotropy) is affecting travel times in a directional manner.

Comparison with the Porter et al.'s (2018) Velocity Model. In their discussion of the role of the NAA in perturbing the anisotropic structure of the upper mantle, Levin et al. (2017) refer to Porter et al.'s (2016) continental-scale model of shear wave velocity. This model has a relatively low-amplitude NAA (about $-0.2$ km/s with respect to the craton in the 150-200 km depth range) with a shape that is narrower in its east-west dimension than Schmandt and Lin's (2014) (~200 km as contrasted to ~400 km). We find that it underpredicts the observed delay of the NAA by about a factor of three (Figure 3D). The Porter et al. (2016) model may best resolve shallow structure, owing to its supplementation of body wave travel times with intermediate-period surface wave dispersion measurements. Consequently, we have examined whether a hypothetical "unresolved" lower asthenospheric anomaly could yield the observed delays. A compact but very intense anomaly at a depth of 400 km, with a peak amplitude of $-0.9$ km/s and standard deviations of 200,200 and 75 km in the east-west, north-south and vertical directions, respectively, can closely fits the Earthquake 1 observations (Figure 3F). However, because of its depth, it leads to parallax for Earthquake 2 of about ~630 km, which is much larger than observed. Hence, lower asthenospheric structure cannot be the source of the discrepancy; the parallax data indicates that the NAA is much more intense at mid-astenospheric depths than in the Porter et al. (2016) model.

References

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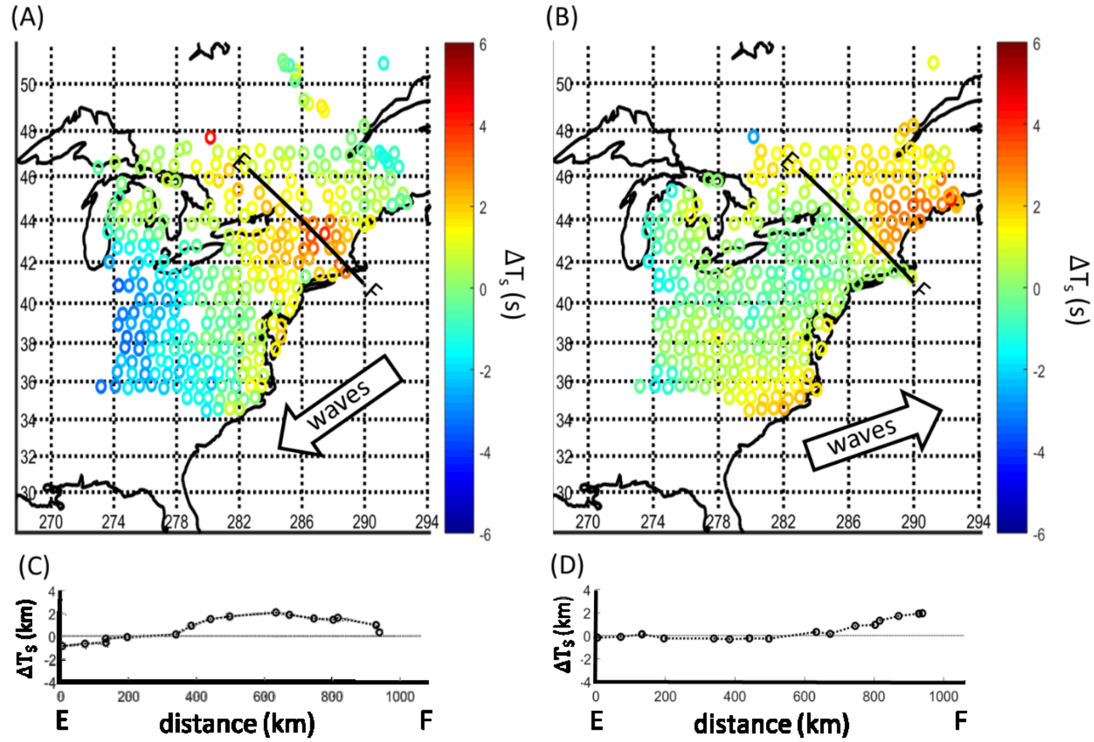


Figure 1. (A) Map showing S-wave differential travel time anomalies $\Delta T_S$ (colored circles) for Earthquake 1. The location of profile E-F and an arrow depicting the propagation direction of the waves are also shown. (B) Same as A, except for Earthquake 2. (C) Differential travel time anomalies $\Delta T_S$ for Earthquake 1, for stations close to profile E-F. (D) Same as C, except for Earthquake 2. The Northern Appalachian Anomaly (NAA) is the region of strongly positive $\Delta T_S$s (late arrivals) in southern New England.

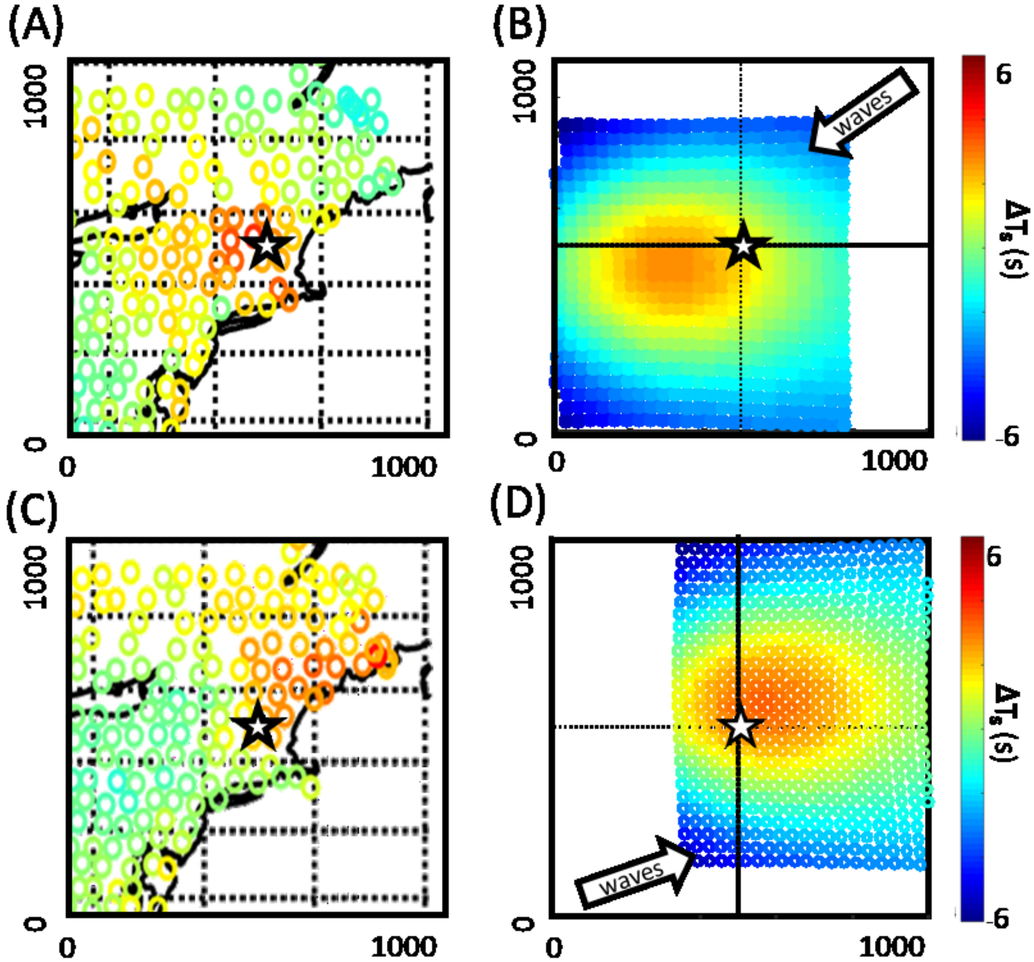


Figure 2. (A) Map showing observed S-wave differential travel time anomalies $\Delta T_S$ (colored circles) for Earthquake 1. A reference point in the center of the region is denoted with a star. (B) Corresponding predicted $\Delta T_S' s$, computed by tracing rays through a simple model of the upper mantle consisting of the vertically-stratified AK135 earth model with one Gaussian-shaped low-velocity anomaly superimposed. (C) and (D) Same as A and B, but for Earthquake 2.

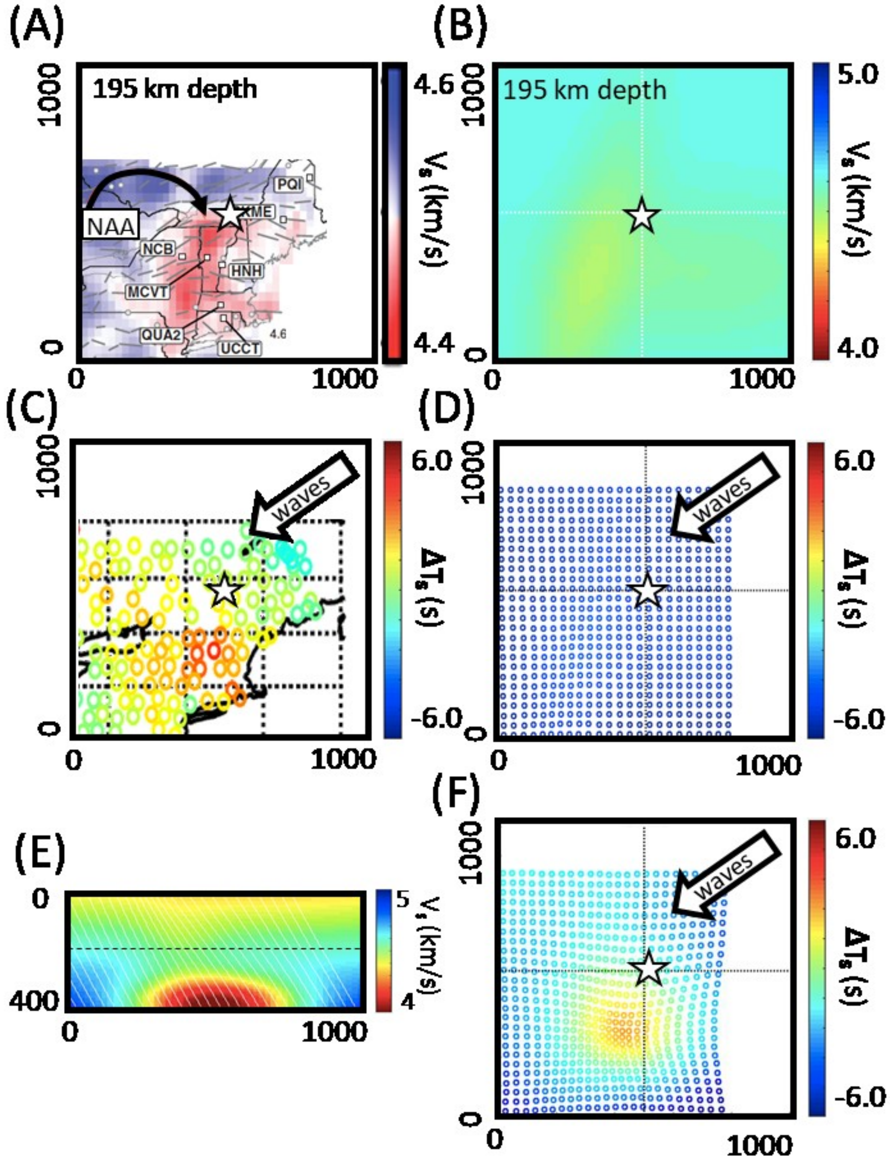


Figure 3. (A) Map showing Porter et al.'s (2018) shear velocity model at 195 km depth, with Levin et al's (2017) shear wave splitting directions (bars) superimposed (adapted from Levin et al. (2017). The Northern Appalachian Anomaly (NAA) is the prominent low velocity anomaly at the center if the map. A reference point in the center of the region is denoted with a star. (B) Simplified velocity model constructed by superimposing two Gaussian-shaped anomalies. (C) Observed S wave differential travel time anomalie $\Delta T_S$ for Earthquake 1. (D) Predicted $\Delta T_S$s for the model in B for Earthquake 1 (E) Model in C, modified with the addition of a strong, deep low-velocity anomaly. (F) Predicted $\Delta T_S$s for the model in E for Earthquake 1.