Upper Mantle Heterogeneity beneath North America from Travel Time Tomography with Global and USArray Transportable Array Data

Scott Burdick,1 Chang Li,1 Vladik Martynov,2 Trilby Cox,2 Jennifer Eakins,2 Taimi Mulder,2 Luciana Astiz,2 Frank L. Vernon,2 Gary L. Pavlis,3 and Robert D. van der Hilst1

Online material: MIT P-wave tomography model for the United States created using travel-time residuals from the global EHB catalogue plus USArray Transportable Array from 2004 to November 2007.

INTRODUCTION

The large volume of broadband waveforms that are being acquired by USArray (http://www.iris.edu/USArray/), the seismology component of the national Earth science program EarthScope (http://www.earthscope.org/), offer unique opportunities for seismic imaging. Constraining structures on a range of length scales and understanding their physical and chemical causes is a prerequisite for understanding the relationship between near surface and deeper mantle processes. One can expect that, eventually, full wave tomography (e.g., De Hoop and van der Hilst 2005; De Hoop et al. 2006; Tromp et al. 2005; Zhao and Jordan 2006) with broadband USArray waveforms will produce superior insight into the structure of the mantle beneath North America, but linearized tomographic inversion of phase arrival time data readily yields exciting results in regions where data from dense seismograph networks is available. We will use travel times from the transportable component of USArray, hereinafter referred to as USArrayTA, and from other sources, such as the EHB data base (Engdahl et al. 1998), to constrain 3-D mantle heterogeneity beneath North America.

Tomographic images based on USArrayTA data will help us understand first-order geological structure of and processes in the mantle beneath North America. Examples include, but are not restricted to: 1) the transition from the stable continental lithosphere at the center of the North American continent to the tectonically active domains farther west, 2) the Cascadian subduction system, 3) the Yellowstone hotspot, and 4) the relationship between current and past episodes of subduction and upper mantle upwellings and processes deeper in the mantle. Before the advent of USArrayTA, insight into mantle structure beneath the western United States was obtained either from pieced-together regional P-wave studies (e.g., figure 1A, after Dueker et al. 2001) or from global travel time or surface wave tomography (figures 1B, C, and D, after Ritzwoller et al. 2002; Montelli et al. 2004; and Grand 2002, respectively). The use of USArray data allows systematic tomographic imaging of the entire continent at or near the resolution of the best currently available regional studies.

We intend to update our tomographic mantle model every six months or so with new USArrayTA data from the Array Network Facility (ANF), and these model updates will be available to the community. This paper summarizes our procedures for data analysis and tomographic inversion and provides a reference point for users of this “community product.” To illustrate the potential of our approach we present results from data from USArrayTA up to November 2007. We note, however, that more spectacular improvements over currently available models are anticipated when the transportable arrays reach the central and eastern states, where station distribution has traditionally been more sparse than in the western part of the continental United States.

DATA

For our travel time tomography we use travel time residuals from regional and teleseismic distance P-wave phases using the method described by Li et al. (2006, 2008). We compute travel time residuals relative to the times calculated in some reference Earth model (here we used ak135 by Kennett et al. 1995) using a global hypocenter catalog and corrections for ellipticity.

The largest single data source for such residuals is the bulletin of the International Seismological Centre (ISC). We use the reprocessed ISC data described by Engdahl et al. (1998), hereinafter referred to as the EHB data set. The global distribution of stations contributing data to this data set is depicted in figure 2, and figure 2A (inset, lower left) depicts the North American stations from which data were available for global tomography before the advent of USArray. The EHB data already includes

1. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts
2. Institute of Geophysics and Planetary Physics, University of California at San Diego
3. Department of Geological Sciences, Indiana University, Bloomington, Indiana

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Figure 1. (A) Model made by piecing together local tomography studies from Humphreys and Dueker (1994) and inverting with global data set (after Dueker et al. 2001). (B) Global S-wave model from surface wave diffraction (Ritzwoller et al. 2002). (C) Global P-wave model using finite frequency kernels (Montelli et al. 2004). (D) Global S-wave travel-time model (Grand 2002).

Figure 2. Distribution of seismic stations from which data is used for travel time tomography. Background map: global distribution of stations reporting to the International Seismological Centre (ISC) and the U.S. Geological Survey’s National Earthquake Information Center (NEIC). These data are used by Engdahl et al. (1998) to produce the EHB data base. (A) Locations of North American stations in EHB catalog. (B) Station locations for USAArrayTA data used in June 2007 iterations are shown in green, while locations added for November are shown in red.
travel time residuals from regional arrays in, for instance, the Skippy project in Australia (van der Hilst et al. 1994).

The global data used in our tomography currently consists of more than 10 million teleseismic $P$, $pP$, $Pn$, and $PKP$ EHB data with earthquake origin times between 1964 and 2004 and more than 20,000 differential travel time residuals of long-period $PP-P$ phases (Bolton and Masters 2001). We augment this data with handpicked travel time residuals, also measured against $ak135$, from USArrayTA stations (figure 2B, inset lower right) produced by the ANF. The results shown here include ~600,000 USArrayTA data from 2004 to November 2007.

**TOMOGRAPHIC METHOD**

For the joint inversion of USArrayTA data we adopt the method developed by Li et al. (2006) for the study of the upper mantle structure beneath Tibet. An iterative least-squares method is used to minimize the cost function

$$E = ||Am - d||^2 + k_1||Lm||^2 + k_2||m||^2 + k_3||C - M_c||^2,$$

where $A$ is the sensitivity matrix, $m$ is the model, $d$ is the data, and $C$ and $M_c$ as defined in the section below on Crust Correction. The model $m$ includes the wave speed perturbations in nonoverlapping, constant-slowness blocks relative to $ak135$ (Kennett et al. 1995) and parameters associated with hypocenter mislocation. In order to deal with noisy data and possible singularity in the inversion, both norm and gradient damping are applied. The norm damping seeks to find the best model with small variations from the original model, and gradient damping smooths the model. The weights for gradient and norm damping are $k_1$ and $k_2$, respectively, and $L$ is a smoothing operator.

For the calculation of the sensitivity matrix $A$ we have been using geometrical ray theory in the spherically symmetric reference model $ak135$ to calculate ray paths associated with short-period data measured by phase picking (e.g., $P$, $Pn$, $PKP$) and 3-D sensitivity kernels for the long-period data measured by waveform cross-correlation such as $PP-P$. In contrast to smoothing in the model space (e.g., through regularization), back projection along such kernels allows constraining long wavelength structure with long-period data without sacrificing spatial resolution in regions of dense coverage by short-period data (e.g., Kárason and van der Hilst 2001). We use an approximation to finite frequency kernels that is different from the approximation that has become known as the banana-doughnut kernel (e.g., Dahlen et al. 2000). With the data, parameterization, and linearization used, such differences are of minor importance (e.g., Kárason 2002; de Hoop et al. 2006), and neither type of kernel should be regarded as a finite frequency sensitivity kernel proper. Indeed, multiscale tomography with broadband USArrayTA data requires consideration of full wave dynamics (e.g., De Hoop and van der Hilst 2005; De Hoop et al. 2006; Tromp et al. 2005).

Li et al. (2008) describe the full details of this methodology, but two aspects of the method are of particular interest for the application to USArrayTA data:

**Adaptive Parameterization.** To mitigate uneven data coverage and benefit optimally from the addition of array and regional network data, we adapt grid-size to the local density of data coverage (figure 3). The smallest grid used is currently $0.3^\circ \times 0.3^\circ \times 45$ km near the surface, which is appropriate for the 70-km station spacing used in USArrayTA, but the minimum size increases with depth to reflect the change in width of associated

▲ Figure 3. Irregular grid used in inversion at a depth of 200 km.
Fresnel zones. In this application, the density of data coverage is determined by the number of ray path segments in a specified mantle volume. Higher spatial resolution is attained in areas such as the western United States, which have smaller grid spacing, whereas (currently) only longer wavelength heterogeneity can be observed farther east. As more USArrayTA data become available, this grid will be adapted to the changes in data coverage. Such adaptive parameterization allows the global inversion to approach the resolution of a regional study in areas of high data coverage (see also, for instance, Bijwaard et al. 1998).

Crust Correction. Without remedial action, structures in the crust that cannot be resolved by the travel time data used here may produce artifacts in the images of the upper mantle. To prevent this from happening we apply a crust correction based on an independent reference model for the crust. In our inversion, this is accomplished through addition of a regularization term—$k_j||C - M_j||^2$—to the cost function (Li et al. 2006). Here, $C$ is the projection of the reference crust model onto the irregular grid, $M_j$ is the crustal part of our model, and $k_j$ is weight factor (Lagrangian multiplier) that controls the effect of this correction. Ideally, for $C$ one uses a detailed regional model, but the current results have been obtained with the projection of the global reference CRUST 2.0 (Bassin et al. 2000, available online at http://mahi.ucsd.edu/Gabi/crust2.html) onto our fine grid. This regularization of the model space has distinct advantages over making explicit time corrections. In particular, new data can easily be added, and updates of the crust model do not require recalculating time corrections. Indeed, when better crust models become available for regions involved in USArrayTA, we will simply update $M_j$ and re-run the inversion.

MODEL UPDATES—“COMMUNITY PRODUCT”

We will update the tomography model periodically and make it readily available to the community. The update process is illustrated in figure 4. Broadband data from USArrayTA stations are constantly collected at the ANF. Travel times for several seismic phases are then handpicked. Every six months we plan to take the new arrival times and combine them with extant USArrayTA and EHB data. At the same time a new irregular grid will be determined from the new ray path density. Finally, crustal corrections are projected onto the new grid, and new inversions done.

The updated models (that is, the velocity values for North America to 1,000-km depth) will be accompanied by a brief announcement in Seismological Research Letters (SRL), which will include pertinent information about the update including model date, revision number, technique refinements, and the time span and station locations of the USArrayTA data used. Each model will be available electronically at the SSA Web site, www.seismosoc.org, along with information on data format and model parameters. Additionally, the model and a series of selected maps and cross-sections will be available at http://web.mit.edu/sburdick/www/tomography.html.

We expect to receive around 200,000 new residuals from USArrayTA every six months. The effect on the images of four months’ worth of USArrayTA data is illustrated in figure 5. We note, however, that image improvement will become even more significant as USArray extends into the Great Plains, where data coverage from existing stations is sparse.

PRELIMINARY RESULTS

The main purpose of this paper is to document our tomographic method and provide information about the model updates. While a detailed discussion of the results is beyond the scope of the paper, we call attention to a few first-order observations.

For a depth of 200 km, figure 5 illustrates the spatial resolution for February (5A), June (5B), and November (5C) 2007 for models based on USArrayTA data only as well as the model using all data (5D). A comparison of the current iteration with USArrayTA only and with all data is shown in figures 5E and 5F. Because many stations reporting to EHB are present in the western United States (figure 2B), the beneficial effect of adding USArrayTA data is likely to be smaller here than farther east (figures 2B,C). Indeed, in the western states the final model (figure 5F) is similar to the USArrayTA-only model (figure 5E), but the differences are larger farther to the east. The low-velocity Basin and Range Province, the subduction of the Juan de Fuca plate beneath the Pacific Northwest, and the wavespeed variations beneath the Columbia plateau all appear very similar in the two models, but we lack, for instance, the ability to resolve the Yellowstone hotspot with only USArrayTA data recorded to November 2007. Even with a few additional months of USArrayTA data, however, the resolution of velocity variations in the first several hundred kilometers beneath the western United States noticeably improved. Indeed, adequate resolution of checkerboard structures expands progressively eastward after each four-month iteration. Between June and November, for instance, the data have begun to resolve the western edge of the craton beneath Wyoming and Colorado.

In map views (figure 6), the subduction of the Juan de Fuca plate can be seen as a distinct high-velocity, shallow mantle fea-

▲ Figure 4. Description of data flow and model update process.
Figure 5. Comparison of model with and without EHB data (all at 200-km depth). Resolution tests performed in (A) February 2007, (B) June 2007, and (C) November 2007 show the results that increasing the USArray data has on resolving structure in the western U.S. (D) Resolution test using both EHB and USArray data improve on USArray-only tests to the southwest and north of USArray. (E) Model from USArray data only. (F) Model from USArray and EHB data (MITP_US_2007NOV).
Figure 6. Depth sections through MITP_USA_2007NOV. Red represents a change from the background model of −2.0% and blue a change of +2.0%.
Figure 7. Cross-sections generated from latest model, MITP_USA_2007NOV. (A) Section across Cascadia subduction and Columbia plateau. (B) Section across southern extent of Juan de Fuca subduction. (C) Section across Sierra Nevada and Basin and Range Province. (D) Section through Yellowstone hotspot track.
ture that extends from British Columbia to California. It is a pronounced feature in the Cascadian subduction zone (figure 7A), but then becomes significantly weaker beneath the High Lava Plains in Oregon, an area notable for its lack of seismicity. As it increases with depth, the high-velocity slab broadens and extends westward, with a “hole” in the slab between 400 and 600 km to the west of Oregon. The slab returns to strength at shallow depths in northern California (figure 7B) before ending abruptly at the Mendocino triple junction. At greater depths, the slab structure continues south past the triple junction, and the slab window created by the northward motion of the triple junction is apparent. We note that preliminary results of finite frequency tomography with USArray data reveal similar structures (Sigloch and Nolet 2007). At around 350-km depth, the maps suggest that the high-velocity zone broadens and continues farther to the east. This trend is also visible in vertical cross-sections (figure 7B). The Yellowstone hotspot is distinctly seen in map views up to ~ 350-km depth, where it appears to be cut off by a high-velocity feature that is connected to structure beneath California. It is possible that the source of the Yellowstone hotspot is shallow, but if the source were deeper, this observation suggests a complex interplay of the upwelling associated with the hotspot and deeper mantle structures.

In the vertical sections (figure 7) the upper mantle beneath the Basin and Range Province and the Colorado plateau is marked by very low wave speeds. At the western edge of the low wavespeed zone is a fast area beneath the Sierra Nevada, and to the east, there is a sharp cutoff where the Rocky Mountains begin (figure 7B). Beyond the Rockies, to the east, the cratonic center of the continent is generally quite high velocity, but here the resolution of the inversion is still low due to poor data coverage. As USArrayTA continues to the east, it will be possible to see whether the mantle beneath the stable craton has the same degree of heterogeneity as the tectonically active west coast.

A BRIEF MODEL COMPARISON

A comparison of the map views in figures 1, 6, and 7 suggests that the main structures detected by our tomographic inversion (e.g., figures 5 and 7) are largely in agreement with the previous generation of global tomography models, for surface waves (Ritzwoller et al. 2002), P waves (e.g., Montelli et al. 2004) and S waves (Grand 2002), but our multiscale model reveals much more detail. By combining high resolution regional and lower resolution global models, Dueker et al. (2001) provided tantalizing depictions of mantle structure beneath the western United States (figure 1A), but a problem arises when results from different regions are to be combined or when a quantitative comparison is needed between different models. The results shown here (e.g., figures 6 and 7) demonstrate that our multiscale tomography can reach the resolution of a regional study in areas of high data coverage. For example, the two-pronged structure of the Yellowstone hotspot is shown with similar resolution to that of a study using a high-density regional array (Yuan and Dueker 2005).

CONCLUSION, OUTLOOK, AND MODEL AVAILABILITY

We have described the aspects of data processing and travel time tomography insofar as they are directly relevant for the tomographic inversion of travel time data from USArrayTA stations. Because of the expected interest in tomographic models of the mantle beneath the continental regions involved in USArrayTA deployments, we will update our model on a regular basis and make it publicly available at the SRL Web site and at http://web.mit.edu/sburdick/www/tomography.html.

Already, there is a strong improvement in the resolution of mantle structures in the western United States in spite of the fact that the area is already well-represented in the global data set. As USArrayTA marches across the various geological terrains in the United States, adding data in areas with traditionally lower station coverage, the updated multiscale images will afford unique new insight into the lateral variations in upper mantle structures and the geological and geodynamical processes that cause them.

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Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
77 Massachusetts Ave. 54-513
Cambridge, Massachusetts 02139 USA
sburdick@mit.edu (S. B.)