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Model Update December 2008: Upper Mantle Heterogeneity beneath North America from P-wave Travel Time Tomography with Global and USArray Transportable Array Data

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Online material: MIT *P*-wave tomography model for the United States created using travel-time residuals from the USArray Transportable Array from April 2004 to December 2008.

INTRODUCTION

As the Transportable Array of USArray (http://www.iris.edu/USArray/), the seismology component of EarthScope (http://www.earthscope.org/), progresses eastward across the United States, the seismological database available for studies of mantle heterogeneity beneath the North American continent is rapidly expanding. Burdick *et al.* (2008) published a tomographic model of mantle heterogeneity beneath North America based on USArrayTA *P*-wave travel time data through November 2007. The purpose of this article is to announce the availability (as an electronic supplement through the SSA Web site. www.seismosoc.org) of model MITP_USA_2008DEC, which is based on USArrayTA data through December 2008.

By the end of 2008 USArrayTA had begun to illuminate mantle structure below the center of the continent, where systematic high-resolution tomography was previously unavailable. Specifically, data from stations east of the Rocky Mountains provides new constraints on the heterogeneity of the stable North American craton and allows for direct comparison with mantle heterogeneity beneath the tectonically active western margin. Compared to the previous version (Burdick *et al.* 2008), the current model update refines estimates of mantle heterogeneity around the Yellowstone hotspot, better defining its boundaries and revealing a strong slow anomaly beneath the transition zone. Large-scale structural features in the west, such as the Basin and Range and the Cascadia subduction zone, where data coverage was already good, remain similar to those in the original model, which suggests that the tomographic images of them are now robust.

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METHODOLOGY

Our tomographic inversions of USArray data are based on the method developed by Kárason (2002) and described by Li *et al.* (2008). We perform global inversions in order to account properly for mantle heterogeneity outside the study area and use an adaptable grid to enhance resolution in mantle volumes densely sampled by the seismic dataset used. For details pertinent to application to USArray we refer to Burdick *et al.* (2008). Of most interest for the model updates are (1) the addition of new USArrayTA data and (2) the grid refinement in response to this addition of this new data. The smallest grid used is currently 0.3° × 0.3°× 45 km near the surface, which is appropriate for the 70-km station spacing used in USArrayTA. The minimum size increases with depth, however, to reflect the change in width of associated Fresnel zones of the transmitted waves. As in our previous paper, a crustal correction is applied to reduce the smearing of strong crustal heterogeneity into the mantle (Li *et al.*, 2006). The least squares (tomographic) inversions yield wavespeed variations relative to reference model *ak135* (Kennett *et al.* 1995).

Our USArray models are inferred from three principal sources of data: (1) the global data base of ~10 million *P*, *pP*, *Pn*, and *PKP* travel time residuals reported to the International Seismological Centre (ISC) and the U.S. Geological Survey's National Earthquake Information Center (NEIC) and reprocessed by Engdahl *et al.* (1998)—hereinafter EHB data; (2) ~20,000 long-period *PP-P* differential travel time data (inter-

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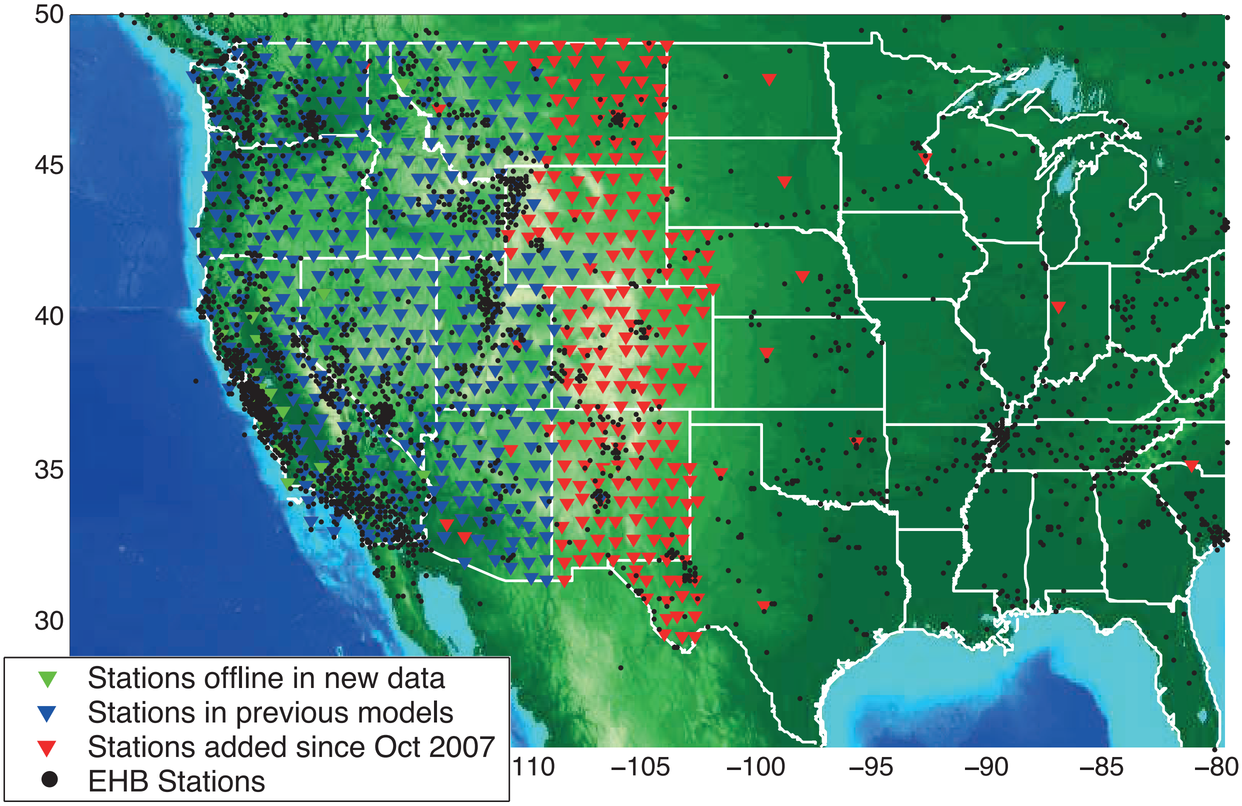


▲ **Figure 1.** Map of stations used in the western half of the United States. Black dots represent the current distribution of stations for the EHB dataset. For worldwide station distribution, please refer to Burdick *et al.* 2008 or Li *et al.* (2008). Blue triangles represent USArrayTA station locations from the previous model update for data between 2002 and October 2007. Red triangles represent USArray stations added to the dataset during the latest model run. Larger green triangles represent stations that were removed prior to the start date of the new dataset. Note the addition of stations in areas that previously had sparse data coverage.

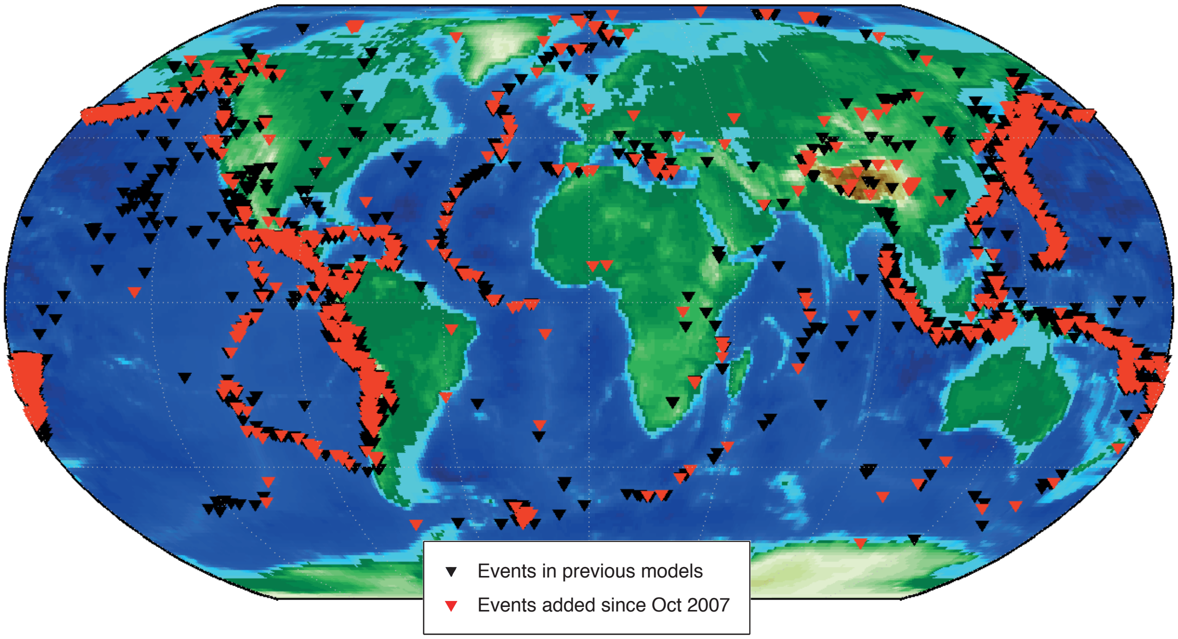
preted by means of approximate finite frequency sensitivity kernels), and (3) the rapidly growing data base of *P*-wave travel times from USArrayTA stations picked and subjected to rigorous quality control at the Array Network Facility (ANF) (Burdick *et al.* 2008).

NEW DATA, MODEL UPDATE, AND CURRENT RESULTS

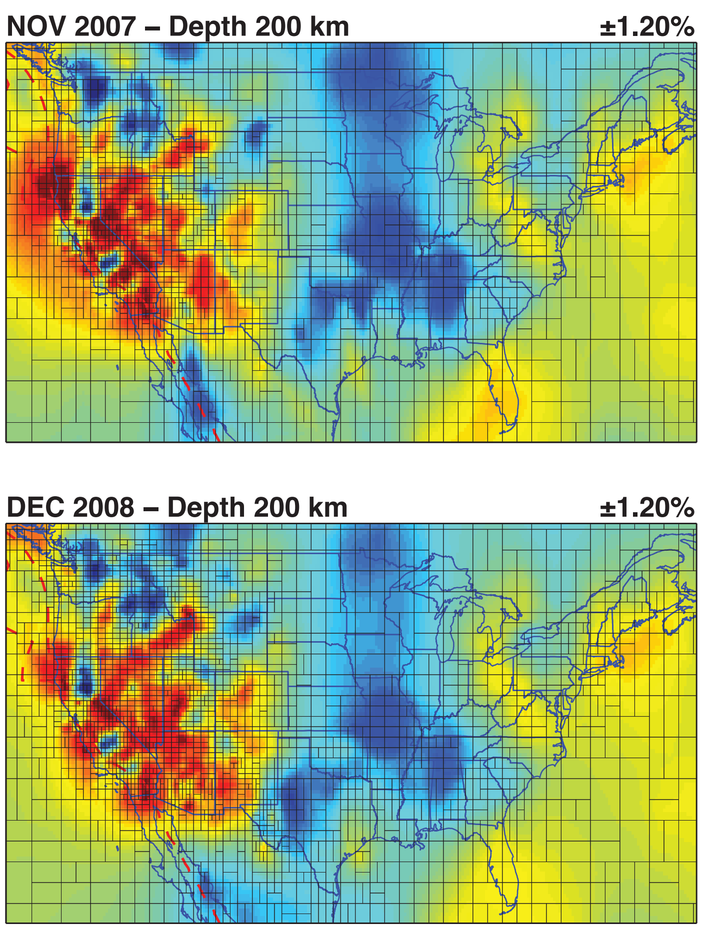
The current USArray database of ~990,000 ANF picks includes ~ 390,000 *P*-wave travel time residuals from 247 new USArrayTA stations (Figure 1) from almost 2,000 teleseismic events between October 2007 and December 25, 2008. The new stations improve coverage in areas that are poorly sampled by data from stations represented in the EHB catalog, particularly in eastern Wyoming and much of Montana and Colorado. Figure 2 shows the distribution of seismic events used in the new dataset (in red) added to the 3,600 events from the previous USArrayTA dataset (in blue).

In response to the addition of new USArrayTA data we refined the model grid (shown in Figure 3 for 200 km depth). Compared to Burdick *et al.* (2008) the most significant grid refinements occur in 1) the Pacific Northwest, where data has continued to accumulate, and 2) in West Texas and New Mexico where stations were being installed around the time of our first report. Near the (current) leading edge of the array, for instance in Wyoming and Montana, grid refinements are still subtle because the recently installed stations have not yet recorded many events. Figure 4 demonstrates the ability of our method to resolve features on the order of 3° × 3° with currently available data.

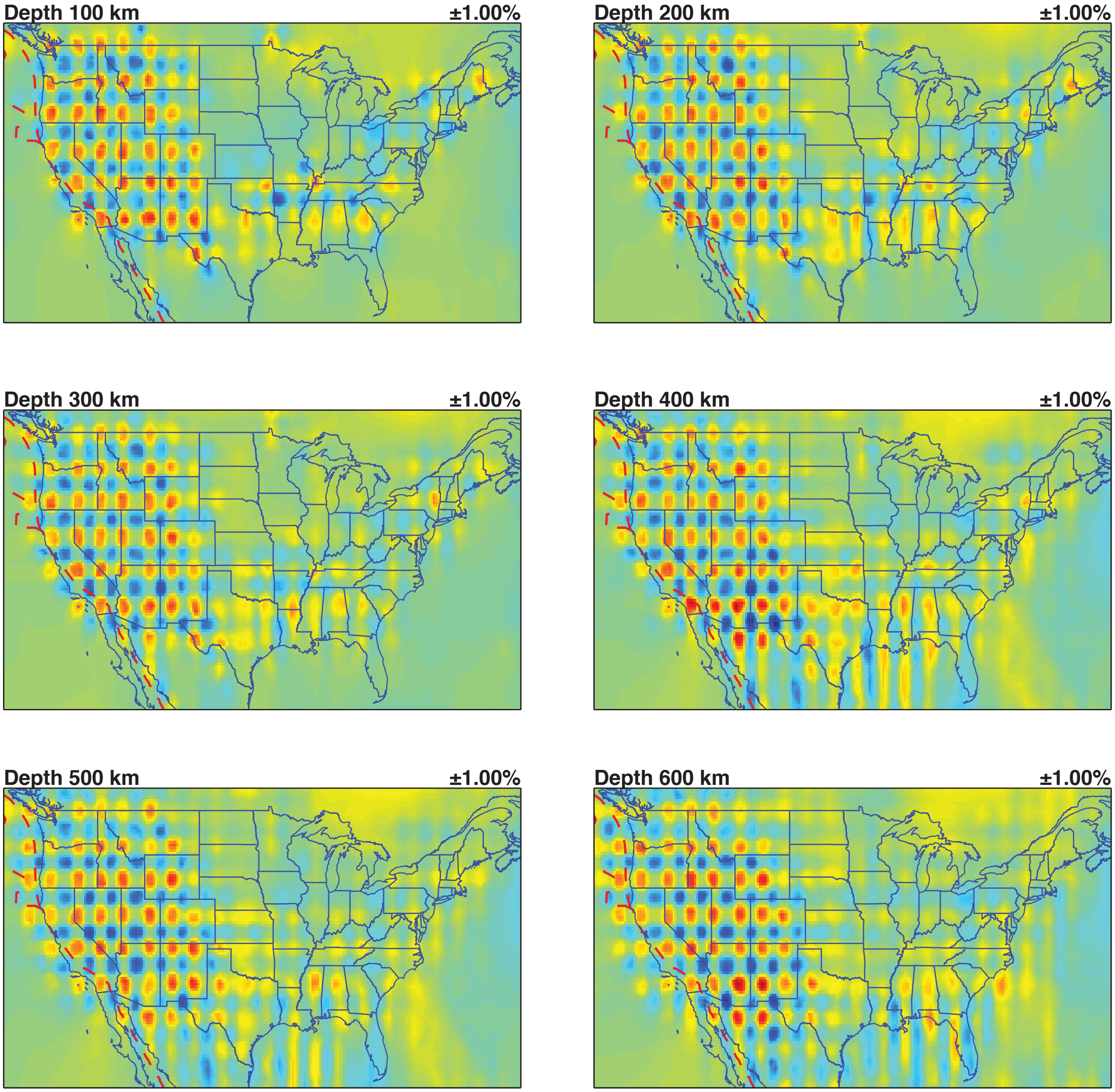
Although new data have been added, the major structures imaged in the Pacific Northwest have not changed significantly compared to Burdick *et al.* (2008). This suggests that the geometry of the Cascadia subduction and the Idaho Batholith observed in the earlier paper are robust when viewed through the resolution window of this representation of the data. Likewise, features beneath California, where the grid was already at the highest level of refinement considered here, appear consistent between the old and new model. On the other hand, new data has increased the contrast between the slow anomaly related to the Yellowstone hotspot and the surrounding craton. Beneath Colorado and New Mexico, grid refinement (and increased spatial resolution) has not affected the scale of inferred mantle heterogeneity, but the shape seems better defined. Previous tomography revealed a decrease in scale length of heterogeneity east of the eastern margin of the Rocky Mountains (~ 105°W) but this variation coincided with



▲ **Figure 2.** Map of events recorded by USArray used in creating the current model. Black triangles denote earthquakes recorded up to October 2007. Red triangles denote events recorded since the previous update.



▲ **Figure 3.** Refinements to the model grid. The irregular grid used in the tomographic inversion is overlain on depth slices from the current and previous models at 200 km depth. The top image shows the grid from the October 2007 model update while the bottom shows the grid for the current model. Grid spacing is representative of the adequate data density within each cell.

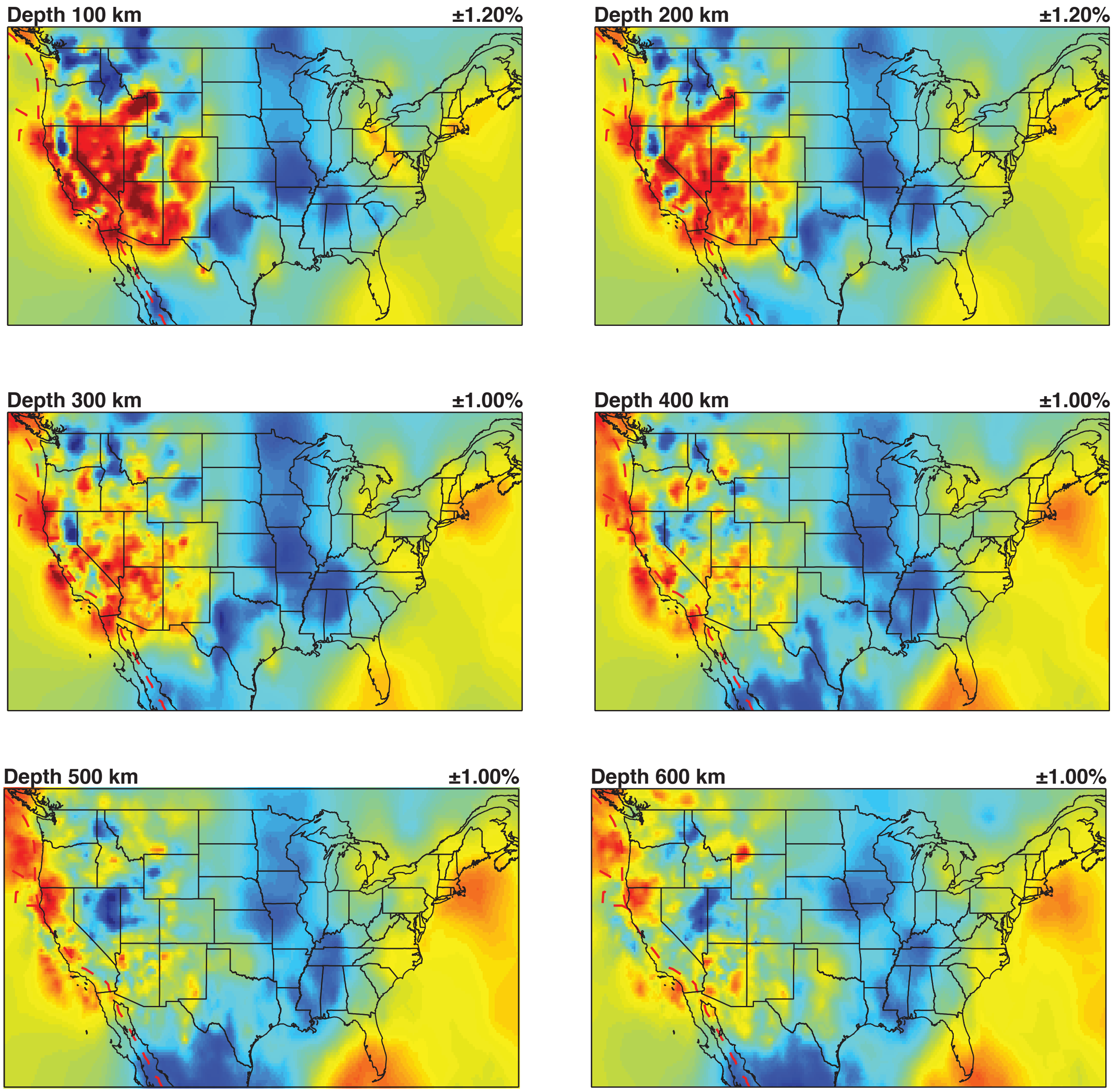


▲ **Figure 4.** Resolution tests using the current full dataset. The current model inversion shows the ability to resolve features on the scale of 3° × 3° beneath the current extent of the USArrayTA. Resolution tests show that greater than half of the amplitude of the heterogeneity is recovered in this region. Elsewhere beneath the United States—and beneath areas where USArrayTA was recently deployed—amplitude recovery is less successful. The elongated checkerboard squares in the Gulf of Mexico below 300 km depth show the effect of low data density on the irregular grid. The current data is unable to constrain longitudinal variations in that region on the order of three degrees.

a change in the spatial resolution of the data, with lower resolution of structure in the east owing to sparser station distribution. Inversion of USArray data demonstrates that the change in scale is real and not due to degraded resolution. Also notable in the present model is the emergence of a localized, slow anomaly at the base of the transition zone associated with the surface location of Yellowstone (Figure 5F). For comparison with our previous model, MITP_USA_2007NOV, in Figure 6 we present mantle slices through MITP_USA_2008DEC in the same positions as the sections in Figure 7 of Burdick *et al.* (2008).

MODEL COMPARISON

Several groups been using USArray data to produce high-resolution *P*-wave tomography models for the western United States that incorporate USArray data (Roth *et al.* 2008; Sigloch *et al.* 2008; Xue and Allen 2008). See Figure 7 for a display of

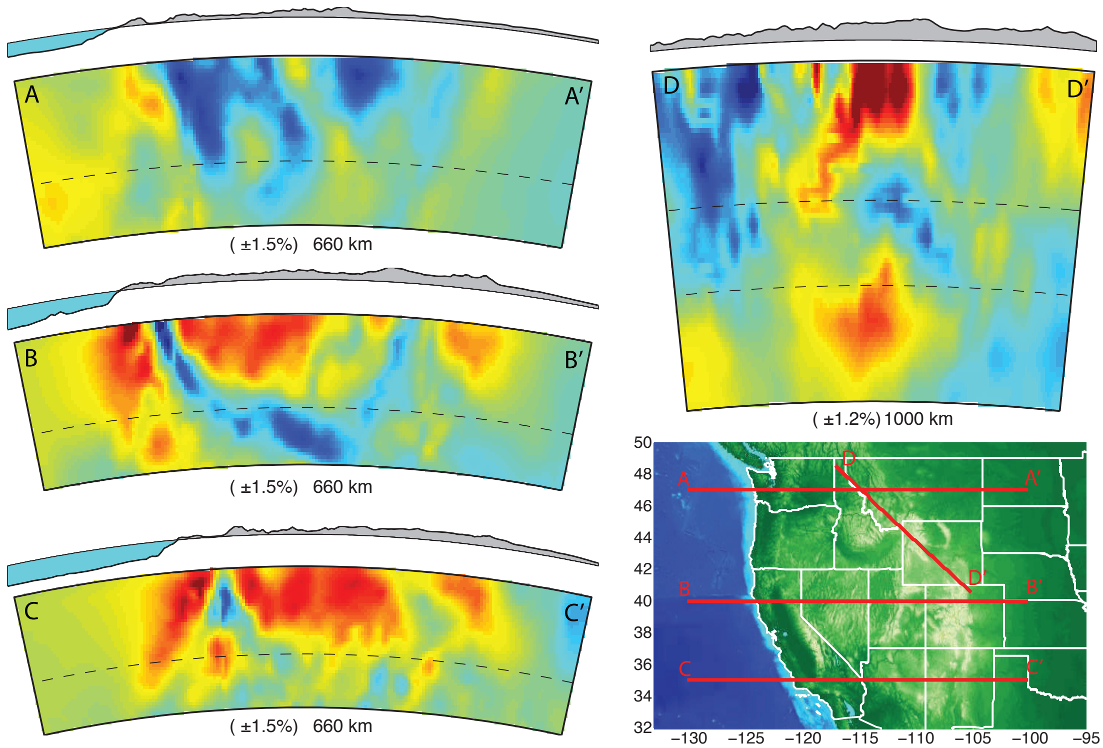


▲ **Figure 5.** Lateral variations in *P* wavespeed according to model MITP_USA_2008DEC for six different depths in the mantle beneath North America.

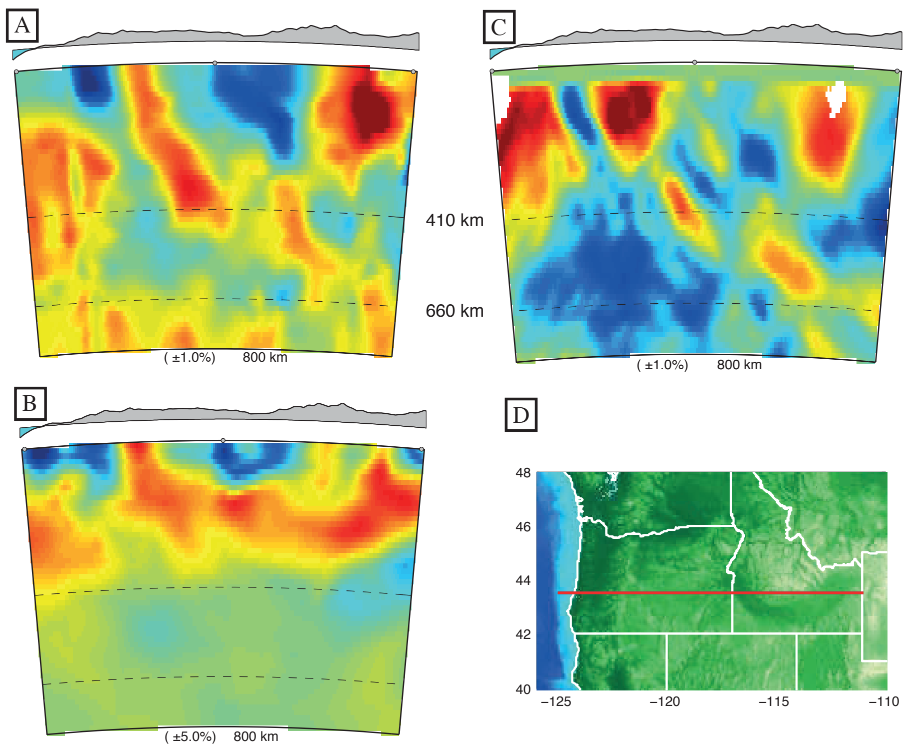
some of these models along one upper mantle section. Roth *et al.* (2008) produced a large regional model combining selected TA data with closely spaced arrays in the Northwest whereas Sigloch *et al.* (2008) incorporated TA data, measured at different frequencies, into a global finite-frequency tomography inversion. In spite of the differences in parameterization, the similarities between the models are encouraging, though there exist also substantial differences in details that will require further discussion.

The three models agree quite well in much of the western United States and at shallow depths the lateral positioning of strong anomalies associated with large-scale tectonic features seems to be robust, but their depth does not yet seem to be well constrained by the travel time inversions. We note that none of these models used the additional constraints provided by surface waves. Each model shows an image of the Cascadian subduction zone, terminating at the Mendocino triple junction and attenuating in central Oregon. The Yellowstone–Snake River plain hotspot track consistently shows as a very slow anomaly to below 200 km depth and the Idaho Batholith can be seen as a fast anomaly extending beyond 300 km. All models show evidence of a fast wavespeed anomaly in central Nevada between 200 and 300 km depth.

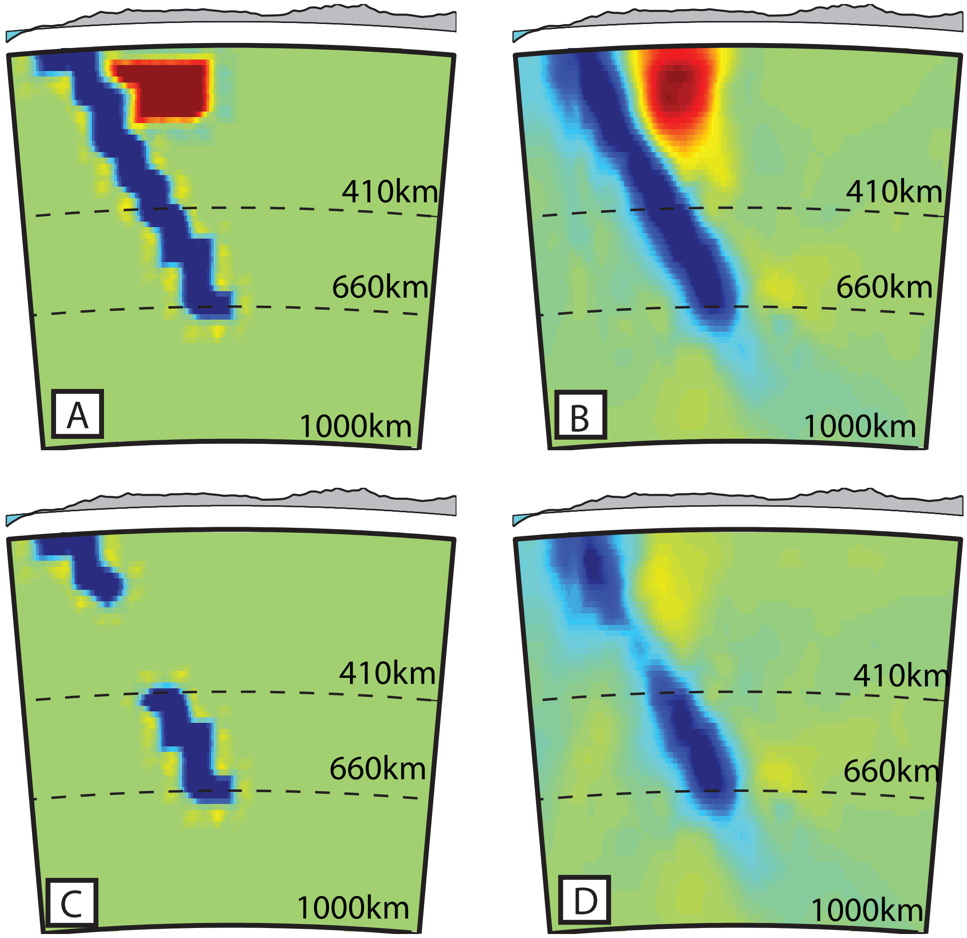
As in Sigloch *et al.* (2008) and Roth *et al.* (2008), our model shows a weakening of the anomaly from the subducted slab to 300 km depth beneath the High Lava Plain, trending



▲ **Figure 6.** Cross sections through MITP_USA_2008DEC for the same locations as in Figure 7 of Burdick *et al.* (2008), which displayed model MITP_USA_2007NOV. The three east-west sections reveal additional heterogeneity to the east, while the updated D-D′ section shows a greater degree of heterogeneity at shallow depths.



▲ **Figure 7.** A comparison between models of *P*-wave heterogeneity in the western United States: (A) model MITP_USA_2008DEC (this paper), (B) *P*-wave model due to Sigloch *et al.* 2008, and (C) *P*-wave model due to Roth *et al.* 2008. The line of section is shown on the map in (D). Cross sections from the west coast to Wyoming are shown crossing the High Lava Plain and the eastern Snake River Plain. Note that the color scale is ± 1% deviation for A and C, and ± 5% for B.



▲ **Figure 8.** Results of inversions with synthetic data to test the hypothesis that the window in the slab could be an imaging artifact caused by the presence of slow anomalies on either side of the slab. Section is the same as in Figure 7. (A) Model with a continuous slab and a slow mantle wedge. (B) Result of inversion with synthetic data calculated from model slab in panel (A). (C) Input model of slab with window. (D) Result of inversion with synthetic data calculated from model slab in panel (C). These test inversions demonstrate that a continuous slab can be resolved by the data used and that the image produced by a slab with a window resembles the image obtained from the observed data. This test suggests that the gap in the slab is real.

eastward to below central Oregon (Figure 5A–C). Roth *et al.* suggest that this feature, which is commonly referred to as the slab window, may be an inversion artifact due to poor ray coverage. However, our resolution tests (for example, Figures 4 and 8) suggest that it may be a robust feature. The window/weakened slab structure appears to extend deeper and further to the east than in the other models, perhaps even connecting to the slow anomaly beneath Idaho down to 600 km depth.

CONCLUSIONS

The updated version of the Massachusetts Institute of Technology (MIT) USArrayTA *P* model now incorporates close to 1 million *P*-wave travel time residuals from 2004 through December 2008 for ~ 700 USArrayTA stations. The addition of more than a year of travel time data has led to refinements in our tomography model, particularly the northwestern United States and in the western end of the Great Plains. A first look suggests that the difference in scale length of mantle heterogeneity beneath the stable center of the continent and the more tectonically active western margin is real and not an artifact of spatial resolution. A comparison with other high-resolution models of the western United States shows encouraging similarities but also substantial differences.

Our new model (MITP_USA_2008DEC) model and simple MATLAB scripts for making cross sections are publicly available at the SSA Web site and at http://web.mit.edu/sburdick/www/esup08/.

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