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Teleseismic surface wave tomography in the western U.S. using the Transportable Array component of USArray

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[1] Fundamental mode Rayleigh waves recorded by the Transportable Array component of EarthScope/USArray from January 2006 through April 2007 are used to generate phase velocity maps at periods from 25 to 100 sec across the western U.S., including Washington, Oregon, California, Nevada and western Idaho. At short periods (25–33 s), low velocity anomalies are observed in western Washington, western and central Oregon, northern California, the southern Sierra Nevada and the Snake River Plain. At intermediate and long periods (50–100 s), high velocities are seen in the Cascades, the southern Central Valley of California, California's Transverse Range, and the Columbia River Flood Basalt Province. The phase velocity maps are consistent with those obtained from ambient noise tomography at comparable periods. Short period phase velocities from ambient noise tomography and the longer-period phase velocities from teleseismic tomography, therefore, present natural data sets to invert jointly 3-D structure across the western U.S.
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1. Introduction

[2] The EarthScope/USArray Transportable Array (TA) is providing a wealth of new seismic data to image Earth's interior beneath the continental U.S. Surface wave tomography is proving particularly useful in imaging Earth's crust and upper mantle on both regional and global scales. Because surface waves propagate in a region directly beneath Earth's surface, they typically generate better path coverage of the upper regions of Earth than body waves.

[3] Several pervious surface wave analyses have been performed using teleseismic events to constrain mantle structures [e.g., *Tanimoto and Sheldrake*, 2002; *Yang and Forsyth*, 2006a] and ambient noise [*Sabra et al.*, 2005; *Shapiro et al.*, 2005] to constrain crustal structures in southern California. Due to the limitation of station coverage, these earlier surface wave studies concentrated in southern California where station coverage was most dense. With the emergence and growth of the TA, however, *Moschetti et al.* [2007] and *Lin et al.* [2008] have applied ambient noise surface wave tomography to the continuous data from the TA between October 2004 and January 2007 across much of the western U.S. Empirical Green's functions for surface waves were retrieved by cross-correlating long noise records between every station-pair in the network. These studies produced high-resolution surface wave dispersion maps at periods from 8 to 40 s with a resolution of 50–100 km. The resulting dispersion maps for Rayleigh and Love waves and group and phase speeds correlate well with the dominant geological features of the western United States.

[4] Surface waves at periods from 8 to 40 s are predominantly sensitive to crustal structures, although above 20 s period they possess growing sensitivity to crustal thickness and the uppermost mantle. To constrain upper mantle structures and to help alleviate the trade-off between crustal thickness and uppermost mantle velocities, therefore, requires longer period measurements than those produced in the studies of *Moschetti et al.* [2007] and *Lin et al.* [2008]. Such measurements arise from ambient noise tomography on a continental scale [e.g., *Bensen et al.*, 2007] and from teleseismic array methods on a regional scale [e.g., *Yang and Forsyth*, 2006a]. In this study, we adopt the latter approach and apply a "two-plane wave" method to teleseismic events to generate phase velocity dispersion maps for fundamental mode Rayleigh waves at periods from 25 to 100 sec across the western U.S. The same two-plane wave tomography method was applied previously to USArray data in southern California [*Yang and Forsyth*, 2006a] prior to the installation of the TA, but we now extend the study region to the western U.S., including California, Nevada, Washington, Oregon and the western part of Idaho and compare the resulting maps with those obtained from ambient noise tomography in the period band of overlap.

2. Data and Method

[5] We use fundamental mode Rayleigh waves recorded at USArray TA stations in the western U.S. within the following boundaries: 32° to 50° North latitude, and 125° to 114° West longitude (Figure 1). About 60 teleseismic events with Ms > 5.5 and epicentral distances from 30° to 120° from the center of the array that occurred in the 16-month period from January 2006 through April 2007 were chosen as sources (Figure 2). These events with the large number of stations used in this study generate very dense ray coverage, which allows us to resolve high-resolution phase velocity maps. Nevertheless, near the eastern edge of the study region, station up-time is as short as a month during the study period, so resolution degrades precipitously near this border.

[6] After the instrument responses, means and trends of seismograms are removed, the vertical components of Rayleigh waves are filtered with a series of narrow-bandpass (10 mHz), four-pole, double-pass Butterworth

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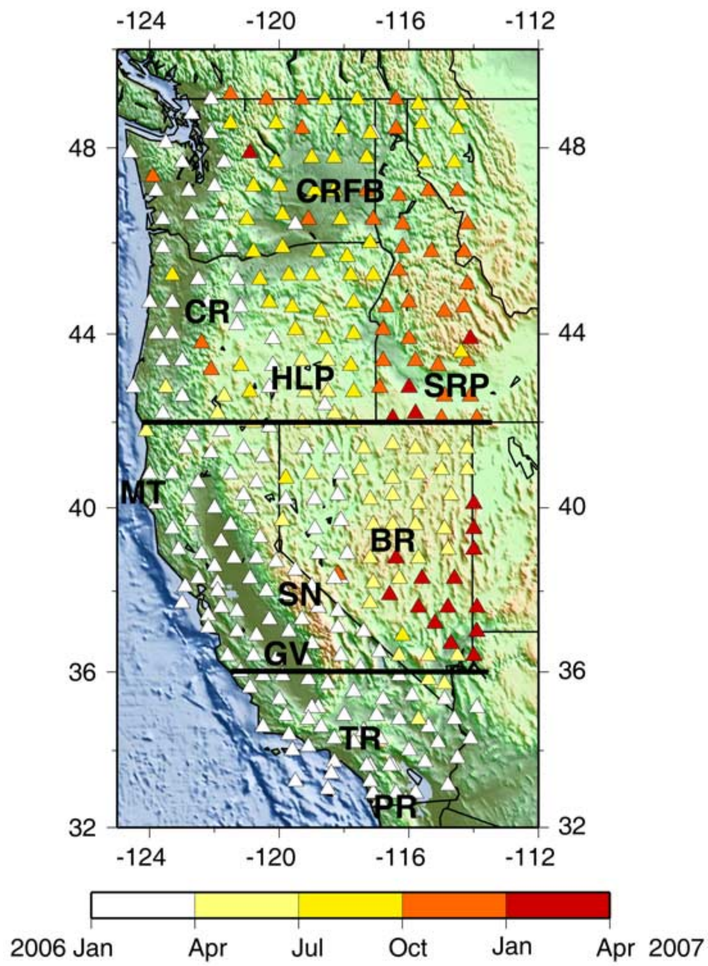

Figure 1. Station coverage and identification of the principal features of the western United States, including the Cascade Range (CR), the Columbia River Flood Basalts (CRFB), the High Lava Plain (HLP), the Snake River Plain (SRP), the Great Valley (GV), the Sierra Nevada Range (SN), the Basin and Range province (BR), the Transverse Range (TR) and the Peninsular Range (PR). Triangles mark the locations of the seismic stations used in this study, color coded by the first month we begin to collect teleseismic data in this study. The two bold lines divide the study region into three sub-regions: the Pacific-Northwest, northern California, and southern California. Teleseismic tomography is performed separately in each of the three sub-regions.

filters centered at frequencies ranging from 10 to 40 MHz. Fundamental mode Rayleigh waves are isolated from other seismic phases by cutting the filtered seismograms using boxcar time windows with a 50 s half cosine taper at each end. The width of the boxcar window is determined according to the width of the fundamental mode Rayleigh wave packet. The filtered and windowed seismograms are converted to the frequency domain to obtain amplitude and phase measurements. Details of the data processing procedure are described by *Yang and Forsyth* [2006a, 2006b].

[7] We adopt the surface wave tomography method developed by *Yang and Forsyth* [2006b]. Because the size of the region of study is near the limit of the two-plane-wave assumption in either Cartesian or spherical coordinates, we partition the western U.S. into three sub-regions with a two degree overlap in latitude, i.e., 32°–38° latitude, 36°–43° latitude, and 41°–49° latitude. The three regions are shown in Figure 1, but without the overlap. The two-plane-wave tomography is performed separately in each of these three sub-regions using a 0.5° × 0.5° grid and the resulting phase velocity maps are composed together and averaged in the area of overlap.

3. Results and Discussion

[8] The results of two-plane-wave phase velocity tomography (TPWT) are plotted in Figure 3 at periods of 25 and 33 sec and in Figure 4 at 50, 66 and 100 sec as perturbations relative to the average phase velocities of southern California taken from *Yang and Forsyth* [2006a]. Thus, the anomalies on each map are not guaranteed to have a zero-average. For comparison, phase velocity maps at 25 and 33 sec from ambient noise tomography [*Lin et al.*, 2008] are plotted relative to the same average phase velocities in Figure 3.

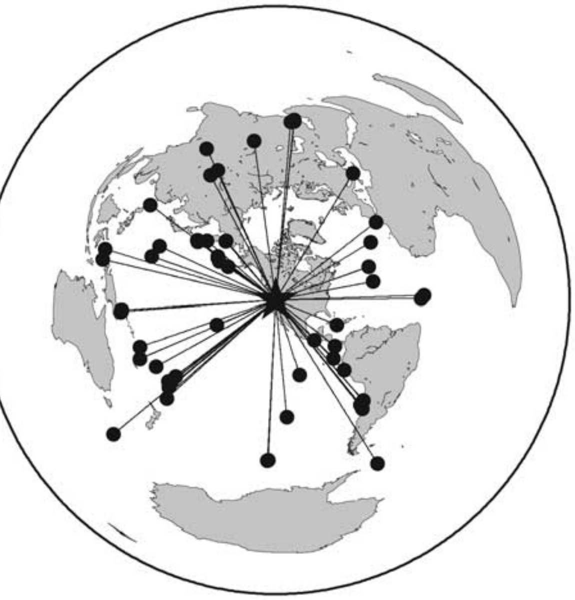

Figure 2. Azimuthal equidistant projection of teleseismic events (black circles) used in this study. The plot is centered at longitude $-118°$ and latitude $42°$ as marked by the star. The straight lines connecting each event to the center are great-circle paths.

[9] At the short-period end of this study (25–33 sec), the phase velocity maps are very similar to those from ambient noise tomography [*Lin et al.*, 2008]. Ambient noise tomography (ANT) provides stable information about surface wave dispersion over an area the size of the study region at periods ranging from 5 s to about 40 s. Two-plane wave tomography (TPWT) provides information only at periods longer than about 25 s because of scattering and attenuation that occurs along the path from the teleseismic sources. Both methods produce similar resolution, estimated to be at about the inter-station spacing of the TA (i.e., ~70 km) at periods below ~40 s. Agreement is best in the middle of the region where data coverage is highest and installation duration of stations is longest for both methods. Differences are most pronounced near the fringes of the array where resolution is lower, particularly near the western and eastern edges in Oregon and Washington. Because most of the TA stations in eastern Washington, Idaho, and southeastern Nevada were installed after September 2006, data completeness for the TPWT is not as good in these as in other regions. Thus, noticeable differences between the ANT and TPWT results are observed in central and north Washington. Differences are also appreciable along the Pacific coast where leakage from oceanic structures may contaminate the TPWP map. Figures 3c and 3f show the phase velocity differences between these two methods at 25 and 33 s. The difference maps are clipped such that the red contour encompasses the region where seismic stations were deployed before September 15, 2006. Inside this region, the overall differences are small except along the Pacific coast. The phase velocity differences within the clipped region average 0.019 km/s, 0.008 km/s, 0.012 km/s and 0.005 km/s (0.5%, 0.2%, 0.3% and 0.1%) lower for the ANT than the TPWT maps at periods of 25, 29, 33 and 40 s, respectively. The sign of these discrepancies is the same as that reported by *Yao et al.* [2006] for Tibet; that is, TPWT yields somewhat faster velocities than ANT. The reason for the slightly slower velocities from ANT is mainly due to the off-great-circle propagation of surface waves between two stations due to inter-station velocity anomalies. This off-great-circle propagation will always underestimate inter-station phase velocities because the length of a off-great-circle path is always larger than that of a great-circle path just as *Yao et al.* [2006] stated. While in TWPT, we use an array-based tomography method, the effect of the off-great-circle propagation has been considered. The discrepancies we estimate, however, are much smaller than the ~3% discrepancies they report and display the opposite trend with period. It should be noted that the methods of tomography we use are also quite different between ANT (based on ray theory with Gaussian shaped sensitivity kernels) and TPWT (based on finite-frequency sensitivity kernels). With these caveats in mind, we regard the similarity between the maps across the western U.S. as being quite high.

[10] At the short period end of this study (25, 33 s), Rayleigh waves are primarily sensitive to crustal thickness and the shear velocities in the lower crust and uppermost mantle. Pronounced low velocity anomalies are observed in western Washington, western and central Oregon, northern California, southern Sierra Nevada, and the Snake River Plain. These low velocity anomalies diminish with increasing periods, indicating a possible origin in the lower crust and uppermost mantle probably due to warmer temperatures. The low velocity anomalies along the Cascadia forearc in the Olympic and Klamath Mountains could be mainly due to the continuous accumulation of offscraped and metamorphosed sediments resulting from ongoing subduction. High volatile content, such as water and partial melt, may also significantly depress the velocity, especially along the Cascadia arc and backarc regions including western Washington, western and central Oregon, and northern California, where extensive volcanism has occurred and the upper mantle wedge is overlying the subducting Juan de Fuca plate and the Gorda plate. *Yang and Forsyth* [2006a] discuss the low velocity anomaly in the southern Sierra Nevada and interpret it as the result of asthenospheric upwelling. The Snake River Plain low velocity anomaly is associated with the Yellowstone hotspot track, which appears to have warmed the lower crust and upper mantle [e.g., *Saltzer and Humphreys*, 1997].

[11] High velocity anomalies are observed throughout the whole period range in the Columbia River Flood Basalt province, the southern Central Valley of California, and the Transverse Range in southern California (Figure 4). *Yang and Forsyth* [2006a] previously imaged the high velocity anomalies in the southern Central Valley and the Transverse Range. These velocity anomalies are consistent with regional P-wave tomography [e.g., *Biasi and Humphreys*, 1992; *Humphreys and Clayton*, 1990]. The high velocity anomaly in the Columbia River Flood Basalt Province may have a compositional origin within the upper mantle resulting from extensive magmatism that may have depleted the upper mantle [*Hales et al.*, 2005]. The low elevations of the Columbia Basin suggest a dense or thin crust, which would be expected to be fast as observed at short periods.

[12] At periods longer than 50 sec (Figure 4), a lineated north-south high velocity anomaly is observed beneath north-

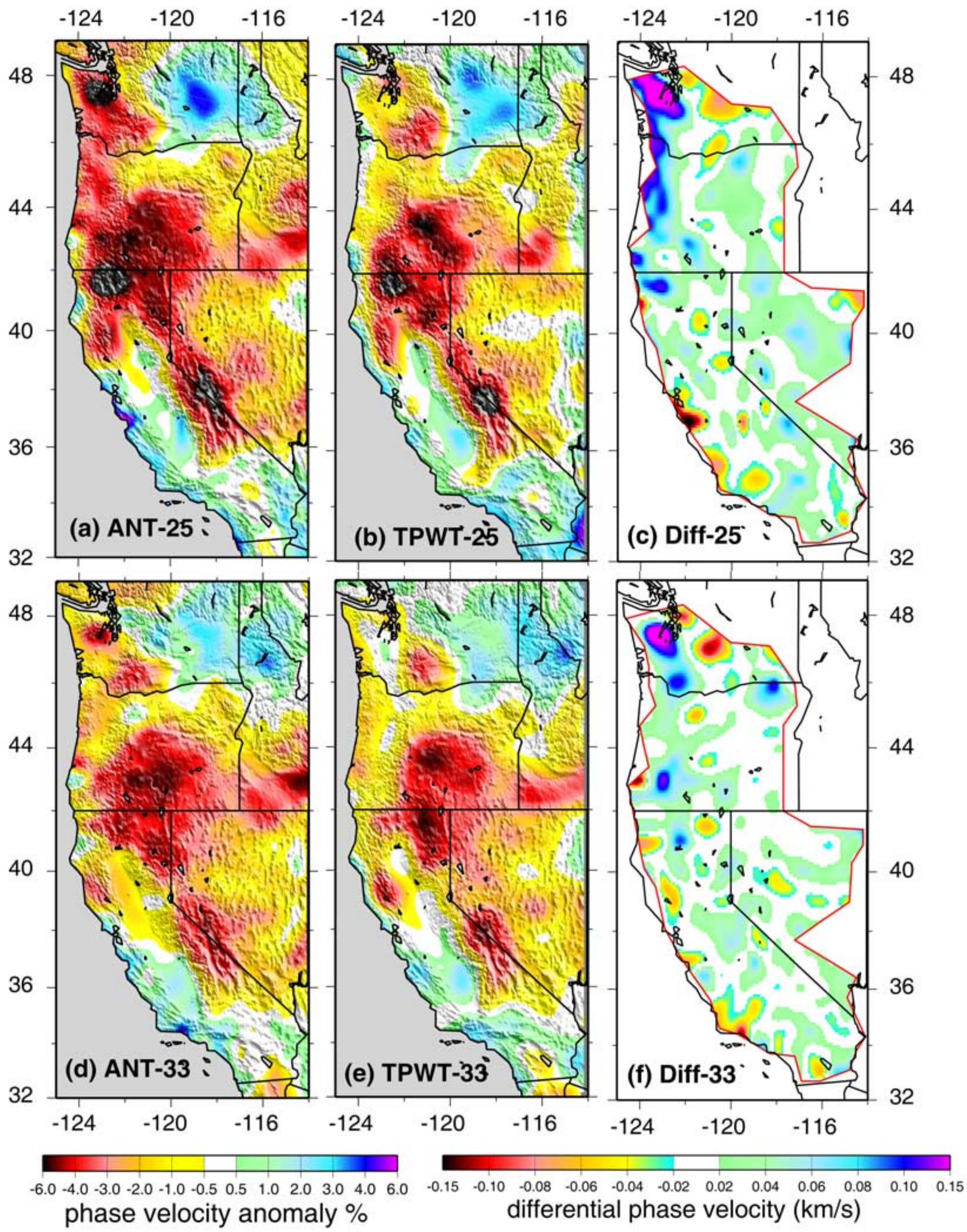

Figure 3. Rayleigh wave phase velocity maps from ambient noise tomography (ANT) compared with teleseismic two-plane wave tomography (TPWT). (a and b) ANT and TPWT at 25 s period, respectively. (d and e) ANT and TPWT at 33 s period, respectively. Anomalies are presented as the percent deviation from the average velocity across Southern California determined by *Yang and Forsyth* [2006a]. (c and f) Phase velocity differences between ANT and TPWT at 25 and 33 sec. The difference maps are clipped such that the red contour encompasses the region where seismic stations were deployed before September 15, 2006.

ern California, Oregon, and Washington, along the entire Cascade Range, presumably due to the subducting Juan de Fuca and Gorda plates. The high velocities initiate in the south near the Mendocino transform, the location of the southern edge of the Gorda plate. The lowest velocity anomalies at 50 and 66 sec period are in southeastern Oregon and northwestern Nevada, and probably reflect high temperatures in the High Lava Plains and Basin and Range provinces which are believed by many to be near the original surface focus of a mantle plume that now underlies Yellowstone.

[13] At periods from 25 to 67 sec, our phase velocity maps in southern California are very similar to those from *Yang and Forsyth* [2006a] using the same TPWT. At 100 sec period, however, we observe some discrepancies between our phase velocity map with that from *Yang and Forsyth* [2006a]. In particular, we do not image the high

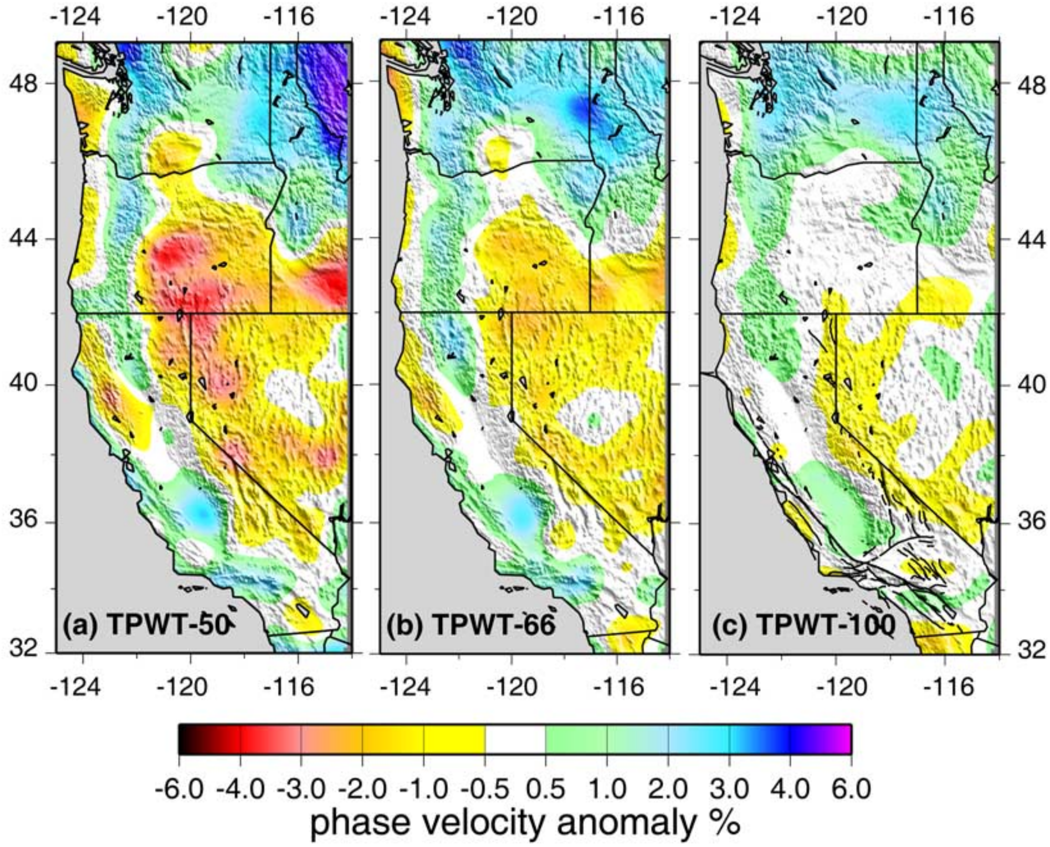

Figure 4. Rayleigh wave phase velocity maps from teleseismic two-plane wave tomography (TPWT) at periods of 50 (a), 66 (b) and 100 sec (c).

velocity anomalies in the vicinity of the Peninsular Ranges by *Yang and Forsyth* [2006a]. These discrepancies could result from inconsistent station responses at long periods, which are not corrected accurately. In this study, we add two parameters for each station in the inversion, one for station amplitude correction and the other for station phase correction, to accurately correct station responses.

[14] The dispersion maps that result from ambient noise and two-plane-wave tomography are now providing information about shear velocities in the crust and uppermost mantle at unprecedented resolution across much of the western U.S. Inversion of these data for the 3-D shear velocity structure of the crust and uppermost mantle is a natural extension of the work presented herein.

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