Exploring the lithospheric velocity structure of the Pacific Northwest

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Introduction

The Pacific Northwest is a near ideal study region for seismic imaging. Earthscope Transportable Array operated for two years in the region and once it rolled eastward it was largely replaced by a pair of denser broadband Flexible Array deployments providing approximately four years of reliable broadband data on a near even grid. The Flexible Array Mendocino Experiment consists of 79 stations in Northern California and the FlexArray along Cascadia Experiment for Segmentation provides another 23 stations in Oregon and Washington, which are available from July 2007 through November 2009. Previous studies were limited to short lived 1D and sparse 2D seismic arrays, but have already shown great regional complexity in both crustal and mantle composition and structure.

Major geologic features are identified in the study region, as shown in figure 1. The subduction zone volcanic arc and forearc regions are the primary features seen in the central part of the study area. The southern region contains the Klamath Mountains and Sierra Nevada ranges divided by the California Great Valley and the southern extent of the Cascades Range. The northern area of the study region is dominated by the Cascades Range with the exception of the Olympic Peninsula, which is an anomalous terrain revealing key features useful in reconstructing the tectonic history of the region.

A lithospheric velocity model can be used to infer geologic parameters such as crustal thickness, sedimentary / volcanic rock unit thickness, geologic interfaces, and dipping structures. These inferences and measurements can be used to quantitatively reconstruct the tectonic history of the greater than 150 million year old subduction zone.

This preliminary study uses a three-month subset of the Flexible Array data and regional broadband data to make a lithospheric scale model of the region with surface wave tomography using ambient noise as the seismic source.

Methodology

This study employs the methodology of Bensen et al (2007) to preprocess single day waveforms available via the Incorporated Research Institutions for Seismology (IRIS), the Northern California Earthquake Data Center (NCEDC), and the Canadian Geological Survey (CGS). For each day of the three month period, cross correlations are computed and stacked into multi-day correlations for each station pair of approximately 170 stations. This results in approximately 14,000 paths for frequency time analysis on fundamental mode Rayleigh waves to measure group and phase velocities. These measurements are then inverted with a ray theoretical approach to estimate group and phase velocity maps for the 8-30 second period band.

The error associated with these maps is a function of measurement error, tomographic misfit, seasonal source variation, and station distribution variation. This is estimated as:

$$\varepsilon_{total}=\sqrt{(\varepsilon_{measurement}^2 + \varepsilon_{tomography}^2 + \varepsilon_{source}^2 + \varepsilon_{station}^2)}$$

where the different ε values are estimates of the various component errors in velocity units of km/s. Measurement errors are assumed negligible due to a minimum signal to noise ratio criterion of 10. The tomography error is calculated as the misfit between average travel times in the tomographic model compared with the measured travel times. The source and station terms are combined into a single term by computing single month tomography models and estimating the deviation from the three-month stacked model. The calculated total misfit, vertical dispersion curves, and a standard one-dimensional reference model are used iteratively in a Monte Carlo inversion scheme (Shapiro and Ritzwoller 2002) to invert for shear wave velocity as a function of depth. This results in a family of potential shear wave models for the upper 100km.

Because this model only uses symmetric component vertical-vertical cross correlations only isotropic structure is considered.

Preliminary Results

The major geologic features of the study region described above are clear in the preliminary model. Figure 4 shows a series of cross sections, which highlight the main features. For instance, in section AA’ the sedimentary cover of the Olympic Peninsula is shown as a slow velocity high elevation feature over a dipping contact with a fast velocity zone at approximately -123.5° longitude. Section BB’ emphasizes the thickening fast volcanic core of the Cascades in the northern part of the region while CC’ shows similar thick crustal zone, but significantly slower velocities.

Section DD’, in the southern part of the region, illustrates the abutting nonconformity of the Sierra Nevada volcanic core and the Great Valley sedimentary basin. Velocity variations throughout the region are shown in section EE’; the southern Great Valley sediments contact the Cascades volcanic rocks and the velocity structure throughout the Cascades has an undulating character.

Some features are more easily seen in map view. For instance the Klamath and Cascades mountain ranges exhibit fast velocities near the surface reflecting their volcanic origin. However at depth these are clear low velocity zones showing the thick crust into the mantle. Also revealed in the model is a connection between the Klamath Mountains and Sierra Nevada Range, does not connect with the

Cascades Range. However, as the image deepens the connection is no longer evident and the shallow mantle in the southern part of the region becomes a clear high velocity anomaly.

Proposed Future Work

This preliminary work shows great variation in the region with a single method and a relatively small subset of available data, which correlates well with known geology. Several improvements can be made to more clearly image the region. First, incorporating longer temporal and spatial correlations will resolve longer period waves to better image the lithosphere-asthenosphere boundary. Second, using stable transverse-transverse correlations resolves Love waves (Lin et al, 2008), which are better able to constrain shallow structure. Third, anisotropy can be estimated from variations between Rayleigh wave based and Love wave based models. However, this contrast will only resolve shallow anisotropy, which can be used to help resolve SKS shear wave splitting due purely to mantle structure. Finally, incorporating receiver functions and evanescent waves will generate an improved starting model, which can be used to improve the accuracy of the final model as well as calculate a three-dimensional Vp/Vs ratio allowing generation of a three-dimensional Vp model in addition to the Vs model.

References

Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang, (2007) Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophys. J. Int., 169, 1239-1260 , doi: 10.1111/j.1365-246X.2007.03374.x.

Lin, F., M.P. Moschetti, and M.H. Ritzwoller (2008), Surface wave tomography of the western United States from ambient seismic noise: Rayleigh and Love wave phase velocity maps, Geophys. J. Int., doi:10.1111/j1365-246X.2008.03720.x.

Shapiro, N.M. and M.H. Ritzwoller, (2002) Monte-Carlo inversion for a global shear velocity model of the crust and upper mantle, Geophys. J. Int., 151, 88-105

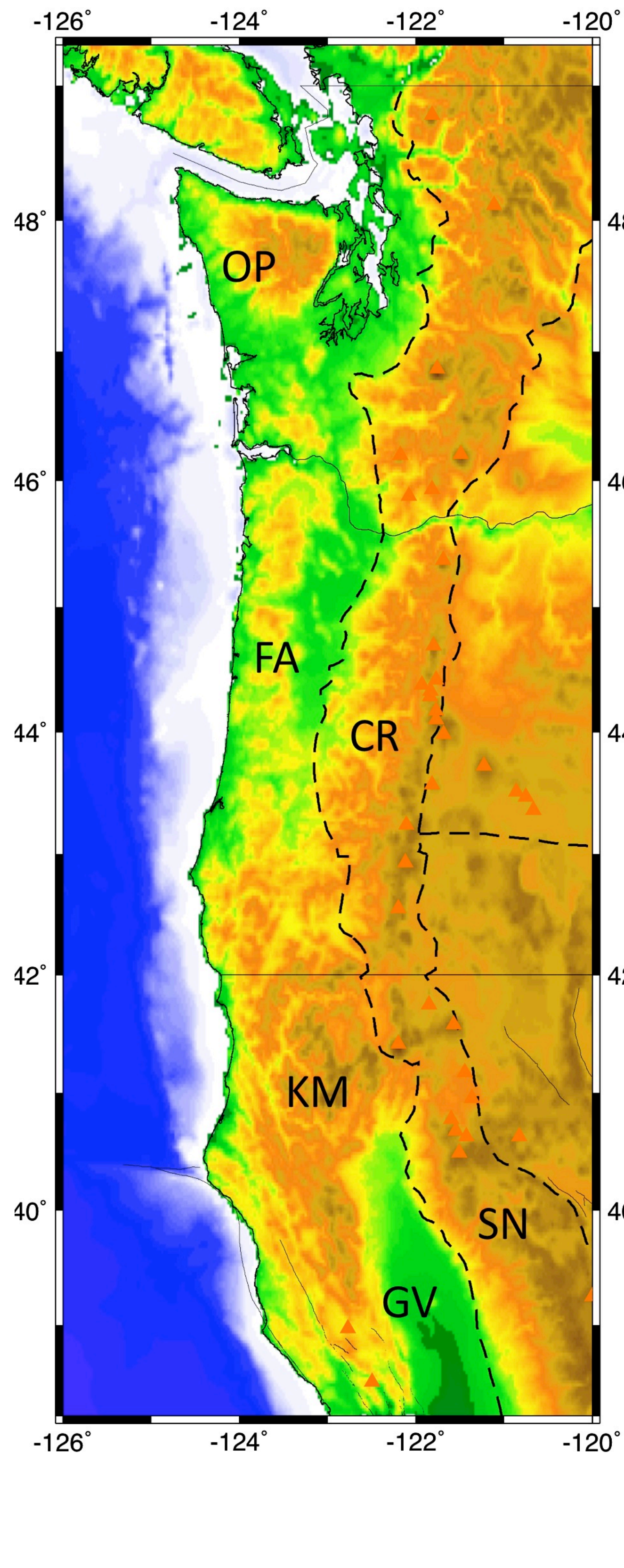

Figure 1: Study region with primary features annotated. GV - Great Valley, SN - Sierra Nevada, KM - Klamath Mountains, CR - Cascades Range, FA - Forearc Flats, OP - Olympic Peninsula

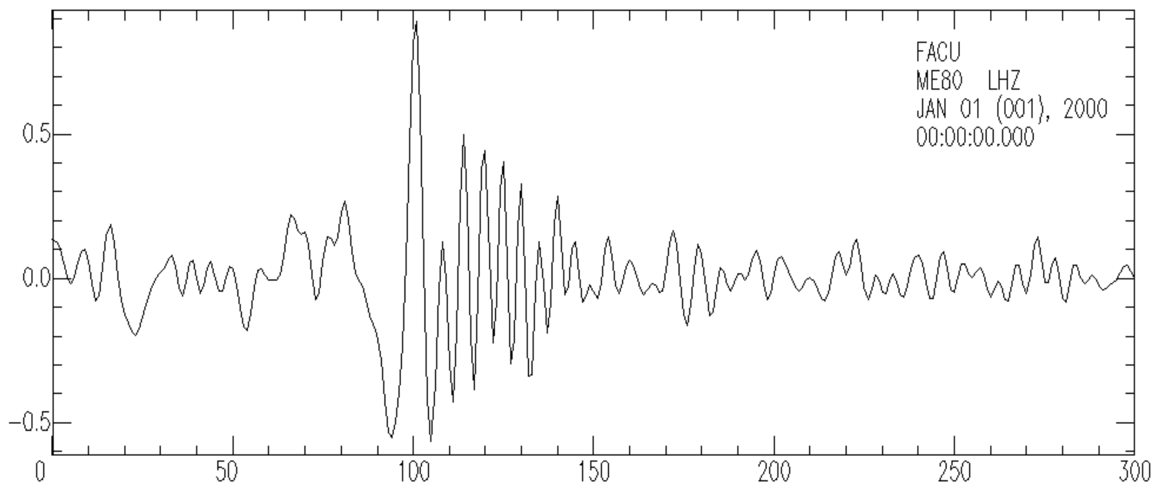

Figure 2: Example cross correlation between Flexible Array stations FACU and ME80

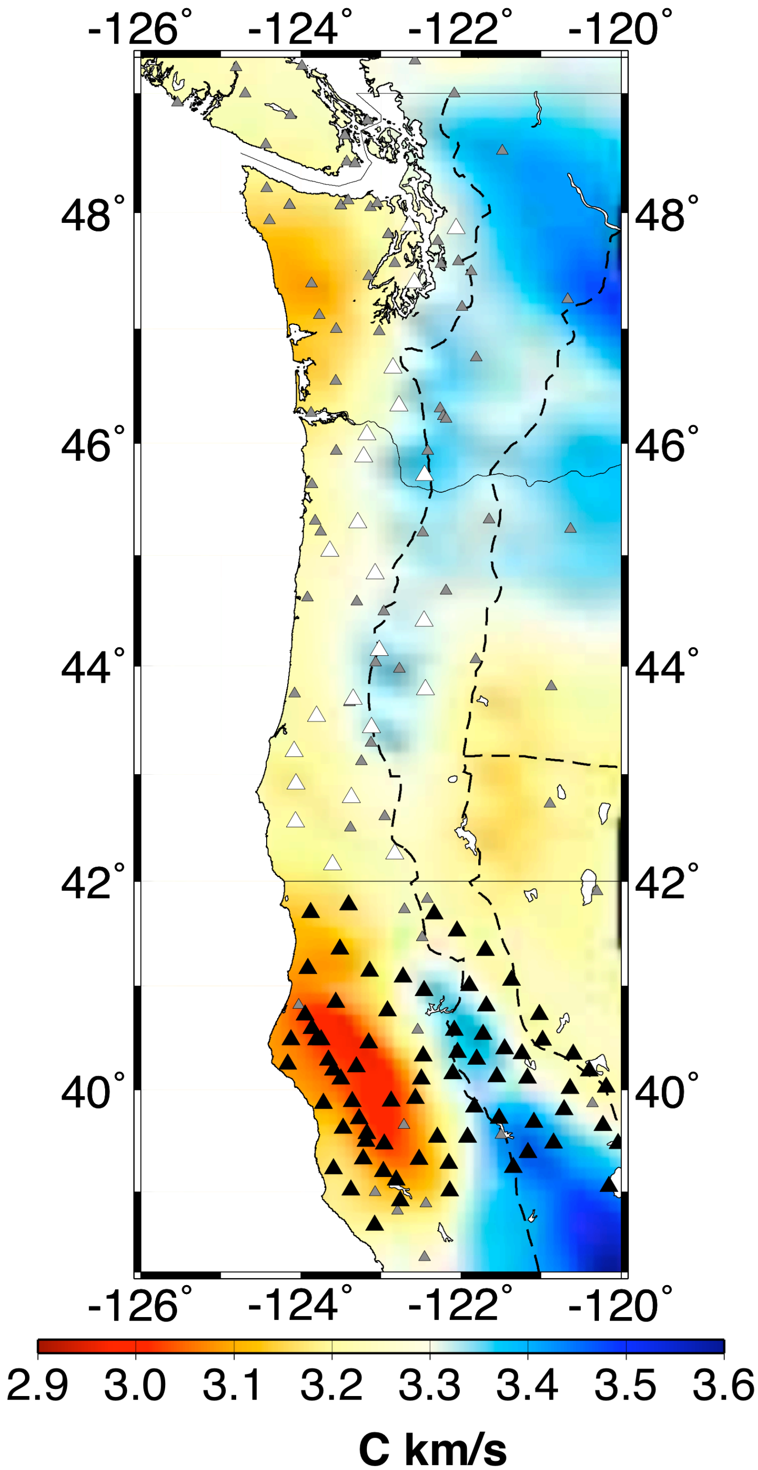

Figure 3: Example phase velocity map at 15 seconds period

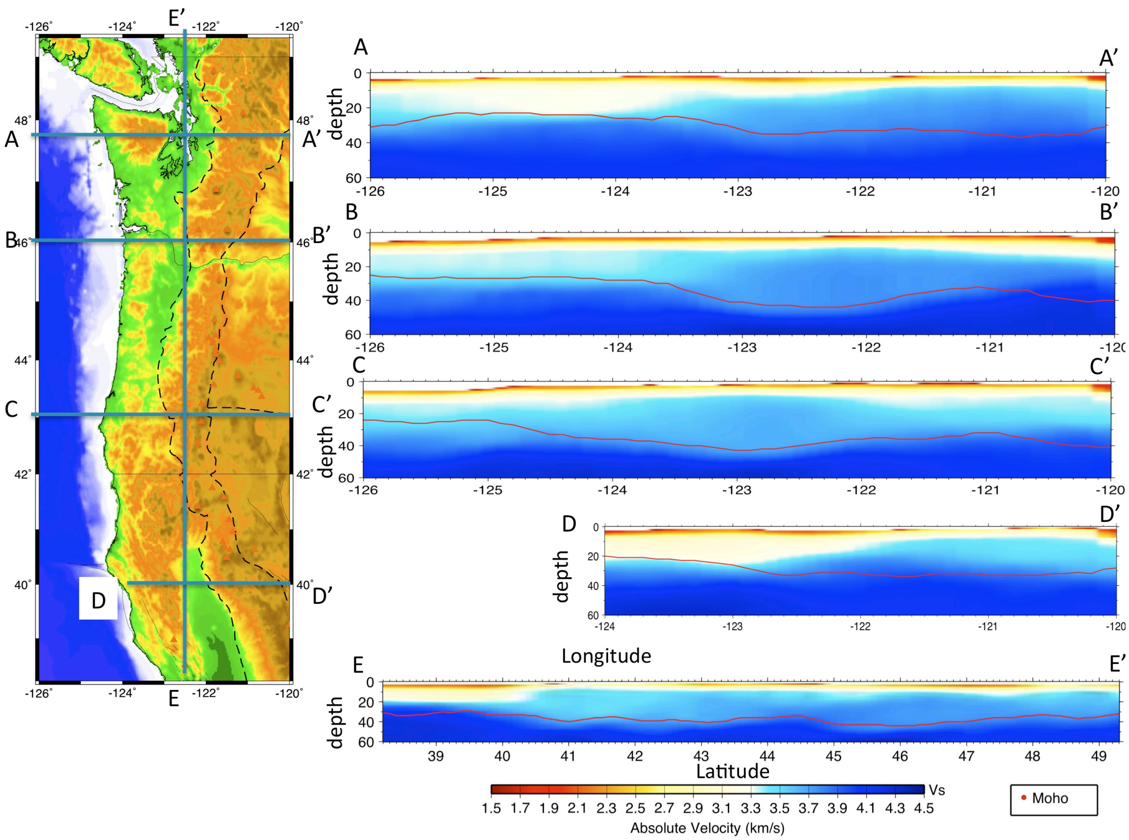

Figure 4: A topographic map (left) and several cross sections illustrating key features. Notice section EE' cuts across the other sections and all sections have the same velocity scale.

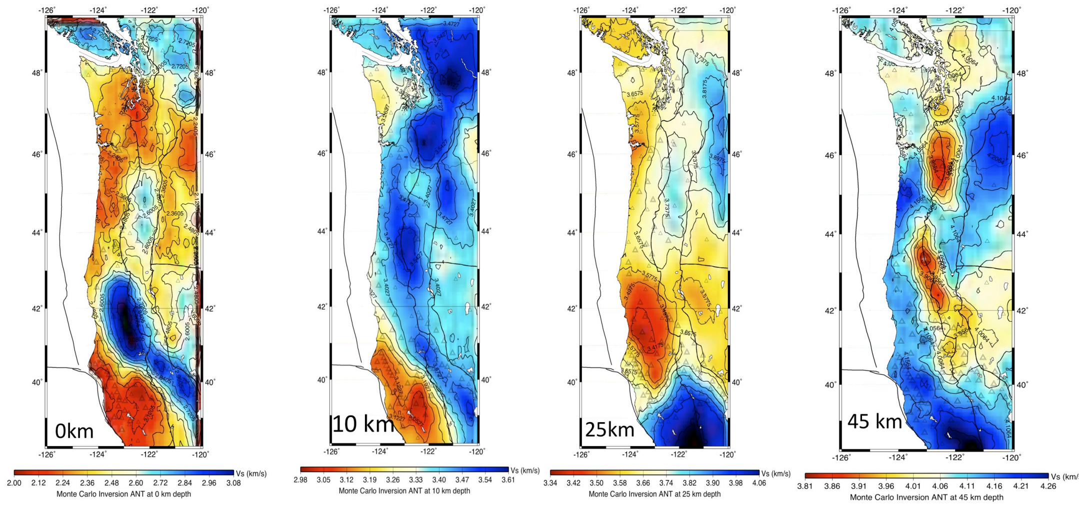

Figure 5: Map view of constant depth at 0, 10, 25, and 45km. Key features are discussed in the main text.