Seismic Hazards of Puget Sound (SHIPS): Collaborative Research with U.S. Geological Survey, Oregon State Un., Un. of Texas at El Paso, Un. of British Columbia, Un. of Washington, Un. of Victoria, Pacific Geoscience Center

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Introduction

The heavily populated Puget Basin is underlain by thick sequences of Cenozoic sedimentary rocks that amplify and focus seismic energy, thus increasing ground shaking during an earthquake. During SHIPS (Seismic Hazards Investigations of Puget Sound), controlled-source seismic data were acquired in order to model and map areas of expected strong ground shaking and to better determine the regional velocity structure and tectonic framework of the Puget Sound region, including the location, configuration, and seismic properties of faults that cross this urban region. This project represents the first phase of SHIPS. Data were acquired during March, 1998, and include marine multichannel seismic data, expanding spread profiles, and ocean-bottom on onshore/offshore large-aperture recording of marine airgun shots. Over 30,000 airgun array shots were recorded on a multichannel streamer, 257 Refteks, and 15 ocean-bottom seismometers. Work at Oregon State University (OSU) has focussed on the structure beneath the Straits of Juan de Fuca and beneath the core of the Olympic Mountains. This study provides new constraints on deformation of the subducting and overriding plates. While this region is west of the zone of greatest earthquake activity, understanding the deformation here is critical for tying the structure beneath Puget Sound to that beneath the well-imaged continental margin and for interpreting the tectonic causes of seismicity further east.

Experiment:

During SHIPS98, the R/V Thompson towed a 2.4-km-long. 96-channel digital seismic streamer and a 13-gun, 79.3 liter (4838 cu. in.) airgun array through the waterways of the Puget Basin, Strait of Juan de Fuca, and Strait of Georgia (figure 1). During the early part of the survey, before deploying the streamer, it was able to fire a 16-airgun, 110.3 liter (6730 cu. in.) array at a 40 s interval. The airgun shots were also recorded on 273 REFTEK seismometers (figure 1) and on 15 ocean-bottom seismometers. OSU was responsible for surveying, permitting, deploying and operating 32 stations on the northern Olympic Peninsula. Most of these stations recorded clear arrivals from shots in the Straits of Juan de Fuca, Puget Sound and Hood Canal. The data include wide-angle reflections from the base of the crust of the Juan de Fuca plate beneath the Olympic peninsula and diving waves traveling through the lower crust in this region (figures 2 and 3).

Results:

In FY1999, a preliminary 2-dimensional model of the crust and upper mantle based on data acquired on stations deployed by OSU on the Olympic Peninsula and on multichannel seismic reflection data acquired by the Thompson in the Strait of Juan de Fuca was developed and presented at the fall 1998 meeting of the American Geophysical Union and at the spring 1999 meeting of the Seismological Society of America. During FY2000, this model was extended to a 3-dimensional model of the upper crust beneath the Straits of Juan de Fuca and a 3-D model of the Moho of the subducting plate beneath the Straits of Juan de Fuca and Olympic Peninsula, presented at the fall 1999 AGU meeting. Since then, we have been expanding the data set for imaging the subducting plate by including data from the 1996 USGS/GEOMAR/OSU onshore/offshore project, stations deployed by other institutions during SHIPS98, and data from the SHIPS99 profile through Seattle. We are also working on integrating this model with other results from Cascadia.

Multichannel seismic data

We processed the multichannel seismic data from line 7 (labeled as JDF1 and JDF2 in Figure 1) through brute stack stage (ie. the data were edited to remove bad traces, sorted, and stacked using a simple velocity function). The primary objective of this analysis was to determine the pattern of lower crustal reflectivity. Because of the relatively low frequency of arrivals from the lower crust and the insensitivity of these arrivals to velocity structure given the relatively short streamer length, this simple analysis is adequate to meet our primary objective. More detailed velocity and static analysis is needed to determine shallow crustal structure. The results of the brute stack are shown in Figure 4. On both profiles, a subhorizontal, 2-s wide band of high reflectivity is observed at a two-way travel-time of 7-9 s beneath the Straits west of ~123.6W. Adopting the LITHOPROBE terminology, these reflections are labeled “E” in figure 4. Beneath this band of reflections, a second reflection is intermittently observed, corresponding the to LITHOPROBE “F” reflection. East of 123.6W, the “E” reflections dip east. The wide-angle analysis discussed below indicates that the “F” reflection comes from the top of the subducted Juan de Fuca plate crust, as previously interpreted by LITHOPROBE.

Onshore/offshore REFTEK/airgun data

We are using these arrivals to image the configuration of the subducted plate beneath the core of the Olympic mountains by first correcting the travel-time observations for effects of upper crustal structure beneath Puget Sound (PS) and the Strait of Juan de Fuca (SoJF) and then inverting the corrected data for the 3-D velocity structure and Moho position beneath the Olympics. This 2-step approach permits us to account for the large effects on observed travel-time of shallow basin structure while using a relatively sparse 3-D grid appropriate for the data distribution available from undershooting the Olympics. The corrections in step 1 are based on a 3-D model for Puget Sound from Brocher et al. (in review), and our model for the Straits of Juan de Fuca (figure 5).

Step 1: Inversion of first arrivals:

During this step, first arrivals from shots on line 4 (Straits of Juan de Fuca) recorded on stations deployed along the northern Olympic Peninsula were inverted to obtain velocities in a volume with 1 km grid spacing. Several horizontal slices through the resulting model are shown in figure 5. The starting model was a 1-D model with velocity increasing with depth. The model converged smoothly, with most of the reduction in misfit occurring after ~5 iterations but continued improvement in fit for another 6 iterations before the model started to oscillate around this “final” model. The pattern of misfit reduction with subsequent iterations was similar for each station, although the absolute level of misfit varies somewhat, with greater misfit for stations located in low velocity basins. The final model is not sensitive to the starting model. Because of the high velocities at relatively shallow, few rays penetrate beneath 15 km depth.

East of km -40, the model of Brocher et al. (in review) has been “patched” into our model because it includes more ray paths (e.g. from shots along line 10). The good match between the two models where they overlap validates our approach of having various groups working on different subsets of the data to address various scientific problems. Eventually, all data will be collated to generate a “super-model”.

The primary use of the first arrival model for this study was to correct the observed PmP arrival times for variable shallow structure to permit a sparser grid spacing for the Moho interface inversion. In figure 6 are shown details of the upper 10 km for the Straits of Juan de Fuca (line4), Hood Canal (line3) and Puget Sound (line9) and the corresponding travel time through the model. These times were used to replace the upper 10 km beneath the shots with material with a constant velocity of 5.5 km/s, which reduces the scatter in PmP arrival-times by about 50%.

The principal scientific result to point out is the presence of a linear basin beneath the western end of the southern line, which is not present beneath the northern line. This basin, also evident in gravity data and known as the Clallam basin where it extends on land on the Olympic Peninsula, indicates warping of the Siletz/Crescent terrane along a NW-trending axis, perhaps in response to compression generated by northward migration of the Tertiary forearc relative to the pre-Tertiary terranes of SW Canada.

Step 2: Inversion of PmP arrivals :

Figure 7 shows our working 3-D model for the Moho of the subducting Juan de Fuca plate. The interface inversion technique developed by John Hole is being used for this study. To date, we have performed inversions assuming a 1D velocity model above the Moho after application of the correction discussed in the previous section. Inversions have been performed for a range of different lower crustal velocities and a starting Moho depth of 45 km. Details of the geometry of the subducted plate are quite dependent on lower crustal velocity. Future plans are to include first-arrival data from SHIPS to constrain lateral variation in lower crustal velocity along the PmP raypaths, to extend the PmP database, and to vary the smoothness of the model.

The model indicates that the Moho is at approximately 36-38 km depth beneath the western Strait of Juan de Fuca. Because the “F” reflection falls at a depth of ~30 km, this result confirms the Lithoprobe interpretation of the “F” reflection being the top of the subducted ocean crust (and probably the plate boundary). The model also suggests a dip of about 7 degrees to the east-southeast. This result is not inconsistent with the apparently subhorizontal “E” and “F” reflections beneath the western Straits of Juan de Fuca since the portion of the subducted plate imaged by the CMP data and that imaged by the PmP wide-angle reflections are not coincident.

This model is generally consistent with the model of Creager, Preston et al. derived using a different modeling approach and a different subset of the data. Their model indicates deeper Moho depths approaching Hood Canal. The relatively shallow depth in our model may be an artifact resulting from the subset of data used and from the specified model smoothing parameters. Generally positive travel time residuals for the easternmost data suggest that dip and depth increase in this region.

Figure 8 shows the model results, converted to depth to the plate boundary by assuming a constant thickness of Juan de Fuca plate crust of 7 km and assuming that the plate boundary is at the top of the Juan de Fuca plate crust, compared to results from Lithoprobe and from the 1995 USGS/UTEP/OSU transect across SW Washington. This comparison confirms that the subducting plate extends with a relatively shallow dip beneath the Olympic Peninsula, resulting in an arch, but suggests that the arch is asymmetric, with the plate dipping more steeply beneath British Columbia than beneath Washington. This may be due to the interaction between the subducting plate and thicker, strong lithosphere beneath the pre-Tertiary terranes of British Columbia.

FY2000 publications and invited presentations resulting from this grant:

Brocher, T.M., et al., 1999, Wide-angel seismic recordings from the 1998 seismic hazards investigation of Puget Sound (SHIPS), western Washington and British Columbia, USGS Open-File report 99-314, 110 pp.

Trehu, A. M., and 11 others, 1999, Structure and reflectivity of the subducting Juan de Fuca plate beneath the Straits of Juan de Fuca and northern Olympic Peninsula , EOS. Trans. Am. Geophys. Un., SHIPS special session (invited).

Scherer, H., A. M Trehu, T.M. Brocher, M.A. Fisher, T. Parsons, 1999, The Juan de Fuca plate beneath the Olympic Peninsula, EOS. Trans. Am. Geophys. Un., SHIPS special session. (presented by Trehu. Scherer was IRIS undergraduate intern at Oregon State Un. during summer, 1999)

Coauthor on 6 additional SHIPS abstracts at 1999 fall AGU meeting.

Trehu, A.M., T.M. Brocher, J.L. Nabelek, 2000, Seismic structure of the subducting plate beneath Cascadia, invited presentation at USGS/CGS workshop on intra-slab earthquake, Victoria, BC.

Brocher, T.M., and A.M. Trehu, 2000, Seismic structure of Cascadia, invited presentation at the GSA Penrose Conference on the 300th anniversary of the last great Cascadia megathrust earthquake.

Trehu, A.M., The Juan de Fuca plate beneath the Olympic Peninsula - an arch or a hinge?, invited presentation at the annual PANGA workshop.

Non-technical summary:

The heavily populated Puget Basin is underlain by thick sequences of Cenozoic sedimentary rocks that amplify and focus seismic energy, thus increasing ground shaking during an earthquake. During SHIPS (Seismic Hazards Investigations of Puget Sound), controlled-source seismic data were acquired in order to model and map areas of expected strong ground shaking and to better determine the regional velocity structure and tectonic framework of the Puget Sound region, including the location, configuration, and seismic properties of faults that cross this urban region. Work at Oregon State University (OSU) has focussed on the structure beneath the Straits of Juan de Fuca and beneath the core of the Olympic Mountains. This study a confirms earlier suggestions that an arch in the downgoing plate underlies the Olympics, but indicates that the arch is asymmetric, with the plate plunging steeply to the north beneath Vancouver Island. These will place new constraints on the thermal structure and on bending stresses within the subducted plate (factors important for controlling intra-plate seismicity) and on the forces driving the uplift of the Olympic Mountains.

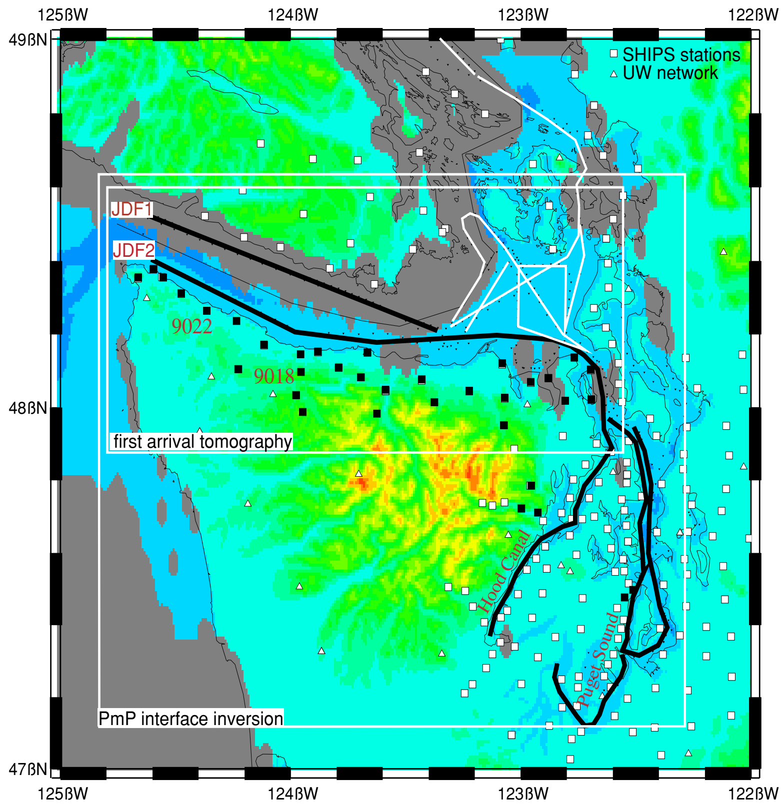

Figure 1. Topographic map of the Olympic Peninsula and Puget Basin showing the locations of MCS profiles (lines), temporary REFTEK seismometers (squares) and UW network stations (triangles). Lines and REFTEKS used to date in our analysis are shown in black. The boxes show the regions included in the first-arrival and wide-angle tomography presented here. These regions overlap and complement analyses done by other participants in SHIPS. Stations for which data are shown in figures 2 and 3 are labeled.

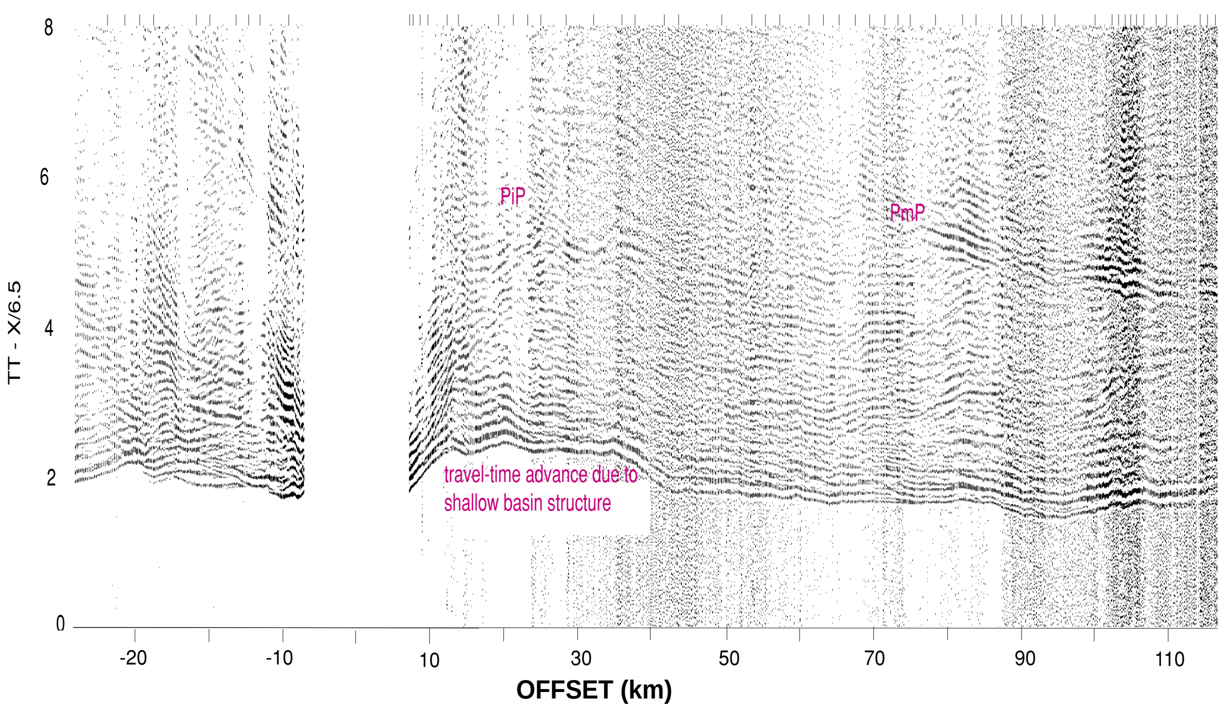

Figure 2. Data from JDF2 recorded at stations 9022. Note wide-angle reflection interpreted as PmP, shallow reflections at nearer offset (PiP), and a 0.5 s travel time delay due to the Clallum basin.

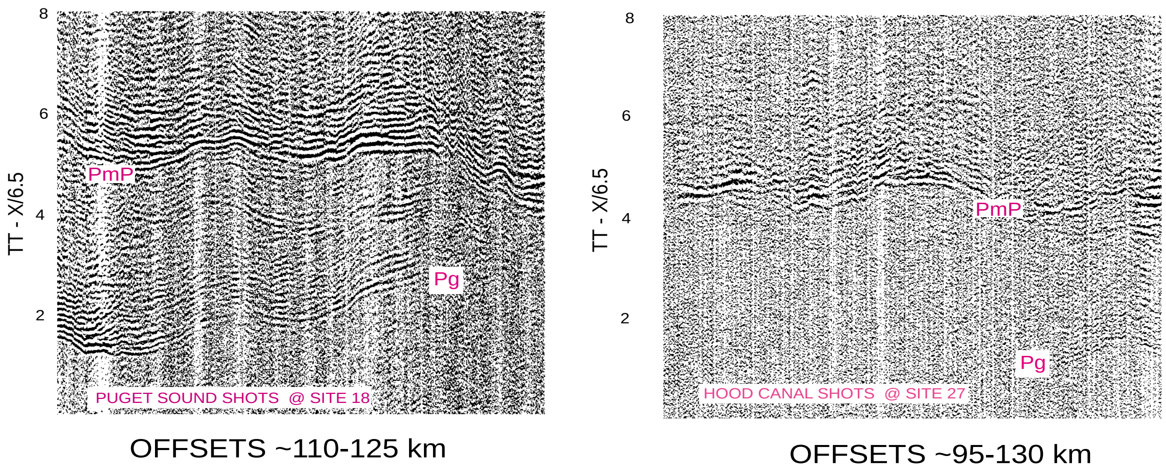

Figure 3. Examples of record sections recorded on the northern Olympic Peninsula from shots in Puget Sound and Hood Canal. Note the strong amplitude of secondary arrivals. Comparison of the travel-time and offset of these arrivals with the arrival interpreted as PmP in figure 2 suggests that these are also PmP.

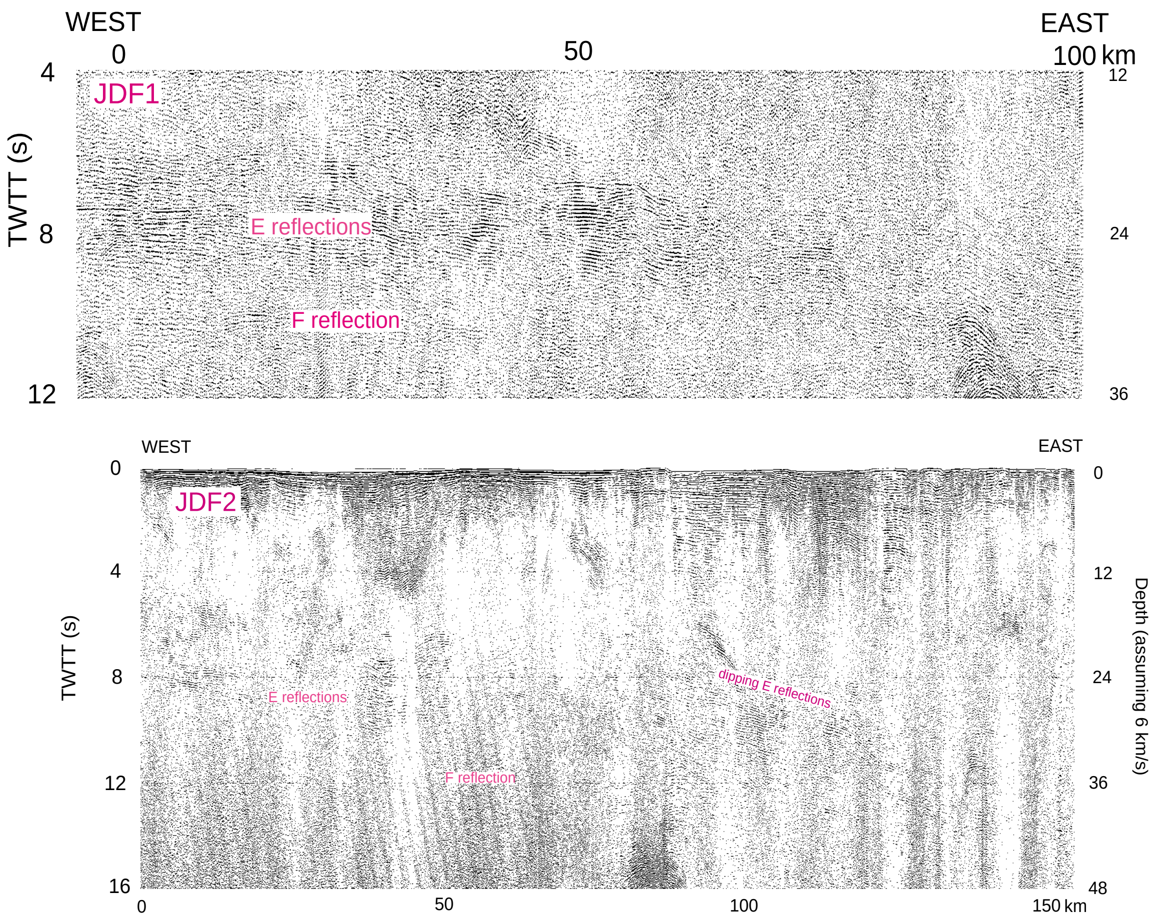

Figure 4. Multichannel seismic lines JDF1 and JDF2 (brute stacks), showing lower crustal reflectivity.

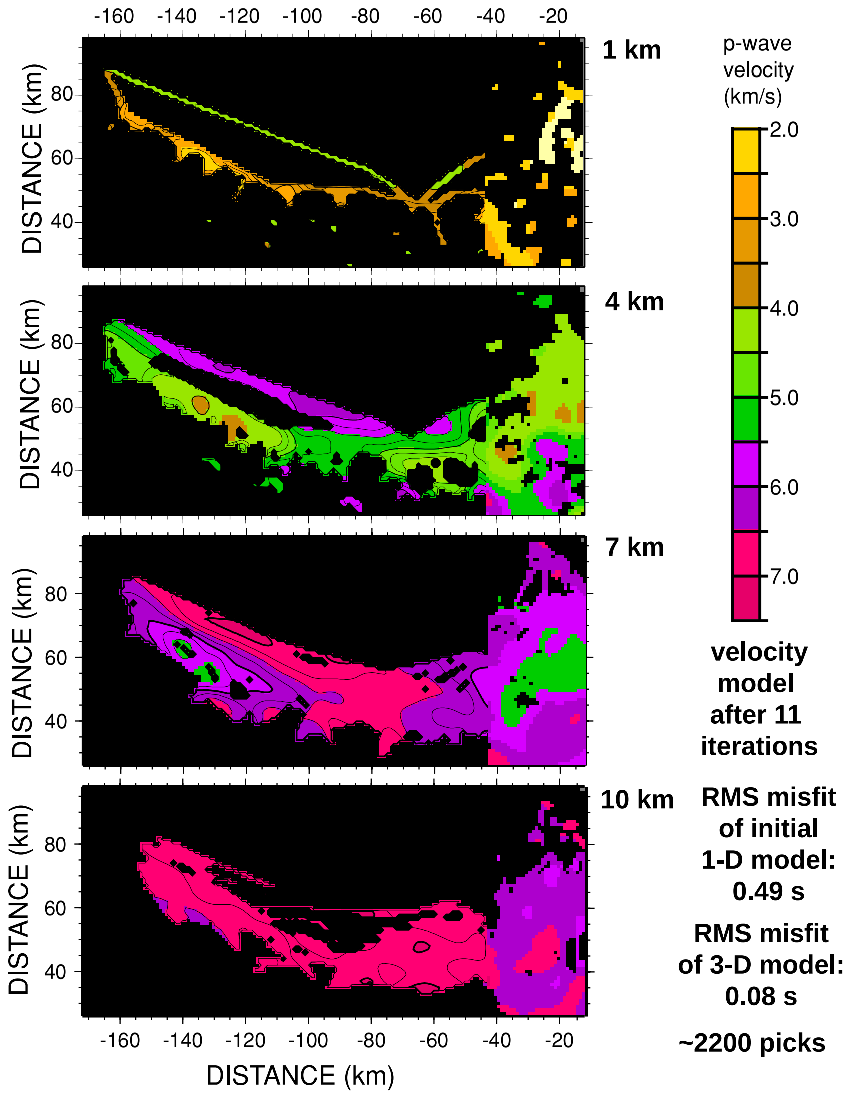

Figure 5. 3D inversion of first arrivals from shots in the Straits of Juan de Fuca recorded on stations along the northern Olympic Peninsual. East of km 40, the model is from Brocher et al. (in review) and contains data from additional lines. Note the contrast in the velocity above 7 km between the two lines of shot, indicating a linear basin parallel to the Strait.

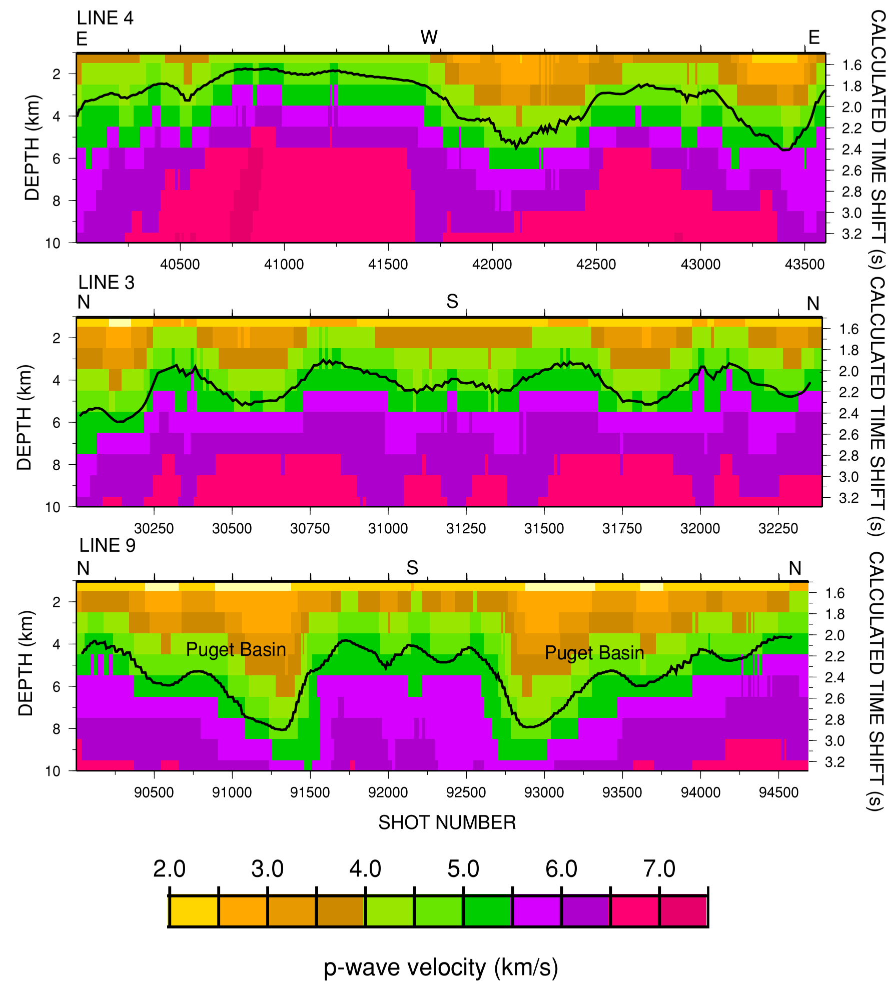

Figure 6. Velocity in the upper 10 km along each line of shots used in the 3D PmP inversion. For the Straits of Juan de Fuca, the model of figure 5 was used. For Hood Canal and Puget Sound, the model of Brocher et al. (in review) was used. The travel-time through this structure is also shown. These times were used to project shots to a depth of 10 km in the model for the 3D moho inversion, permitting use of a 5 km grid spacing.

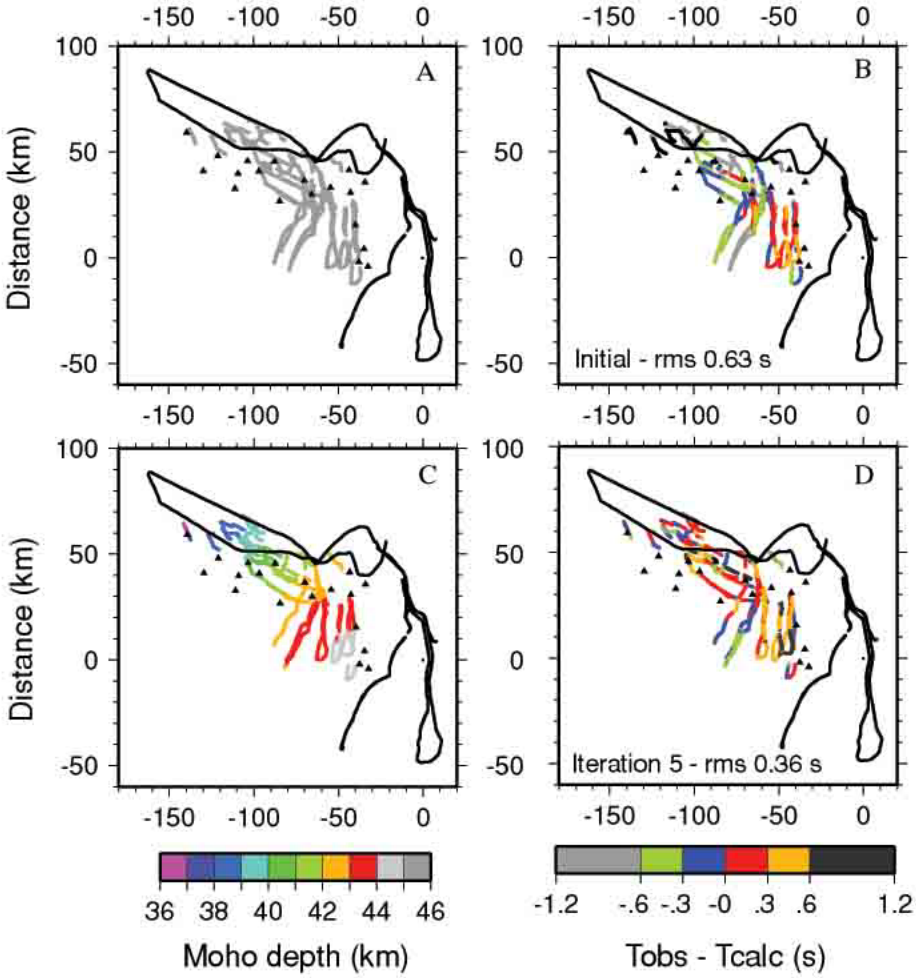

Figure 7. Initial Moho model (A) and travel-time misfit (B) and Moho model and misfit after 5 iterations (C and D). Most of the misfit reduction occurs during the first 2 iterations. Because data are not fit to within the picking uncertainty, other systematic sources of error, such as velocity variations in the lower crustal are likely to be important.

The model indicates a SE dipping Moho, with dip of ~7 degrees. Relatively large misfits at the SE reflection points suggests that dip increases in this region but that stiffnes constraints in the inversion are too strong.

Current efforts are focussed on improving the lower crustal velocity model and increasing coverage to the east.

Depth to plate boundary assuming JdF plate crust 7 km thick

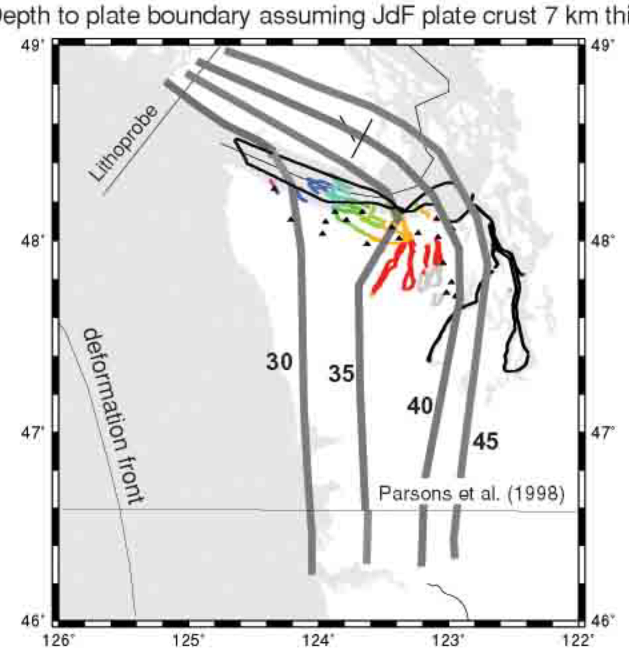

Figure 8. Comparison of preliminary results from PmP inversion with Lithoprobe results in British Columbia and results of Parsons et al. (1998) in southwest Washington. The apparently sharp bend in the 35 km depth contour is probably an artifact, and plate dip and depth are probably underestimated east of 123.5W. None-the-less, the results confirm earlier reports of an arch in the subducting plate beneath the Olympic Peninsula, but suggest that the arch is assymetric, with the plate dipping more steeply beneath Vancouver Island than to the east beneath Washington, at least at these depths.