Structure of the Seattle Basin, Washington State - Results from Dry SHIPS '99 and Kingdome SHIPS '00 (Seismic Hazards Investigations of Puget Sound): Collaborative Research (USGS, OSU, UTEP)

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Introduction

The geology of the Pacific Northwest of North America was evolved thru a series of tectonic events extending from Cambrian to Recent time (e.g., Monger and Nokleberg, 1996). This tectonic history includes Mesozoic accretionary events, inception of a Tertiary subduction zone with associated volcanism, changes in plate motions leading to the formation and accretion of the Siletz terrane, and uplift of the accretionary wedge in late Tertiary time (e.g., Monger and Nokleberg, 1996). The current tectonic regime is an active subduction zone where the Juan de Fuca plate is subducting beneath the North American plate (e.g., Riddihough, 1984). Because convergence is oblique, both dextral strike-slip faults and east-west trending thrust faults formed in the fore-arc basin (Puget Lowland - Willamette Valley) (Figure 1) (e.g., Johnson et al., 1996; Pratt et al., 1997). Faulting in the Puget Lowland - Willamette Valley has been accompanied by formation of a series of deep, fault-bounded basins (Finn, 1990).

In September of 1999, the SHIPS (Seismic Hazards Investigations in Puget Sound) working group acquired seismic data (Dry SHIPS) along a high resolution seismic profile that started in the Olympic Peninsula and continued through the city of Seattle into the foothills of the Cascades (Figure 1). In March, 2000 the SHIPS working group acquired additional seismic data (Kingdome SHIPS) centered on the Kingdome sports arena implosion in downtown Seattle (Figure 1). These projects are components of a series of studies designed to assess the seismic hazard in the Seattle region (Brocher et al., 2000). The city of Seattle overlies a deep basin which may focus energy and enhance ground shaking when an earthquake occurs (Frankel et al., 1999). The Dry and Kingdome SHIPS results provide data that can better determine the seismic hazard for the Seattle region. In this report we present our velocity model for the Seattle basin based on analysis of these data and our plans for future work.

Experiment

The Dry SHIPS (Seismic Hazards Investigation of Puget Sound) experiment was carried out in September 1999 by the U. S. Geological Survey and university collaborators. The seismic profile is approximately 112 km long and extends from the Olympic Mountains, through Seattle to the foothills of the Cascades (Figure 1). Because the line crossed through the city of Seattle and several of its suburbs, instrument deployment was challenging and relied on the cooperation of residents. For many of our ~1000 stations, spacing along the profile was ~100 m, except for the far ends where the spacing was ~200 m. Data were recorded on five different types of instruments. During the experiment, 38 shots ranging in size from 25 - 2800 lb. were detonated. The shot points were spaced ~4 km along the profile, and included several locations within the city limits of Seattle. A subsequent experiment in March of 2000, the “Kingdome SHIPS” phase, was designed to look directly at the site response within the upper 2 km of the Seattle basin. Approximately 206 TEXANS and RefTeks were deployed in a hexagonal grid in the city of Seattle, with a nominal station spacing of about 1 km (Figure 1). In addition to recording the implosion of the Kingdome sports arena, four additional shots were fixed at the corners of the grid. The four corner shots were ca. 68 kg in size, whereas the Kingdome implosion was ca. 100,000 kg. An article that reviews some of the challenges of the experiment and preliminary results was publication in EOS (Brocher et al., 2000).

Data Analysis

The process of merging the data, for Dry SHIPS, from all the different instrument types into shot records was completed by Tom Pratt at U. S. Geological Survey. An open file report that documents the data was also published (Brocher et al., 2000) and a copy of the data have been transmitted to the IRIS Data Management Center (http://www.iris.washington.edu). The process of merging the data, for Kingdome SHIPS, from the RefTeks and Texans into shot records was completed by Catherine Snelson at UTEP, which is described is an open file report (Brocher et al., 2000). Overall the data quality, for Dry SHIPS, from the experiment was high. Several shots carried the length of the profile. The Seattle basin is a very distinct feature in all the record sections where it is marked by as much as a 2 s travel time delay (Figure 2) relative to arrivals in the Olympic Mountains and the Cascades (Figure 2). The Kingdome data recorded offset out to about 10 km which is sufficient for studying the upper 2 km of the Seattle basin.

To produce a velocity model along the profile, ca. 13,000 P-wave first arrivals have been picked and input to the 3-D travel time tomography of Hole (1992). This algorithm calculates travel times through a starting model using the finite difference solution to the eikonal equation of Vidale (1988; 1990) and then uses the difference between calculated and observed travel times to invert for changes to the velocity model. The velocity model is then updated and the whole process is repeated until the RMS of the residual travel time is minimized. Smoothing the velocity model between iterations regularizes the inversion. The initial velocity model was calculated from a 1-D average of velocity versus depth into a 3-D grid. The dry SHIPS profile was sufficiently crooked that both the travel time computations and the inversion were conducted in three dimensions. Two-dimensional displays of velocity and ray coverage (Figures 3 and 4) represent weighted averages of the 3-D model space.

Our current velocity model (Figure 3) was derived using a 137 x 51 x 40 km model space, and a 400 m grid interval (Figure 3). Ray coverage is good throughout the model to depths of 20 km (Figures 4 & 7). The final RMS travel time residual is ~ 0.10 s and reflects an excellent fit of the observed data to the calculated travel times through the model (Figure 5).

Interpretation

Tomographic Model

Overall the velocity field shows slower velocities (~1.7 to 4.5 km/s) near the surface which are associated with the Seattle basin (Figures 3 & 6). The base of the basin is indicated by the strong velocity gradient at 4.5 km/s (Figure 3). The velocity then increases with depth with velocities reaching a maximum of ~ 7.2 km/s (Figure 3). The model shows the basin is ~ 6 to 7 km deep at its center (Figure 3). The length of the basin is ~ 70 km, which is indicative of the length of the Seattle fault (Figure 3). The 4.5 km/s contour was chosen as the base of the basin for two reasons. First, where Siletz outcrops, the 4.5 km/s contour reaches the surface. This velocity is also consistent with fractured and porous basalt (e.g., Mavko et al., 1998). The second reason comes from the Mobil-Kingston well that is stratigraphically tied to the “Dry” SHIPS profile by a N-S reflection line in the Puget Sound (ten Brink et al., in review, Figure 1). Mapping of the stratigraphy in the well to the velocity field for the section shows that the 4.5 km/s parallels the top of Siletz volcanic rocks. By following the 4.5 km/s contour, one can see that the Siletz - basin contact dips smoothly at ~ 29° on the west-side of the profile. In the east, the Cascades - basin contact dips less steeply at ~ 20°. The increase in velocity just below the basin - bedrock contact, east of Puget Sound, could be pre-Tertiary basement rocks. An isolated high velocity anomaly (> 6.5 km/s) occurs on the west side of the model, this could be indicative of the Siletz terrane at depth. The model does not confirm whether or not the accretionary wedge is pushed under the Siletz terrane, as the model lacks ray coverage where the accretionary wedge rocks are expected. Velocities at the base of the model are not well resolved and therefore, the velocity estimates are probably only accurate to within 0.3 km/s. The maximum depth of ray penetration is about 14 km at the center of the model.

Results from “Wet” SHIPS suggest that the Seattle basin contains several sub-basins (Brocher et al., 2001). In map view, the “Dry” SHIPS results suggest a sub-basin in only the eastern portion of the model (Figure 6), however, in cross section there is some evidence for four sub-basins in the velocity contours. The density model does not require distinct sub-basins. The “Dry” SHIPS profile extended further east than the model of Brocher et al. (2001) and provides additional information for the entire basin. The length of the basin is about 70 km measured from Hood Canal to a step up in contours on the eastern portion of the model. The length of the Seattle basin can be used to determine the length of the Seattle fault. The Seattle basin is symmetric, therefore, either the bounding faults are active and moving at the same rate or that the Seattle fault is the source controlling the geometry of the Seattle basin.

A tie to a N-S reflection line within the Puget Sound from the “Wet” SHIPS '98 results confirms that the depth to the top of basement along the “Dry” SHIPS profile is 6 km (ten Brink, in review). This reflection line is tied to the Mobil-Kingston well #1, where the stratigraphy is well defined. The velocity field from the N-S line also correlates well with the “Dry” SHIPS profile. On the north-south line, the 4.5 km/s contour correlates with the top of the Siletz as marked by from the Mobil-Kingston well where the top of Siletz is interpreted as basalt interbedded with siltstone, tuff, and conglomerate (Rau and Johnson, 1999). These results also show the basin is asymmetric in the north-south direction.

Deeper velocities in the “Dry” SHIPS model are consistent with other tomographic studies (Brocher et al., 2001; Van Wagoner et al., in review; R. S. Crosson, person. comm., 2001). East of the Puget Sound at about 70 km there is a decrease in velocity in the upper part of the crust. This contact is also consistent with postulated strike-slip faults through the Puget Sound (Figure 3). These strike-slip faults are also coincident with seismicity in the upper 5 km.

Gravity

In order to see how the new “Dry” SHIPS velocity model fits into the existing gravity framework, a gravity model was constructed along the profile. In addition, the gravity model provided additional constraints to “Dry” SHIPS tomographic results. In the past, the gravity field has been a major source of information for understanding the structures within the Puget Lowland. First, a gravity map was constructed from data extracted from UTEP’s National database and merged with stations collected by the U. S. Geological Survey collected gravity along the “Dry” SHIPS profile (Figure 1) (V. E. Langenheim, writ. comm., 2000). In order to look at the upper crustal contribution to the gravity field, a 2nd order polynomial fit was removed from the Bouguer anomaly. Gravity lows in this second order residual shows the extent of the Seattle basin as well as several other basins within the Puget Lowland. The Olympic Mountains are represented by a large gravity low which is consistent with the lithologies within the exposed accretionary prism. A large gravity high between the Olympic complex and the Seattle basin is interpreted as the Siletz terrane (Figure 1).

Density Modeling

A gravity model was constructed along the “Dry” SHIPS transect (Figure 1). Bouguer gravity values from stations within 1 km of the profile were extracted from the gravity database for use in a 2 ½ - D forward modeling program (Cady, 1980). The model was initially constructed using structures observed in the “Dry” SHIPS velocity model. Constraints on the east end of the model were provided from a gravity model constructed for PacNW ‘91 (Miller et al., 1997). The slab geometry was compiled from “Wet” SHIPS seismic studies of the Moho (Tréhu et al., 2001; Preston et al., 2001) and gravity models south of the study area (Finn, 1990; Parsons et al., 1998; Kilbride, 2000). A velocity model derived from a tomographic study of earthquake arrivals was also used as a guide for depths greater then 15 km (R. S. Crosson, person. comm., 2001). Near surface constraints were provided by existing geologic maps (e.g., Gower et al., 1985).

Initial densities were calculated using a typical velocity/density relationship (Christensen and Mooney, 1995) and from lab measurements of samples from local outcrops (Brocher and Christensen, 2001) (Figure 8). The accretionary wedge was assigned a density of 2560 kg/m^3 and the Siletz terrane has a density of 2890 kg/m^3on the basis of lab results obtained by Brocher and Christensen (2001). A pluton on the east end of the profile under the foot-hills of the Cascade Range was necessary to fit a small wavelength feature in the upper crust, which has a density contrast of 150 kg/m^3. The upper crustal rocks beneath the Cascades have a density of 2600 kg/m^3 which is consistent with PacNW '91 (Miller et al., 1997). The middle crust has a density of ~ 2800 kg/m^3, the lower crust has a density of 2900 kg/m^3, and the transitional layer has a density of 3150 kg/m^3 which is consistent with PacNW '91 (Miller et al., 1997). The oceanic crust has a density of 2900 kg/m^3, the upper mantle of the slab has a density of 3280 kg/m^3, and the downgoing crust and upper mantle of the slab has a density of 3300 kg/m^3, which is consistent with models south of the study area (Finn, 1990; Kilbride, 2000). The Cascade upper mantle wedge has a density of 3250 kg/m^3 (Miller et al., 1997) and the Juan de Fuca upper mantle has a density of 3280 kg/m^3 (Finn, 1990).

The large gravity signature is primarily produced by the contrast between the Olympic accretionary rocks, the Siletz terrane, and the Seattle basin. Deeper features such as the Juan de Fuca slab and upper mantle contribute little to the gravity signature. From west to east, the main features of the density model in the upper crust include the Hurricane Ridge fault, the Hood Canal fault and the Seattle basin (Figure 8). The Olympic accretionary wedge underthrusts the Siletz at the Hurricane Ridge fault and is underlain by denser material. The model (Figure 8) suggests that the Olympic accretionary complex is indistinguishable from the middle crust below 5 to 6 km depth. The Siletz terrane is distinguishable to a depth of 17 km and underlies the Seattle basin out to 65 km (Figure 8). Beneath the Seattle basin, the Siletz terrane is truncated near the location of the Coast Range Boundary fault. The Seattle basin is stratified with lower density, less consolidated material of about 4 km thickness and higher density, more consolidated material of about 3 km thickness. The oceanic plate is about 7 km thick and the slab dip about 7° out to a distance of 75 km where it increases its dip to 11° (Tréhu et al., 2001).

The density model can be interpreted several different ways, but with the constraints of the seismic and other geologic data the upper 8 km of the model are well defined. The slab geometry is well defined by other studies (e.g., Tréhu et al., 2001), but the remainder of the model below 8 km becomes more speculative as to the true geologic structure. It cannot be determined where the Siletz terrane ends and the pre-Tertiary basement rocks begin, but the location of the eastern end of the Siletz terrane in the preferred density model is coincident with a change in the velocity field in the "Dry" SHIPS model (Figure 3).

Future Work

Further analysis of the S-wave data will aid in further assessing the seismic hazard. Also, additional testing of various stacking methods for the low-fold stack will provide mid- to lower crustal information along the profile.

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Non-Technical Summary

The Dry SHIPS experiment was designed to determine the structure and geometry of the Seattle basin in order to further assess ground shaking and potentially seismogenic structures in the Seattle area. We have now analyzed the data and produced a velocity model that shows the structure of the Seattle basin. The model shows that the basin is 70 km wide and 6 to 7 km deep along the profile. The width of the basin may be a good measure of the length of the Seattle fault, which is known to produce earthquakes. The basin geometry derived from the velocity model will be an important constraint in modeling earthquake site response.

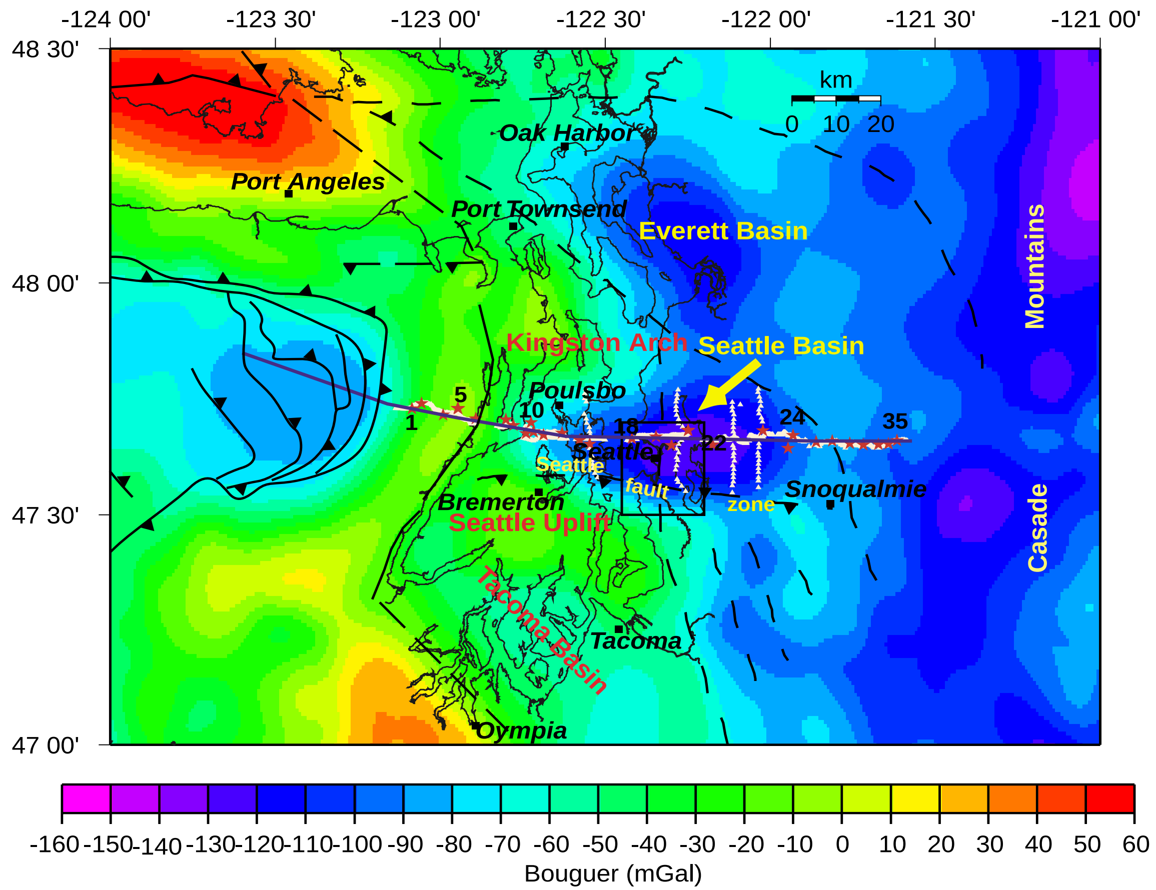

Figure 1. Bouguer anomaly gravity map. White dots are the receiver stations and the red stars are shot point locations for the Dry SHIPS experiment. The black square shows the Kingdome grid. Major basins and uplifts in the Puget Lowland are annotated. Thick black lines are faults and are dashed where speculative (Faults compiled from Tabor and Cady, 1978; Gower et al., 1985; Whetten et al., 1988; Yount and Gower, 1991; Tabor et al, 1993; Tabor, 1994; Johnson et al., 1999).

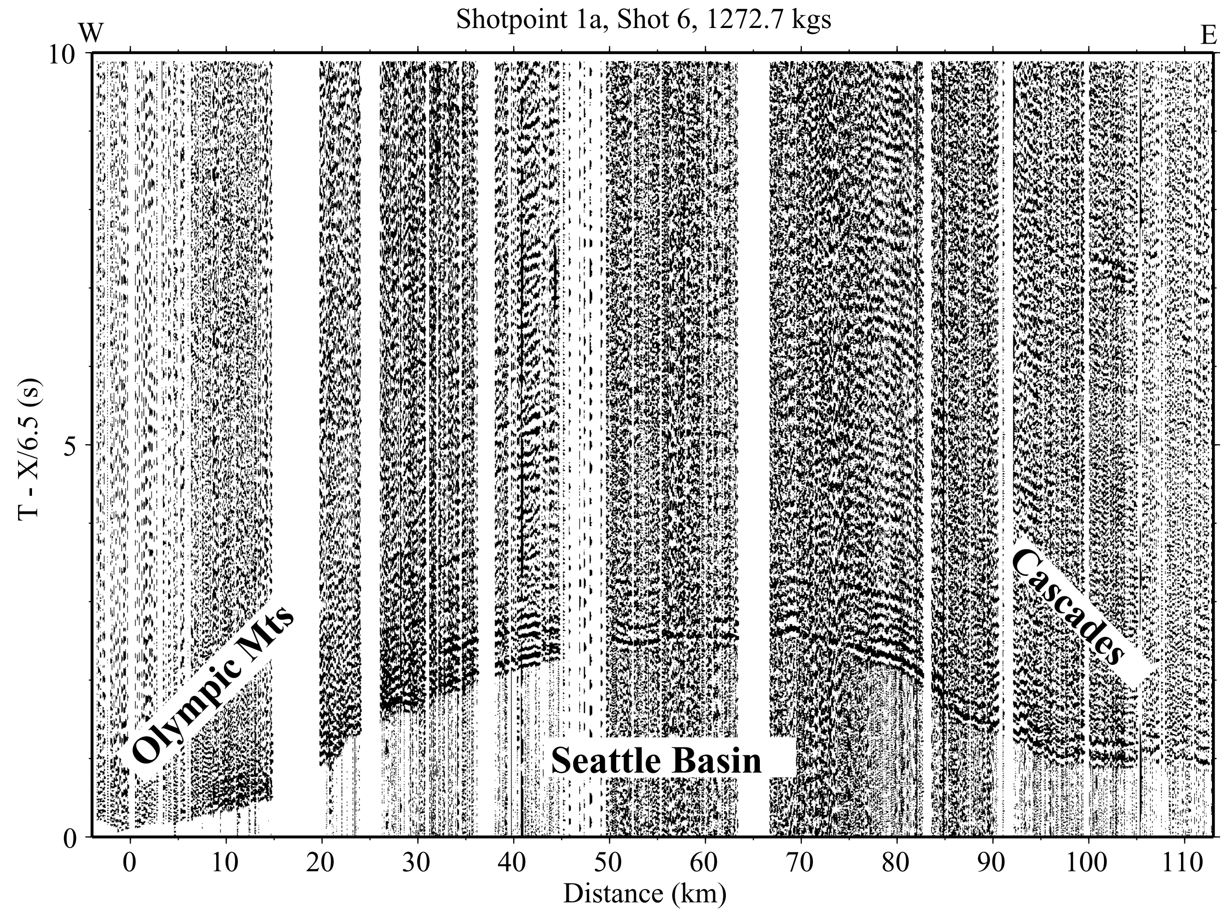

Figure 2. Seismic record section of shot point 1a. A total of 2800 lbs. of explosives were detonated at this site. The signal carried the length of the profile. The section is reduced at 6.5 km/s. The Seattle basin shows as much as a ~ 2 s traveltime delay relative to the Cascade Range.

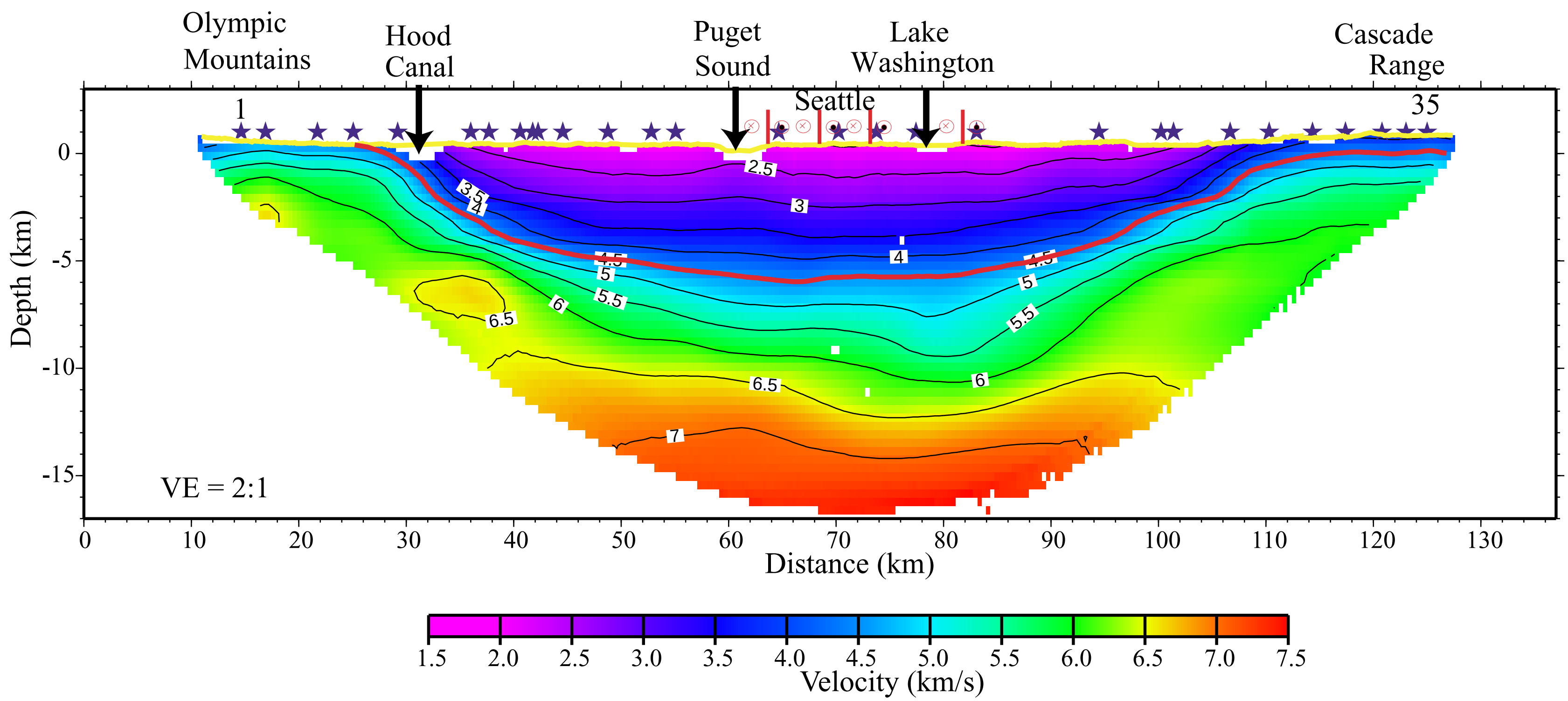

Figure 3. 2-D weighted slice of the velocity model. Shotpoints are signified by blue stars. Elevation is represented by the yellow line. Contour interval is 0.5 km/s. The 4.5 km/s contour is highlighted in red. Major waterways along the profile are annotated. The basin ranges in velocity from 1.7 km/s to 4.5 km/s. Mid-crustal velocities increase from 4.5 km/s to 6.5 km/s. Lower crustal velocities increase from 6.5 km/s to 7.2 km/s.

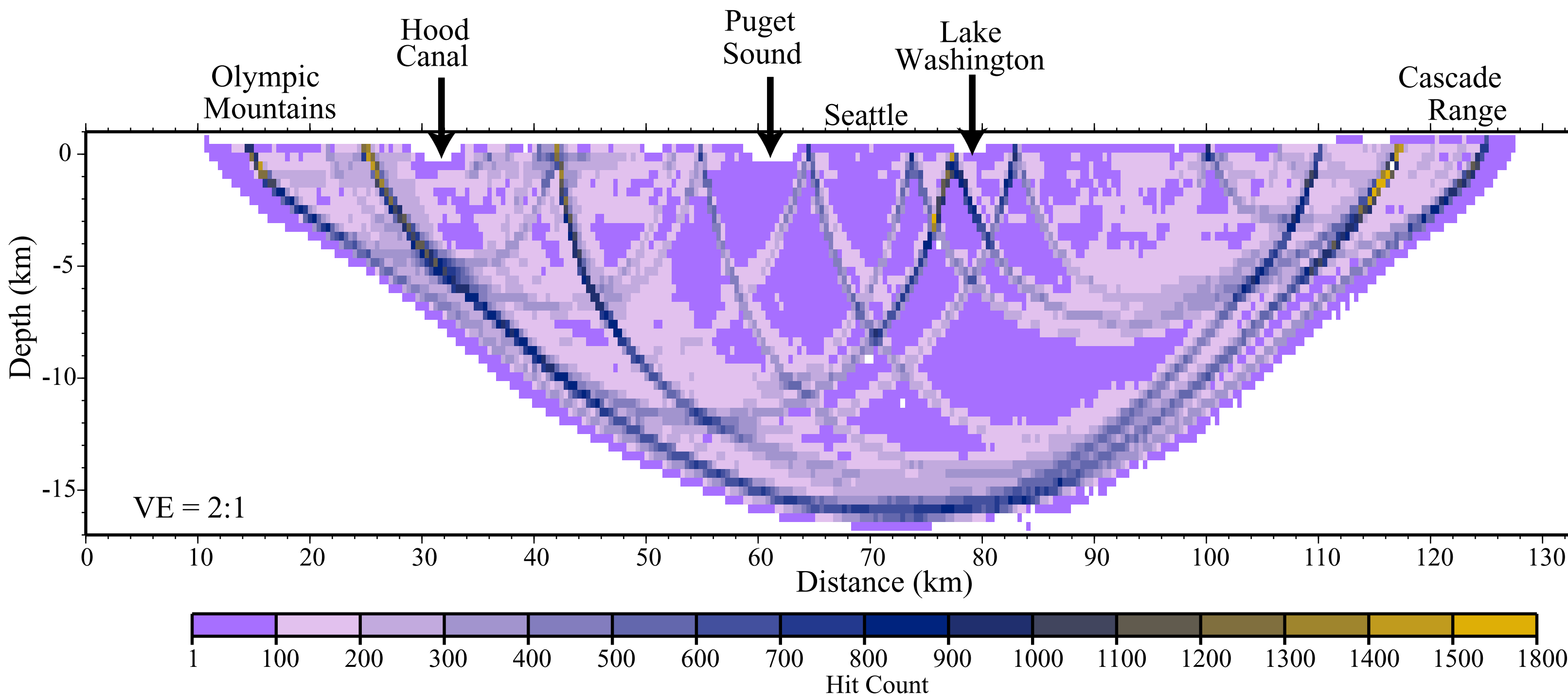

Figure 4. Hit count for the model. This is also a weighted average of the 3-D model space. The coverage number represents the number of hits per node within the model space. Overall the ray coverage is very good and shows the model is sampled well.

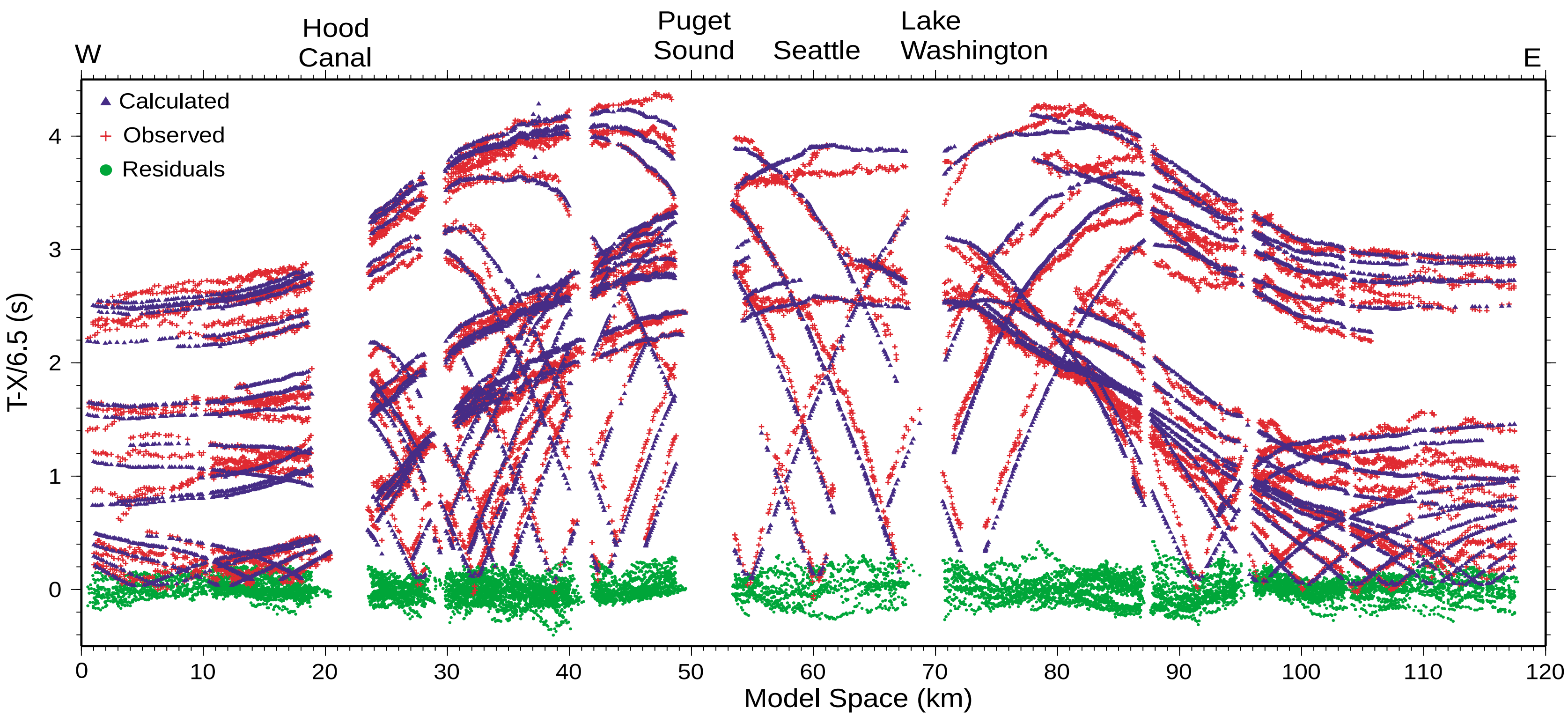

Figure 5. Traveltime fits for the model. Red circles represent the observed picks, blue triangles represent the calculated picks and the green crosses represent the residuals. The RMS residual for the model is ~ 0.10 s.

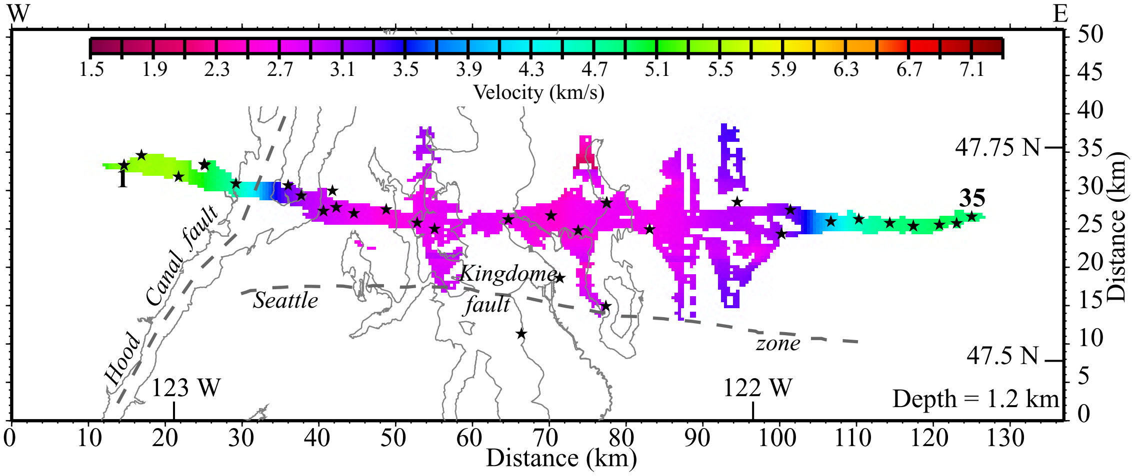

Figure 6. Masked velocity along the Dry SHIPS profile in map view at 1.2 km depth. Small stars are shotpoint locations.

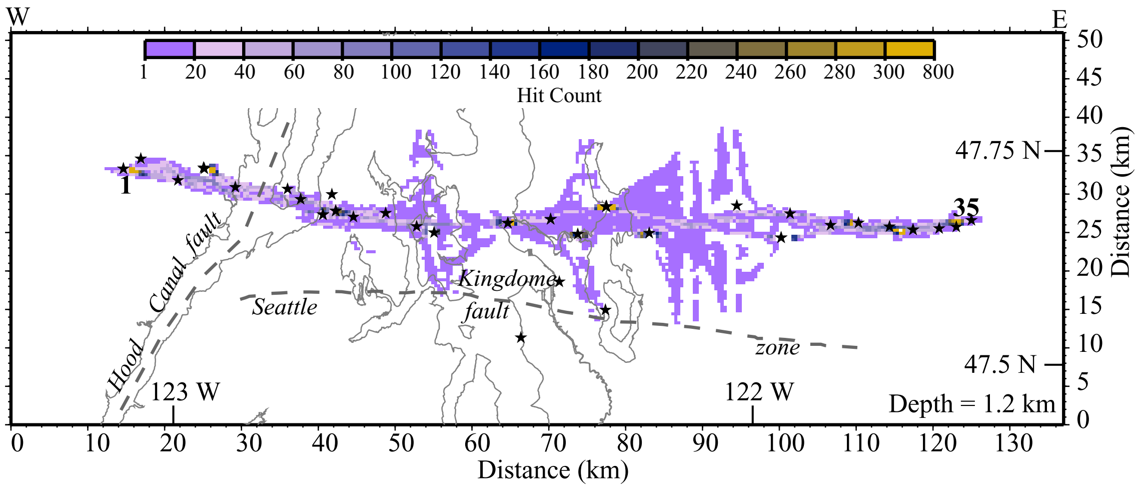

Figure 7. Ray coverage along the Dry SHIPS profile in map view at 1.2 km depth. Small stars are shotpoint locations.

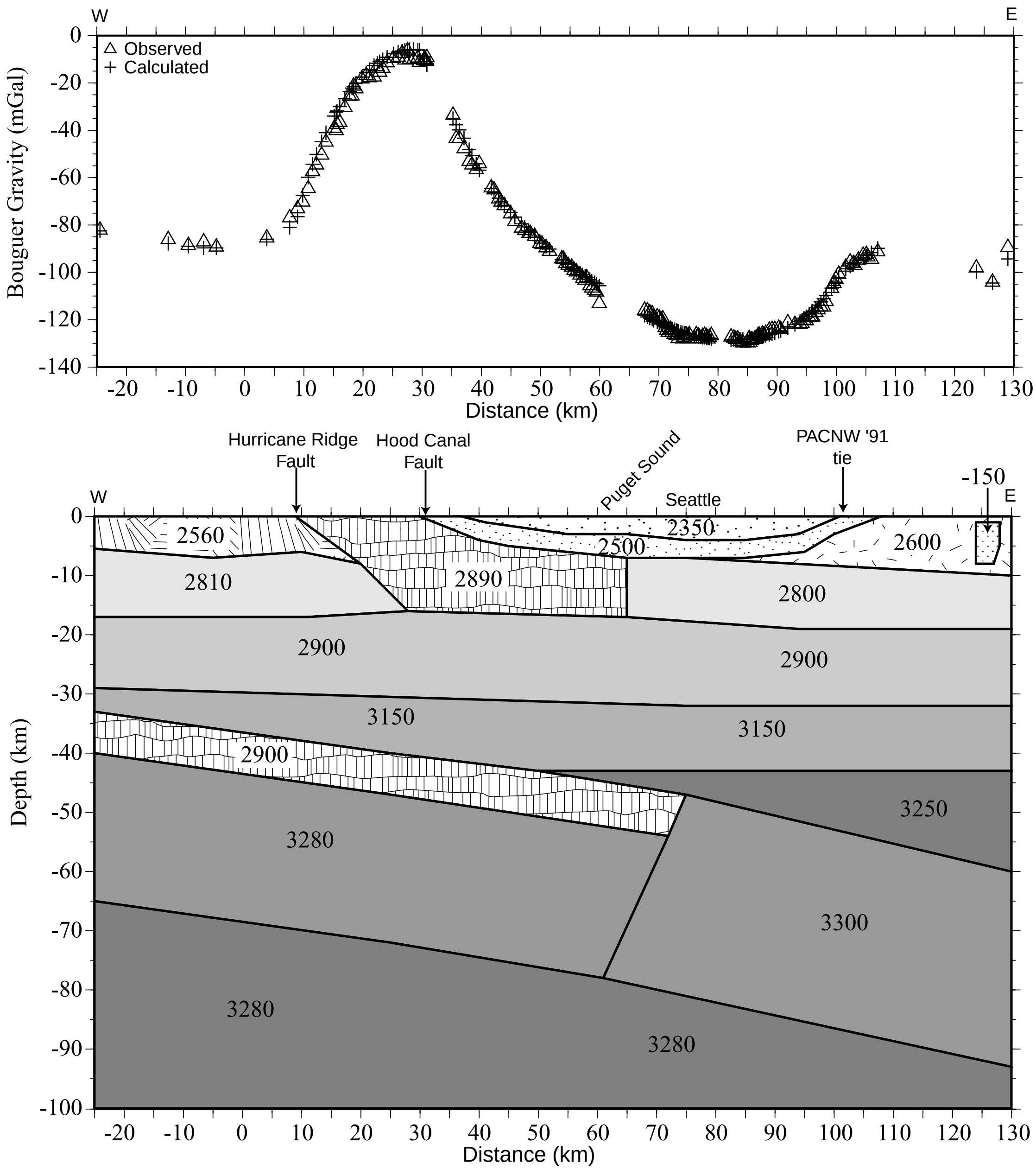

Figure 8. Density model along the Dry SHIPS profile. Densities are in kg/m^3. Model co-ordinates are the same as for the velocity model.