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

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Kate C. Miller and Catherine M. Snelson
University of Texas at El Paso
Department of Geological Sciences
El Paso, TX 79968-0555

Phone: 915-747-5501
Fax: 915-747-5073
Email: miller@geo.utep.edu
URL: www.geo.utep.edu

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Introduction

The overall objectives of the Seismic Hazards Investigation of Puget Sound (SHIPS) are to understand the distribution and size of earthquake sources (fault locations and geometry) as well as earthquake effects (the influence of the regional velocity structure on strong ground motion) in this urban area. Over tens of millions of years, oblique convergence in the Pacific Northwest has led to the development of a series of strike-slip faults as well as east-west trending reverse faults within the Puget - Willamette Lowland (e.g., Riddihough, 1984; Johnson, 1985). This system of faults has created a series of deep fault bounded basins (e.g., Johnson and others, 1994; Pratt and others, 1997). The city of Seattle overlies one of these deep basins, which may focus energy and enhance ground shaking when an earthquake occurs (Frankel and others, 1999). The Dry SHIPS phase of this project is designed to assess the seismic hazard in the Seattle region through acquisition and analysis of wide-angle seismic reflection/refraction data along a transect from the Olympic Peninsula through the city of Seattle in to the foothills of the Cascades (Figure 1). In this report we present our preliminary 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. An article that reviews some of the challenges of the experiment and preliminary results has been accepted for publication in EOS (Brocher and others, in press).

Data Analysis

The process of merging the data from all the different instrument types into shot records was completed by Tom Pratt in February 2000. An open file report that documents the data was also published this year (Brocher and others, 2000) and a copy of the data have been transmitted to the IRIS Data Management Center (http://www.iris.washington.edu). Overall the data quality 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 2s travel time delay (Figure 2) relative to arrivals in the Olympic Mountains and the Cascades (Figure 2).

To produce a velocity model along the profile, ca. 8800 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 (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 133 x 22 x 31 km model space, and a 400 m grid interval (Figure 3). Ray coverage is good throughout the model to depths of 20 km (Figure 4). The final RMS travel time residual is ~0.08 s and reflects an excellent fit of the observed data to the calculated travel times through the model (Figure 5).

Preliminary Interpretation

The model (Figure 3) shows that at this crossing the basin is ~6 to 7 km deep, assuming that the strong velocity gradient at 4.5 km/s represent s the basin-bedrock contact. This estimate agrees well where it ties an interpretation of a N-S reflection/refraction profile within the Puget Sound (ten Brink and others, in preparation). The contact with the Siletz terrane to the west of basin dips smoothly at ~25 degrees whereas the contact with the Cascades dips less steeply at ~20 degrees. East of Puget Sound, the velocities within the upper part of the basement are slower as would be expected for the pre-Tertiary basement of the Cascades. This change corresponds well with the location of inferred strike slip faults in the region. The length of the basin is ~70 km, which is probably a good indicator of the length of the basin-bounding Seattle fault to the south.

Gravity Data

During the Dry SHIPS experiment, the UTEP group collected 30 gravity stations in the Tacoma basin and on the Seattle uplift (Figure 1). In addition the U. S. Geological Survey collected 184 gravity stations along the Dry SHIPS profile (Langenheim, 2000, written communication). These data have been reduced and merged with existing NGS (Hittelman, 1994) and Canadian gravity data (Hearty and Gibb, 1994) (Figure 1).

Future Work

Future work on the velocity model will include incorporation of data recorded during a deployment associated with the implosion of the Kingdome in March, 2000 (Brocher and others, in press) as well as travel times from a transect recorded in 1991 (Miller and others, 1997). The resolution of the final velocity model will be assessed with checkerboard tests. We will use the final velocity model as a constraint on stacking velocity, in an effort to produce a low fold stack of the data. The quality of S-wave arrivals in the data will also be evaluated and will be modeled if of sufficiently high quality. In addition detailed analysis of the upper 1 km of the basin, in conjunction with colleagues from the U. S. Geological Survey, for further analysis of site response in the Seattle basin. Finally a 2.5-D density model will be made along the main profile using the gravity data collected along the profile and the velocity model as constraints.

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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. In the future our velocity model will be used to study possible patterns of ground shaking in the Seattle area.

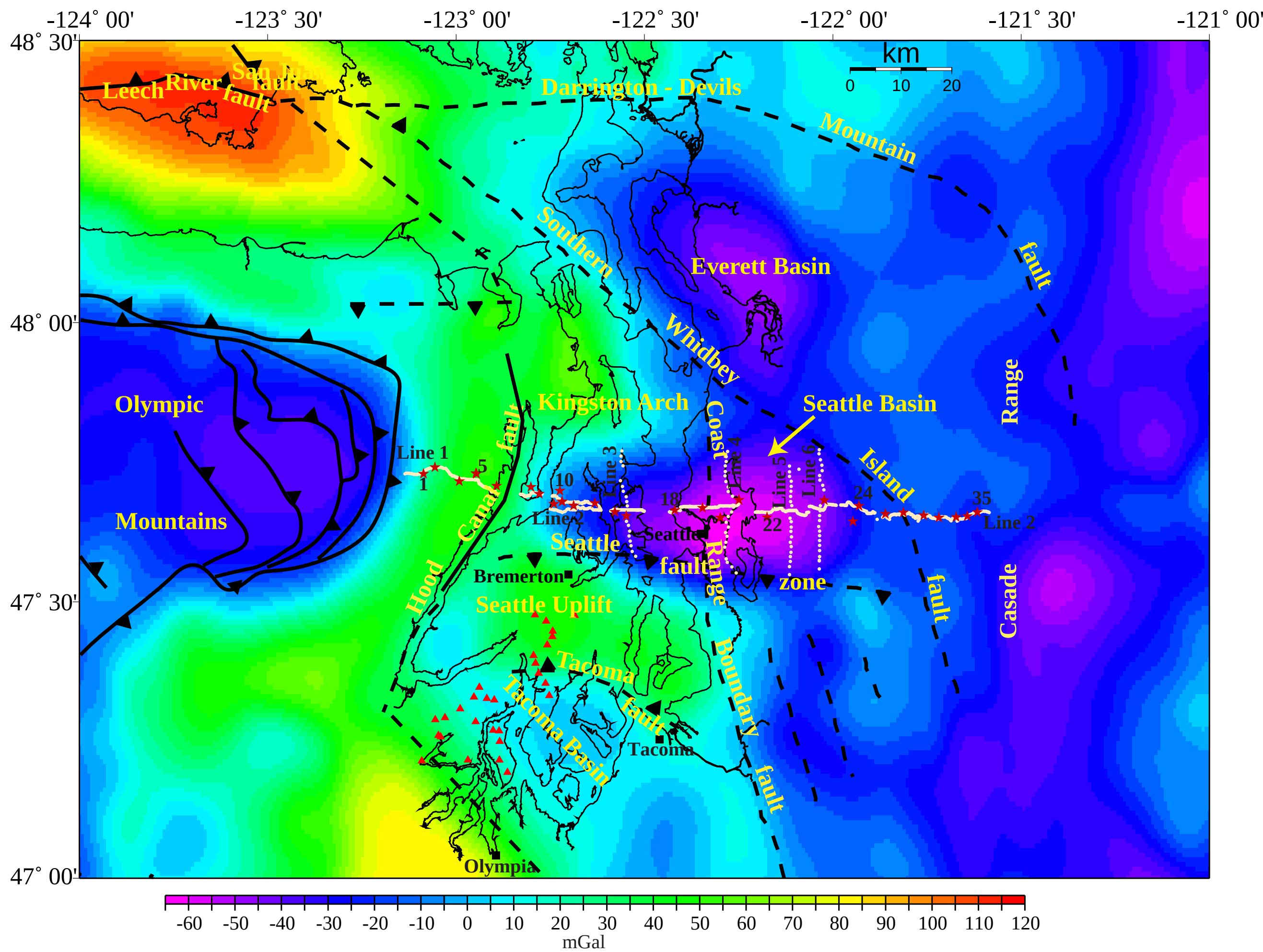

Figure 1. Second order residual gravity anomaly map. White dots are the receiver stations and the red stars are shot point locations for the Dry SHIPS experiment, Numbers are selected shot point numbers for reference. Red triangles are gravity station locations collected by UTEP during the Dry SHIPS experiment. Additional gravity stations were collected by the U. S. Geological survey along the Dry SHIPS profile. Thick black lines are faults and are dashed where speculative (Faults are 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).

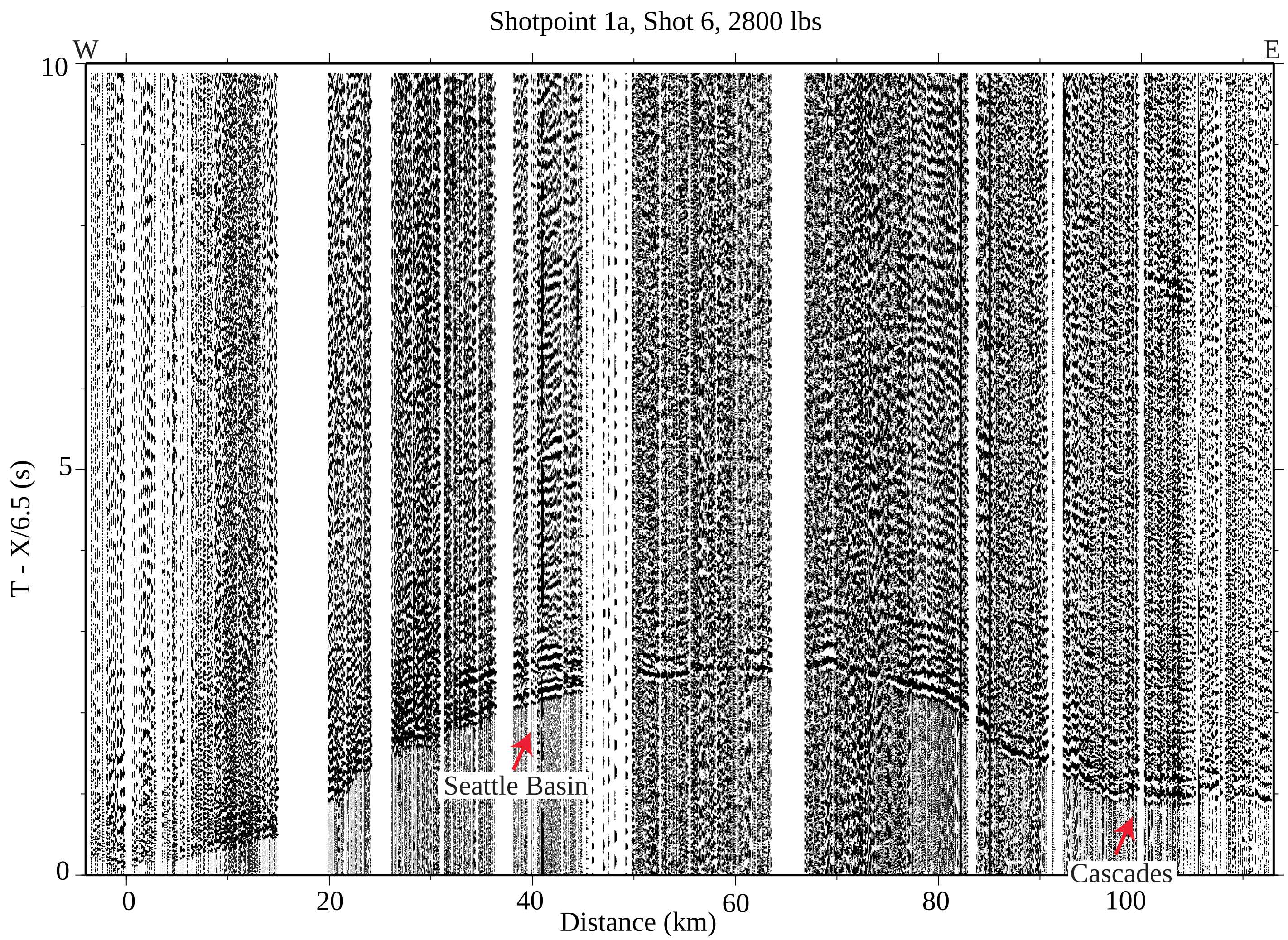

Figure 2. Seismic record section of shot point 1. A total of 2800 lbs of explosives were detonated at this site. The signal carried the length of the profile. The section is reduced at 6.5 km/s. The Seattle basin shows as much as a ~2 s travel time delay relative to the Cascade Range.

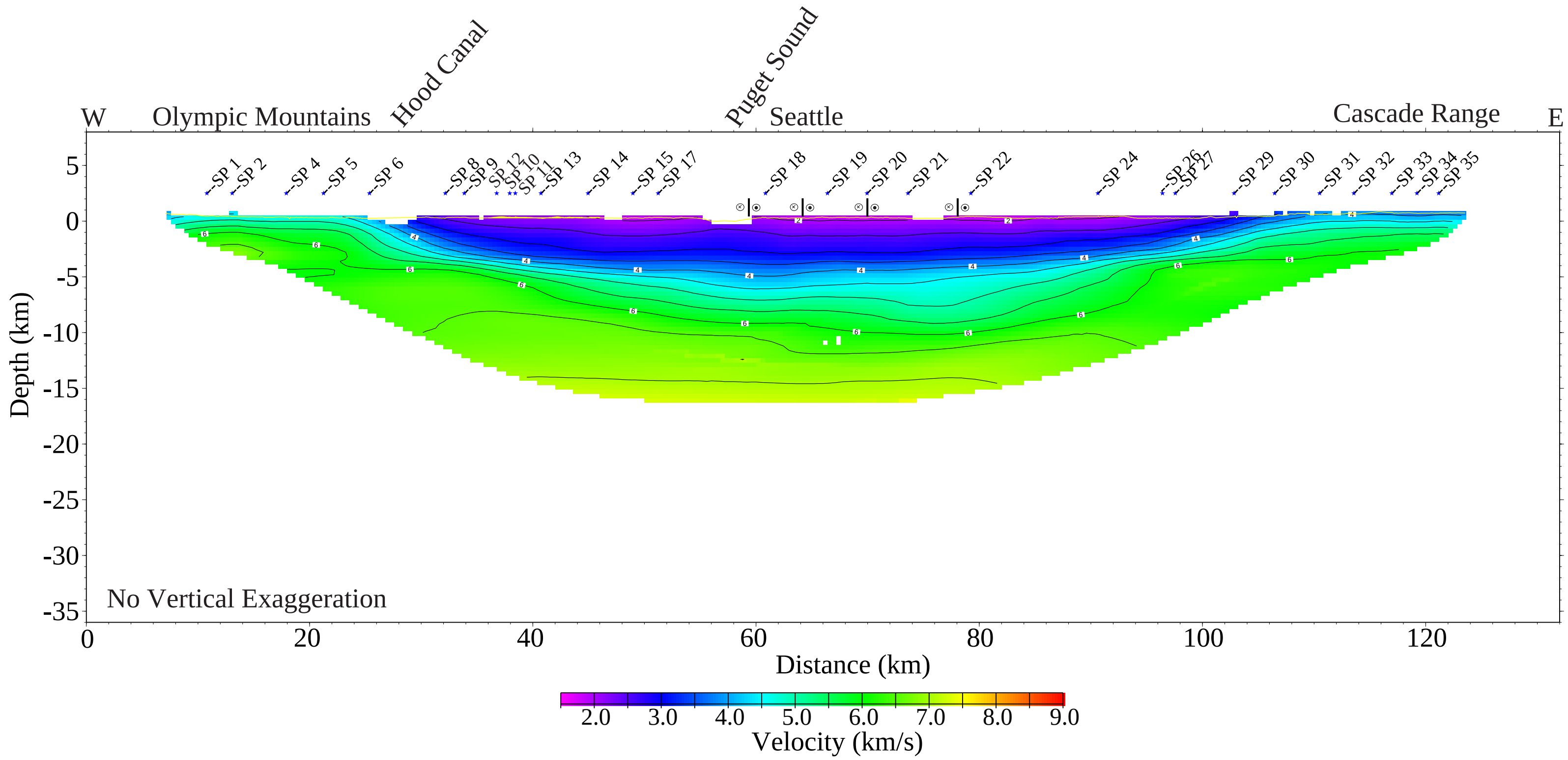

Figure 3. Preliminary velocity model for the Dry SHIPS profile. This model is a weighted average of the 3-D model space. The final RMS is ~0.08 s. Along this profile the basin is ~ 6 to 7 km deep, assuming that the strong velocity gradient at 4.5 km/s represents the basin-bedrock contact. This results ties well with a N-S Wet SHIPS profile (ten Brink et al., in prep.). The dip along the west side of the basin is ~25 degrees where the dip along the east side is more gentle at ~20 degrees. East of Puget Sound, the velocities within the upper part of the basement are slower as would be expected for the pre-Tertiary basement of the Cascades. This change corresponds well with the location of inferred strike slip faults in the region. The length of the basin is ~70 km, which is probably a good indicator of the length of the basin-bounding Seattle fault to the south.

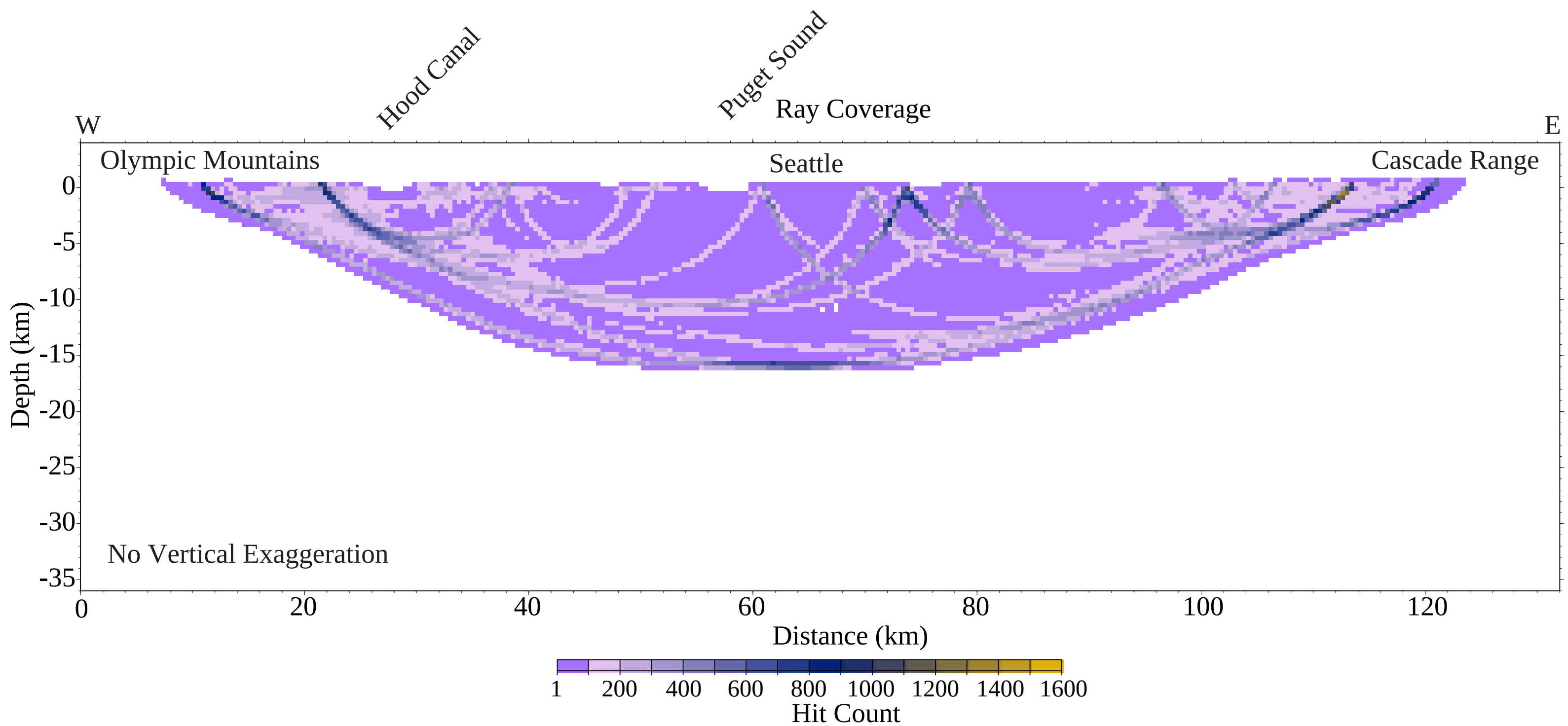

Figure 4. Ray coverage for the preliminary model. This is also a weighted average of the 3-D model space. The coverage number represents the number of hits per node within the model space. Overall the ray coverage is very good and shows the model is sampled well.

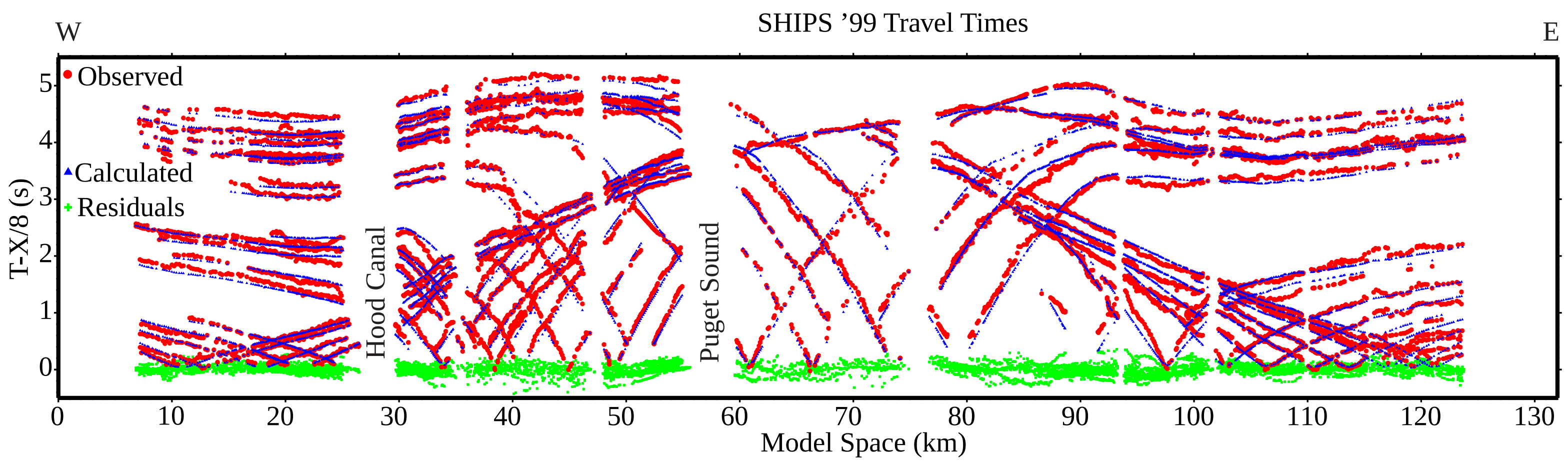

Figure 5. Travel time fits for the preliminary model. Red circles represent the observed picks, blue triangles represent the calculated picks and the green crosses represent the residuals. The RMS residual for the model is ~0.08s.