Urban seismic experiments in Puget Lowland, Washington, investigate the Seattle fault and Seattle basin

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In the past decade earth scientists have come to recognize the seismic hazards posed by crustal faults and sedimentary basins to Seattle, Washington (Figure 1). In 1998, the U.S. Geological Survey and its collaborators initiated a series of urban seismic studies of the upper crust to better map seismogenic structures and sedimentary basins in the Puget Lowland. We call these studies the Seismic Hazard Investigations of Puget Sound (SHIPS).

In March 1998 we conducted our first SHIPS study, an investigation of the upper crustal structure of the Puget Lowland, nicknamed Wet SHIPS, using marine airgun sources and land recorders [Fisher et al., 1999]. In September 1999, we obtained a seismic refraction line to study the upper crustal structure in the Seattle area, in a land-based study nicknamed Dry SHIPS [Brocher et al., 2000] (Figure 1). In March 2000, we recorded the demolition of the Seattle Kingdome sports stadium using a dense array of seismic recorders for a detailed site response study, nicknamed Kingdome SHIPS (Figure 1).

Collectively, the three SHIPS experiments have provided new images of the subsurface geometry of the crustal faults and sedimentary basins in Puget Lowland, as well as evidence that these sedimentary basins significantly focus seismic waves from earthquakes at periods between 1 and 5 seconds. Siting explosions and thousands of receivers in a densely-populated region, however, has provided challenges and opportunities. In the following, we describe some of the challenges and successes from the Dry and Kingdome SHIPS experiments.

Challenges of urban seismology

Urban seismology poses different challenges and opportunities than seismic work in remote areas. Seismologists and residents are forced to interact because many landowners must be contacted in order for seismologists to gain access to property. The use of explosives and the large team (nearly 100 individuals) needed to perform the work at this level of detail also naturally attract the attention of the citizenry and the media, leading to additional opportunities for public education concerning earthquake hazards. That there are more constituencies to satisfy when working in densely-populated areas is also inescapable. These groups include police and fire departments, Park and Recreation Departments, emergency management and 911 departments, and in this case, demolition crews. The efforts of all these participants and stakeholders must be coordinated with the seismological field activities. The stakeholders and residents of the Puget Sound region have been extremely interested in and supportive of our efforts despite our late-night disturbances during Dry SHIPS (see below), and our interaction with the public has been an extremely rewarding part of SHIPS.

<u>Dry SHIPS Experiment</u>

The Dry SHIPS survey provided high-resolution seismic refraction coverage along an east-west line through the center of the Seattle basin (Figure 1). Four shorter N-S trending fan lines, lines 3 to 6, provided three-dimensional control on the geometry of the eastern end of the Seattle basin (Figure 1).

We detonated explosions at 29 different locations; including four within the City of Seattle [Brocher et al., 2000]. Shot sizes ranged from 11 to 1130 kg of ammonium nitrate emulsion. Our late-night shots in Seattle, although small (180 kg or less), were much more energetic than we expected and were felt by Seattle residents as far as 4.5 km from the shotpoints, waking and alarming some residents. We attribute this energetic propagation both to the well-coupled detonation of the explosions within the water table and the trapping of the seismic energy by low velocity surficial units within the basin.

Several of our larger detonations triggered the Pacific Northwest Seismic Network (PNSN), allowing us to calculate the average hypocentral location errors of PNSN along the Dry SHIPS line [Brocher et al., 2000]. The average horizontal error in shot point location is 2.0 km; the average depth error is 2.1 km. The errors are systematically smaller, on average, in the middle of the Dry SHIPS line, between Bainbridge Island and Redmond, than on either end of the seismic line [Brocher et al., 2000].

We were remarkably lucky that 24 of our RefTek seismographs, deployed at 4 km intervals along the Dry SHIPS line, also recorded the M_w 7.6 Chi-Chi (Taiwan) earthquake of 9/20/1999 and several of its aftershocks [Shin et al., 2000]. These stations also recorded six local earthquakes and quarry blasts having magnitudes larger than 2 [Figure 1; Brocher et al., 2000]. The closest local event, with a local magnitude of 2.8, located near the eastern end of the Dry SHIPS line, provided high quality compressional and shear wave recordings (Figure 1).

Kingdome SHIPS Experiment

The Seattle Kingdome was a domed, concrete sports stadium approximately 192 m wide, 73 m high, and weighing 100,000 kg. The Kingdome was located near the northernmost strand of the Seattle fault in Seattle's downtown area (Figure 1). The Kingdome was imploded at 8:32 AM local time on March 26, 2000 to make room for a new professional football stadium. The more than 1820 kg of demolition charges were detonated as hundreds of small explosions during approximately 15 seconds. These explosions weakened the Kingdome's arches and the vertical supporting columns, but kept the massive central compression ring intact, allowing it to pull the dome structure inward and downward. The demolition contractor attempted to minimize the shaking produced by the implosion by piling concrete debris from the Kingdome beneath the compression ring, but the impacts nevertheless produced signals equivalent to those of a magnitude 2.3 earthquake. The collapse of the stadium was well recorded on the SHIPS network, with a series of arrivals emanating from the larger pieces of debris hitting the ground (Figure 2).

To further investigate upper crustal structure in Seattle we also detonated four small (68 kg) explosions located at the corners of the recording array in City of Seattle parks: Discovery, Lincoln, Magnusson, and Seward Parks (Figure 1). Based on lessons learned from our experiences during Dry SHIPS, we mitigated the impact of our late-night explosions on Seattle residents in several ways. First, the shot sizes were reduced to 68 kg from 182 kg. Second, we distributed leaflets to neighborhoods surrounding the shots to inform local residents of the possibility that they might feel shaking from our shots. Third, the local media was used to help broadcast our planned work to Seattle residents. Fourth, we manned the UW Seismology Lab at the time of the shots to answer questions from Seattle residents. Fifth, the shots were fired later at night, around 3:45 AM local Seattle time. Last, we notified Seattle's 911 services in case they received any calls resulting from our shots. Our mitigation efforts were successful this time, as no felt reports were made.

During Kingdome SHIPS, Texan and RefTek seismographs were spaced throughout Seattle at 1-km intervals on an approximately hexagonal grid from Green Lake in the north to Boeing field in the south (Figure 1). The grid was centered on the Seattle Kingdome, straddled the Seattle fault, and encompassed most of the important transportation, industrial, and commercial areas in Seattle. In addition to this regular grid, we recorded data at 23 special sites already being investigated as part of an on-going study of site response (squares) [Figure 1; Frankel et al., 1999].

A large majority of the recording sites were located at private residences or businesses. Due to the large number of recording sites needed throughout Seattle, we advertised our plans for Kingdome SHIPS and solicited volunteers. Over 101 of our sites were voluntarily offered to us via email, web, and telephone. The remaining 102 sites were located by contacting landowners (or property managers) directly.

Most (about 80%) of our recording sites were situated on Pleistocene deposits, mainly stiff soils that include glacial till and outwash deposits [Frankel et al., 1999]. The remaining sites were located on artificial fill, “modified land” (where the topsoil had been hydraulically removed), Holocene alluvium, and Tertiary sedimentary rocks [Frankel et al., 1999].

During the Kingdome SHIPS experiment, we once again were very fortunate that 35 RefTek seismic recorders, scattered throughout Seattle (Figure 1), recorded the M_w = 7.6 Volcano Islands, Japan earthquake (22.407˚N, 143.589˚E, depth 104 km) of March 28, 2000 (NEIC). Large-amplitude, coherent compressional, shear, and surface wave arrivals from this earthquake were recorded on our array.

Seismic Wave Amplification in Seattle Basin

Radial (E-W) horizontal component recordings for the M_w = 7.6 Chi-Chi (Taiwan) main shock of September 20, 1999 [Shin et al., 2000], show amplification of the shear-wave arrivals in the Seattle basin relative to sites in the Olympic Mountains (Figure 3). The (E-W) horizontal component corresponds to the radial component because the azimuth of propagation of these arrivals was 89˚E. The seismic recordings were made using identical RefTek models, geophones, and gains and hence the amplitudes of the recordings are directly comparable. Waveforms in Figure 3 are aligned on the predicted time for the S-wave arrival (calculated from the radially symmetric iasp91 standard earth model) and then shifted using cross correlation for optimal alignment of the waveforms. Traces are shown in true relative amplitude and have been low-pass filtered with a corner at 0.25 Hz (4 s period).

Similar amplification in the Seattle basin is observed for the shear-waves recorded on the transverse (N-S) horizontal components and for compressional-wave arrivals recorded on the vertical component (Figure 3). Note the large (factor between 6 and 10) amplification of the signal in Seattle, in the middle of the Seattle basin, relative to sites in the Olympic Mountains west of Hood Canal and to sites in the Cascade foothills, outside of the Seattle basin. Figure 3 shows in addition that the duration of compressional and shear wave arrivals at stations in the Seattle basin (approaching 100 seconds in Seattle) is significantly longer than for stations located outside of the Seattle basin (Figure 3).

In Figure 3 we also show the approximate E-W geometry of the base of the Seattle basin, compiled from Wet SHIPS and gravity results and preliminary inversions of Dry SHIPS first arrival times. There are two possible explanations for the strong correlation between the geometry of the basin filled with sediments and the amount of amplification. The first possibility is that the amplification results from focusing associated with the entire basin. The second possibility is that the amplification results from resonances and trapping of seismic energy within specific layers in the basin, probably the uppermost, lower velocity Quaternary deposits, whose geometry may mirror the geometry of the entire basin.

Length of Seattle fault

Dry SHIPS also provided a new understanding of the eastern end of the Seattle basin and Seattle fault. Due to the sparsity of receivers in this region during Wet SHIPS, tomography models resulting from our Wet SHIPS study failed to image this end of the basin. Gravity inversions for the depth to the top of volcanic basement rocks in the

Seattle basin, have greater uncertainty in the eastern end of the basin. This greater uncertainty is a result a lower density contrast between the basin fill and the Tertiary basement rocks in the east relative to the western part of the basin, where higher density Crescent Formation volcanics form the basement. Record sections from Dry SHIPS, such as Figure 4, clearly show a prominent travel time delay introduced by the lower velocities of the basin filling sediments extending eastward to the foothills of the Cascades. The distance over which travel times are delayed by basin sediments (Figure 4) implies that the Seattle basin is approximately 70 to 75 km wide, as opposed to the 60 km inferred from gravity data.

Thus the length of the Seattle fault is at least 70 km, assuming that the Seattle basin was formed by the fault [Johnson et al., 1994]. Standard fault-length earthquake-magnitude relations [Wells and Coppersmith, 1994] suggest that the Seattle fault could produce a magnitude 7.2 to 7.5 earthquake, for a fault length of 70 km, fault plane depths between 20 and 30 km and fault plane dips between 35˚ and 60˚. The dip of the Seattle fault has not yet been well resolved by SHIPS; estimates vary from 20˚ and 70˚ [Johnson et al., 1994, 1999; Pratt et al., 1997]. Although uncertainty in the dip of the fault has only marginal significance for calculations of earthquake magnitude, it is vital for calculations of the earthquake moment, total fault slip rate, and for the response of the basin to strong shaking.

Continuing and future research

Determining the origin of the amplification of the seismic waves within the Seattle basin remains a high-priority research topic. The 3-D velocity models we obtained in the basin should help us address the question of whether the basin amplification is mainly determined by the thickness and seismic velocities of the upper, unconsolidated sediments, or whether the geometry and seismic velocities of the entire basin fill is important. Merging of the data from all three SHIPS experiments will provide the data needed for final 3-D tomographic imaging of the seismic velocity structure of the entire Seattle basin. A site response study based on the comparison of the seismic amplitudes generated by the Kingdome implosion and our four shots as recorded during Kingdome SHIPS is just underway. Finally, we need to compare our recordings of the Chi Chi and Japanese Volcano Island earthquakes obtained during Dry and Kingdome SHIPS that provide detailed information about variations in site response in the Seattle area.

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Figures

Figure 1. Map showing locations of Dry and Kingdome SHIPS seismic shots and recorders. Inset map shows locations of Kingdome SHIPS seismic shots and seismographs used to record its implosion. Dry SHIPS profile is shown for reference. Abbreviations: BI-Bainbridge Island, LS-Lake Sammamish, LW-Lake Washington, MI-Mercer Island, VI-Vashon Island.

Figure 2. Data recorded by the Texan seismographs during the implosion of the Seattle Kingdome. The parallel bands of compressional-wave arrivals are interpreted as being caused by different pieces of the Kingdome impacting the ground over 15 seconds.

Figure 3. (Top) East-west horizontal component recordings of the M7.6 Chi Chi earthquake of September 20, 1999. Dotted line shows locations of SKS and S-wave arrivals calculated from the iasp91 standard earth model. Data have been low pass filtered with an upper corner frequency at 0.25 Hz. (Bottom) Relative amplitudes of compressional (triangles) and shear wave (asterisks) arrivals from the Chi Chi earthquake plotted against an approximate profile of the thickness of the Seattle basin. These amplitudes represent the relative amplitudes of the vertical component for P-waves and east-west horizontal (nearly radial) component for S-waves. The P-wave data were first low pass filtered with an upper corner frequency of 1 Hz; the S-wave data were low pass filtered with an upper corner frequency of 0.25 Hz.

Figure 4. Reduced record section for Shot point 1 in the Olympic Peninsula, showing vertical component traces only. Note the large time delays associated with the Seattle basin, and evidence for vertical steps (breaks) in the basin floor.

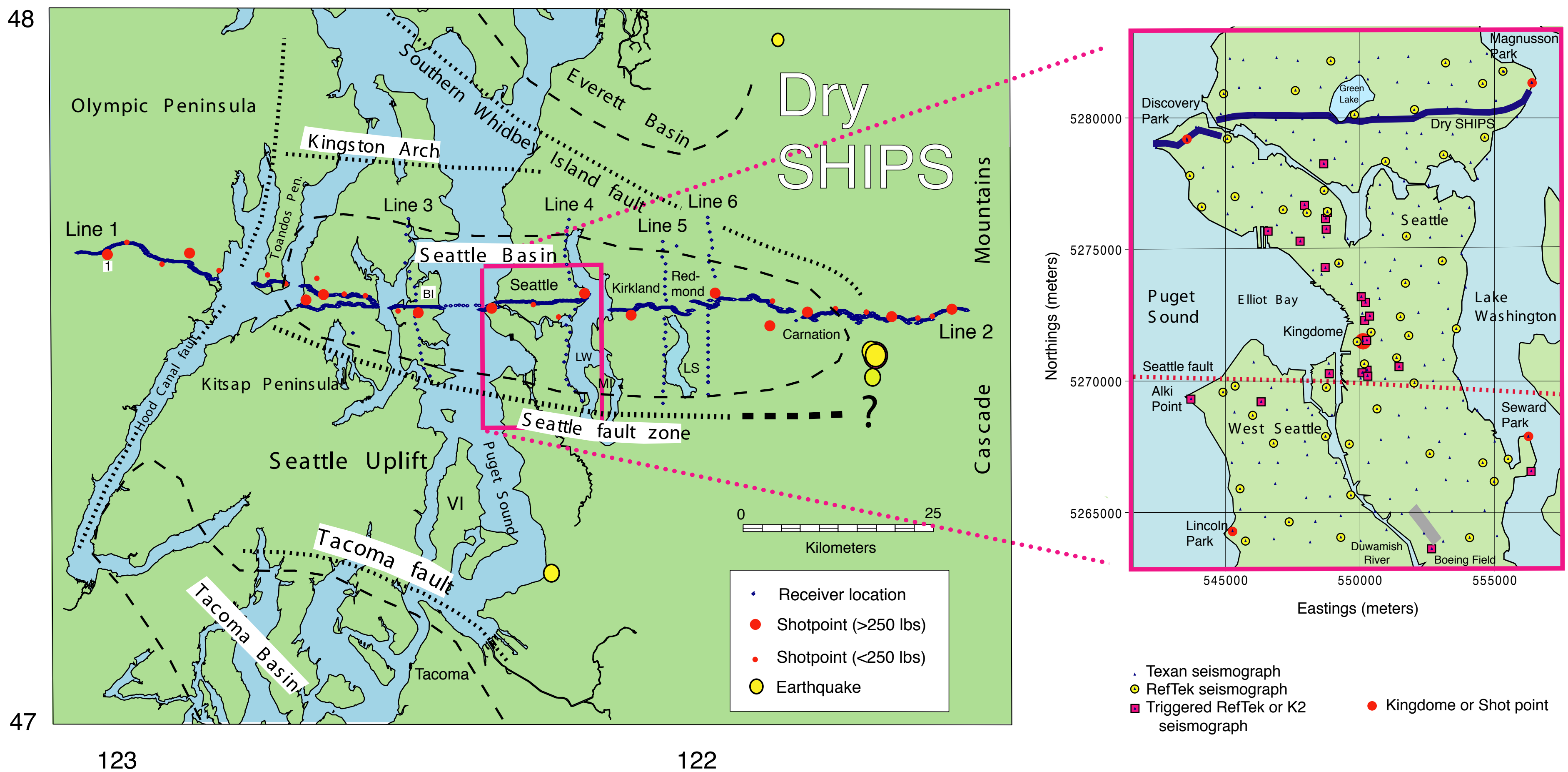
48
47
123
122
Olympic Peninsula
Kingston Arch
Southern Whidbey Island fault
Everett Basin
Dry SHIPS
Line 1
Line 2
Line 3
Line 4
Line 5
Line 6
Seattle Basin
Seattle
Kirkland
Red-mond
Carnation
BI
LW
MI
LS
Kitsap Peninsula
Hood Canal fault
Toandos Pen.
Seattle fault zone
Seattle Uplift
VI
Puget Sound
Tacoma fault
Tacoma Basin
Tacoma
Cascade Mountains
0
25
Kilometers
Receiver location
Shotpoint (>250 lbs)
Shotpoint (<250 lbs)
Earthquake
Magnusson Park
Discovery Park
Green Lake
Dry SHIPS
Seattle
Puget Sound
Elliot Bay
Kingdome
Lake Washington
Seattle fault
Alki Point
West Seattle
Seward Park
Lincoln Park
Duwamish River
Boeing Field
5280000
5275000
5270000
5265000
Northings (meters)
545000
550000
555000
Eastings (meters)
Texan seismograph
RefTek seismograph
Triggered RefTek or K2 seismograph
Kingdome or Shot point

Figure 1.

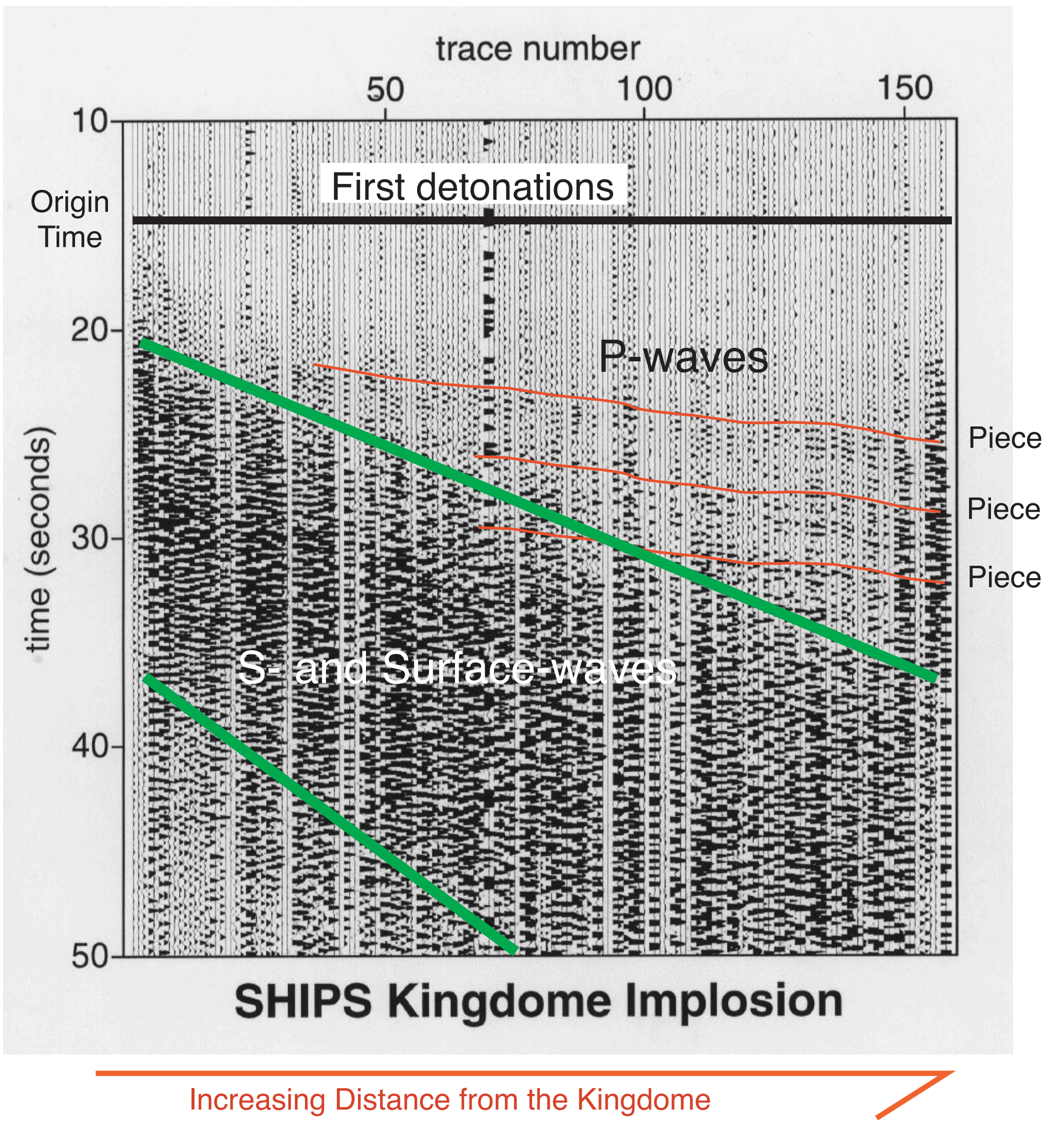

Figure 2. Brocher et al.

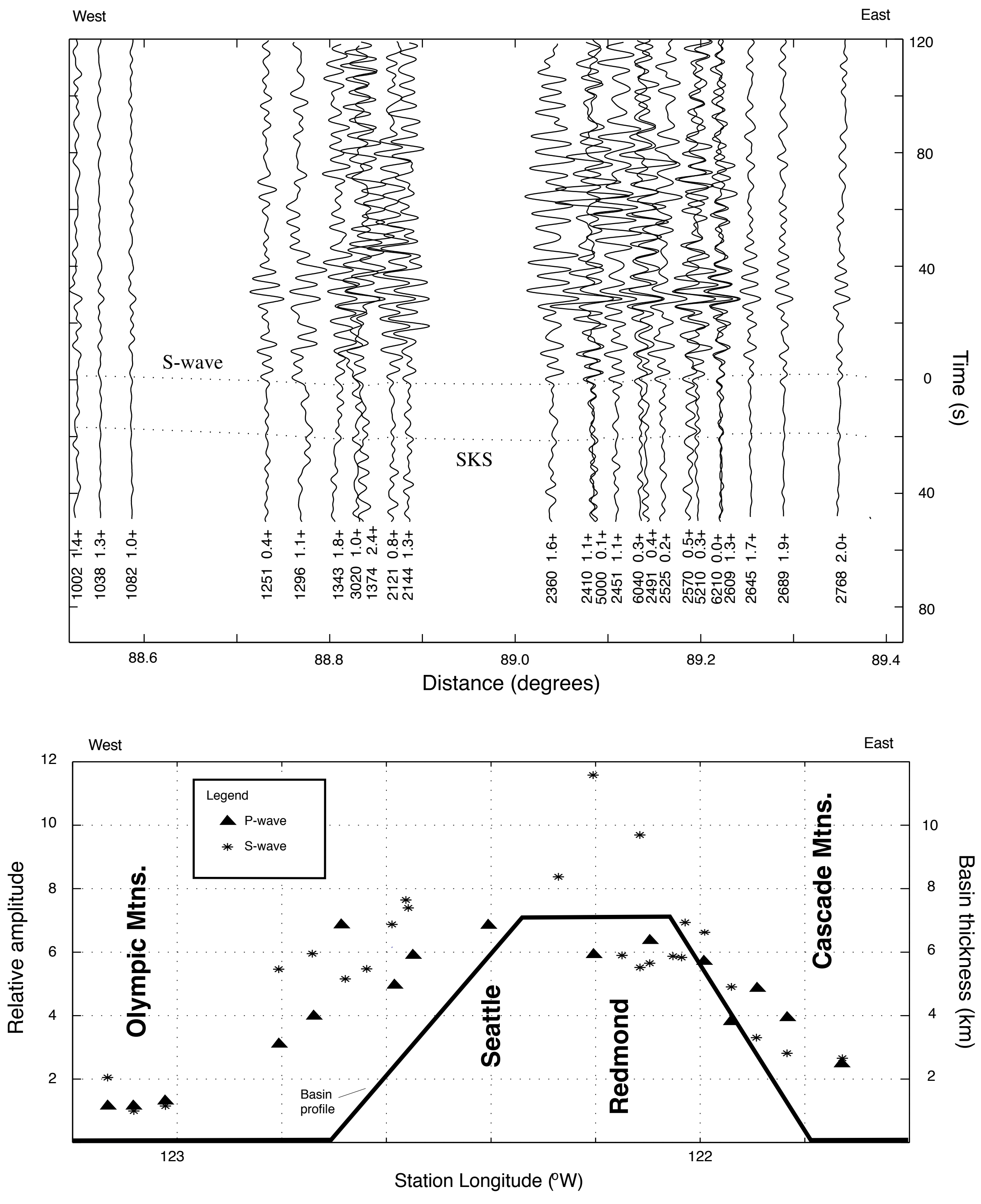

Figure 3.

Brocher et al.

Seattle Basin Delay Times

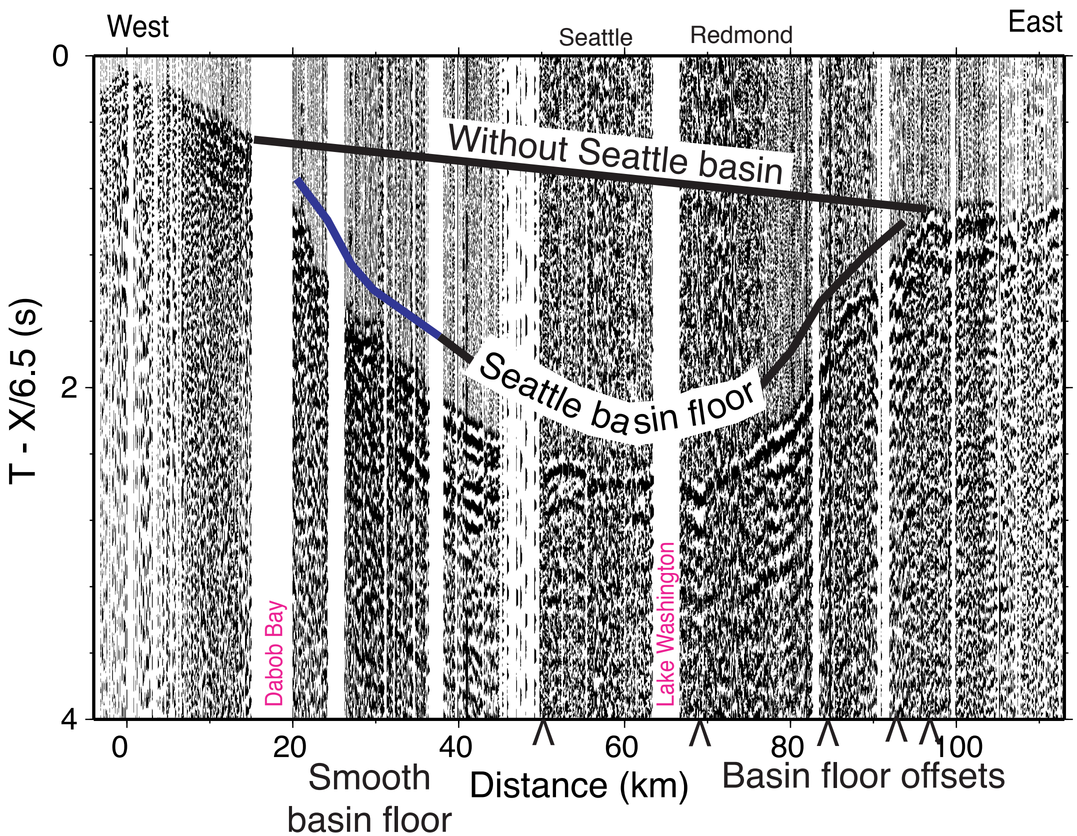

Fig.4. Brocher et al.