地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 81 (2006) pp. 283-289

Site Response, Basin Effects, and Attenuation in the Puget Lowland, Washington State, U. S.

Thomas L. Pratt

U. S. Geological Survey, School of Oceanography, University of Washington, Seattle, WA 98195 USA

Abstract

Site response, basin amplification, and attenuation within the Puget Lowland, in the Cascade forearc of Washington State, have been measured using large temporary deployments of seismometers during 3 Seattle Seismic Hazard Investigation of Puget Sound (SHIPS) experiments, and the permanent strong-motion network. Horizontal-component recordings of shear waves from teleseisms and local earthquakes were used to compute spectral ratios with respect to the average of several bedrock sites. Results show amplifications of 0.3 to 0.8 Hz seismic waves by factors of 6 to 12 at sites over the deep Seattle sedimentary basin (>2.5 km of sedimentary strata), with the peak amplification being at about 0.3 Hz. All sites in the central Puget Lowland are amplified significantly, however, which indicates that the deposits in the upper 2.5 km extending beyond the margins of the deep basin are responsible for much of the amplification. The deep basin itself appears to amplify waves by factors of up to 2 in the 0.05 to 0.2 Hz frequency range, which is consistent with resonance in the deep strata. The horizontal to vertical ratios and crosscorrelations of arrivals at adjacent stations on the basin are consistent with the presence of scattered body-wave energy and Rayleigh waves in the later portions of the long-period signal. Estimates of the shear-wave attenuation factors (Qs) between 2 to 20 Hz increase from 5 to 40 for shallow sedimentary deposits to about 250 for the deep sedimentary strata (7 km depth).

Key words : site response, ground shaking, attenuation

1. Introduction

Earthquakes are inevitable in subduction-zone settings such as Cascadia or Japan, and estimating likely levels of ground shaking therefore is crucial to designing structures. Subduction-zone regions are subject to earthquakes on the subduction zone itself, in the subducted oceanic crust, and in the overlying continental crust (e.g., Ludwin *et al.*, 1991). Ground shaking during these earthquakes is heavily influenced by local geologic conditions, with both the shallow deposits and the underlying sedimentary basins able to focus and trap energy, and cause resonances.

Eventually we may estimate earthquake ground motions using computer models that accurately simulate wave motions through complex, three-dimensional crustal models. However, empirical ground-motion data are needed to calibrate these models. Although there is a rapidly increasing strong motion network in the U.S., that network has still not reached a density of stations suitable for adequately studying the effects of underlying geologic features. Dense temporary deployments of seismometers are therefore useful for understanding ground motions.

This paper summarizes results of ground-motion analyses from the Seismic Hazard Investigations of Puget Sound (SHIPS) experiments, a series of major seismic experiments in the Cascadia region organized by the U.S. Geological Survey over the past 8 years (Fig. 1). These experiments have used large numbers of temporary deployments of seismometers (up to 1008 in one experiment) to collect reflection and refraction data to determine the crustal velocity structure and delineate active faults, but they have also recorded useful ground-motion data during local earthquakes and teleseisms.

* e-mail: tpratt@ocean.washington.edu

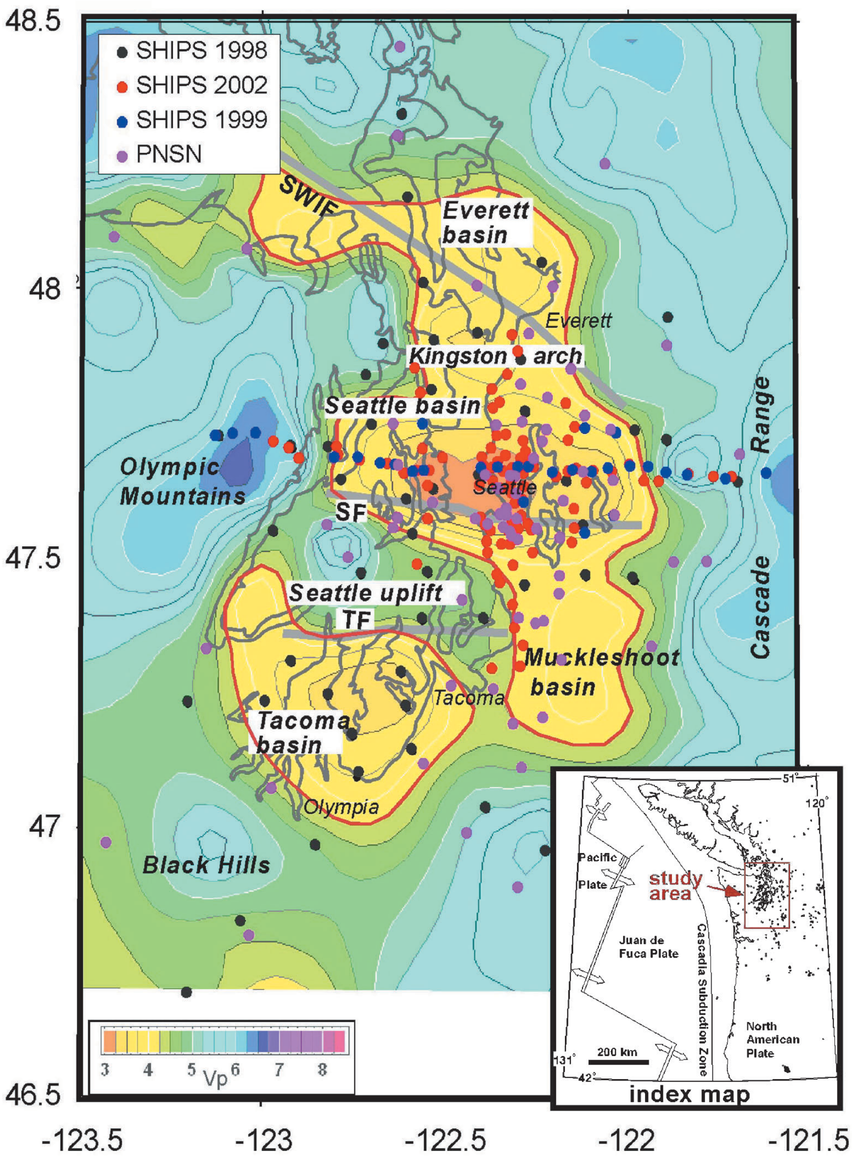

Fig. 1. Map of the Puget Lowland region of Washington state showing the locations of the seismograph stations used in the studies. Colors show the P-wave velocity at 2.5 km depth from a tomographic model (Van Wagoner *et al.*, 2002), with low-velocity regions outlined by the red lines defining the deep sedimentary basins.

2. Geologic Setting

The Puget Lowland is a broad valley, occupied by nearly 3 million people, between the Cascade Range arc and the Olympic Mountain coast range. Beneath the Lowland, Eocene volcanic basement rocks are folded and faulted into a series of structural uplifts and basins (Pratt *et al.*, 1997; Brocher *et al.*, 2004). Four major sedimentary basins beneath the Lowland, the Everett, Seattle, Muckleshoot, and Tacoma basins, reach depths of 5 to 9 km (Johnson *et al.*, 1994; Pratt *et al.*, 1997; Brocher *et al.*, 2001a; Van Wagoner *et al.*, 2002). Structurally uplifted blocks of basement rocks, including the Seattle uplift, Kingston Arch, and the area around the Southern Whidbey Island fault zone [SWIF], separate these sedimentary basins. Even these uplifted areas, however, have a sedimentary cover up to 2 km thick (Fig. 1; Johnson *et al.*, 1994; Pratt *et al.*, 1997; Brocher *et al.*, 2001a, 2004).

The Seattle basin is the deepest of the sedimentary basins beneath the Puget Lowland, and underlies the cities of Seattle, Bellevue, Kirkland and Bremerton. The Seattle basin is a 70 km by 30 km, 7 to 9 km deep trough in the crystalline volcanic basement rocks filled with Eocene to Quaternary sedimentary strata (Fig. 1; Johnson *et al.*, 1994; Pratt *et al.*, 1997). Strata within the Seattle basin, and the adjacent Tacoma and Everett basins, consist of marine sedimentary rocks in the deeper portions of the basin (Johnson *et al.*, 1994), covered with as much as 1.1 km of unconsolidated, primarily Quaternary sediments (Jones, 1996). The thickness of these unconsolidated deposits approximately correlates with the thickness of older sediments, with the Seattle basin containing the greatest accumulations of all ages.

The entire Puget Lowland region was covered by at least 4 glacial advances in the Quaternary, which left behind a sequence of deposits that extend across almost the entire Lowland (Booth, 1994). The uppermost of these Quaternary sediments are Pleistocene glacial deposits consisting of stiff glacial tills that were compressed by the advancing ice sheet (Galster and Laprade, 1991; Booth, 1994), and uncompacted recessional deposits that filled the lower areas of the Puget Lowland.

Soft sediments of Late Pleistocene and Holocene age fill the river valleys and other depressions carved by rivers and glaciers. Portions of the city of Seattle are also underlain by artificial fill created by hydraulically sluicing dirt from downtown hills onto the nearby tide flats (Galster and LaPrade, 1991). S-wave velocities in the Seattle area average 140 to 680 m/sec in the upper 30 m (Williams *et al.*, 1999).

3. Ground-Motion Measurements

The Puget Lowland shows considerable variation in ground shaking due to near-surface materials and the sedimentary basins. A number of studies document seismic wave amplification at the soft-fill sites in the Duwamish River valley south of downtown Seattle and over the Seattle basin (Langston and Lee, 1983; Ihnen and Hadley, 1986; Frankel *et al.*, 1999 and 2003; Hartzell *et al.*, 2000). Although the larger basin effects have been documented (Frankel *et al.*, 2003; Pratt *et al.*, 2003a), they have not been studied in detail because previous work has been concentrated on the Seattle urban area where most of the strong motion instruments of the Pacific Northwest Seismic Network (PNSN) are located.

In the last 8 years several temporary arrays of seismometers have been deployed on the Seattle sedimentary basin (Fig. 1), providing more extensive measurements of its response relative to the surrounding region. The 1998 SHIPS experiment included 50 continuously recording, 3-component instruments throughout the Puget Lowland (Brocher *et al.*, 1999; Brocher *et al.*, 2000a and 2001a), and the 1999 SHIPS experiment included 29 continuously recording, 3-component seismometers in an east-west array across the Seattle basin (Brocher *et al.*, 2000a, 2001a, 2001b; Pratt *et al.*, 2003a). In 2002 the USGS deployed 87 seismometers across the Seattle basin for 4 to 5 months specifically to examine its influence on ground shaking (Pratt *et al.*, 2003b). In the meantime, a rapid increase in the number of strong motion instruments in the Seattle region has provided recordings of local and teleseismic earthquakes. Barberopoulou *et al.* (2004 and 2006) used the PNSN strong-motion instruments to study the response of the Seattle basin to strong S-wave and surface-wave arrivals from the 2002 M7.9 Denali, Alaska, earthquake located 2400 km to the northwest.

The 2001 M6.8 Nisqually earthquake, located about 60 km southwest of Seattle, is the only event in the past 35 years to cause ground shaking strong enough to damage buildings and cause non-linear soil response (Frankel *et al.*, 2003; Booth *et al.*, 2004). Frankel *et al.* (2003) document the presence of basin surface waves during the Nisqually earthquake. Computer simulations of ground shaking in the Seattle region during the Nisqually earthquake led Pitarka *et al.* (2004) to conclude that the basin significantly amplifies long-period ground shaking.

4. Basin Effects and Site Response

The spectral ratios at sites over the Seattle basin relative to bedrock sites on the east and west sides of the Lowland are characterized by amplifications of as much as 6 to 12 at frequencies of 0.2 to 1 Hz, with decreasing amplification at higher and lower frequencies. Where there is a single, well-defined amplification peak, it lies between 0.2 and 0.5 Hz. Above 1 Hz, there is commonly a small amplification peak at 2 to 5 Hz, then decreasing amplification at higher frequencies. This pattern of amplification is not restricted to the Seattle basin, however, as other sites in the central Puget Lowland north and south of the Seattle basin also show substantial amplification. These results suggest that much of the amplification occurs in the shallow sedimentary section that covers nearly all of the Puget Lowland rather than in the deep sedimentary basin fill. Looking at the average spectral ratios at sites over the deep basin compared to those at surrounding sites shows the deep basin causes about a 2-fold amplification in the 0.05 to 0.2 Hz range (Barberopoulou *et al.*, 2006). This frequency range is consistent with vertical resonance caused by strata near the bottom of the basin.

Figure 2 shows maps of the Puget Sound region with spectral ratios at frequencies of 0.1, 0.3, 3 and 7 Hz, with each instrument site shown as a dot whose diameter is proportional to the amplitude of the spectral ratio. At 0.1 Hz the map shows a clear correlation between the deepest parts of the Seattle basin, or the geographic center of the basin, and spectral amplifications. The largest amplifications are at sites within the contour defining the 2.5 km thickness of sedimentary strata. The basin sites show moderate amplifications (3–6) at this frequency, whereas sites on bedrock and on the Seattle uplift all have spectral amplifications of 1 to 3. Sites on the Kingston arch, at the north edge of the basin, show amplification values between those on bedrock and those on the basin. Areas of soft fill, specifically the Duwamish and Snoqualmie River valleys, have spectral amplifications comparable to that at surrounding sites.

At 0.3 Hz the basin sites show their largest average amplifications (values of 8–12), with the maximum amplifications over the central portions of the basin. It is apparent, however, that all sites in the Puget Lowland show significant amplification relative to the bedrock sites at the east and west ends of the array, with large amplifications also occurring at sites over the Kingston Arch north of the Seattle basin and at the south end of the array, near Tacoma.

At 3 Hz the basin and non-basin sites are approximately equal in amplification. At this frequency, the

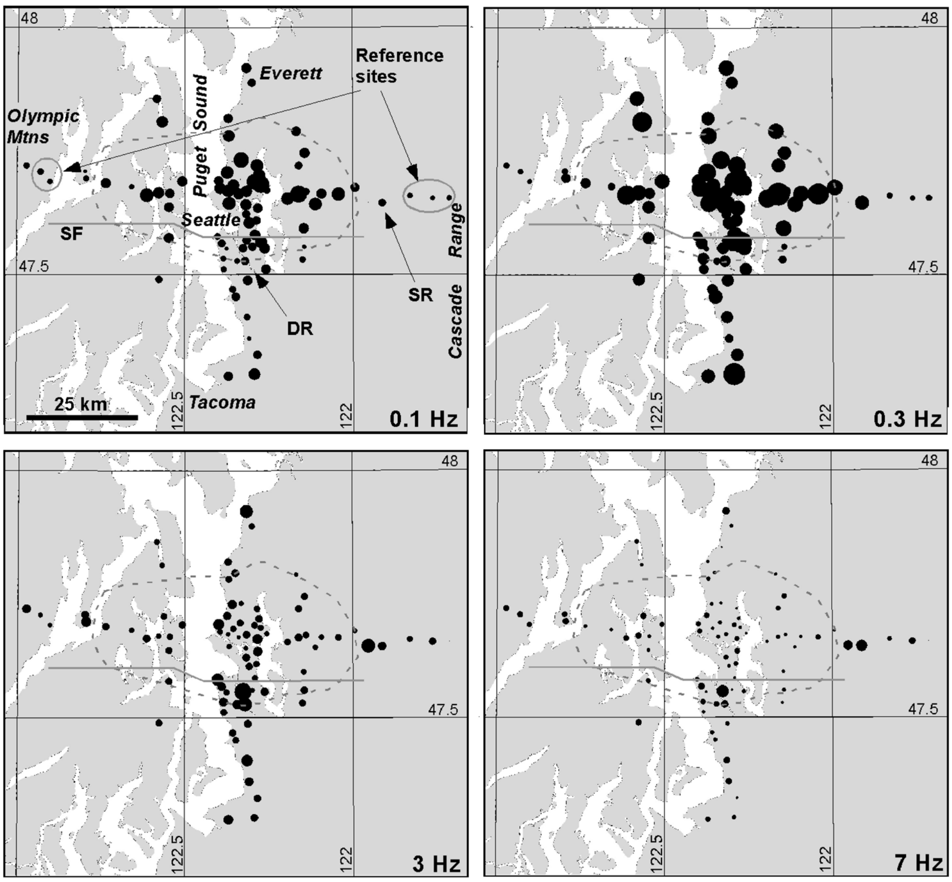

Fig. 2. Spectral ratios over the Seattle basin relative to the average of 5 reference sites located at the east and west sides of the array. Each dot is a seismometer site, with the diameter proportional to the amplification. Amplifications are substantial at 0.1 Hz, are largest at 0.3 Hz, are similar inside and outside of the basin between about 3 and 7 Hz, and above about 7 Hz are smaller in the basin than outside the basin. Gray dashed line is the outline of the Seattle basin from figure 1. Also note the large amplifications at 3 and 7 Hz at the Duwamish River and Snoqualmie River sites (DR and SR).

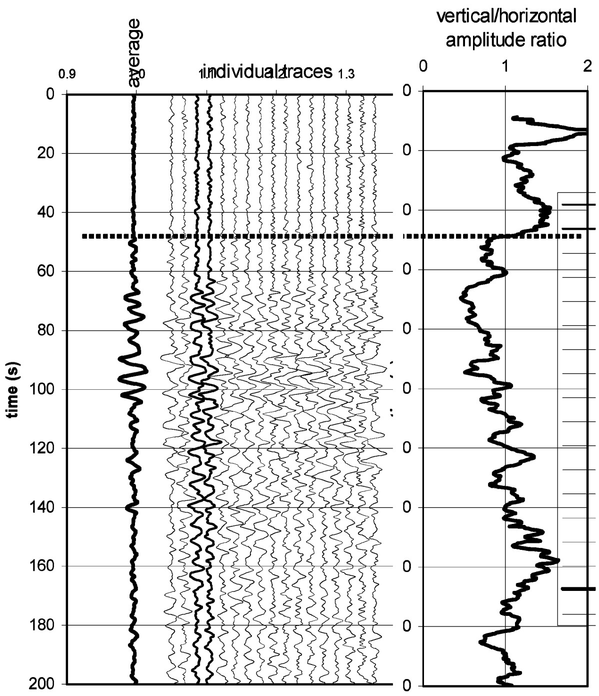

Fig. 3. Evidence for surface waves in the Seattle basin. Left: Traces showing arrivals from a teleseism, recorded on seismographs near the center of the Seattle basin, plus the average of all the traces. Right: Ratio of the vertical to horizontal ratio of the arrivals. Note that the traces have coherent arrivals and large average values in the 60 sec after the initial arrival (gray dashed line), but incoherent arrivals after that make the average values small. The vertical-to-horizontal ratio drops at the shear wave arrivals, but increases after the initial 60 sec. The incoherent arrivals and high vertical-to-horizontal ratio are consistent with the presence of basin surface waves.

influence of soft fill becomes apparent as large amplifications measured at the two Duwamish River sites ('DR' in figure 2). Large amplifications are also apparent in the west Seattle area, immediately west of the Duwamish River, which sustained unusually heavy damage during past earthquakes (Hartzell *et al.*, 2000; Booth *et al.*, 2004). At 7 Hz, the largest amplifications are again located at the soft fill sites in the Duwamish and Snoqualmie River valleys. Attenuation within the basin sediments is evident from the uniformly smaller amplifications at sites over the deep Seattle basin than at the bedrock sites on the east and west ends of the array.

Records of a M7.1 Taiwan earthquake from seismometers on the Seattle basin show several lines of evidence for scattered phases and surface waves within the basin. A 200 sec time window was examined, beginning about 48 sec before the initial S-wave arrival (Fig. 3). The largest S-wave arrivals (48 to 110 sec in Fig. 3) show similar waveforms and coherent arrivals throughout north Seattle, despite the sites being several km apart. The average of the 17 traces shows strong S-wave signals from the initial arrival at 48 sec to about 110 sec, indicating consistent waveforms, but after 110 sec the average amplitude drops significantly despite large amplitudes on the individual traces (Fig. 3). This evidence is consistent with the initial S-wave arrivals being dominated by waves that are nearly in phase at all the stations because of a near-vertical incidence angle, as would be expected for a teleseism from this distance ($\Delta = 88^{\circ}$). After the 110 sec mark, individual traces still have relatively large amplitudes but show little continuity between sites, suggesting the presence of phases arriving from different azimuths.

Further evidence for scattered phases comes from plotting the amplitude ratio of the vertical component to the horizontal components. Figure 3 shows this ratio, computed using the vertical component amplitude divided by the vector sum of the horizontal component amplitudes at each site. The individual ratios in each trace were averaged and then smoothed with a 5-sec time window. The vertical to horizontal amplitude ratio is 1.2 to 1.5 before the S-wave arrivals, but immediately drops to less than 1 at the first S-wave arrivals (48 sec). These low vertical to horizontal amplitudes are consistent with S-wave arrivals at nearly vertical incidence angles, resulting in large horizontal motions but little vertical motion. After the initial S-wave arrivals, the vertical to horizontal amplitude ratio increases steadily to greater than 1. This increase in the ratio is consistent with the ending of the direct S-waves and the presence of locally-generated Rayleigh waves having a significant vertical component of motion.

Our data confirm that sites on soft fill in the Duwamish River valley are subject to the strongest shaking at high frequencies, supporting previous studies that indicated the river valley will experience large amplifications and non-linear effects during strong local earthquakes (Langston and Lee, 1983; Ihnen and Hadley, 1986; Frankel *et al.*, 2003). Comparing the average response at the Duwamish River valley sites with the response at surrounding sites

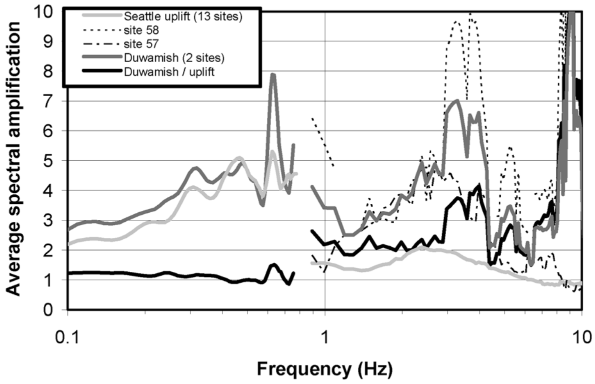

Fig. 4. Average spectral amplification at the 2 Duwamish River valley sites compared to the average at the 13 surrounding sites. Below 1 Hz (from teleseisms) the valley sites have amplifications nearly the same as the surrounding sites. Above 1 Hz the valley sites show strong amplification and prominent resonance peaks.

shows this amplification by the soft river-valley fill (Figure 4).

5. Attenuation in the Sedimentary Basins

Li *et al.* (2006) used waveform data from the 1999 SHIPS seismic refraction experiment to constrain the attenuation structure of the Seattle basin. They inverted the spectral amplitudes of compressional- and shear-wave arrivals for source spectra, site responses, and one- and two-dimensional *Q-1* models at frequencies between 1 and 40 Hz for *P*-waves and 1 and 10 Hz for *S*-waves. They also obtained *Q-1* models from t^* values calculated from the spectral slopes of *P*-waves between 10 and 40 Hz. One-dimensional inversions show that Q_p at the surface is 22 at 1 Hz, 130 at 5 Hz and 390 at 20 Hz. At 18 km depth, Q values were 100, 440 and 1900. Q_s at the surface is 16 and 160 at 1 Hz and 8 Hz, respectively, increasing to 80 and 500 at 18 km depth. They inferred that Q^{-1} values may be ~30% higher in the center of the basin than the one-dimensional models predict. It thus appears that seismic attenuation in the Seattle basin may significantly reduce ground motions at frequencies at and above 1 Hz, partially countering amplification effects within the basin.

Pratt and Brocher (2005) showed that sites over the Seattle, Tacoma and Everett basins are characterized by site response curves with moderate (2 to 6) amplification at 2 to 6 Hz, and decreasing amplification with increasing frequency. In contrast, bedrock sites had a wide variety of shapes to the site response curves. They conclude that the decreasing amplification with higher frequency at basin sites is primarily caused by attenuation within the basins, or within the shallow strata near the top of the basins. Computing the frequency independent, depth dependent attenuation factor (*Qs*) from the spectral decay between 2 and 20 Hz gives values of 5 to 40 for shallow sedimentary deposits and about 250 for the deepest sedimentary strata (7 km depth). These values are consistent with Li *et al.* (2005), whose values are better constrained. This attenuation reduces amplitudes at frequencies above 7 to 10 Hz on the basin to less than those in surrounding bedrock areas.

Acknowledgments

This work has benefited from discussions with Thomas Brocher, Anthony Qamar and Aggeliki Barberopoulou, and reviews by William Stephenson and Steven Hartzell.

References

Barberopoulou, A., A. Qamar, T.L. Pratt, K.C. Creager, and W.P. Steele (2004). Local amplification of seismic waves from the Mw7.9 Alaska Earthquake and damaging water waves in Lake Union, Seattle, Washington, *Geophys. Res. Lett.* 31, L03607, doi: 10.1029/2003GL018569.

Barberopoulou, A., Qamar, A., Pratt, T.L., and Steele, W., 2006, Long-Period Effects of the Denali Earthquake on Water Bodies in the Puget Lowland: Observations and Modeling, *Bulletin of the Seismological Society of America,* v. 96, p. 519–535.

Booth, D.B. (1994). Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation, *Geology* 22, 695–698.

Booth, D.B., R.E. Wells and R.W. Givler (2004). Chimney Damage in the Greater Seattle Area from the Nisqually Earthquake of 28 February 2001, *Bull. Seism. Soc. Am.* 94, 1143–1158.

Brocher, T.M., Parsons, T., Creager, K.C., Crosson, R.S., Symons, N.P., Spence, G.D., Zelt, B.C., Hammer, P.T.C., Hyndman, R.D., Mosher, D.C., Trehu, A.M., Miller, U.S., Fisher, M.A., Pratt, T.L., Alvarez, M.G., Beaudoin, B.C., Louden, K.E., and Weaver, C.S., 1999, Wide-angle seismic recordings from the 1998 seismic hazards investigation of Puget Sound (SHIPS), western Washington and British Columbia, *U. S. Geological Survey Open-File Report* 99-314, 110 pp.

Brocher, T.M., T.L. Pratt, K.C. Creager, R.S. Crosson, W.P. Steele, C.S. Weaver, A.D. Frankel, A.M. Tréhu, C.M. Snelson, K.C. Miller, S.H. Harder, and U.S. ten Brink (2000a). Urban seismic experiments investigate Seattle fault and basin, *Eos, Trans. Am. Geophys. Un.* 81, p. 545, 551–552.

Brocher, T.M., T.L. Pratt, K.C. Miller, A.M. Tréhu, C.M. Snelson, C.S. Weaver, K.C. Creager, R.S. Crosson, U.S. ten Brink, M.G. Alvarez, S.H. Harder, and I. Asudeh (2000b). Report for explosion and earthquake data acquired in the 1999 Seismic Hazards Investigation in Puget Sound (SHIPS), Washington, *U.S. Geol. Surv. Open-File Report 00-318,* 85 p. http://geopubs.wr.usgs.gov/open-file/of 00-318/.

Brocher, T.M., T. Parsons, R.J. Blakely, N.I. Christensen, M. A. Fisher, R.E. Wells, and SHIPS working group (2001a). Upper crustal structure in Puget Lowland, Washington: Results from the 1998 Seismic Hazards Investigation in Puget Sound, *J. Geophys. Res.* 106, 13541–13564.

Brocher, T.M., and Pratt, T.L. (2001b). Data files from the "Dry SHIPS" recordings of the Chi-Chi earthquake, Seattle, Washington, *Bulletin of the Seismological Society of America,* 91, 1395.

Brocher, T.M., R.J. Blakely, and R.E. Wells (2004). Interpretation of the Seattle uplift, Washington, as a passive roof duplex, *Bull. Seism. Soc. Am.,* 94, 1379–1401.

Frankel, A., D. Carver, E. Cranswick, M. Meremonte, T. Bice, and D. Overturf (1999). Site response for Seattle and source parameters of earthquakes in the Puget Sound region, *Bull. Seism. Soc. Am.* 89, 468–483.

Frankel, A.D., D.L. Carver, and R.A. Williams (2003). Nonlinear and linear site response and basin effects in Seattle for the M6.8 Nisqually, Washington, earthquake, *Bull. Seism. Soc. Am.* 92, 2090-2109.

Galster, R.W., and W.T. Laprade (1991). Geology of Seattle, Washington, United States of America, *Bull. Assoc. Eng. Geol.* 28, 235–302.

Hartzell, S., D. Carver, E. Cranswick and A. Frankel (2000). Variability of site response in Seattle, Washington, *Bull. Seism. Soc. Am.* 90, 1237–1250.

Ihnen, S.M., and Hadley, D.M. (1986). Prediction of strong ground motion in the Puget Sound region: The 1965 Seattle earthquake, *Bull. Seism. Soc. Am.* 76, 905–922.

Johnson, S.Y., C.J. Potter, and J.M. Armentrout (1994). Origin and evolution of the Seattle fault and Seattle basin, Washington, *Geology* 22, 71–74.

Jones, M.A. (1996). Thickness of unconsolidated deposits in the Puget Sound Lowland, Washington and British Columbia, *U.S. Geol. Surv. Water Res. Invest. Report 94-4133, 1 plate, scale 1: 454545.*

Langston, C.A., and J.-J. Lee (1983). Effect of structure geometry on strong ground motions: The Duwamish River valley, Seattle, Washington, *Bull. Seism. Soc. Am.* 73, 1851–1863.

Li, Q., Wilcock, W.S.D., Pratt, T.L., Snelson, C.M., and Brocher, T.M., 2006, Seismic attenuation structure of the Seattle basin, Washington State, from explosive-source refraction data, *Bulletin of the Seismological Society of America,* v. 96, p. 553–571.

Ludwin, R.S., C.S. Weaver, and R.S. Crosson, Seismicity of Washington and Oregon, in *The Geology of North America,* vol. 1, *Neotectonics of North America,* edited by D.B. Slemmons *et al.*, Geological Society of America, pp. 77–98, 1991.

Pitarka, A., R. Graves and P. Somerville (2004). Validation of a 3D velocity model of the Puget Sound region based on modeling ground motion from the February 28, 2001 Nisqually Earthquake, *Bull. Seism. Soc. Am.*. 94, 1670–1689.

Pratt, T.L., S. Johnson, C. Potter, W. Stephenson, and C. Finn (1997). Seismic reflection images beneath Puget Sound, western Washington State: the Puget lowland thrust sheet hypothesis, *J. Geophys. Res.* 102, 27469–27489.

Pratt, T.L., T.M. Brocher, C.S. Weaver, K.C. Miller, A.M. Trehu, K.C. Creager, and R.S. Crosson (2003a). Amplification of seismic waves by the Seattle basin, Washington State, *Bull. Seism. Soc. Am.* 93, 533-545.

Pratt, T.L., K. Meagher, T.M. Brocher, C.S. Weaver, T. Yelin, L. Hultgrien and E. Barnett (2003b). Earthquake and blast recordings from the 2002 Seattle Seismic Hazard Investigation of Puget Sound (SHIPS) Experiment, Washington State, *U. S. Geol. Surv. Open-File Report* 03-361 (http://geopubs.wr.usgs.gov/openfile/of03-361).

Pratt, T.L., and Brocher, T.M., 2006, Site response and attenuation in the Puget Lowland, Washington State, *Bulletin of the Seismological Society of America,* v. 96, p. 536–552.

Van Wagoner, T.M., R.S. Crosson, K.C. Creager, G. Medema, L. Preston, N.P. Symons, and T.M. Brocher (2002). Crustal structure and relocated earthquakes in the Puget Lowland, Washington from high resolution seismic tomography, *J. Geophys. Res.* 107, B12, ESE 22-1 to ESE 22-23, joi: 10.10129/2001JB000710.

Williams, R.A., W.J. Stephenson, A.D. Frankel and J.K. Odum (1999). Surface seismic measurements of near-surface P- and S-wave seismic velocities at earthquake recording stations, Seattle, Washington, *Earthquake Spectra* 15, 565–584.

(Received November 14, 2005)
(Accepted October 2, 2006)