Award Number: 02-HQ-GR-0049

THE EFFECT OF SEDIMENTARY BASINS IN THE PUGET SOUND METROPOLITAN AREAS ON STRONG GROUND MOTIONS FROM CRUSTAL EARTHQUAKES

FINAL REPORT
AUGUST 11, 2003

Arben Pitarka and Robert Graves

URS Group, Inc.

566 El Dorado St.
Pasadena, CA 91101

Tel: 626-449-7650
Fax: 626-449-3536
email: arben_pitarka@urscorp.com

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 02-HQ-GR-0049. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Abstract

In this study we prepared a 3D velocity model suitable for modeling long-period wave propagation in the Puget Sound region. The model is based on products of SHIPS (Seismic Hazard Investigation in Puget Sound) and geophysical information from other studies of the region. The adequacy of the velocity model was evaluated based on analyses of goodness of fit between recorded and simulated ground motion velocity from the M6.8 Nisqually earthquake. The earthquake was located about 60 km south of Seattle with a hypocentral depth of 52 km. The analyses were performed in the frequency range of 0.02-0.5 Hz. using data from 40 stations. Although our model covers a wide area of the Puget Sound region its quality is assessed in the Seattle region in which the distribution of stations that recorded the Nisqually earthquake was denser. Our 3D finite-difference ground motion modeling suggests that the propagation of long-period waves (periods longer than 3 s) in the Seattle basin is mostly affected by the deep basin structure. The tomographic velocity model of Parsons et al. (2001) combined with the model of depth to the basement of the Seattle basin of Blakely (1999) were essential in preparing and constraining geometrical features of the proposed velocity model.

Introduction

Important advances have been made in recent years regarding our understanding of the deep and shallow crustal structure in the Puget Sound region, and its influence on the ground shaking from recorded earthquakes and other seismic sources. Much of the knowledge has arisen from the SHIPS experiments (e.g. Brocher et al., 1999; Brocher et al. 2001; Parsons et al., 2001; Calvert and Fisher, 2001; Wagoner et al., 2002) and ground motion analyses and modeling (e.g. Frankel and Stephenson, 2000; Frankel et al., 2000, Hartzell et al., 2000; Frankel et al., 2002; Pratt et al., 2003). Based on the SHIPS data many comprehensive studies of the underground structure have provided valuable information that can improve the quality of existing crustal velocity models that are used in strong ground motion modeling and prediction in the Puget Sound metropolitan regions.

Investigations of geological structure in the Puget Sound metropolitan regions indicate the presence of strong lateral variations in the near surface geology (e.g. Finn et al. 1991, Johnson, 1999; Pratt et al., 1997, Brocher et al., 2001; Calvert and Fisher, 2001). These basin structures have the potential to significantly increase the amplitude and duration of strong ground motions (e.g. Frankel et al. 1999; Frankel and Stephenson, 2000) which could cause significant damage to the built environment even during moderate earthquakes. This is demonstrated by the magnitude 6.8 February 28, 2001 Nisqually earthquake, which caused $2 billion in damage. Development of 3D velocity models capable of accurately reproducing the effects of deep and shallow geology on ground motions from faults within the Puget Sound metropolitan regions is therefore an important task for seismic the hazard assessment. The work presented here describes the development of a 3D velocity model of the Puget Sound region suitable for modeling long period ground motion. We discuss the details of the model parameterization and show results of the model validation analyses using recorded ground motion from the 2001 Nisqually earthquake.

Velocity Model Parameterization

The extensive SHIPS geophysical experiment, as well as other high resolution surveys, have helped to better characterize the crustal architecture and basin geometry, and map the sediment thickness and location of fault zones in the Puget Sound region. These investigations are summarized in Table1. Based on results of some of these investigations we produced a 3D velocity model for an area that includes parts of the Puget Sound region. The location of the area covered by our model and ground motion recording stations used in this study are shown in Figure 1.

Our velocity model is characterized by three main components: 1) the background 3D crustal structure, 2) the basement and sedimentary layers of the Seattle basin, and 3) the thickness of the quaternary deposits throughout the region. The 3D tomographic P-wave velocity crustal model of Parson et al (2001) was used to generate the background velocity of our model. The Parson et al. (2001) model was obtained by inverting combined dense seismic reflection travel times and gravity anomaly data. The model gives the P-wave velocity on a regular grid with constant spacing of 1km. We resampled it on a finer grid with variable vertical spacing. The velocity at each point of the refined grid was calculated by linearly interpolating the velocity corresponding to the eight closest grid points of the original grid. The S-wave velocities in our model were derived from the P-wave velocities using the Vp/Vs ratio. Following Frankel and Stephenson (2000) the Vp/Vs ratio was assumed to be 2.2 and 1.75 at depths above 2.5 km and below 2.5 km, respectively, while the density increases from 2.3 gm/cm3 to 2.7 gm/cm3. Another velocity model parameter used in our wave-propagation finite-difference modeling technique is the anelastic attenuation, which is represented by the Q factor. Our technique considers Q as frequency independent. We assumed Q to be 100 and 500 at depths smaller and greater than 2.5 km, respectively, except for the Quaternary deposits where Q was assumed to be 50.

The part of the model that includes the Seattle basin to a depth of 10 km was prepared using combined data from the depth to basement map of Blakely (1999) and a N-S cross-section of the Seattle basin sediments based on the interpretation of seismic reflection profiles during the SHIPS experiment (Brocher et al., 2001). This velocity profile as well as a high-resolution tomographic model of the area suggest that the southern edge of the Seattle basin dips toward the south. This important feature of the southern edge of the basin was not resolved by the gravimetric and aeromagnetic data used by Blakely (1999), and is therefore not present in his depth to basin basement model. The profile, that extends to more than 10 km in depth, suggests that the basin sediments below 1 km consist of at least four distinctive layers with strong velocity contrast. In our model the profile was used to derive the geometry of the southern edge of the Seattle basin and the decreasing thickness of the sedimentary layers toward the north. The lateral variation of the layers thickness was assumed to be proportional to the corresponding basin depth and its N-S variation was assumed to be similar to that in the N-S velocity profile (see Figure 2). This procedure produces a basin velocity model that is in agreement with a 2D velocity model along an E-W cross section of the basin proposed by Miller and Snelson (2001). Their model indicates that the geometry of the boundaries between the sedimentary layers is similar to that of the basin basement. The assumed seismic parameters of the sedimentary layers are given in Table 2.

Table 1. Recent Investigations of Crustal Structure in the Seattle Area Considered in this Study

Objective	Type of Data and Investigation	Product	References
Crustal Structure	Seismic Reflection Travel Time Tomography	3D Tomogr. P-wave Model	Brocher et al. (2001)
	Inversion of Travel Time & Gravity Data	3D Tomogr. P-wave Model	Parsons et al. (2001)
	Seismic Reflection & Seismicity, Travel Time Tomography	3D Tomogr. P-wave Model	Crosson et al. (1976)
	Travel Time Tomography	3D Tomogr. P-wave Model	Wagoner et al. (2003)
Shallow Crustal Structure	Inversion of Gravity & Aeromagnetic Data	Depth to Basement	Blakely et al. (1999)
	High Resolution Seismic Reflection	2D Tomogr. P-wave Model	Miller and Snelson (2001)
	High Resolution Seismic Reflection	2D Tomogr. P-wave Model	Calvert and Fisher (2001)
	Inversion of Gravity Data	Velocity Structure	Pratt et al. (1997)
		3D Sedimentary Layer Model	Finn et al. (1991)
Quaternary Layer	Geotechnical Investigations	Depth to Bedrock Northern Puget Sound	Yount et al. (1985)
	Geotechnical Investigations	Depth to Bedrock Southern Puget Sound	Hall and Othberg (1974)
	Seism. Refl & Borehole Data	Thickness of Quaternary Deposits	Johnson et al. (1999)
Shallow Velocities	Borehole Logging	Velocity and Density	Mc. Farland (1983) Brocher and Ruebel (1998)
	Shallow Seismic Refraction	Seismic Velocity	Williams et al. (1999)
	Geotechnical and Geophysical Data	Shear–wave velocity	Wong et al.(1998) Silva et al. (1995)

Besides the Seattle basin structure, a key feature in our velocity model is the thickness of the Quaternary layer. The thickness of the Quaternary layer is well resolved only in the Seattle region (Johnson et al. 1999). In the other areas of the model it was derived from the maps of depth to basement of Yount et al. (1985) and Hall and Othberg (1974) for the northern part and the southern part of the Puget Sound region, respectively. These maps are based on geotechnical investigations using extrapolations between data that are sparsely distributed. Other studies of the shallow seismic velocity of the Quaternary layers suggest that the shear-wave velocity increases rapidly with depth, with values as low as 150 km/s at the surface (Wong et al., 1998). The representation of small scale variations of the Quaternary layer in our model would require a very fine grid with spacing on the order of ten meters. Because of its extremely large computational requirement such a dense grid is not practical for wave-propagation modeling using available numerical techniques. In the velocity model we tested, the minimum grid spacing is 200 m, and the Quaternary deposits are represented by a single layer with a minimum shear-wave velocity of 0.6 km/s. For this layer we assumed Vp =1.5 km/s, density = 2.1 g/cm3 and Q=50. As will be discussed in the following section, the analyses of the model validity indicate that our simple parameterization of the Quaternary layer needs further improvement, especially in the basins where the shallow structure is more complex.

Vertical cross sections of the 3D velocity model oriented in the E-W and N-S directions across the Seattle basin are shown in Figures 2a and 2b, respectively. The location of the profiles is indicated by blue lines in Figure 1a. The strong discontinuity in the geological structure caused by the Seattle fault creates a zone of velocity contrast along the southern edge of the Seattle basin. The velocity contrast between the basement and the basin sediments, and the geometry of the basin edge in this area are key features of the basin structure that generate secondary basin waves. As will be seen in the simulation results, these waves mostly affect the amplitude and duration of the ground motion at basin sites.

Modeling Ground Motion from the 2001 Nisqually earthquake

As a first step in the process of testing the velocity model, we computed long-period ground motion (2-10 sec) for the February 28, 2001 Nisqually earthquake (M=6.8) and compared the synthetic and recorded velocity seismograms at 40 strong motion recording sites. The hypocenter was located at –122.4E and 32.5N and a depth of 59 km (Ichinose et al., 2002). The earthquake was recorded by strong ground motion stations operated by the United States Geological Survey and University of Washington. Because the earthquake source was relatively deep, most of the ground motion recorded in the basin sites was dominated by the direct shear waves and basin generated secondary waves. The recordings of such waves and the relatively dense station distribution in the Seattle basin provided excellent information that were useful in analyses of the ability of the velocity model to reproduce the main characteristics of the observed ground motion, especially in the Seattle basin area.

The simulation was performed using the finite-difference method of Pitarka (1998) using a regular grid with variable spacing in the vertical direction. The minimum grid spacing of 200 m, and its vertical variation insured accurate calculations of the wave-field up to a frequency of 0.5 Hz. The earthquake source was modeled by two double couple point sources separated in time by 1.5 s. Our source model was derived from the slip model obtained by Ichinose et al. (2002) based on the inversion of teleseismic data. The source model used in the finite-difference simulation is described in Table 3. The source time function for each point source was assumed to be of triangular shape.

The comparison between the synthetic and recorded velocity seismograms at sites inside and outside the Seattle basin is shown in Figures 3 and 4, respectively. Both synthetic and recorded data are band-pass filtered at 0.1-0.5 Hz. The model does a good job at reproducing the phases carrying most of the seismic energy, and the duration of the ground motion at the Seattle basin sites. At sites south of the basin the waveform fit is less satisfactory. At these sites scattered waves with periods shorter than 3 sec are less developed in the synthetic seismograms. Such waves consist of reverberations of waves trapped within the surface layers. The discrepancy may be related to the minimum shear-wave velocity of 600 m/s imposed to our model, which may alter wave propagation effects within the surface layers. It is also possible that the absence of high frequency waves in the synthetics is caused by the lack of high frequency variation in our slip velocity function. At sites in the southern and central parts of the Seattle basin, the travel time of the largest pulse associated with the direct shear wave is shorter in the E-W component than in the N-S component. If there is anisotropy in the rock properties, this indicates that the sedimentary rocks in the southern edge of the basin are highly fractured. This phenomenon is not observed at sites outside the basin or northern part of the basin.

Table 2. Velocity Model of the Seattle Basin Sediments

Layer	Vp (km/sec)	Vs (km/sec)	Density (g/cm3)	Q
Quaternary	1.5	0.6	2.1	50
1	1.8	1.2	2.2	50
2	2.7	1.6	2.4	50
3	3.3	1.9	2.6	250
4	4.0	2.3	2.7	300
5	5.3	3.1	2.8	400

Table 3. Point Source Model of the Nisqually Earthquake

Point Source	Strike (o)	Dip (o)	Rake (o)	Depth (km)	Rise Time (sec)	Mo (dyne cm)
1	356	68	-90	55.	4.0	0.7x1026
2	356	68	-100	55.	4.5	1.1x1026

Goodness of fit Between Observed and Simulated Ground Motion Velocity

In order to evaluate the quality of our velocity model, we analyzed the goodness of fit between simulated and recorded ground motion. Goodness-of-fit factors were derived for different ground motion parameters such as peak velocity and Fourier amplitude spectra in a given frequency range. The goodness-of-fit factor f_l corresponding to a ground motion parameter is given by (John Anderson, 2003, personal communication):

$$f_l = \exp[-(\frac{Syn - Obs}{\min(Syn, Obs)})^2]$$

where Obs and Syn are measures of the ground motion parameter using observed and synthetic seismograms, respectively, and min (Syn,Obs) is the smaller of the two. f_l varies from 0 to 1, with 1 corresponding to identical observed and simulated ground motion measures. In this study we calculated f_l using the peak ground velocity (PGV) corresponding to three frequency ranges, 0.05-0.2 Hz, 0.05-0.3Hz and 0.05-0.5 Hz, and Fourier Spectra Amplitude (FSA) at 0.2, 0.3 and 0.4 Hz.

In addition to f_1 we calculated factor f_2 which is given by the following formula:

$$f_2 = 2 \frac{\int p(t)_{obs} p(t)_{syn} dt}{\int p(t)_{obs}^2 dt \quad \int p(t)_{syn}^2 dt}$$

where $p(t)_{obs}$ and $p(t)_{syn}$ are the observed and synthetic seismograms, respectively. If the synthetic seismogram is null then f_2=0, and if the synthetic and observed seismograms are perfectly matched than f_2=1. f_2 was calculated using a time window of 60 sec starting several seconds before the P-wave arrival time. Estimates of both factors in different frequency ranges provide a quantitative measure of the goodness of fit. Combined with the waveform comparison, they give a general picture of the waveform fit between the observed and synthetic ground motions. Variations of the f_1 and f_2 factors with epicentral distance for different frequency ranges are given in Figure 5.

The f_1 values for PGV shown in Figure 5a suggest that, except for a few sites, our velocity model does a very good job at predicting the peak velocity at sites in and outside the Seattle basin, for all three considered frequency ranges. The f_1 for the FSA is relatively high at 0.2 Hz (periods of 5 s) while it decreases substantially at frequencies 0.3 and 0.4 Hz, for which the signal energy is small (Figure 5b). Since most of the energy of the ground motion velocity is carried by waves with predominant period around 5 sec and longer, the value of f_1 at 0.2 Hz is a good representation of the model quality.

Compared to f_1 the goodness-of-fit factor f_2 is more sensitive to the waveform than the amplitude of the motion at a particular frequency. The variation of f_2, shown in Figure5c, suggests that our model performs reasonably well at matching both three components at sites in the Seattle basin. At sites outside the basin f_2 is low especially in the broader frequency range of 0.02-0.5 Hz.

Overall the best fit is obtained in the N-S component of the velocity recorded at sites in the central part of the basin where the ground motion is dominated by two large pulses corresponding to the direct S-wave and the basin surface wave generated at the southern edge of the Seattle basin. This is an indication that the large scale basin structure along the southern edge of the Seattle basin is well represented in our model.

Discussion

Analyses of ground motion from the Nisqually earthquake and other seismic events recorded in the Seattle region reveal the significant effect of the shallow and deep geological structure in increasing the amplitude and duration of the ground motion in the Seattle basin. Among the many results of such analyses, two have direct implications for the ongoing process of refinement and validation of 3D velocity models of the Seattle area. The first is that in the Seattle basin the basin surface waves affected by the deep basin geometry dominate the ground motion, especially at frequencies lower than 1Hz (e.g. Pitarka et al., 1999; Frankel et al., 2002; Carver et al., 2002). The second is that there is a clear correlation between variations in the site response and Quaternary deposits (Troost et al., 2002, Hartzell et al., 2002; Pratt et al., 2003) especially at frequencies higher than 0.5 Hz.

In this section we show results of analyses of the effects of deep versus shallow geological structure on the ground motion based on our modeling of recorded data in the Seattle basin. Because the period range used in our simulation is between 2s and 10 s, our analyses is focused on long-period basin structure effects.

Figure 6 shows the distribution of calculated peak ground velocity in the E-W, N-S and vertical components of motion. In this figure we also show contour lines of the Quaternary layer thickness. The peak velocity distribution indicates that the peak velocity amplification pattern is very complex, and it does not fully coincide with the Quaternary layer thickness, especially in the Seattle basin. In the Seattle basin the peak velocity amplification is very different between the two horizontal components. The E-W component of the ground motion is strongly amplified only along the southern edge, and in a small area of the central part of the basin, whereas the zone of amplification of the N-S component covers a large portion of the basin, off-set from the southern basin edge. In general the lateral extension of these zones of amplification does not correlate with the thickness of the Quaternary. This indicates that the long period waves are mostly affected by the deep geological structure of the basin.

Based on the peak velocity distribution, there is striking evidence of very large amplification of the ground motion in the N-S direction in both Seattle and Tacoma basins. In the Seattle basin the N-S component is dominated by basin surface waves generated at the southern edge of the basin along a zone of strong velocity contrast. The N-S component, which roughly corresponds to the radial component of motion, may also contain Rayleigh waves that were generated in the Tacoma basin and then channeled through the Seattle uplift into the Seattle basin without being scattered (e.g. Pitarka and Irikura, 1996). Our simulation suggests that the amplification pattern is due to the 3D basin focusing and basin-edge effects. The surface waves remain trapped within the basin sediments. Their constructive superposition may create complex amplification patterns, even at long periods, such as that observed in the E-W component.

Two recent site response studies in the Seattle region (Frankel et al., 1999; Hartzell et al., 2000) have identified several areas of high response in the Seattle basin. These findings, which are based on analyses of ground motion data at frequencies higher than the ones considered in our study, suggest that the high amplification is due to several factors such as 3D basin-edge effects, basin focussing effects and higher impedance contrast between the basin sediments and the bedrock. Our modeling results suggest that the 3D deep basin structure has a strong effect at periods longer than 3s.

In Figure 7 we show the effect of the Quaternary layer on the ground motion at the Seattle basin sites. In this figure we compare Fourier amplitude spectra of recorded (thick line) and synthetic seismograms calculated with the proposed 3D velocity model (thin solid line), and a 3D velocity model without the Quaternary layer (thin dashed line). The panels are aligned following the station epicentral distance starting with the station closest to the epicenter. The recorded ground motion at stations located close to the basin edge, such as HAR, SDN, KIMB, BHD, and KDK has a broad spectrum. At these stations the simulation does not match the high frequency part of the spectrum. In contrast, at deep basin sites the energy is concentrated at frequencies lower than 0.3 Hz, and the comparison between the simulated and recorded spectra is favorable. At these sites the shape of the spectra indicates that the energy associated with frequencies higher than 0.25 Hz is highly attenuated by the basin sediments. The comparison of results obtained with the two 3D velocity models shows that our representation of the Quaternary layer tends to over-amplify the horizontal ground motion around the predominant frequency of 0.18 Hz. The inclusion of the Quaternary layer in our model causes the broadening of the frequency range of the maximum basin response. This is in agreement with the observations. As expected, the inclusion of the Quaternary layer improves to some extent the spectral fit at higher frequencies, too. We recognize that our assumption of representing the Quaternary sediments by a single layer with strong velocity contrast may create unrealistic effects and that a velocity gradient within this layer may yield a better result.

The comparison of the simulated and recorded amplitude spectra support the conclusion that the recorded long-period ground motion in the Seattle basin is mainly affected by the deep basin structure and that the combination of the velocity model of Parsons et al. (2001) and basin basement geometry proposed by Blakely (1999) do a good job at capturing such effects.

Our model shares some similarities and dissimilarities with another velocity model of the Seattle basin area proposed by Frankel and Stephenson (2000). Both velocity models use the same depth to the basin basement and Quaternary layer data. The main differences are in the way the basin sedimentary layers are represented, the geometry of the southern edge of the basin, and background regional velocity model. Recent interpretations of refraction survey data and high-resolution tomographic models of the Seattle basin have provided new information about the geometry of the southern edge of the basin. They suggest that the basin edge created by the Seattle fault dips toward the south. Also, recently compiled tomographic velocity models of the Puget Sound region (e.g. Parsons et al., 2001; Brocher et al., 2001; Crosson et al., 2001; Wagoner et al., 2003) are characterized by marked lateral variation of the velocity in the crust, and the existence of deep basin structures. In order to provide accurate information on the effects of these underground structure complexities on the ground motion from earthquakes in the region, we need to progressively improve our velocity models by modeling more ground motion data as they become available, and extend the modeling capability to frequencies higher than the ones modeled here. By modeling higher frequencies we will be able to provide constraints that are crucial for solving ambiguities in the velocity models inherited from the generalization of limited geophysical and geotechnical information. The analysis of modeling presented here is a part of such efforts.

In order to supplement the analysis of our 3D model quality in the Seattle region, we calculated the basin amplification at a linear station array across the Seattle basin (line E-W in Figure 1a), and compared it with the amplification estimated by Pratt et al. (2003) using ground motion recordings of the Chi-chi, Japan earthquake. The location of our station array is very close to that of the 1999 SHIPS array that was used by Pratt et al., (2003) in their study of the amplification of the seismic waves in the Seattle basin. The first and last stations of our array correspond to stations 1296 and 2570 in their study, respectively. The stations are equally spaced at 400 m. Following the procedure used by Pratt et al. (2003), we estimated the basin amplification at 0.2 Hz and 0.33 Hz by calculating the spectral ratios of the simulated horizontal motion from the Nisqually earthquake relative to a bedrock site. Pratt et al. (2003) estimated the basin amplification based on the average of spectral ratios of the recordings of the horizontal motion from Chi-chi, Taiwan earthquake relative to the average of two bedrock sites at the west end of the array in the Olympic Mountains. Because these two sites are located outside our 3D model area, we choose a site at -122.25 E, 47.549 N as a reference (see Figure 6). This soft rock site at Seward Park, located south of the basin edge, was used as a reference in previous site response studies of the Seattle area (station SQ1 in Frankel et al., 1999; Hartzell et al. 2000). Based on recordings of the Chi-chi earthquake, Pratt et al. (2003) estimated that the site response relative to the Seward Park reference site will be at least about 30% smaller than the site response relative to the Olympic Mountains reference site that was used in their study. We reduced their amplification factors by 30% in order to obtain the corresponding amplification relative to the Seward Park reference site used in our calculation.

The comparison between the two amplifications at 0.2 Hz and 0.33 Hz relative to the Seward Park reference site is shown in Figure 8. The variation of the basin amplification factor along the considered E-W array is very similar between the two studies. Basically its shape is similar to the basin basement geometry. Our simulated amplification tends to be larger in the central part of the basin, and smaller in the western part of the basin. Although generated by a deep source, the simulated long-period ground motion from the Nisqually earthquake is affected by the radiation pattern. This is not the case FOR the recorded teleseismic ground motion from the Chi-chi earthquake. Given the completely different nature of the earthquake sources, the similarity between the two basin amplification factors is very encouraging. It demonstrates that the overall long-scale basin structure features along the E-W direction are adequately presented in the model. Seismological constraints based on modeling of amplification factors derived from recordings of local and regional earthquakes in the Puget Sound region will be very helpful in future refinements of proposed 3D velocity models.

Our model is given on a regular grid, and is available upon request.

Acknowledgments.

We thank Tom Parsons and Tom Brocher for providing their tomographic model of the Puget Sound area, and information on the SHIPS experiment related publications. We thank Tom Pratt for providing his amplification profile across the Seattle basin, and Samuel Johnson for providing his model of the Quaternary layer thickness in the Seattle region. The help of Susan Rhea who prepared the data in a format suitable for our codes is appreciated.

References

Blakely, R.J.R.E. Wells and Weaver, Puget sound aeromagnetic maps and data (1999). U.S. Geol. Surv. Open-File Rep. 99-514

Brocher T.M., and Ruebel, L.A. (1998). Compilation of 29 Sonic and density logs from 23 oil test wells in western Washington state. USGS U.S. Geol. Surv. Open-File Rep. 98-249

Brocher T.M.,T. Parsons, Ken Creager, R. Crosson, N. Symsons, P. Hammer, R. Hyndman, K. Miller, M. Fisher, T. Pratt, B. Beodoin, K. Louden and C. Weaver (1999). Wide-Angle seismic recordings from the 1998 Seismic Hazards Investigation of Puget Sound (SHIPS), western Washington and British Columbia, USGS Open-File Report.

Brocher T.M.,T. Parsons, R.J. Blakely, N.I. Christensen, M.A. Fisher, R.E. Wells and SHIPS Working Group (2001). Upper crustal structure in Puget Lowland, Washington: Results from the 1998 Seismic Hazards Investigation in Puget Sound, *J. Geoph. Res*., **106**, 13,541-13,564.

Calvert, J.A and M.F. Fisher (2001). Imaging the Seattle Fault Zone with high-resolution seismic tomography, *Geoph. Res. Lett*. (in press)

Carver, D., A. Frankel, and T. Bice (2002). Seattle urban array records of the 28 February 2001, M6.8 Nisqually earthquake and its aftershocks, *Seim. Res. Lett*., **73**, 266.

Crosson, R.S. (1976). Crustal structure modeling of earthquake data. Velocity structure of the Puget Sound region, Washington, *J. Geophys. Res*., **81**, 3047-3054.

Finn, C.A., W.M. Philips and D.L.K. Williams (1991). Gravity anomaly and terrain maps of Washington, U.S. Geol. Surv. Geoph. Inset Map GP-988

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., and W. Stephenson (2000). Three-dimensional simulations of ground motions in the Seattle region for earthquakes in the Seattle fault zone, *Bull. Seism. Soc. Am*., **90**, 1251-1267.

Frankel, A., D. Carver, R.A. Williams (2002). Nonlinear and linear site response and basin effects in Seattle for the M6.8 Nisqually, Washington, earthquake. *Bull. Seism. Soc. Am*., **92**, 2090-2109.

Graves, R.W., A. Pitarka, and P.G. Somerville (1998). Ground motion amplification in the Santa Monica area: effects of shallow basin edge structure., *Bull. Seism. Soc. Am*., **88**, 1224-1242.

Hall, J.B. and K.L. Othberg (1974). Thickness of unconsolidated sediments, Puget Lowland, Washington, State of Washington, Department of Natural Resources, Geologic Map GM-12, Washington.

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

Ichinose, G.A., H.K. Thio, and P.G. Somerville (2002). Rupture process and near-source shaking of the 1965 Seattle-Tacoma and 2001 Nisqually, intraslab earthquakes. *Geophys. Res. Lett*. (submitted).

Johnson, S.Y, S.V. Dadisman, J. Childs and W.D. Stanley (1999). Active tectonics of the Seattle Fault and cross-cutting strike-slip faults in the central Puget Sound Lowlands, Washington: implications for earthquake hazards, *Geol. Soc. Am. Bull*, 1042-1053.

Miller K.C and C.M Snelson (2001). Structure and geometry of the Seattle basin, Washington state-results from Dry SHIPS'99: Collaborative research (USGS, OSU, UTEP), Progress Report to USGS.

Parsons, T., R.J. Blakely, and T.M. Brocher (2001). A simple algorithm for sequentially incorporating gravity observations in seismic traveltime tomography, *International Geology Review*, **43**, 1073-1086.

Pitarka, A. and K. Irikura (1996). Basin structure effects on long period strong motions in the San Fernando valley and the Los Angeles Basin from the 1994 Northridge earthquake and an aftershock, *Bull. Seism. Soc. Am*., **86**, S126-S137.

Pitarka, A. (1998) 3D elastic finite-difference modeling of seismic wave propagation using staggered-grid with non-uniform spacing, *Bull. Seism. Soc. Am*., **89,** 54-68.

Pitarka, A., N.F. Smith, R.W. Graves, P.G. Somerville (1999). Modeling the effect of the Puget basin on strong motions from earthquakes on the Seattle fault. *Seism. Res. Lett.* SSA Meeting Abstr., 220.

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, *Journ. Geoph. Res*., **102**, 27,469-27489.

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

Silva. W.J., I.G. Wong, and R.B. Darragh (1995). Engineering Characterization of earthquake strong ground motions in the Pacific Northwest. Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest, U.S. Geological Survey Professional Paper 1560.

Troost, K.G.,D.B. Booth, S.A. Simel (2002). Geologic controls on site response and ground failures in Seattle during the 2001 Nisqually earthquake, *Seism. Res. Lett.*, **73**,214.

Wagoner, T.M. Van, R.S. Crosson, K.C. Creager, G. Medema, and L. Preston (2002). Crustal structure and relocated earthquakes in the Puget Lowland, Washington, from high-resolution seismic tomography. *J. Geoph. Res*., **107**.

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.

Wong, I., Bott, J., Silva W., Anderson D., Mabey M., Metcalfe B., Olig S., Sanford A., Lin. K., Wright, D., Sparks, A., Sojourner, A. (1998). Microzoning for earthquake ground shaking in three Urban areas in the Western United States. 6th U.S. National Conference on Earthquake Engineering, Seattle, WA, June 1998.

Yount, J.C.,G.R. Dembroff, and G. M. Barats (1985). Map showing depth to bedrock in the Seattle 30' by 60' quadrangle, Washington, U.S.G.S. Miscellaneous Field Investigations Map, MF-1692.

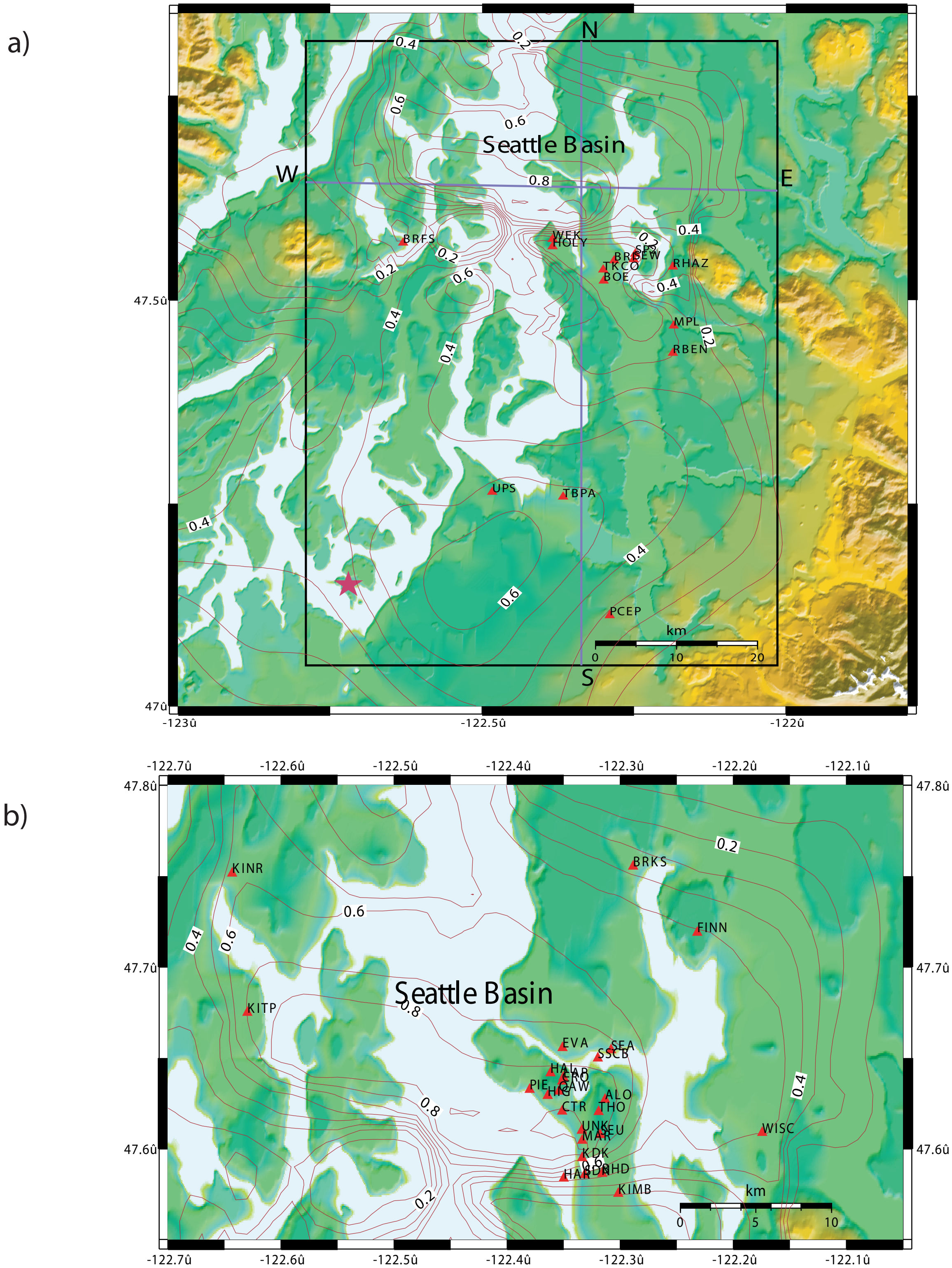

Figure 1. a) Map of the Puget Sound area. Black rectangle delineates the area covered by the 3D velocity model. Blue lines indicate the location of N-S and E-W vertical cross-sections of the model. Red triangles show the location of the strong motion stations outside the Seattle basin, and red star shows the epicenter location of the Nisqually earthquake. The red contours represent the depth to base of Quaternary from Johnson et al. (1999).

b) Map of the Seattle basin area showing strong motion station locations (red triangles) and depth to base of Quaternary frm Johnson et al.(1999)

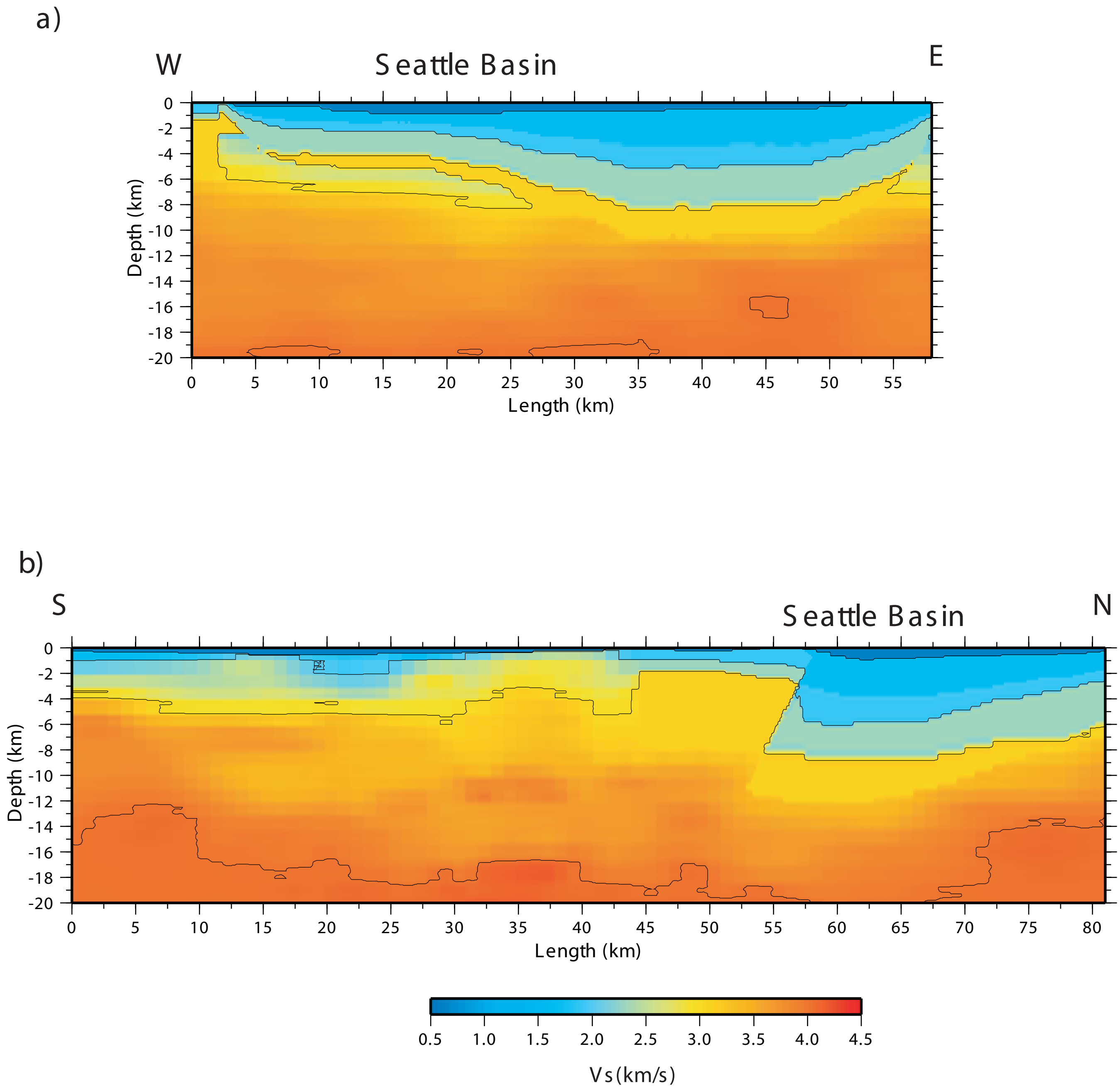

Figure 2. Vertical cross-sections of the 3D velocity model along E-W and N-S profiles shown in Figure 1.

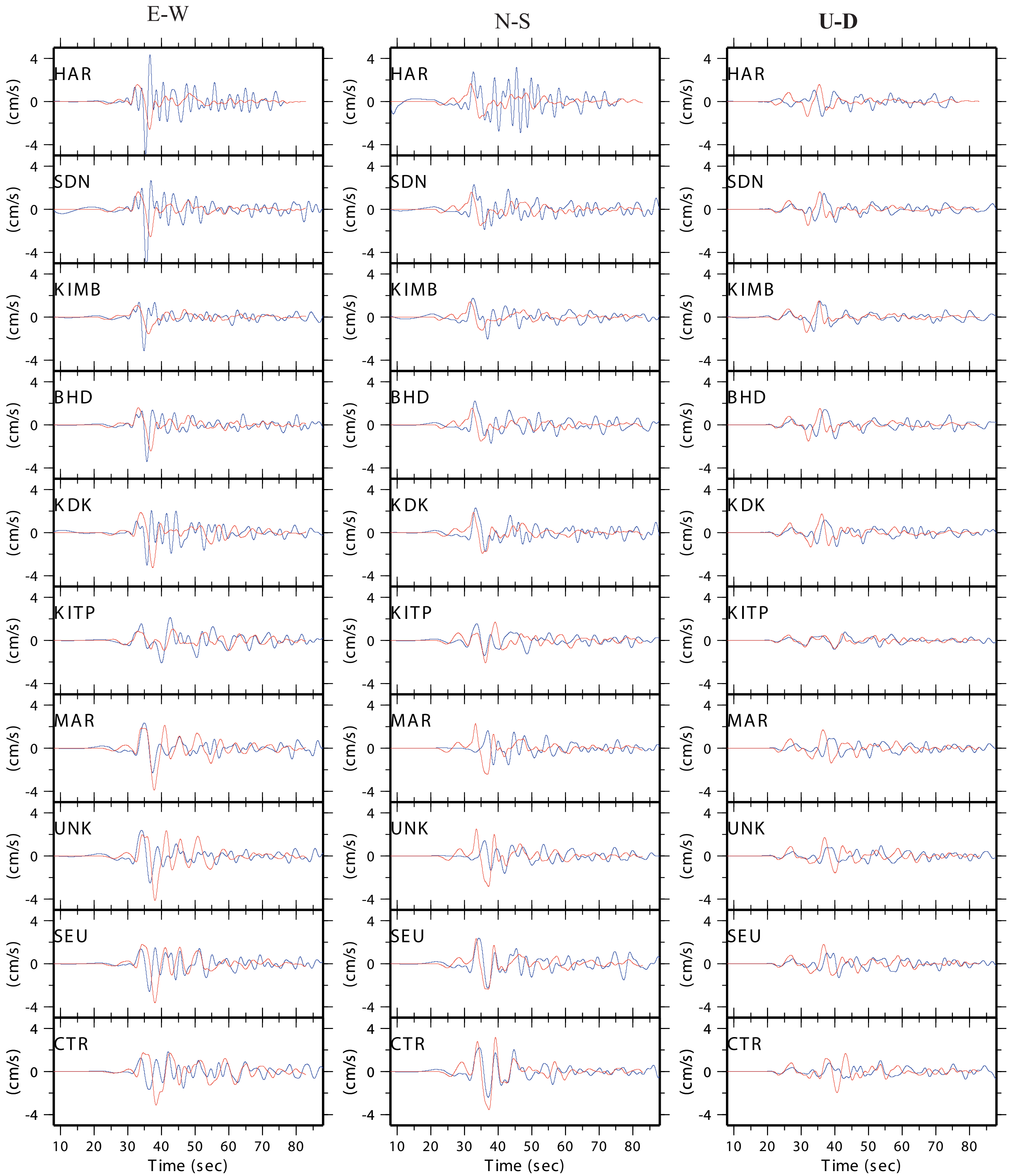

Figure 3. Comparison of recorded (blue) with synthetic (red) velocity seismograms at sites in the Seattle basin

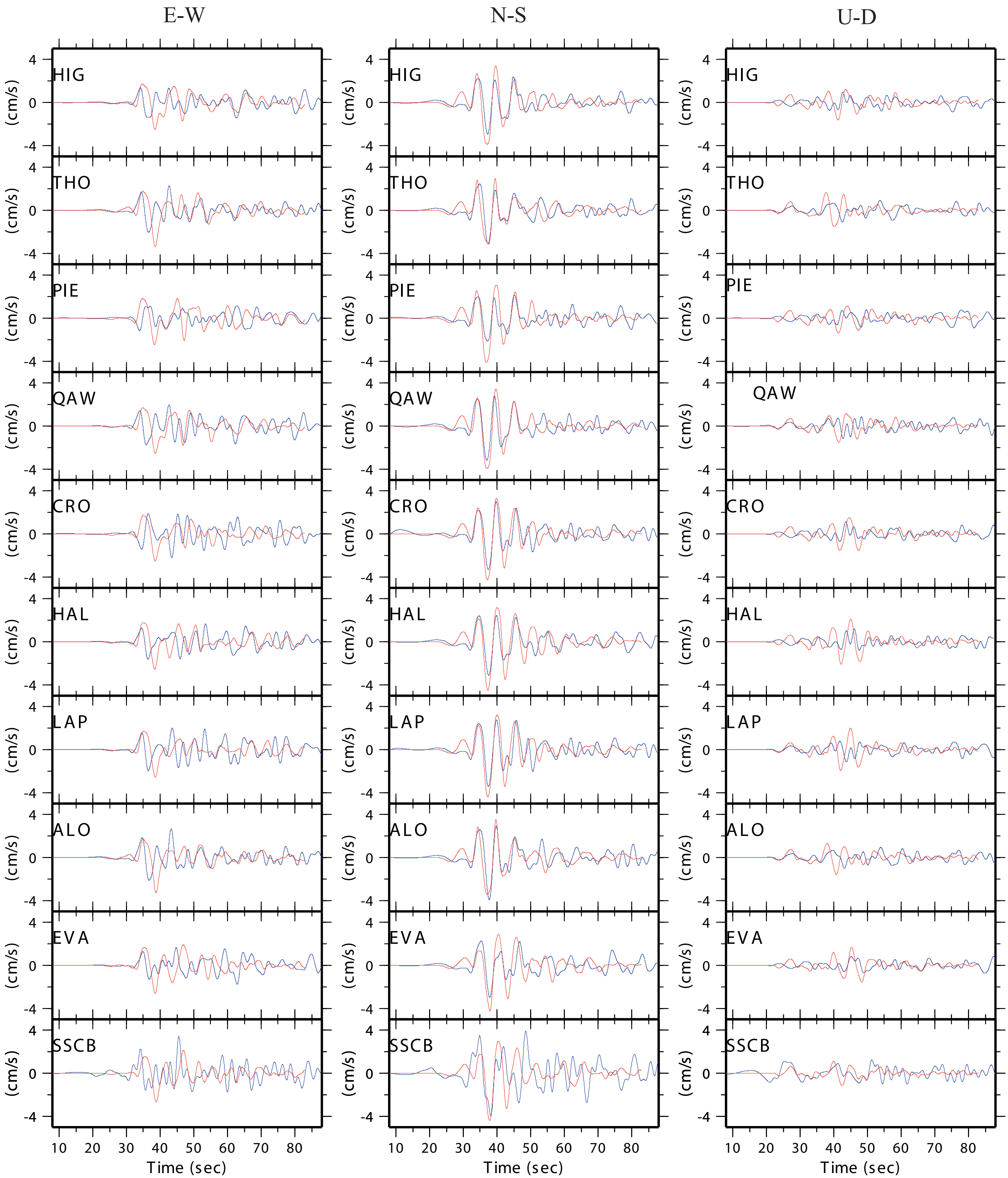

Figure 3. ... continued

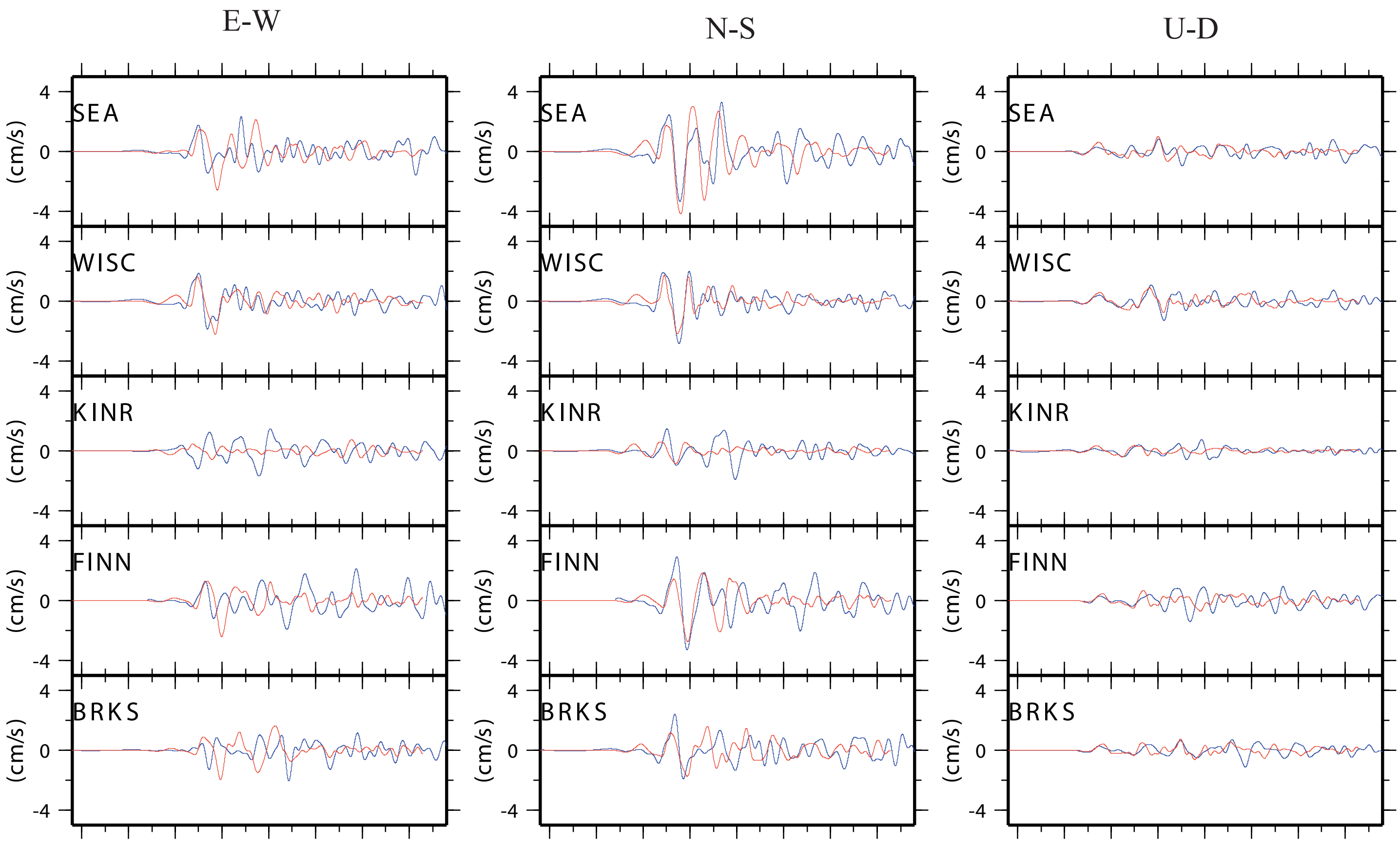

Figure 3. ... continued

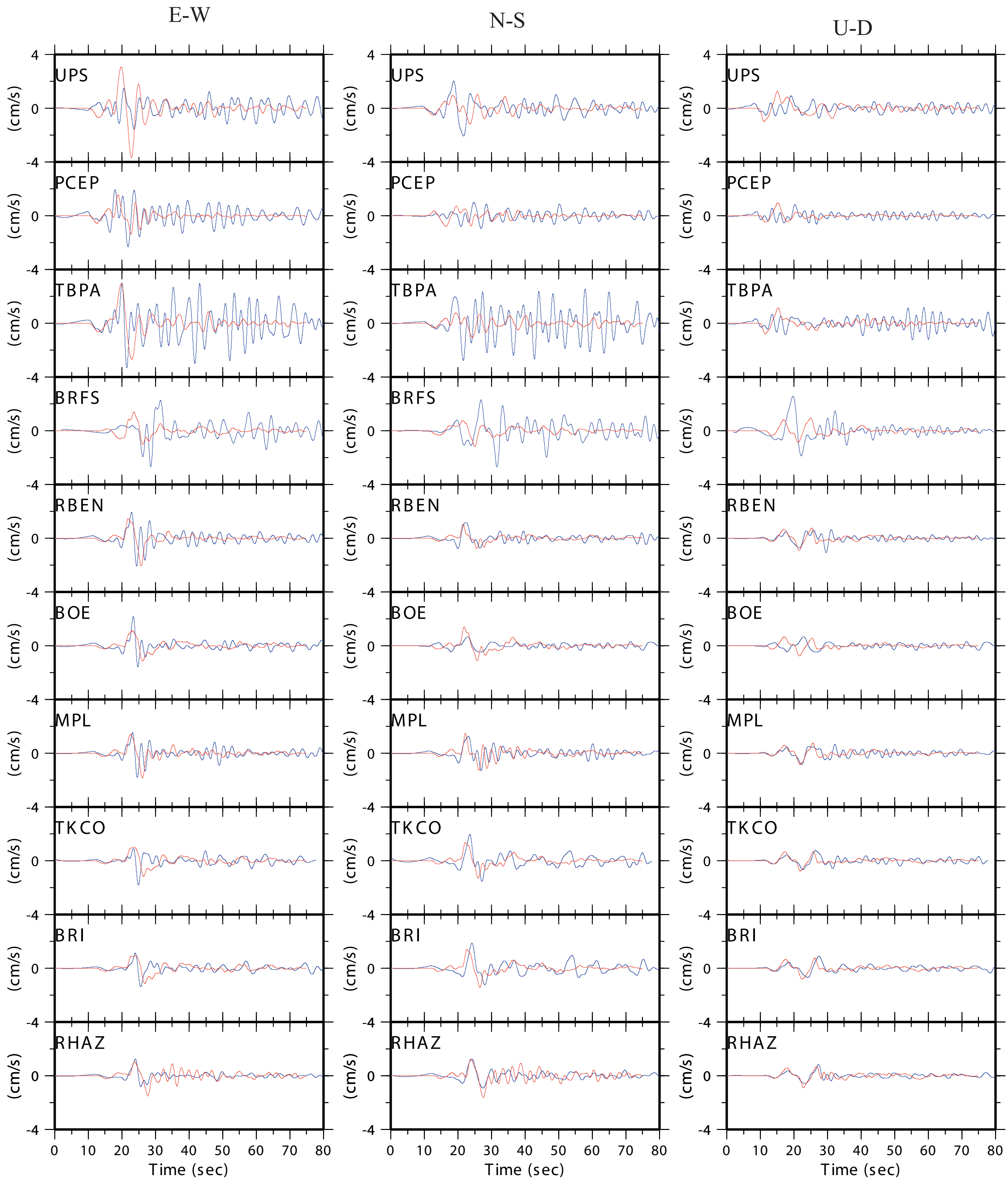

Figure 4. Comparison of recorded (blue) and synthetic velocity seismograms at sites outside the Seattle basin.

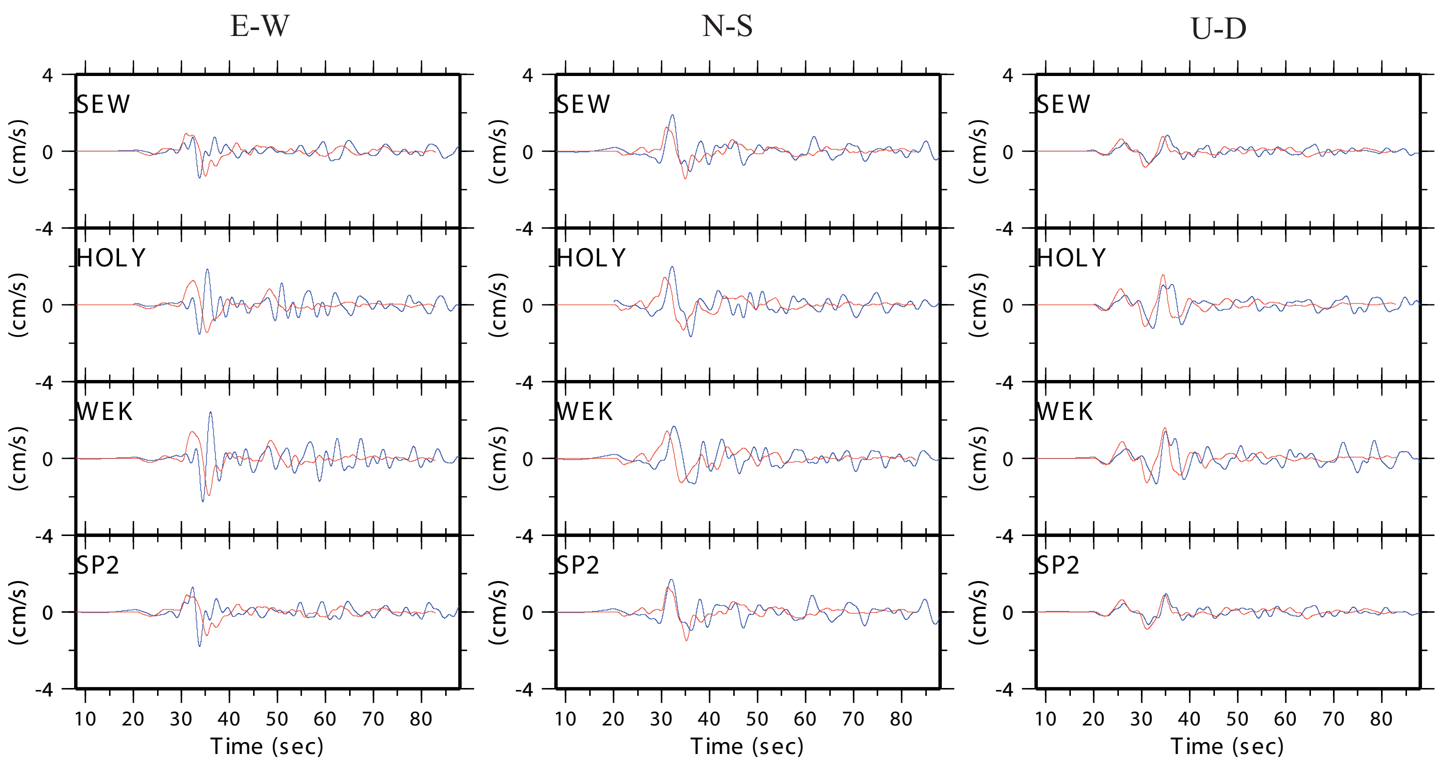

Figure 4. ... continued

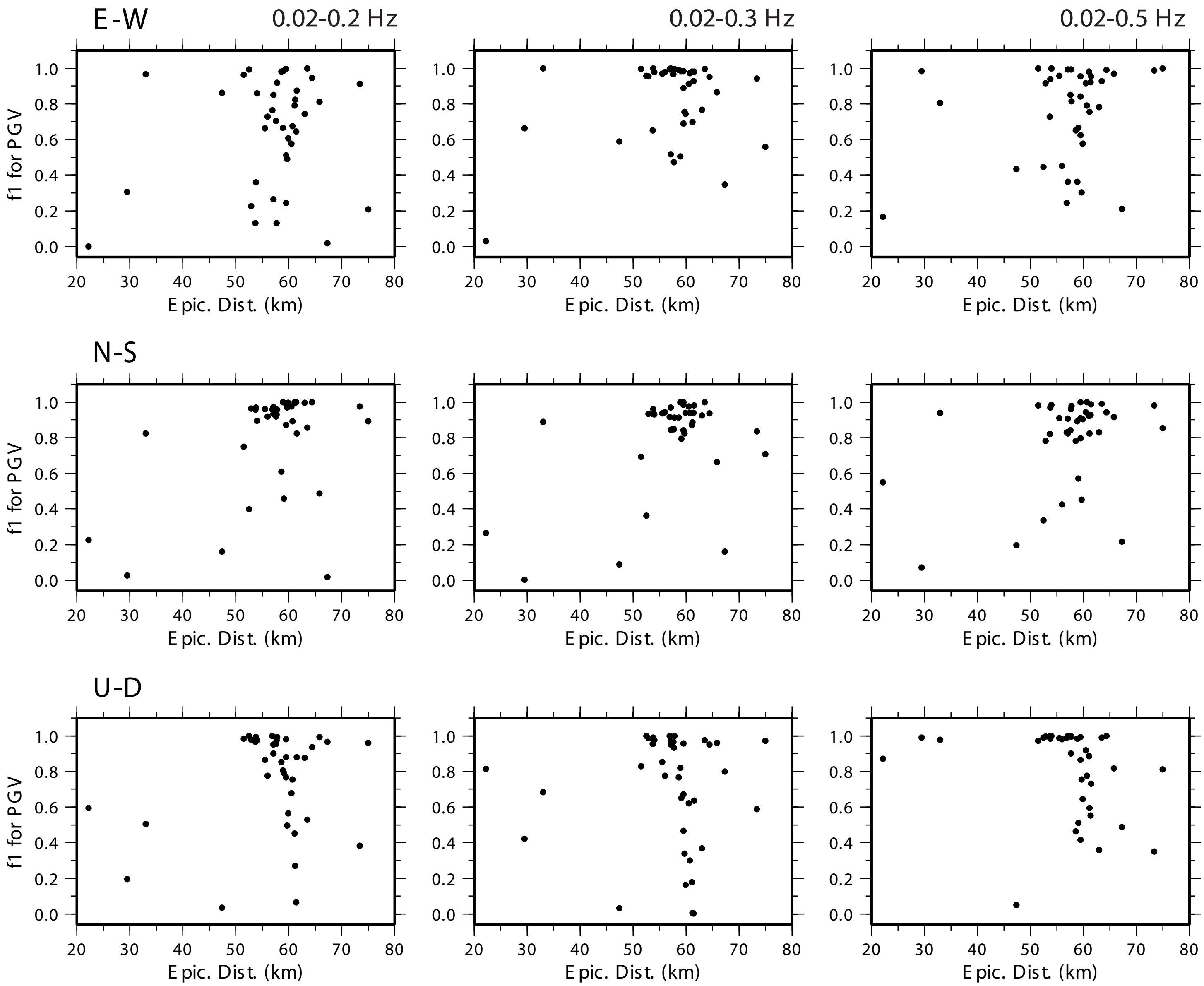

Figure 5a. Goodness-of-fit factor f1 for peak ground velocity measured at three frequency ranges indicated on first row panels.

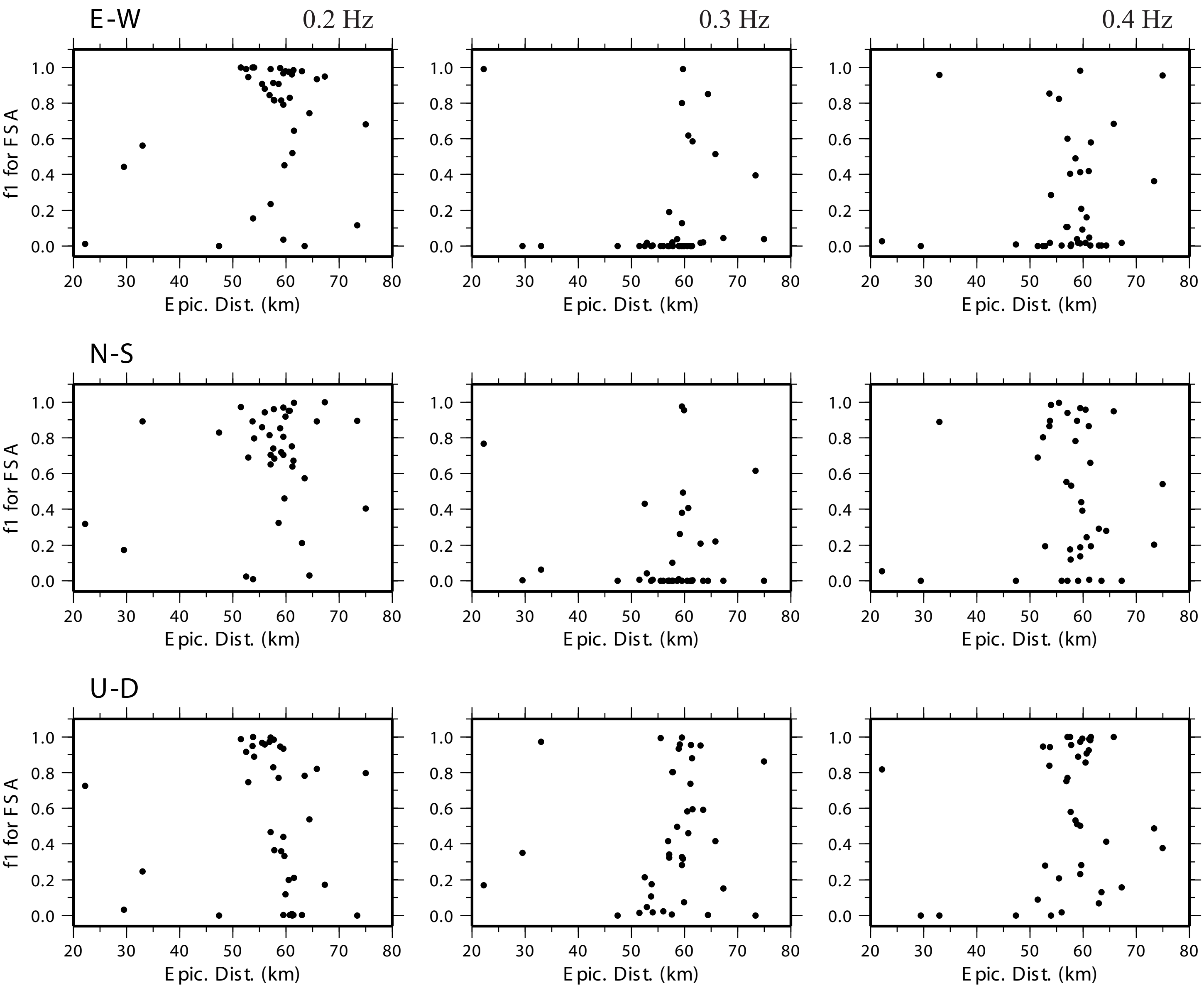

Figure 5b. Goodness-of-fit factor f1 for Fourier amplitude spectrum of velocity calculated at 0.2 Hz, 0.3 Hz and 0.4 Hz.

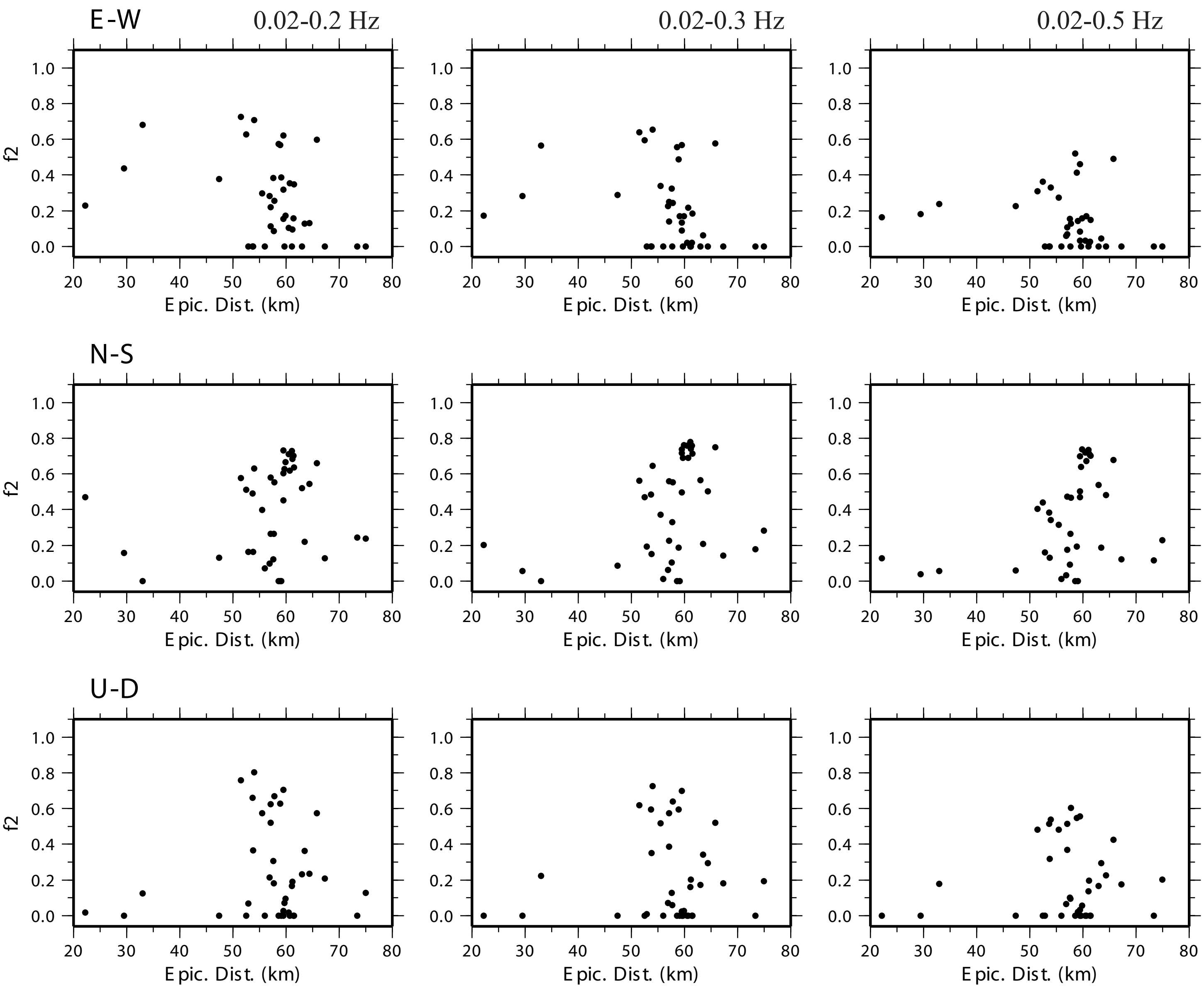

Figure 5c. Goodness-of-fit factor f2 for velocity ground motion seismograms band-pass filtered at three frequency bands indicated on the top row panels.

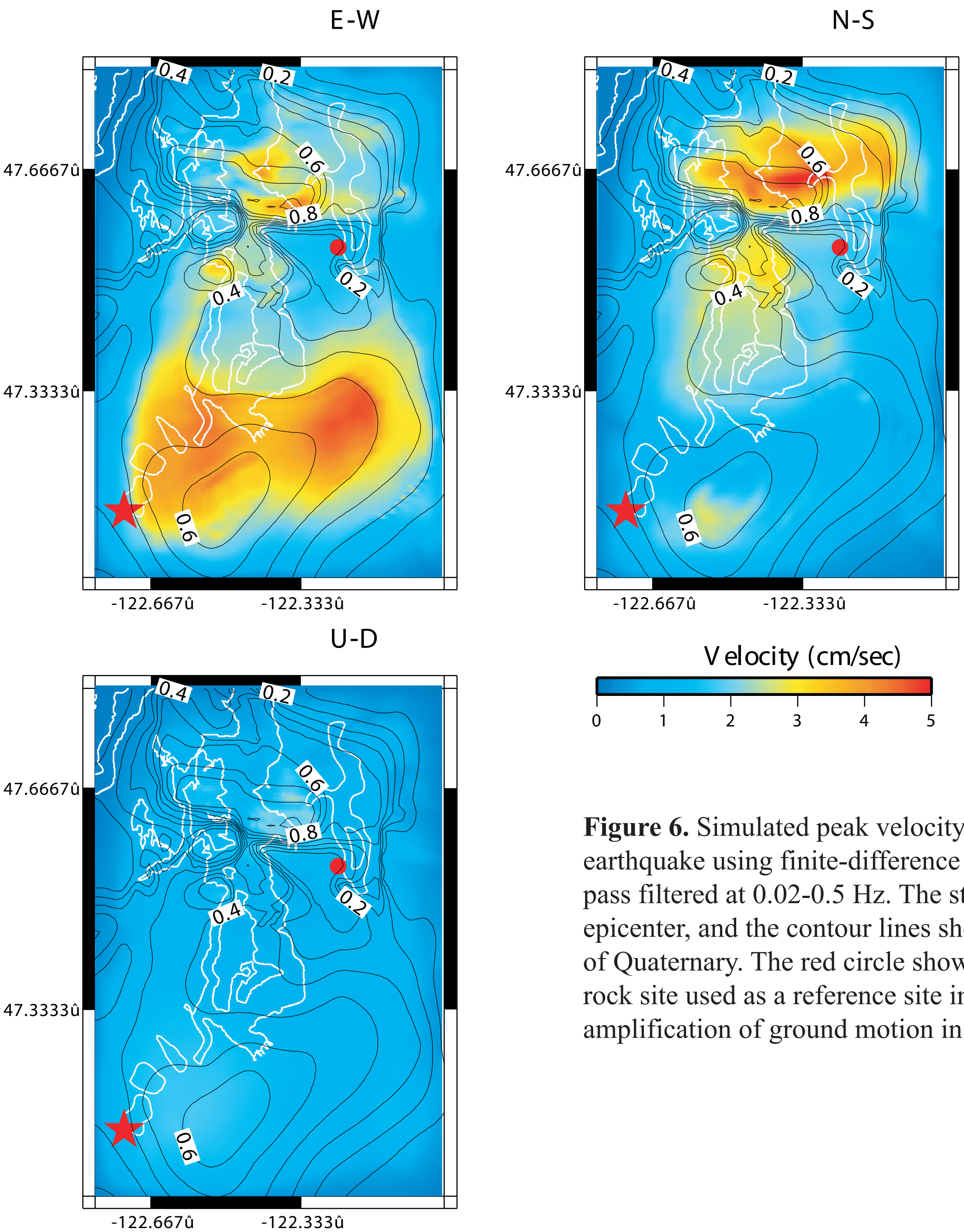

Figure 6. Simulated peak velocity for the Nisqually earthquake using finite-difference seismograms band-pass filtered at 0.02-0.5 Hz. The star indicates the epicenter, and the contour lines show the depth to base of Quaternary. The red circle shows the location of the rock site used as a reference site in estimating the relative amplification of ground motion in the Seattle basin.

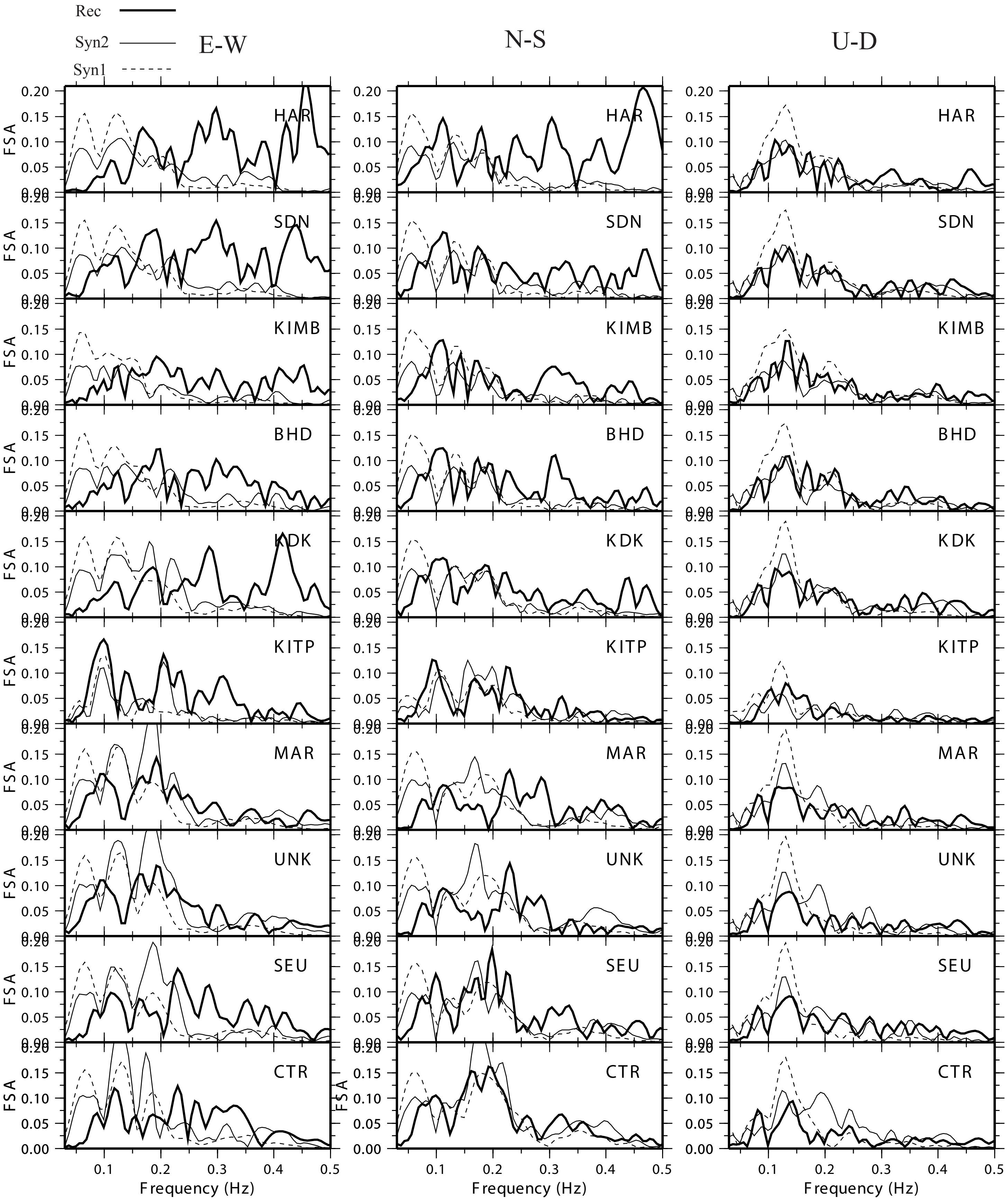

Figure 7. Comparison of Fourier amplitude spectra using recorded (thick line) and synthetic ground motion velocity computed using the 3D basin model (thin line), and a modified version of the 3D basin model without the Quaternary layer (dotted line).

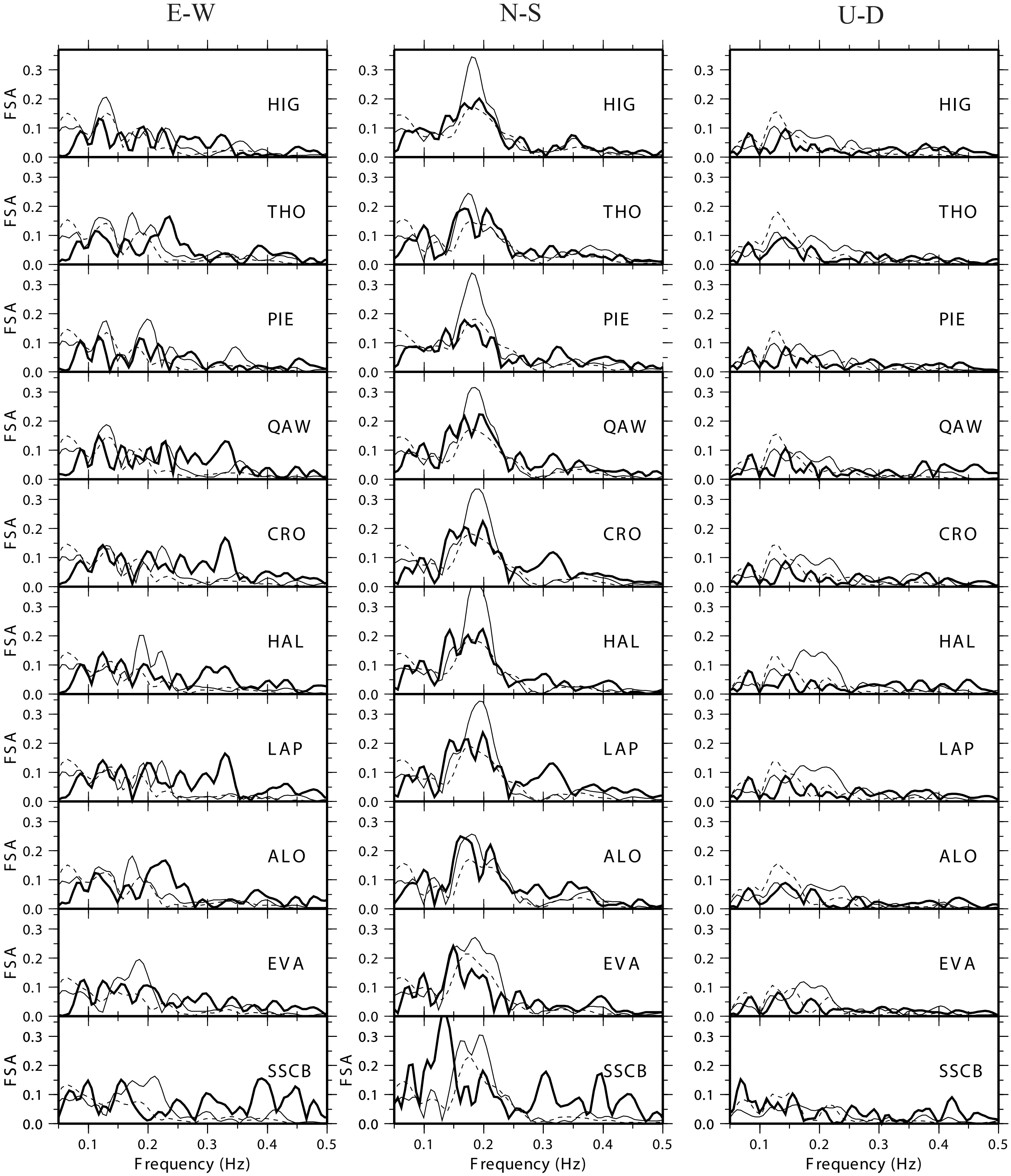

Figure 7. ... continued

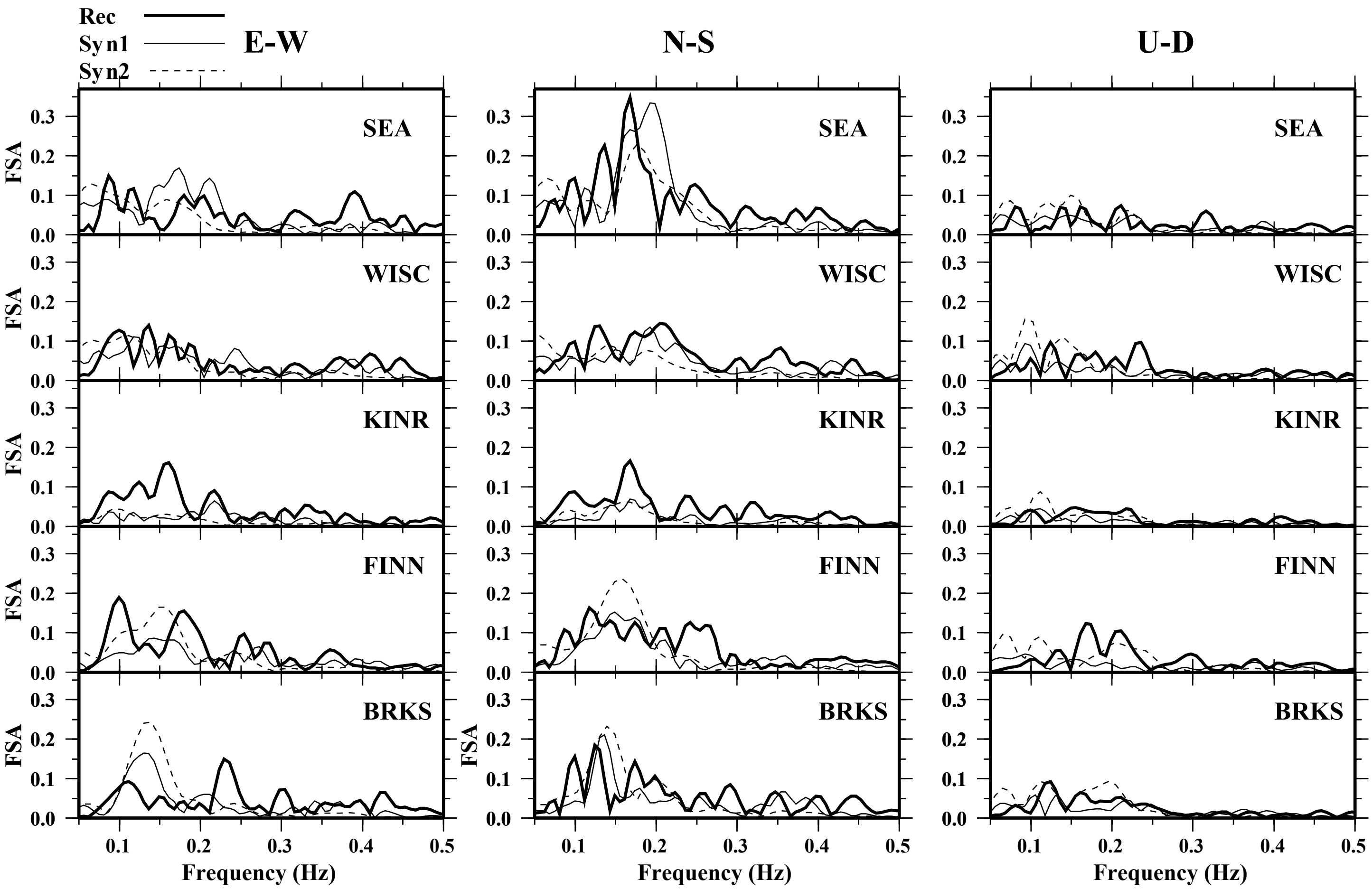

Figure 7. ... continued

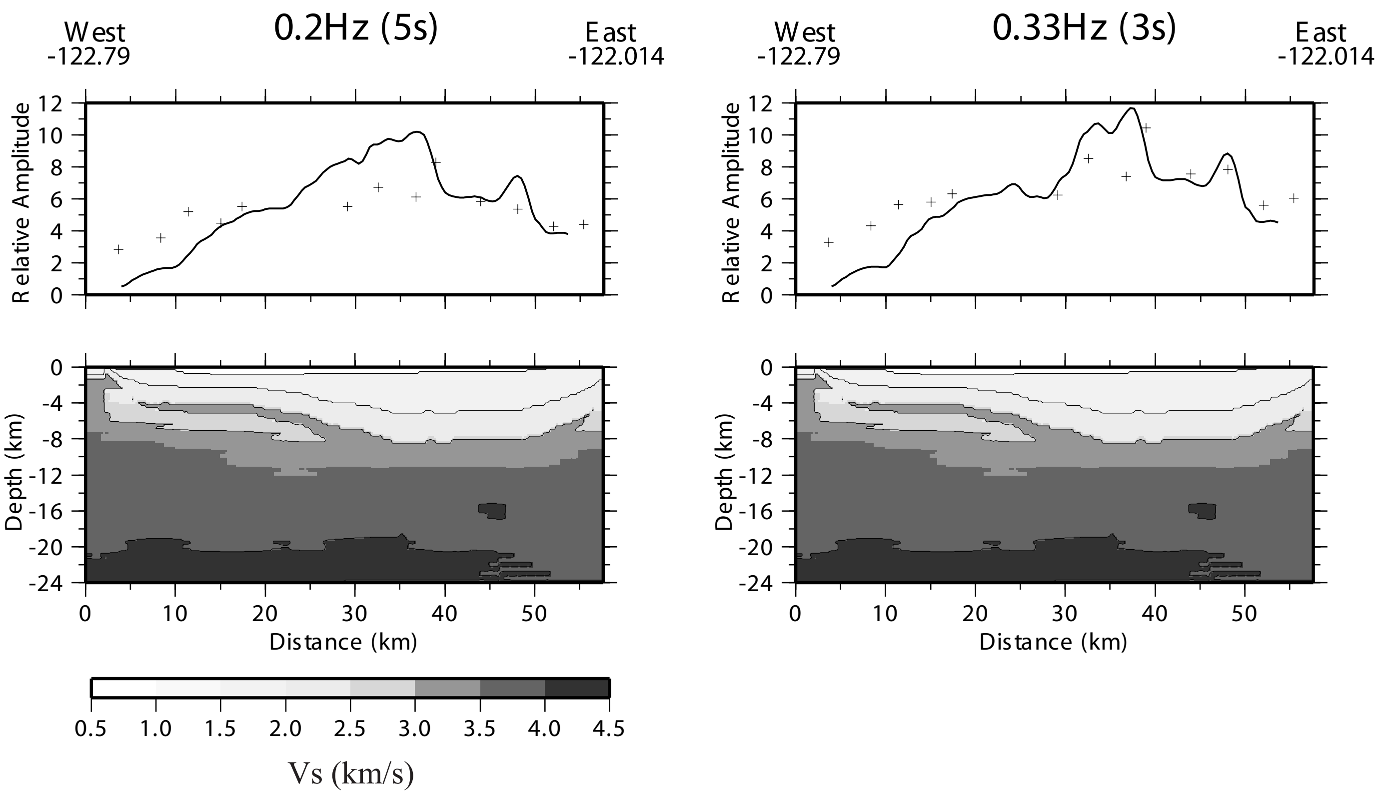

Figure 8. Spectral amplitudes at specific frequencies relative to the rock site indicated in Figure 6.
Top panels. Comparison of spectral amplitudes using synthetic seismograms from the Nisqually earthquake (solid line) and recorded ground motion from the Chi-chi , Taiwan earthquake (crosses) (Pratt et al., 2003) along the E-W line shown in Figure 1.
Bottom panels. Vertical cross-section of the 3D velocity model used in calculating synthetic seismograms along the E-W line.