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3D crustal structure and long-period ground motions from a M9.0 megathrust earthquake in the Pacific Northwest region

Kim B. Olsen · William J. Stephenson · Andreas Geisselmeyer

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Abstract We have developed a community velocity model for the Pacific Northwest region from northern California to southern Canada and carried out the first 3D simulation of a M_w 9.0 megathrust earthquake rupturing along the Cascadia subduction zone using a parallel supercomputer. A long-period (<0.5 Hz) source model was designed by mapping the inversion results for the December 26, 2004 Sumatra–Andaman earthquake (Han et al., *Science* 313(5787):658–662, 2006) onto the Cascadia subduction zone. Representative peak ground velocities for the metropolitan centers of the region include 42 cm/s in the Seattle area and 8–20 cm/s in the Tacoma, Olympia, Vancouver, and Portland areas. Combined with an extended duration of the shaking up to 5 min, these long-period ground motions may inflict significant damage on the built environment, in particular on the highrises in downtown Seattle.

Keywords Finite-difference simulation · Long-period ground motion · Megathrust earthquake

1 Introduction

Around 9:00 P.M. local time, on January 26th, 1700, a giant earthquake struck the Pacific Northwest (approximately magnitude 9), caused by movement of the Juan de Fuca plate beneath the North American plate along the Cascadia subduction zone (see Fig. 1) in the Pacific Northwest region (Ludwin et al. 2005). The ~1,000-km-long plate boundary poses one of the largest earthquake hazards in the Pacific Northwest region. Paleoseismic studies reveal a long history of large earthquakes (moment magnitudes larger than 8, hereafter referred to as megathrust events) with a recurrence period of approximately 500 years (Heaton and Hartzell 1986; Atwater and Hemphill-Haley 1997). No earthquake of such magnitude has occurred since the deployment of strong ground motion instruments in the Pacific Northwest, and a large uncertainty is associated with the ground motions expected from such an event. In addition, three major metropolitan areas are located in the model region namely, Seattle (3 million+ people), Vancouver (2 million+ people), and Portland (2 million+ people), all located above sedimentary basins prone to amplify the waves

K. B. Olsen (✉)
Department of Geological Sciences,
San Diego State University,
5500 Campanile Dr.,
San Diego, CA 92182, USA
e-mail: kbolsen@sciences.sdsu.edu

W. J. Stephenson
US Geological Survey,
1711 Illinois Street,
Golden, CO 80401, USA

A. Geisselmeyer
Ulm University,
89069 Ulm, Germany

generated by a megathrust event. Therefore, it is imperative to estimate the level of ground motion to be expected in a future large subduction earthquake in the Pacific Northwest region. In this paper, we present a 3D community velocity model (CVM) for the Pacific Northwest region extending from southern Canada to northern California and use the model to compute the first 3D simulation of a M9.0 megathrust earthquake nucleating in the Cascadia subduction zone.

2 Community velocity model for the Pacific Northwest

Several ground motion modeling studies (e.g., Frankel and Stephenson 2000; Pitarka et al. 2004) have found strong basin effects for local earthquakes in the Seattle region, including basin-edge effects and amplification with basin depth. These studies show that a detailed 3D model of the Puget Sound Region is necessary to obtain realistic ground motions. To provide a model for estimation of ground motions, in particular for large megathrust earthquakes in the Cascadia subduction zone, we have developed a 3D CVM version 1.3 of the crust and mantle in the Pacific Northwest (Stephenson 2007). The areal extent of the model is shown in Fig. 1.

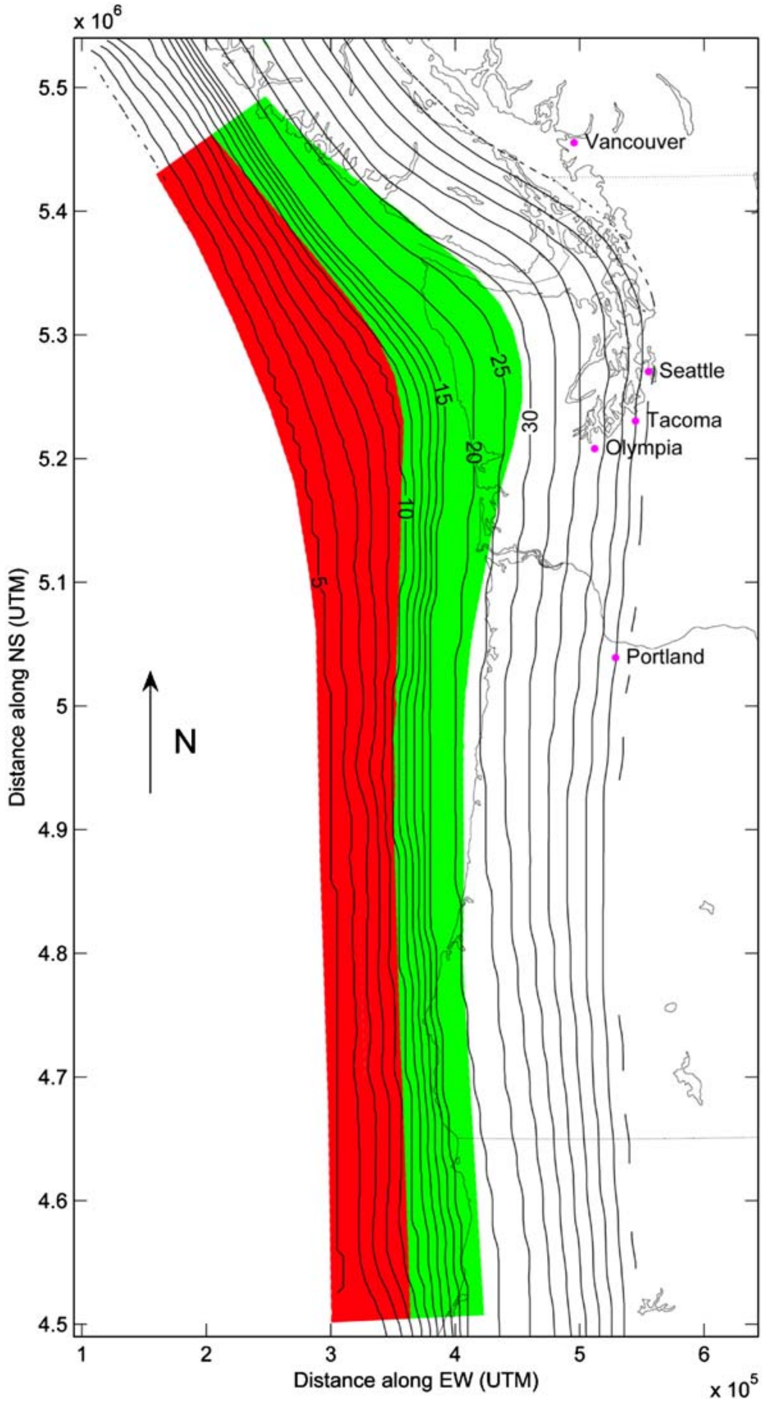
The model consists of six geologic units: continental sedimentary basins, continental crust, continental mantle, oceanic sediments, oceanic crust, and oceanic mantle. The Seattle fault represents the only other fault incorporated in the model, in addition to the Cascadia megathrust, because of its role as a seismogenic source in the Seattle Urban Hazards Maps (Frankel et al. 2007). The Seattle fault trace was extracted from Blakely et al. (2002) and projected to a depth of about 20 km assuming a 45° dip toward south. The P-wave velocity was derived for each unit from the available data. Except for the continental sedimentary basins, all densities and the S-wave velocities were then derived from the empirical relationship with the P-wave velocity by Brocher (2005). The minimum and maximum densities were constrained to 2,000 and 3,500 kg/m^3, respectively.

The continental sedimentary basins are subdivided into Quaternary and Tertiary geologic units. The thickness of the Quaternary deposits through the southern Puget Lowland was compiled by Jones (1996) and Johnson et al. (1999) and used by Frankel and Stephenson (2000) for ground motion modeling in the Seattle basin. The data of Mosher and Johnson (2000) were incorporated to create the Quaternary–Tertiary interface in the Puget Lowland. A 1D profile of V_p was derived for the Quaternary deposits from land measurements and high-resolution marine seismic surveys (e.g., Williams et al. 1999; Calvert et al. 2003) with values of 1,500, 1,905, and 1,980 m/s at 0, 200, and 1,000 m depth, respectively. Quaternary V_s was then derived from V_s30 and V_p30 measurements by constraining the V_p/V_s ratio at the surface and 1 km depth to approximately 2.5 and 2.2, respectively.

The base of the Tertiary sediments within the Puget Lowland is inferred to be at the 4,500-m/s isosurface, based on oil industry data (Brocher and Ruebel 1998). This isosurface was extracted from the Seismic Hazards Investigation in Puget Sound (SHIPS) and 3D P-wave earthquake data tomography from Ramachandran et al. (2006) that incorporates the same or similar data from many previous tomography studies in the Puget Lowland (e.g., Stanley et al. 1999; Brocher et al. 2001; Van Wagoner et al. 2002). The Willammette Valley basin deposits in the Portland area are derived from well data intersecting crystalline rocks under generally Tertiary deposits (Yeats et al. 1996; Gannett and Caldwell 1998). Quaternary deposits are generally less than 30 m thick and are currently not included in the model. V_p of the Tertiary deposits in the Puget Lowland basins is based on tomography results from SHIPS and local earthquake data as calculated by Ramachandran et al. (2006). A V_p depth structure similar to that of the Puget Lowland is assumed for the Willammette Valley, while V_s is estimated assuming a constant V_p/V_s ratio of 2.

The top of the continental crust below mean sea level was controlled by the smoothed continental shoreline as well as results of numerous published active and passive source studies along the continental margin (e.g., Trehu et al. 1994; Clowes et al. 1997; Flueh et al. 1998; Fuis 1998; Gulick et al. 1998; Fleming and Trehu 1999; Parsons et al. 1999; Stanley and Villasenor 2000; Bostock et al. 2002; Ramachandran et al. 2006). V_p is derived from the abovementioned studies and, most prominently, from the 3D tomography model of Ramachandran et al. (2006) through the Puget Lowland. The top surface of the continental mantle is derived from data of Chulick and Mooney (2002). We used the tomography of Stanley et al. (1999) from the Puget Lowland area to constrain upper-mantle V_p by

Fig. 1 The subduction slab in the Cascadia area (contours in kilometers below sea level). *Red* and *green colors* depict estimates of the locked and transition zones, respectively, from Fluck et al. (1997)



extrapolating a generalized V_p-depth structure throughout the unit.

The ocean sediment unit represents accreted and sedimentary deposits overlying the top of the continental crustal unit and underlying the eastern portion of the bathymetric surface. V_p is derived from 3D tomography results of Parsons et al. (1999) and numerous active-source marine seismic surveys (e.g., Trehu et al. 1994; Flueh et al. 1998; Fuis 1998; Gulick et al. 1998; Fleming and Trehu 1999). The top of the oceanic crustal unit is based on bathymetry and the results of Fluck et al. (1997) and McCrory et al. (2005) below the oceanic sediments and is also defined to be the top of the Cascadia megathrust (subducting slab). Based on available marine-reflection data (e.g., Fuis 1998) and studies from other parts of the world (e.g., Turcotte and Shubert 1982), the thickness of the oceanic crust was set to 5 km. V_p was extrapolated from bulk values in marine seismic surveys (e.g., Trehu et al. 1994; Flueh et al. 1998; Fuis 1998; Gulick et al. 1998; Fleming and Trehu 1999; Ramachandran et al. 2006). Finally, the top of the oceanic mantle is derived by down projecting the top of the oceanic crust 5 km and smoothing the resulting surface. V_p was set to vary from 7.9 to 8.3 km/s between 10 and 60 km depth, respectively.

An isosurface of a constant shear-wave velocity of 2,500 m/s is shown in Fig. 2. Notice the thick layer of

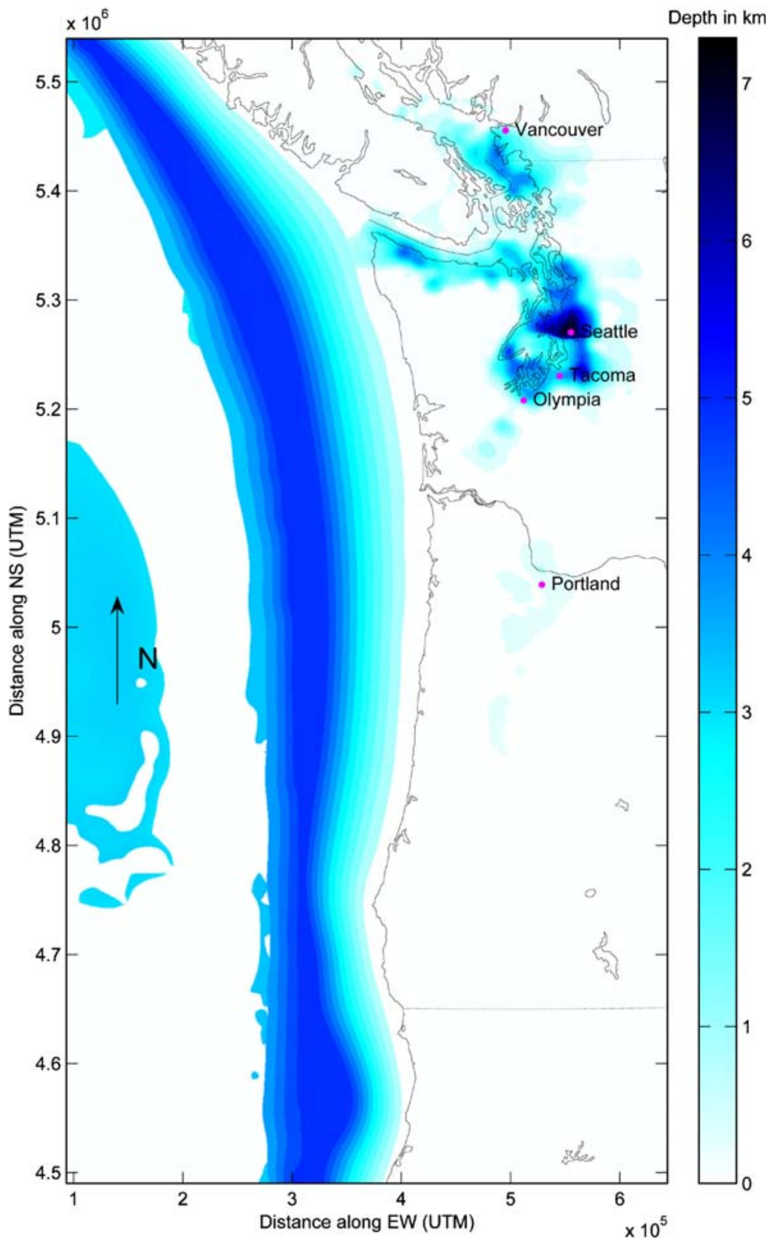


Fig. 2 Isosurface of a shear-wave velocity of 2,500 m/s in the Cascadia 3D CVM V1.3

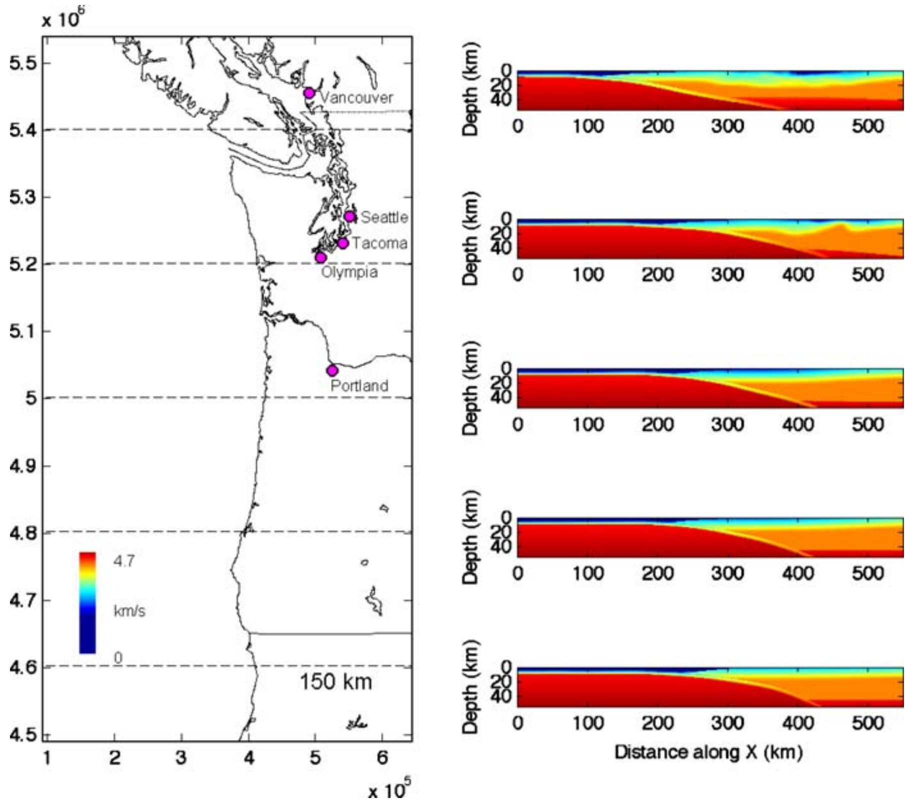


Fig. 3 Cross-sections of the S-wave velocity (*right*) along 5 E–W profiles (*left*) in the Pacific Northwest CVM V1.3

oceanic sediments along the coast in the model, as well as the sedimentary basins in the Seattle and Vancouver areas. The east–west cross-sections of the model in Fig. 3 show the north–south variation in geometry of the Cascadia subduction zone, including the subducting slab. Surface topography is not included in the CVM V1.3.

3 Source model for a M9.0 megathrust scenario

Because the most recent megathrust event in the Cascadia subduction zone dates back more than 300 years, no seismological data for such an event is available to constrain the earthquake rupture parameters specific to this area. Instead, we have used a source characterization derived from the December 26, 2004 M_w 9.1–9.3 Sumatra–Andaman earthquake, which generated an unprecedented amount of seismic data. Specifically, we used an inversion result updated from Han et al. (2006; Ji, personal communication, 2006).

The shape and extent of the Sumatra and Cascadia subduction zones are reasonably similar. However, some adjustments were necessary to map the results for the Sumatra–Andaman earthquake onto the Cascadia subduction zone. The slip inversion considered by Han et al. (2006) approximated the rupture plane for the Sumatra–Andaman earthquake by six planes with dips of 6–8 1/4° for the shallow part and 15–25° for the deeper sections (see Fig. 4). The two northernmost planes, where limited moment release occurred (see Fig. 4), were discarded because of the smaller area of the Cascadia subduction zone. The two southernmost rupture planes from the Sumatra–Andaman source inversion were translated and rotated to align with the strike (226°), dip, and depth of the northernmost part of the Cascadia subduction zone with nucleation point in the deeper northern end (see Fig. 4). The two central rupture planes were translated and rotated to match the north–south striking central and southern part of the subduction slab in the Cascadia model, with subfault dimensions of 4 by 4 km. The sources were then inserted into the uppermost part of the subduction slab

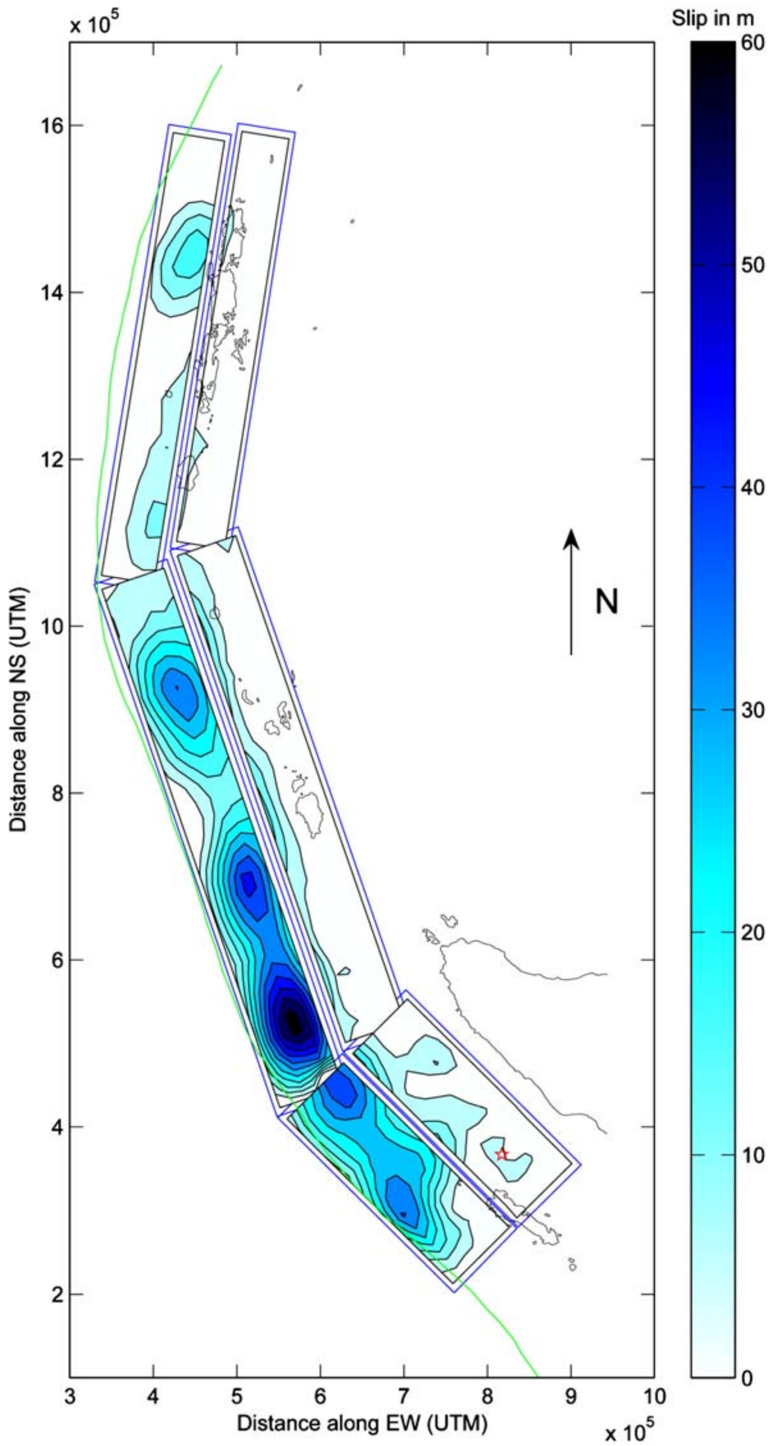


Fig. 4 Slip distribution for the M9.3 Sumatra–Andaman earthquake (Han et al. 2006)

dipping between 6 and 21° in the model area (see Figs. 5 and 6).

The translation of the slip considered constraints from dislocation modeling and the thermal regime on the depth distribution of expected slip. In particular, the Cascadia subduction zone can be divided into a locked zone (~4–12 km depth) and a transition zone (~13–30 km depth) toward the east, with the majority

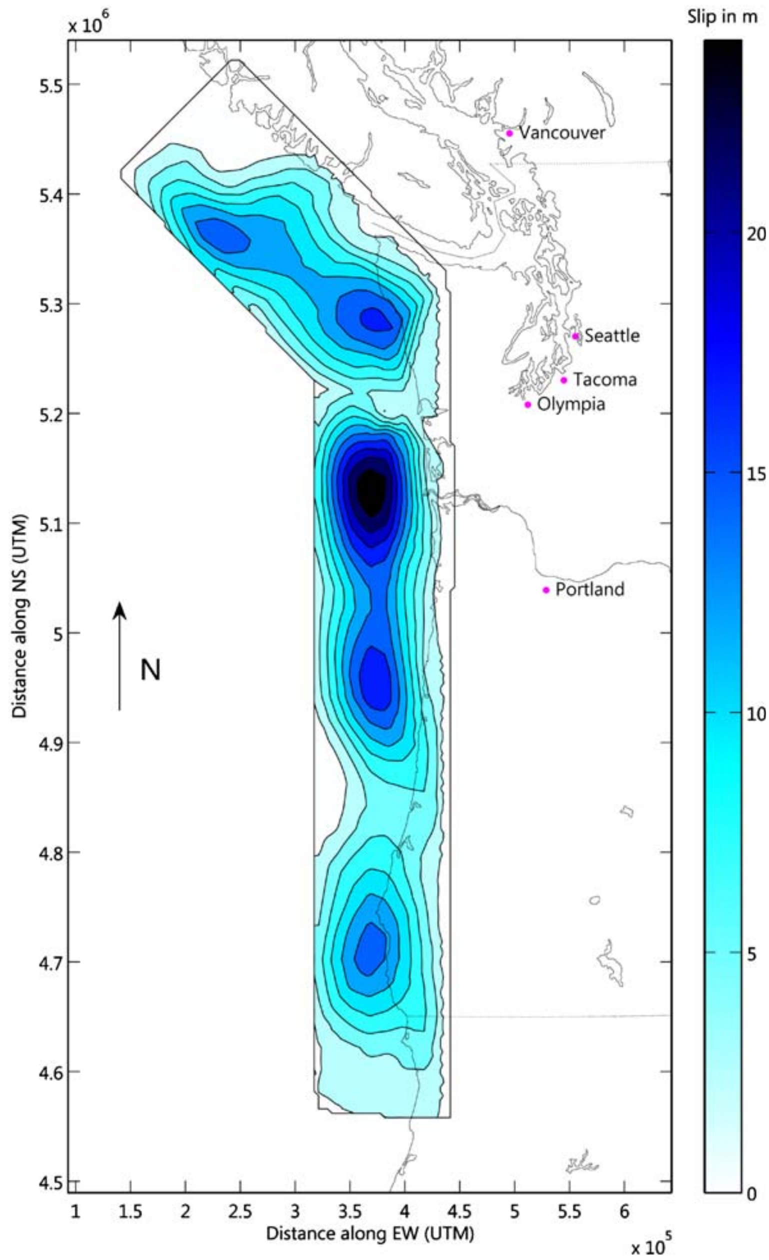


Fig. 5 Slip distribution used in the Cascadia megathrust scenario simulation

of the slip expected to occur in the locked zone (Fluck et al. 1997). The slip distribution was scaled to a M_w 9.0 event and translated from the Sumatra–Andaman results to reflect this trend, assuming a rupture nucleation point at about 20 km depth (Fig. 6). The maximum and average slip for the M_w 9.0 scenario was 22 and 6.3 m, respectively. The rupture initiation times were taken from the slip inversion and mapped into the Cascadia model (see Fig. 6). The distribution of rupture initiation times from the source inversion generated an average rupture velocity of about 2.5 km/s, corresponding to 55–70% of the local shear-wave velocity on the Cascadia subduction slab. We used the double-triangle representation of sliprate functions as proposed by Graves and Pitarka (2004), with rise times obtained from the inversion for the Sumatra–Andaman earthquake. The mean and maximum rise times for the source were 32 and 59 s,

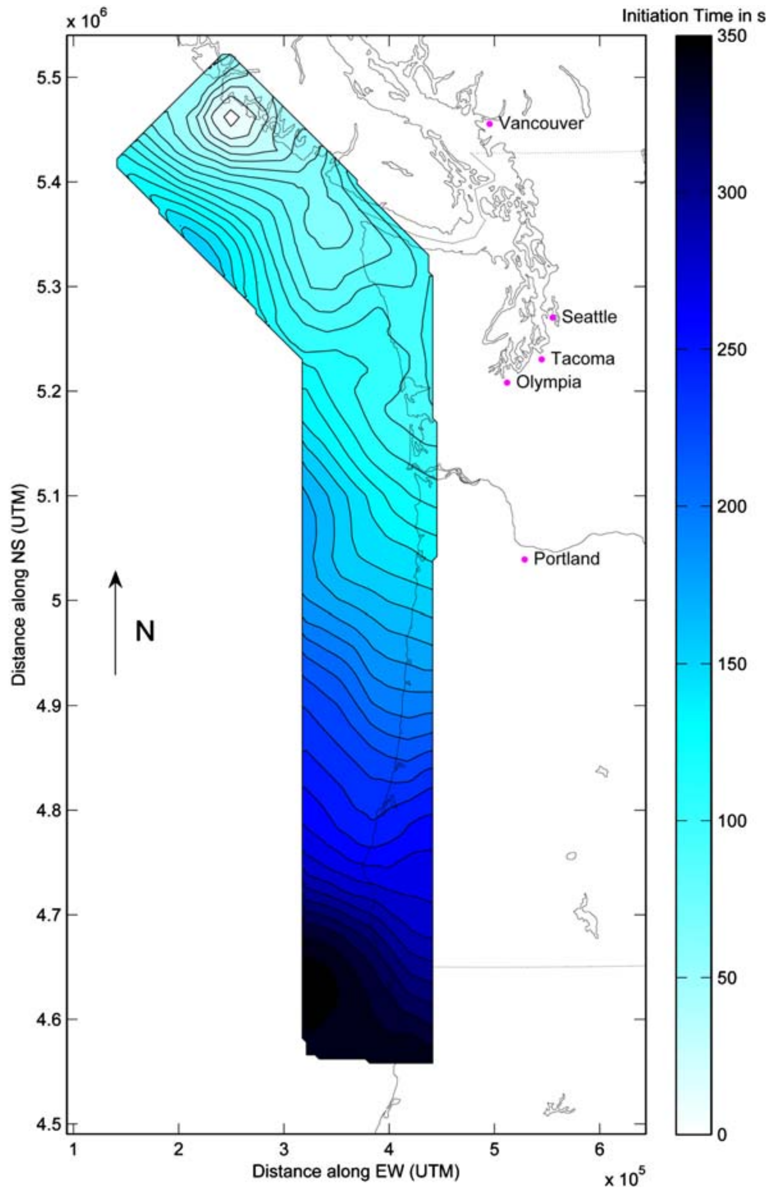


Fig. 6 Rupture time distribution used in the Cascadia megathrust scenario simulation

respectively. Finally, the rake was generated as a randomized distribution between 45 and 135°. Thus, our source description includes considerable complexity in all parameters, a requirement to ensure realistic ground motions in the surrounding areas. For example, Olsen et al. (2008) found that the maximum PGVs in Los Angeles were reduced considerably using a source description for M_w 7.7 southern San Andreas fault scenarios with strong variation in rupture speed and pulse shape, as compared to those generated by a source with fixed pulse shape and constant rupture velocity (Olsen et al. 2006).

4 Numerical modeling parameters

The megathrust ground motion simulation was carried out using a fourth-order staggered-grid finite-difference code (Olsen 1994) with a coarse-grained implementation of the memory variables for a constant-Q solid

(Day and Bradley 2001) and Q relations from Olsen et al. (2003). The model dimensions are 1,050 km along north–south, 550 km along east–west, and 55 km along vertical, corresponding to 2,200 by 4,200 by 220 or approximately 2 billion grid points with a spatial resolution of 250 m throughout the grid. The ocean water is included in the model, represented by V_p= 1,500 m/s, V_s=0 m/s, and a density ρ=1025 kg/m^3. We use the Cerjan et al. (1985) absorbing boundary conditions and simulated 6.5 min of ground motion in the Pacific Northwest CVM for the megathrust event. The minimum velocity included in the computational model was 625 m/s because of computational limitations, only marginally higher than the minimum S-wave velocity of 600 m/s in the 3D Cascadia CVM V1.3. The simulation took about 40 wall clock hours on the ten teraflops IBM Power4+ DataStar supercomputer at the San Diego Supercomputer Center (SDSC) using 1600 processors communicating via the message-passing interface.

5 Results

The peak ground velocities (PGVs) in the model area are shown in Fig. 7. The maximum onshore velocities are found along the coastline and reach about 105 cm/s, just south of the entrance to the Puget Sound, where an asperity in the rupture zone extends below the continental crust. The ground motions generally subside eastward away from the subduction zone, with local amplification above the sedimentary basins, e.g., in the Seattle and Tacoma areas. Offshore PGVs are estimated on the ocean bottom.

Of particular interest is the level of ground motion expected in the population centers of the model. The velocity seismograms predicted for the five most populous cities within the model extent (Vancouver, Seattle, Tacoma, Olympia, and Portland) are shown in Fig. 8, and their PGVs are listed in Table 1. Of the five urban areas, Seattle experiences the largest motions in the scenario, with peak velocities reaching 42 cm/s, amplified by the underlying sedimentary basins in the Puget Sound (e.g., Frankel and Stephenson 2000). PGVs reach about 20 cm/s in Tacoma, 16 cm/s in Olympia, 10 cm/s in Vancouver, and 8 cm/s in Portland. The larger motion in Seattle, as compared to the other cities, is caused by a deeper underlying sedimentary basin (see Fig. 2 for depths to the V_s= 2,500 m/s isosurface).

While the peak ground motions predicted in the larger cities in the Pacific Northwest for the megathrust earthquake are sufficiently large to cause damage on the built environment, particularly for Seattle, the extended duration of the ground motions poses an additional concern. Two to five min of long-period ground motions can be expected from the scenario (see Fig. 8), which may significantly weaken buildings. In particular, such duration of long-period ground motion may be a problem for highrises, with the largest concentration in downtown Seattle.

6 Discussion and conclusions

We have simulated wave propagation for a megathrust earthquake nucleating in the Cascadia subduction zone in a new 3D CVM of the Pacific Northwest. The largest onshore long-period ground velocities are found along the coast, close to the largest asperities in the earthquake slip distribution, with the largest values near the entrance to the Puget Sound (~105 cm/s). Our simulation provides the first area-wide estimates of the ground motions to be expected from such an event, including the large urban areas of the Pacific Northwest, such as Vancouver, Seattle, and Portland. Seattle experiences the largest long-period PGVs (42 cm/s), while the values for Portland and Vancouver are much smaller (≤10 cm/s). Two to five min of long-period ground motions are expected in the largest cities. The sedimentary basins of the Pacific Northwest, in particular those in the Seattle area, show strong amplification effects.

The conclusions from this study are subject to several limitations related to the earthquake source. We have only modeled a single scenario of a megathrust earthquake in the Cascadia subduction zone. We have no evidence for a preferred rupture direction in the Cascadia subduction zone, and the modeled event with nucleation toward the North is only one of many possible rupture scenarios. Because the resulting ground motion is expected to be strongly dependent on the rupture propagation, future efforts should consider additional scenarios with different source parameters, in particular hypocentral location and slip distribution. The rise times for the megathrust

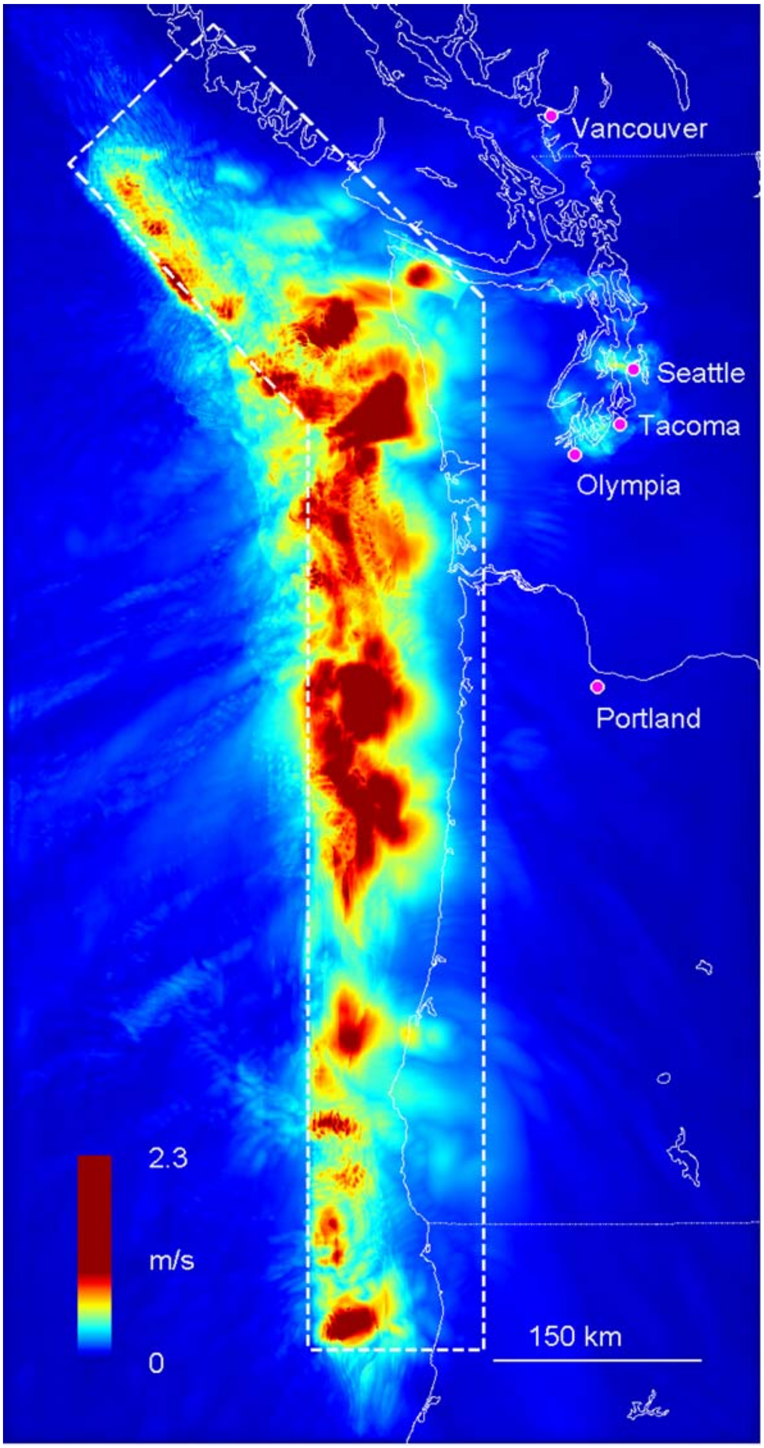


Fig. 7 PGVs computed in the Pacific Northwest for the M_w 9.0 megathrust earthquake

source inferred from the 2004 Sumatra–Andaman earthquake were relatively long, compared to those expected from the empirical relation by Somerville et al. (1999). The relatively long rise times are limiting the PGVs to values less than about 2.3 m/s on the sea bottom above the subduction zone, more than a factor of two smaller than the maximum near-fault PGVs produced by M_w 7.7 earthquake scenarios on the San

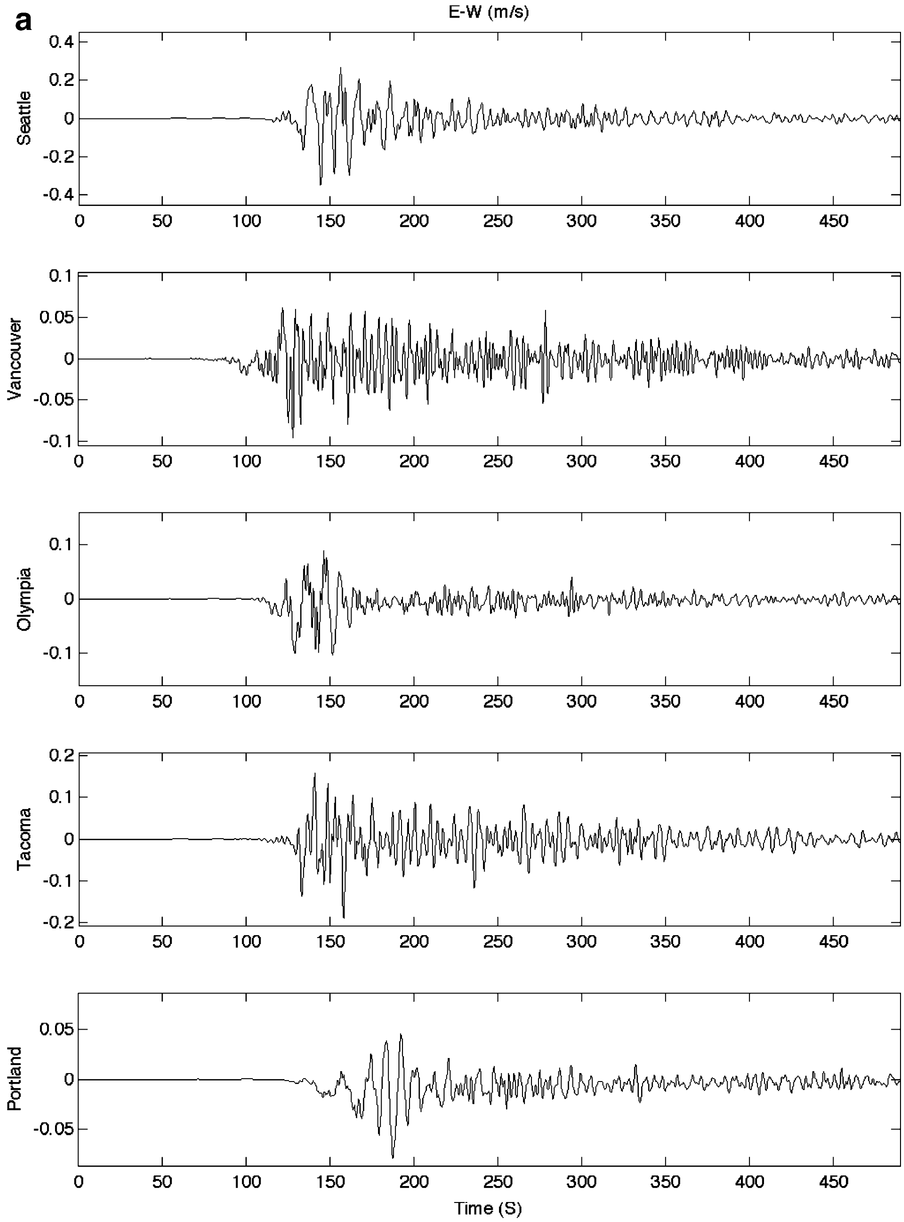


Fig. 8 **a** E–W ground velocities at selected sites (see maps). **b** N–S ground velocities at selected sites (see maps). **c** Vertical ground velocities at selected sites (see maps)

Andreas fault (Olsen et al. 2006, 2008). Future work should examine the effects of decreasing the rise times in the megathrust source time functions and include constraints from studies on large subduction earthquakes when available. Finally, as an alternative to the large M9 megathrust scenarios simulated in this study, a series of smaller (~M8.5) events may effectively release the strain energy accumulated in the Cascadia subduction zone and should be considered in future ground motion estimates for the region.

The resolution of the velocity model for the Pacific Northwest varies strongly within the area considered in this study. The urbanized regions, in particular the sedimentary basins in the Puget Lowland, are generally well constrained. However, other parts of the model, in particular the southern part of the model where

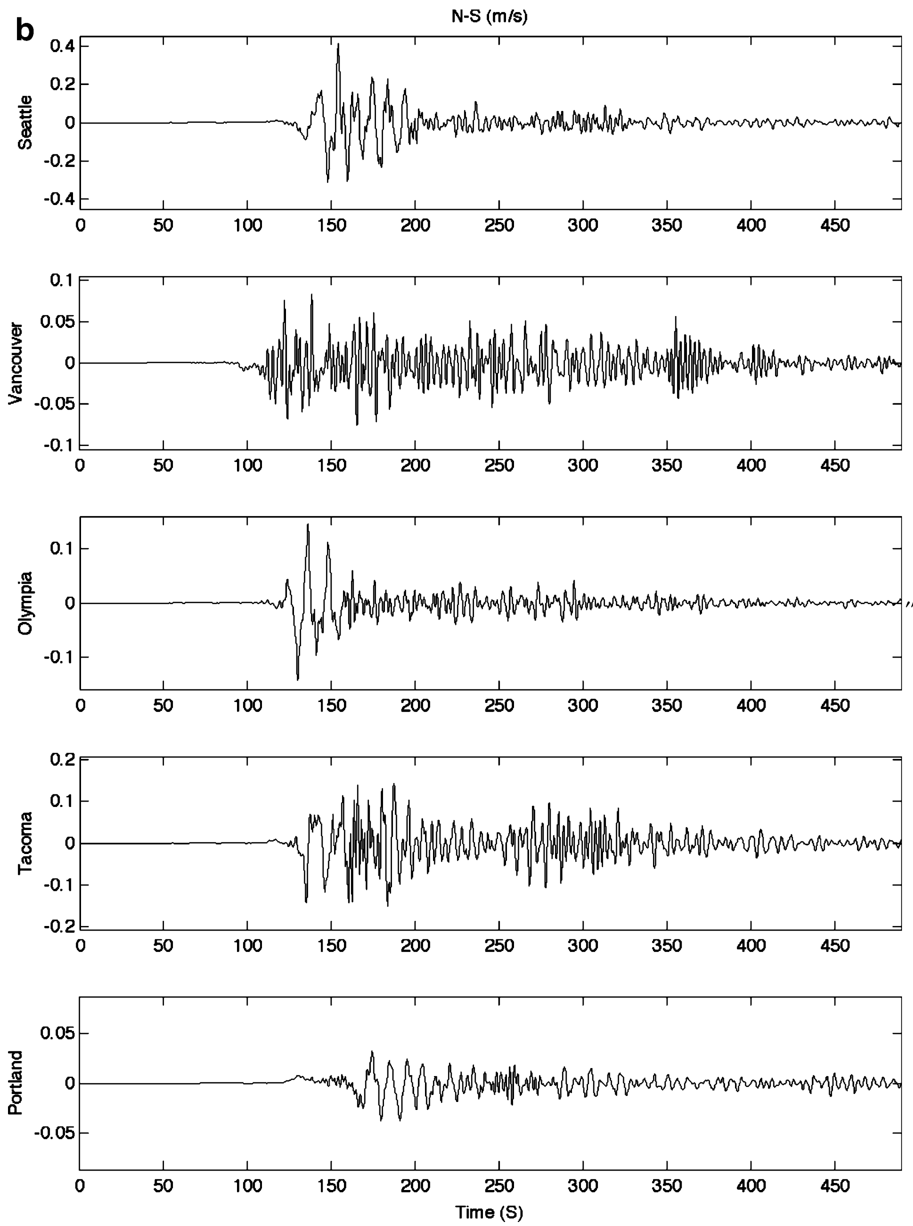


Fig. 8 (continued).

constraints from data are sparse, contain larger uncertainties. For example, little or no information was available to construct the velocity model for most onshore areas south of Olympia, and near-surface shear-wave velocities are likely overestimated (see Fig. 2). Parts of the CVM have already been validated against recorded data (Frankel and Stephenson 2000; Pitarka et al. 2004), and additional validation of the 3D velocity model of the Cascadia subduction zone should be carried out in future studies. Such validation studies should also target the relations for Q_p and Q_s used in this study (Olsen et al. 2003).

Despite these limitations and uncertainties of the CVM and ground motion estimates, our results indicate that the societal impact of a megathrust earthquake in the Pacific Northwest will be enormous.

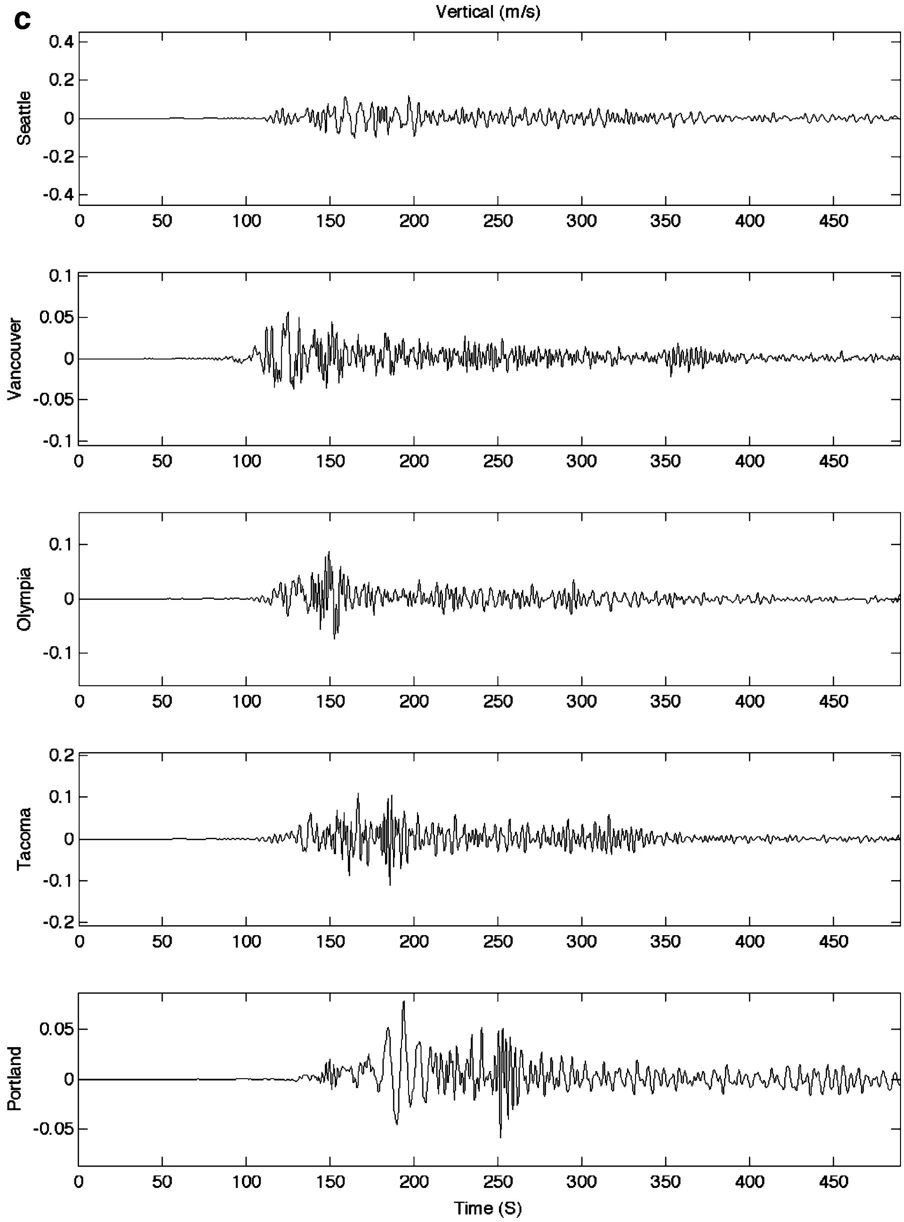


Fig. 8 (continued).

Table 1 Peak ground velocities (cm/s) predicted in five major cities of the Pacific Northwest

Site	EW	NS	V	RMS
Vancouver	10	8	6	10
Seattle	35	41	12	42
Tacoma	19	15	11	20
Olympia	10	15	9	16
Portland	8	4	8	8

Long-period PGVs of tens of centimeters per second in Seattle and surrounding areas (possibly much higher if the rise times obtained from the Sumatra–Andaman are indeed too long) are bound to cause widespread damage, particularly for the highrises in the area. Additional megathrust scenarios should be simulated in the future to more accurately assess the impact on man-made structures and population of the Pacific Northwest.

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